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Andrew Lugg

Energy and Cost Efficient Fuzzy Environmental Services Control Strategies for Achieving High Standards of Indoor Environmental Quality and Human Comfort

Supervisor Dr. William J. Batty

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This thesis is submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy

Abstract

Building designers aim to create buildings with high quality internal environments which are energy and cost efficient in their use. Failure to attain these objectives simultaneously can lead to reduced building occupant productivities. An important aspect of the building services system which can have a major effect on the provision of occupant comfort within a building is the adopted control strategy.
The research project investigated the use of fuzzy control strategies as a means of achieving good standards of comfort provision for occupants while maintaining or improving energy and cost efficiencies for the operation of the building HVAC services. This represented a multi-variant controls objective which was capable of being fulfilled by a fuzzy controller.

A one zone building computer model was developed using Matlab and Simulink software as a platform for the development of fuzzy control strategies. The model incorporated building services Heating Ventilating and Air-Conditioning (HVAC) system models. A Proportional + Integral + Derivative (PID) control strategy was used as a benchmark control methodology against which to compare the developed fuzzy control strategies.

Three types of fuzzy controller were developed during the course of the research project. These were a Proportional Derivative Fuzzy Controller (PDFC), a Fuzzy Ventilation Controller, and the Fuzzy High Level Controller. The PDFC used the inputs of error and rate of change of error from a specified zone environmental condition set point in much the same way as a PID controller would to control the HVAC plant. Simulation results indicated that the PDFC control strategy was capable of achieving performance levels equal to the conventional PID control strategy. The Fuzzy Ventilation Controller was used to control the rate of fresh outside air entering the building zone through the mechanical ventilation system in order to make use of the "free" cooling and dehumidification available by purging the indoor air when possible. Simulation results showed improvements in the indoor environmental quality provided, and the energy efficiency and cost efficiency of running the HVAC plant. Finally, the Fuzzy High Level Controller used a fuzzy supervisor to control the actions of the fuzzy ventilation controllers. Simulation results showed that the fuzzy supervisor was able to improve the comfort conditions provided and the energy and cost efficiencies of the operation of the HVAC plant when compared to the use of the fuzzy ventilation control strategies alone.

Acknowledgements

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1. Introduction

1.1 Providing Comfortable Environments for Building Occupants

Buildings are used to modify the external environment in order that occupants can carry out their desired activities in a comfortable, safe and efficient internal environment. The human body is able to cope with large variations in surrounding environmental conditions for short periods of time, i.e. minutes, although a person may not be comfortable. However, only a relatively small band of environmental conditions provide comfort in which humans can be comfortable and satisfied over longer periods of time, i.e. hours.
Building designers aim to satisfy these requirements by creating buildings with high quality internal environments that are energy and cost efficient in their use. Failure to attain these objectives simultaneously can lead to reduced building occupant productivities.

Buildings have evolved to, and should, provide for various performance requirements including a pleasing appearance, durability, dimensional stability, structural stability, weather exclusion, sound control, thermal comfort, fire protection, adequate lighting, adequate ventilation, adequate sanitation and security. The indoor environment therefore represents a complex interaction between these various parameters.

Many influences affect the quality of the indoor environment and include:-

- the building envelope and internal divisions
- the space conditioning system i.e. Heating, Ventilating and Air Conditioning (HVAC)
- the outdoor environment
- the building occupants and their activities, i.e. people and processes.

Current problems with existing buildings are often the result of:-

- the cooling capacity for which the HVAC system was designed being exceeded due to the introduction of new technology, such as computers,
- the design being focused on energy conservation and the reduction in ventilation rates in many office buildings constructed during the 1970s, especially after the oil crisis, leading to poor indoor environmental quality.

1.2 Influences Affecting the Comfort of Building Occupants

There are many influences affecting the comfort of building occupants; see Figure 1.1.

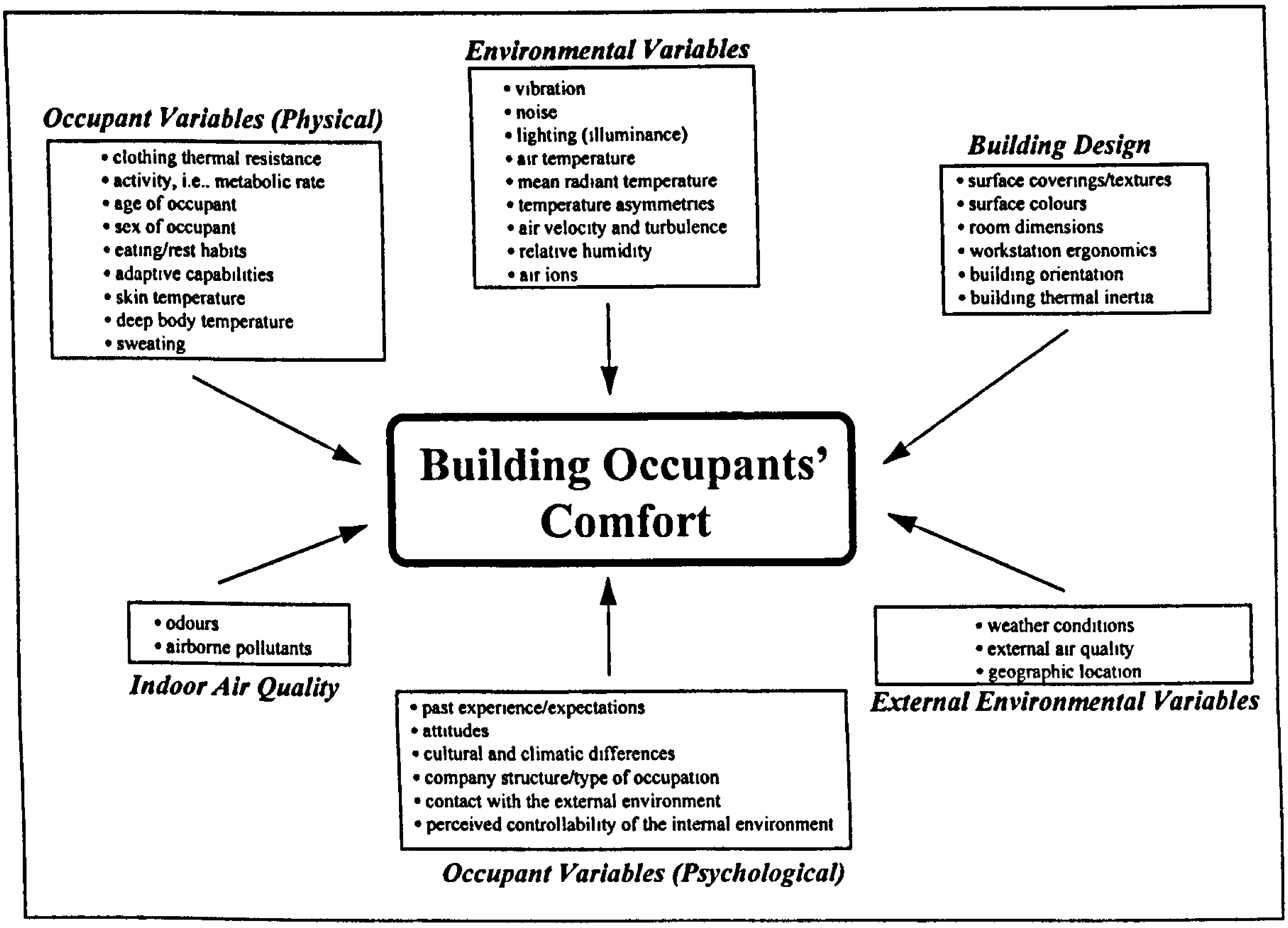

Figure 1.1. Influences affecting the comfort of building occupants.

If occupants are not satisfied with their environment, either physically or psychologically they may experience stress, see Figure 1.2.

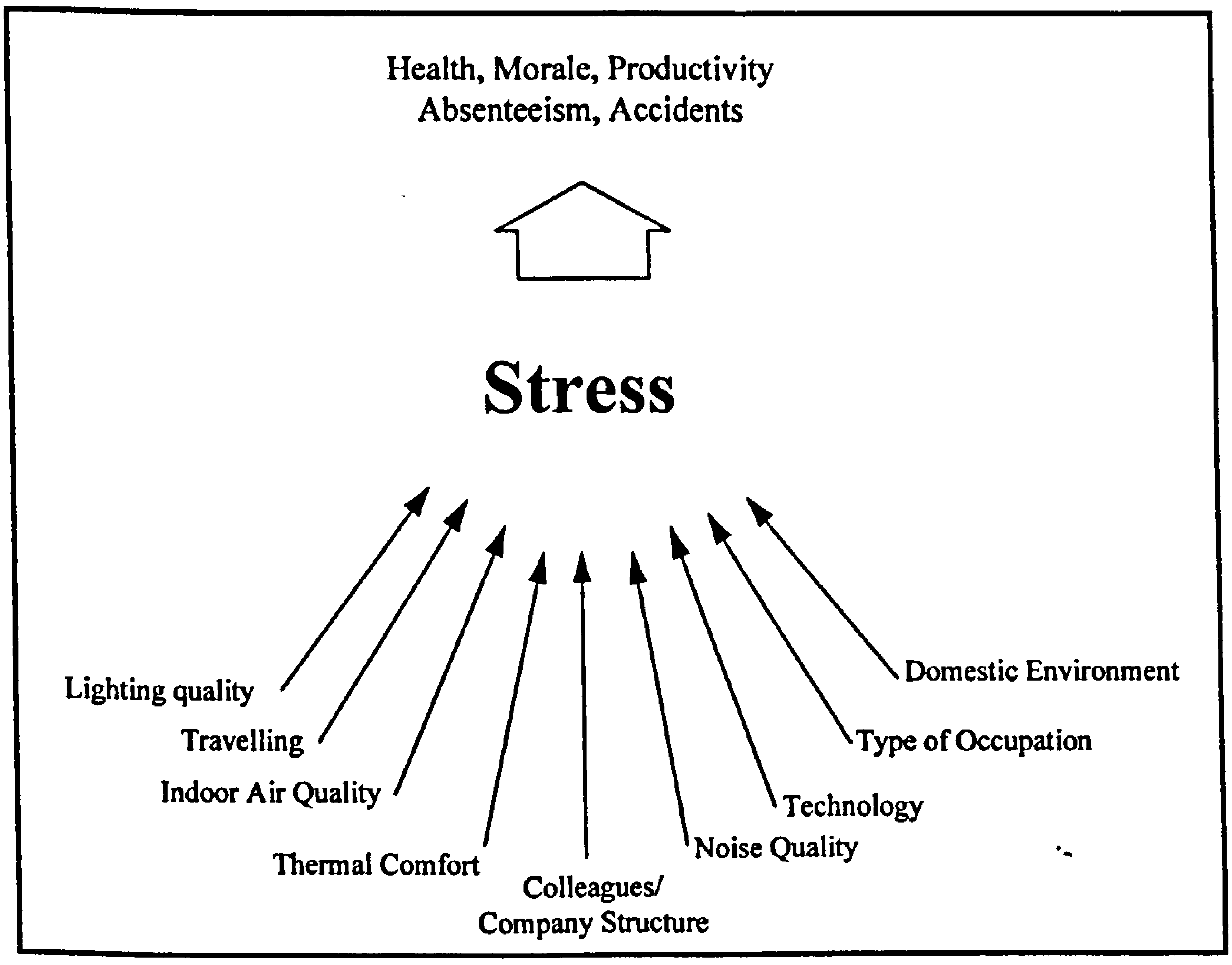

Figure 1.2. Causes and effects of work and building related environmental stressors.

Not all environmental stressors encountered during working hours are necessarily experienced in the workplace directly, e.g. travelling to work and the domestic environment.

Some environmental stressors have a direct action, e.g. temperature, humidity, light and noise. Others are more subtle or indirect, e.g. tension arising from lack of ability to control the environment due to an inability to change levels of lighting, open windows or eliminate cigarette smoke.

In buildings where there are problems of stress and ill health due to the environmental conditions prevailing, the term Sick Building Syndrome (SBS) (London Hazards Centre 1990) is often used. SBS is characterised by a large percentage of building occupants experiencing unexplained sickness and increased absences from work. Symptoms of sick building syndrome include lethargy, tiredness, headache, dry blocked nose, sore dry eyes, sore dry throat, dry skin, skin rashes, watering eyes, itchy eyes, runny nose, flue like illness, difficulty in breathing and chest tightness. A detailed account of SBS is given by the London Hazard Centre (1990), Jaakkola (1994) and Wilson and Hedge (1987).

1.3 Building Environmental Systems Performance

The "Building Environmental Systems Performance" was a key issue in defining the objectives of the research project and was defined by the following three descriptors:-

1. Indoor Environmental Quality (IEQ)
2. Cost Efficiency
3. Energy Efficiency

1.3.1 Indoor Environmental Quality (IEQ)

For the purposes of the research project, this has been defined as the perceived comfort building occupants feel due to the physical and psychological conditions to which they are exposed by their surroundings, i.e. the building structure, fabric and services. When occupants are dissatisfied with their surrounding environment some degree of stress is induced. Stressful environments lower productivity levels (Wilson and Hedge 1987) and hence cost efficiency may be reduced.

1.3.2 Cost Efficiency

For the purposes of the research project, this has been defined as the financial expenditure on energy relative to the comfort and productivity provided for building occupants. By improving the indoor environmental quality and/or energy efficiency of a building the cost efficiency can be improved and the building operator can realise the advantages of:-

- reduced building services running costs
- reduced staff training costs due to reduced staff turnover

- a more content and productive work force
- improved profits
- release of finance for other uses, e.g. research and development

60-70% of a typical company's expenditure is on salaries (Miller 1995). It is therefore prudent to keep the staff content with their environment to maintain good levels of productivity.

1.3.3 Energy Efficiency

For the purposes of the research project, this has been defined as providing the desired indoor environmental conditions for the minimum energy use. Building space conditioning systems are responsible for a significant proportion of energy use. In the UK, nearly half the total delivered energy is used in buildings, 29% domestically and 19% by the public sector (Shorrock and Henderson 1989). Within a typical building, 60% of the energy is used by the space conditioning system, e.g. heating, cooling and ventilating, representing approximately 12% of the total UK energy consumption (Energy Efficiency Office 1991). It is therefore desirable to reduce energy consumption and increase building performance in the light of: depleting world energy reserves, the increasing rate of use of world energy reserves and the pollution of the environment.

In terms of the thermal environment it has been suggested that a decrease in the cooling and heating load for a building of 1°C could decrease building space conditioning energy requirements by 10% (Nicol 1993), not an insignificant amount.

1.4 Interaction of the Building Performance Descriptors

The three building performance descriptors see Figure 1.3, have been defined as Indoor Environmental Quality (IEQ), Energy Efficiency and Cost Efficiency. These interact in a manner that may be complementary or antagonistic towards each other.

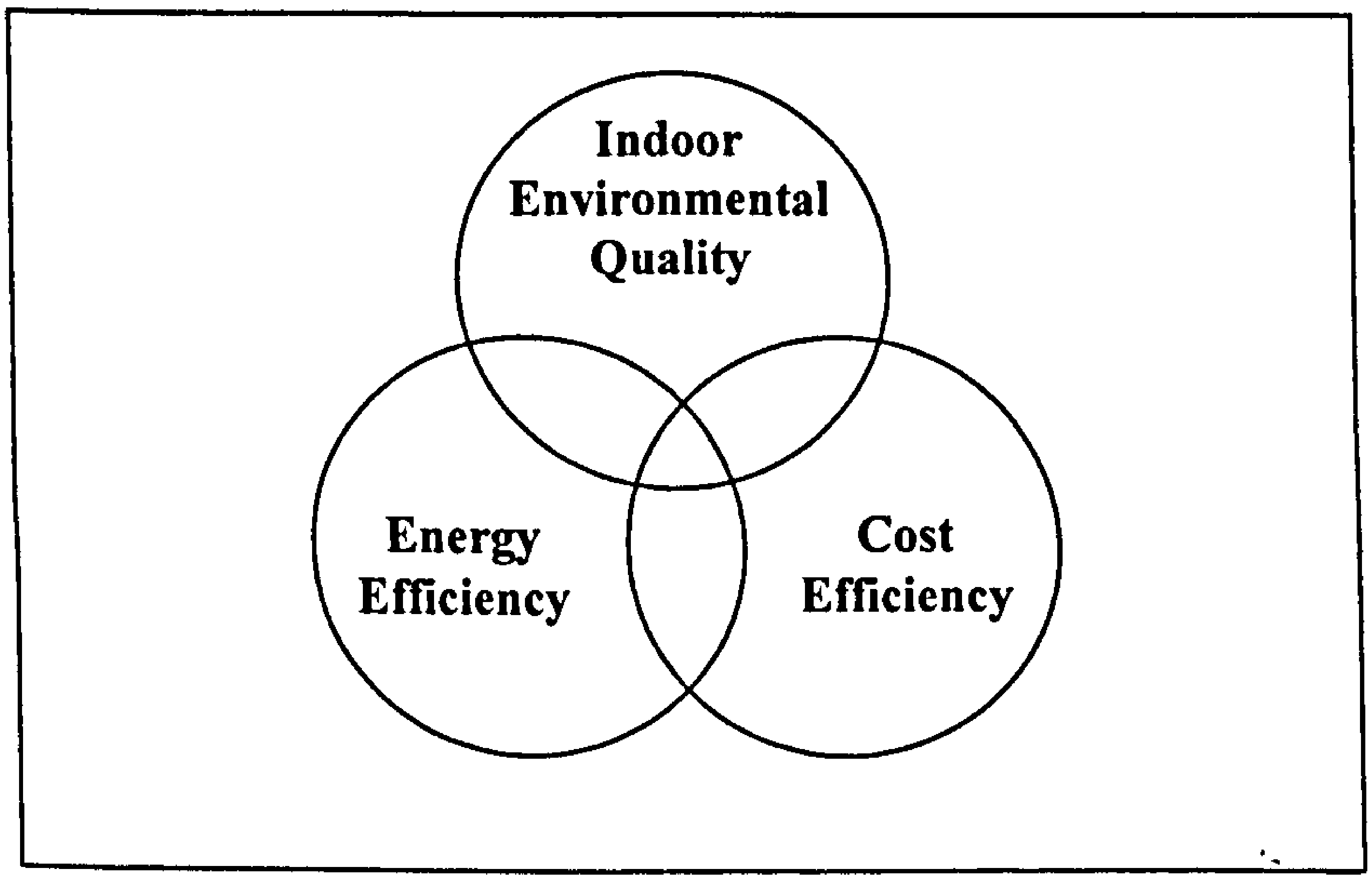

Figure 1.3. Interaction of the three building performance descriptors.

For example, a high level of indoor environmental quality achieved through the use of HVAC plant may give rise to a perceived high energy cost, but if productivity increases then the overall cost efficiency will be improved. The building performance descriptors should therefore not be considered in isolation from each other. A multi-variant problem comprising a range of conflicting parameters exists. This is highlighted by Croome and Baizhan (1995) viz.,

"In 1994, the energy use in an average commercial office building in the United States costs approximately \$20/m^2/year, whereas the functional cost is approximately \$3,000/m^2/year. The functional cost includes the salaries of employees, the retail sales in a store, or the equivalent production value of a hotel, hospital or school. This means that 1% gain in productivity (\$30/m^2/year) has a larger economic benefit than a 100% reduction (\$20/m^2/year) in energy usage. In addition the productivity gains will increase the benefits such as repeat business in hotels, faster recovery times in hospitals, and attainments of better jobs due to a better education in schools. A small gain in worker productivity has major economic impacts and it makes sense to invest in improving the indoor environment to achieve productivity benefits."

In the light of this statement, care should be taken not to regard any one of the building performance criteria as more important than another without careful consideration, evaluation and assessment of the effects on the objectives that are sought. A multi-variant and multi-conflicting problem with cause and effect relationships arises as a result.

1.5 Advantages of Improving Indoor Environmental Quality

The advantages of improving indoor environmental quality are many and varied. The main advantages include:-

- more contented and satisfied employees
- less absenteeism
- fewer accidents

These desirable advantages can lead to improved productivity. These are inter-related. For example, a poor quality environment, such as the incorrect provision of temperature can affect the number of errors made by workers, the accident at work rate and hence their productivity, see Figure 1.4 and Figure 1.5.

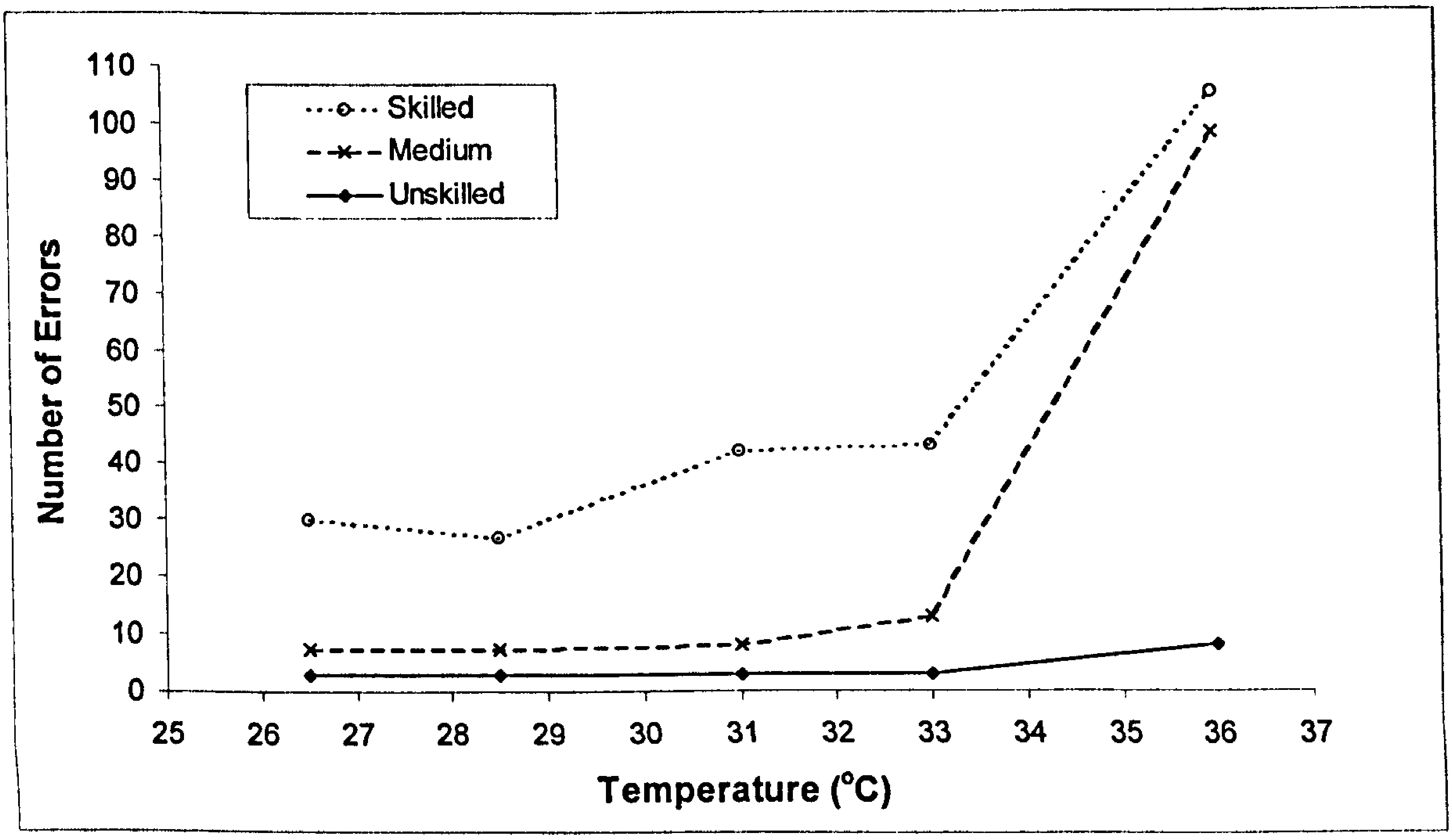

Figure 1.4. The effect of temperature on the error of operating telecommunications equipment (Mackworth 1946).

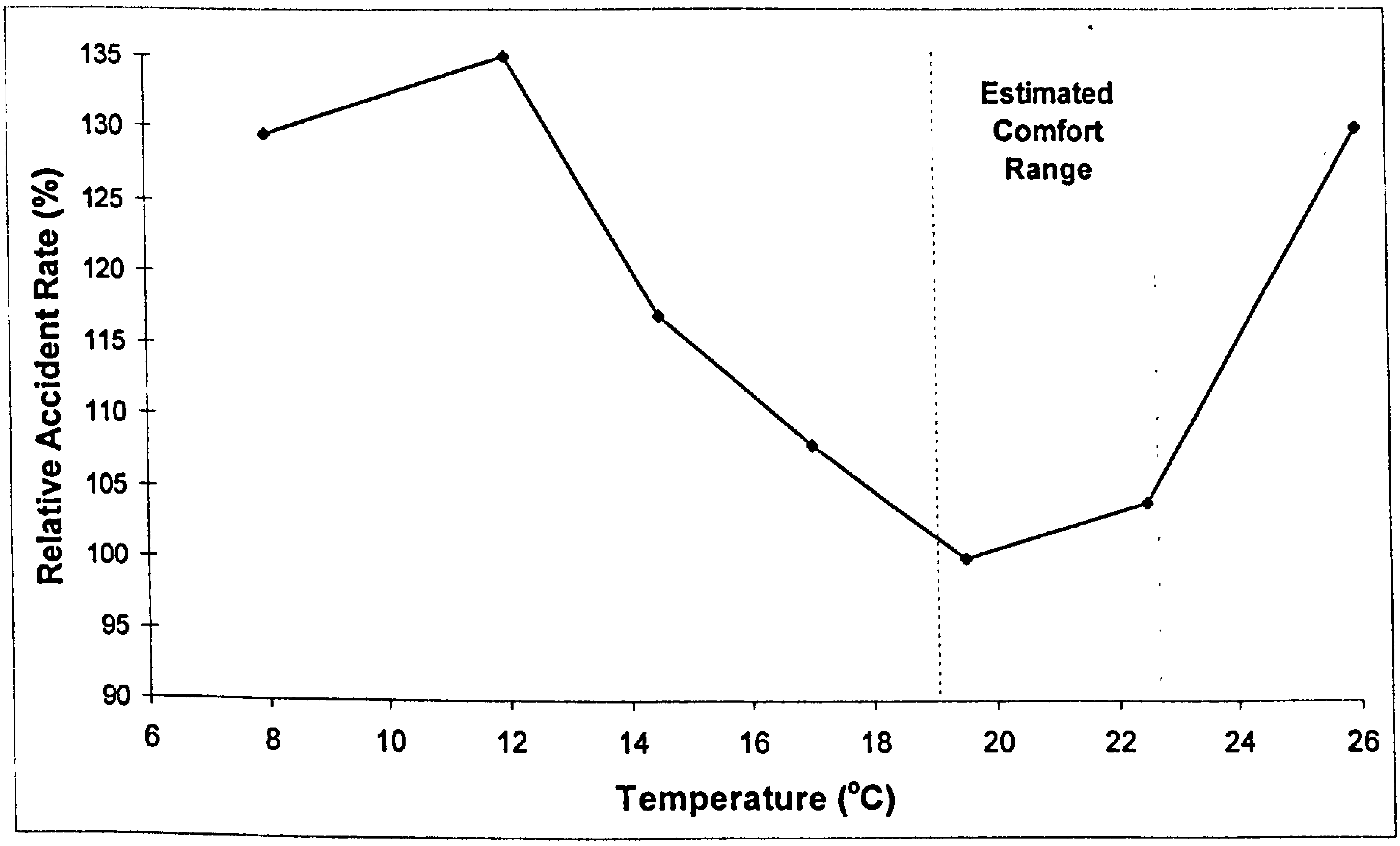

Figure 1.5. Relative accident frequencies of British munitions plant workers at different temperatures (mean values for men and women) (Croome 1981).

The provision of poor indoor environmental conditions often results in occupants suffering symptoms of ill health. The number of symptoms of ill health, attributable to poor indoor environmental conditions, are shown as in the results of self assessed productivity survey, see Figure 1.6.

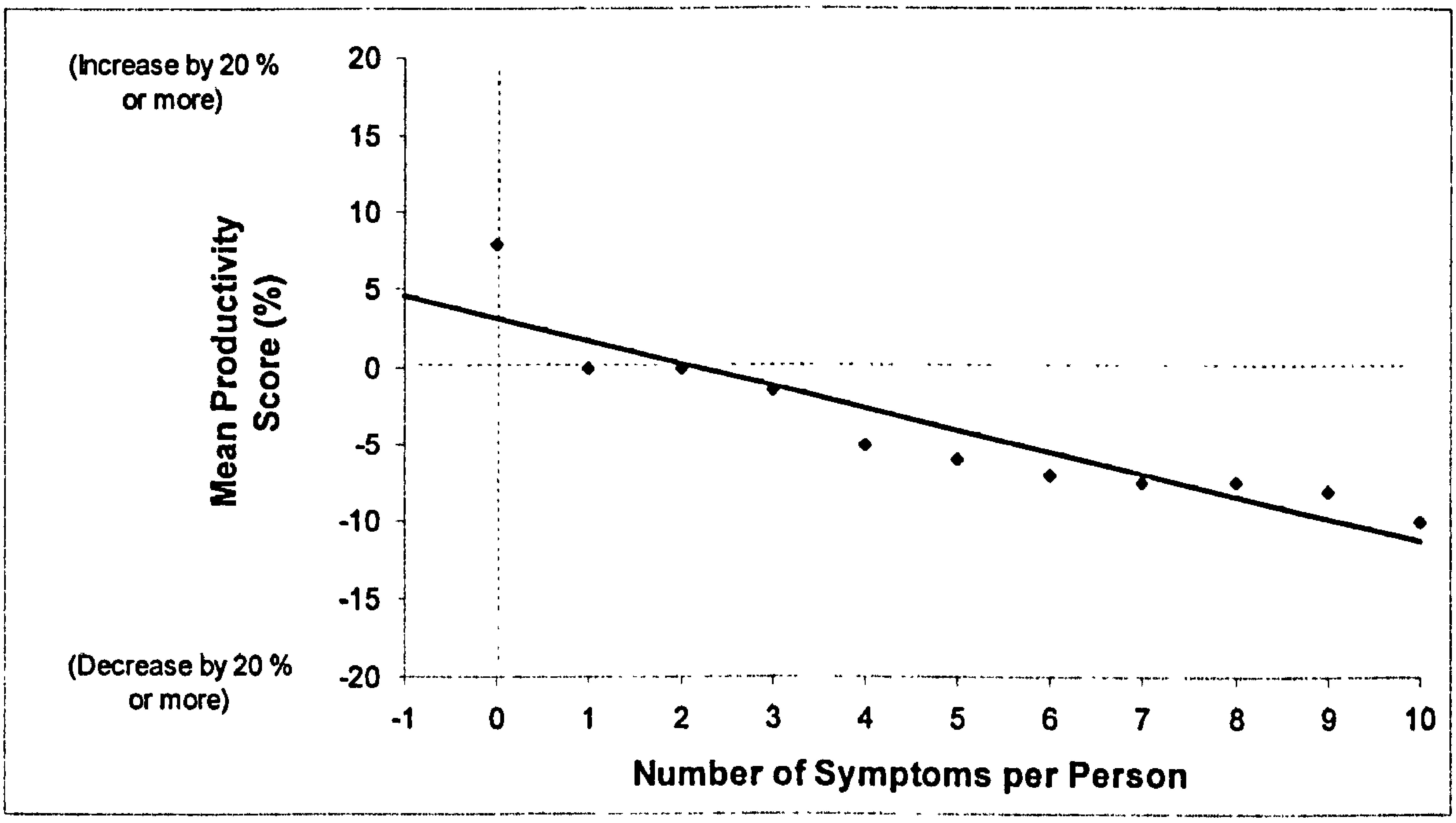

Figure 1.6. Perceived productivity and ill health symptoms (Wilson and Hedge 1987).

Referring to Figure 1.6, the number of symptoms was based on self-reports of chronic ill-health symptoms. Productivity was self assessed by questionnaire on a 9 point scale. An average of 2 or more symptoms is a likely indicator of overall productivity losses.

Lower productivities represent hidden costs to the building operator that are often taken for granted as being unavoidable. However, the sum of all these factors may be considerable in financial terms and should not be ignored.

1.6 Aims and Objectives of the Research Project

The research described in this thesis aimed to improve control techniques and hence provide improved comfort and health conditions while improving building services operation energy and cost efficiencies. The first objective was to determine the limits of the environmental parameters, which characterise within air conditioned and mechanically ventilated office buildings, a high quality internal environment. Defining "a quality internal environment" enabled the objectives of providing energy and cost efficient environments to be achieved within this constraint. The quality of the internal environment, energy and cost efficiencies were, for the purposes of the research project, collectively defined as the Building Performance Descriptors.

The second objective was to utilise fuzzy building services system control strategies to provide a high quality internal environment while maintaining / improving energy and cost efficiencies. These objectives are shown in Figure 1.7.

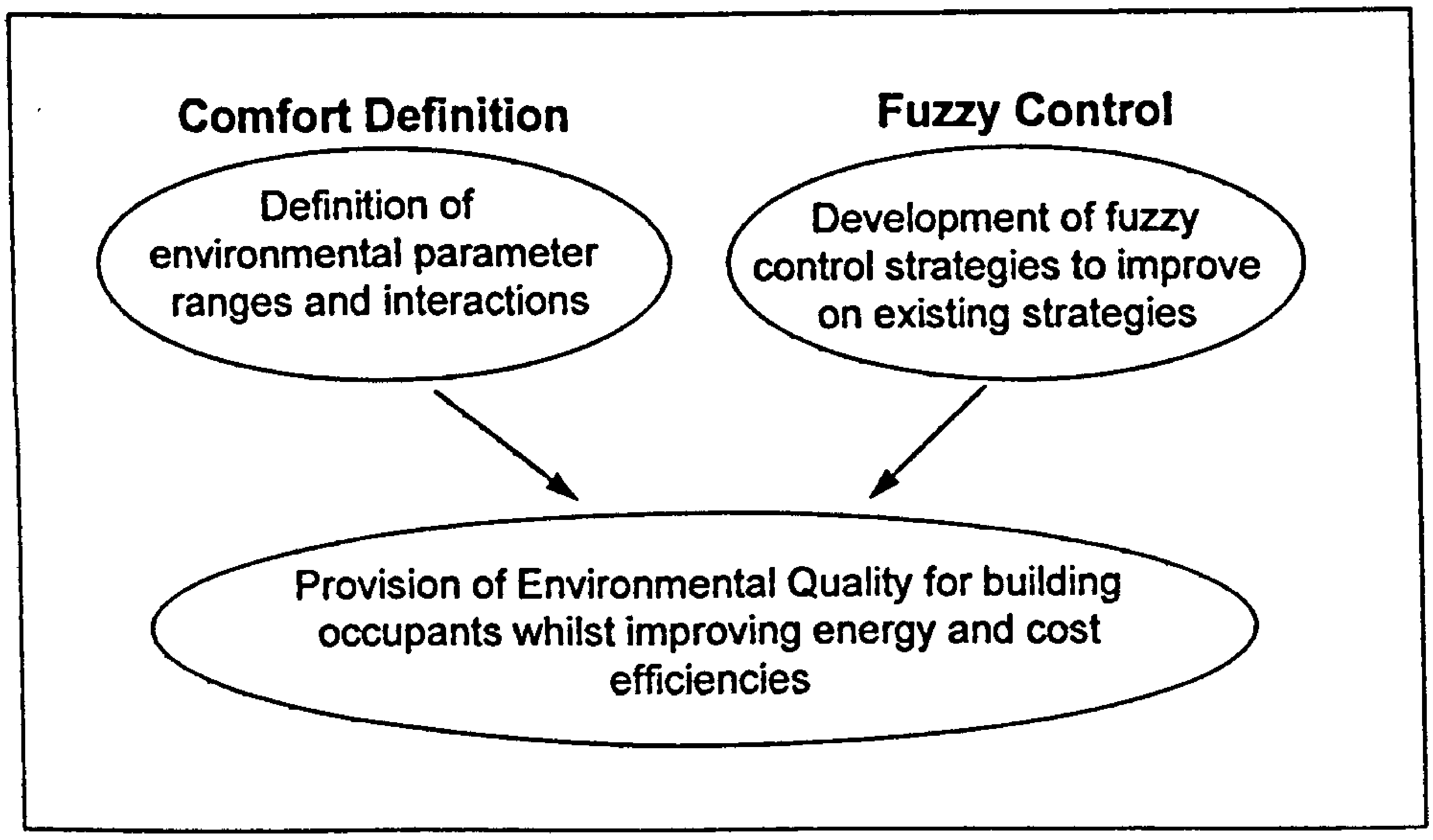

Figure 1.7. Schematic of the research project objectives.

Fuzzy logic control strategies were identified as a method of improving building services performance within air-conditioned and mechanically ventilated buildings. Fuzzy logic has the advantages of being able to model imprecise conditions whilst not requiring an exact mathematical model of the control process, and is capable of decision making. Fuzzy logic is also capable of dealing with multi-variant problems. Hence, fuzzy logic lent itself to the control of the multiple parameters affecting the provision of healthy internal environments and provided the possibility of improving or maintaining energy and cost efficiencies simultaneously.

1.7 Overview of the Thesis

A brief description of the Chapters of this thesis is given below outlining the content of each.

Chapter 1. Introduction (This Chapter)
The Introduction outlines the context in which the research project was carried out with a view to providing the reader with a broad understanding of the overall aims and objectives of the project.

Chapter 2. Literature Review - Building Occupant Comfort
This chapter reviews the current research understanding of the environmental criteria against which occupant comfort within buildings can be assessed. The reviewed research findings include those on thermal comfort, indoor air quality, noise, lighting and company managerial structure. The investigation and definition of human comfort has been primarily carried out by reviewing currently available books, journal papers, conference proceedings and recognised standards. Recent developments have been addressed by attending seminars such as the UK Thermal Comfort Group Meetings which give a review of the most recent research findings. The aim of this literature review was to establish the environmental parameter ranges and limits that define a high

environmental standard for internal environments. This provided the background information to be applied in developing the fuzzy control strategies.

Chapter 3. Literature Review - Fuzzy Logic and Fuzzy Control
This chapter reviews previous applications of fuzzy logic to the control of heating, ventilating and air-conditioning (HVAC) plant and hence the provision of occupant comfort within buildings. This chapter reviews the currently available published literature and aims to identify possibilities for further exploring the use of fuzzy logic control to improve building services control techniques.

Chapter 4. Fuzzy Logic and Fuzzy Control Theory
This chapter introduces the reader to the theory behind fuzzy logic and provides an introduction to the theory of fuzzy control. Examples of fuzzy logic and fuzzy control are used to further describe mathematical principles of their operation. This chapter aims to give the reader a good theoretical background to fuzzy logic control in order to aid the understanding of the fuzzy logic control systems developed during the research project.

Chapter 5. One Zone Dynamic Model - "Free Running" Building Components Theory
The main part of the research project was based on a computer model of a single zone of a building. This was used to assess the performance of the fuzzy control strategies developed in later chapters of the thesis. This chapter first describes the Matlab and Simulink computer software used to develop a one zone computer model of a "free running" building, i.e. no heating ventilating and air-conditioning components operational. The reasoning for constructing such a model and the theory used for the model is explained. The suitability of the developed model for building services control modelling purposes is then assessed by comparison with Thermal Analysis Software (Tas), a widely accepted method of modelling the thermal performance of buildings.

Chapter 6. One Zone Dynamic Model - Heating Ventilating and Air-Conditioning (HVAC) Component Theory
This chapter considers the theory of the HVAC components that were developed and built into the "free running" one zone Simulink model. It also considers the theory of Proportional + Integral + Derivative (PID) control which was used as the benchmark against which the fuzzy control strategies were assessed.

Chapter 7. Fuzzy Control Strategy Development Methodology
This chapter describes the aims and objectives of the development of the fuzzy control strategies developed for the research project described in Chapters 8, 9 and 10.

Chapter 8. Proportional Derivative Fuzzy Control (Pure Fuzzy Control)
This chapter investigates the use of proportional derivative fuzzy controllers (PDFCs) as an alternative to conventional controllers. The error and rate of change of error from the pre-defined set points are used as inputs to the fuzzy controllers which provide an output signal to control the valve and damper positions of the HVAC plant components. Proportional + Integral + Derivative (PID) controllers are used as bench marks against which to compare the PDFCs.

Chapter 9. Fuzzy Ventilation Control
This chapter considers the use of fuzzy control strategies to control the use of free cooling and dehumidification by varying the rate of supply of fresh air to the occupied space. The reasoning behind using the fuzzy ventilation controllers and their theoretical basis is explained using example computer simulations. Proportional + Integral + Derivative (PID) controllers are used as bench marks against which to compare the fuzzy ventilation controllers.

Chapter 10. Fuzzy High Level Control
This chapter describes the use of the fuzzy ventilation control strategies detailed in Chapter 9 in conjunction with a high level fuzzy supervisor which supervises the fuzzy ventilation strategy controllers to achieve enhanced performance. Proportional + Integral + Derivative (PID) controllers and fuzzy ventilation controllers are used as bench marks against which to compare the fuzzy high level controller's performance.

Chapter 11. Conclusions and Recommendations
This final chapter considers the findings of the research project and presents the main conclusions. Further, recommendations are made with regard to areas of the research that are worthy of further investigation identified during the execution of the research project.

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2. Literature Review - Building Occupant Comfort

Nomenclature

η	external mechanical efficiency of the body
A_{DU}	DuBois area: body surface area of the human body (m^2)
DR	draught risk, i.e. percentage of people dissatisfied due to draught (%)
f_{cl}	clothed to nude body surface area ratio (clothing area factor)
h_c	convective heat transfer coefficient (W/m^2K)
h_r	radiative heat transfer coefficient (W/m^2K)
M	metabolic rate in Watts per m^2 of body surface area (W/m^2)
p_a	partial pressure of water vapour in ambient air (Pa)
t_{ai}	indoor air temperature (°C)
t_{cl}	mean radiant temperature of outer surface of clothed body (°C)
t_{mrt}	mean radiant temperature (°C)
t_o	operative temperature (°C)
t_{res}	dry resultant temperature (°C)
T_u	turbulence intensity (%)
v	mean air velocity (m/s)

2.1 Introduction

This Chapter reviews current research findings into building occupant comfort. Standards and guidelines related to indoor environmental comfort are considered within this scope. The aim of the occupant comfort literature review was to identify and define the important parameter ranges, limits and interactions that provide building occupants with their perception of comfort. This provided the basis for developing fuzzy control strategies to control internal environmental conditions and assessing any improvements in provided comfort, energy and cost efficiencies.

When considering indoor environmental quality two aspects should be assessed, those of comfort and health. Occupants health should be safeguarded against any adverse effects that may be inflicted on the human body due to surrounding environmental conditions. Many of the environmental factors effecting health will become apparent due to discomfort, e.g. very high or low temperatures, before they cause any adverse health effects. However, some health problems may arise where no prior warning is given by comfort effects, e.g. high concentrations of indoor-radon gas (which is carcinogenic) or legionaries disease.

Another factor is the short-term versus long-term effect. For example, a very high or low temperature can cause death by hypothermia and hyperthermia respectively in a very short period of time. However, small temperature drifts from those that are comfortable for long periods of time may have health implications in terms of stress to the occupant.

The environmental descriptors effecting human comfort include thermal comfort, indoor air quality, noise comfort, lighting comfort and company management policy. These were identified as the main influences on occupant comfort and form the basis of the literature review described in this chapter. In addition, methods of assessing occupant comfort within buildings are reviewed. Finally, the environmental parameters of interest for developing the fuzzy control strategies are considered and selected with justification of these choices.

2.2 Environmental Parameters Effecting Human Comfort

Factors effecting indoor environmental quality based on the classification used in Figure 1.1, Chapter 1, were investigated by reviewing existing literature, standards and guidelines. The findings are given in the following sections.

2.2.1 Occupant Variables (Physical)

These can be defined as the variables associated with the building occupants themselves that have an effect on an individuals comfort.

2.2.1.1 Activity (metabolic rate)

The metabolic rate is the rate of energy production of the body and is dependant on the activity level of the occupant. As the metabolic rate varies, the environmental conditions in which occupants feel comfortable will change, see Figure 2.1. With respect to temperature, the higher the activity rate of the person, i.e. metabolic rate, the lower the temperature required for human comfort.

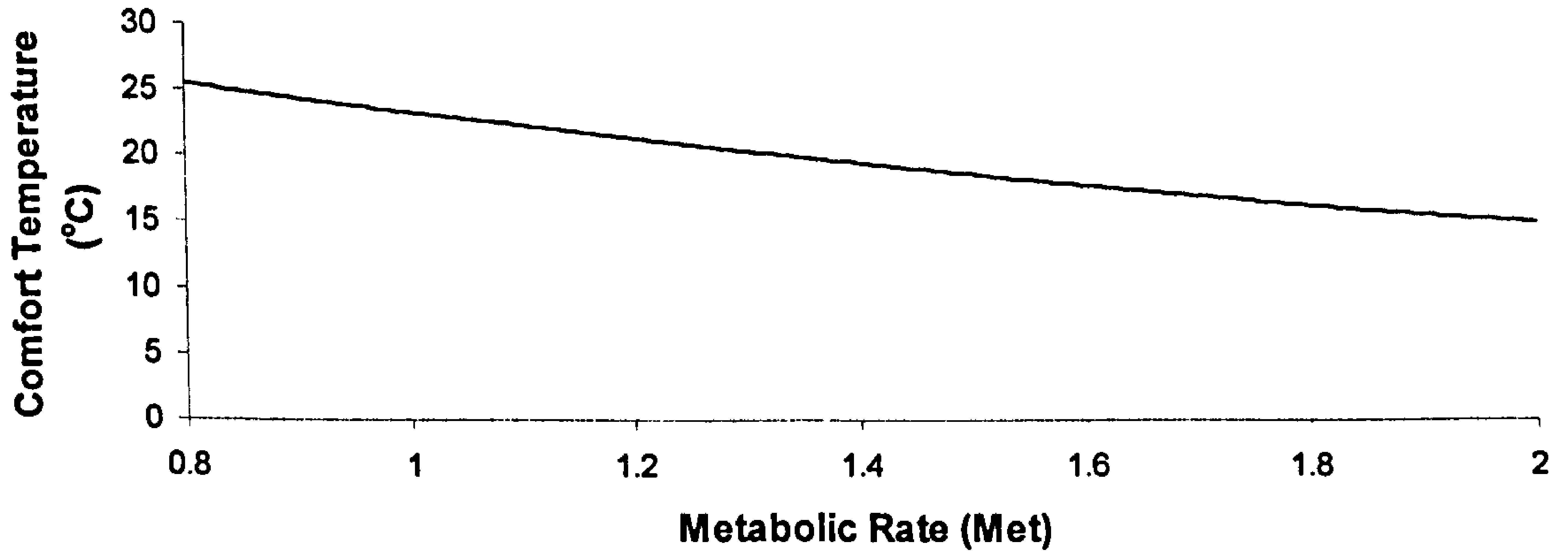

Figure 2.1. Comfort Temperature as a function of metabolic rate (Ong 1995).

The SI unit commonly used for metabolic rate is the met. 1 met = 58.2 W/m^2 of body area. Metabolic rates for typical tasks are listed in Table 2.1.

Activity	met	W/m^2
Reclining	0.8	46.6
Seated and quiet	1.0	58.2
Sedentary activity	1.2	69.8
Standing, relaxed	1.2	69.8
Light activity, standing	1.6	93.1
Medium activity, standing	2.0	114.4
High activity (sustained)	3.0	174.6

Table 2.1. Metabolic Rates for typical activity levels (ASHRAE 1992).

2.2.1.2 Clothing thermal resistance

Occupants can regulate their thermal comfort by the addition or removal of clothing items e.g. a jumper. Different types of clothing possess different values of thermal resistance, some examples of which are given in Table 2.2. A commonly used unit for clothing thermal resistance is the Clo (1 Clo = 0.155 m^{2}K/W).

Clothing Ensemble	Clothing Resistance (Clo)
Nude	0
Light Summer Clothing	0.5
Typical business suit	1
Typical business suit and cotton overcoat	1.5
Heavy wool pile ensemble	3 - 4

Table 2.2. Typical thermal resistances of clothing ensembles (Fanger 1972).

A detailed methodology for the estimation of thermal insulation of clothing is given in ISO 9920 (1995). For calculation purposes it is assumed that a piece of clothing adds thermal resistance uniformly to the whole body surface. This is not the case but seems to work well in practice (Nicol 1993). Chair upholstery may contribute as much as 0.2-0.4 Clo to that of an occupants total clothing thermal resistance which is not included in any of the standard methods for estimating clothing thermal insulation (Nicol 1993). However, in recent years it has become common practice to include a chair's thermal resistance into calculations. An example of the relationship between clothing thermal resistance and comfort temperature is given in Figure 2.2.

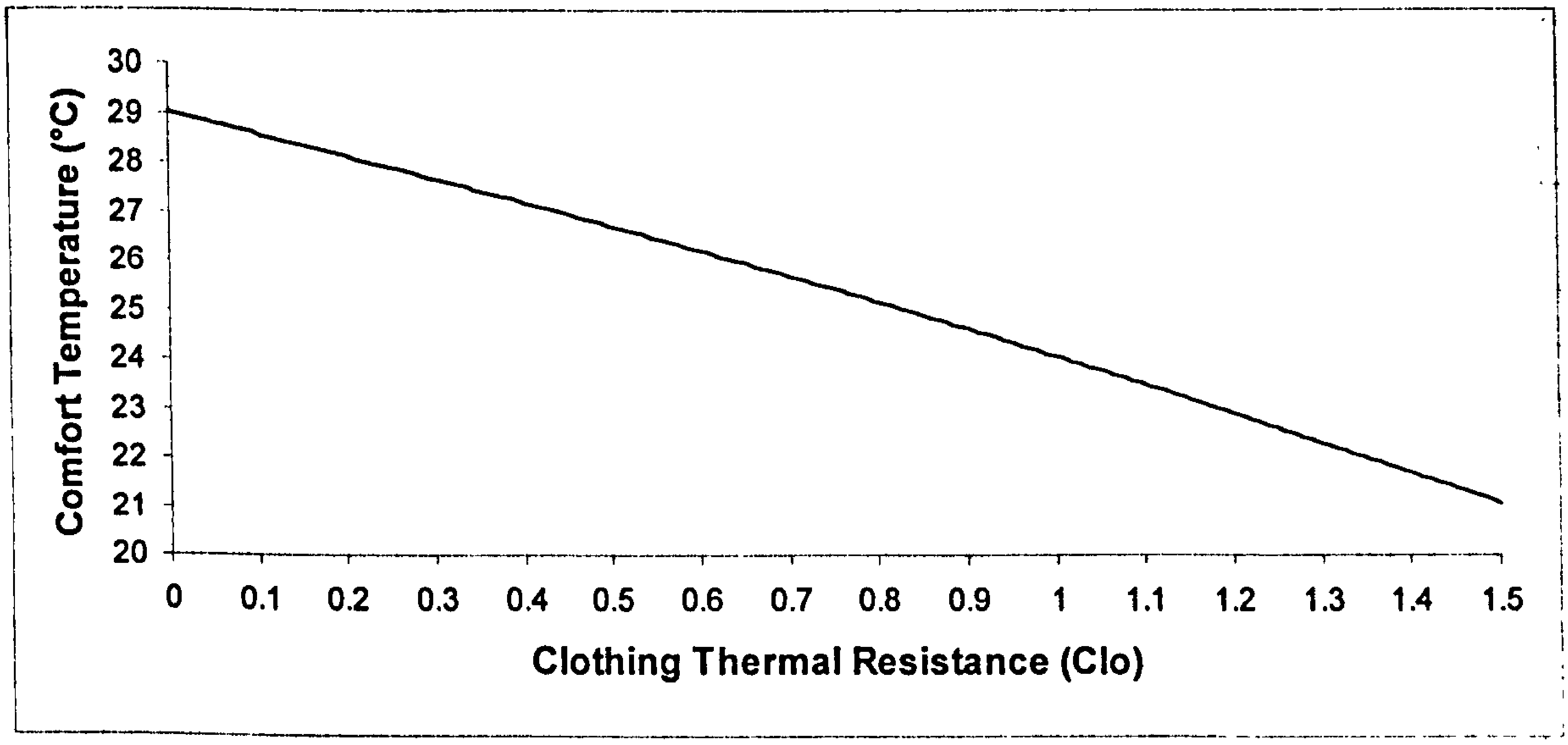

Figure 2.2. Comfort temperature as a function of clothing thermal resistance. (air velocity = 0.2 m/s, RH = 50%, sedentary activity 1.2 met)(Fanger 1972).

2.2.1.3 Occupant Age

Fanger (1972) and Rohles (1969) suggest that there is no significant difference between the comfort conditions preferred by different age groups.

2.2.1.4 Occupant Sex

Investigations show that there is no significant difference in preferred comfort conditions for males and females (Angus and Brown 1957, Ellis 1953, Rummel et. al. 1939, McConnell and Spiegelman 1945, Black 1954, Hindmarsh and Macpherson 1962, Fanger 1972).

2.2.1.5 Skin Temperature

Research by Gagge et al. (1967) and Benzinger (1979) shows that skin temperature varies as a function of environmental temperature, see Figure 2.3.

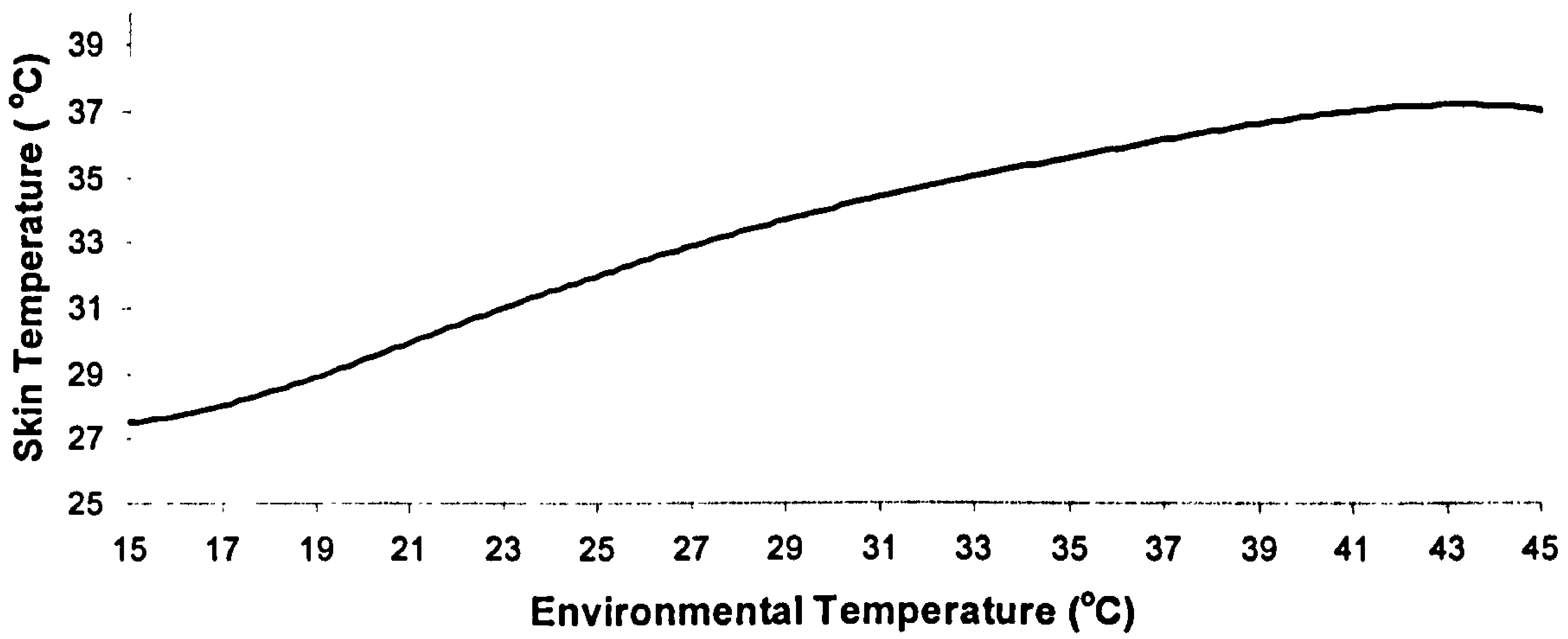

Figure 2.3. Skin temperature as a function of environmental temperature (young man, sedentary activity, wearing only trunks) (Benzinger 1979).

2.2.1.6 Deep Body Temperature

Research by Benzinger (1979) showed that deep body, or core, temperature varies with environmental temperature, although less significantly than for skin temperature, see Figure 2.4. Tympanic temperature is taken as a good indication of deep body temperature, i.e. brain temperature, although rectal temperature can also be used.

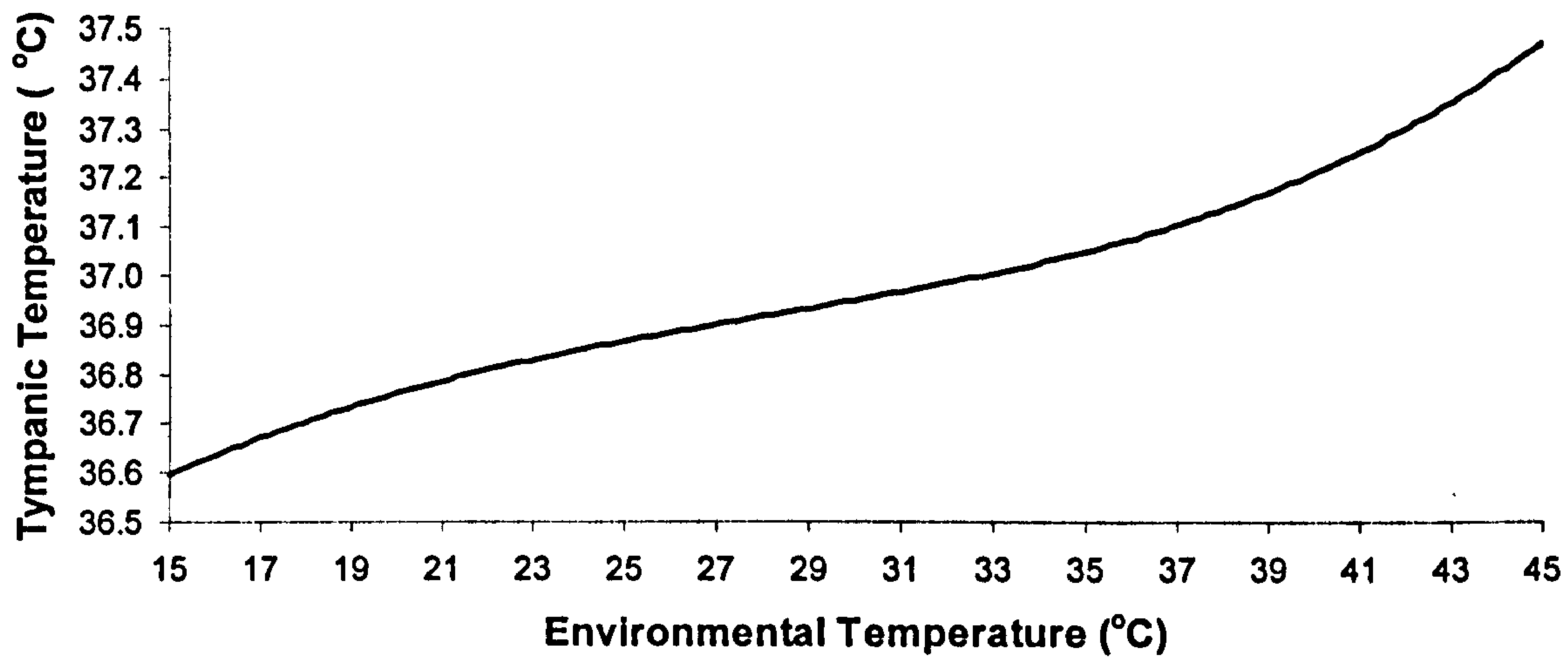

Figure 2.4. Tympanic temperature as a function of environmental temperature (young man, sedentary activity, wearing only trunks) (Benzinger 1979).

The core temperature is of interest as it represents the temperature of the brain, where the controls for body temperature regulation are located.

2.2.1.7 Sweating (evaporative heat loss)

As the environmental temperature rises, the human body's thermoregulatory system compensates by increasing its rate of heat loss in order to maintain, as far as possible, a uniform core body temperature. One of the ways in which the body achieves this equilibrium is by sweating, i.e. evaporative heat loss, see Figure 2.5.

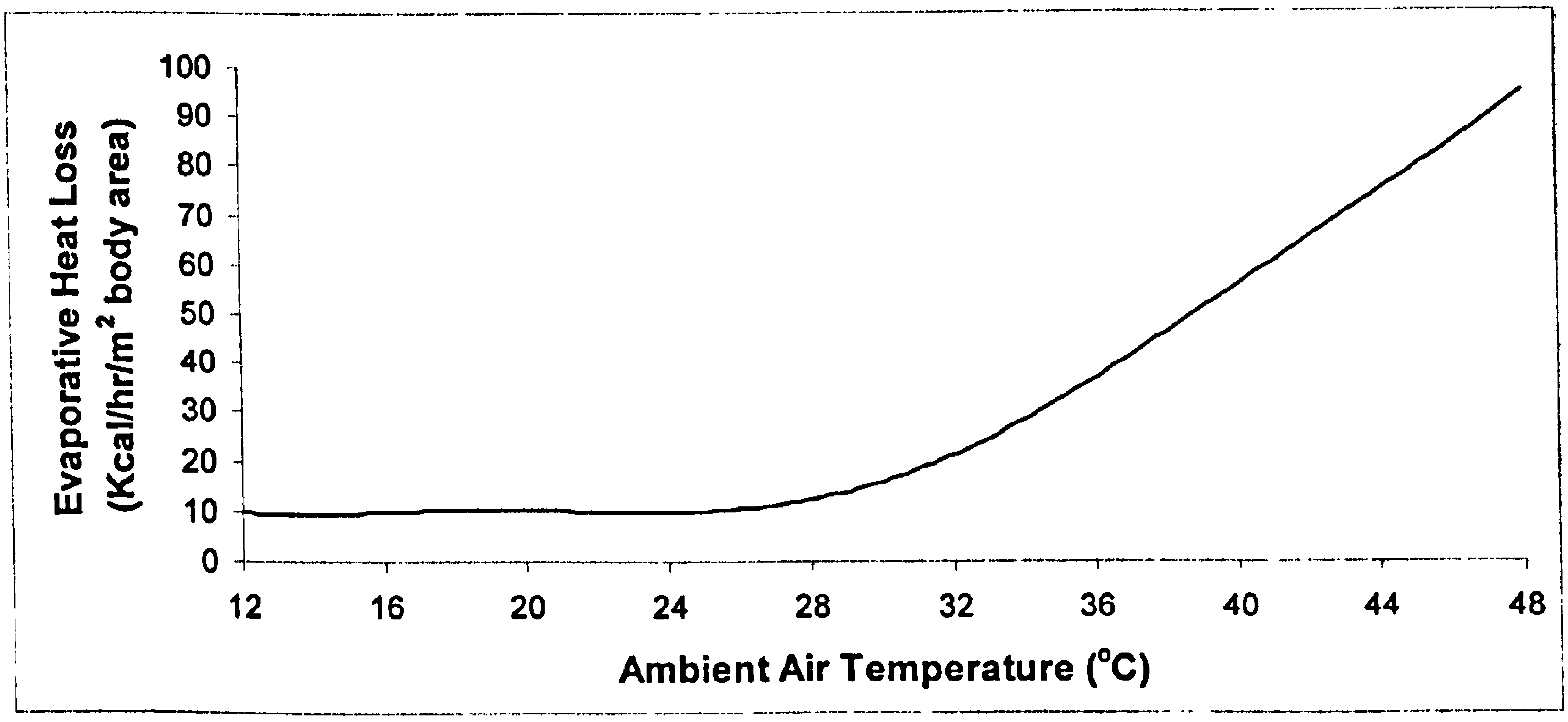

Figure 2.5. Evaporative heat loss as a function of ambient air temperature (sedentary activity, still air and low humidity) (Hardy and Stolwijk 1966).

2.2.2 Environmental Variables

This section considers the variables effecting occupant comfort that are associated with the surrounding environment.

2.2.2.1 Vibration

Vibration can have physical and biological effects on the human body:-

1. **Physical** - oscillation of parts of the body can cause physical damage if amplitude and/or frequency is too great.
2. **Biological** - the physiological and psychological effects of vibration are dependant on the type of vibration and an individuals sensitivity and tolerance to this vibration. In an office building context, this type of effect is more relevant than the physical effect which is unlikely to cause damage in such environments.

A detailed review of the effects of vibration on the human body is given by Oborne and Gruneberg (1983).

2.2.2.2 Noise

The human frequency of hearing ranges from 15 Hz to 20,000 Hz. Noise in the workplace can have a detrimental effect on the occupants in terms of (i) people don't like it (ii) it can cause damage to hearing, and (iii) it can reduce productivity.

Loud or high pitched noises are the most annoying. Interrupted or sudden unexpected noises are more annoying than steady noises. Steady background noise, e.g. air conditioning or running fountain water can serve to mask unwanted noise and create

acoustic privacy in open plan, multiple occupancy spaces. People also find a completely noise free environment irritating, thus a steady background noise is also desirable. A maximum sound level of 90 dBA is recommended for an 8 hour exposure time (HMSO 1972).
With respect to control systems there is little that can be done to effect the noise environment once the building has been designed and built. Noise control should be dealt with during the initial design of a building, e.g. use of different areas considered and designed accordingly, i.e. compartmentalisation where a high level of privacy is required, orientation of work stations, the hardness of noise reflecting surfaces accounted for and the use of partial partitioning.

White/destructive noise may be considered useful for overcoming noise problems in some specific situations. The use of vegetation has also been explored as a means of noise attenuation (Costa 1995). A useful overview of noise is given by Cowell (1995).

2.2.2.3 Lighting

Lighting serves three main purposes within buildings:-

- to enable occupants to work and move in safety
- to enable tasks to be performed by occupants
- to make interiors look pleasant to occupants

There are several aspects of lighting which can effect health (Wilkens 1993):-

- low frequency magnetic fields produced by lights - effects uncertain but possibly linked with cancer.
- ultra-violet emissions - natural daylight exceeds artificial lighting emissions, possibly causes eye disease and strong link with skin cancer.
- glare - can cause severe discomfort.
- variation in luminous intensity - can cause discomfort or impair vision.
- frequency - flickering lighting can effect the human nervous system causing epileptic fits, headaches and eye strain.

To provide comfortable lighting it is recommended that an illuminance of between 200 and 2000 lux, dependant upon task, is provided whilst avoiding glare and low supply frequency lighting. Detailed recommendations are given by CIBSE (1987).

2.2.2.4 Air Temperature

Many different temperature scales are in use for defining the temperature of the air in internal environments. Those commonly used include:-

Air Temperature - the dry-bulb temperature of the air surrounding the occupant (ASHRAE 1992).

Dew-Point Temperature - the temperature at which moist air becomes saturated (100% relative humidity) with water vapour when cooled at constant pressure (ASHRAE 1992).

Mean-Radiant Temperature - the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space (ASHRAE 1992).

Resultant Temperature - the temperature recorded by a thermometer at the centre of a black globe 100mm in diameter, see Equation 2.1.

$$t_{res} = \frac{t_{mrt} + t_{ai}\sqrt{(10v)}}{1 + \sqrt{(10v)}}$$

Equation 2.1

Where indoor air speeds are less than 0.1 m/s, Equation 2.1 can be simplified to Equation 2.2 without significant loss of accuracy.

$$t_{res} = {}^1/_2 t_{mrt} + {}^1/_2 t_{ai}$$

Equation 2.2

The resultant temperature is the index recommended for use in the UK (CIBSE 1987). Field studies indicate that within occupied buildings the difference between air temperature and mean radiant temperature is small (Bedford 1936, Webb 1959, Humphreys and Nicol 1970, Nicol 1974, Grandjean 1973).

Operative Temperature (t_o) - the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment. Operative temperature is numerically the average of the air temperature (t_a) and the mean radiant temperature (t_{mrt}), weighted by their respective heat transfer coefficients (h_c and h_r) (ASHRAE 1992). Operative temperature is defined by Equation 2.3.

$$t_o = \frac{(h_c t_{ai} + h_r t_{mrt})}{(h_c + h_r)}$$

Equation 2.3

Effective Temperature (ET)* - the operative temperature of an enclosure at 50% relative humidity that would cause the same sensible plus latent heat exchange from a person as would the actual environment (ASHRAE 1992)

Recommendations regarding comfort temperatures from CIBSE, ASHRAE and ISO are as follows:-

CIBSE (1987)
Resultant temperature between 19°C and 23°C when the air speed is less than 0.1 m/s

ISO 7730 (1994)

1. Operative temperatures of 22°C ± 2°C and 24.5°C ± 1.5°C for winter and summer conditions respectively
2. Vertical air temperature difference between 1.1m and 0.1m above floor height (head and ankle level) shall be less than 3°C
3. Surface temperature of the floor shall normally be between 10°C and 26°C, but floor heating systems may be designed for 29°C

These recommendations apply to light, mainly sedentary activities.

ASHRAE (1997)

1. winter - operative temperature 20°C - 24.5°C dependant on RH
2. summer - operative temperature 22.5°C - 27°C dependant on RH

Figure 2.6 shows details of the ASHRAE summer and winter comfort zones (acceptable ranges of operative temperature and humidity for people in typical summer and winter clothing during light, primarily sedentary activity, i.e. less than 1.2 met). The comfort zones are based on a 10% dissatisfaction criteria.

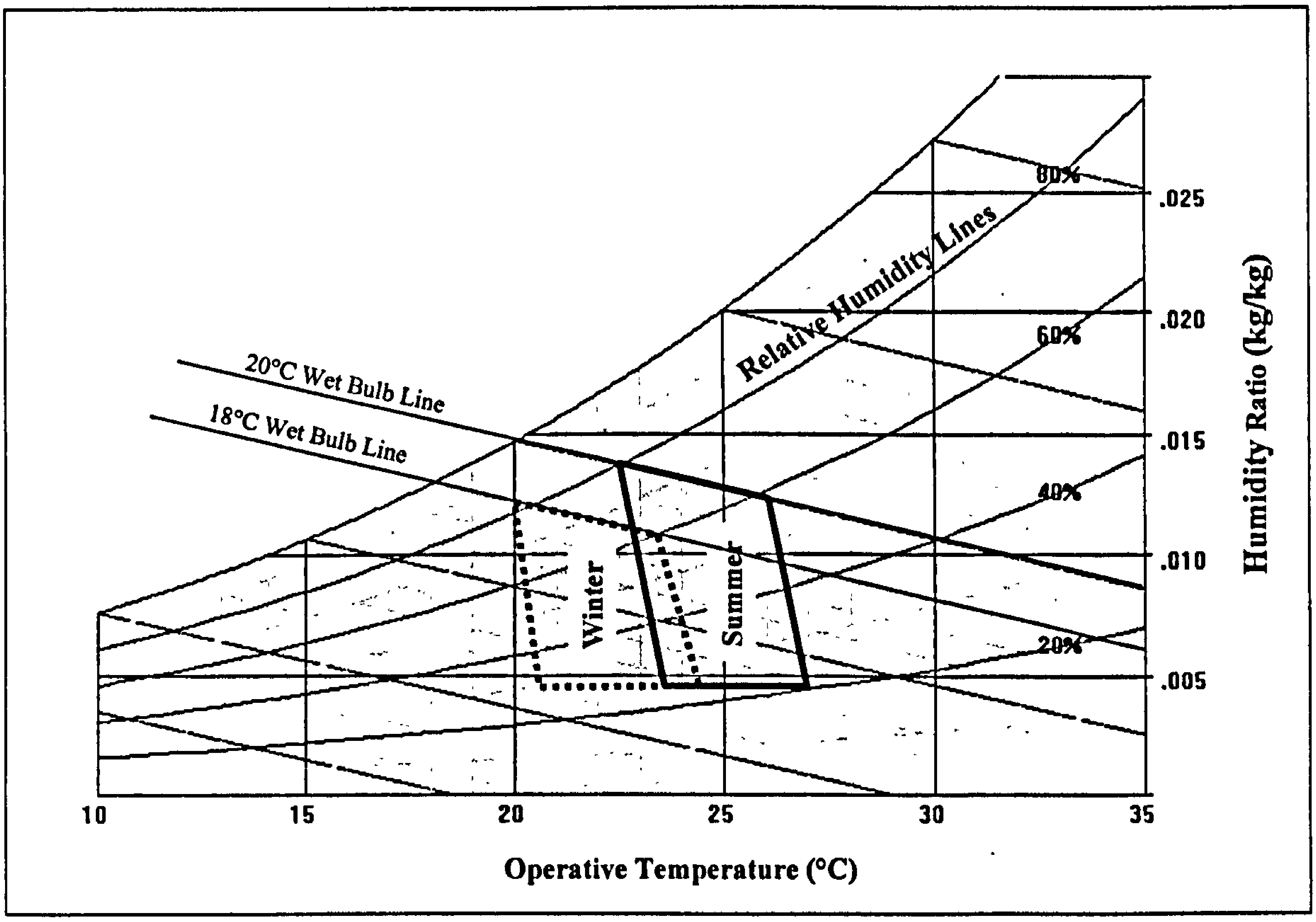

Figure 2.6. ASHRAE summer and winter comfort zones (ASHRAE 1997).

ASHRAE (1997) further states that:-

1. The temperature ranges of Figure 2.6 can be lowered by 0.6°C for each 0.1 clo increase in clothing insulation.
2. For sedentary occupancy of more than one hour, the minimum operative temperature shall not be less than 18°C.

3. Vertical air temperature difference between 1.7m and 0.1m above floor height shall be less than 3°C
4. Local radiant temperature asymmetry in the vertical and horizontal directions shall be less than 5°C and 10°C respectively.
5. The surface temperature of the floor for occupants wearing typical indoor footwear shall be between 18°C and 29°C.

ASHRAE (1997) also considers conditions that should be satisfied for non steady state conditions. These are:

1. If the peak cyclic operative temperature variation, in any period of 15 minutes or less, exceeds 1.1°C the rate of temperature change should not exceed 2.2°C/h. There are no restrictions if the peak to peak temperature difference is less than 1.1°C.
2. The maximum allowable drift or ramp condition from a steady state starting temperature of between 21°C and 23.3°C is a rate of 0.5 °C/h. A temperature drift or ramp should not extend beyond the upper temperature limits of the comfort zone guidelines, see Figure 2.6, by more than 0.5°C and should not remain beyond this temperature zone for more than 1 hour. (Drifts and ramps are steady, non-cyclic operative temperature changes. Drifts refer to passive temperature changes while ramps refer to active temperature changes).

Temperature is often the first perceivable parameter that influences the comfort of occupants. However, indoor temperatures are often far from satisfactory as shown in Figure 2.7.

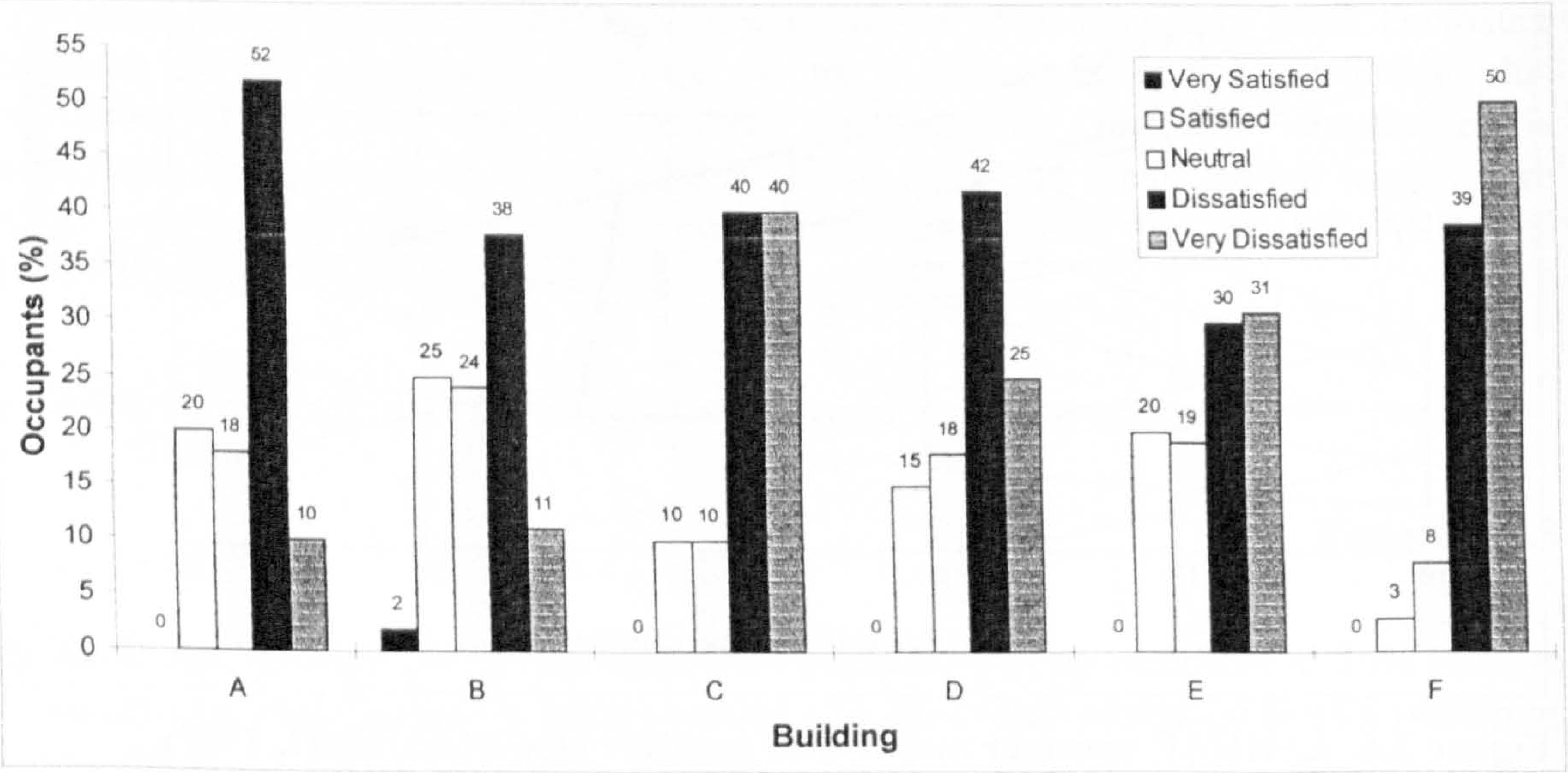

Figure 2.7. Levels of dissatisfaction with temperature for six British office buildings (Croome and Baizhan 1995).

The results of the office survey shown in Figure 2.7 clearly indicates that peoples perception of the thermal environment is skewed towards being dissatisfied. This is likely to be due to incorrect temperature control rather than lack of knowledge as to preferred space temperature provision.

2.2.2.5 Temperature Asymmetry

Feelings of discomfort may be induced by asymmetric radiation within a space due to:-

1. Local cooling - radiation exchange with adjacent cool surfaces such as single glazed widows. ISO 7730 (1994) recommends that radiant temperature asymmetries from windows or other cold surfaces shall be less than 10°C (relative to a small vertical plane 0.6m above the floor for light, mainly sedentary activities during winter conditions).
2. Local heating - i.e. radiation exchange with hot surfaces such as radiant panels. ISO 7730 (1994) recommends that the radiant temperature asymmetry from a warm (heated) ceiling shall be less than 5°C (relative to a small horizontal plane 0.6m above the floor for light, mainly sedentary activities during winter conditions).
3. Intrusion of short wavelength radiation - e.g. solar irradiation through glazing. This can particularly be a cause of discomfort for occupants located near windows and or directly in the path of sunlight entering the building.

2.2.2.6 Relative Humidity

This is defined as "the ratio of the mole fraction of water vapour present in the air to the mole fraction of water vapour present in saturated air at the same temperature and barometric pressure" (ASHRAE 1992).
CIBSE suggests that for most applications, relative humidity should be between 40% and 70% to achieve human comfort (CIBSE 1987). ASHRAE (1997) recommendations are slightly more complex, see, Figure 2.6, but can be generally defined as being between 30% and 60% with a dependence on temperature. ISO 7730 (1994) recommends that relative humidity should be between 30% and 70%

At higher temperatures, where the thermoregulatory system of the human body induces sweating in order to achieve heat balance, relative humidities at the lower end of the recommended band are preferred as this aids heat loss by evaporation. Other considerations with regard to relative humidity are:-

- the preservation of the building fabric and contents, e.g. furniture/carpets - high relative humidity can induce the growth of moulds and fungi and cause deterioration of the building fabric as well as having adverse health effects
- electrostatic shocks can be experienced by occupants in buildings with low humidities, i.e. less than 40%

Figure 2.8 summarises the relative humidity ranges for health and comfort. The triangular sections indicate greater risk with greater height. The central shaded band indicates the preferable humidity condition to avoid occupant discomfort and building fabric degradation problems. The darker portion of the central band indicates least risk of these problems occurring.

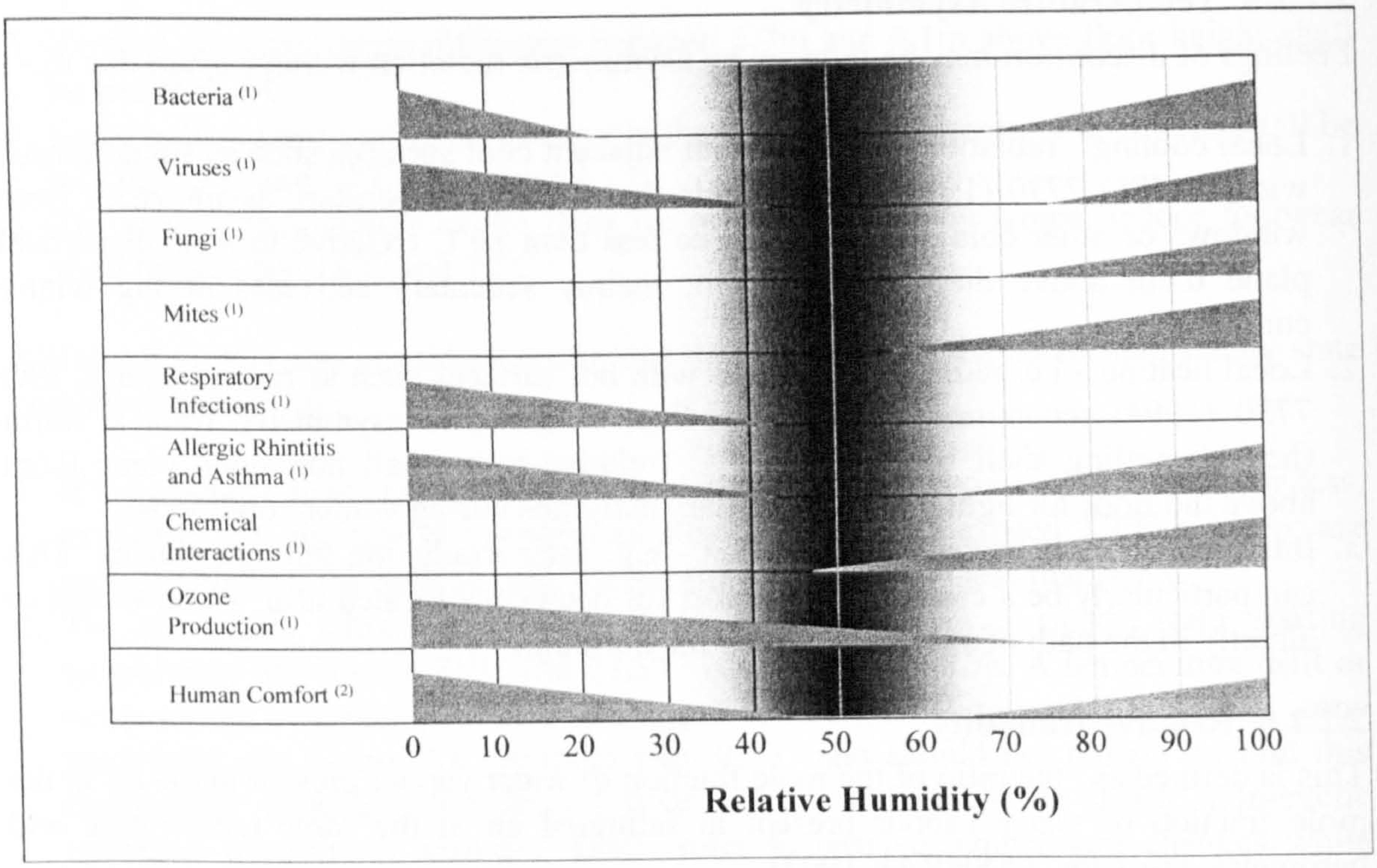

Figure 2.8. Relative humidity ranges for comfort and health [1. Stirling et. al. (1985), 2. CIBSE (1987)].

2.2.2.7 Air Ions

Croome and Roberts (1975) suggest that negative and positive air ions are an important factor in consideration of human comfort indoors. This research suggests that sensations of freshness and well being are induced by negative ions.

2.2.2.8 Air Velocity and Turbulence Intensity

Turbulence intensity is defined as the ratio of the standard deviation of the air speed to the mean air speed (ASHRAE 1992). Air velocity and its turbulence intensity have an effect on an individuals comfort, see Figure 2.9. The curves are based on the model of draught for 15% dissatisfied due to draught. This figure applies to light, mainly sedentary activity (70 W/m^2 =1.2 met)

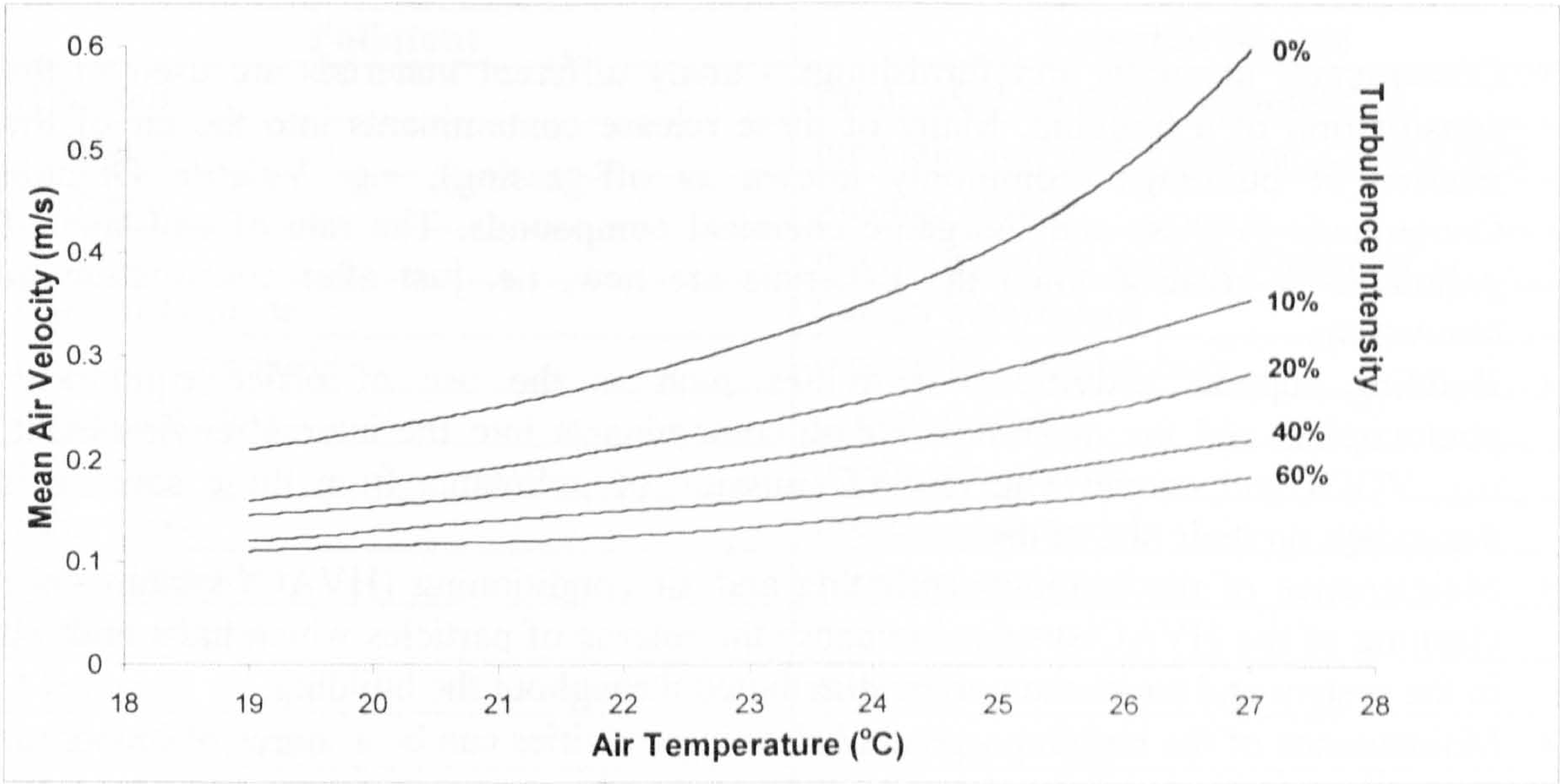

Figure 2.9. Allowable mean air velocity as a function of air temperature and turbulence intensity (ISO 7730 1994).

A draught risk model was developed to predict the percentage of people dissatisfied caused by draught as a function of air temperature, mean air velocity and turbulence intensity, see Equation 2.4.

$$DR = (34 - t_{ai})(v - 0.05)^{0.62}(0.37vT_u + 3.14)$$

Equation 2.4

Equation 2.4 applies for sedentary occupants (ISO 7730 1994, CEN 1994, ASHRAE 1992).

2.3 Indoor Air Quality

Research into indoor air quality has focused on ascertaining the level and types of pollutants released into the internal environment and subsequently correlating with humans psychological and physiological reactions. Two sources of pollutant are commonly investigated:-

- pollutants from building materials and processes, i.e. from the structure and fabric, internal fittings and office machines
- bioeffluents from humans, *i.e. carbon dioxide and odours*

2.3.1 Sources of Indoor Air Pollutants

These include:-

- Humans - building occupants emit bioeffluents and germs. These include odours, exhaled carbon dioxide, viruses and bacteria.

- Construction materials and furnishings - many different materials are used in the construction of a building. Many of these release contaminants into the air of the interior of buildings (commonly known as off-gassing), e.g. Volatile Organic Compounds (VOCs) and inorganic chemical compounds. The rate of emission of pollutants is greatest when the materials are new, i.e. just after construction or renovation.
- Building support activities - activities such as the use of office equipment, photocopiers and fax machines release contaminants into the internal environment, e.g. VOCs and ozone. The rate of emission of pollutants from these sources is dependant on their rate of use.
- Maintenance of the heating ventilating and air conditioning (HVAC) system - the cleaning of the HVAC system can cause the release of particles which have built up in the system and cause them to be distributed throughout the building.
- Maintenance of the building - general cleaning activities can be a source of indoor air contaminants. Lack of cleaning can allow dirt and germs to accumulate on surfaces and in carpets etc. The cleaning processes themselves may use solvents which contaminate the indoor air. Poor cleaning methods may redistribute contaminants which have settled onto surfaces into the indoor airborne environment.
- External air - it is normally assumed that outdoor air is clean and fresh. However, poor positioning of air intakes can cause the air entering the building to be already contaminated, e.g. an air intake situated on a busy street where the air is already contaminated by vehicle emissions.

2.3.2 Types of indoor air pollutants

There are numerous types in indoor air pollutant. Some of the more commonly encountered indoor air pollutants and their potential sources are listed in Table 2.3.

Pollutant	Potential Source
Ammonia	fluids used for cleaning buildings
Asbestos	pipe lagging, boiler lagging, ceiling tiles
Benzene	tobacco smoke
Biocides	micro-organism growth controller
Carbon-Dioxide	human bioeffluent
Carbon-Monoxide	incomplete combustion
Detergent Dust	carpet cleaning
Ethanol	duplicating fluids
Fibreglass	insulation materials
Formaldehyde	furniture out-gassing
Hydrocarbons	paints / solvents
Methanol	duplicating machines
Micro-Organisms	bacteria and fungi
Motor Vehicle Exhaust	outside make up air in built up areas
Nitrogen Oxides	tobacco smoke
Ozone	photocopiers
Paint Fumes	new and refurbished buildings
Polychlorinated biphenyls (PCBs)	ageing electrical equipment
Pesticides	fungi treatment
Photochemical Smog	interaction between airborne chemicals
Radon - radioactive gas	underlying ground of buildings
Solvents	correction fluids
Sterilent Gases	air conditioning systems
Sulphur Oxides	vehicle exhausts
Tobacco Smoke	building occupants
Vinyl Chloride	carpets

Table 2.3. Commonly encountered indoor air pollutants and their potential sources.

2.3.3 Perceived Indoor Air Quality

The perceived quality of indoor air is assessed by two human senses:-

- olfactory senses - these senses are sensitive to thousands of odourants in the air and are situated in the nasal cavity
- general chemical sense - these senses are sensitive to thousands of irritants in the air and are situated all over the mucous membranes in the nose, lips and the eyes

The combined olfactory and chemical senses serve to provide occupants with an overall perception of the quality of the air. If the air in a space becomes polluted due to the build up of pollutants from the lack of fresh air provided, occupants may become dissatisfied, see Figure 2.10.

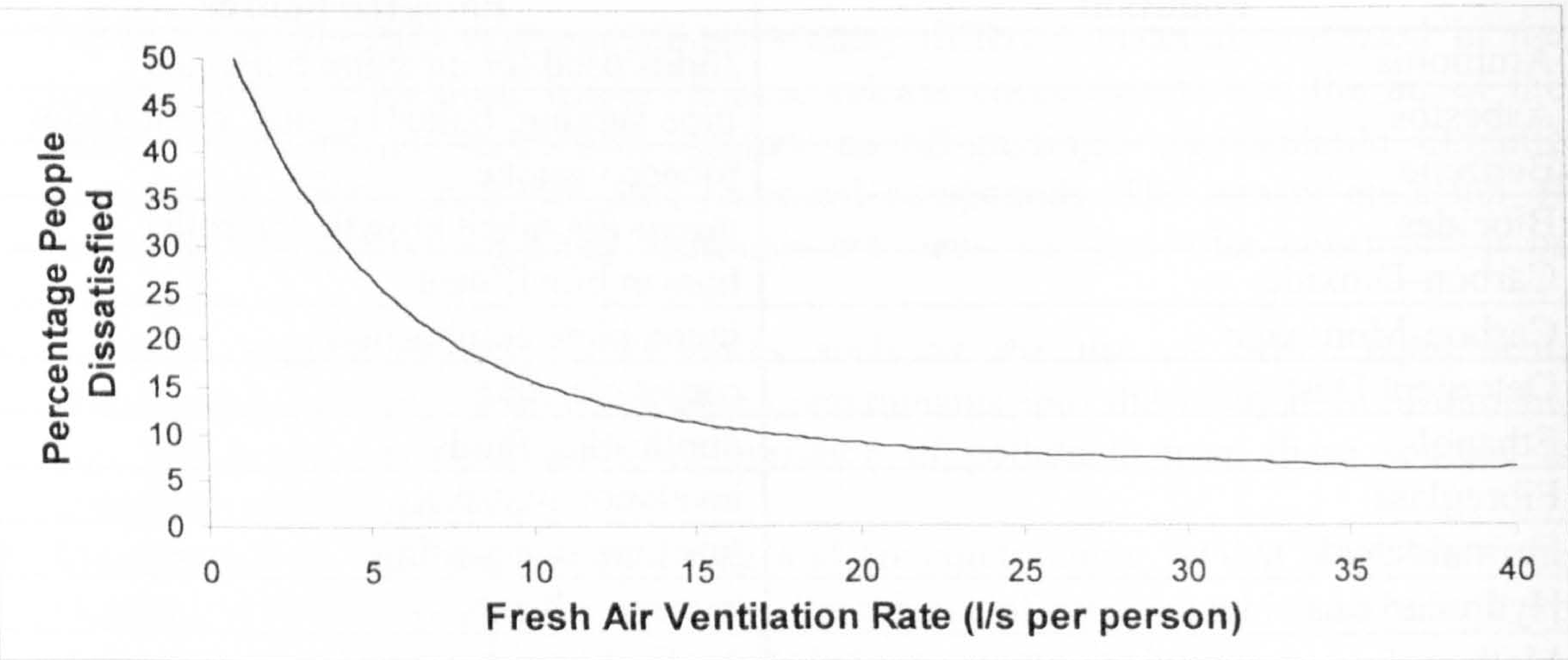

Figure 2.10. Percentage of people dissatisfied caused by the bioeffluents generated by a standard person as a function of ventilation rate (CEC 1992).

Levels of satisfaction with ventilation in office environments gained from field studies in the UK are shown in Figure 2.11.

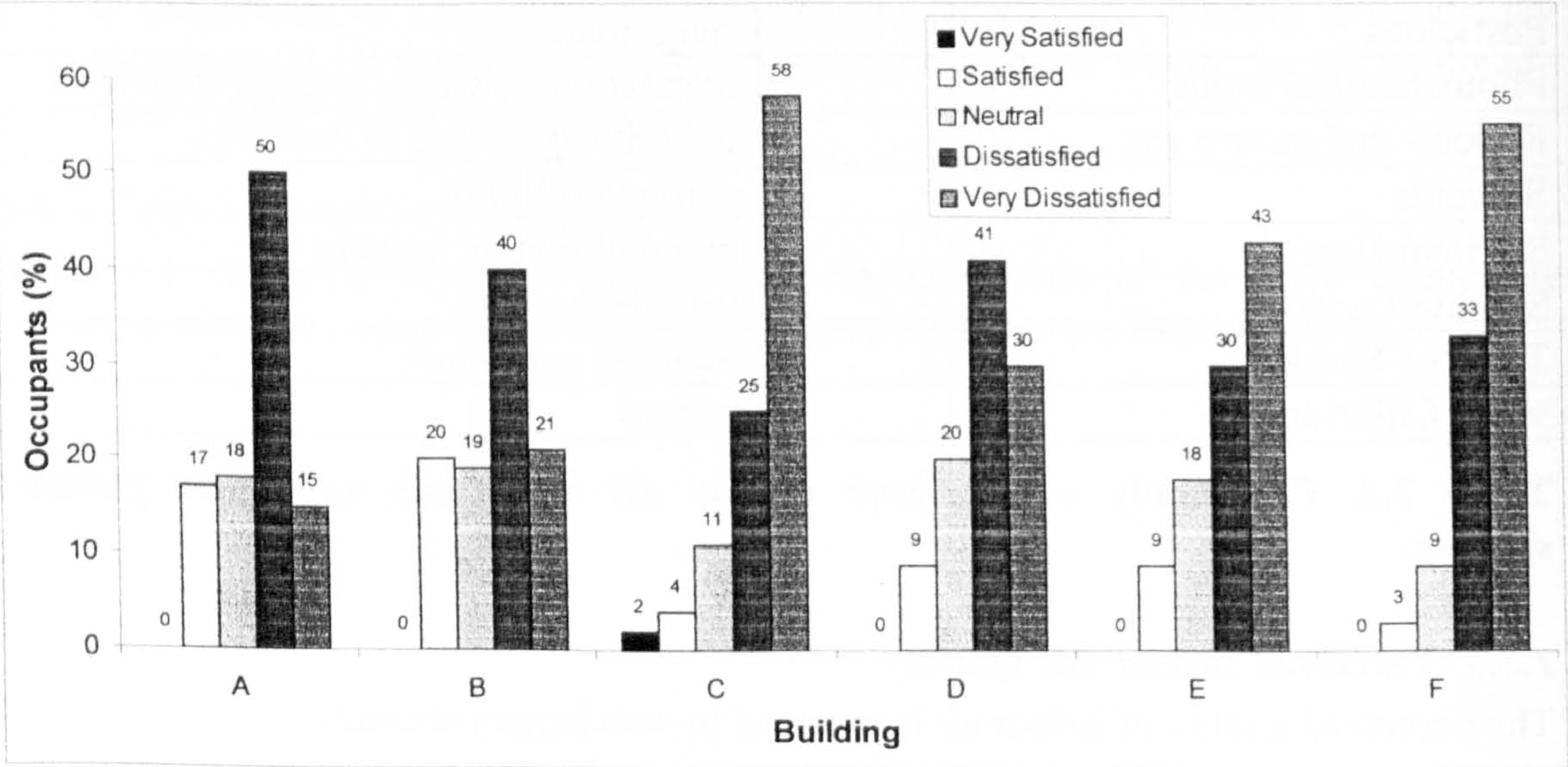

Figure 2.11. Levels of satisfaction with ventilation for six UK office buildings (Croome and Baizhan 1995).

As with the responses for thermal comfort, see Figure 2.7, the occupants perceptions of ventilation are skewed towards being dissatisfied. Again, it is likely that this is due to ineffective ventilation strategies rather than a lack of knowledge as to what the ventilation requirements are. This may often be a result of energy thrift in order to minimise building HVAC system running costs.

2.3.4 Occupant Requirements of Indoor Air Quality

Occupants have two main requirements of indoor air quality:-

1. the risk to health of breathing air within the building should be negligible
2. the air within the building should be perceived as fresh and pleasant

Large individual differences occur in individual human requirements, i.e. some people may spend a relatively large amount of time in the same location while others may only visit the building for a short period of time. Long term residents may become accustomed to the environment from the comfort viewpoint, but may be in danger from longer term health effects due to exposure to indoor air pollution. With respect to short term occupants, e.g. visitors "first impressions count" is very relevant. The human smelling senses become quickly accustomed to different odours in a matter of minutes. Long term occupants may therefore become accustomed to a slow build up of pollutants during the working day. However, visitors to buildings, who it is often desirable to impress, may find the odours on entering a space very unpleasant while longer term occupants do not even notice. For commercial reasons this is probably not a desirable situation.

2.3.5 Carbon Dioxide Concentrations as an Indicator of Indoor Air Quality

Carbon dioxide (CO_2) concentrations are commonly used as an indicator of the quality of the indoor air. CO_2 provides a good indicator of the indoor air quality where occupant densities are high and people are considered the main sources of pollutants. However, due to the increasing use of modern building materials , e.g. synthetic materials, and office machines, e.g. photocopiers and fax machines, pollutants from these sources have become increasingly important.

Although carbon dioxide is not directly perceived at the low, unharmful concentrations usually found in indoor air it is a good indicator of the concentrations of other pollutants and human bioeffluents being perceived as a nuisance. Figure 2.12 shows an example of how the carbon dioxide concentration can vary within an enclosed space with the number of occupants present.

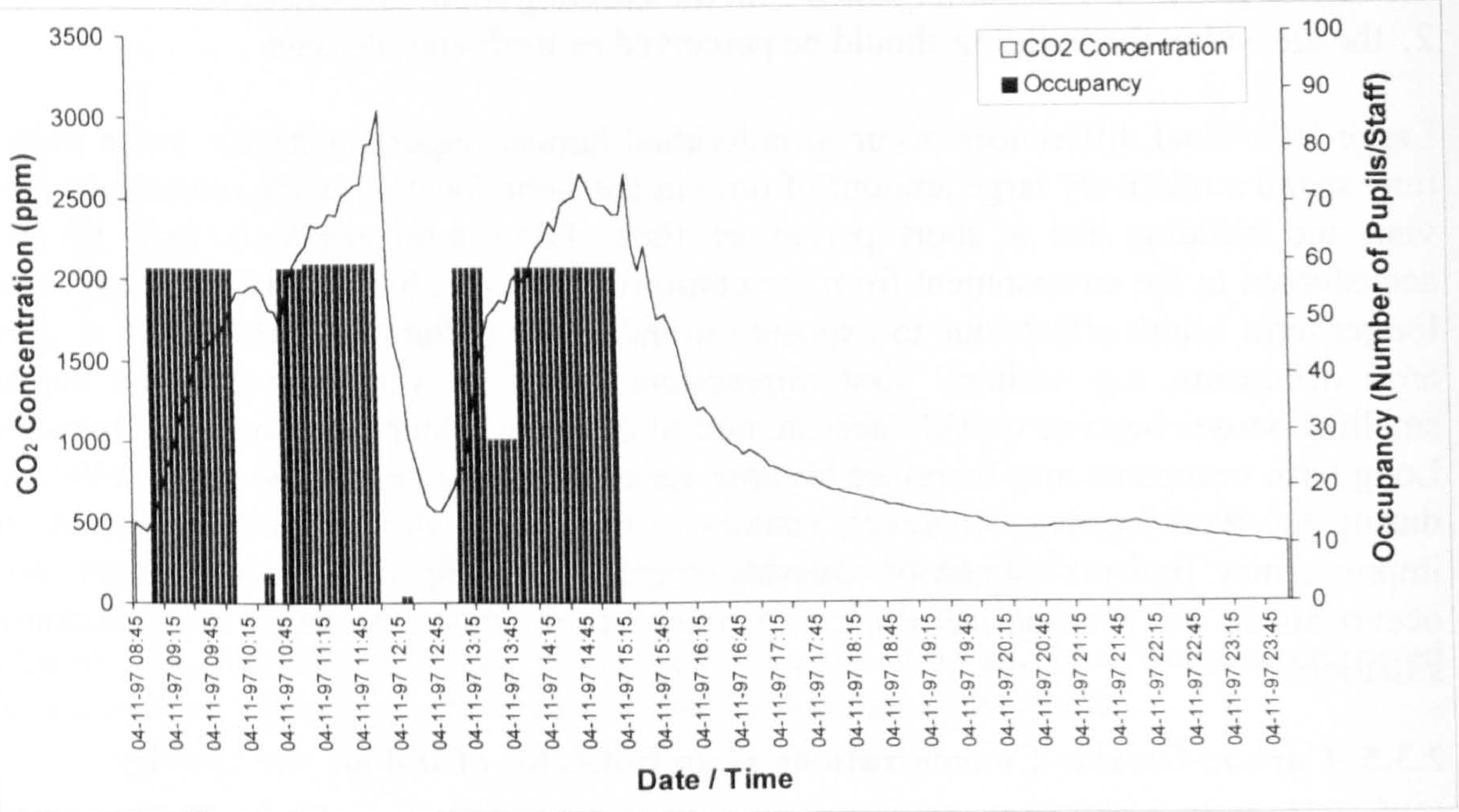

Figure 2.12. Occupancy patterns and resulting carbon dioxide concentrations for a school class base.

Figure 2.12 clearly shows that CO_2 concentrations reach high levels during the occupied periods of the day. The recommended carbon dioxide concentrations given in Table 2.4 and outdoor air supply rates given in Table 2.5 serve to highlight the lack of acceptable air quality provision depicted in Figure 2.12.

CO_2 Concentration (ppm)	Recommended Air Quality Rating
300 - 400	Typical background (atmospheric) concentrations (Potter et. al. 1994)
800	BSRIA level for acceptable indoor air quality (Potter et. al. 1994)
1000 or less	Limited or no concern (short term exposure) (WHO 1984)
1000	ASHRAE limit to satisfy comfort and odour criteria (ASHRAE 1989)
≈ 1000	20% Percentage People Dissatisfied Threshold (CEC 1992)
3500	Recommended threshold to avoid adverse health effects (CEC 1992)
5000	8 hour occupational exposure limit (CIBSE 1986, HSE 1985)
6600 and above	Concentration of concern (short term exposures) (WHO 1984)

Table 2.4. Carbon dioxide concentrations in indoor air and associated quality ratings.

Condition	Recommended Outdoor Air Supply Rate (l/s per person)
with no smoking	8
with some smoking	16
with heavy smoking	24
with very heavy smoking	32

Table 2.5. CIBSE recommended outdoor air supply rates for sedentary occupants (CIBSE 1987).

When carbon dioxide levels exceed those recommended for "acceptable indoor air quality", see Table 2.4, occupants may become dissatisfied with their internal environment, see Figure 2.13.

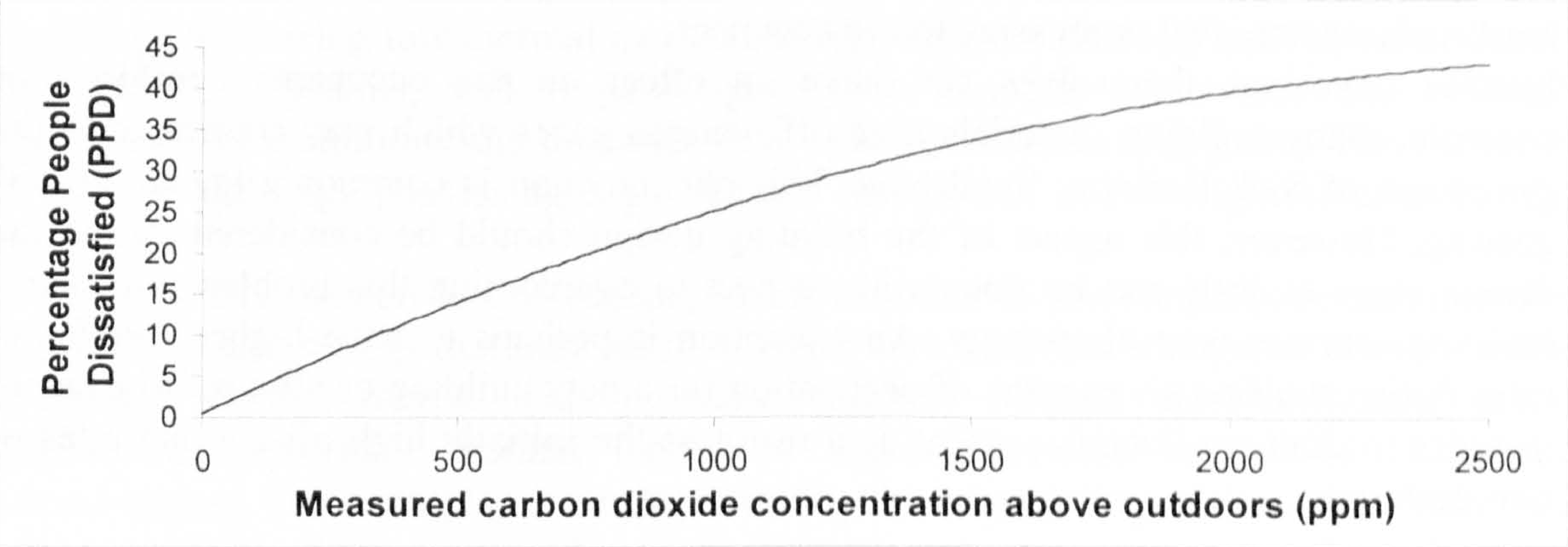

Figure 2.13. Percentage of people dissatisfied as a function of carbon dioxide concentration (CEC 1992).

Note: Outdoor carbon dioxide concentrations are commonly between 300 and 400 ppm.

Figure 2.11 indicates that many occupants are dissatisfied with the air quality of their indoor working environments. Figure 2.12 indicates that insufficient fresh air is introduced to the school classroom in question. Air quality is a problem that should be considered and overcome if a good working environment is to be provided.

During the research project an investigation was made into the air quality in school classrooms based on CO_2 measurements. Two papers are presented in Appendix A and Appendix B detailing this research. The papers also give an in depth discussion on indoor air quality.

2.3.6 The Olf and the Decipol as Measures of Air Quality

Fanger (1988) introduced methods of measuring the quantity of the pollution generated by a person and the perceived air quality within a space in the form of the olf and decipol units respectively:-

1 olf = the pollution generated by one standard person
1 decipol = the perceived air quality in a space with a pollution strength of 1 olf, ventilated by 10 l/s of clean air, i.e. 1 decipol = 0.1 olf/(l/s)

This method of assessing the indoor air quality relies on the subjective opinion of a trained panel, usually ten people. Therefore it does not represent a feasible method for introduction into a building services control strategy within the scope of the research project.

2.4 Building Design

This section considers the impact on human comfort of the physical design of an occupants surroundings and materials present in buildings.

2.4.1 Surface Coverings and Textures

The texture of a surface, can contribute to an occupants overall feeling of comfort. For example, soft textures can make occupants feel at ease with their environment while hard surfaces may feel oppressive to the occupant.

Surface coverings themselves can have an effect on the occupants comfort. For example, many building materials give off noxious gases which may contribute to the symptoms of Sick Building Syndrome. This phenomenon is commonly known as off-gassing. However, this aspect of the building design should be considered during the design stage as little can be done with respect to overcoming this problem utilising a building services control strategy. An exception is perhaps to have higher ventilation rates during the first six months of occupation for a new building or after refurbishment in order to dilute pollutants present as a result of the initially high off-gassing rates of new materials.

2.4.2 Surface Colours

Research by Morgenson and English (1926) and Ross (1938) suggested that colours from the red end of the spectrum initiate feelings of warmth while those from the blue end initiate feelings of cold. However, Houghton et al. (1940) and Berry (1961) carried out research in environmental chambers in which they showed there was no change in thermal comfort with change in the colour of the environment. Fanger (1972) concludes from the above results that "as colour has no thermal influence on man, any influence on the thermal sensation must therefore be of a psychological nature". This phenomenon is commonly experienced on entering a room which is blue in colour. The human psychological response is one of coldness. However, the occupant does not experience this physiologically. After a short period of time physiological senses will normally override the psychological senses. The influence colour has on an individuals thermal comfort will vary from person to person.

2.4.3 Room Dimensions

Small rooms may give rise to feelings of confinement whereas large rooms may give feelings of anonymity and bareness. However, room dimensions lie outside the bounds of this research project as they are generally specified in the design brief. They are a "fixed" component of the building and do not come within the scope of control systems and hence the research project described in this thesis.

2.4.4 Workstation Ergonomics

Factors such as seating position, desk height, and movement required can effect the physical comfort of building occupants and is well documented, e.g. Oborne (1987). Again this aspect lies outside the bounds of the environmental systems control concerns of the research project described in this thesis.

2.4.5 Building Orientation

This can effect the rates of ventilation, infiltration, external surface temperatures, and hence internal surface temperatures, the quantity of solar radiation entering the building through openings and shading provision. Ultimately therefore, building orientation can effect the internal environment and the comfort experienced by occupants. Such effects are described by Givoni (1969). Building orientation is considered during simulations using the control strategies developed during the research project in Chapter 9 and Chapter 10.

2.4.6 Building Thermal Inertia

Buildings possessing low thermal inertia, i.e. lightweight buildings, such as metal frame and cladding systems, will respond quickly to changes in internal and external environmental conditions and demands from space conditioning systems. The converse is true of buildings possessing high thermal inertia, i.e. heavyweight structures, e.g. masonry.

This can effect the comfort of building occupants due to the temperature asymmetries and temperature swings that may result. Careful consideration is required in matching a buildings thermal inertia with probable external thermal conditions and space conditioning systems. Thermal inertia of heating systems is also an important consideration. For example, underfloor heating in a space exposed to solar gain can cause problems of overheating due to the long time constants inherent of heated floors. A building environmental control strategy should take into account a buildings thermal inertia and match appropriately with the heating and cooling systems employed.

2.5 External Environmental Variables

These variables are concerned with conditions external to the building which have an effect on occupant comfort.

2.5.1 Weather Conditions

Weather conditions have the obvious implications regarding the energy input required into a building in order to maintain occupant comfort, e.g. cooling in summer, heating in winter. It may also have an effect on the preferred environmental indoor conditions as a result of the adaptive reactions of building occupants as suggested by Humphreys (1976), see Section 2.7.2.

2.5.2 External Air Quality

Space conditioning systems rely on replacing all or part of the air in the occupied zone within a building with "fresh" external air in order to reduce airborne pollutant concentrations. This assumes that the external air is itself relatively free from pollutants. This may not be the case in urban areas. The air may need to be filtered in order to reduce these pollutant levels. Human comfort within buildings may be dependant on the quality of the air occupants experience outside. Therefore external air quality will have an influence on peoples comfort within buildings and should be accounted for.

2.6 Occupant Variables (Psychological)

These variables are the most difficult to define with respect to human comfort but probably go a long way to explaining the discrepancies between steady state thermal comfort models and the results obtained during field studies, see 2.7.4. These variables can be the root cause of discomfort or may act to reduce occupants' tolerances due to the physically induced building related stressors of thermal comfort and indoor air quality.

Ways in which building occupants perceive their environment are described in the following sections.

2.6.1 Past Experiences and Expectations

Humans become accustomed to different environments due to experiences during their everyday lives. For example, people expect the temperature to be warmer in summer than in winter. Therefore, during the summer months people tend to wear lighter clothing. However, on some of the cooler summer days, people still wear lighter clothing because of their expectations and past experiences of the temperature during that time of the year. It is often not until a physiological reaction occurs, such as a shiver, that a person actually realises it is colder than they first assumed. If people in this situation were aware of the real temperature they would probably wear heavier clothing. Research on this aspect has been reported by Auliciems (1984).

2.6.2 Attitudes

Restraints other than an occupants preferred comfort may effect actual comfort conditions achieved. For example, with respect to thermal comfort, occupants may opt for lower room temperatures in winter, which they perceive as being comfortable, if they are responsible for energy costs (Griffiths et al. 1988, Crashaw and Williams 1988).

2.6.3 Cultural and Climatic Differences

Humphreys (1975) suggests that climate effects preferred comfort conditions, i.e. occupants from warmer climates prefer warmer indoor temperatures when compared to those from cooler climates, where other conditions remain constant, i.e. clothing and activity. This may be due to the physiological reaction of acclimatisation but may also be influenced by cultural interpretations of what is accepted as comfortable (McIntyre 1982, McIntyre 1980, Heijs and Stringer 1988). For example, in air-conditioned offices Humphreys (1978) found that different cultures preferred different comfort temperatures when compared to the world average:-

- 2°C higher than the world average in America.
- 2°C lower than the world average in the former USSR.
- 1°C lower than the world average in the UK.

Research by Cena (1990) shows that the meaning of the words warm, hot or cool and cold vary around the world, i.e. cultural semantics can alter the way occupants interpret the environment and can effect the results obtained when conducting studies to assess peoples responses to their surrounding physical environment.

2.6.4 Company Management Style and Type of Occupation

The manner in which a company is run can effect the occupants perception of conditions experienced at work. Traditional hierarchical, top down management is often a cause of stress to those lower in the hierarchy who may feel unimportant and lacking control. This may lower the tolerance of occupants to small inadequacies in the internal environment. The same effects may be experienced as a result of the type of work. Manual and or repetitive work can cause the occupants to become psychologically dissatisfied meaning the discomfort caused by any deviations from preferred comfort conditions will be amplified. For example, the Hawthorne Experiments carried out by Elton Mayo (Cole 1990) began as a study into the physical conditions on productivity at work but ended up as a series of studies into social factors, e.g. membership of groups and relationships with supervision. The main conclusions drawn from the Hawthorne Experiments were:-

- individual workers cannot be treated in isolation, but must be seen as members of a group
- the need to belong to a group and have status within it is more important than monetary incentives or good physical working conditions
- informal, or unofficial groups at work exercise a strong influence over the behaviour of workers
- supervisors and managers need to be aware of these social needs and cater for them if workers are to collaborate with the official organisation rather than work against it.

Hence situations arise where building related illnesses could be initiated as a result of the company management structure or type of occupation rather than the actual internal environmental conditions. This is not always obvious as it is difficult to distinguish causes and effects.

2.6.5 Contact with the External Environment

Humans generally like to have contact with elements of the natural world whether it is a view, natural daylight or sounds. Having contact with the outside world enables us to identify where we are and the time of day. Deprivation of these indicators can initiate feelings of discomfort or lower the tolerance to other physical conditions such comfort perception.

2.6.6 Perceived Controllability of the Internal Environment

The majority of people would agree that they would prefer to be in control of what they are doing. For example, people would generally feel happier being the driver of a car rather than the passenger as they have control. This is also true of control over environmental conditions within a building.

Research suggests that occupants of buildings put more importance on control over heating, ventilation and cooling than control of lighting and noise (Bordass and Leaman 1993). This may be partly due to the fact that the former are controlled centrally whilst the latter are controlled more directly by internal layout and workstation arrangement which can be partly controlled by users. However, throughout this century, the introduction of ever more sophisticated building environmental conditioning systems has taken the control of the internal environment away from the occupants and placed it with centralised building control systems. This trend has been exacerbated by the use of deeper and open plan buildings with decreased window to floor ratios in the pursuit of greater spatial efficiency.

Research has found that people are often as comfortable in naturally ventilated buildings as in air-conditioned buildings (Wilson and Hedge 1987). However, indoor environmental conditions in naturally ventilated buildings tend to fluctuate far more than in air-conditioned buildings. If the conditions were to fluctuate as much in air-conditioned buildings complaints would probably arise. It is likely that the reason for people not complaining about these large fluctuations in naturally ventilated buildings is that they feel in control of their environment as a consequence of this type of building's design, i.e. openable windows for natural ventilation as opposed to totally sealed windows in air-conditioned buildings. Occupants also have expectations of how the building should perform. People often expect air conditioned buildings to perform better than naturally ventilated buildings and are therefore disappointed when their expectations are not met. Research has shown that the tolerance of occupants to conditions of thermal comfort is greater where they have control over the temperature than where they don't (de Dear 1993). This is confirmed by research carried out on the effect of perceived control over thermal comfort in houses, see Figure 2.14.

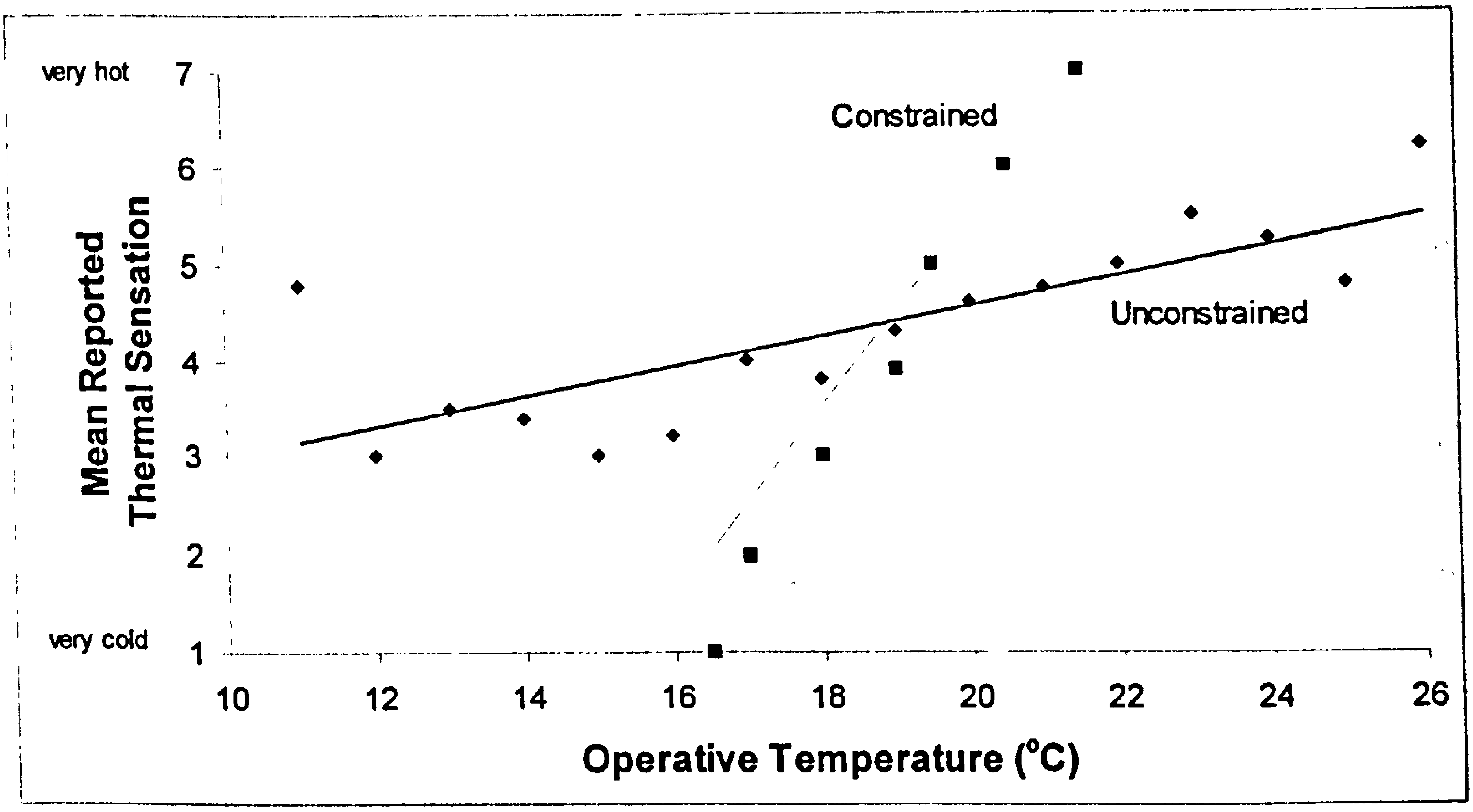

Figure 2.14. Relationship between temperature and thermal comfort under constrained and unconstrained conditions in homes (Leaman and Bordass 1995).

Referring to Figure 2.14, the "constrained" results were obtained while occupants had no control over their thermal environment, i.e. were not able to adjust the heating controls in their houses. The "unconstrained" results were obtained by allowing occupants to have control over their heating and hence comfort in their homes. The steeper "constrained" line implies that occupants had a much narrower comfort band than for "unconstrained" use of their heating system.

Similarly, perceived productivity and perceived controllability are related, see Figure 2.15.

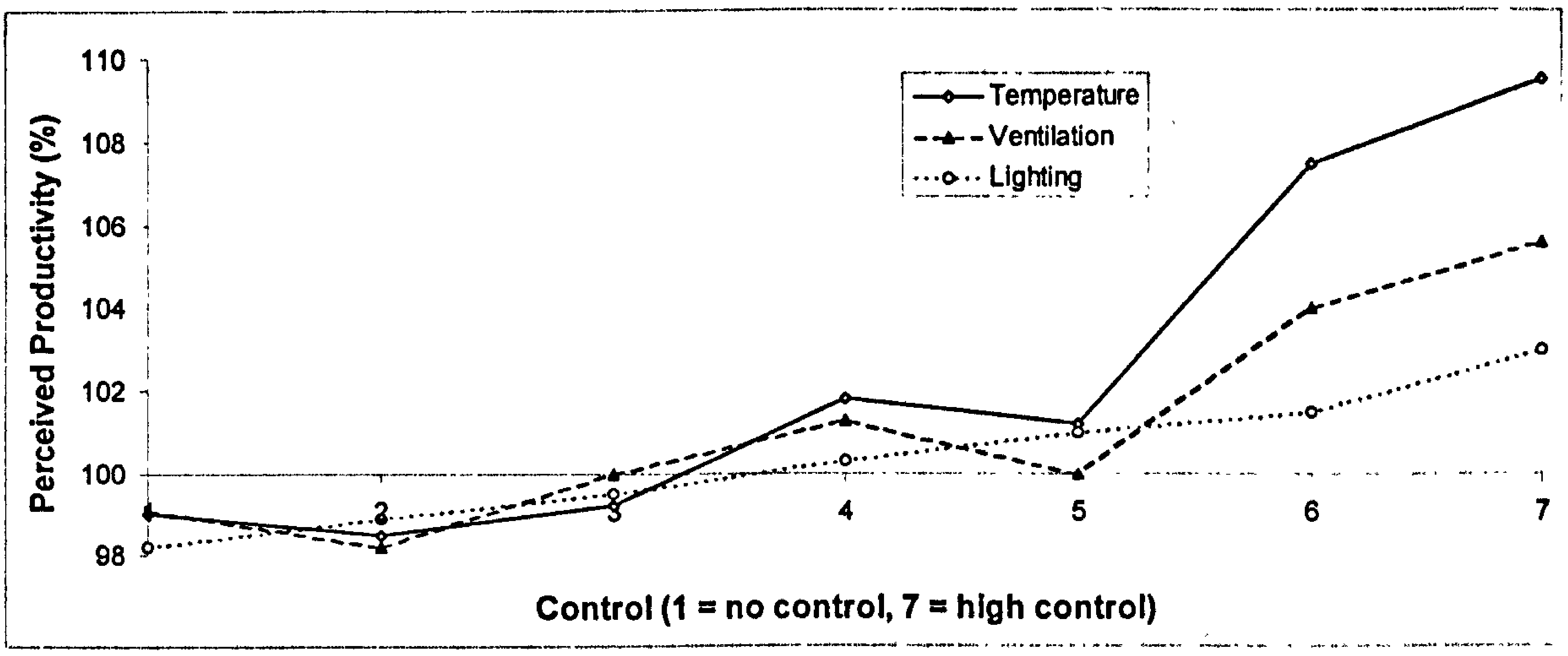

Figure 2.15. Perceived productivity and perceived control over temperature, ventilation and lighting (Raw et al. 1990).

Figure 2.15 shows that occupants' perceived productivity increases with increased control of the temperature, ventilation and lighting.

The depth of the building, i.e. how far occupants are from windows, also effects their perceived control over the environment. Figure 2.16 shows how occupants perceived control of their environment decreases with increased room size.

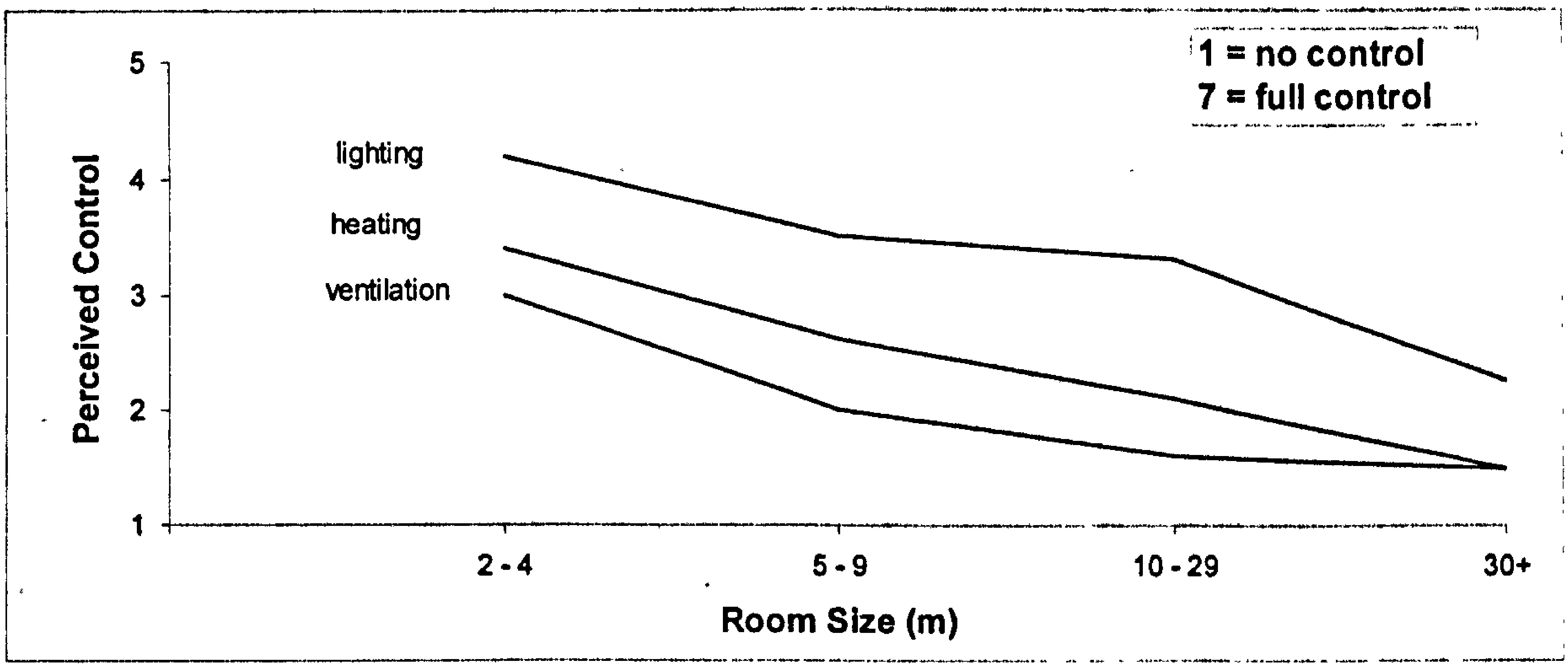

Figure 2.16. Perceived control over the internal environment as a function of room size (Wilson and Hedge 1987).

Figure 2.14, Figure 2.15 and Figure 2.16 conclusively show that occupants control over their internal environment has an influence their environmental comfort.

2.7 Defining and Assessing Thermal Comfort

Thermal comfort can be defined as "the condition of mind that expresses satisfaction with the thermal environment" (ASHRAE 1992), i.e. a thermally comfortable environment is one where the occupant would prefer neither warmer nor cooler surroundings, i.e. thermally neutral.

Historically, thermal comfort research has concentrated on steady state conditions provided by environmental climate chambers. More recently, research has increasingly involved field studies and hence transient (dynamic) thermal conditions and occupant responses.

Within this context there have been three main approaches to the analysis of thermal comfort:-

1. **Physical** - this approach considers the heat balance of the human body, i.e. the human body maintaining thermal equilibrium by losing heat at the same rate that it is being produced through internal metabolic processes.
2. **Physiological** - this approach studies the mechanisms by which the human body attempts to maintain optimal temperatures, for example by vaso-constriction and vaso-dilation to decrease or increase the rate at which body heat is lost to the environment respectively.
3. **Psychological** - this approach attempts to quantify and describe degrees of warmth and cold sensation by rating the strength of sensation on a numerical scale. The sensations are then related to the actual environmental conditions prevailing and parameters such as clothing and activity level.

At present thermal comfort research is generally categorised into two different approaches.

- **Environmental Chamber Studies (steady state)** - this considers peoples thermal response after a period of time exposed to steady thermal conditions. Studies are normally carried out in environmental chambers with artificially created thermal environments. Environmental chamber studies have the advantage of providing a range of environmental conditions on demand but are commonly criticised for creating artificially steady conditions to which building occupants are not normally exposed.
- **Field Studies (adaptive approach)** - this type of study considers peoples perception of their thermal environment in their normal environment, e.g. under normal thermal conditions in an office environment. This type of study takes into account that people adapt to their thermal environment which is normally constantly varying both in the long and short terms. Field studies have the advantage of studying subjects in their normal working environment but suffers from the disadvantage of the experimental procedure having little or no control over the environmental conditions occurring.

An introduction to the steady state and adaptive approaches are given in the following sections.

2.7.1 Steady State Heat Balance Models

Fanger (1972) conducted research on the heat exchange between a person, the environment and thermal comfort based on a steady state comfort equation. The results of this research have been embedded in current standards, e.g. ISO 7730 (1994). Fanger proposed that the most important variables which influence the condition of thermal comfort are:-

Physical Variables
- activity level (heat production rate in the body)
- thermal resistance of the clothing

Environmental Variables
- air temperature
- mean radiant temperature
- relative air velocity
- water vapour pressure in ambient air

Fanger suggests that thermal comfort can be achieved by many different combinations of the above variable values as long as they (i) satisfy Equation 2.5, i.e. heat produced = heat lost, and (ii) the conditions for thermal balance are consistent with comfort.

Fanger's Heat Balance Equation (Fanger 1972) for thermal comfort is defined by Equation 2.5.

$$\frac{M}{A_{DU}}(1-\eta)-0.35[43-0.061\frac{M}{A_{DU}}(1-\eta)-p_a]-0.42[\frac{M}{A_{DU}}(1-\eta)-50]-0.0023\frac{M}{A_{DU}}(44-p_a)$$
$$-0.0014\frac{M}{A_{DU}}(34-t_{ai})=3.4\times10^{-8}f_{cl}[(t_{cl}+273)^4-(t_{mrt}+273)^4]+f_{cl}h_c(t_{cl}-t_{ai})$$

Equation 2.5

Fanger's studies were carried out for steady state thermal conditions, i.e. people rated their thermal sensation after being exposed to constant thermal conditions in an artificial environment, i.e. a climate chamber.

Because of differences in the perception of preferred comfort conditions between individuals it is not possible to provide a thermal environment which will satisfy all people simultaneously. It is therefore not an easy task to rate a thermal environment quantitatively. However, Fanger extended the heat balance theory to provide an index called the Predicted Mean Vote (PMV) for a group of occupants. He assumed that the sensation experienced by a person was a function of the physiological strain imposed on a person by the environment. This is defined as "the difference between the internal heat production and the heat loss to the actual environment for a man kept at the comfort values for skin temperature and sweat production at the actual activity level" (Fanger 1972). The PMV was determined during thermal comfort studies in environmental chambers. Due to the applicability to the "Adaptive Theory" the method of determining PMV is detailed in Section 2.7.3 after the introduction to the Adaptive Theory in Section 2.7.2.

2.7.2 Adaptive Approach to Thermal Comfort

Thermal comfort heat balance models which assume steady state conditions have been challenged on two grounds:-

1. the models were developed in climate chambers and may be unreliable in predicting actual comfort in real buildings (Humphreys 1995).
2. designing for fixed internal environmental parameters may be inappropriate and unnecessarily expensive. There is now a tendency to take into account peoples capability to adapt to their thermal environment, i.e. the adaptive approach (Humphreys 1995).

People are able to adapt to their environments in both the short and long terms:-

1) long term - Humphreys (1976) suggests that the preferred mean indoor temperature varies with the monthly mean outdoor temperature as shown in Figure 2.17.

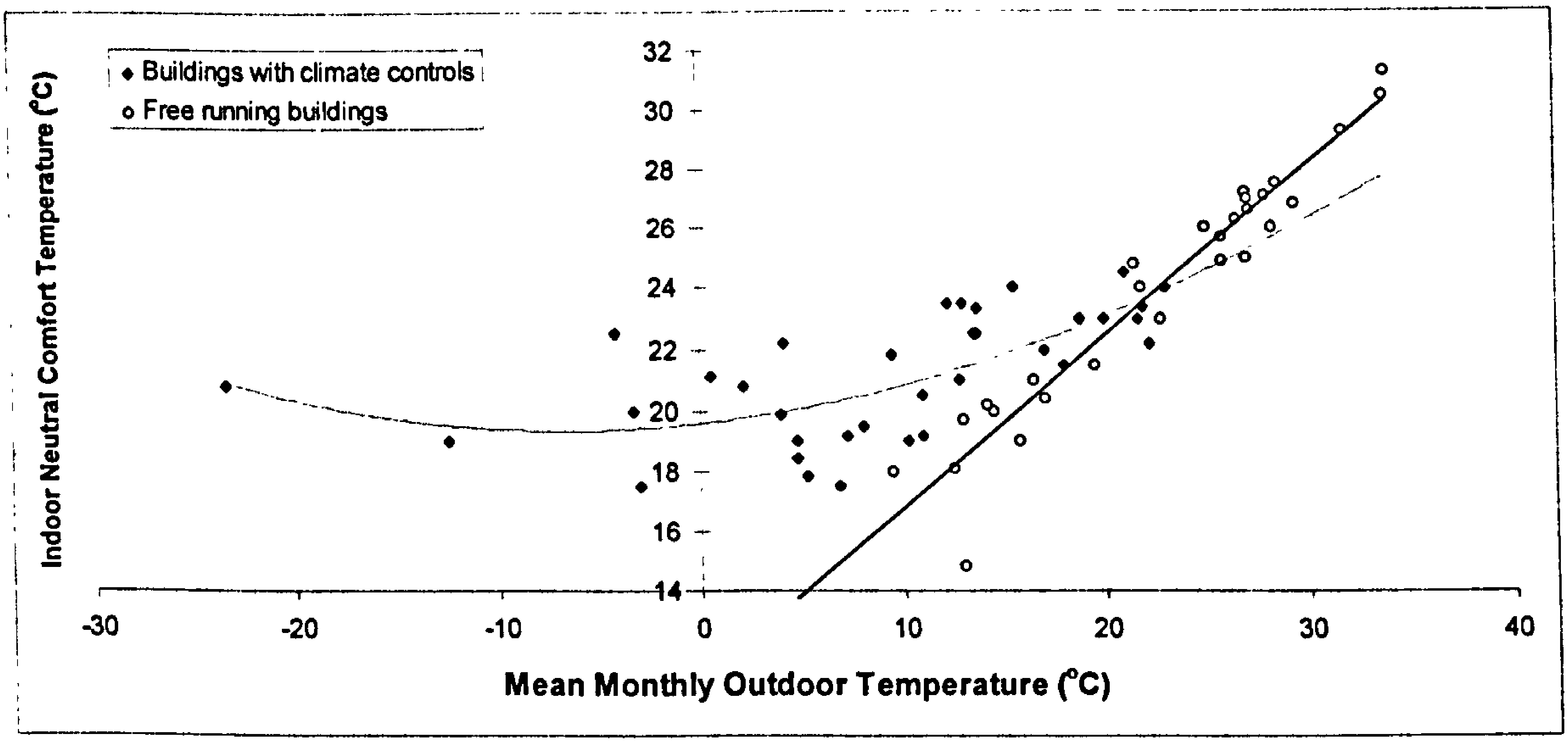

Figure 2.17. The statistical dependence of indoor thermal neutralities on outdoor temperature (Humphreys 1976).

Figure 2.17 indicates that the conditions that people prefer indoors for comfort will mimic the average outdoor temperature conditions encountered and that people in free running buildings have greater tolerances. This is thought to be achieved by occupants having the opportunity to use adaptive options such as opening or closing windows and blinds and adjusting expectations. Occupants with adaptive options available to them are also likely to have more control over their internal environment than for occupants of buildings with climate controls.

Humphreys also suggests that the mean internal air temperature effects the preferred neutral indoor temperature for comfort, see Figure 2.18.

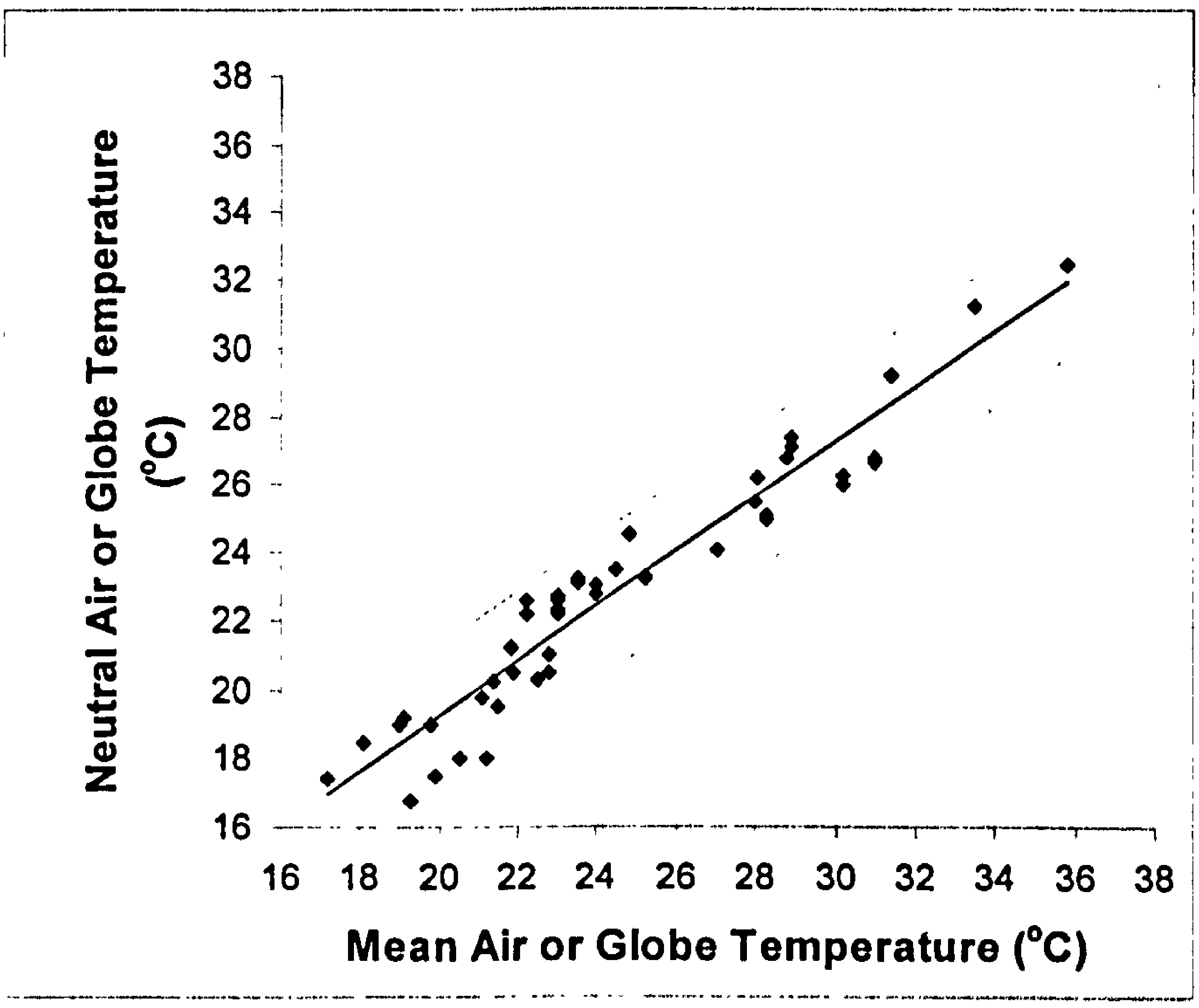

Figure 2.18. Scatter diagram of mean indoor temperature experience and the neutral, i.e. preferred, comfort temperature (Humphreys 1995).

Figure 2.18 suggests that the preferred comfort temperature is that commonly experienced by the occupant and provides evidence for the assertion that, given opportunity and time, people will take adaptive measures to maintain comfort for the prevailing conditions.

2) Short Term - Research conducted by Gagge et al. (1967) in which occupants were exposed to "neutral-cold-neutral" and "neutral-warm-neutral" environmental conditions suggests that human sensory mechanisms are anticipatory for both transients. However, it is more pronounced for the cold transient. Short term reactions include such actions as adding or removing clothing and opening or closing windows to modify sensations of comfort.

There are four categories of adaptive actions that can be taken:-

1. modifying the rate of internal heat production
2. modifying the rate of body heat loss
3. modifying the thermal environment
4. selecting a different thermal environment.

Some of the actions are consciously taken whilst others are unconsciously pursued by physiological reaction, i.e. active and passive reactions to the environment respectively.

Some examples of the adaptive reactions the human body takes when the deep body temperature gets too cool are given in Table 2.6.

Reaction	Effect	Passive / Active
vasoconstriction	reduce rate of body heat loss	passive
shivering	increase rate of internal heat production	passive
increase activity	increase rate of internal heat production	active
eat food	increase rate of internal heat production	active
add clothing	decrease rate of body heat loss	active
increase room temperature	modifies the thermal environment	active
adopt a more closed posture	reduce rate of body heat loss	active

Table 2.6. Human adaptive reactions to deep body temperature becoming too cool.

Some examples of the adaptive reactions to the body being too warm are given in Table 2.7.

Reaction	Effect	Passive / Active
sweating	increase rate of body heat loss	passive
sit forward in chair	increase rate of body heat loss	active
vasodilation	increase rate of body heat loss	passive
adopt an open posture	increase rate of body heat loss	active
remove some clothing	increase rate of body heat loss	active
decrease activity	decrease rate of internal heat production	active
turn on a fan	increase rate of body heat loss	active
open a window	increase rate of body heat loss	active
acclimatise	longer term adaptation to environment	passive

Table 2.7. Human adaptive reactions to deep body temperature becoming too hot.

Discomfort may still arise even when adaptive reactions occur where temperatures:-

- change too fast for adaptation to take place
- are outside normally accepted limits
- are unexpected or sudden
- are outside individual control.

The time variable in the adaptive process plays an important role. This can be considered over four generalised time periods:-

1. Instantaneous - for example, clothing can be changed in anticipation of thermal change, e.g. putting on a jumper before going outside during winter in anticipation of the outside air being cool.
2. Within 24 hours - e.g. clothing, posture or environmental adjustments used to cope with unexpected environments during the day.
3. Day to day - e.g. occupants learn from day to day how to cope with the changing environment, i.e. the weather.

4. Longer term - e.g. seasonal changes in clothing, use of buildings and other similar activities learnt over a longer time period.

However, there are many constraints on the way in which comfort can be modified using the adaptive approach such as:-

- time scale for change - e.g. changing clothing level is easy to achieve and can be done quickly. However long term changes, such as constructing a new building takes time and may not give the immediate benefits required.
- cost - some strategies are free, e.g. modifying clothing level, whilst some are expensive, e.g. air-conditioning.
- relative costs - some strategies may be cheaper than others, e.g. increasing fuel usage compared to modifying clothing level. The method chosen may depend on the financial capabilities of the individual or company and therefore represents a constraint.
- personality - people with rigid personalities are less likely to adopt new technology than those who are more open minded.
- gender - the type of clothes men and women wear varies. Therefore the options for clothing modification may be different.
- physiology - the thermoregulatory system is not fully developed in new-born children and deteriorates in old age. Therefore the thermoregulatory system may not be capable of initiating the correct adaptive actions to avoid discomfort and in some cases death.
- fixed glazing - occupants of some types of building, especially modern office building may not find the option of opening windows is available due to the building being sealed.
- uniform - some companies or cultures may have strict clothing policies. The option of modifying clothing levels is limited in these cases.
- cultural / religious - some countries have strict codes about what clothes are worn, e.g. the middle east.
- formal occasions - e.g. board meeting, academic presentations and weddings may require formal dress unsuitable for the prevailing conditions. The lack of choice to modify clothing level may lead to discomfort.
- fixed locations - some people are not able to relocate to a different part of a building in order to move to an area with different prevailing conditions, e.g. secretary, production line worker or retail sales checkout person.
- thermal control operated by another - the temperature control in modern buildings tends to be operated and set centrally, therefore the individual has no control.
- the requirement to save energy - the environmental setting to the individual may be limited for reasons of energy efficiency, legal requirements or cost.

A detailed account of the adaptive approach is given by Nicol (1993).

2.7.3 Assessing Thermal Comfort

To provide a methodology for assessing the thermal comfort of a group of individuals researchers developed the thermal sensation scales. Commonly used thermal sensation scales are shown in Table 2.8. These are filled in by individuals while the environmental conditions are simultaneously measured and recorded. A persons perception of the thermal environment can then be compared to the thermal conditions at a particular time. Thermal sensation scales have been comprehensively used in both steady state and adaptive studies.

Vote	ASHRAE (1992)	Bedford (1964)	Preference Scale
+3	hot	much too hot	much warmer
+2	warm	too warm	warmer
+1	slightly warm	comfortably warm	slightly warmer
0	neutral	comfortable	no change
-1	slightly cool	comfortably cool	slightly cooler
-2	cool	too cool	cooler
-3	cold	much to cool	much cooler

Table 2.8. Commonly used thermal sensation scales.

The Bedford scale incorporates the notion of comfort whereas ASHRAE's scale evaluates thermal sensation only. The relative merits of each of these sensation scales is given by Oseland (1992).

A problem arising when using the comfort vote can be the occupants' interpretation of the sensations associated with the words. For example, the word "warm" may be associated with both comfortable and uncomfortable in cold and hot environments respectively. In order to overcome this potentially misleading interpretation of the words it is often common practice to ask occupants to simultaneously fill in a preference scale. A preference scale using 7 descriptors is shown in Table 2.8.

A comprehensive guide to the recommended use of thermal sensation scales is given in ISO 10551 (1995). However, the ASHRAE thermal sensation scale is the one most commonly in use today.

Miller (1956) suggests that a seven point scale represents the optimum number of descriptors of sensation which can be reproducibly distinguished between. A thermal sensation vote of zero indicates thermal neutrality which implies that the occupant would prefer neither colder or warmer thermal conditions. Those dissatisfied are normally defined as those voting outside the three central categories on a thermal sensation scale. A non-neutral vote indicates a degree of thermal discomfort with a maximum discomfort at the "-3" and "+3" outer limits of the scale.

When implementing environmental chamber experiments, occupants are generally requested to remain in the chamber for approximately three hours, the votes used for analysis being those at the end, i.e. in the last hour, when it is assumed that steady state metabolic, and hence thermal comfort perception, has been reached. During field studies people are asked to complete thermal sensation scale when they have settled at their work station, i.e. not just after getting to work or after breaks. Groups of people are used during the experiments to provide statistically meaningful results.

A measure of "occupant comfort" obtained from experimental studies is normally achieved by first calculating the Predicted Mean Vote (PMV). In order to ascertain the PMV of a group of occupants they are asked indicate their thermal sensation on a thermal sensation scale at regular intervals during experimental assessments. The mean of the thermal votes at specific temperatures are then calculated for the group. However, the mean vote does not give an instantly meaningful value. Fanger (1972) proposed the curve shown in Figure 2.19 which was derived from the results of his comfort studies to overcome this problem. Figure 2.19 allows the Predicted Percentage Dissatisfied (PPD), the number of people in the population in question that would be expected to be dissatisfied with their thermal environment, to be derived from the Predicted Mean Vote (PMV).

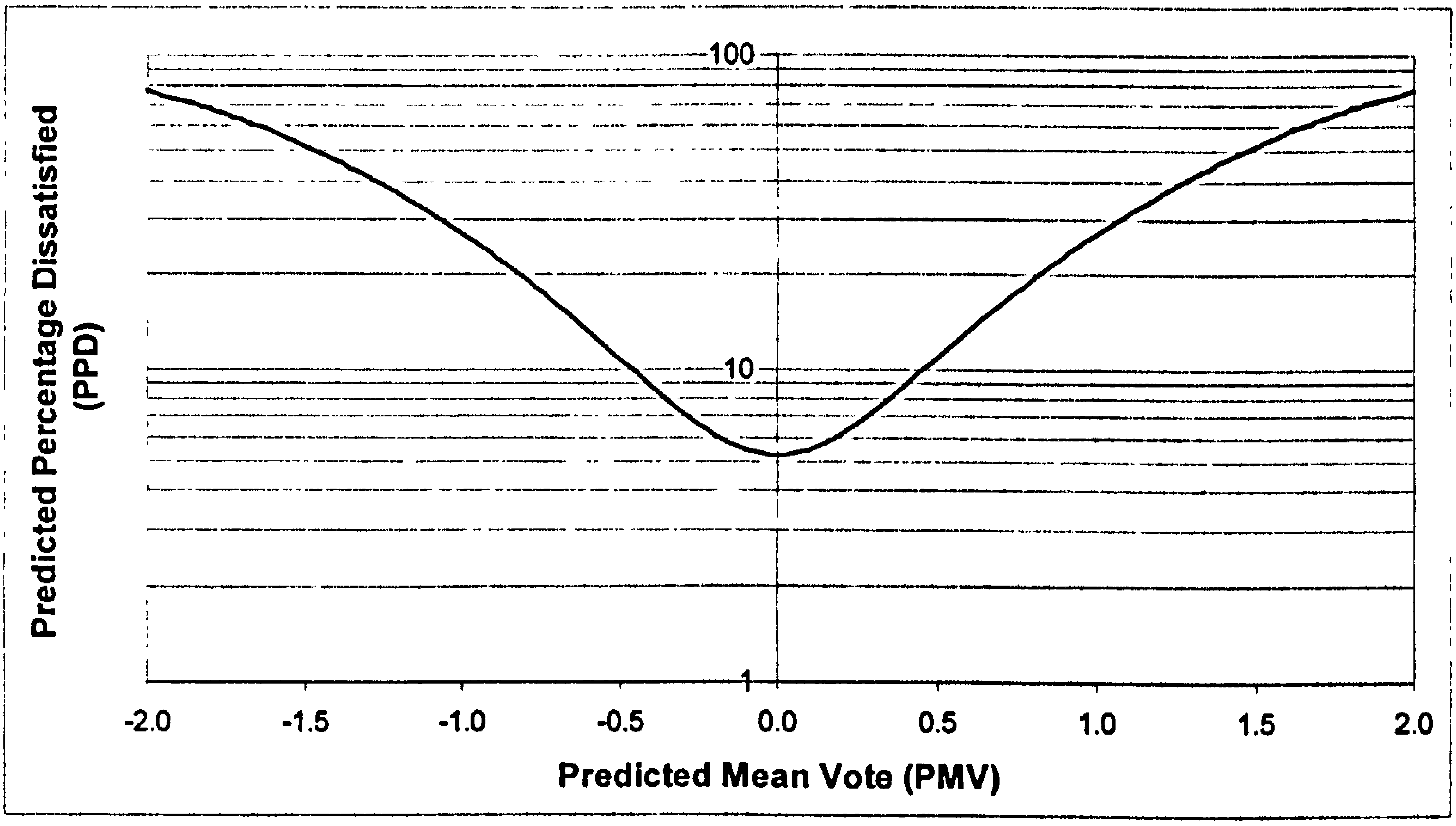

Figure 2.19. Predicted Percentage Dissatisfied (PPD) as a function of Predicted Mean Vote (PMV) (Fanger 1972).

Research results suggest that, at best, 5% PPD can be achieved (Fanger 1972). Current standards suggest that < 20% PPD (WHO 1987, ASHRAE 1992) and < 10% PPD (ISO 7730 1994) are reasonable figures to be obtained in operational buildings.

2.7.4 Discrepancies Between Thermal Comfort Models and Observed Field Studies

The discrepancies between the thermal comfort models and observed field results, see Figure 2.20 for example, are not clearly understood but would appear to be attributable to inadequate allowance for peoples physiological, psychological and behavioural adaptive responses to indoor and outdoor climate.

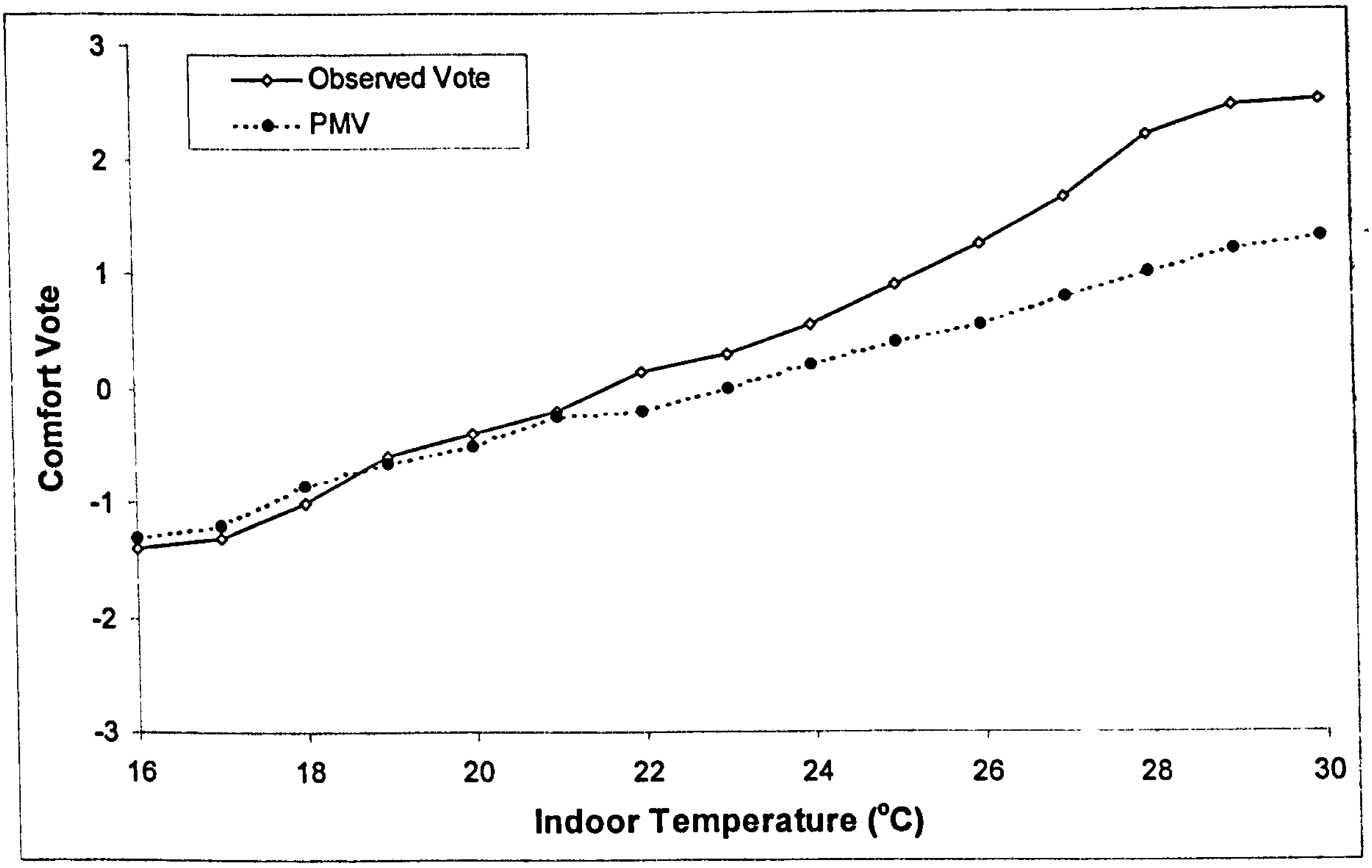

Figure 2.20. Comparison of observed mean thermal comfort votes with predictions using the PMV model in a UK office building (Fishman and Pimbert 1979).

PMV consistently overestimates the number of dissatisfied (Nicol 1993) implying that in reality buildings are heated or cooled to an extent which is unnecessary to maintain thermal comfort.

Fanger's thermal comfort model suggests that environmental conditions should be kept within strict limits, giving little opportunity for adaptation, see Figure 2.21.

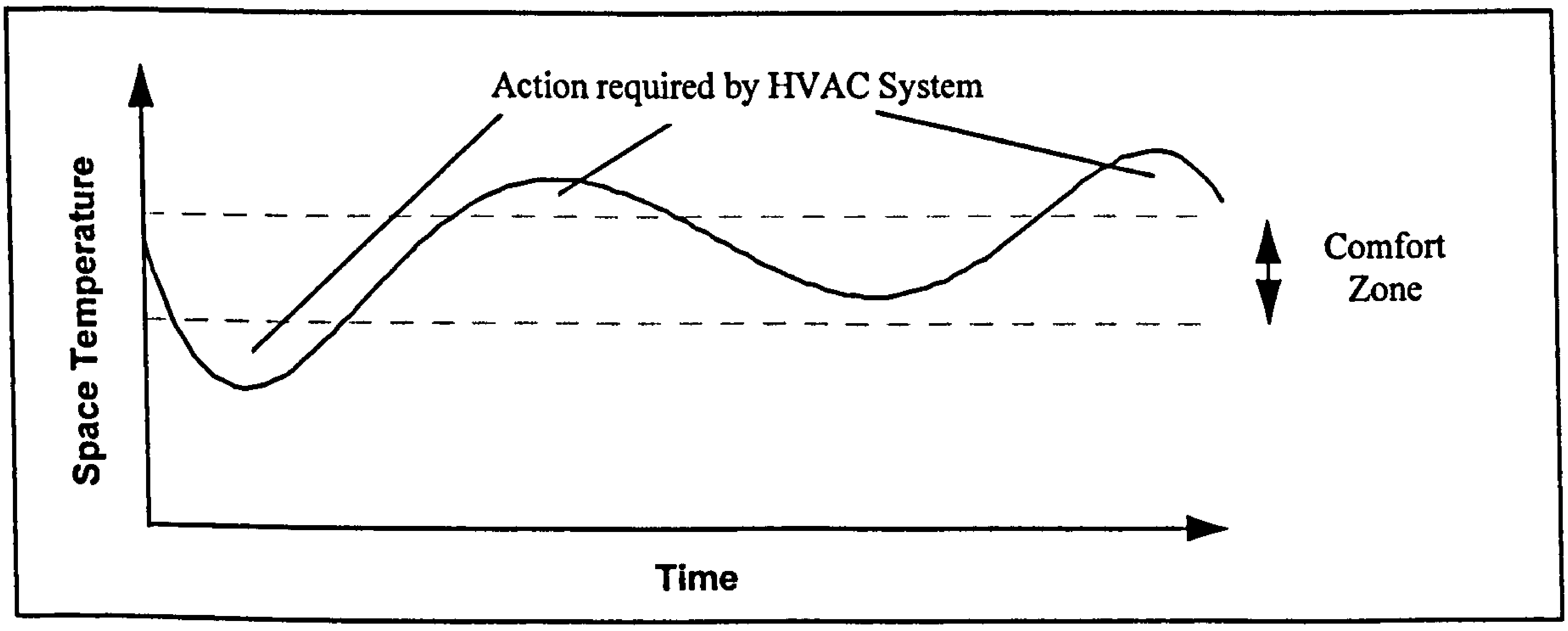

Figure 2.21. Comfort zone with no opportunity to adapt.

Figure 2.21 implies that the temperature is drifting beyond the comfort zone and would need correcting via the use of HVAC systems. By giving occupants some opportunities to adapt, e.g. open windows, control temperature or adapt clothing, the comfort zone ranges and limits can potentially be extended, see Figure 2.22.

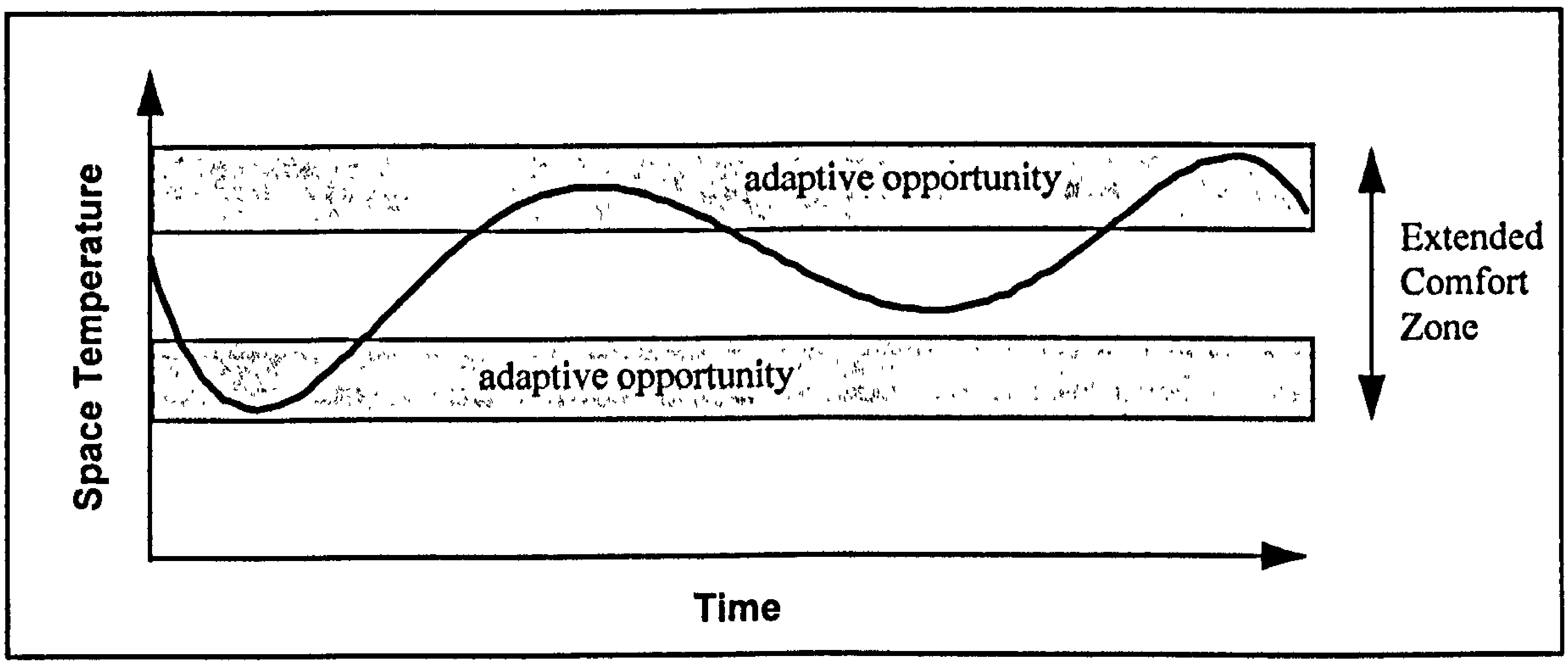

Figure 2.22. Extended comfort zone provided by allowing occupants to adapt and have some control over the environment.

By extending the comfort zone using the adaptive approach it is possible for the occupants to be comfortable for a greater amount of the time with less use of the HVAC plant, i.e. providing improved building operation cost and energy efficiencies.

The extent to which this approach can be implemented largely depends on the design of the building and the HVAC system and its controls. Naturally ventilated buildings lend themselves to providing the greatest opportunity for adaptation. However, air-conditioned buildings can accommodate this approach to a certain extent. The main criteria may be whether or not occupants must comply with a strict clothing policy (changing the amount of clothing represents a significant opportunity to adapt). The other significant determinant of whether the adaptive approach is possible is the control system, i.e. whether it is based centrally or locally. Locally based plant often provides better control to the immediate occupants and hence provides them with the opportunity to adapt their thermal environment.

2.8 Conclusions and Discussion

This chapter described the findings of the literature review carried out into building occupant comfort. Standards and guidelines related to indoor environmental comfort were considered within this scope. The aim of the occupant comfort literature review was to identify and define the important parameter ranges, limits and interactions that provide building occupants with their perception of a comfortable indoor environment. This provided a basis for developing fuzzy control strategies for the control of internal environmental conditions and the assessment of any improvements in provided comfort, energy and cost efficiencies.

From the perspective of developing the fuzzy control strategies later in the research project, this chapter identified the main environmental parameters suitable for control as temperature, humidity and air quality. The decision was made on the basis of the literature review not to consider the environmental parameters which were not totally controllable by the building services control system. Such parameters included noise, air velocity and lighting. Although important environmental parameters in their own rights with respect to providing comfortable conditions, the assumption was made that this type of environmental variable would be kept at suitable levels. Hence, air temperature and relative humidity were chosen as being representative of occupants' thermal comfort and CO_2 concentrations were chosen as being representative of occupants' satisfaction with air quality provision. These selected environmental parameters also have the advantage that sensors for their measurement are relatively inexpensive, reasonably accurate over prolonged periods of time and readily available.

The literature review also identified two main approaches to considering comfort within buildings. These were the steady state and adaptive approaches. Much discussion has taken place regarding these two approaches with arguments for and against each. With regard to the research project and the use of fuzzy logic control it was decided to adopt an approach where the controlled environmental conditions chosen were allowed to drift between upper and lower set point limits analogous to the adaptive approach. This assumes that occupants will take actions such as the addition or removal of clothing within certain limits to correct slight feelings of discomfort. Simultaneously, a preferred set point was defined between the upper and lower set points based on calculations using the steady state PMV method to define preferential controlled zone parameter values. Thus a combination of the adaptive and steady state approaches was taken. The definition of the controlled environmental parameter set point ranges and preferred set points are described in Chapters 8, 9 and 10.

A separate literature review was also carried out into fuzzy logic control for building services systems to identify areas for exploration within the research project. This literature review is detailed in Chapter 3.

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3. Literature Review - Fuzzy Logic and Fuzzy Control

3.1 Introduction

This chapter aims to give the reader an overview of the research previously carried out into the use of fuzzy logic and more specifically fuzzy control. Fuzzy logic allows the implementation of rule of thumb experience, intuition and heuristics, without the need for a mathematical model of the process. Human operators commonly execute control strategies which can be formulated as rules and are simple to carry out manually. However, these control strategies are often difficult to implement using conventional control algorithms. A qualitative approach is often a better approach under these circumstances to approximate the manner in which human operators would carry out the control actions. Previous research examples are described where this approach has been used in this chapter. The theory underlying the use of static fuzzy controllers, the basis for nearly all types of fuzzy control, is dealt with in more detail in Chapter 4.

3.2 A Brief History of Fuzzy Logic

Black (1937) was the first to publish a paper on what we commonly know today as fuzzy logic. He then used the term "vague" to describe this type of logic. However, fuzzy logic theory was shunned as being imprecise, and perceived by some as a disguised form of probability theory. It was not until many years later that fuzzy logic began to be developed as a recognised and useful tool. It was Lotfi Zadeh, then Professor of Systems Theory at the University of California, Berkeley, who theoretically developed the principle during the first half of the 1960s and used the word "fuzzy" to describe the logic. The first publication on fuzzy logic by Zadeh appeared in 1965 (Zadeh 1965). However, many sceptics still existed and fuzzy logic remained a poorly funded area of research. After Zadeh's paper on fuzzy logic, the theory attracted the comments of many critics, two examples of which are given below:-

"Fuzzy theory is wrong, wrong and pernicious. What we need is more logical thinking, not less. The danger of fuzzy logic is that it will encourage the sort of imprecise thinking that has brought us so much trouble. Fuzzy logic is the cocaine of science"
Professor William Kahan, University of California, Berkeley (Kosko 1993).

"Fuzzification is a kind of scientific permissiveness. It tends to result in socially appealing slogans unaccompanied by the discipline of hard scientific work and patient observation."
Professor Rudolph Kalman, University of Florida at Gainesville (Kosko 1993)

A relatively small number of academics ignored such comments and continued to research and develop fuzzy theory, but often only as a sideline to their main research due to the lack of funding and recognition for fuzzy logic in its own right. Although Zadeh is credited as the founder of fuzzy logic today he risked his reputation and academic standing in his quest to convince the rest of the world the benefits of utilising fuzzy logic.

It was not until the benefits and advantages of fuzzy logic were recognised commercially that it began to be taken seriously and research funding granted. The first fuzzy logic controller was built by Ebrahim Mamdani during the early 1970's (Assilian 1974, Evans et. al. 1989) and was used to control a steam generator that could not be controlled adequately by conventional control techniques. During the 1970s other fuzzy logic control applications were developed such as the control of cement kilns (Kosko 1993, Mamdani 1977) and the control of traffic lights (Mamdani 1974)
During the 1980s the Japanese manufactured the first commercial products which utilised fuzzy control strategies and have since produced many more consumer goods utilising fuzzy logic such as washing machines, camcorders, and vehicle transmission systems (Kosko 1993, Ross 1995). By 1992 the Japanese were selling more than $1 billion of fuzzy products annually (Kosko 1993). In 1994 Japan exported products that utilised fuzzy and neurofuzzy theory totalling $35 billion (von Altrock 1995).

The Japanese grasped the theory of fuzzy logic firmly and left the Western world behind in its development. There are several reasons for this:

1. The Japanese culture does not associate the word "fuzzy" with the meaning imprecise. This was a definite advantage in terms of the acceptance of fuzzy logic compared to Western cultures where the word "fuzzy" often conjured up negative images of fuzzy theory.
2. Japanese engineers are not pre-occupied with exact solutions and conventional logic as in the West. Hence, fuzzy logic provided a theory for solving problems in this manner.
3. Japanese engineers tend to start with a simple solution and then develop it to improve its performance. Fuzzy logic lends itself to this type of development technique.
4. Japanese engineers involved in the development of systems as a team like to understand how the overall system works. Fuzzy logic systems, even quite complex ones, remain relatively simple to understand when compared to conventional systems as they use words to describe the logic. Hence the Japanese work culture finds fuzzy logic a benefit in this sense. In contrast, members of Western design teams often don't require, or don't want to understand, parts of the system they are not directly involved with and so this is not such an important benefit.

The Japanese Government realised the potential of fuzzy logic and set up technology transfer programs to realise the benefits fuzzy logic could offer and support research in the area. The first to be set up was the International Fuzzy Systems Association (IFSA), Japan Division, in 1985. The success of the IFSA prompted the setting up other industrial support centres such as:-

- Japan Society for Fuzzy Theory and Systems (SOFT)
- Biomedical Fuzzy Systems Association (BMFSA)
- Laboratory for International Fuzzy Engineering Research (LIFE)
- Fuzzy Logic Systems Institute Iizuka (FLSI)
- Centre for the Promotion of Fuzzy Logic at TITech

These industrial support centres provided the necessary funding and research to enable the realisation of commercial products utilising fuzzy theory. Some examples of fuzzy logic products that were developed in Japan are given in Table 3.1.

Product	**Company**	**Fuzzy Logic Role**
Air-Conditioner	Hitachi, Matsushita, Mitsubishi, Sharp	prevents overshoot-undershoot temperature oscillation and consumes less on-off power
Anti-Lock Brakes	Nissan	controls brakes in hazardous conditions
Auto Engine	NOK / Nissan	controls fuel injection and ignition
Auto Transmission	Honda, Nissan, Subaru	selects gear ratio based on engine load, driving style, and road conditions
Chemical Mixer	Fuji Electric	mixes chemicals based on plant conditions
Copy Machine	Canon	adjusts drum voltage based on picture density, temperature and humidity
Cruise Control	Isuzu, Nissan, Mitsubishi	adjusts throttle setting to set speed based on car speed and acceleration
Dishwasher	Matsushita	adjusts cleaning cycle, rinse and wash strategies based on the number of dishes and the type and amount of food encrusted on the dishes.
Dryer	Matsushita	converts load size, fabric type, and flow of hot air to drying times and strategies.
Elevator Control	Fujitec, Mitsubishi Electric, Toshiba	reduces waiting time based on passenger traffic
Factory Control	Omron	schedules tasks and assembly line strategies
Golf Diagnostic System	Maruman Golf	selects golf clubs based on a golfer's physique and swing
Health Management System	Omron	over 500 fuzzy rules track and evaluate an employee's health and fitness
Humidifier	Casio	adjusts moisture content to room conditions
Kiln Control	Mitsubishi Chemical	mixes cement
Microwave Oven	Hitachi, Sanyo, Sharp, Toshiba	sets and tunes power and cooking strategy
Palmtop Computer	Sony	recognises hand-written Kanji characters
Plasma Etching	Mitsubishi Electric	sets etch time and strategy
Refrigerator	Sharp	sets defrosting times and cooling times based on usage. A neural network learns the user's usage habits and tunes the fuzzy rules accordingly.
Rice Cooker	Matsushita, Sanyo	sets cooking time and method based on steam temperature and rice volume.
Shower System	Matsushita (Panasonic)	suppresses variations in water temperature
Still Camera	Canon, Minolta	finds the subject anywhere in the frame and adjusts autofocus. (Shingu and Nishimori 1989)
Stock Trading	Yamaichi	manages portfolio of Japanese stocks based on macroeconomic and microeconomic data.
Television	Goldstar, Hitachi, Samsung, Sony	adjusts volume based on viewers position

Translator	Epson	recognises and translates in a pencil sized unit
Toaster	Sony	sets toasting time and heat strategy for each type of bread
Vacuum Cleaner	Hitachi, Matsushita, Toshiba	sets motor suction strategy based on dust quantity and floor type
Video Camcorder	Canon, Sanyo	adjusts autofocus and adjusts for lighting level
Video Camcorder	Matsushita (Panasonic)	provides image stabilisation (Egusa et. al. 1992) and adjusts autofocus
Washing Machine	Daewoo, Goldstar, Hitachi, Matsushita, Samsung, Sanyo, Sharp	adjusts washing strategy based on sensed dirt level, fabric type, load size and water level. Some models use neural networks to tune rules to the users tastes.

Table 3.1. Japanese fuzzy logic products, manufacturing company and fuzzy logic role within the product (Kosko 1993).

Table 3.1 gives an indication of a wide range of fuzzy logic applications that have emerged from Japan. In comparison the West has not grasped the benefits and marketing potential of utilising fuzzy logic. Over one thousand fuzzy logic patents are held by Japanese companies in Japan. In 1990, 30 of the 38 patents involving fuzzy logic given by the United States patent office were held by Japanese companies (Kosko 1993).

The previous paragraphs give a brief history of fuzzy logic theory. With respect to the current research project the use of fuzzy logic as applied to the control of building services was the primary interest. The following sections review some of the more important published applications of fuzzy logic control in the building services field.

3.3 Applications of Fuzzy Control to Building Services

Table 3.1 mentions air-conditioning units that have been produced by Japanese companies. The application of fuzzy theory suitable for the control of the internal environments of buildings has also been researched during the past two decades. Some of the research findings of published articles on the application of fuzzy logic to building services and or comfort provision are briefly described:-

Willey (1979) considered the use of fuzzy logic to model occupant actions and hence their control of the internal environment. The study suggests that fuzzy logic is better suited to estimating the imprecise actions an occupant may take to control their environment, e.g. window opening, than conventional algorithms.

Geng and Dexter (1990) examine the use of fuzzy gain scheduling methods to deal with the non-linearities of HVAC plant. The paper considers the fuzzy gain scheduling of the control loops of a conventional proportional integral controller and a self-tuning predictive controller. The paper shows that the fuzzy gain scheduling schemes used in the control loop improved the overall performance of the system.

Ling et. al. (1991) examined the development of fuzzy rule-based supervisors for a self-tuning controller based on the Generalised Predictive Control Algorithm (Clarke et. al. 1987, Clarke and Mohtadi 1989). A fuzzy rule based fuzzy gain scheduler is first used to make use of the qualitative prior knowledge about changes in the plant gain over the entire operating region. A simple fuzzy rule based fuzzy supervisor was then used to adjust the tuning parameters of the controller according to expert opinion based on qualitative descriptions of application dependent performance criteria, so improving the control loop performance gradually. The research suggests that the fuzzy gain scheduling provides a means of incorporating the uncertain prior knowledge about the process and improves the stability and or performance of the controller.

Haung and Nelson (1991) describe the use of PID Law Combining Fuzzy Controller (PFC) which uses the properties of a conventional Proportional + Integral + Derivative (PID) controller with a fuzzy rule based system to improve the operation of a HVAC controller. The PFC controller uses the error, error derivative and error integral as inputs to provide a control output. The research claims improvements in stability and response time in achieving desired space temperature using models of HVAC plant for the PFC controller over PID control. A controller similar to this was developed and assessed as part of the research project detailed in this thesis and is described in Chapter 8.

Dounis et. al. (1992) describe a proposed methodology for the implementation of artificial intelligence techniques in thermal comfort control for passive solar buildings based on assessing the PMV. This was the first of several papers published as the research developed and outlines the theory used to develop fuzzy control techniques for comfort control.

Dounis et. al. (1993) describe the use of a fuzzy reasoning process to provide visual comfort within buildings. A fuzzy logic controller is used to control lighting levels and glare by the use of window blinds and the turning on and off of artificial lights within the space. The fuzzy control was not compared to any conventional control techniques available. It therefore shows that fuzzy control in this case is better than no control but does not prove any improvements over conventional control techniques. However, the research does bring out the ease with which fuzzy logic can be implemented without the availability of a mathematical model by incorporating human knowledge in the form of natural language.

MacConnell and Owens (1994) used a fuzzy supervisor to ensure user comfort is maximised. The commissioning costs of the controller were minimised, the fuel economy was maximised by efficient use of the plant, maintenance costs were reduced by eliminating stop-start cycles and allowing adaptation to unscheduled disturbances. The theory could also be implemented using low cost chip technology for real applications. Results of using the fuzzy logic controller compared favourably with those of a conventional controller.

Dounis et. al. (1994) investigated the impact of natural ventilation on the thermal comfort index assuming the implementation of fuzzy reasoning control for visual thermal comfort as described by Dounis et. al. (1993). Thermal comfort was provided by controlling the window openings, and hence ventilation flow, by conventional controllers responding to the difference between the outside and zone temperatures. Free cooling was made available using this approach. The paper claims that the fuzzy visual comfort reasoning machine was capable of exploiting natural ventilation to control thermal comfort.

Hurtta (1994) describes the use of fuzzy logic as a gain scheduler for a PID controller. The basic principle of operation of the fuzzy control mechanism was to adjust the controller gain (K_p), the integral time (T_i) and the derivative time (T_d) of a conventional PID controller during operation to improve control performance. A building model constructed using Matlab and Simulink software based on a Variable Air Volume (VAV) mechanical ventilation system was used as the comparison tool. The results of simulations indicated that the fuzzy scheduled PID controller out performed the normal PID controller under all operating conditions.

So et. al. (1994) considered the use of fuzzy controllers as replacements for PID controllers in an HVAC system used for cooling and dehumidifying the air supply to a zone using a Variable Air Volume (VAV) system. The fuzzy controllers used the error and rate of change of error for inputs and gave an incremental output for the control of the actuator operating the valve. The paper claims three benefits of fuzzy control compared to conventional control. These are:-

1. fuzzy logic control is more robust since slight changes in the values of parameters do not greatly affect the performance compared with a detuned PID controller.
2. the response of the fuzzy logic based control is faster when there is a sudden change in the environment.
3. energy savings are possible as a result of the use of fuzzy control when compared to the use of conventional controllers.

However, two criticisms of this paper can be made:-

1. The comparison of the fuzzy controller is made against detuned PID controllers. The value of the proportional gain (K_p) of the well tuned PID controller is reduced in the range of 9% - 50%. The values of the integral time (T_i) and the derivative time (T_d) were increased by approximately 50%. The PID controllers are therefore severely detuned. This may represent a realistic case in practical situations due to the inevitabilities that they will not be well tuned. However, it should be remembered that the fuzzy controllers also require tuning in the form of the definition of the membership functions and the tuning values for the inputs of error and rate of change of error for the input values for the controller. Hence in practical situations the fuzzy controllers also need tuning and are as likely to be detuned as the PID controllers.
2. The results of the simulations indicate very fast response rates with large rates of change in space temperature and RH, e.g. 34°C - 22°C and 80% - 60% RH in less than 500s and 1000s respectively. These are very fast response rates and should be considered unrealistic with real HVAC systems. Also there was a very small, or even no overshoot, in the zone conditions whilst there was no asymptotic approach to these desired conditions. However, these criticisms are not as important as the first criticism as the fuzzy and PID controllers are compared in a model operating under the same conditions and subject to identical system characteristics.

Huang and Nelson (1994a) present a rule based fuzzy logic controller which considered the error and rate of change of error as inputs to the controller. The paper discusses three important elements that have a critical influence on the behaviour of such controllers. These are the rule base, the membership functions and the scale factors (or tuning parameters). The scale factors are the proportional gain (K_p), the derivative gain (K_d) and the output gain (K_o). In a companion paper Huang and Nelson (1994b) described an experiment using the developed rule based fuzzy logic controller to control an HVAC system. The rule development and adjustment strategies were presented for the fuzzy controller structure. Experimental results indicated that the fuzzy logic controller performed better than a conventional PID controller. The design of the fuzzy logic controller is similar to that reported by So et. al. (1994). The fuzzy controller was again compared to a PID controller. This time however, the controller is not detuned but is tuned to give (i) a slow response with no overshoot, i.e. asymptotic approach of the zone temperature towards the desired set point (ii) a quick response but with a large overshoot and (iii) a response between the other two with a reasonable response time and some overshoot. This allowed a fair comparison between fuzzy and PID control strategies.

Ling and Dexter (1994) use a fuzzy rule based supervisor to evaluate control performance and adjust the temperature set point of an air-conditioning system within a given comfort band. The overall control objective aims to use free cooling by altering the amount of fresh air entering a zone in a constant volume system to maintain the zone temperature close to the upper limit of the comfort band. When free cooling is not capable of achieving this, plant cooling is used. Good control is required to avoid discomfort when this type of methodology is used. It is claimed that fuzzy supervisory control meets this objective. The paper also claims substantial energy savings can be achieved compared to traditional fixed-point control strategies.

von Altrock (1995) describes the use of a fuzzy controller to create an adaptive controller for use with a home heating system. The controller ensures optimal adaptation to customer heating demands while using one sensor less than a conventional control system. The findings of this paper are also given in Ross (1995)

Dounis et. al. (1996) investigated the performance of a fuzzy reasoning machine for the control of indoor air quality in naturally ventilated buildings. Simulations were carried out using an airflow and pollutant transport model that used CO_2 concentrations as an index for indoor air quality. The aim of the fuzzy controller was to maintain the CO_2 concentration within certain limits while ensuring good stability of the window opening area. Using conventional control techniques to adjust actuators for the window opening would cause continuous window movement and would bother the occupants. Hence fuzzy control provided an alternative improved solution. The results showed that satisfactory indoor air quality can be maintained, while good control of the openable windows was achieved. The impact of the controller on indoor air temperature was also assessed. The performances of the controllers were not as good as expected but were not negligible when compared with the normal conditions of use of the building.

Egilegor et. al. (1997) presented a paper at the Building Simulation Conference entitled "A Fuzzy Control Adapted by a Neural Network to Maintain a Dwelling within Thermal Comfort". The paper describes the results of simulations using a neuro fuzzy controller to adjust the air flow rate through fan coils for three zones of a dwelling to improve thermal comfort. The input variables of zone temperature and humidity are used to calculate the value of Fanger's PMV thermal comfort index which is then used as a comfort variable. Fuzzy proportional derivative control is used to provide the desired zone conditions while a neural network is trained to tune the fuzzy controller to optimise the fuzzy tuning parameters and improve the control performance for different situations. The simulations carried out for the neuro fuzzy controller indicate an improvement in the PMV compared to the bench mark simulations using thermostatic control. The paper presents some promising results and reports that a real system has been installed, the results of which were not available at the time of publication of the article.

So et. al. (1997) considered the use of a self learning fuzzy air handling system controller. "Static" fuzzy controllers, as considered in So et. al. (1994), were used to control 5 HVAC plant actuators for the purposes of controlling the internal environment. An artificial neural network (ANN) was used to model the plant in real time and assess its status using seven monitored parameters and the signals of the 5 actuating commands. The neural network acted as a system identification tool. The static fuzzy controller was modified into an adaptive fuzzy controller which observed the process while generating appropriate control actions from a long term memory rule base. Using the results of the control actions through a performance measure determined statistically, the control decision process is altered to improve controller performance further. The use of the self-learning fuzzy controller in computer simulations revealed that the controller could achieve a faster response rate and a better energy consumption profile than for a static fuzzy controller.

3.4 Capabilities of Fuzzy Logic

The applications of fuzzy logic to the control of building services components reviewed in this chapter shows that fuzzy logic is extremely adaptable to many control situations. Fuzzy logic is an extension of conventional Boolean logic and is therefore, in theory, capable of doing anything that conventional logic systems can. Fuzzy logic often provides a method of solving control system problems where conventional control systems cannot due to problem complexities and lack of mathematical definition. Although fuzzy logic is capable of doing anything that conventional systems can they do not always provide the best solution because conventional and simple systems are sometimes a better and less time consuming solution. This is often the case where established control systems have been implemented for a number of years and redesigning would cause major disruption in its implementation both in terms of hardware and service engineer training.

3.5 Conclusions

This chapter introduced the reader to a brief history of the use of fuzzy logic and its application as a control technique particularly within the field of building HVAC services control. The review of previous applications of fuzzy logic to the control of building services components suggests that fuzzy logic is capable of providing control techniques which are often simpler to implement than conventional control systems and sometimes capable of providing superior control. Where a lack of knowledge regarding system behaviour exists, a solution using fuzzy logic may be possible where conventional control techniques are not suitable.

The research project described by this thesis aimed to provide building services control techniques to satisfy a multi-variant control requirement. A building services control strategy was required to consider indoor environmental quality, energy efficiency and cost efficiency simultaneously. The literature review carried out into fuzzy logic suggested that a fuzzy control system would be capable of dealing with such a multi-variant control objective. The literature review aimed to review the history of the development of fuzzy logic theory and examples of its use with reference to building services control. Details of the theory of fuzzy logic and control is described in Chapter 4.

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4. Fuzzy Logic and Fuzzy Control Theory

Nomenclature

χ	the unambiguous membership value, of an element, to the classical set, i.e. 1 or 0
$\in$	belongs to
$\notin$	does not belong to
μ	the membership value of an element to the fuzzy set, i.e. 0 - 1
u	an individual element on the universe of discourse U
U	universe of discourse

4.1 Introduction

This chapter is intended as an introduction to the theory of fuzzy logic and fuzzy control. The structure of the chapter incorporates both generalised mathematical theory and examples to help the reader gain an understanding of the basic principles behind fuzzy control. Numerous books have been published on the subjects of fuzzy logic and fuzzy control. Three recommended examples are von Altrock (1995), Ross (1995) and Yen et. al. (1995).

Chapter 3 gives a history of the development of fuzzy logic and control as well as examples of its use with respect to the control of building services HVAC components. This chapter first introduces the reader to the theory of fuzzy logic and fuzzy control by comparing it to classical logic. This is followed by an in depth description of the theory of fuzzy logic. The theory of fuzzy control and the structure of a fuzzy controller are then described. Finally, the operation of a fuzzy controller is illustrated by the use of an example which shows the calculations taking place within a fuzzy controller with the aid of graphics.

4.2 Classical Logic, Fuzzy Logic, Membership Functions and Membership Values

Fuzzy logic is an extension of classical (Boolean logic) which can handle the concept of partial truth values which lie between completely true and completely false. To explain this concept it is useful to briefly consider classical logic theory in order that similarities with fuzzy theory can be observed. However, it is first useful to introduce the concept of membership values, or degrees of membership, as these terms are commonly used throughout the text of this thesis. These two descriptions essentially have the same meaning and refer to the degree of belonging of an element to a set. For example, an ocean liner is a member of the set "ships" while a car is not. It can also be said that an ocean liner is very much a member of the set "ships". However, a canoe could also be a member of the set "ships" but would not normally be strongly associated with the set "ships". Therefore the membership value or degree of membership of a canoe to the set "ships" is less than for that of an ocean liner.

Another term commonly referred to is the “universe of discourse” and is denoted by “U”. For a given physical parameter the universe of discourse U describes the interval of interest. For example, when considering comfort temperatures for occupants of buildings, the range of temperatures considered could be chosen as between 10°C and 32°C on the basis that outside this range people are likely to be too cold or too hot. If the room temperature is outside this range, then its fuzzy value is associated to the corresponding extreme. Hence the universe of discourse is U{10°C, 32°C}. Within the universe of discourse U, individual elements are denoted by “u”. For example, the universe of discourse U for temperatures between 10°C and 32°C will contain, amongst others, the elements 12°C, 15°C and 27°C. These are individual elements, u, on the Universe of discourse U. Further, various combinations of these individual elements, u, on the universe of discourse U, make up sets. For example, considering Figure 4.1, the elements u_1, u_2 and u_3 make up the Set X on the universe of discourse U while elements u_4, u_5 and u_6 make up the Set Y on the universe of discourse U.

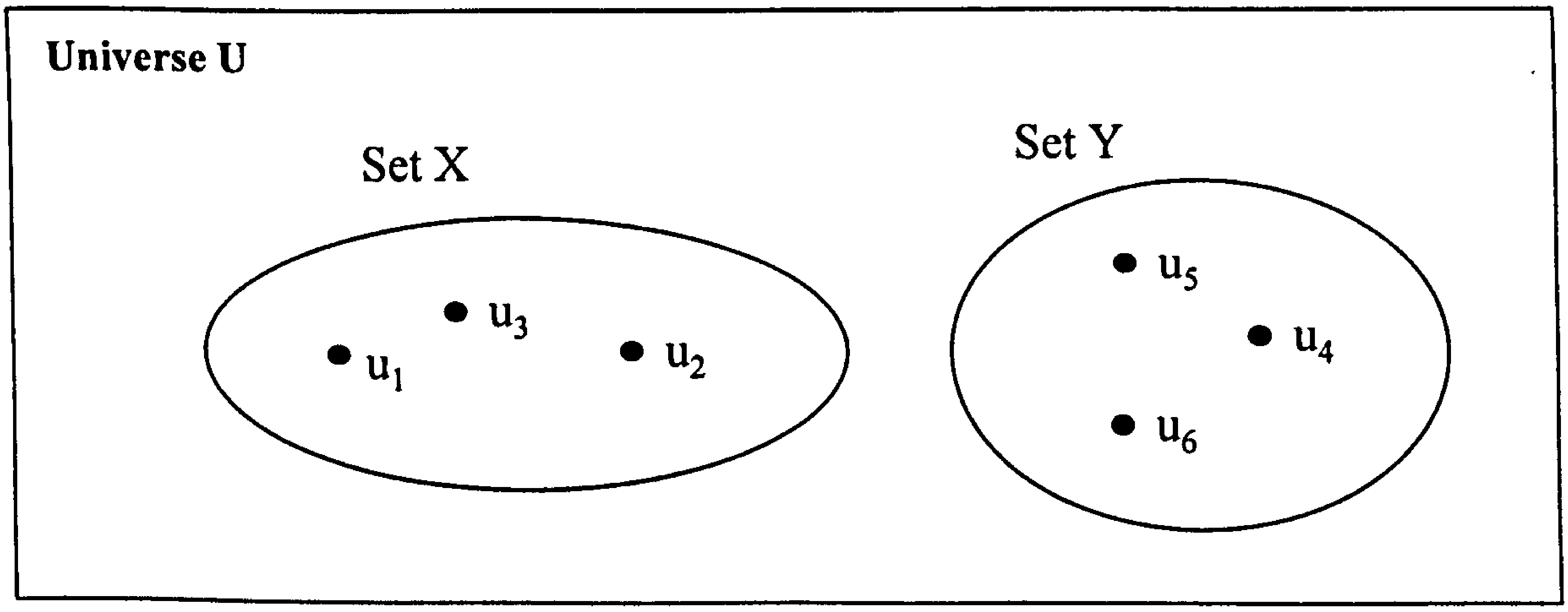

Figure 4.1. Individual elements u defined as sets X and Y on the universe of discourse U.

The following discussion regarding classical and fuzzy sets builds on these concepts..

Referring to Figure 4.2, classical set theory dictates that element A is completely a member of the classical set X on the universe of discourse U while the element B is not. This is commonly defined by the expressions given in Equation 4.1 and Equation 4.2.

$$\chi_X(A) = 1, \quad A \in X$$

Equation 4.1

$$\chi_X(B) = 0, \quad B \notin X$$

Equation 4.2

In words Equation 4.1 and Equation 4.2 can be written as follows.

Equation 4.1 - Element A has an unambiguous membership value of one to the set X, element A is a member of the classical set X.

Equation 4.2 - Element B has an unambiguous membership value of zero to the set X, element B is not a member of the classical set X.

Classical set theory allows the membership value of an element to a set to be 1 or 0 only.

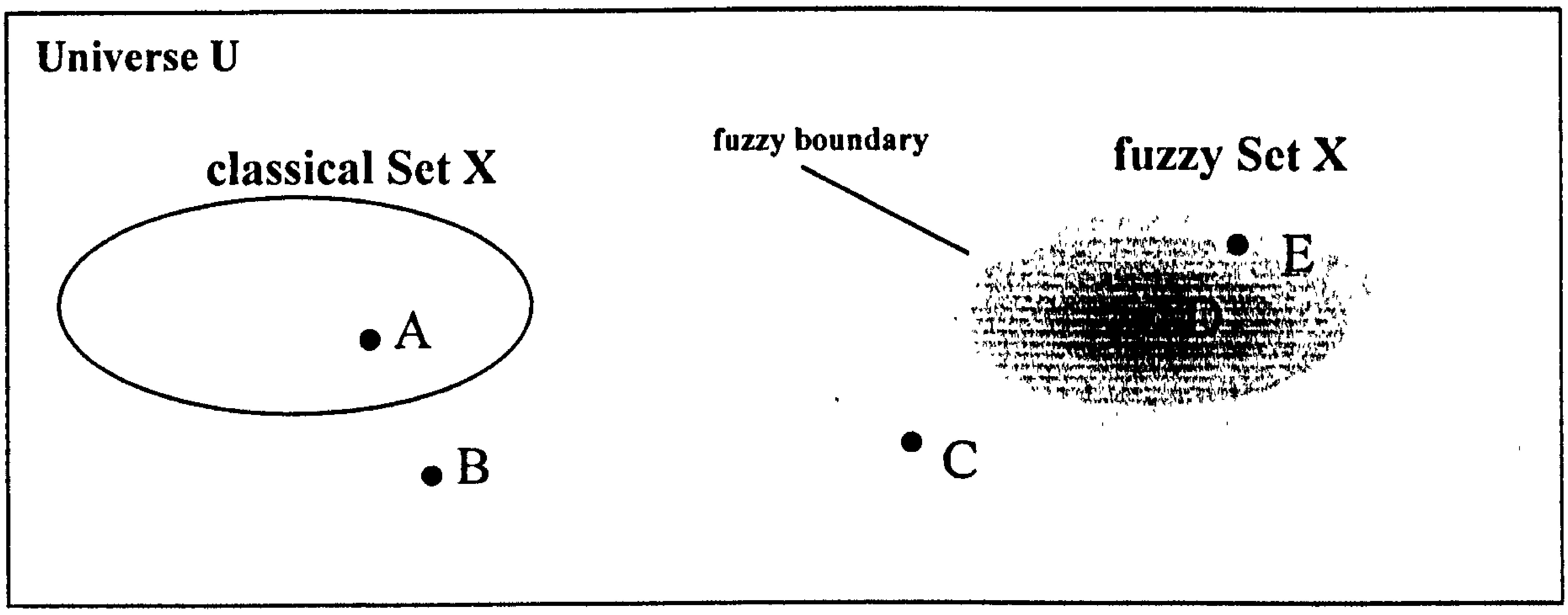

Figure 4.2. Classical Set X and fuzzy Set X on the universe of discourse U.

Fuzzy set theory allows an element to possess the same membership values as for classical set theory, e.g. element C in Figure 4.2 can be considered completely not a member of the fuzzy set X while element D is completely a member of the fuzzy set X. However an element can also be assigned a membership value between zero and one depending on its degree of membership of the fuzzy set X, as with element E, which could be considered to have a degree of membership of fuzzy set X less than D but is still a member, see Figure 4.2. This can be described by Equation 4.3.

$$\mu_X(E) \in (0,1), \quad E \in U$$

Equation 4.3

In words Equation 4.3 can be written as:-
Element E is a member of the fuzzy set X, element E's membership value or degree of membership to the fuzzy set X is between zero and one, element E is on the universe of discourse U.

Kosko (1993) refers to classical sets as being a special type of the more generalised fuzzy set. For instance an element with a membership value of 0 or 1 can be defined as belonging to a classical or fuzzy set. However, an element with a membership value of 0.73 to a fuzzy set cannot be defined using classical set theory.

People commonly use natural linguistic variables such as warm, thin and old which are difficult to define precisely and can be interpreted in different ways, often depending on the social or cultural context in which they are used. Linguistic variables can have grades of meaning. For example, the descriptor “old” can cover a wide range of ages when applied to people.

The concept of membership values or the degree of membership lies at the heart of fuzzy logic and fuzzy control. Fuzzy theory expands on the concept of membership values by using membership functions. A number of fuzzy membership functions may span across the fuzzy boundary shown in Figure 4.2. Each membership function is assigned to part of the region across the fuzzy boundary. Membership functions can overlap or may have spaces between them. Membership functions are dealt with in Section 4.3.

4.3 Fuzzy Membership Functions

Membership functions are used in fuzzy logic to describe the degree of membership of an element u within a universe of discourse U to a fuzzy set. Membership functions can take on many different forms. Figure 4.3 shows examples of commonly used membership functions.

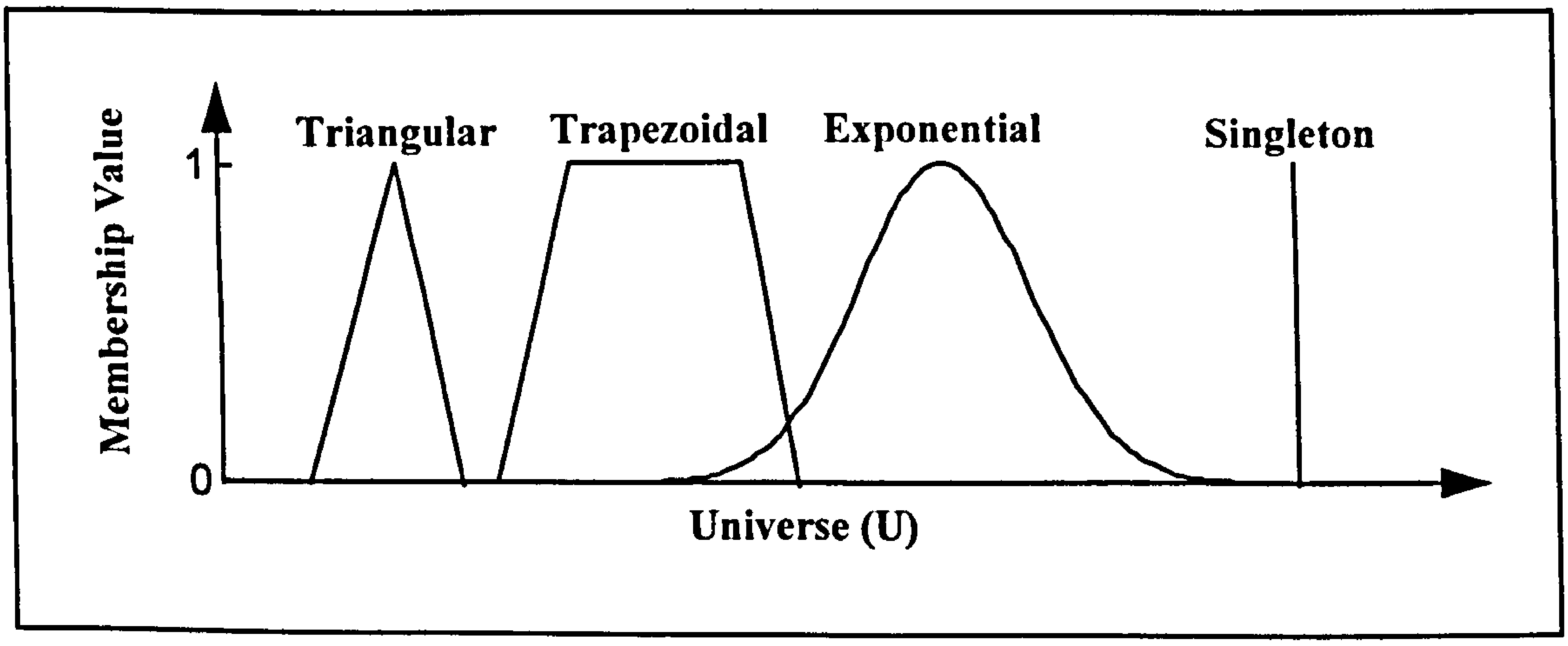

Figure 4.3. Commonly used types of fuzzy membership function.

However, triangular membership functions are the most commonly used due to their versatility and the ease of definition from a practical viewpoint.

An example of the usefulness of membership functions is given in the following text. The descriptor "too hot" has different meanings depending on the context in which it is used. "The car radiator is too hot" would imply that it has a temperature approaching 100°C. “Too hot” to the human touch would be approximately 50°C. Further, descriptors can have different meanings to different people even when used in the same context, e.g. "room temperature too hot".

Thus, when referring to “room temperature too hot”, a definition of “too hot” has first to be established. This may be chosen as 25°C for example. Once the “room temperature too hot” has been defined as 25°C it is implied by classical logic that temperatures above and below this value are “too hot” and “not too hot” respectively. Hence, classical logic implies a step membership function occurring at a particular value, see Figure 4.4.

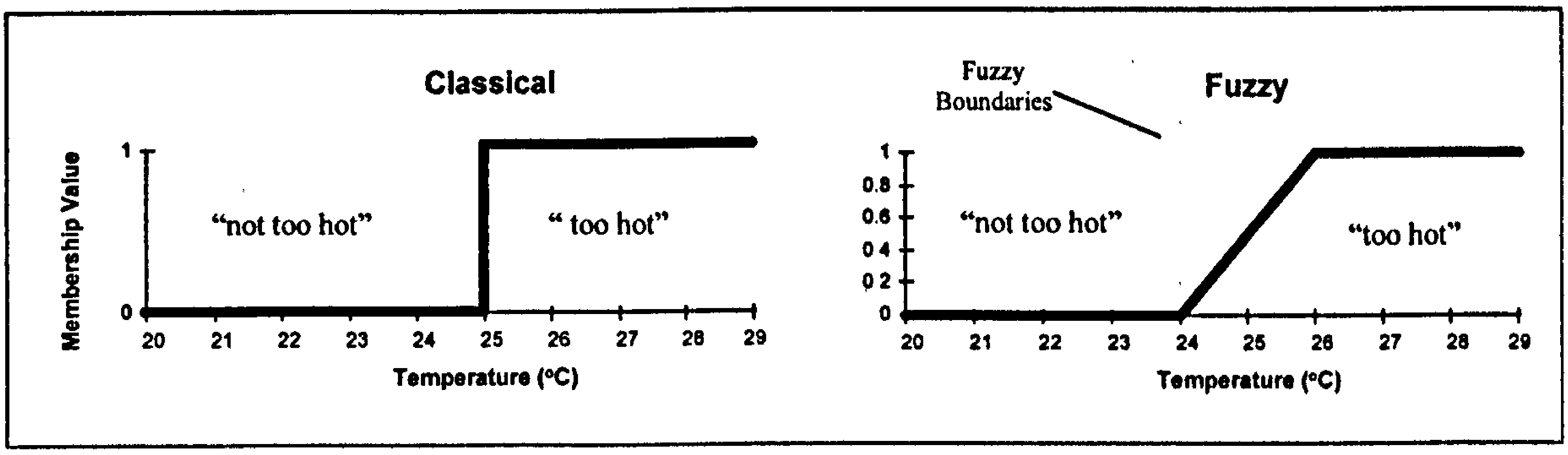

Figure 4.4. Classical and fuzzy membership functions for the descriptor "too hot" in a room.

However, this is not representative of the way humans perceive changes in temperature, or the fact that variations in response might be expected from a large population depending on their health or recent climatic experience, for example.

Fuzzy logic is better able to accommodate these subjective interpretations of temperature. In the example shown in Figure 4.4, an individual may consider 23°C - 24°C as "hot" but not "too hot". However, beyond 24°C the perception changes. If a large group of people were questioned then it might be that all will describe the environment as "too hot" at 26°C but only a few at 24°C. Consequently, the slope seen in the fuzzy set boundary in Figure 4.4 represents the variation in response to the onset of a change of condition from "hot" to "too hot" by a number of individuals. This example highlights the underlying concept of fuzzy logic, i.e. it is able to deal with partial truths in a similar way to human thinking. Linguistic descriptions can be given degrees of meaning. Consequently, it can provide a means of incorporating incomplete expert human knowledge into a system.

The fuzzy membership function shown in Figure 4.4 provides a coarse representation of the descriptor "room temperature too hot". To enable a less coarse definition of a descriptor over a range of temperature values on the universe, multiple membership functions are required.

For instance, if we consider the seven point scales developed by thermal comfort researchers, e.g. (Fanger 1972), to assess human response to the temperature environment, the occupants are required to choose a descriptor of environmental conditions, in this case temperature, in relation to a thermal scale. Scales commonly used include the descriptors hot, warm, slightly warm, neutral, slightly cool, cool and cold.

In other words, a temperature can be translated into a linguistic descriptor by an individual who is experiencing the sensations of the room temperature. If the occupant response lies within the categories of "slightly cool", "neutral" or "slightly warm" then the temperature conditions are normally considered to be adequate.

If room temperature is described by linguistic variables then these can be written as a fuzzy logic Term Set (TS):-

$$TS\{HR\} \equiv \{\text{hot, warm, slightly warm, neutral, slightly cool, cool, cold}\}$$

where
TS{HR} ≡ linguistic Term Set description of the <u>H</u>uman <u>R</u>esponse to zone temperature.

Each linguistic term of the Term Set can be characterised by a fuzzy membership function on the universe of discourse U = (10°C, 32°C). Such a Term Set is shown in Figure 4.5.

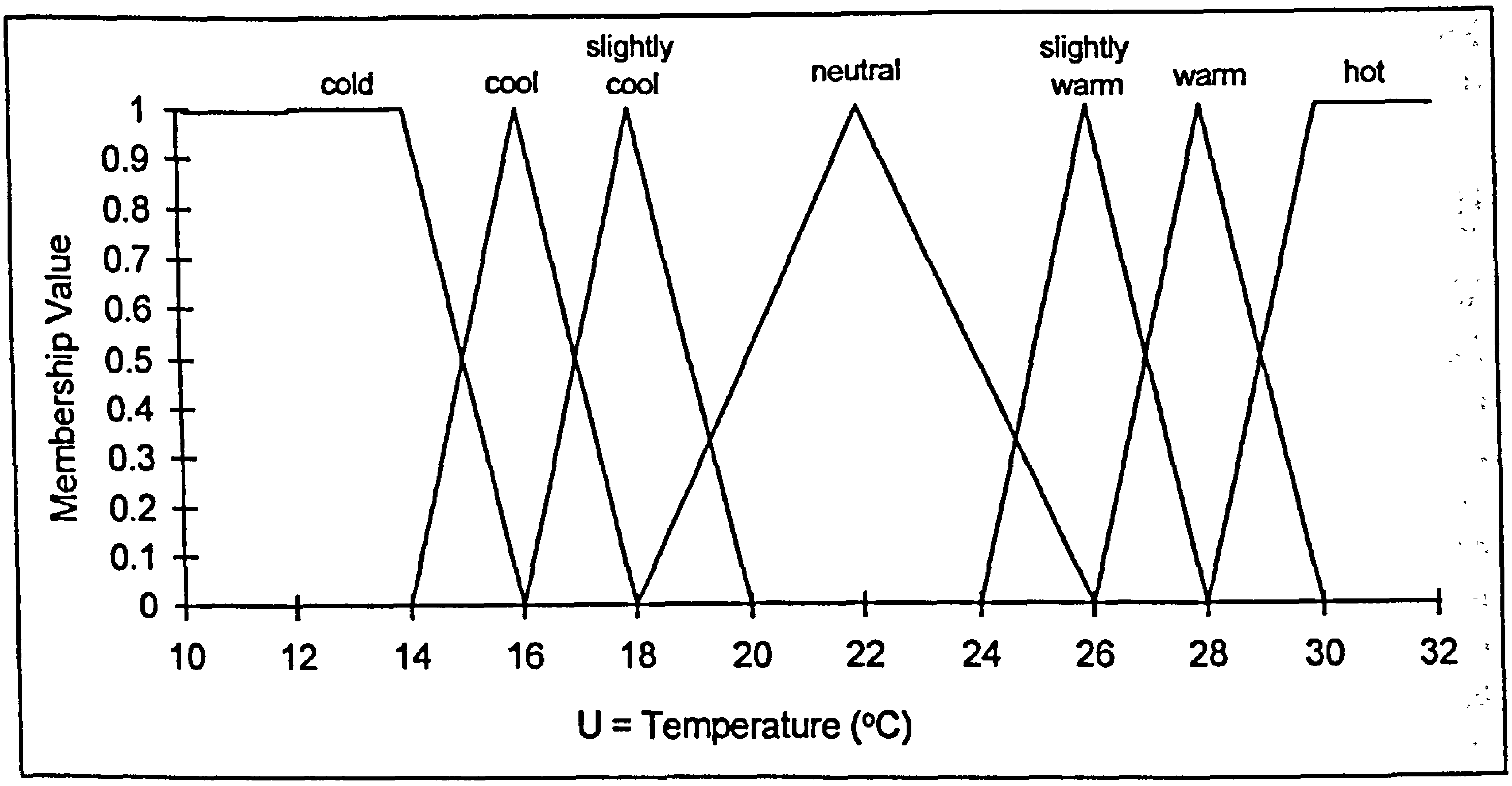

Figure 4.5. Linguistic terms translated into membership functions on the universe of discourse U = (10°C, 32°C).

Considering the linguistic term "slightly warm" in Figure 4.5, a temperature of 26°C is designated a membership value of 1 to this membership function. The membership values of temperatures between 26°C and 24°C then range from 1 to 0 respectively for the "slightly warm" membership function. Similarly, for temperatures between 26°C and 28°C the value of the membership function "slightly warm" ranges from 1 to 0. Hence, as the temperature diverges from 26°C its membership of "slightly warm" decreases, but the temperature membership value of the categories "neutral" or "hot" increases for lower and higher temperatures respectively.

A collection of linguistic terms describing a person's thermal sensation has been defined in Figure 4.5 by the triangular membership functions. However, uncertainties as to exactly what the definitions should be do exist. Fuzzy logic is able to deal with these uncertainties more comfortably than classical logic theory and serves to highlight one of the key advantages of fuzzy logic theory. There is not a unique membership function for any linguistic variable described within a term set. The definition of a membership function's shape should be determined by those considering the solution of a problem. This is a key difference between classical and fuzzy sets, i.e. a classical set has a unique membership function while a fuzzy set can have an infinite number of membership functions to describe it. This introduces flexibility because membership functions can be adapted to maximise their appropriateness for specific applications. This is especially useful where an exact mathematical model of a system is not available.

Properties of a membership function often have the following three characteristics:-

1. ***normality*** - the membership function allows a variable to have a membership value of unity for at least one specific value of the variable in question
2. ***monotonicity*** - the closer the value of a variable is to the centre of a membership function, the closer a variables membership function is to unity
3. *symmetry* - the membership value of variables equidistant from the centre of a membership function should have the same value

Triangular membership functions as shown in Figure 4.5 exhibit these characteristics with the exception of the membership functions at each end of the term set.

In order to make use of fuzzy membership functions an understanding of their mathematical operations is required. These are introduced in Section 4.4.

4.4 Fuzzy Set Operations

The mathematical fuzzy set operations can be defined in the same manner that classical set operations are, i.e. union, intersection and complement.

Let the fuzzy sets A and B be defined on the universe of discourse U, with membership functions denoted by μ_A and μ_B respectively. The fuzzy function theoretic operations of union, intersection and complement of fuzzy membership functions can be defined as follows:

4.4.1 Union

The union of the fuzzy membership functions μ_A and μ_B on the universe of discourse U is described by the notation of Equation 4.4 and shown diagrammatically in Figure 4.6.

$$\mu_{A \cup B}(u) = \max\{\mu A(u), \mu B(u)\}, \quad u \in U$$

Equation 4.4

Equation 4.4 in words can be written as:-

The membership function for the union of the membership functions μ_A and μ_B on the universe of discourse U is the maximum value of the membership functions μ_A or μ_B, element u belongs the universe of discourse U.

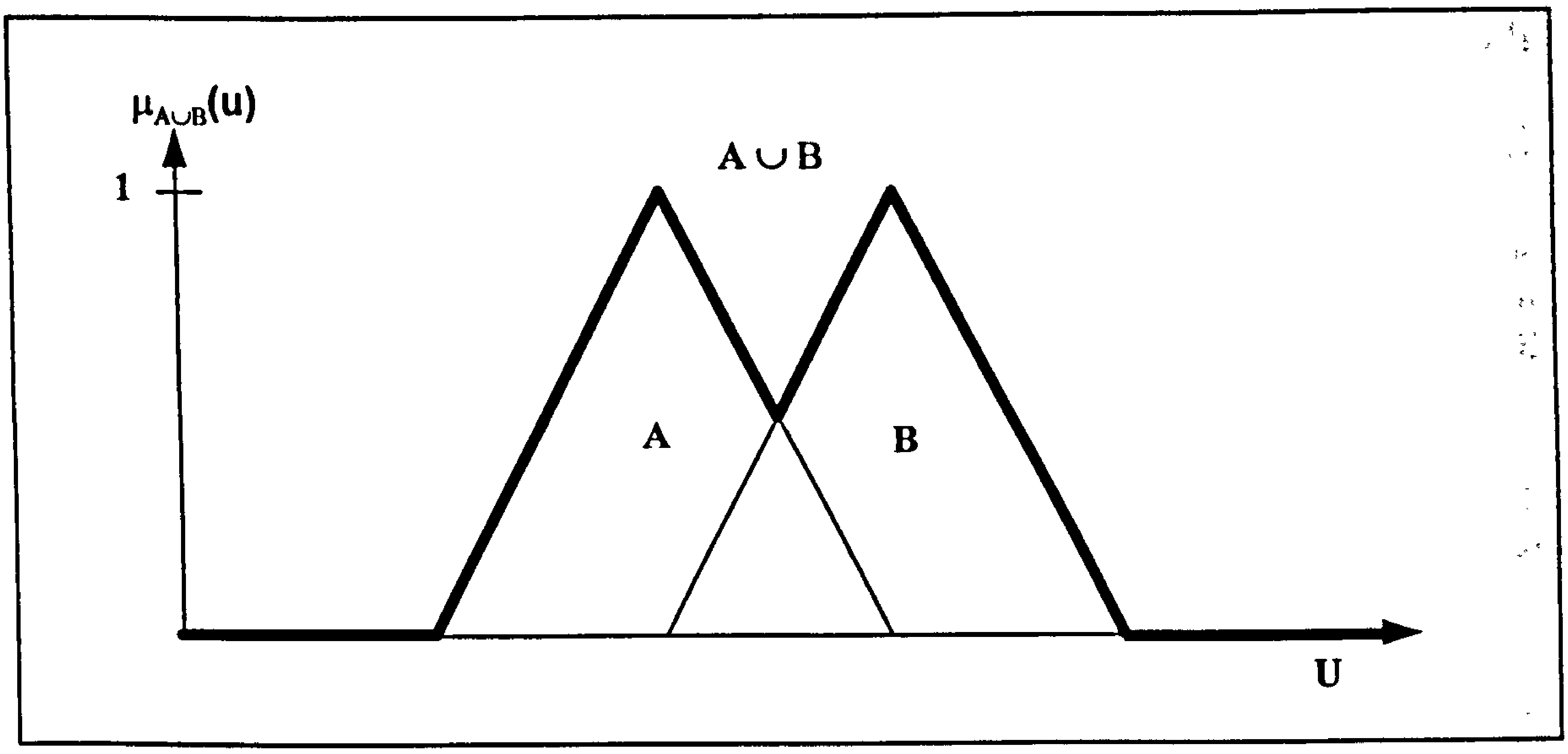

Figure 4.6. The membership function for the union of the membership functions μ_A and μ_B on the universe of discourse U.

4.4.2 Intersection

The intersection of the membership functions μ_A and μ_B, $A \cap B$, is described by the notation of Equation 4.5 and shown diagrammatically in Figure 4.7.

$$\mu_{A\cap B}(u) = \min\{\mu_A(u), \mu_B(u)\},\ u \in U$$

Equation 4.5

Equation 4.5 in words can be written as:-
The membership function for the intersection of the membership functions μ_A and μ_B on the universe of discourse U is the minimum value of the membership functions μ_A or μ_B, element u belongs the universe of discourse U.

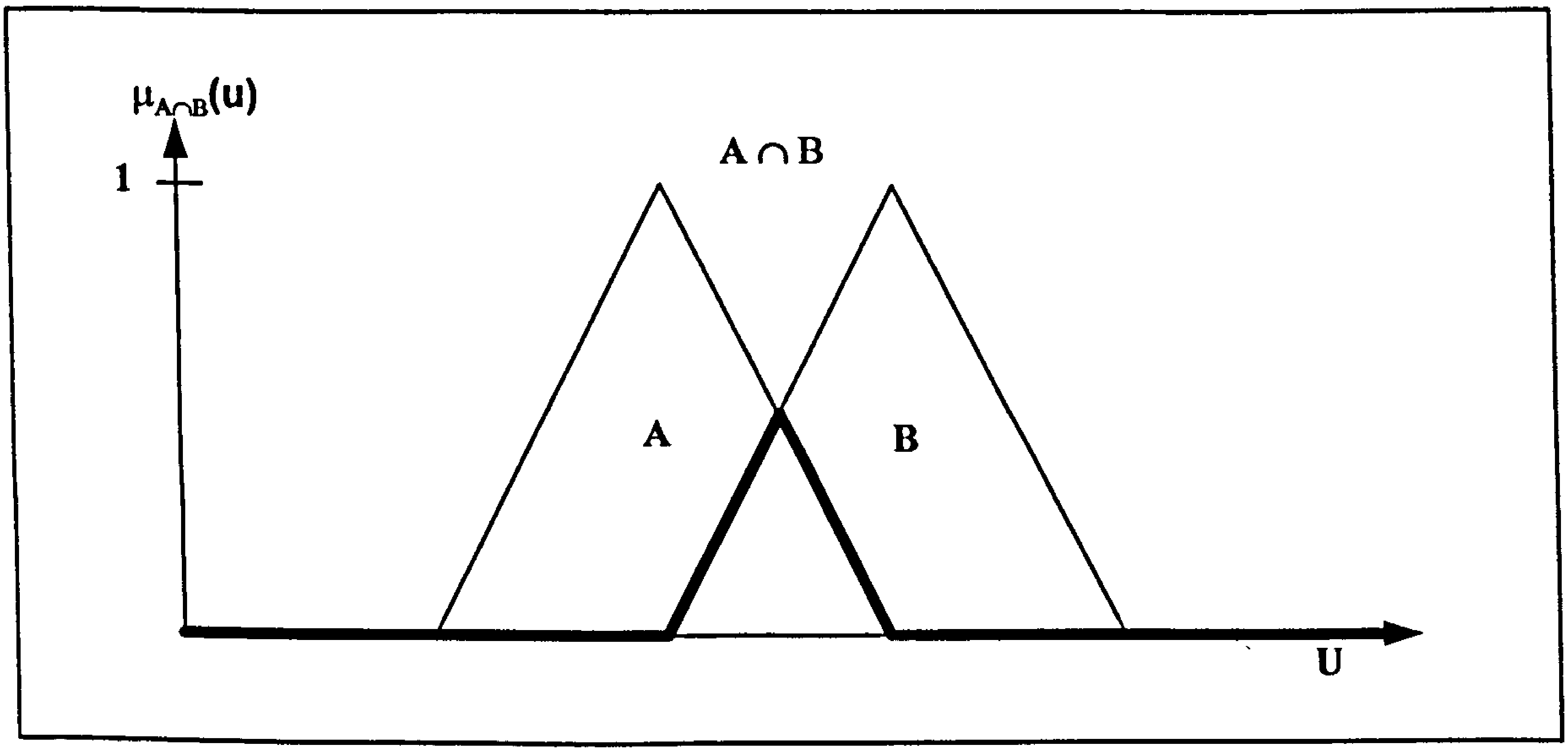

Figure 4.7. The membership function for the intersection of the membership functions μ_A and μ_B on the universe of discourse U.

4.4.3 Complement

The complement of the fuzzy membership function μ_A is described by the notation of Equation 4.6 and shown diagrammatically in Figure 4.8.

$$\mu_{\bar{A}}(u) = 1 - \mu A(u), u \in U$$

Equation 4.6

Equation 4.6 in words can be written as:-
The membership function for the complement of the membership function μ_A on the universe of discourse U is equal to one minus the membership function μ_A, element u belongs the universe of discourse U.

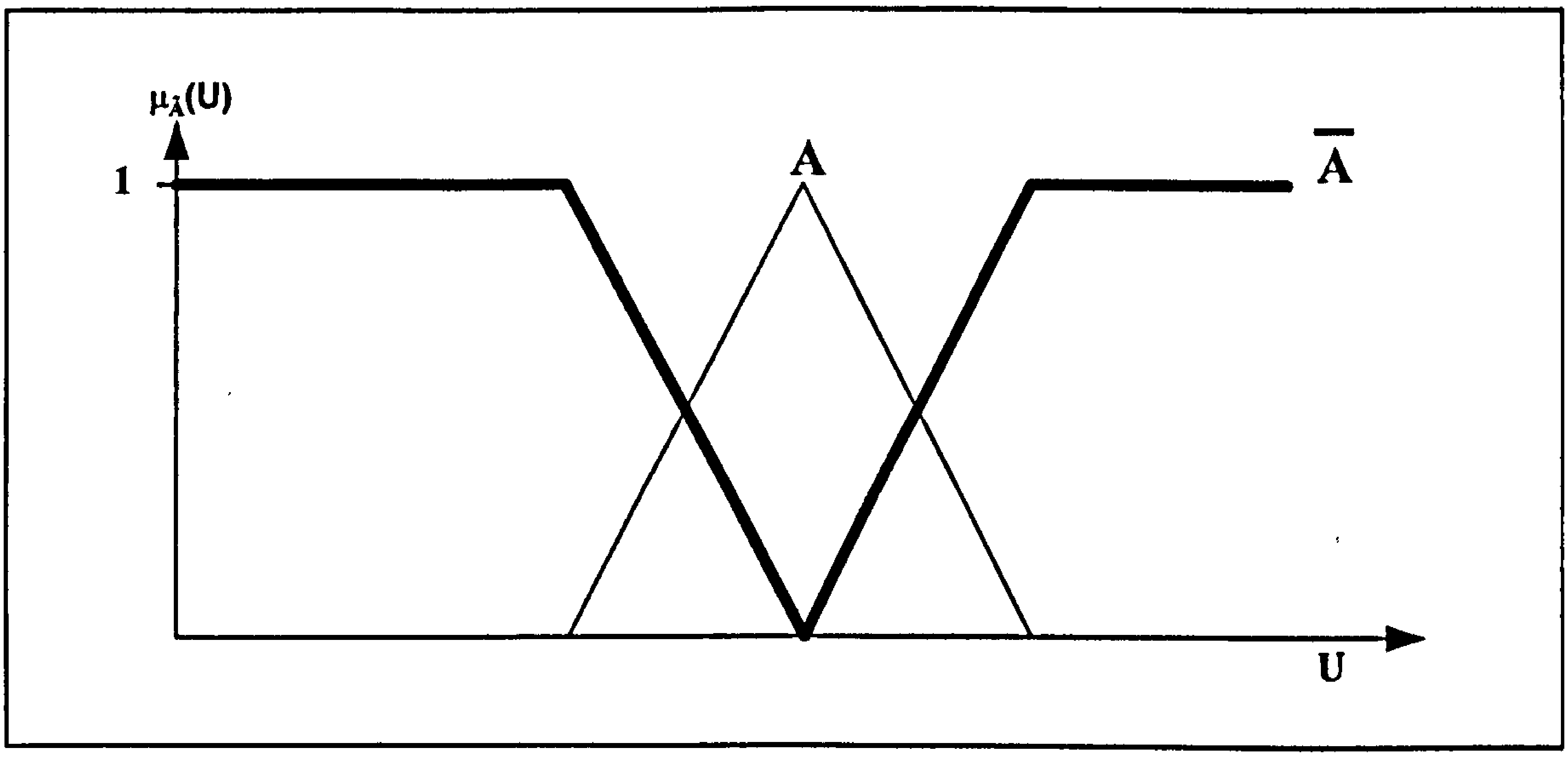

Figure 4.8. The membership function for the complement of the fuzzy membership function μ_A on the universe of discourse U.

The fuzzy set operations described by union, intersection and complement describe the fuzzy set logical operations of AND, OR and NOT respectively as defined by Equation 4.7, Equation 4.8 and Equation 4.9 respectively.

$$\mu_{A \cap B}(u) = \min\{\mu_A(u), \mu_B(u)\} \text{ (AND)}$$

Equation 4.7

$$\mu_{A \cup B}(u) = \max\{\mu_A(u), \mu_B(u)\} \text{ (OR)}$$

Equation 4.8

$$\mu_{\bar{A}}(u) = 1 - \mu A(u) \quad \text{(NOT)}$$

Equation 4.9

Of the three, the AND (min) and the OR (max) operators are the most frequently used fuzzy operators used with fuzzy controllers.

4.5 Fuzzy Approximate Reasoning

The ultimate aim of using fuzzy logic is to make a reasoned judgement about imprecise propositions. That is, for a given set of input values, make a reasoned decision about the value(s) of the output(s). With respect to fuzzy logic this reasoning is referred to as approximate reasoning (Zadeh 1976, Zadeh 1979). Two important fuzzy implication inference rules are the Generalised Modus Ponens (GMP) and the Generalised Modus Tollens (GMT).

Modus Ponens is commonly used in forward-chaining rule-based expert systems. It is used to find the truth value of a consequent (output) given the truth value of the anecdote (input). For example:

If A
And A implies B (General Modus Ponens)
Then B

i.e. given that A is true and A implies B, then B is also true (McNeill and Thro 1994)
This means that A implies B, but B does not necessarily imply A.

Modus Tollens, meaning "denial mode", is commonly used in backward-chaining expert systems. For example:

If B
And A implies B (General Modus Tollens)
Then A

i.e. given that B is false and A implies B, then A is also false (McNeill and Thro 1994)

For the purposes of the current research project the General Modus Ponens, i.e. the forward chaining method, is used as the implication method. An example of fuzzy reasoning using the Generalised Modus Ponens implication method is given below:

Consider the basic operation of a warm air heating system for a zone in a building. The heating system consists of a water heating coil to heat the air, a valve to control the flow rate of the hot water to the heating coil and a control system for regulating an actuator attached to the valve. The room temperature can then be controlled by altering the flow rate of hot water through the heating coil. The zone temperature and rate of change of zone temperature are input values to the controller while the desired valve position is the output.

The linguistic variables to be used by a fuzzy controller are defined by the membership functions of zone temperature (T), rate of change of zone temperature (dT) and heating coil valve position (V). The linguistic variables for each Term Set (TS) are defined as membership functions on specific universes of discourse as follows:

Input Term Sets (anecdotes)
TS{zone temperature} = TS{T} = {low, neutral, high}
TS{rate of change of zone temperature} = TS{dT} = {negative, zero, positive}

Output Term Set (Consequent)
TS{heating coil valve position} = TS{V} = {closed, medium, fully open}

The membership functions for input and output Term Sets are shown diagrammatically in Figure 4.9.

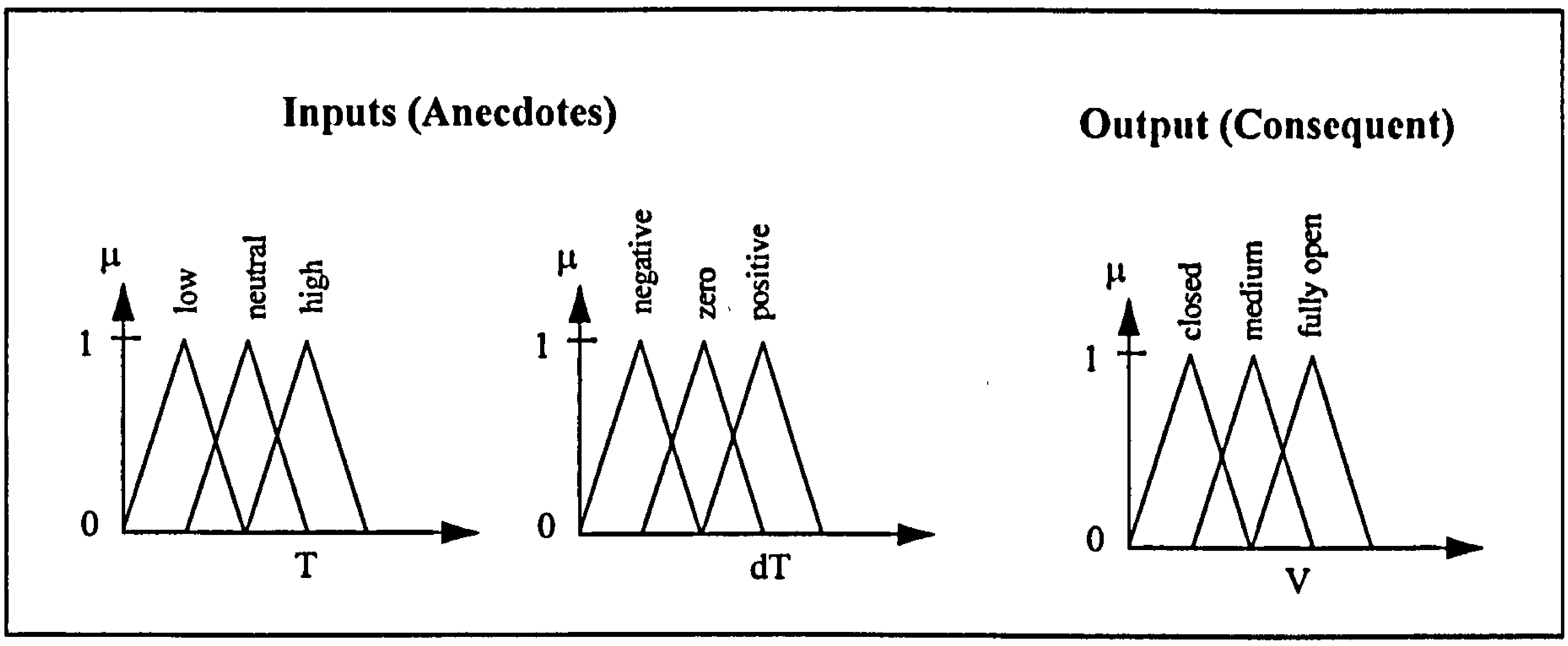

Figure 4.9. Membership functions for the Term Sets zone temperature (T), rate of change of zone temperature (dT) and heating coil valve position (V).

The rule base would normally consist of $3^2 = 9$ rules, i.e. the number of membership functions on each input universe to the power of the number of inputs. These rules, to illustrate the principle, could be:-

1. IF (T is low) AND (dT is negative) THEN (V is fully open)
2. IF (T is low) AND (dT is zero) THEN (V is medium)
3. IF (T is low) AND (dT is positive) THEN (V is medium)
4. IF (T is neutral) AND (dT is negative) THEN (V is medium)
5. IF (T is neutral) AND (dT is zero) THEN (V is closed)
6. IF (T is neutral) AND (dT is positive) THEN (V is closed)
7. IF (T is high) AND (dT is negative) THEN (V is closed)
8. IF (T is high) AND (dT is zero) THEN (V is closed)
9. IF (T is high) AND (dT is positive) THEN (V is closed)

Considering rules 2 and 4, i.e.

2. IF (T is low) AND (dT is zero) THEN (V is medium)
4. IF (T is neutral) AND (dT is negative) THEN (V is medium)

and the membership functions, as shown in Figure 4.9, it can be seen that it is possible for one input value, in this case T, to give two input membership values that have the same output consequent. This is the case for rules 2 and 4. Only one output value can be obtained for the membership value of "medium" and hence a method is required to determine this singular value, i.e. the consequent value to be used.
A widely used method for determining this singular value is the "maximum of minimum principle" or "max min principle". This uses the **AND** (min) and **OR** (max) fuzzy set logical operations to overcome the problem of the two rules having the same consequent. There are two steps to the procedure as described below and illustrated in Figure 4.10.

Step 1
The minimum of the membership values for zone temperature (T) and rate of change of zone temperature (dT) is determined for rules 2 and 4 using the **AND** (minimum) operation, see Figure 4.10. This can be written, for rule 2 and rule 4 as Equation 4.10 and Equation 4.11 respectively.

$$\mu_{\text{medium, rule2}}(V) = \min\{\mu_{\text{low}}(T), \mu_{\text{neutral}}(dT)\} \quad \text{(Rule 2)}$$

Equation 4.10

$$\mu_{\text{medium, rule4}}(V) = \min\{\mu_{\text{neutral}}(T), \mu_{\text{negative}}(dT)\} \quad \text{(Rule 4)}$$

Equation 4.11

In words, Equation 4.10 and Equation 4.11 can be written as:-

- ***Rule 2:*** the membership value for the "medium" output membership function μ_{medium} by rule 2 is equal to the minimum membership value of the "medium" membership function mapped from the membership functions "low" on the universe of discourse "Temperature", $\mu_{\text{low}}(T)$, and the membership function "neutral" , $\mu_{\text{neutral}}(T)$, on the universe of discourse "rate of change of temperature", $\mu_{\text{neutral}}(dT)$.
- ***Rule 4:*** the membership value for the "medium" output membership function by rule 4 is equal to the minimum membership value of the "medium" membership function mapped from the membership functions "neutral" on the universe of discourse "Temperature", $\mu_{\text{neutral}}(T)$, and membership function "negative" on the universe of discourse "rate of change of temperature", $\mu_{\text{negative}}(dT)$.

Step 2
Rules 2 and 4 have the same consequent. i.e. "medium". The **OR** (maximum) operator is used to determine the final value of the output consequent. This can be written, for the two rules being evaluated, as Equation 4.12.

$$\mu_{\text{medium}}(V) = \max\{\mu_{\text{medium, rule2}}(V), \mu_{\text{medium, rule4}}(V)\}$$

Equation 4.12

In words the consequent for rules 2 and 4, i.e. Equation 4.12, can be written as:-
the membership value for the "medium" membership function μ_{medium} is equal to the maximum membership value of the "medium" membership function mapped from the membership functions "medium", Rule 2, on the universe of discourse "Valve Position" and membership function "medium", Rule 4, on the universe of discourse "Valve Position"

Hence, the consequent with the largest membership value for the medium membership function, i.e. of the two consequents shown as shaded in Figure 4.10 (Step 2), is the one selected, i.e. the selected consequent originates from Rule 2.

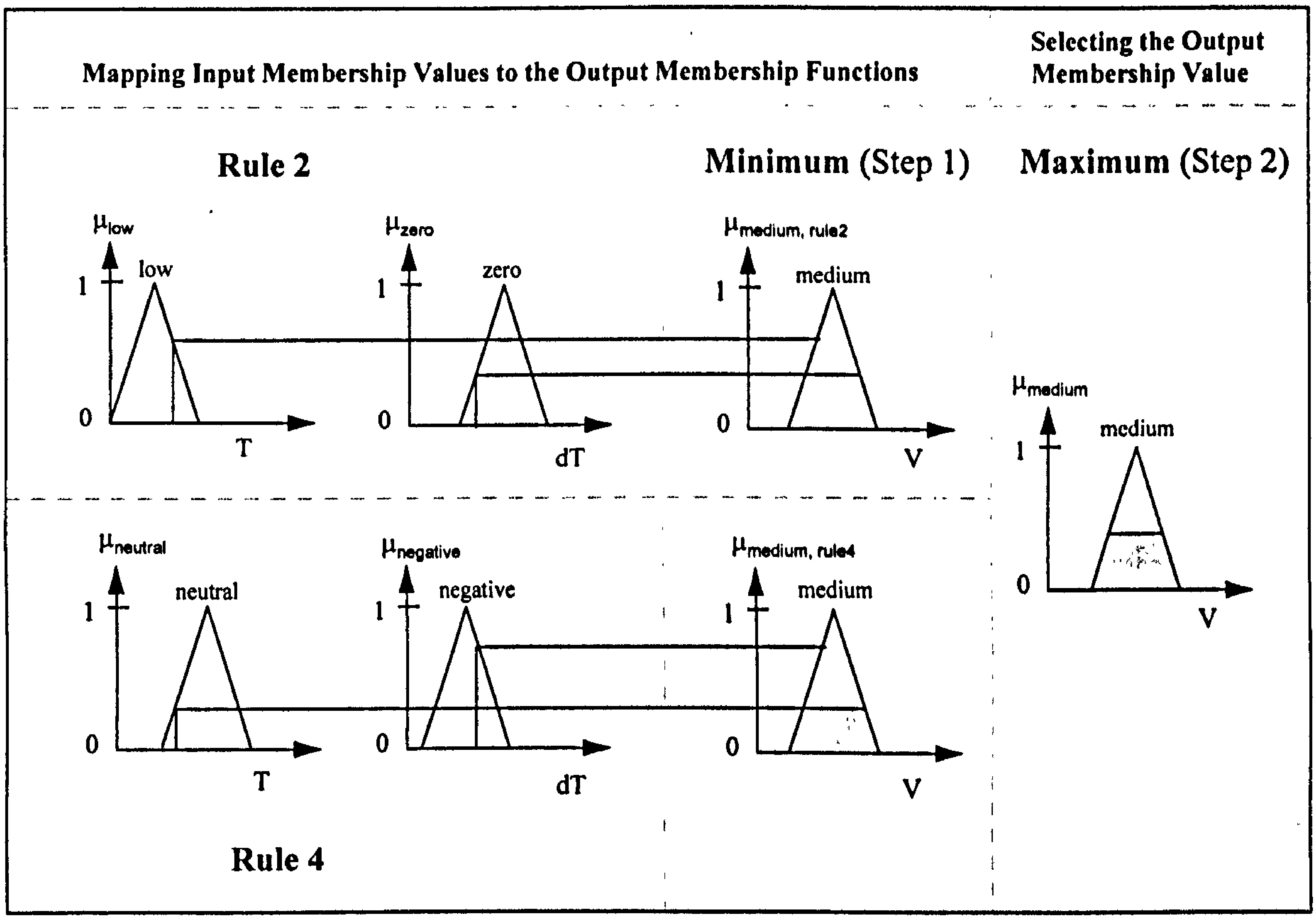

Figure 4.10. Schematic showing the use of the maximum of minimum principle to evaluate the membership value where two rules have the same consequent for Rules 2 and 4.

However, the above explanation is not the end of the procedure required. Other consequences are normally activated simultaneously due to the overlap of membership functions. The final value for the valve position is obtained by defuzzifying the values obtained for each consequent. This is described in Section 4.6.4 of this chapter. First, the theory of fuzzy control is considered.

4.6 Fuzzy Logic Controllers

Previous sections described the basic principles of fuzzy logic, i.e. the concepts of membership functions, membership values and fuzzy operators. The four basic components of a fuzzy controller are shown within the broken line box in Figure 4.11.

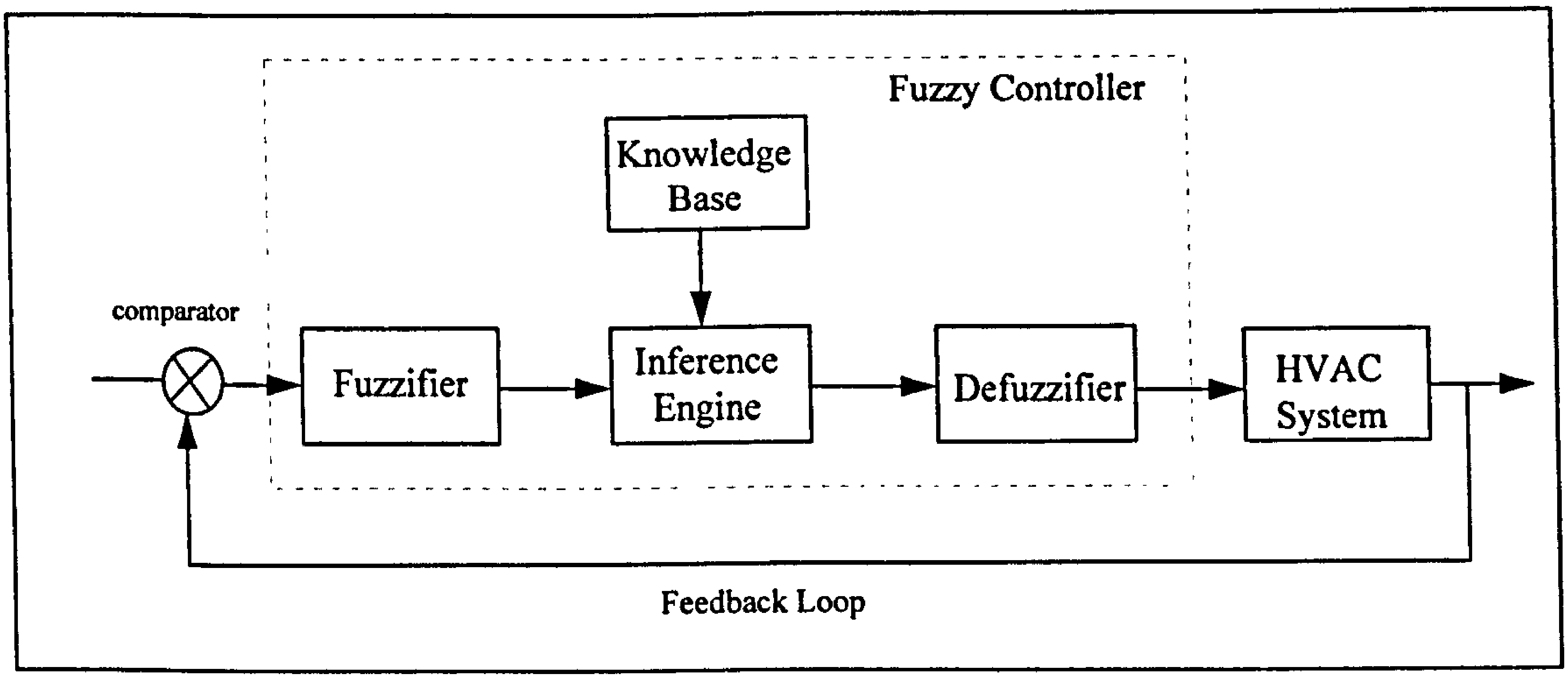

Figure 4.11. Schematic of fuzzy building environmental control system.

These components are:-

4.6.1 Fuzzifier

The fuzzifier takes specific numerical input data (crisp data), e.g. an error signal, and converts it into fuzzy values by assigning membership values to membership functions. The membership value of a crisp data point related to a membership function is calculated by drawing a vertical line where the crisp data point is located on the x-axis and drawing a line perpendicular to the location at which the vertical crosses the membership function. This is shown for the crisp input temperature of 16.5°C in Figure 4.12. A crisp input value will normally possess differing degrees of membership to more than one membership function. In the example, a crisp input temperature of 16.5°C, has membership values for each of the membership functions for the comfort categories of cold, cool, slightly cool, neutral, slightly warm, warm and hot. However, only two membership functions have membership values greater than zero for the crisp input of 16.5°C.

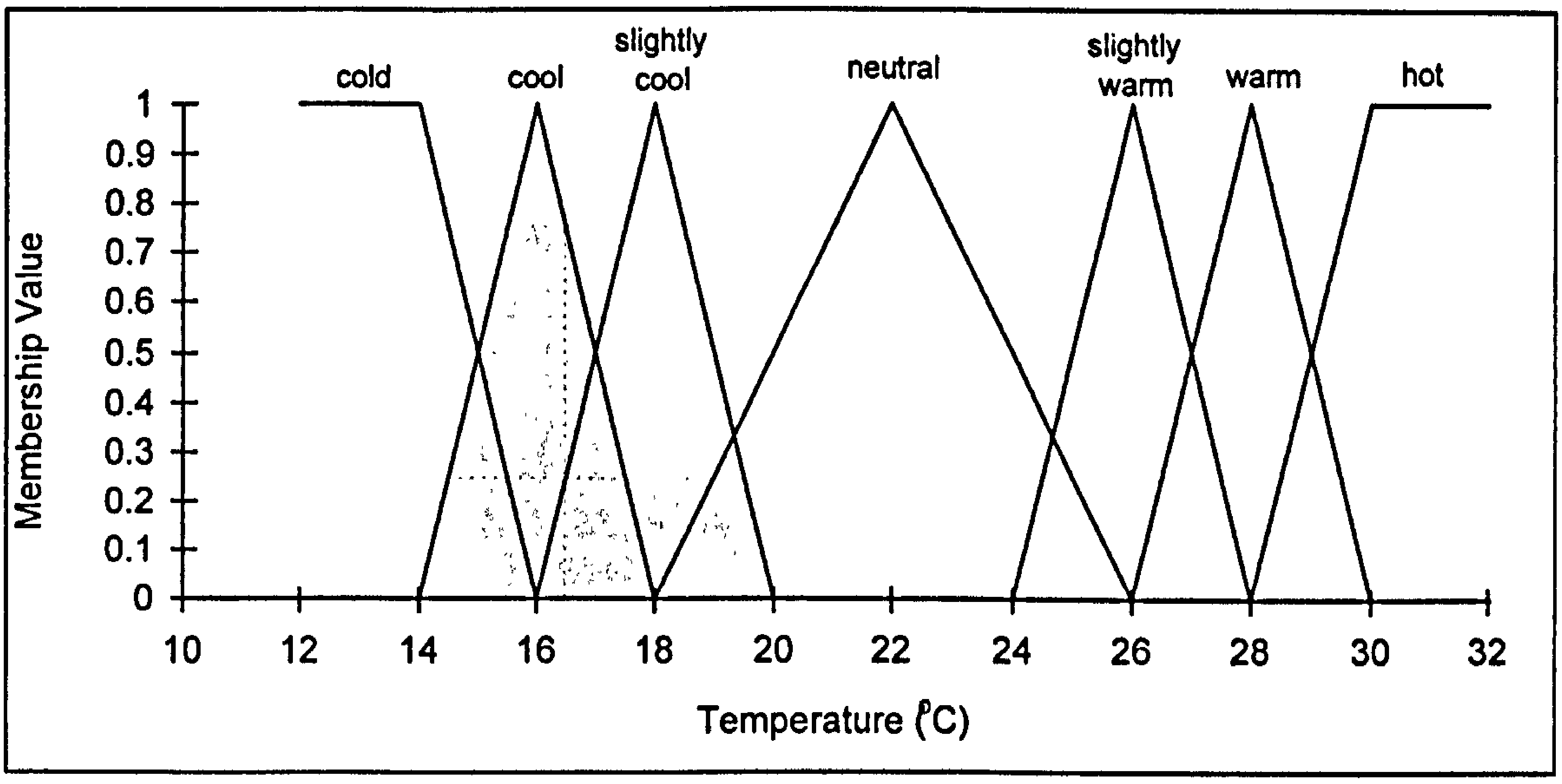

Figure 4.12. Temperature membership functions and membership values for a crisp temperature input of 16.5°C.

The membership value for each membership function shown in Figure 4.12 for the temperature 16.5°C can be written as follows:-

$\mu_{\text{cold}} = 0$, $\mu_{\text{cool}} = 0.75$, $\mu_{\text{slightly cool}} = 0.25$, $\mu_{\text{neutral}} = 0$, $\mu_{\text{slightly warm}} = 0$, $\mu_{\text{warm}} = 0$, $\mu_{\text{hot}} = 0$

Hence the fuzzifier of a controller is capable of converting a singular crisp input value into fuzzified input values defined by their degree of membership to each membership function. The information required for the calculations carried out by the fuzzifier are defined in the knowledge base.

4.6.2 Knowledge base

The knowledge base of a fuzzy controller comprises two components, a data base and a rule base. These contain the information necessary for the controller to operate and are described below.

4.6.2.1 Data Base

This contains the information which defines and links the linguistic definitions and physical variables for each universe of discourse. The limits of each universe of discourse are defined and membership functions are assigned for each term set. Attached to the membership functions are the linguistic labels. Universes of discourse are defined for both input and output variables. For example, the membership functions defined for the temperature universe of discourse in Figure 4.12 would be defined in the data base given in Table 4.1 for the temperature term set.

Membership Function	Temperature °C											
	10	12	14	16	18	20	22	24	26	28	30	32
cold	1	1	1	0	0	0	0	0	0	0	0	0
cool	0	0	0	1	0	0	0	0	0	0	0	0
slightly cool	0	0	0	0	1	0	0	0	0	0	0	0
neutral	0	0	0	0	0	0.5	1	0.5	0	0	0	0
slightly warm	0	0	0	0	0	0	0	0	1	0	0	0
warm	0	0	0	0	0	0	0	0	0	1	0	0
hot	0	0	0	0	0	0	0	0	0	0	1	1

Table 4.1. Membership functions for temperature defined for Figure 4.12.

Table 4.1 in effect describes the location of the triangular membership functions on the universe of discourse "temperature" between the limits of 10°C and 32°C.

4.6.2.2 Rule Base

This contains expert knowledge in the form of linguistic statements or rules which are used for mapping, i.e. relating, input membership functions to the output membership functions which are of the form:-

Rule: **IF** (A_1 is X_1) **AND** (A_2 is X_2) **AND** (A_i is X_i) **THEN** (B_1 is Y_1) **AND** (B_i is Y_i)

where A_i is a universe of discourse and X_i is a membership function. To make this clearer consider the following rule as an example:-

Rule: **IF** (zone temperature is low) **AND** (rate of change of zone temperature is zero)
THEN (heating valve position is medium)

For the above rule the universes of discourse are zone temperature, rate of change of zone temperature and heating valve position. The membership functions associated with this rule are "low", "zero" and "medium" on their respective universes of discourse.

Various methods are documented in published literature for defining the rule base (Vadiee 1993). These include:

- *Observation of Human Expert Operator Actions* - The rules for the fuzzy rule base can be deduced from the observations of human experts familiar with the control of a physical process or system. By observing input-output data pairs and the operators' responses to these pairs the rules can be deduced. Pattern classification, clustering and statistical analysis are means of achieving this. The resulting systems are capable of mimicking the way in which human expert operators react after long periods of training and experience. The gathered information can readily be expressed in the form of IF-THEN rules.
- *Expert Knowledge and Engineering Knowledge* - Common sense and the intuitive knowledge of experts, such as design engineers, about the physical process or system under investigation can be incorporated in the rules.

- *Use of General Physical Principles* - Where the physical principles and laws governing the dynamics of the system under consideration are known, possibly with only some certainty, these can be incorporated into the rule base.
- *Fuzzy Model of the Process* - Linguistic descriptions of the dynamic characteristics of a controlled process may be viewed as a fuzzy model of the process. A set of control rules may be deduced from the fuzzy model for obtaining the optimal performance of a dynamic system.
- *Based on Learning* - Self learning or self organising fuzzy controllers have the ability to learn and adapt their rule base in order to obtain the optimal rule set or adapt to changing system characteristics. These types of system often incorporate artificial neural networks as their means of learning.

4.6.3 Inference Engine

The inference engine carries out the control reasoning process using the information stored in the knowledge base, i.e. the data base and the rule base. It takes the input membership values and relates them to the output membership functions using the fuzzy set logical operations and the rules defined in the rule base. It can be viewed as the mathematical computational engine of the fuzzy controller that implements the processes of calculation.

4.6.4 Defuzzifier

The final output of a fuzzy controller normally needs to be a crisp value which can be used for the control process, e.g. a signal to an actuator operating a valve. Defuzzification is the conversion of a fuzzy quantity to a precise quantity The defuzzifier takes the output membership function formed by the union of two or more output membership functions on the universe of discourse for the output variable. For example, the union of the membership functions A_1 and A_2 in Figure 4.13 produces the membership function A_3.

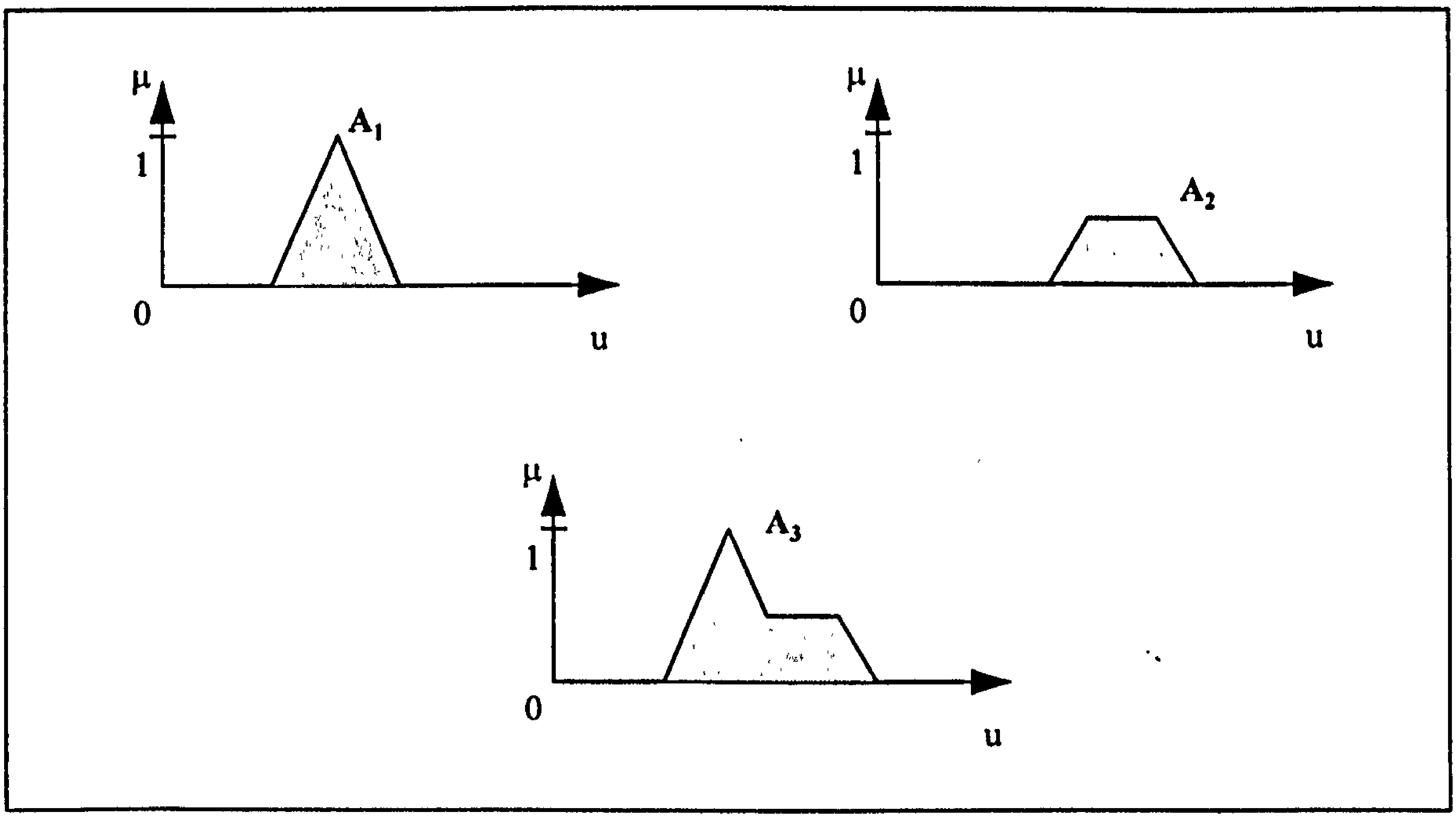

Figure 4.13. The union of membership functions A_1 and A_2 to produce A_3.

The defuzzifier is then required to defuzzify the membership function A_3 to a singular crisp value. There are many defuzzification methods. Four of the more commonly used defuzzification methods are illustrated below. In Sections 4.6.4.1 to 4.6.4.4 the membership function for the union of the consequent membership functions is denoted by "A".

4.6.4.1 Max-Membership Method (or Height Method)

This method can only be applied to peaked output membership functions and is described by the algebraic expression of Equation 4.13.

$$\mu_A(u^*) \geq \mu_A(u), \quad \text{for all } u \in U$$

Equation 4.13

In words Equation 4.13 can be written as:-
The crisp output value u* is the maximum membership value of the membership function created by the union of the consequents, i.e. membership function A, u belongs to the universe of discourse U.

This is shown graphically in Figure 4.14.

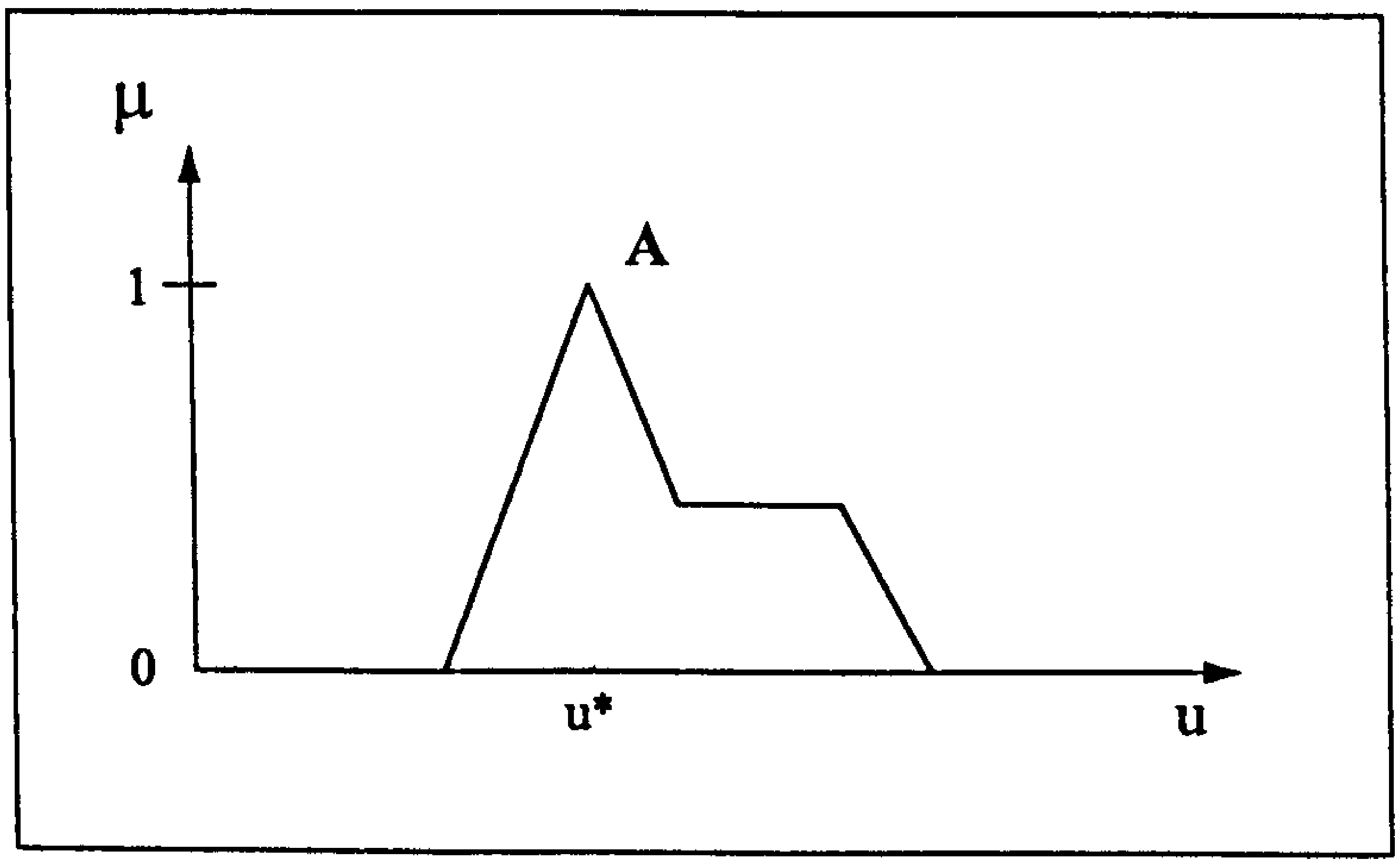

Figure 4.14. Defuzzification using the Max-Membership Method.

4.6.4.2 Centroid Method (centre of area, centre of gravity method)

This is one of the most commonly used methods of defuzzification and is described by the algebraic expression given by Equation 4.14.

$$u^* = \frac{\int \mu_A(u) \cdot u\,du}{\int \mu_A(u)\,du}$$

Equation 4.14

where $\int$ denotes an algebraic integration. The centroid method of defuzzification is shown graphically in Figure 4.15.

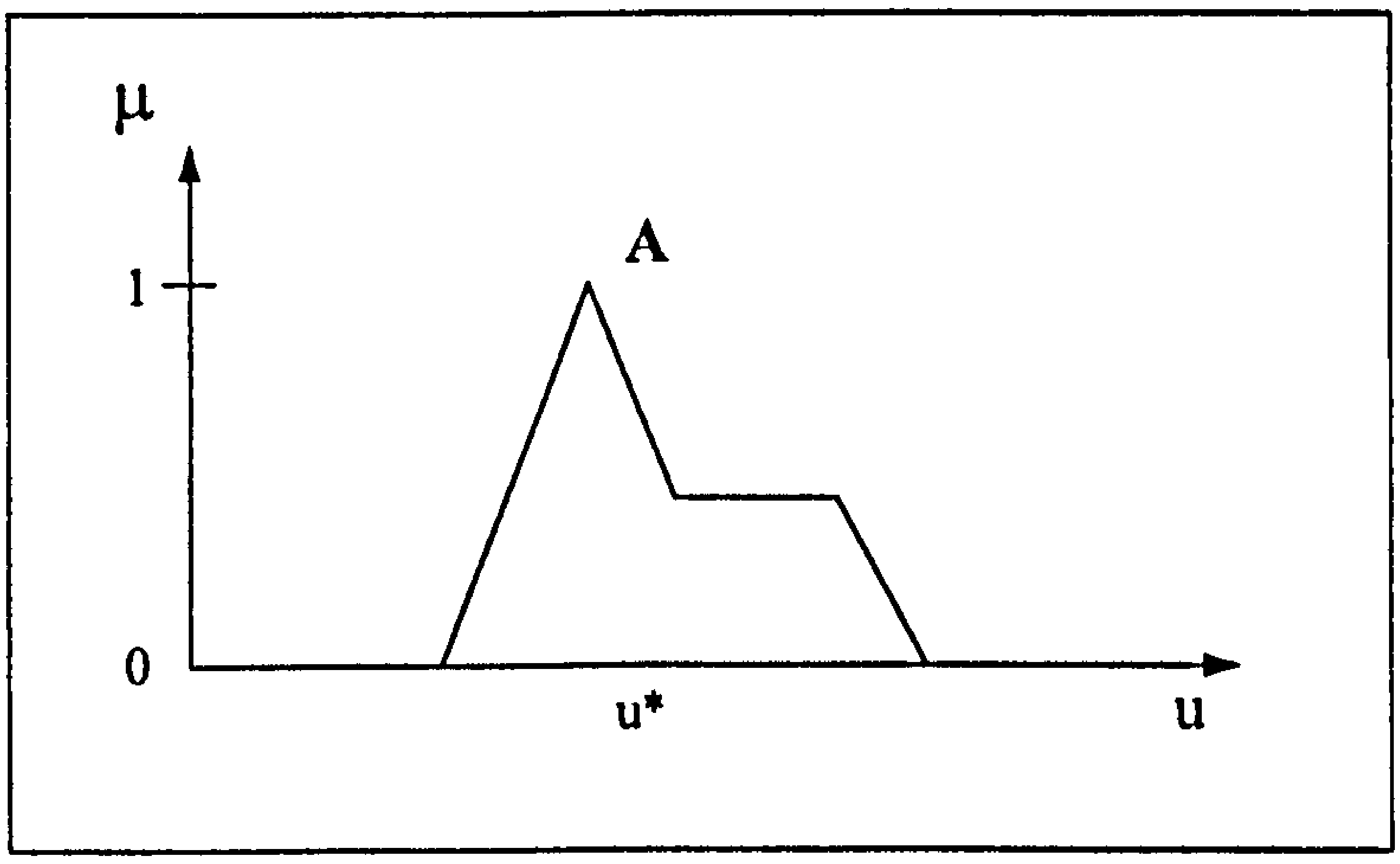

Figure 4.15. The centroid method of defuzzification.

4.6.4.3 Weighted Average Method

This method can only be used for symmetrical output membership functions and is described by the algebraic expression given by Equation 4.15 and is shown graphically in Figure 4.16.

$$u^* = \frac{\sum \mu_A(\bar{u}) \cdot \bar{u}}{\sum \mu_A(\bar{u})}$$

Equation 4.15

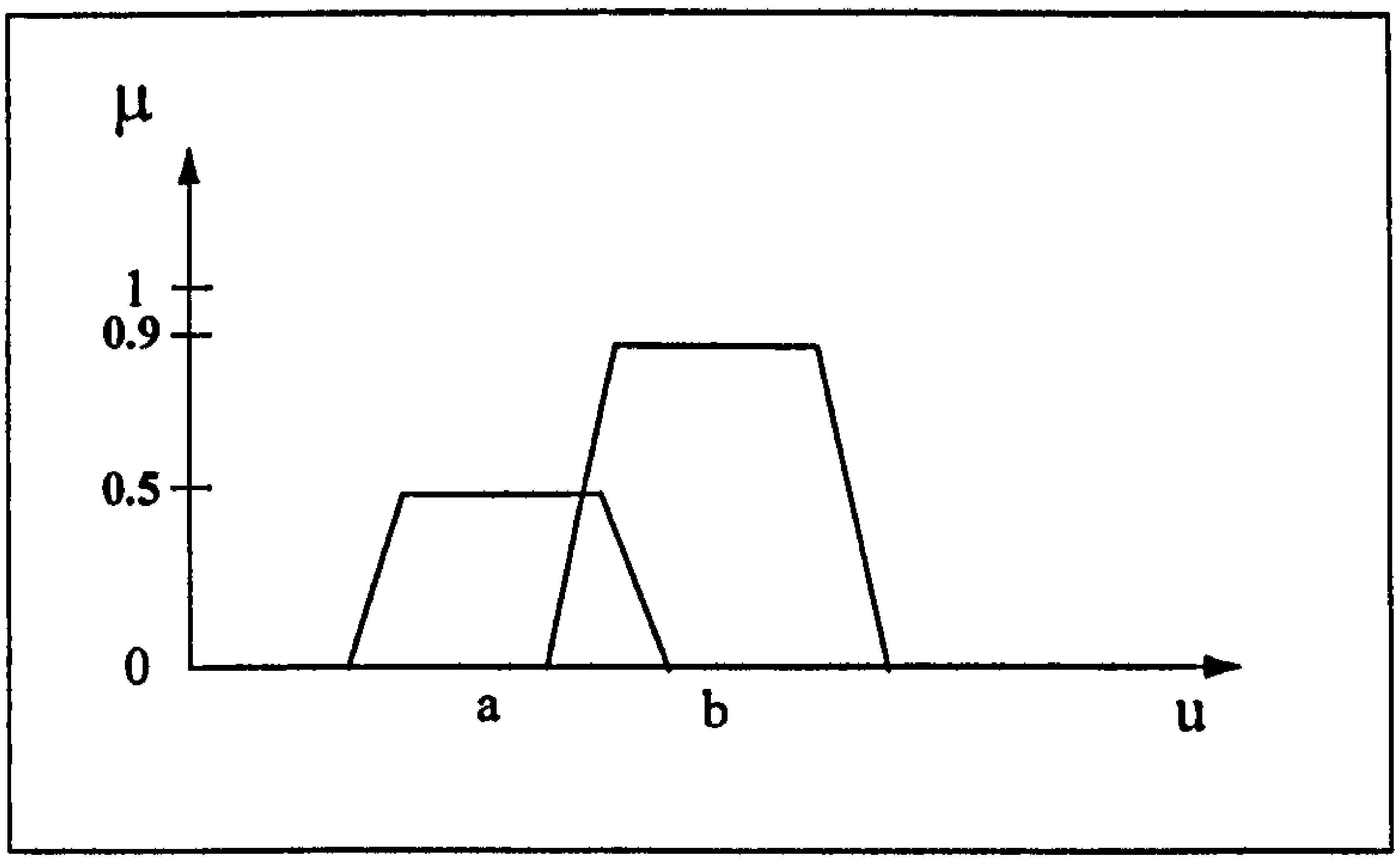

Figure 4.16. The weighted average method of defuzzification.

Each consequent membership function is weighted by its maximum value, i.e. values a and b. For the example shown in Figure 4.16 the result for the defuzzified value would be:-

$$u^* = \frac{a(0.5)+b(0.9)}{0.5+0.9}$$

Because this method of defuzzification is limited to symmetrical membership functions, the values a and b are the means of their respective shapes.

4.6.4.4 Mean-max Membership Method (Middle of Maxima Method)

This method is similar to that of the Max-Membership Method, except that the locations of the maximum membership can be a plateau instead of a single point. The algebraic expression describing this method is given by Equation 4.16 and is shown graphically in Figure 4.17.

$$u^* = \frac{a+b}{2}$$

Equation 4.16

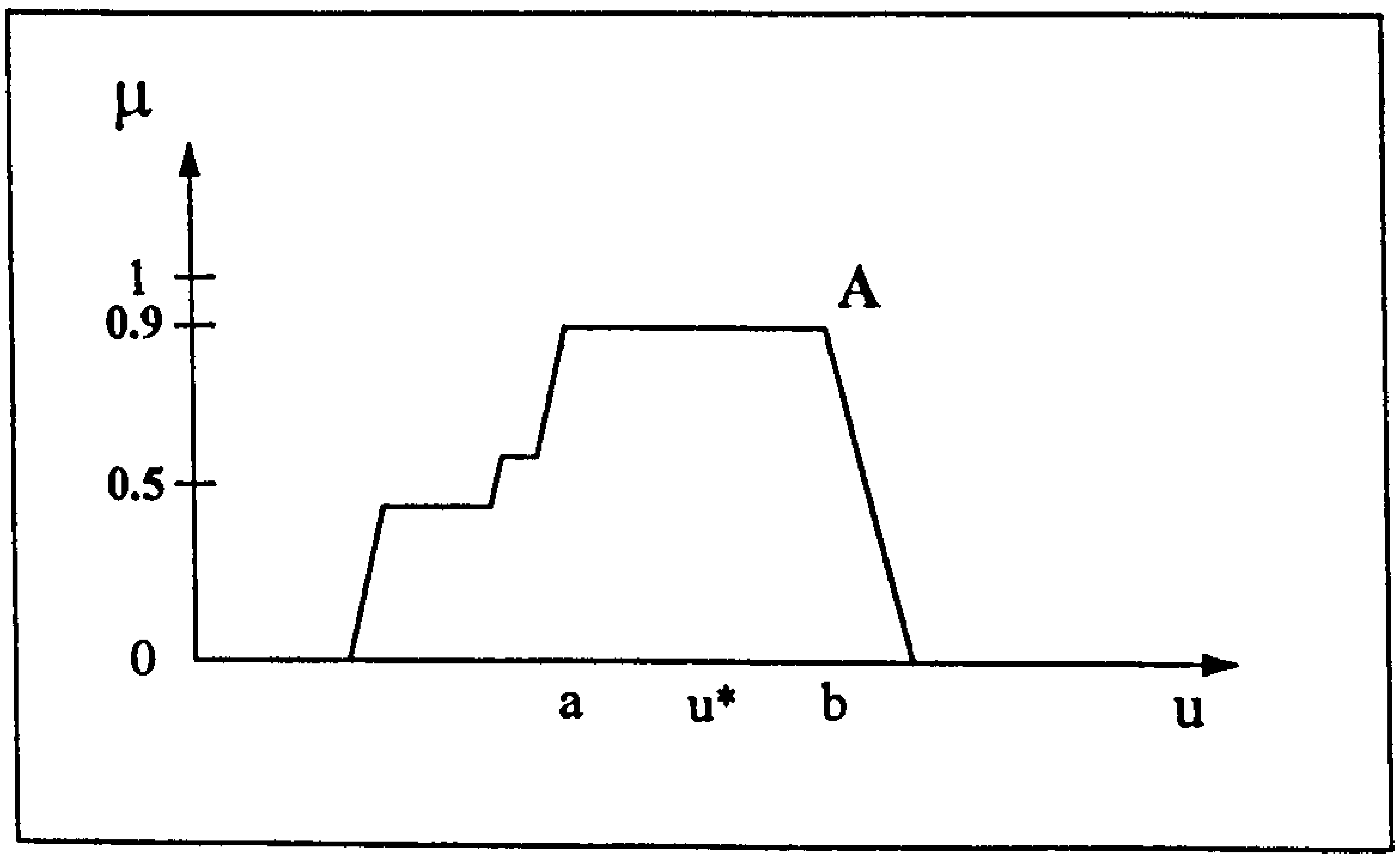

Figure 4.17. Mean-max membership method of defuzzification.

4.7 Fuzzy Logic Controller Example

The previous sections of this chapter have considered the theory of fuzzy logic and fuzzy control. As with the majority of theoretical explanations, a more practical example can aid the understanding of the subject. For this reason an example of a fuzzy controller capable, in theory, of maintaining a room temperature at a predetermined set point through the use of heating plant is considered. The brackets in the section heading indicate the component of the fuzzy controller to which the descriptions apply.

The first steps involve defining the universes of discourse, term sets and membership functions for the input and output universes.

4.7.1 Environmental Temperature Membership Function (Fuzzifier)

For the purposes of this example it is assumed that all occupants would judge the zone temperature as completely neutral for temperatures between 20°C and 24°C with some also judging the temperature as neutral 2°C either side of this range. As the temperature rises above or falls below these limits the proportion of occupants who become progressively too hot or too cold increases. This knowledge is embedded in the fuzzy controller within the fuzzification interface as depicted by the membership functions in Figure 4.18.

The fuzzifier converts a crisp zone temperature value into a weighted linguistic value by interpreting the membership value of this crisp value to the membership functions for the corresponding comfort classifications. The crisp value in this type of application would normally be a temperature sensor signal. Considering Figure 4.18 and assuming the zone temperature has a crisp value of 16.5°C then it would have a membership value of 0.75 to the "cool" membership function, 0.25 to the "slightly cool" membership function and zero for the remaining membership functions on the zone temperature universe of discourse {10°C, 32°C}. Hence, the crisp value can be considered as being related only to the linguistic categories "cool" and "slightly cool" with any consequence. The membership values of the membership functions are now representative of the human response to this temperature environment.

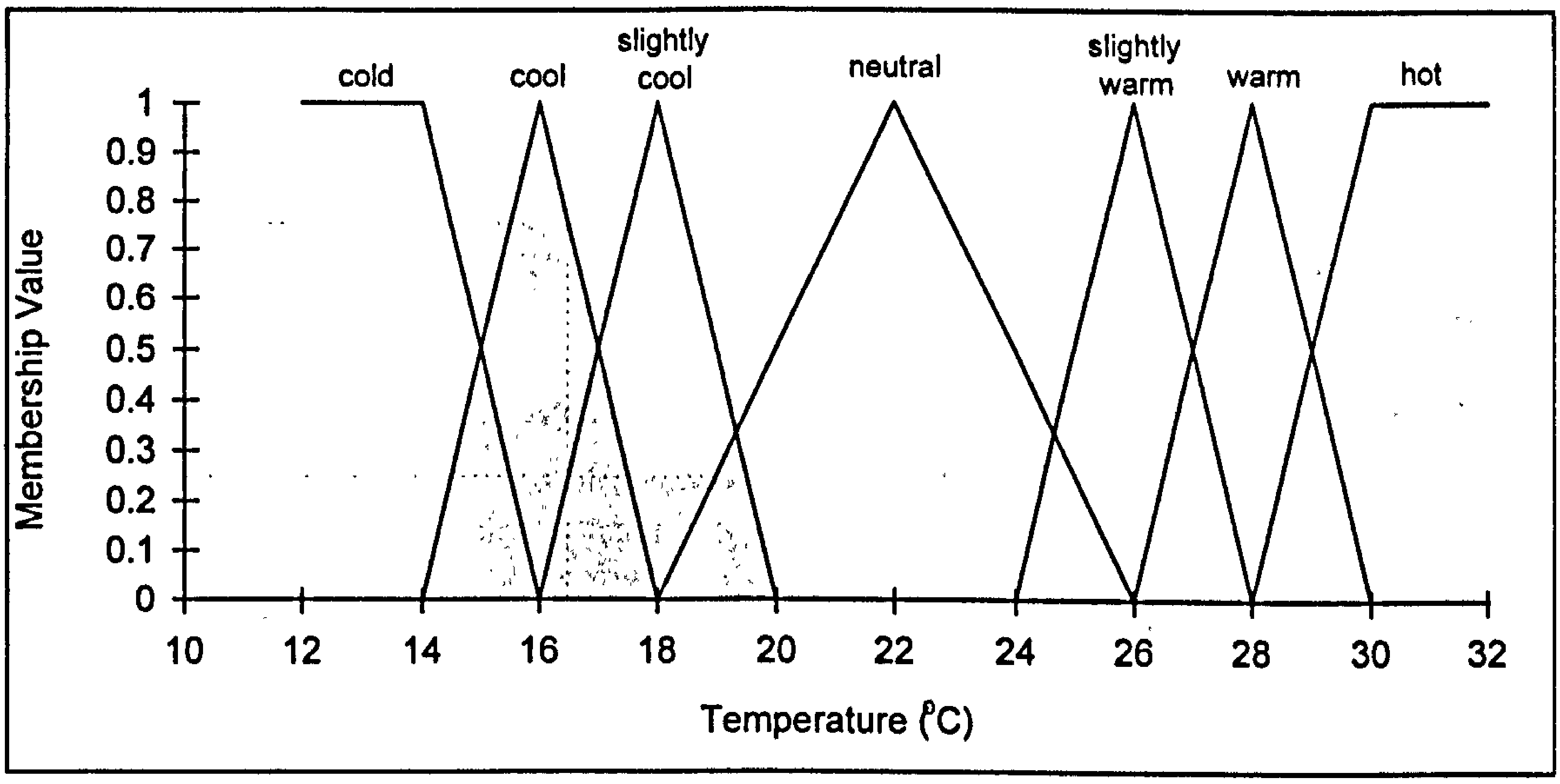

Figure 4.18. Environmental temperature membership functions.

4.7.2 Fuzzy Membership Functions for the Control Action (Defuzzifier)

In this example membership functions are defined for the control output of heat input into the zone, see Figure 4.19. For example, the membership function "large -" represents an arbitrary heat input of minus 4 or less, i.e. a large amount of cooling. The control action, e.g. the valve position (V) is defined on the universe of discourse V{-10, 10}. The membership functions and linguistic labels for the control action, or output, are defined in the data base of the knowledge base.

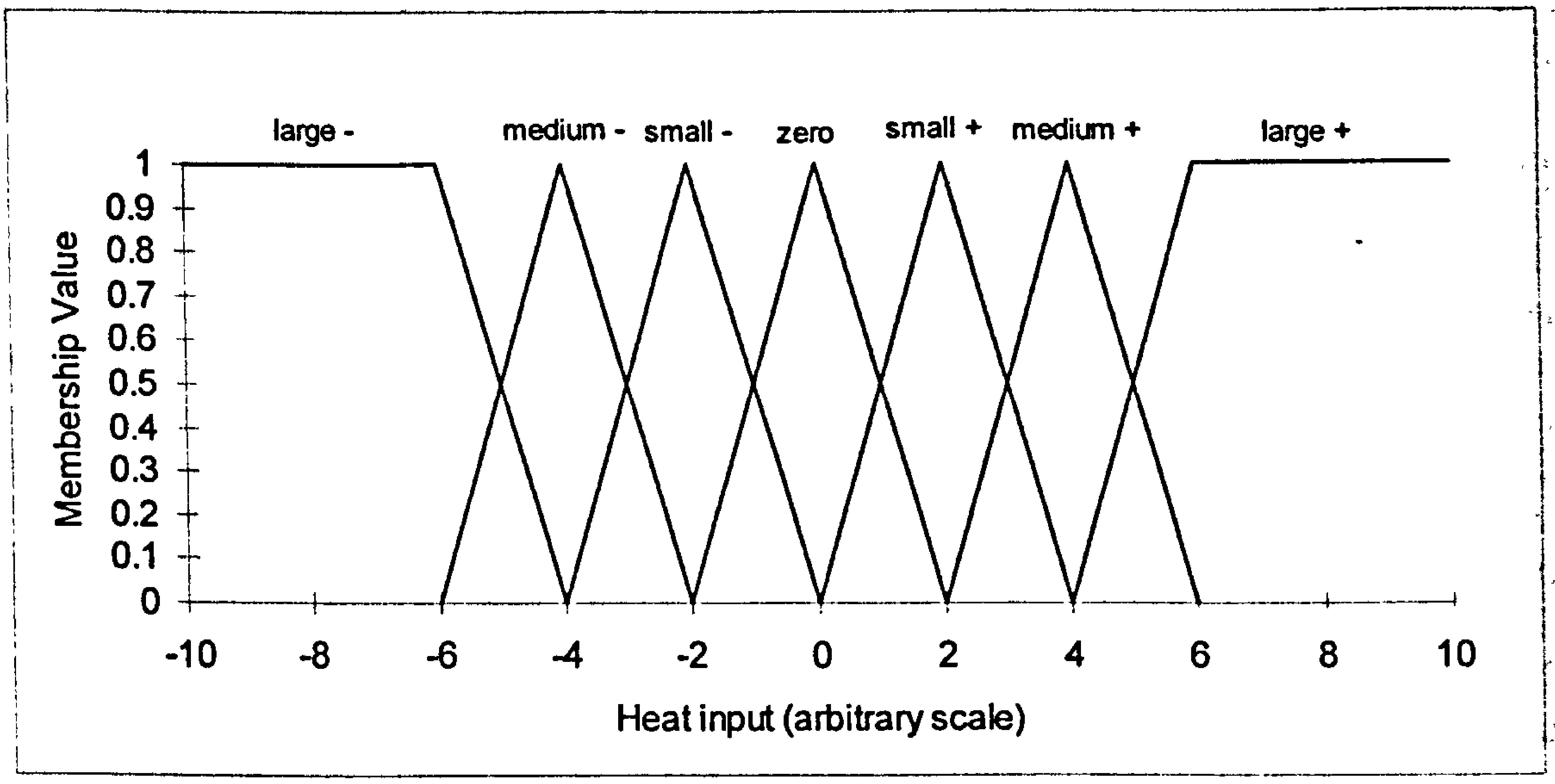

Figure 4.19. Fuzzy membership functions for control output (cooling -ve, heating +ve).

After the input and output membership functions have been defined and the crisp input data point has been fuzzified into a fuzzy input value the inference engine then carries out the mapping of the fuzzy input values to the output membership functions using the knowledge base.

4.7.3 Mapping of the Fuzzy Input to the Fuzzy Output (Knowledge Base)

The inference engine uses the knowledge base, which defines the input and output membership functions, to relate a fuzzified input membership values to a fuzzy output membership functions using the set of linguistic rules defined in the rule base. These are in the form of **IF-THEN** rules as discussed in Section 4.6.2.2. The **IF-THEN** rules for the considered fuzzy controller could take the following form:-

1. **IF** (zonetemp is hot) **THEN** (plant is large-)
2. **IF** (zonetemp is warm) **THEN** (plant is medium-)
3. **IF** (zonetemp is slightly warm) **THEN** (plant is small-)
4. **IF** (zonetemp is neutral) **THEN** (plant is zero)
5. **IF** (zonetemp is slightly cool) **THEN** (plant is small+)
6. **IF** (zonetemp is cool) **THEN** (plant is medium+)
7. **IF** (zonetemp is cold) **THEN** (plant is large+)

where
"large-" = "large minus" i.e. a large amount of cooling
"large+" = "large plus" i.e. a large amount of heating

For a single parameter fuzzy system as described regarding temperature, a basic assumption is that the fuzzified control output membership function will be affected to the same degree as the input membership function from which it is mapped, by the rule base. This is known as the extension principle Zadeh (1965). The theoretical discussion regarding the "Maximum of Minimum" principle in Section 4.5 is not required in this example as each input membership function is mapped to only one output membership function by a rule and so the maximum membership value for each input membership function of each rule is considered. For the zone temperature under consideration in this example of 16.5°C, the input membership functions "cool" and "slightly cool", are mapped, via rules (6) and (5), to the output membership functions "medium+" and "small+" respectively. The output membership functions will possess the same membership value as the corresponding input membership function. Thus, the degree to which the membership functions will be affected for the outputs "medium+" and "small+" are 0.75 and 0.25 respectively, see Figure 4.20. Although rules (5) and (6) would appear to be the only rules under consideration, rules (1), (2), (3), (4) and (7) are also operational. However, the membership values for these input membership functions are zero for a crisp input of 16.5°C and the rules are affected to zero degree. The resulting membership values of the corresponding output membership functions are therefore also zero by the extension principle.

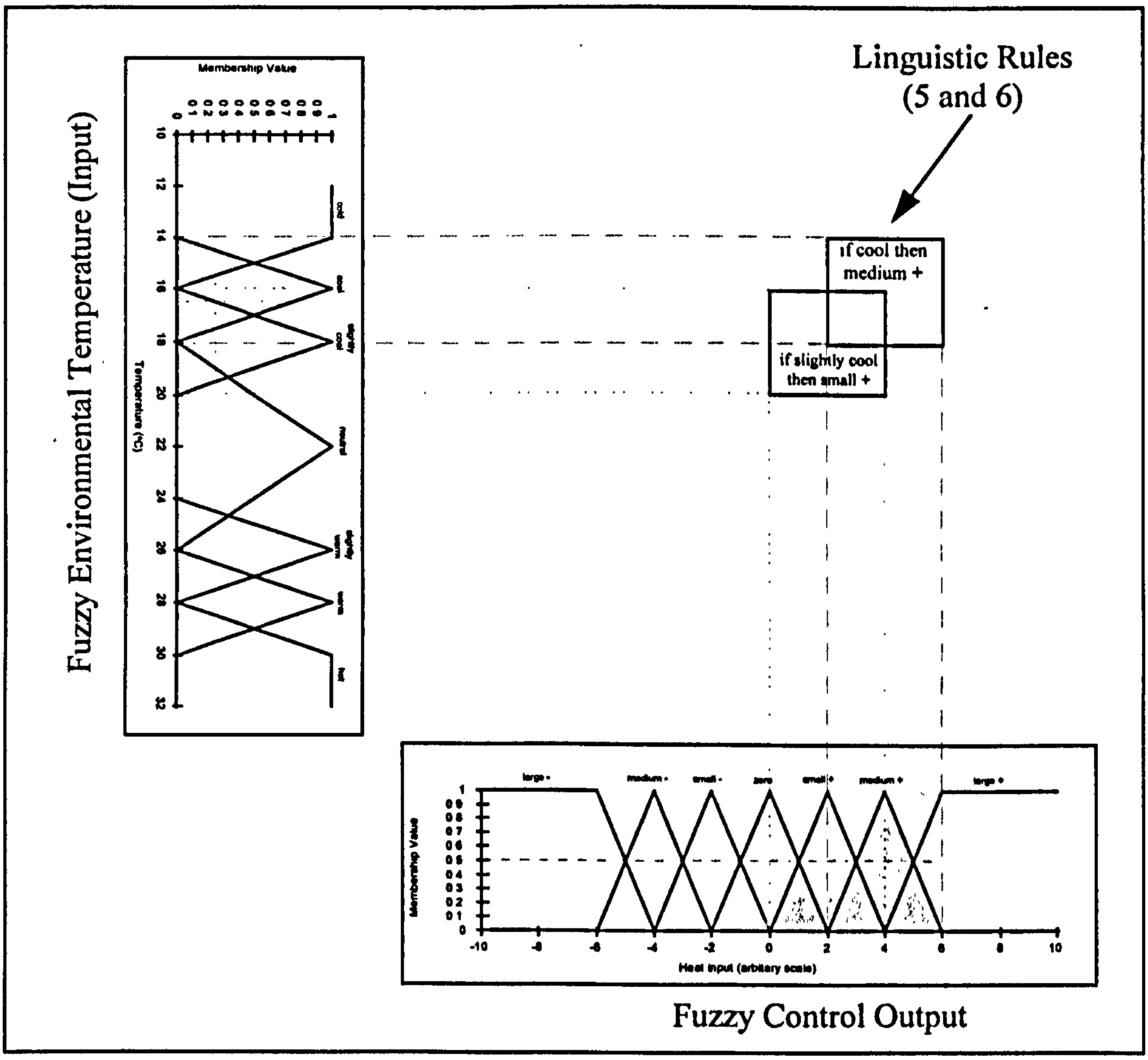

Figure 4.20. Fuzzy input membership functions and output membership functions for an input of 16.5°C. Grey shaded areas indicate the membership values for the input of 16.5°C.

4.7.4 Converting from Fuzzy to Crisp Output (Defuzzification)

This is carried out by the defuzzifier and can be achieved using many different methods as discussed in Section 4.6.4. The fuzzy output is the union of the affected output membership functions, i.e. the shaded area of the output membership functions "small+" and "medium+" in the example, see Figure 4.20.

If the weighted average defuzzification method, as described in Section 4.6.4.3, is used the result is described by Equation 4.17.

$$u^* = \frac{(2 \times 0.5) + (4 \times 0.75)}{0.25 + 0.75} = 3.5$$

Equation 4.17

Using the centroid method, as described in Section 4.6.4.2, the defuzzification process results in a crisp output of approximately +3.5 arbitrary units, i.e. heating, see Figure 4.21.

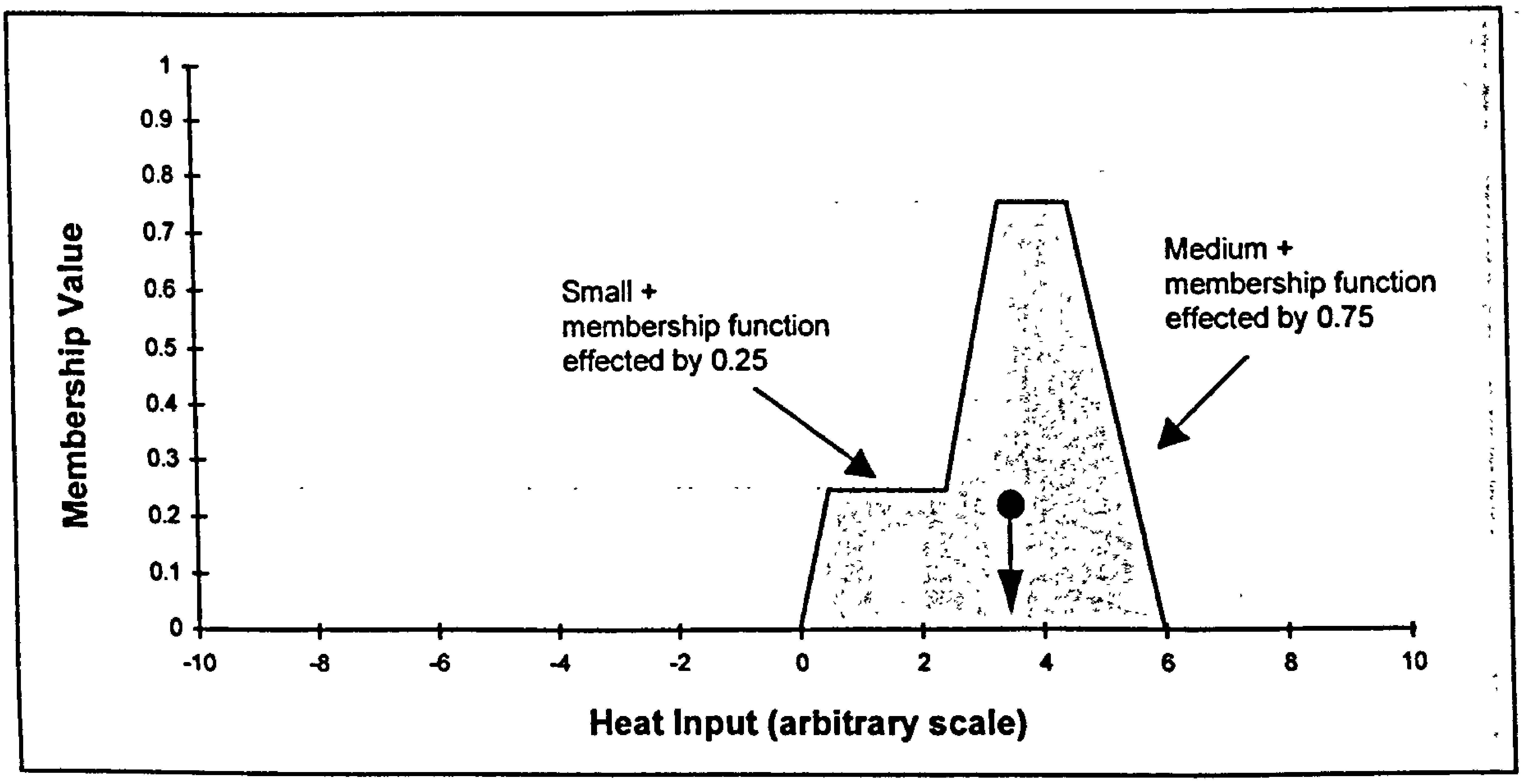

Figure 4.21. Defuzzification of the union of the "small+" and "medium+" membership functions using the centroid method.

The fuzzy controller output value could be used to control the HVAC heating plant via an actuator. As the temperature within the space changes the sensor value changes and the fuzzy controller re-evaluates the new heating / cooling valve position required for the heat input into the space.

The example described shows the basic principles and theory of a fuzzy environmental temperature control system. It has shown that for an input of 16.5°C an output of +3.5 arbitrary units of the heating plant is inferred. The example is analogous to conventional proportional control. In order to eliminate the inherent offset from the set point obtained using proportional type controllers a derivative control action is a recognised method of achieving the desired effect. This was investigated in detail during the research project and is presented in chapter 8.

In practical systems a key advantage of using fuzzy logic is that control decisions can be made on the basis of more than one input variable by defining multiple input universes of discourse. The demonstration of the fuzzy control process using one crisp input parameter was aimed at facilitating the reader's understanding.

With respect to environmental control, the concept of fuzzy sets offers several benefits, including:-

- fuzzy control does not require an exact mathematical model of the control process
- modelling of fuzzy conditions and requirements allows the possibility of implementing effective control strategies
- non-linear processes can be modelled
- the control system is capable of approximate reasoning and decision making
- multi input and output parameter systems can be controlled

(Ross 1995)

This thesis describes the research carried out to utilise these advantages and model a building environmental controls system which maximises the environmental comfort, cost and energy efficiencies.

4.8 Conclusions and Discussion

The theory of fuzzy logic and fuzzy control described in this chapter showed how fuzzy logic can handle the concept of partial truth values which lie between completely true and completely false in a similar way to human thought processes. This provided the possibility of constructing fuzzy controllers which incorporate human expert knowledge and thus the solution of control problems using an easily understood methodology. Further, fuzzy logic enables the building of controllers which can solve problems for which exact mathematical models do not exist. This can also allow control problems to be solved where a solution using conventional techniques may be very complex.

The research project described in this thesis aimed to take advantage of the benefits offered by fuzzy control. One of the more interesting aspects of fuzzy controllers was considered to be their ability to deal with multi-input and multi-output parameter systems. Control of indoor environmental quality while providing energy and cost efficiency with respect to the operation of HVAC building services equipment represents a multi-variant problem that does not have a simple "best solution" answer. Hence the development of a computer model to assess the usefulness of applying fuzzy control to such a multi-variant problem represented a sensible platform for research into this area. To achieve this goal, thermal, moisture (relative humidity) and air quality parameters were taken as the inputs to the controller. The outputs considered were heating, cooling, humidification, dehumidification and fresh air ventilation rates. Complex interactions exist between these parameters and hence fuzzy logic was capable of providing an easily understood control methodology. Conventional control algorithms would be more difficult to implement for this multi-variant problem. The implementation of the theory discussed in this chapter is described in Chapters 7, 8, 9 and 10.

4.9 References

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5. One Zone Dynamic Model - "Free Running" Building Components Theory

Nomenclature

α	transient heat transfer constant (m^2/s)
β	surface slope (°)
γ	surface azimuth angle (°)
δ	declination angle (°)
Δt	simulation time step (seconds)
Δx	building partition division thickness (m)
ε	surface emissivity (dimensionless)
ε_i	emissivity of surface i (dimensionless)
ϕ	latitude (°)
θ	angle of incidence (°)
θ_z	zenith angle (°)
θ_t	transmission angle (°)
σ	Stefan-Boltzmann Constant = 5.670×10^{-8} (W/m^2K^4)
ρ	density of material (kg/m^3)
ρ_{air}	density of air (kg/m^3)
ρ_g	reflectance of the ground (dimensionless)
$\tau(\theta)$	glass layer transmittance at angle of incidence 0 (dimensionless)
τ_o	glass layer normal transmittance (dimensionless)
τ_{para}	transmittance parallel to plane of incidence (dimensionless)
τ_{perp}	transmittance perpendicular to plane of incidence (dimensionless)
ω	hour angle (°)
A_{floor}	zone floor area (m^2)
A_g	area of the glazing (m^2)
A_i	area of surface i (m^2)
$b(\theta)$	attenuation factor at angle of incidence θ (dimensionless)
b_o	attenuation factor normal angle of incidence(dimensionless)
Bi	Biot Number (dimensionless)
Bi_i	internal surface Biot Number (dimensionless)
Bi_o	external surface Biot Number (dimensionless)
$c(\theta)$	ratio of the cosine of the transmission angle to the cosine of the angle of incidence (dimensionless)
c_p	specific heat capacity (J/kgK)
c_{pair}	specific heat capacity air (J/kgK, J/m^3K)
C	cloudiness factor (dimensionless)
Cj	view coefficient for radiant heat input (dimensionless)
CO_2*	CO_2 removal rate from zone (g/s)

CO_2^{amb}	ambient air carbon dioxide concentration (g/m^3)
CO_2^{nat}	removal rate of carbon dioxide due to natural infiltration (g/s)
CO_2^{occup}	total metabolic CO_2 production rate of occupants (g/s)
CO_2^{zone}	zone air carbon dioxide concentration (g/m^3)
d	thickness of glass layer (m)
F_o	Fourier Number (dimensionless)
g_{amb}	moisture content of ambient air (g/kg)
g_{zone}	moisture content of zone air (g/kg)
$G_{direct\ plant+casual}$	direct radiant plant and casual gains (W/m^2)
$G_{scat\ plant+casual}$	scattered radiant plant and casual gains (W/m^2)
G_{sol}	solar gain (W/m^2)
G_{surf}	surface radiation (W/m^2)
h	convective heat transfer coefficient (W/m^{2}K)
h_i	internal surface convective heat transfer coefficient (W/m^{2}K)
h_o	external surface convective heat transfer coefficient (W/m^{2}K)
h_{ro}	external surface radiative heat transfer coefficient (W/m^{2}K)
H	surface height (m)
$I_{diffusemean}$	mean surface diffuse irradiance (including scattered) (W/m^2)
I_{Htotal}	total radiation on a horizontal surface (W/m^2)
$I_{Hdiffuse}$	diffuse radiation on a horizontal surface (W/m^2)
$I_{Hdirect}$	direct radiation on a horizontal surface (W/m^2)
$I_{Idiffuse}$	diffuse radiation on an inclined surface (W/m^2)
$I_{Idirect}$	direct radiation on an inclined surface (W/m^2)
I_{Igref}	ground reflected radiation on an inclined surface (W/m^2)
I_{Itotal}	total radiation on an inclined surface (W/m^2)
I_L	long wave thermal radiation loss to sky (W/m^2)
k	thermal conductivity (W/mK)
L	water latent heat of evaporisation (J/g)
m_{nat}	natural ventilation air mass flow rate (kg/s)
m_{occup}	metabolic moisture generation rate (g/person/s)
n	refractive index ($n = 1.52$ for glass)
n_d	day number (Jan 1st = 1, Dec 31st = 365)
M_{CO2}	metabolic CO_2 production rate(g/s/person)
M_{nat}	moisture gain rate due to natural ventilation (g/s)
$M_{occup\ tot}$	total metabolic moisture generation rate (g/s)
N	number of occupants (persons)
$p_{equipment}$	proportion of sensible heat gain which is in the form of radiant heat for equipment (dimensionless)
p_{lights}	proportion of sensible heat gain which is in the form of radiant heat for lighting (dimensionless)
$p_{occupants}$	proportion of sensible heat gain which is in the form of radiant heat for occupants (dimensionless)
q_{int}	internal surface heat transfer rate (W/m^2)
$q_i^{surfrad}$	total surface radiant gain (W/m^2)
q_{rad}	radiant heat transfer to internal surface (W/m^2)
$Q_{equipment}$	total sensible heat gain from equipment (W)
Q_{glass}	rate of glass heat transfer (W)

Q_j	radiant heat gain to surface j (W)
Q_{lights}	total sensible heat gain from lighting (W)
$Q_{nat\ latent}$	rate of latent energy transfer to zone air by natural ventilation (J/s)
$Q_{occupants}$	total sensible heat gain from occupants (W)
$Q_{radiant\ gains}$	total radiant gain from equipment, lights and occupants (W)
$Q_{sens\ nat}$	rate of sensible heat transfer to zone air (W)
R_b	the ratio of direct radiation incident on a tilted surface to that on a horizontal surface (dimensionless)
R_{int}	mean effective irradiance (W/m^2)
R_s	surface resistance (m^{2}K/W)
R_{si}	internal surface resistance (m^{2}K/W)
R_{so}	external surface resistance (m^{2}K/W)
RH_{zone}	zone relative humidity (%)
SMC_{Tei}	saturation moisture content (g/kg) at zone temperature (°C)
t_{para}	surface transmittance parallel to plane of incidence (dimensionless)
t_{perp}	surface transmittance perpendicular to plane of incidence (dimensionless)
T_{air}	air dry bulb temperature (°C)
T_{ao}	external air temperature (K)
$T_{ceiling}$	ceiling surface temperature (°C)
T_{ei}	internal air temperature (K)
T_{eo}	external sol-air temperature (K)
T_{floor}	floor surface temperature (°C)
T_i	temperature of surface i (°C)
T^{MRT}	mean radiant temperature (°C)
T_{rear}	rear and side wall surface temperature (°C)
$T^{resultant}$	resultant air temperature (°C)
T_{so}	the external wall outer surface temperature (K)
T_{wall}	exterior wall inside surface temperature (°C)
T_{window}	window surface temperature (°C)
U_g	U-value (thermal insulation) of glass (W/m^{2}K)
v	wind speed (m/s)
V_{nat}	natural ventilation rate (m^3/s)
x	building partition thickness (m)
x_c	extinction coefficient for a material (m^{-1})
ZMC_{Tei}	zone moisture content (g/kg) at zone temperature (°C)

5.1 Introduction

For the purposes of the development of the fuzzy control strategies described in Chapters 8, 9 and 10, a dynamic computer model of the behaviour of the building fabric and internal environmental conditions for a building zone was required that exhibited characteristics similar to real buildings. The model developed was a single zone model representing a single office unit with a width of 10m, depth of 5m and height of 3m. One face of the zone was exposed to the external environment and contained a window, allowing solar radiation to enter the zone interior. The development of the model of the single building zone was carried out using Matlab and Simulink software.

This chapter is concerned with the development of the basic one zone model which takes account of the thermal properties of the construction materials, weather variables, occupancy gains from people and machinery and infiltration of external air. The model described in this chapter represents a free running building zone where there was no intervention in the form of heating and cooling, humidity control or mechanical ventilation. The development of the model to incorporate HVAC components is described in Chapter 6.

The "free running" one zone model was compared with results obtained for an identical one zone model from simulations with Thermal Analysis Software (Tas), a software tool which simulates the thermal performance of buildings. This provided a benchmark against which the simulink model could be tested and its performance compared.
This chapter first describes the Matlab and Simulink software used during the research project for modelling purposes. The theory of the one zone model developed using the Matlab and Simulink software is then described. Finally, the performance of the Simulink model is compared with results obtained from the Tas software to assess the suitability of the Simulink model for carrying the development of the fuzzy control strategies.

5.2 Matlab and Simulink Software

Matlab was chosen as the platform on which to develop the one zone building model. The name "Matlab" is short for "Matrix Laboratory". Matlab is a powerful mathematical tool which provides a technical computing environment for high performance numeric computation and visualisation. Matlab integrates numerical analysis, matrix computation, signal processing, and graphics in an easy to use environment where problems and solutions are expressed just as they are written mathematically without the need for traditional programming techniques. Matlab is an interactive system whose basic data element is a matrix that does not require dimensioning. Matlab provides the platform on which Simulink operates. Simulink is a software package which allows modular based program elements to be represented in a graphical format. Standard function libraries are provided with the software package which enables the user to construct system models graphically on the computer screen. Matlab also features a family of application specific solutions that are called "toolboxes". These are comprehensive collections of Matlab functions that extend the Matlab and Simulink environments to solve particular classes of problems. Toolboxes include those for neural networks, system identification, fuzzy logic and control. For the research project described in this thesis the "Fuzzy Logic Toolbox" was used and allowed the integration of fuzzy control strategies into the dynamic building model with reasonable ease. Figure 5.1 shows schematically the way in which Matlab, Simulink and the Fuzzy Logic Toolbox are integrated to operate in conjunction with each other. Matlab is a level 1 program and will operate in isolation of the level 2 programs. Simulink and the Fuzzy Logic Toolbox are level 2 programs and will not operate without the Matlab program. The Fuzzy Logic Toolbox can interface with Matlab directly or can interface with Matlab through Simulink.

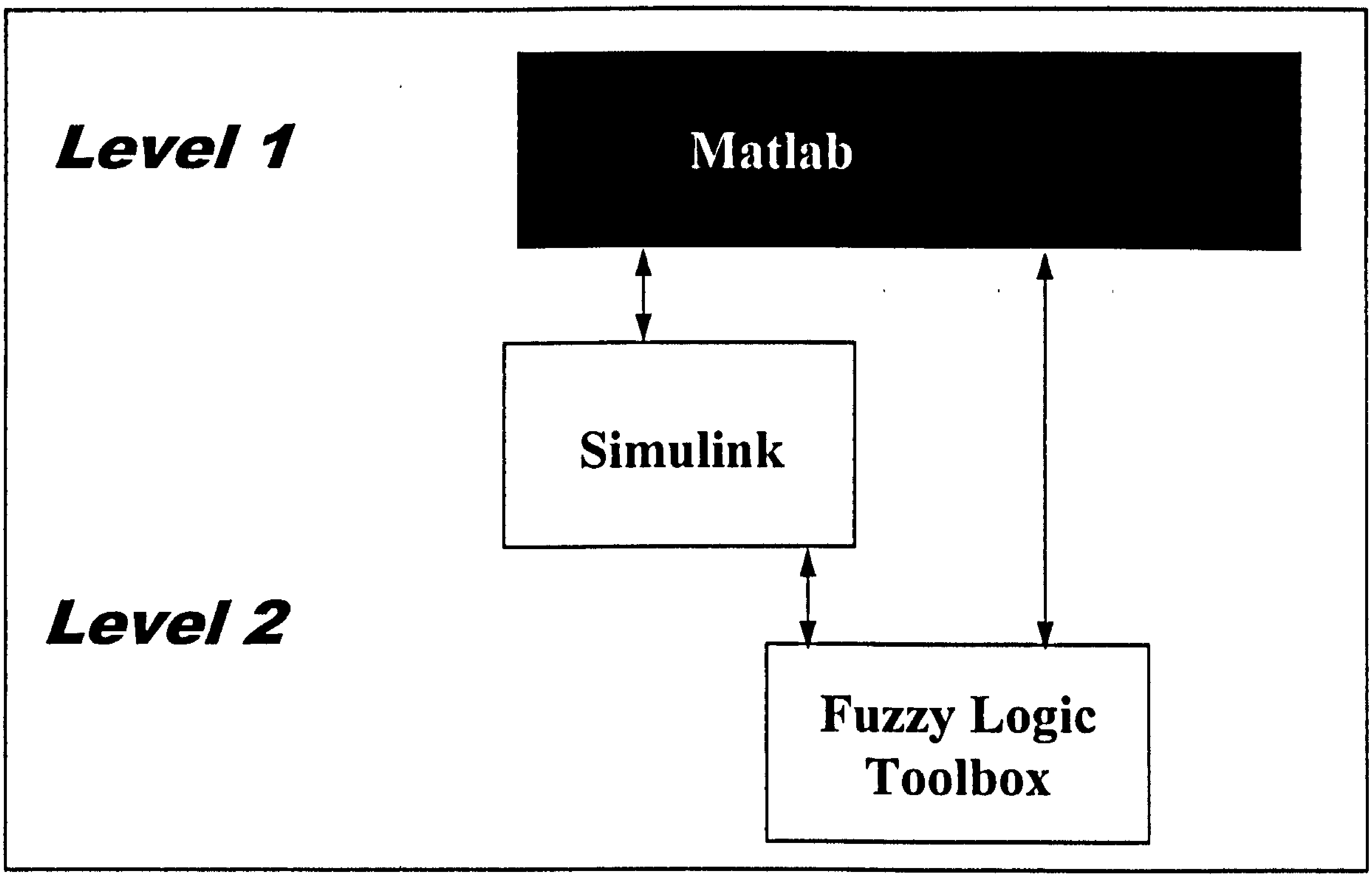

Figure 5.1. Schematic relationships between Matlab, Simulink and the Fuzzy Logic Toolbox.

To illustrate the manner in which Simulink uses graphical icons to build system models consider the Simulink representation of Equation 5.1 as shown in Figure 5.2 where t is the time in seconds.

$$y = 2t \times 3$$

Equation 5.1

The "clock" icon returns the system time. The simulation time step is set before simulations are commenced. If the simulation time step is set to 1 second and the simulation start time is set to zero in the example shown in Figure 5.2, the "clock" icon will return the values 1, 2, 3, 4, 5, 6, ... at each successive time step. The "clock" values will then be multiplied by 2 ("constant" and "inner product" icons) and multiplied by 3 ("gain" icon). For the "clock" values given, the values returned by the "gain" icon will be 3, 12, 18, 24, 30, 36 .... respectively. Icons such as the "clock" and "constant" functions are "sources" and have outputs only. Icons such as the "inner product" and "gain" carry out mathematical operations on the input(s) and return them as an output(s). The other two icons, i.e. "to workspace" and "auto-scale graph" icons, shown in Figure 5.2, are outputs. Output icons only receive values and store them in the Matlab workspace or show them graphically. The "to workspace" icon stores values in the Matlab workspace for later retrieval or manipulation. The "auto-scale graph" shows a graph during simulation that is automatically scaled for the y-axis input. Icons are joined by clicking on the output of an icon and dragging a line to the input of another icon. Multiple lines can be taken from the output of an icon. The simulink representation of a model allows systems to be quickly constructed and allows the logic of a system to be readily traced visually. Output icons can be attached to any line to allow the output at any part of the model to be logged or viewed during simulation.

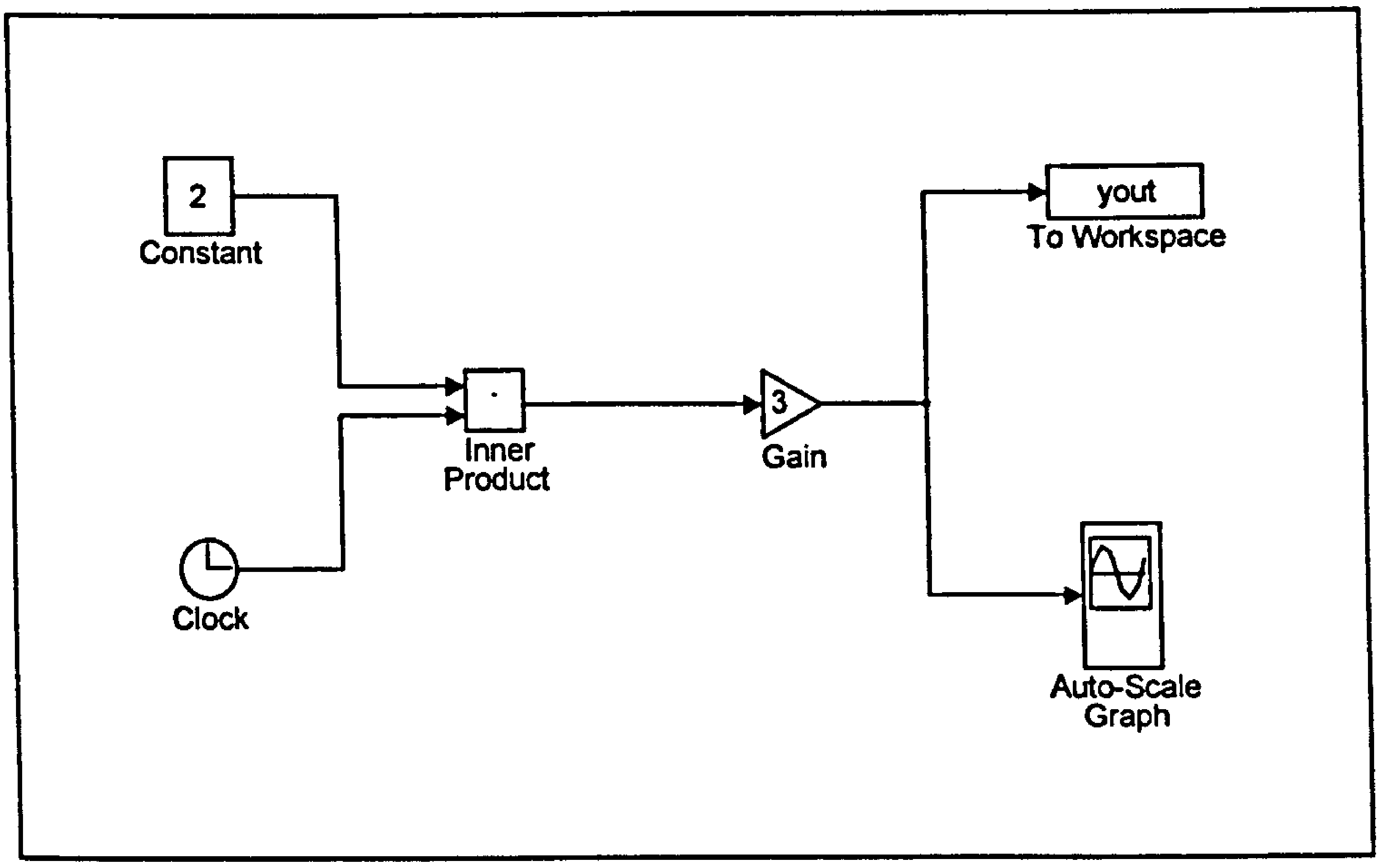

Figure 5.2. Graphical representation of Equation 5.1 as a simple Simulink model.

Simulink uses the Matlab program as its computational engine for performing simulations. Due to the complexity of the one zone model, Simulink provided a suitable development tool where bugs and problems could be easily traced graphically and fixed. The Matlab, Simulink and Fuzzy Logic Toolbox combined provided the required integrated software tool necessary to obtain the objectives of the research project. Further details on the operation of the software used for the research described in this thesis can be found in the Matlab User Guide (Math Works 1992a), the Simulink Users Guide (Math Works 1992b), and the Fuzzy Logic Toolbox Users Guide (Math Works 1995).

5.3 General One Zone Building Model Configuration

The one zone model is represented by a single cell within a building such as is common in repeated cellular office buildings, see Figure 5.3. It is assumed that all adjacent zone environmental conditions are identical to that of the zone being considered during simulation. Therefore the internal walls, ceiling and floor are adiabatic about their mid-planes. The external wall is subjected to varying external air temperatures, solar gains, and wind speeds due to dynamic ambient weather conditions . Internal surfaces are subject to dynamic solar gains due to the presence of the window in the external wall which allows solar radiation to enter the zone.

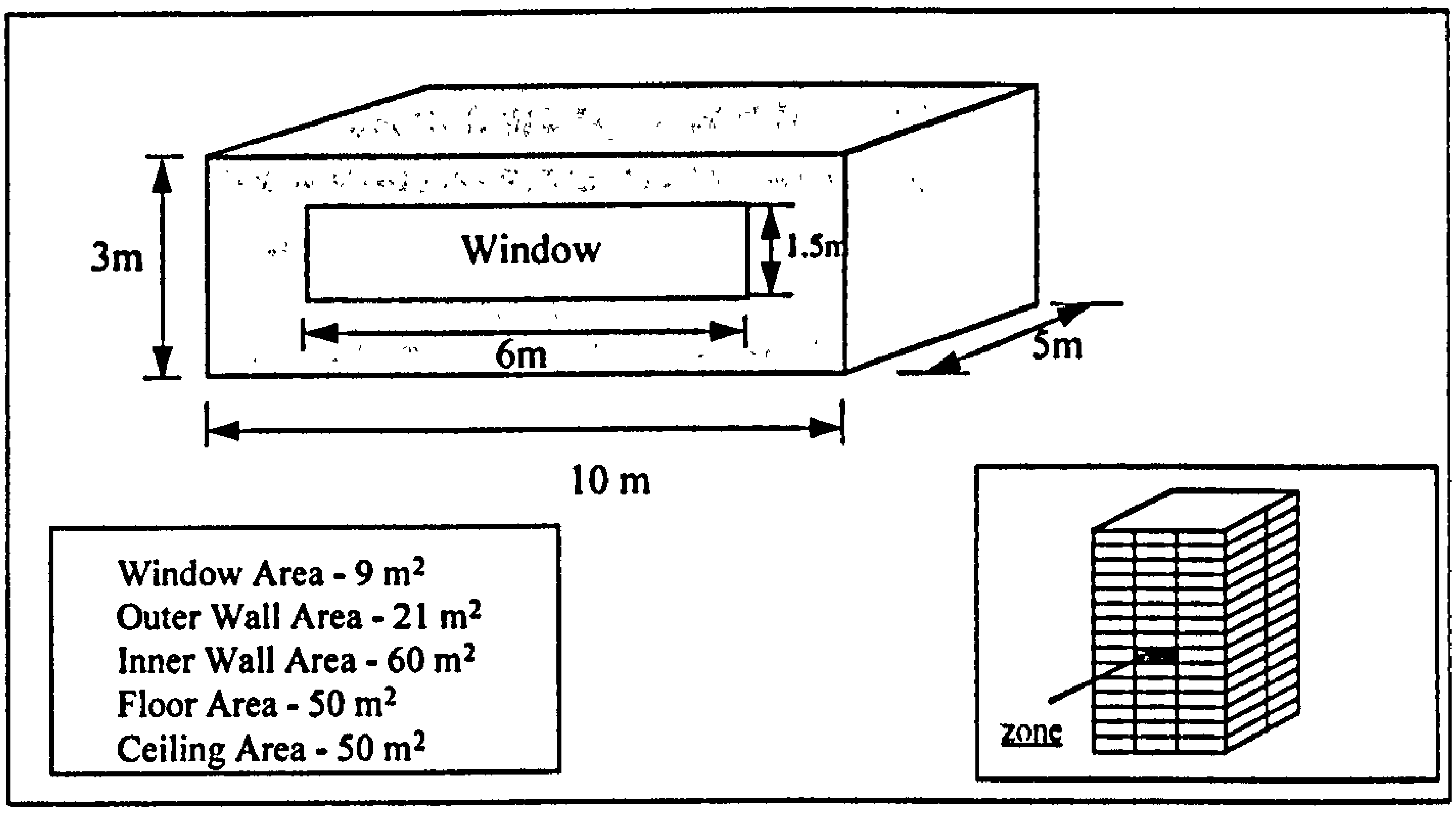

Figure 5.3. Schematic of the building cell for the one zone dynamic model.

For the purposes of simulation the temperature, humidity and carbon dioxide distributions are assumed to be uniform throughout the zone. However, time delays were introduced with regard to the sensor measurements to simulate the time delay associated with environmental parameter measurement.

Hourly weather data files from Thermal Analysis Software (Tas) (EDSL not dated) were used as the source for external environmental conditions, i.e. temperature, humidity, wind speed and solar radiation. This allowed a benchmark assessment of the Simulink model performance against a fully developed, commercially available software package. The dynamic model created using Matlab and Simulink described in this chapter calculates the internal environmental conditions as a result of the external environmental parameter variation and interaction with the building components for a free running building. This chapter does not consider the HVAC components or their control. However, Figure 5.4 shows the schematic of the zone and HVAC plant arrangement for the one zone model for clarity. The HVAC model components and the controls components are considered in Chapter 6.

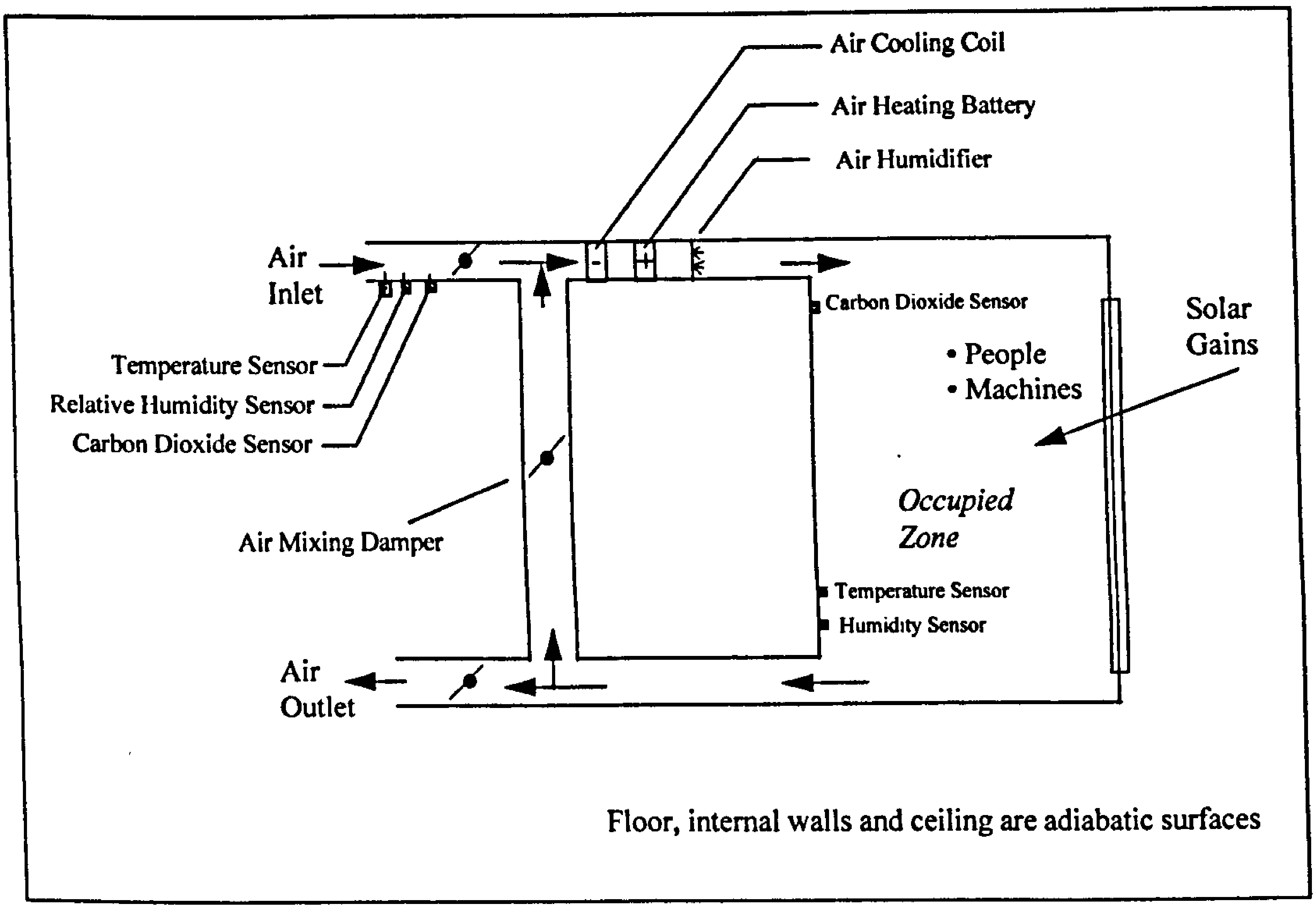

Figure 5.4. Schematic of the Simulink one zone model including HVAC plant components.

5.4 Parameters Effecting Zone Environmental Conditions

For the purposes of the research project these were divided into three categories. Each category is listed below along with influences on its value.

Temperature

- HVAC (energy input to zone from plant)
- People (number of, heat production of)
- Equipment (number of, heat production of)
- Solar Gains (radiation entering through window, conduction through external wall)
- Natural Infiltration (energy content of fresh air entering the zone)

Relative Humidity

- HVAC (moisture exchange to zone from the building services plant)
- People (number of, moisture production of)
- Natural Infiltration (moisture content of external air entering zone)

Carbon Dioxide

- HVAC (CO_2 exchange between internal and external air due to building services plant operation)
- People (number of, CO_2 production of)
- Natural Infiltration (CO_2 exchange between internal and external air)

5.5 General Building One Zone Dynamic Model Theory

The one zone model developed using Matlab software essentially adopts an energy, moisture content and carbon dioxide concentration balance methodology, see Figure 5.5.

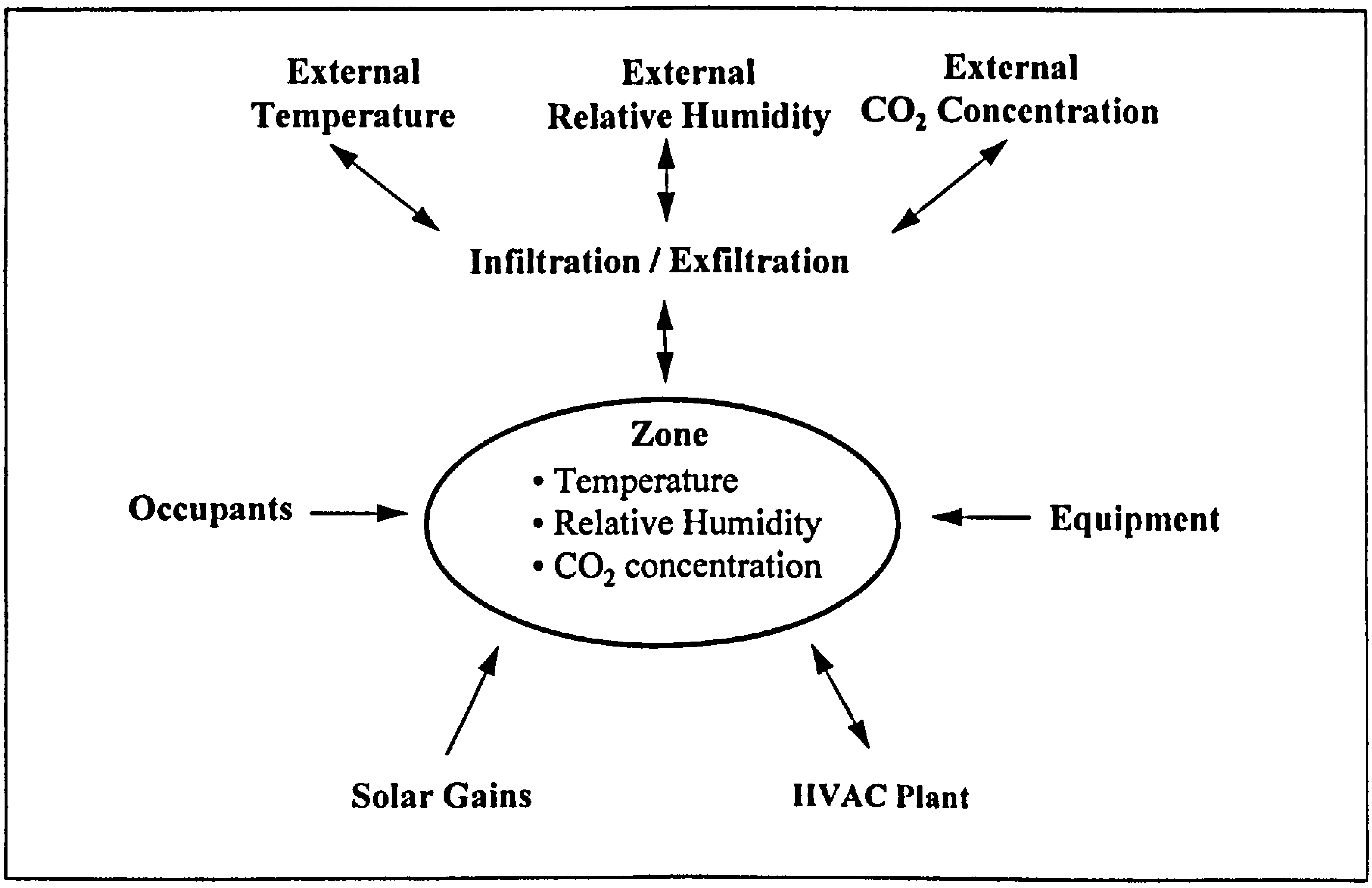

Figure 5.5. Schematic of the energy, moisture and CO_2 concentration balance methodology adopted by the Simulink one zone model.

It was assumed that fresh and recirculated air mixes adiabatically for the purposes of the model. It is also assumed that internal walls were structurally symmetrical, homogeneous and adiabatic about their mid-plane. This assumption allowed the thermal storage capacity of the wall half-thickness to be linked to the convective and radiative exchanges within the zone.

The thermal interaction of the zone with the external environment using these assumptions is shown diagrammatically in Figure 5.6.

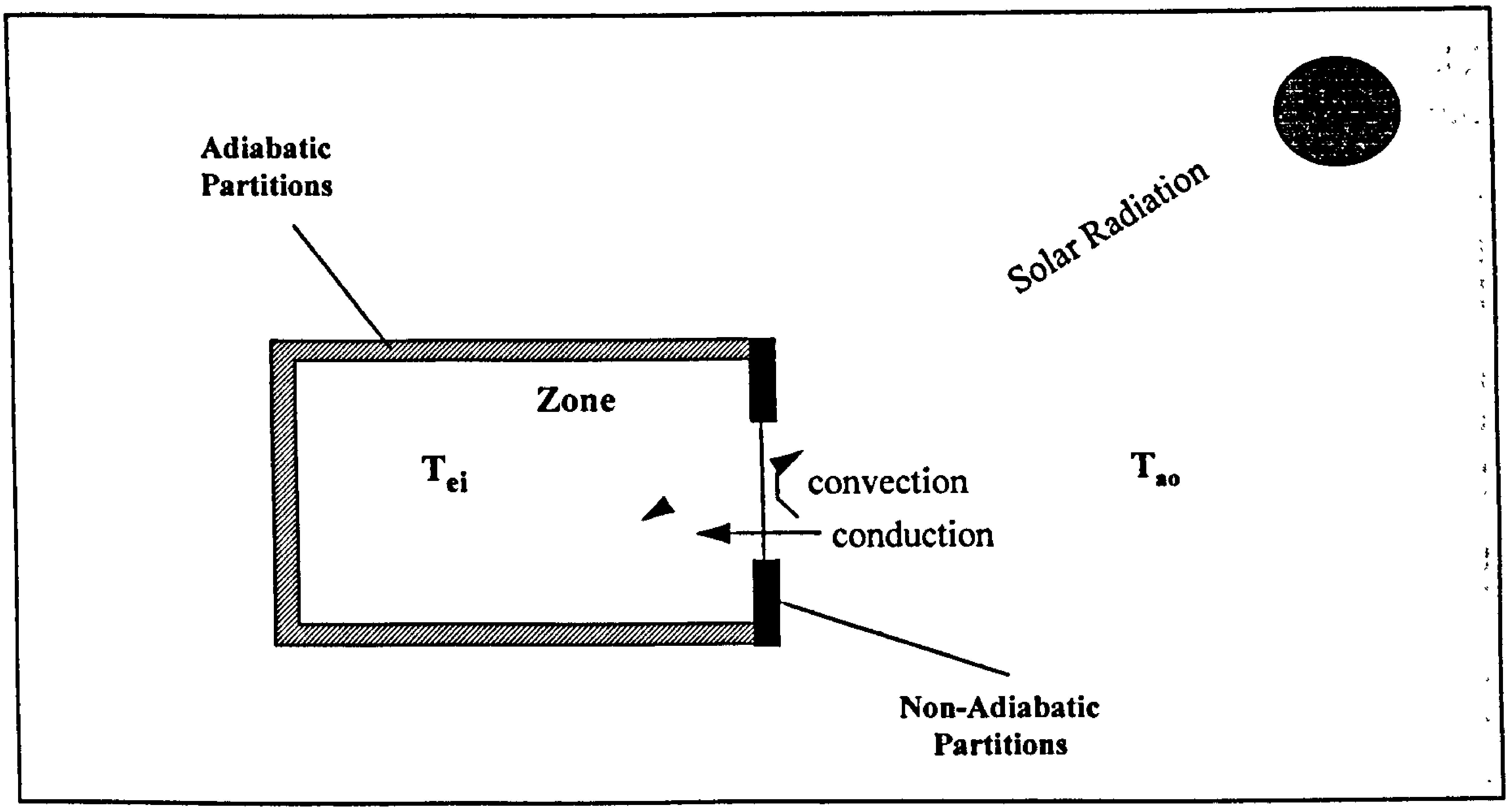

Figure 5.6. Thermal interaction of the Simulink one zone model with the external environment.

5.6 One Zone Dynamic Model Theory

The previous sections gave an introduction to the simulation software used and the general set up of the one zone dynamic model. The following sections give a detailed description of the Simulink simulation model theory.

5.6.1 Solar Gains

Available weather data for hourly averaged values of "Total" and "Diffuse" solar radiation on a horizontal surface was obtainable directly from Tas weather data files (EDSL not dated). The "beam" or "direct" radiation is calculated as the difference between the total and diffuse radiation, see Equation 5.2.

$$I_{Hdirect} = I_{Htotal} - I_{Hdiffuse}$$

Equation 5.2

However, values of solar radiation on a horizontal plane in their raw form are of limited use, especially with regard to the direct radiation, as values are needed for surfaces other than horizontal. With respect to the one zone model, solar radiation incident on the vertical plane is required to calculate the solar flux on external walls and solar radiation entering the zone through the window area. The first step involved in calculating these values was the determination of the solar angles between the building surface under consideration and the sun.

5.6.1.1 Definition of Solar Angles

To calculate the value of direct radiation on a surface the angle between the surface under consideration and the sun was required. A relationship exists between the global location of a building, the orientation of a building surface, the angular position of the sun and the time of the day. The values of the solar angles, as defined in Figure 5.7, were required in order to ascertain the angle of incidence of direct radiation on the surface of a building. The horizontal solar direct radiation component can then be resolved for the radiation incident upon the inclined or vertical surface.

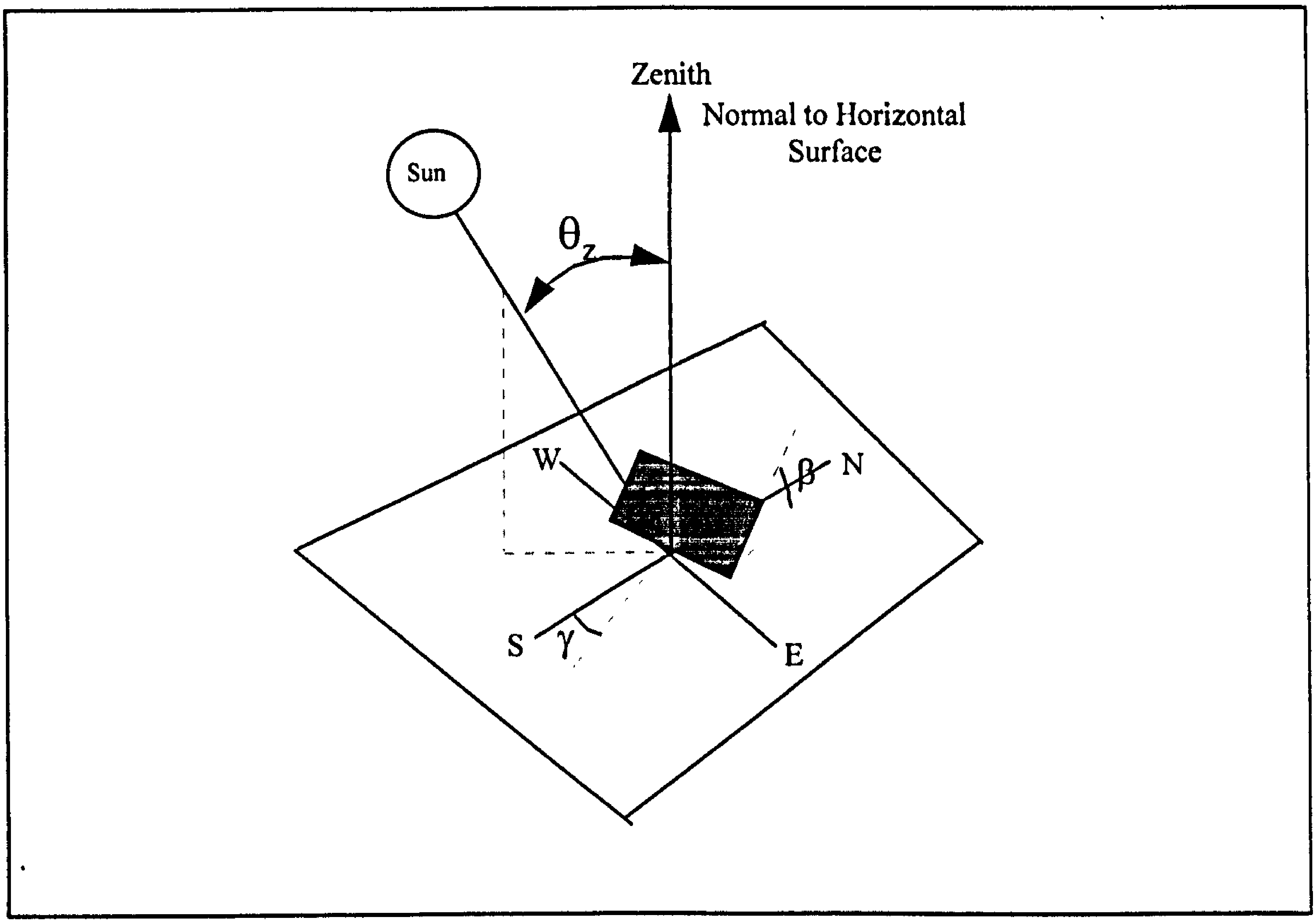

Figure 5.7. Definition of solar angles between an inclined surface and the sun.

Detailed descriptions of the solar angles and related definitions shown diagrammatically in Figure 5.7 are given:-

Latitude (ϕ) - the angular location of the building on the Earth's surface. North is positive (+ve) and South is negative (-ve) in relation to the Equator, $-90^\circ \leq \phi \leq 90^\circ$ (Duffie and Beckman 1980). For the purposes of the model Kew, London is used as the location of the building, $\phi = 51.7^\circ$.

Declination Angle (δ) - the angular position of the sun at solar noon with respect to the plane of the equator, North positive, $-23.45^\circ \leq \delta \leq 23.45^\circ$. The declination angle is defined by Equation 5.3 (Duffie and Beckman 1980).

$$\delta = 23.45 \sin\left[360\left(\frac{284 + n_d}{365}\right)\right]$$

Equation 5.3

<u>Surface Slope (β)</u> - the angle between the plane surface and the horizontal, $0 \leq \beta \leq 180^\circ$. For vertical surfaces $\beta = 90^\circ$ (Duffie and Beckman 1980).

<u>Surface Azimuth Angle (γ)</u> - the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian. South (zero), East (negative), West (positive), $-180^\circ \leq \gamma \leq 180^\circ$ (Duffie and Beckman 1980). In simple terms this describes the direction in which a surface faces. For example, a south facing wall has a surface azimuth angle (γ) of 0°.

<u>Hour Angle (ω)</u> - the angular displacement of the sun East or West of the local meridian due to the rotation of the Earth on its axis at 15° per hour, morning negative, afternoon positive (Duffie and Beckman 1980).

<u>Angle of Incidence (θ)</u> - the angle between direct radiation on a surface and the normal to that surface (Duffie and Beckman 1980).

<u>Zenith Angle (θ_z)</u> - the angle between direct radiation and the normal to a horizontal surface.

The angle of incidence (θ) is related to the other angles by the Equation 5.4 (Duffie and Beckman 1980).

$$\cos(\theta) = \sin(\delta)\sin(\phi)\cos(\beta) - \sin(\delta)\cos(\phi)\sin(\beta)\cos(\gamma) + \cos(\delta)\cos(\phi)\cos(\beta)\cos(\omega) + \cos(\delta)\sin(\phi)\sin(\beta)\cos(\gamma)\cos(\omega) + \cos(\delta)\sin(\beta)\sin(\gamma)\sin(\omega)$$

Equation 5.4

For vertical surfaces facing due south, ($\beta = 90^\circ$ and $\gamma = 0^\circ$) Equation 5.4 reduces to Equation 5.5.

$$\cos(\theta) = -\sin(\delta)\cos(\phi) + \cos(\delta)\sin(\phi)\cos(\omega)$$

Equation 5.5

Equation 5.5 can also be written as Equation 5.6.

$$\cos(\theta) = \cos(\phi-\beta)\cos(\delta)\cos(\omega) + \sin(\phi-\beta)\sin(\delta)$$

Equation 5.6

The zenith angle for horizontal surfaces, see Equation 5.7, is obtained by using Equation 5.4 and setting the surface slope angle to zero, i.e. $\beta = 0^{\circ}$.

$$\cos(\theta_z) = \sin(\delta)\sin(\phi) + \cos(\delta)\cos(\phi)\cos(\omega)$$

Equation 5.7

The angular relationships between vertical and horizontal surfaces is shown diagrammatically in Figure 5.8.

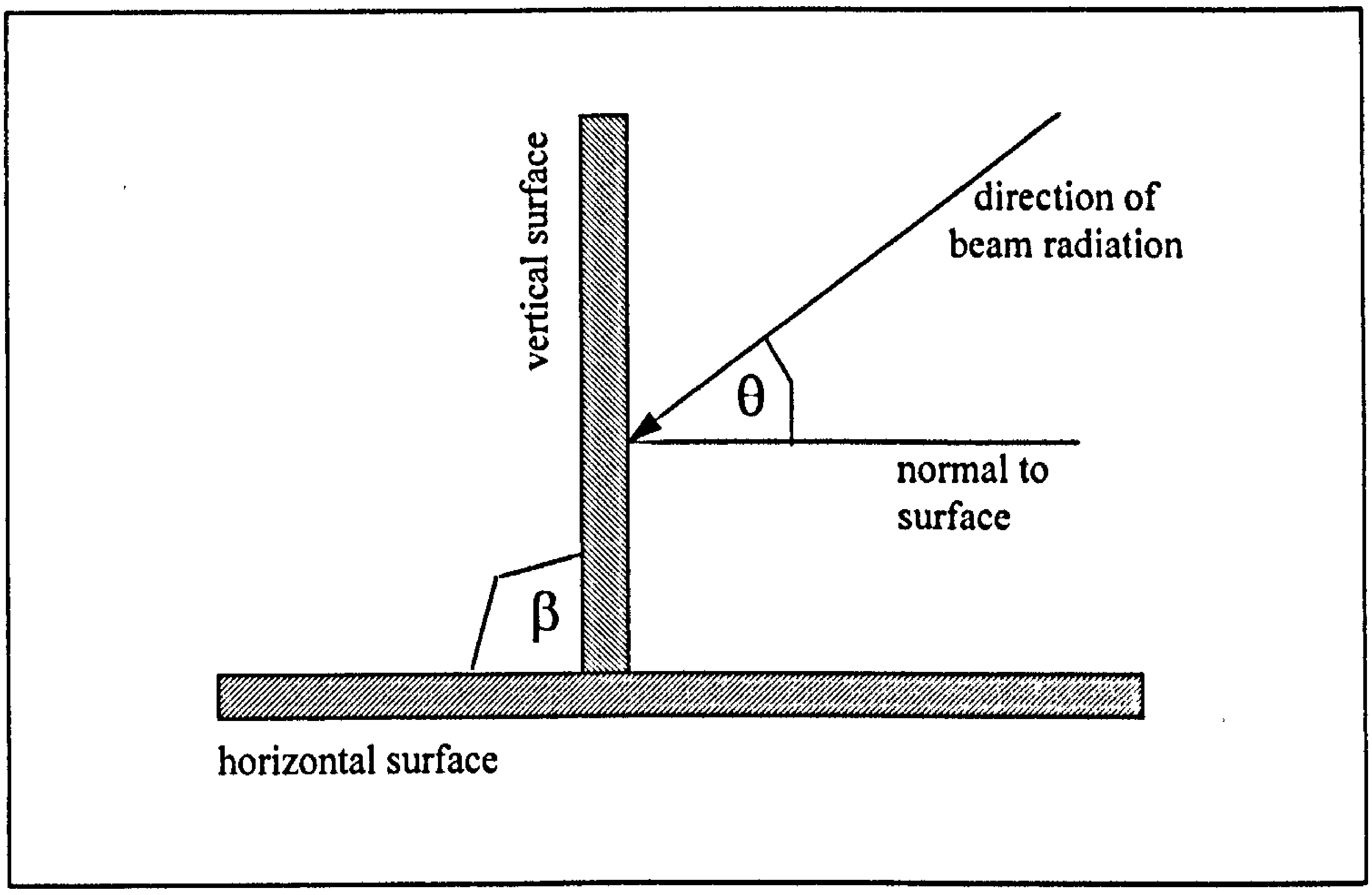

Figure 5.8. Relationship of angles for horizontal and vertical surfaces.

Once the angle between a surface and the sun has been calculated the value of the direct radiation can be calculated.

5.6.1.2 Direct (Beam) Radiation on an Inclined Surface

This is calculated from the value of the ratio of direct radiation incident on a tilted surface to that on a horizontal surface (R_b) which is calculated from $\cos(\theta)$ and $\cos(\theta_z)$, see Equation 5.8.

$$R_b = \frac{\cos(\theta)}{\cos(\theta_z)}$$

Equation 5.8

The direct radiation incident on an inclined surface is given by Equation 5.9.

$$I_{Idirect} = I_{Hdirect} \times R_b$$

Equation 5.9

5.6.1.3 Diffuse Radiation on an Inclined Surface

The diffuse component is assumed to be isotropically distributed and can be calculated for an inclined surface using Equation 5.10.

$$I_{Idiffuse} = I_{Hdiffuse} \cos^2(\beta)$$

Equation 5.10

5.6.1.4 Ground Reflected Radiation

This is a function of surface tilt, the diffuse radiation incident on a horizontal surface and the ground reflectance. The value of the ground reflected radiation incident on an inclined surface was calculated using Equation 5.11.

$$I_{Igref} = \rho_g \, I_{Htotal} \sin^2(\beta/2)$$

Equation 5.11

The ground reflectance, ρ_g, typically has a value of 0.2 for soil.

5.6.1.5 Total Radiation Incident on an Inclined Surface

On a cloudy day the total radiation incident on an inclined surface can be calculated using Equation 5.12.

$$I_{Itotal} = I_{Igref} + I_{Hdiffuse} + R_b I_{Hdirect}$$

Equation 5.12

For a clear day the total radiation incident on an inclined surface is calculated using Equation 5.13.

$$I_{Itotal} = I_{Igref} + R_b(I_{Hdiffuse} + I_{Hdirect})$$

Equation 5.13

For the purposes of the Simulink model developed it was assumed that it was a cloudy day and the radiation is isotropically distributed. Hence, Equation 5.12 was used for all simulations.

5.6.1.6 Solar Radiation Transmission Through Glass

For vertical surfaces the equivalent angle of incidence for diffuse and ground reflected radiation is 60° (Duffie and Beckman 1980). For radiation incident at 60° the transmittance through glass is equal to 50% of the total. Applying this value allows diffuse and ground reflected radiation to be treated as direct radiation.

Transmission of direct radiation through glass is dependent on the angle of incidence of the radiation with the glass surface. Figure 5.9 shows a schematic of the path of direct (Beam) radiation through a sheet of glass and the associated nomenclature for the angles.

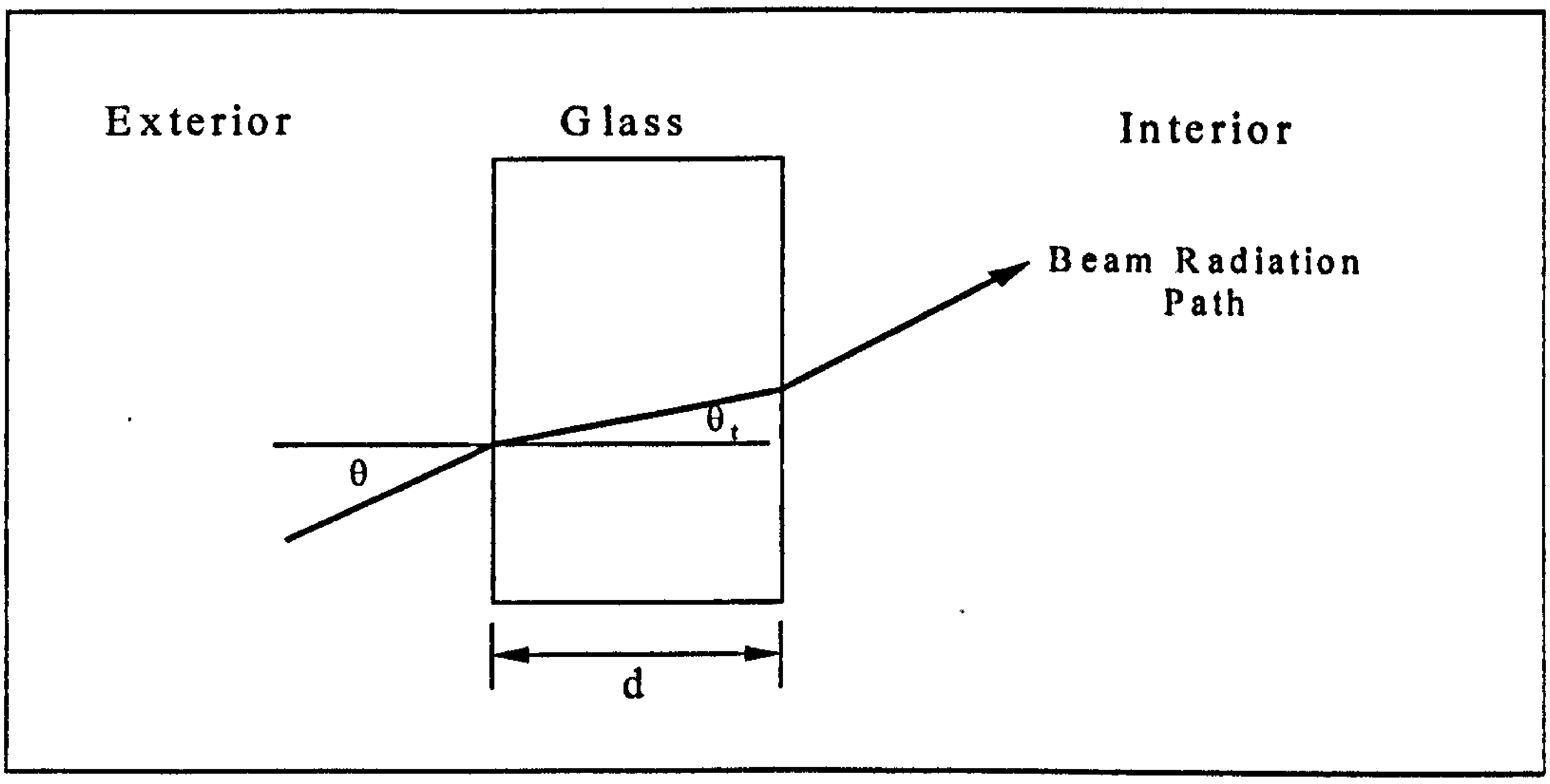

Figure 5.9. Schematic for transmission of direct solar radiation through a single layer glass construction.

The relationship between the angles is described by Snells Law, see Equation 5.14.

$$\sin(\theta_t) = \frac{\sin(\theta)}{n}$$

Equation 5.14

The transmittance for each of the two surfaces is given by the Fresnel equations for polarisation perpendicular and parallel to the plane of incidence using Equation 5.15 to define the ratio of the transmission angle to the angle of incidence, see Equation 5.16 and Equation 5.17 (EDSL not dated).

$$c(\theta) = \frac{\cos(\theta_t)}{\cos(\theta)}$$

Equation 5.15

$$t_{perp} = \frac{4n.c(\theta)}{(1+n.c(\theta))^2}$$

Equation 5.16

$$t_{para} = \frac{4n.c(\theta)}{(n + c(\theta))^2}$$

Equation 5.17

If the layer is absorbing, the factor by which the ray is attenuated on passing through is described by Equation 5.18.

$$b(\theta) = \exp\left(\frac{-x_c d}{\cos(\theta_t)}\right)$$

Equation 5.18

By setting θ to zero, i.e. normal incidence, and rearranging Equation 5.18 the result is given by Equation 5.19. The "o" subscript in Equation 5.19 to Equation 5.22 denotes evaluation at θ = 0.

$$b(0) = b_o^{\frac{1}{\cos(\theta_t)}}$$

Equation 5.19

To calculate b_o Equation 5.20, Equation 5.21 and Equation 5.22 were used for the dynamic one zone model.

$$b_o \cong \left(\frac{\tau_o}{\tau_o^2}\right)\left(1 - \frac{\tau_o r_o^2}{t_o^4} + \frac{2\tau_o^4 r_o^4}{t_o^8}\right)$$

Equation 5.20

where

$$t_o = \frac{4n}{(n + 1)^2}$$

Equation 5.21

$$r_o = 1 - t_o$$

Equation 5.22

Analysis of an infinite number of internal reflections (EDSL not dated) shows that the transmittance of the complete layer, for the two polarisations, are given by Equation 5.21 and Equation 5.22, and the use of Equation 5.23 and Equation 5.24.

$$\tau_{perp} = \frac{bt_{perp}^2}{(1 - r_{perp}^2 b^2)}$$

Equation 5.23

$$\tau_{para} = \frac{bt_{para}^2}{(1 - r_{para}^2 b^2)}$$

Equation 5.24

where

$r_{perp} = 1 - t_{perp}$

Equation 5.25

$r_{para} = 1 - t_{para}$

Equation 5.26

The transmittance of the layer for randomly polarised radiation is found by averaging the two polarisations, see Equation 5.27.

$$\tau(\theta) = \frac{\tau_{perp}(\theta) + \tau_{para}(\theta)}{2}$$

Equation 5.27

The model assumes that the direct and diffuse solar radiation which passes through the glazing is distributed over the interior surfaces of the zone on an area weighted basis. It is also assumed that 88% of the energy is absorbed by the walls and 12% is reflected back out of the window (EDSL not dated).

5.6.2 Zone Fabric Temperatures and Energy Storage

It was necessary to calculate fabric surface temperatures, i.e. walls, floor and ceiling, in order to calculate the convective heat transfer a) to the zone from the internal surfaces, and b) to external environment from the exterior surface of the exterior wall.

The temperatures within partitions are also required to calculate the conductive heat transfer through the materials making up the zone enclosure as well as their thermal storage characteristics. The thermal mass of the materials introduces time delays in the thermal response of the zone conditions to varying weather conditions and other influences on the zone such as building services. Thermal storage characteristics of the zone structure were implemented within the Simulink model using an explicit finite difference method (Incropera and de Witt 1990).

The assumptions made during these calculations were:-

- one dimensional heat transfer
- transient heat transfer
- constant material properties
- homogenous material

5.6.2.1 Exterior Wall - Fabric Temperatures and Energy Storage

The exterior wall was modelled by dividing the wall into four sections, through the vertical plane, of equal width with five nodes as shown in Figure 5.10.

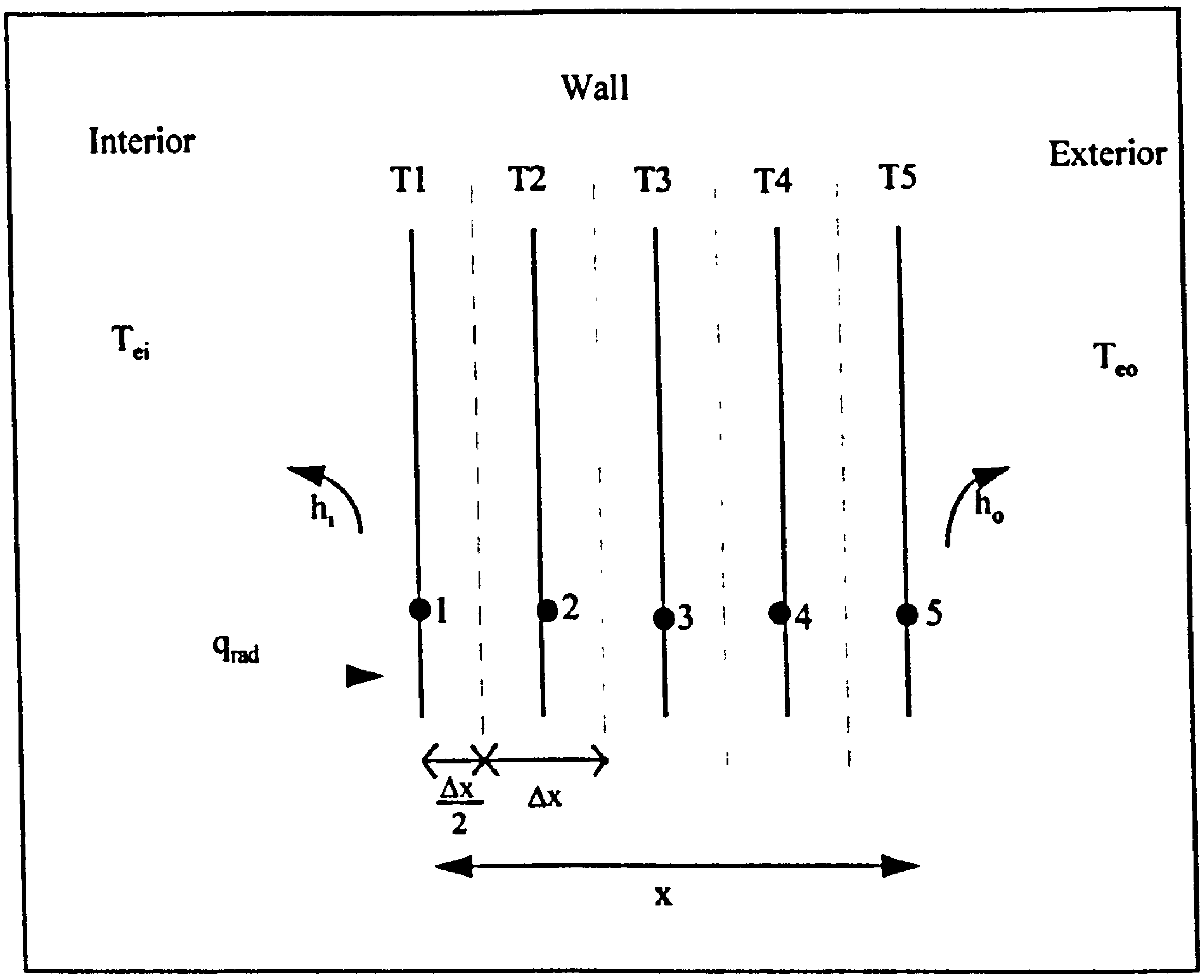

Figure 5.10. Schematic of the explicit finite difference model used for the exterior wall.

The explicit finite difference model uses a set of equations which are solved simultaneously and updated at each time step as required by the Simulink model. To simplify the final equations, the Biot Number (Bi), Thermal Diffusivity (Alpha) and Fourier Number (F_o) are defined by Equation 5.28, Equation 5.29 and Equation 5.30 respectively.

$$Bi = \frac{h\Delta x}{k} = \frac{\Delta x}{R_s k} \quad \text{(Biot Number)}$$

Equation 5.28

$$\alpha = \frac{k}{\rho c_p} \quad \text{(Alpha)}$$

Equation 5.29

$$F_o = \frac{\alpha \Delta t}{\Delta x^2} \quad \text{(Fourier Number)}$$

Equation 5.30

The explicit finite difference method uses an energy balance method to calculate the nodal equations which describe the characteristics of the wall.
The nodal equations for Figure 5.10 are given by Equation 5.31 to Equation 5.35.

Node 1 $2F_o(Bi_iT_{ei} + T_2^p + q_{rad}\Delta x/k) + T_1^p(1 - 2FoBi_i - 2F_o) = T_1^{p+1}$

Equation 5.31

Node 2 $F_o(T_1^p + T_3^p) + (1 - 2F_o)T_2^p = T_2^{p+1}$

Equation 5.32

Node 3 $F_o(T_2^p + T_4^p) + (1 - 2F_o)T_3^p = T_3^{p+1}$

Equation 5.33

Node 4 $F_o(T_3^p + T_5^p) + (1 - 2F_o)T_4^p = T_4^{p+1}$

Equation 5.34

Node 5 $2F_o(Bi_oT_{eo} + T_4^p) + T_5^p(1 - 2F_oBi_o - 2F_o) = T_5^{p+1}$

Equation 5.35

where
^{p} = previous time step
$^{p+1}$ = current time step

The remaining terms in the nodal equations not so far defined are given by Equation 5.36 and Equation 5.37.

$$T_{eo} = (\alpha I_{Itotal} - \varepsilon I_L)R_{so} + T_{ao}$$

Equation 5.36

$$I_L = 21 - 17C$$

Equation 5.37

The external surface resistance is calculated using Equation 5.38.

$$R_{so} = \frac{1}{\varepsilon h_{ro} + h_o}$$

Equation 5.38

The terms used in Equation 5.38 are defined by Equation 5.39 and Equation 5.40.

$$h_o = 5.8 + 4.1v$$

Equation 5.39

$$h_{ro} = 4\sigma T_{so}^3$$

Equation 5.40

For the external wall, T_{so} in Equation 5.40 is defined by T_5 in Figure 5.10.

For vertical surfaces the internal surface convective heat transfer coefficient is defined by Equation 5.41 and Equation 5.42.

$$h_i = h^H + 1.23(T_4 - T_{ei})^{1/3}$$

Equation 5.41

$$h^H = (670.656H^6 + 120.43H^{8.7})^{-1/6}$$

Equation 5.42

The internal heat transfer coefficient defined by Equation 5.41 can be expressed as a surface resistance using Equation 5.43.

$$R_{si} = \frac{1}{h_i}$$

Equation 5.43

The heat transfer from the internal surface of the external wall to the zone is defined by Equation 5.44.

$$q_{int} = \frac{(T_1 - T_{ei})}{R_{si}}$$

Equation 5.44

Equation 5.44 can be redefined using the internal convective heat transfer coefficient as Equation 5.45.

$$q_{int} = h_i(T_1 - T_{ei})$$

Equation 5.45

For the purposes of the Simulink model, the heat transfer rate (q_{int}), defined by Equation 5.45, represents the required value of the energy transfer rate to the internal zone air from the external wall.

5.6.2.2 Internal Walls, Floors and Ceilings - Fabric Temperatures and Energy Storage

Surface and internal material temperatures of internal partitions, i.e. walls, floor and ceiling, are calculated using the explicit finite difference method with three sections and four nodes, see Figure 5.11.

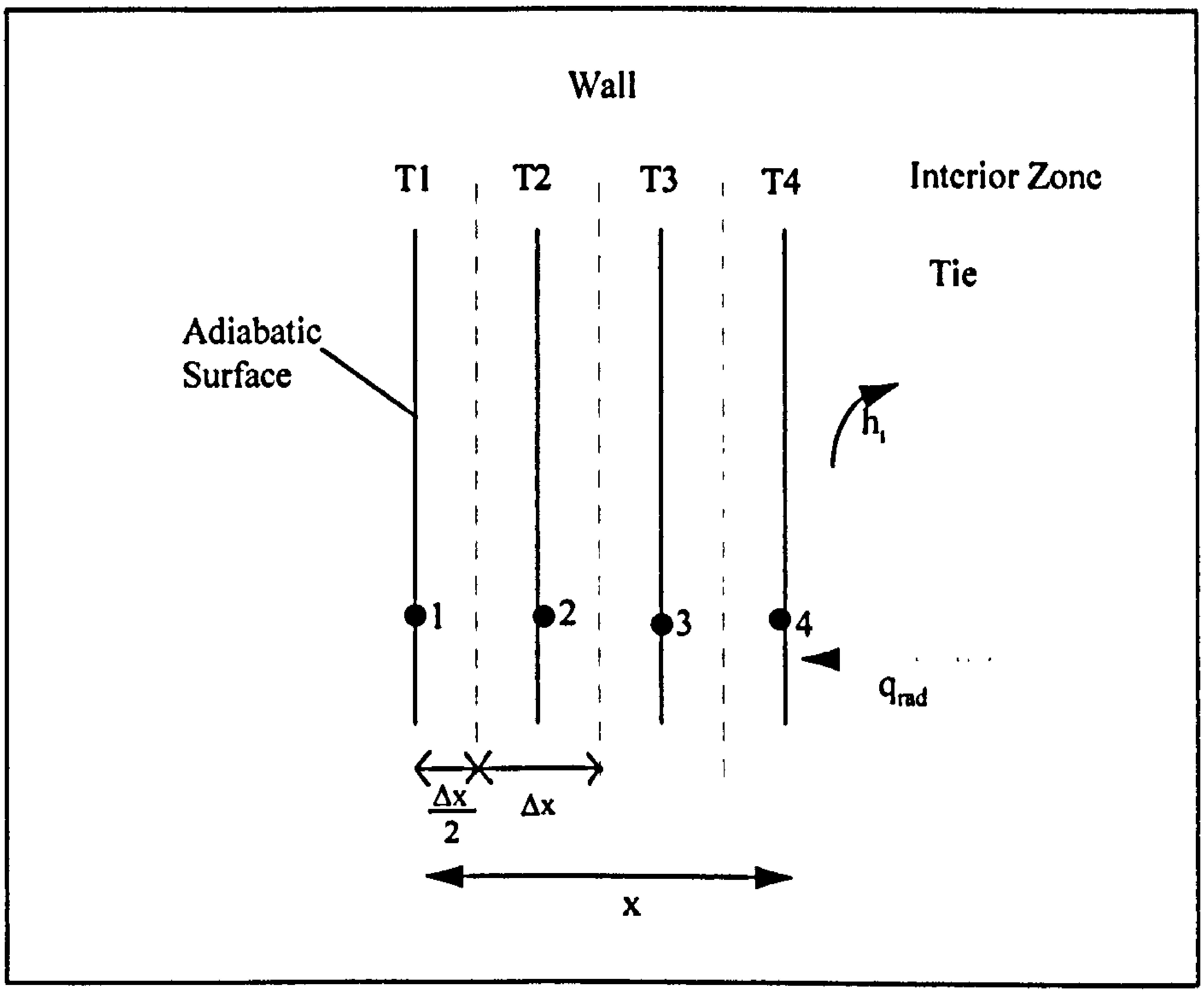

Figure 5.11. Explicit finite difference model for internal walls, ceiling and floor.

The Biot Number, Alpha and the Fourier Number are defined by Equation 5.28, Equation 5.29 and Equation 5.30 respectively as for the external walls.

The nodal equations are defined by Equation 5.46 to Equation 5.49.

Node 1: $2F_o(T_2^p + T_1^p) + T_1 = T_1^{p+1}$

Equation 5.46

Node 2: $F_o(T_1^p + T_3^p) + (1 - 2F_o)T_2^p = T_2^{p+1}$

Equation 5.47

Node 3: $F_o(T_2^p + T_4^p) + (1 - 2F_o)T_3^p = T_3^{p+1}$

Equation 5.48

Node 4: $2F_o(Bi_iT_{ei} + T_3^p + q\Delta x/k) + T_4^p(1 - 2FoBi_i - 2F_o) = T_4^{p+1}$

Equation 5.49

For vertical surfaces, i.e. the internal walls, the convective heat transfer coefficient is described by Equation 5.50 and Equation 5.51 (EDSL not dated).

$$h_i = h^H + 1.23(T_4 - T_{ei})^{1/3}$$

Equation 5.50

where

$$h^H = (670.656H^6 + 120.43H^{8.7})^{-1/6}$$

Equation 5.51

For horizontal surfaces with a downward heat flow, i.e. the ceiling, the convective heat transfer coefficient is described by Equation 5.52.

$$h_i = 0.6((T_4 - T_{ei})/H^2)^{1/5}$$

Equation 5.52

For horizontal surfaces with an upward heat flow, i.e. the floor, the convective heat transfer coefficient is described by Equation 5.53.

$$h_i = 1.63(T_4 - T_{ei})^{1/3}$$

Equation 5.53

The heat transfer from the internal surfaces to the zone is described by Equation 5.54.

$$q_{int} = \frac{(T_4 - T_{ei})}{R_{si}}$$

Equation 5.54

Equation 5.54 can be redefined using the internal convective heat transfer coefficient as Equation 5.55.

$$q_{int} = h_i(T_4 - T_{ei})$$

Equation 5.55

For the purposes of the simulink model, the heat transfer rate (q_{int}), defined by Equation 5.55, represents the required value of the energy transfer rate to the internal zone air from internal surfaces.

5.6.3 Zone Temperature

The Simulink model uses an energy balance method to determine the zone temperature. The model calculates the quantity of energy added or removed from the zone air at each time step. This change in energy content of the zone air is added to or subtracted from the total energy content of the zone and stored in an integration function within the model. With knowledge of the specific heat capacity of the air, the temperature is calculated and made available to other parts of the model by means of a conversion factor.

For each Joule of energy added to or removed from the zone air, there will be a corresponding dry bulb temperature change. The model used J/m^3 as the unit of energy content for air. The temperature change of the air for each joule of energy added to or subtracted from the volume of 150 m^3 was calculated in the model using the following conversion factors.

$\rho_{air} = 1.21$ kg/m^3, $Cp_{air} = 1012$ J/kgK

therefore
$C_{pair} = 1224.52$ J/m^{3}K

For a room volume of 150 m^3, i.e. 10m x 5m x 3m.

$$\text{Temperature change per Joule} = \frac{1}{1224.52 \times 150} \text{ (K/J)}$$

$$= 5.44310151 \times 10^{-6} \text{ (K/J)}$$

Various sources add or remove energy to or from the zone air. Those used in the Simulink model are described below.

5.6.3.1 Glass Conductive Heat Transfer

Glass has a very small capacitance. The heat transfer across the glass was therefore treated as a function of the temperature difference between the zone and outdoor environments. A U-value relationship was then used as an approximation to calculate the glass conductive heat transfer, see Equation 5.56.

$$Q_{glass} = U_g A_g (T_{ao} - T_{ei})$$

Equation 5.56

Other relevant properties of the glass obtained from Tas (EDSL not dated) that were used by the model are listed in Table 5.1.

Light	
Transmittance	0.797
Solar Radiant Heat	
Direct Transmittance	0.676
Reflectance	0.117
Absorbtance	0.207
Total Transmittance	0.755

Table 5.1. Glass properties for light and solar radiant heat.

5.6.3.2 Lighting

A value of 10 W/m^2 was used as a representative value for office buildings when lights are on. These were considered as totally sensible gains to the zone. Property assumptions are defined in Table 5.2.

Radiant proportion	0.48 of total lighting gain
Convective Proportion	0.52 of total lighting gain
View Coefficient	0.49

Table 5.2. Lighting property assumptions made for the Simulink model.

5.6.3.3 Equipment

Equipment includes office machines such as computers and photocopiers. A value of 10 W/m^2 was used as a representative value for office buildings. These were considered as totally sensible gains to the zone. Property assumptions are defined in Table 5.3.

Radiant Proportion	0.1 of total equipment gain
Convective Proportion	0.9 of total equipment gain
View Coefficient	0.372
Diversity	0.75

Table 5.3. Equipment property assumptions made for the Simulink model.

5.6.3.4 Occupants

Occupants of a building represent an energy source due to metabolic activity. The value of an occupants' metabolic output varies depending on activity. For the purposes of the model it was assumed that the occupants were adults and they were carrying out light, mainly sedentary activities. 140 W/m^2 has been used as representative value for sedentary adult occupants in an office type building. The gains have been considered as having a sensible and latent proportion, see Table 5.4.

Sensible Gain	90 W/person
Latent Gain	50 W/person
Convective Proportion	0.8 of sensible gain
Radiative Proportion	0.2 of sensible gain
View Coefficient	0.227

Table 5.4. Properties for adult occupant metabolic gains in an office type environment for light, mainly sedentary activity.

Input files specifying occupancy patterns, lighting and equipment gains were generated in the Matlab workspace and read by the Simulink model. View coefficients are used in the calculation of mean radiant temperature - see Section 5.6.5.

5.6.4 Radiant Heat Gain from Occupants, Lights and Equipment

The radiant gains from occupants, lights and equipment have an associated radiant proportion and view coefficient as stated in 5.6.3.

The radiant proportion indicates the proportion of sensible heat gain which is in the form of radiant heat. If $p_{occupants}$, p_{lights} and $p_{equipment}$ are the radiant proportions for occupants, lights and equipment respectively then the total radiant gains can be specified by Equation 5.57.

$$Q_{radiant\ gains} = p_{occupants}Q_{occupants} + p_{lights}Q_{lights} + p_{equipment}Q_{equipment}$$

Equation 5.57

The radiant gain is distributed over the zones internal surfaces using an area times emmissivity weighting. Each surface therefore receives a surface radiant gain, see Equation 5.58.

$$q_i^{surfrad} = \frac{Q_{radiant\ gains}\,\varepsilon\ A_i}{\Sigma(\varepsilon\, A_i)}$$

Equation 5.58

5.6.5 Zone Mean Radiant Temperature (T^{MRT})

This is an estimate of an occupant's perception of the radiant temperature within the zone. It is calculated as a weighted average of the zone's surface temperatures, modified by the effects of radiant gains due to occupants, lights and equipment. The zone mean radiant temperature is calculated from the mean effective irradiance (R_{int}). The $\varepsilon_i A_i$ weightings are calculated for the 150 m^3 zone model and given in Table 5.5. The values are used in Equation 5.60 and Equation 5.62.

Element	$\varepsilon_i A_i$	$\varepsilon_i A_i$ Weighting
Rear wall	0.9 x 30 = 27	0.158
Side wall	0.9 x 30 = 27	0.158
Ceiling	0.9 x 50 = 45	0.264
Floor	0.9 x 50 = 45	0.264
External wall	0.9 x 21 = 18.9	0.111
Window	0.845 x 9 = 7.6	0.045
Total	170.5	1.000

Table 5.5. The $\varepsilon_i A_i$ weightings for calculation of zone mean radiant temperature.

R_{int} comprises four components as described in Equation 5.59.

$$R_{int} = G_{surf} + G_{direct\_plant+casual} + G_{scat\_plant+casual} + G_{sol}$$

Equation 5.59

Equation 6.56 uses Equations 6.57 to 6.60 to calculate R_{int}.

$$G_{surf} = \frac{\sum A_i \varepsilon_i \sigma (T_i + 273.15)^4}{\sum \varepsilon_i A_i}$$

Equation 5.60

$$G_{direct\_plant+casual} = \frac{\sum 0.5 C_j Q_{j\ radiant\ gains}}{A^{floor}}$$

Equation 5.61

$$G_{scat\_plant+casual} = \left(\frac{1}{\sum \varepsilon_i A_i} - \frac{1}{\sum A_i} \right) Q_{radiant\ gains}$$

Equation 5.62

$$G_{sol} = \frac{\alpha_{skin} I_{diffusemean}}{\varepsilon_{skin}}$$

Equation 5.63

where

$\frac{\alpha_{skin} I_{diffusemean}}{\varepsilon_{skin}}$ = ratio of solar absorptance to emmissivity for skin

With respect to the one zone model the surface radiation as a result of direct radiant plant and casual gain inputs is described by Equation 5.64.

$$= \frac{\begin{array}{c} 60\sigma(T_{rear} + 273.15)^4 + 50\sigma(T_{floor} + 273.15)^4 + 50\sigma(T_{ceiling} + 273.15)^4 \\ + 21\sigma(T_{wall} + 273.15)^4 + 9\sigma(T_{window} + 273.15)^4 \end{array}}{(0.9 \times 181) + (0.845 \times 9)}$$

Equation 5.64

Finally, the Mean Radiant Temperature is calculated using Equation 5.65.

$$T^{MRT} = \frac{R_{int}^{1/4}}{\sigma^{1/4}} - 273.15$$

Equation 5.65

5.6.6 Zone Resultant Temperature

The resultant temperature is a measure of the temperature perceived by occupants. Its value is the mean of the air temperature and the mean radiant temperature as defined by Equation 5.66.

$$T^{resultant} = \frac{T^{air} + T^{MRT}}{2}$$

Equation 5.66

5.6.7 Ventilation

Natural infiltration and exfiltration through cracks, gaps, window openings and door openings are responsible for energy, moisture and carbon dioxide concentration changes in the zone air. Fresh air supply through mechanical ventilation is another potential influence on energy, moisture and carbon dioxide balances, see Chapter 6. For the purposes of this chapter changes in energy, moisture and carbon dioxide balances due to ventilation are limited to natural infiltration and exfiltration.

5.6.7.1 Sensible Heat Transfer Due to Ventilation

The sensible heat transfer due to ventilation was calculated using Equation 5.67.

$$Q_{sens\_nat} = m_{nat}c_{pair}(t_{ei} - t_{ao})$$

Equation 5.67

For the purposes of the dynamic Simulink model the density of the air is assumed to remain constant at 1.21 kg/m^3 at or about normal room temperatures for comfort. Therefore 1kg of air = 0.8264 m^3 of air and Equation 5.67 can be rewritten as Equation 5.68.

$$Q_{sens\_nat} = 0.8264V_{nat}c_{pair}(t_{ci} - t_{ao})$$

Equation 5.68

5.6.7.2 Latent Heat Transfer due to Ventilation

Latent heat transfer to the zone by ventilation is defined by Equation 5.69.

$$Q_{nat\_latent} = V_{nat}L(g_{zone} - g_{amb})$$

Equation 5.69

For water at 20°C the latent heat of evaporation can be taken as 2450 J/g (Incropera and de Witt 1990). For the purposes of simulation with the one zone model, the moisture is added to the zone at constant temperature. Therefore, there is an associated enthalpy increase and relative humidity level increase. The addition of moisture does not therefore effect the dry-bulb temperature of the zone.

5.6.8 Zone Humidity

For indoor environments there are primarily four sources of moisture:-

1. occupants - metabolic processes
2. machines - e.g. kettles, industrial processes
3. HVAC components
4. infiltration / exfiltration

Moisture production from machines (2) has been ignored in the Simulink dynamic model as these sources are negligible in office type environments. Effects on the zone air moisture content due to HVAC components is considered in Chapter 6.

5.6.8.1 Moisture Generated by Occupants

The perspiration and respiration of sedentary occupants generates between 0.04 and 0.1 kg/h/person (CIBSE 1987). For the purposes of the one zone model an upper value of 0.1 kg/person/hour has been used in order to simulate a worst case scenario. This translates to approximately 0.027 g/s/person. The total metabolic moisture generation rate due to occupants is given by Equation 5.70.

$$M_{occup\_tot} = Nm_{occup}$$

Equation 5.70

5.6.8.2 Moisture Gain due to Infiltration and Exfiltration

The moisture gain due to natural infiltration and exfiltration is defined by Equation 5.71.

$$M_{nat} = V_{nat}(g_{zone} - g_{amb})$$

Equation 5.71

5.6.8.3 Determination of Zone Relative Humidity

Sections 5.6.8.1 and 5.6.8.2 describe the calculation of the rate of moisture loss or gain to the zone due to occupant gains and natural infiltration and exfiltration. In order to calculate the relative humidity of the zone a knowledge of the saturation moisture content is required. This is dependant on the zone air temperature. From a psychrometric chart the saturation moisture content for a given dry bulb temperature can be determined from Equation 5.72.

$$\begin{aligned} SMC_{Tei} = {} & 0.0003175691T_{ei}^3 + 0.0065229563T_{ei}^2 \\ & + 0.2903375631T_{ei} + 3.6943700814 \end{aligned}$$

Equation 5.72

The relative humidity can then be calculated by Equation 5.73

$$RH_{zone} = \frac{ZMC_{Tei}}{SMC_{Tei}} \times 100\%$$

Equation 5.73

5.6.9 Zone Carbon Dioxide Concentration

The air quality in the one zone model was represented by the carbon dioxide concentration of the air. Metabolic carbon dioxide is generated within the zone by occupants. It may also enter or be removed from the zone by the ventilation system and natural infiltration. The following sections describe the mechanisms affecting zone carbon dioxide concentrations.

5.6.9.1 Carbon Dioxide Generation by Occupants

The carbon dioxide generation rate per person quoted by Bearg (1993) is 5.3×10^{-6} m^3/s/person. The generation rate quoted by CEC (1992) is 5.0×10^{-6} m^3/s/person (18 litres/hour/person). For the purposes of the research project the worse case value of 5.3×10^{-6} m^3/s/person was used. Assuming the density of carbon dioxide to be 1.773 kg/m^3 at room temperatures for comfort, the carbon dioxide generation rate of 9.3969×10^{-6} kg/s/person was used for modelling purposes. The total generation rate of CO_2 for occupants within the building zone is described by Equation 5.74.

$$CO_2^{occup} = NM_{CO2}$$

Equation 5.74

Occupancy patterns specified for the Simulink model allowed the total carbon dioxide generation rate within the zone to be calculated. In order to give the values calculated greater meaning it was useful to express the zone carbon dioxide concentration in parts per million (ppm) for the simulation results. The conversion factor used during the simulations was:-

$$1 g/m^3 = 555 \text{ ppm}$$

5.6.9.2 Zone Air CO_2 Concentration Variations due to Natural Infiltration

Carbon dioxide concentrations within the one zone model generally decreased after occupants had vacated the space due to the infiltration of fresh air with a lower carbon dioxide concentration. Carbon dioxide concentrations in outdoor air can vary depending on factors such as weather conditions and location. For the purposes of the Simulink model it was assumed that outdoor carbon dioxide concentrations remain constant at 350 ppm.

The removal rate of carbon dioxide due to natural infiltration is defined by Equation 5.75.

$$CO_2^{nat} = V_{nat}(CO_2^{amb} - CO_2^{zone})$$

Equation 5.75

The influence of mechanical ventilation on the zone CO_2 concentration is described in Chapter 6.

5.7 Assessing the Suitability of the Dynamic One Zone Building Model for Control Strategy Development Modelling

The one zone dynamic model developed using Matlab and Simulink was compared to an identical building model generated using Thermal Analysis Software (Tas). Identical ambient weather conditions, occupancy patterns, lighting and equipment gains were also applied for three week long comparison periods selected to assess the performance of the model when it was subjected to various weather conditions.

The main objective of carrying out the comparison of the Simulink and Tas models was to compare the resulting zone temperature and humidity conditions calculated for the free running, i.e. no HVAC components operational, mode of operation. Tas simulates using hourly time steps while the Simulink model uses time steps commonly less than 10 seconds in order to fulfil its purpose of developing the fuzzy control strategies detailed in later chapters. HVAC control methods used within Tas were not suitable for the purposes of the research project as the code was not accessible and simulations were limited to hourly time steps. Hence, specific model control components were developed within Simulink and Matlab. The comparison of the models with regard to the HVAC and Control components was not possible. It is emphasised that the purpose of the Simulink model was to provide a comparative tool to observe performance differences between conventional and fuzzy control strategies with a view to improving comfort and energy and cost efficiencies of the HVAC system. To this end the absolute accuracy of the model is not crucially important. However, as a basis for creating a realistic model it was desirable to assess whether the Simulink model was performing to a reasonable standard during its development. This is the primary reason for comparing the Simulink model against the Tas model for the free running building zone.

5.7.1 Comparison Between Tas and Simulink Dynamic Modelling Results

The Tas model used 10 days pre-conditioning (default program setting) to ensure that the building fabric and zone conditions are at the correct values before running the desired simulation period.

Initial modelling indicated that the Simulink model requires approximately two days of preconditioning to ensure that the building fabric zone conditions are near the correct values prior to the desired simulation period, see Figure 5.12.

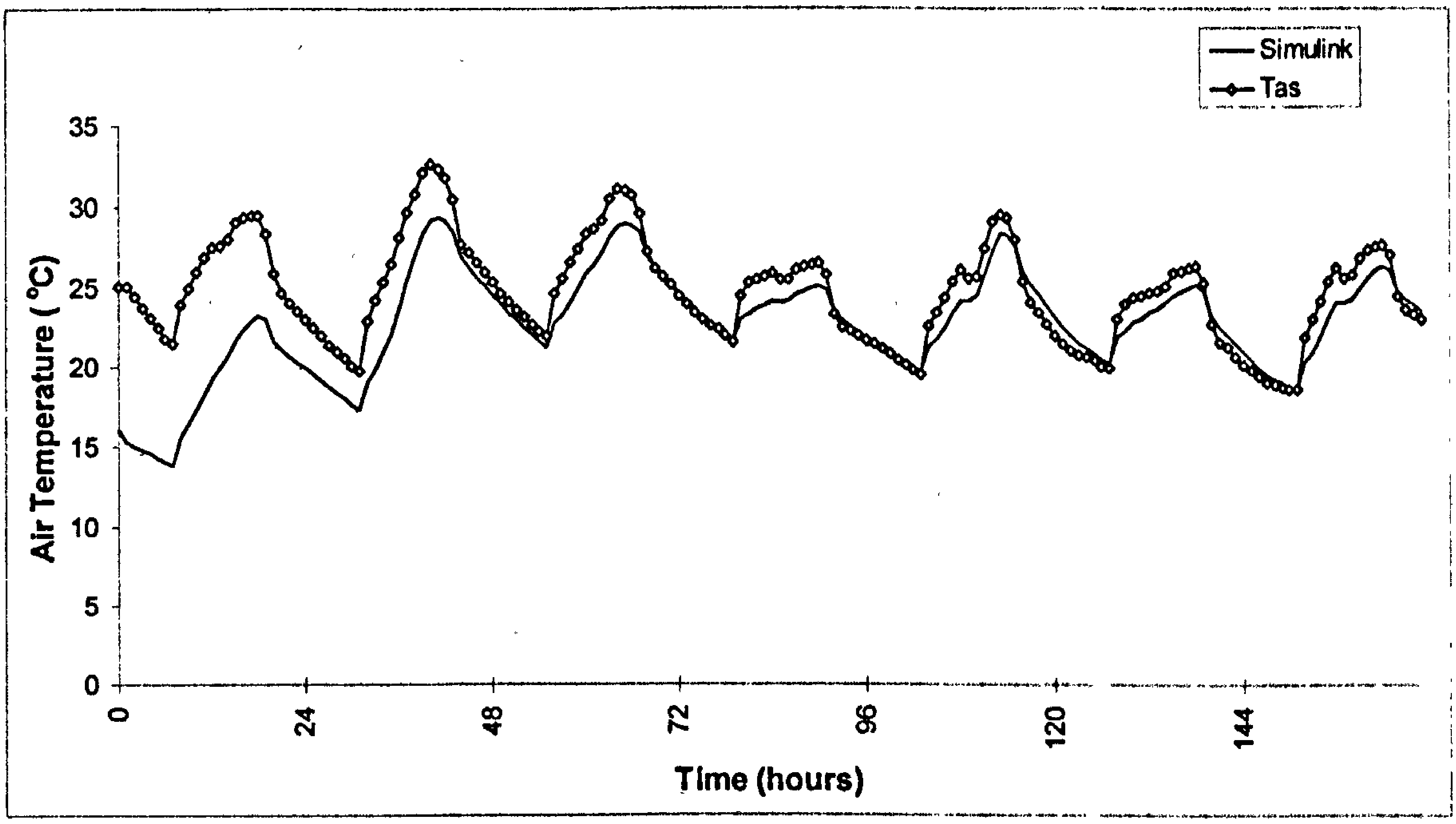

Figure 5.12. Simulink and Tas model simulations showing zone air temperature.

Figure 5.12 indicates that the Simulink model requires approximately 48 hours of preconditioning where the initial structure temperatures and zone temperature are set at approximately 10°C below those determined by the pre-conditioned Tas model. The required pre-conditioning period varies and is dependent on the initial conditions set, i.e. fabric and zone temperatures. Pre-conditioning for the other environmental quality parameters of relative humidity and CO_2 concentration are affected to a lesser degree by pre-conditioning as they are only affected by the initial air condition and not by the fabric conditions. However, initial zone temperature offsets due to lack of preconditioning can have a knock on effect with regard to relative humidity. For the purposes of the benchmark comparisons described in this chapter the Tas model was run first with 10 days pre-conditioning and the zone conditions at the start of the desired simulation period were then used as the initial conditions for the Simulink model.

However, due to the simulation time step required for modelling the control aspects within the Simulink model as described in later chapters, the need for pre-conditioning was undesirable because of increased modelling time implications. In order to overcome the need for pre-conditioning two possible methods were considered:-

1. Setting the initial zone conditions and fabric temperature to values determined by first running the Tas model using a pre-conditioning period. This was not considered

practical due to the need to set up and run an equivalent Tas model for each simulation period considered and the associated time required. This method was also considered unsuitable where the internal environmental parameters were being controlled as the equivalent Tas model had not been developed with HVAC components. The Simulink model with controlled environmental parameters would not necessarily have the same fabric and zone temperatures at the beginning of simulations.

2. Set the initial conditions and fabric temperatures to values within the desired set point ranges of the control system being considered. This method allows a relatively short pre-conditioning period as model conditions will be close to the desired set point value.

The second method was deemed the more practical and was used for the simulations carried out during the research project during the development of the control strategies and described in Chapters 8, 9 and 10.

5.7.2 Comparative Results for Three Representative Simulation Periods

In order to ensure that the dynamic one zone model responds realistically to ambient weather conditions three different 7 day simulation periods during the year were selected. These were then simulated using the Simulink and the Thermal Analysis Software (Tas) models.

The selected 7 day periods were in the months of January, May and September and started at days 1, 130, and 270 respectively for 7 days. These were selected on the basis that they provided diverse weather conditions in terms of ambient temperature and solar gain.

The comparison results for days 1 - 7 inclusive, i.e. January 1 - 7 are shown graphically in Figure 5.13 to Figure 5.20. The results for the remaining simulated periods are summarised in Table 5.6. Zone parameters compared include zone air temperature, zone mean radiant temperature, zone resultant temperature, zone relative humidity, surface solar gains and floor surface temperature. For the purposes of comparison the Tas model simulations were executed first and the initial zone conditions at the start of the desired simulation period used as initial inputs to the Simulink model. Hence, the Simulink model simulations were effectively pre-conditioned.

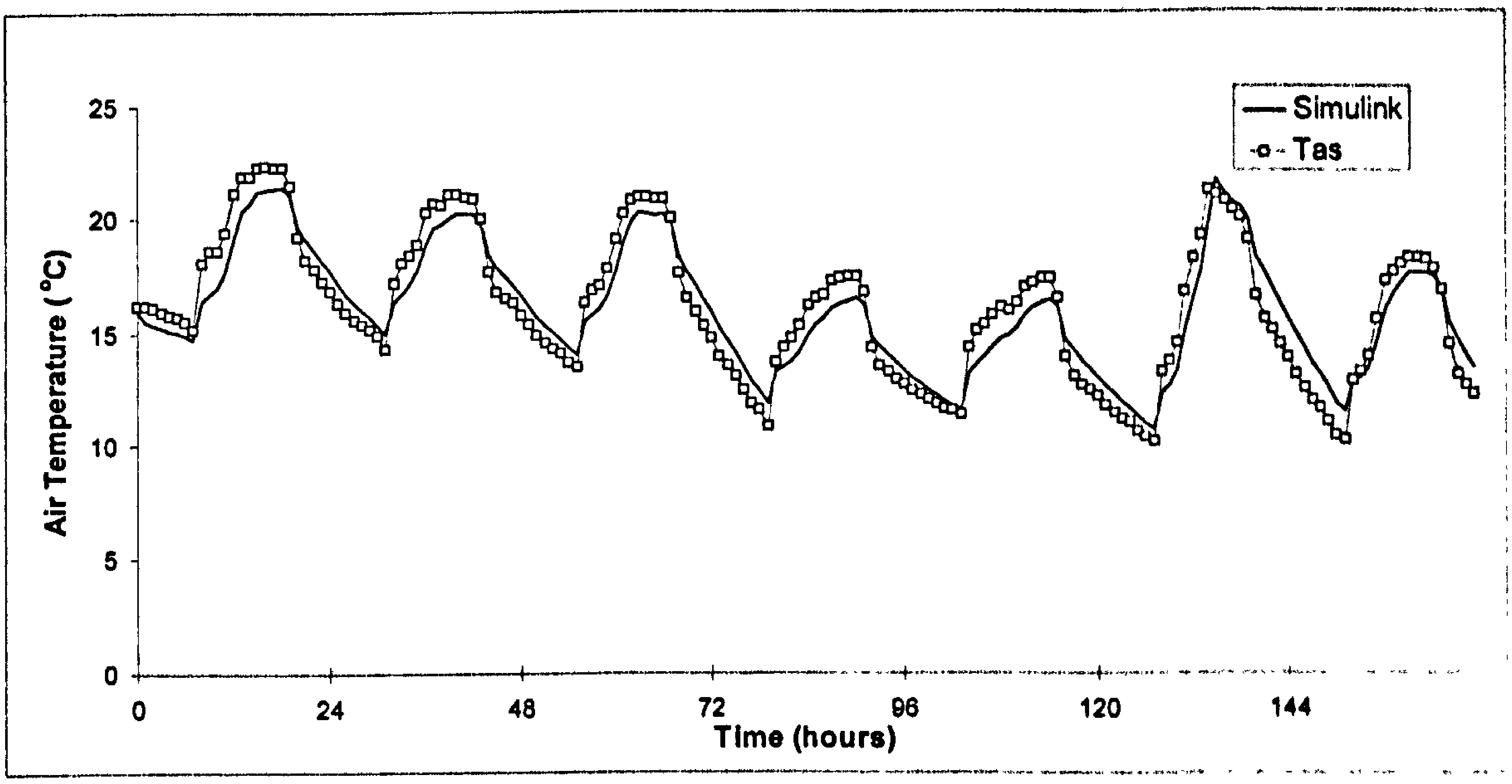

Figure 5.13. Comparison of zone air temperatures. Simulink and Tas simulations days 1 - 7 inclusive.

To compare the results of the Simulink and Tas simulations in a meaningful way, the "coefficient of determination", R^2, value was calculated for the results of each parameter of each simulation. Briefly, using the example shown in Figure 5.14, the results of the Simulink simulation (x-axis) are plotted against the results of the Tas simulation (y-axis) for the desired parameter. A best-fit straight line is then drawn through the points. The R^2 value measures the proportion of the total variation in the Simulink simulations that can be explained by a regression equation for the best fit line. Hence, higher values of R^2 represent a better correlation between the two models. A Microsoft Excel spreadsheet was used to compile the results in this chapter.

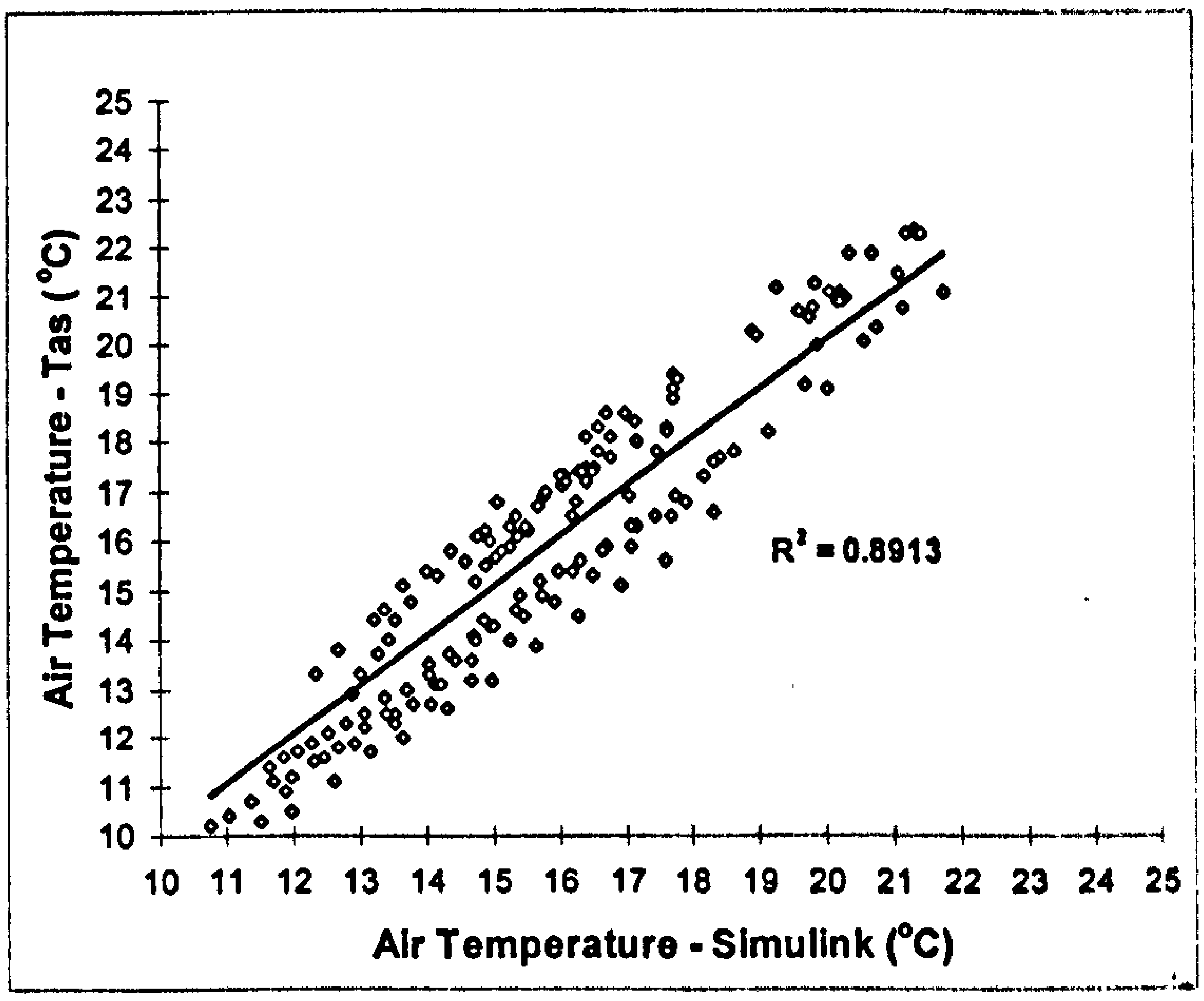

Figure 5.14. R^2 for zone air temperature simulated using the Simulink and Tas models. Days 1 - 7 inclusive.

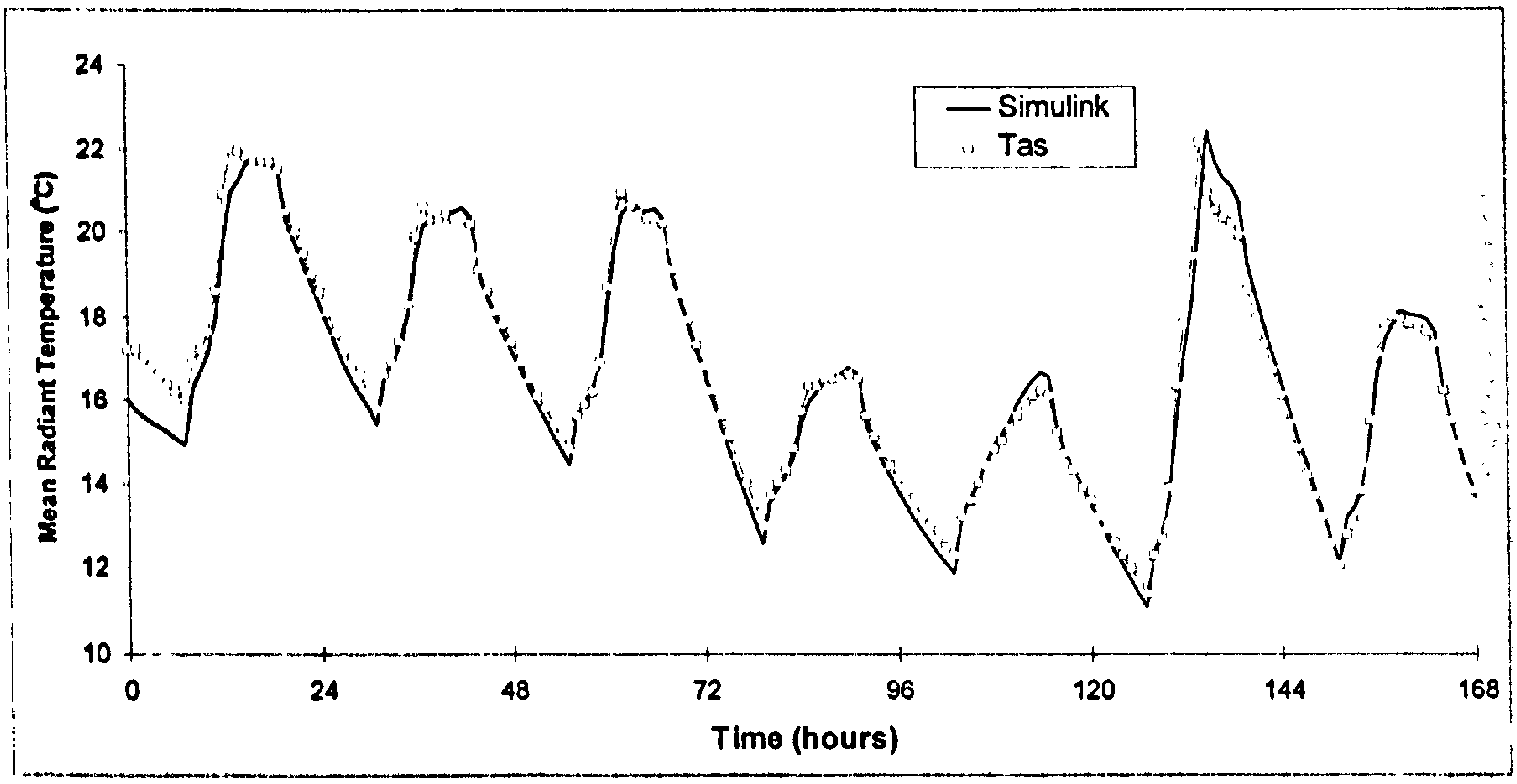

Figure 5.15. Comparison of zone mean radiant temperatures. Simulink and Tas simulations days 1 - 7 inclusive.

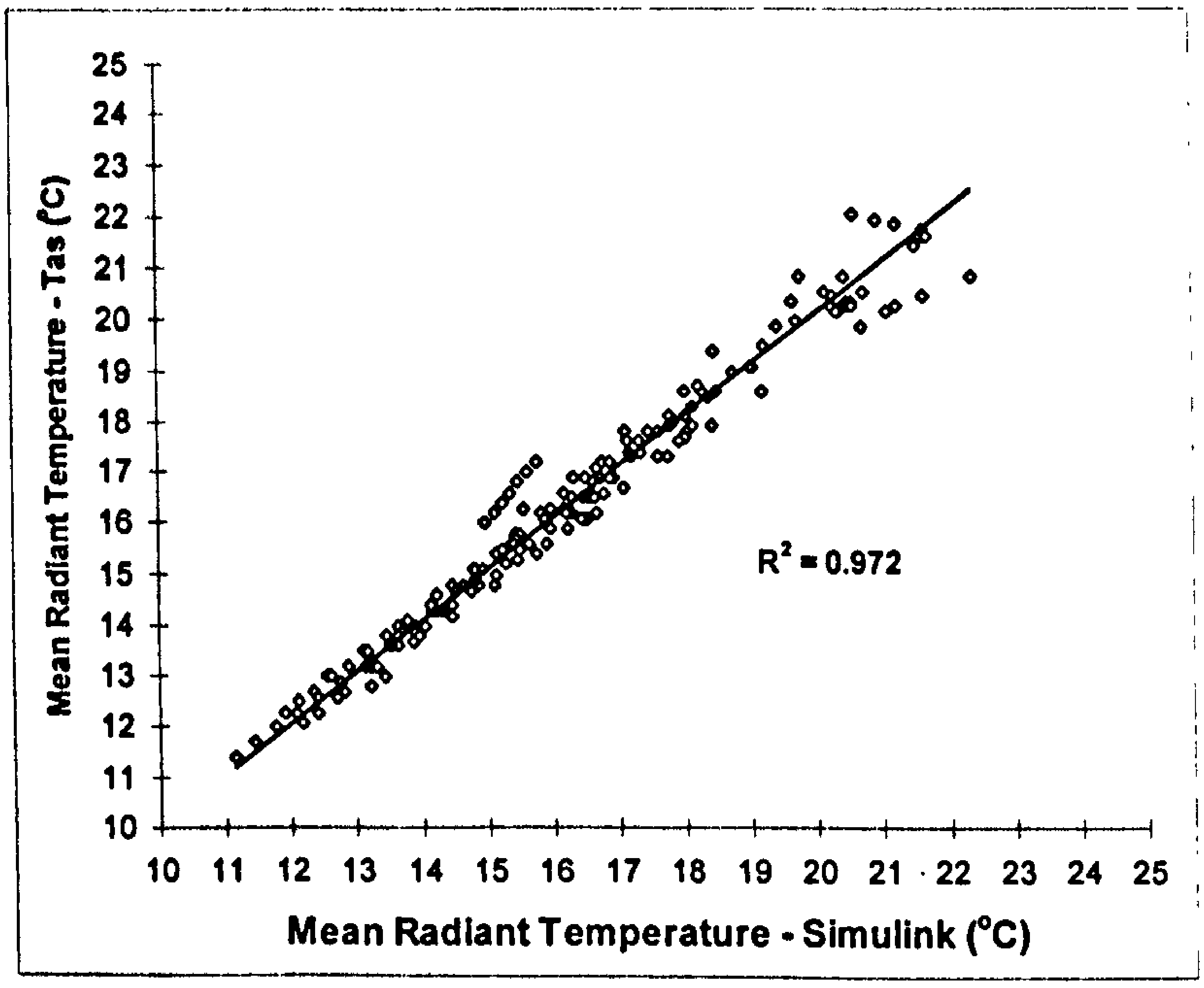

Figure 5.16. R^2 for zone mean radiant temperature simulated using the Simulink and Tas models. Days 1 - 7 inclusive.

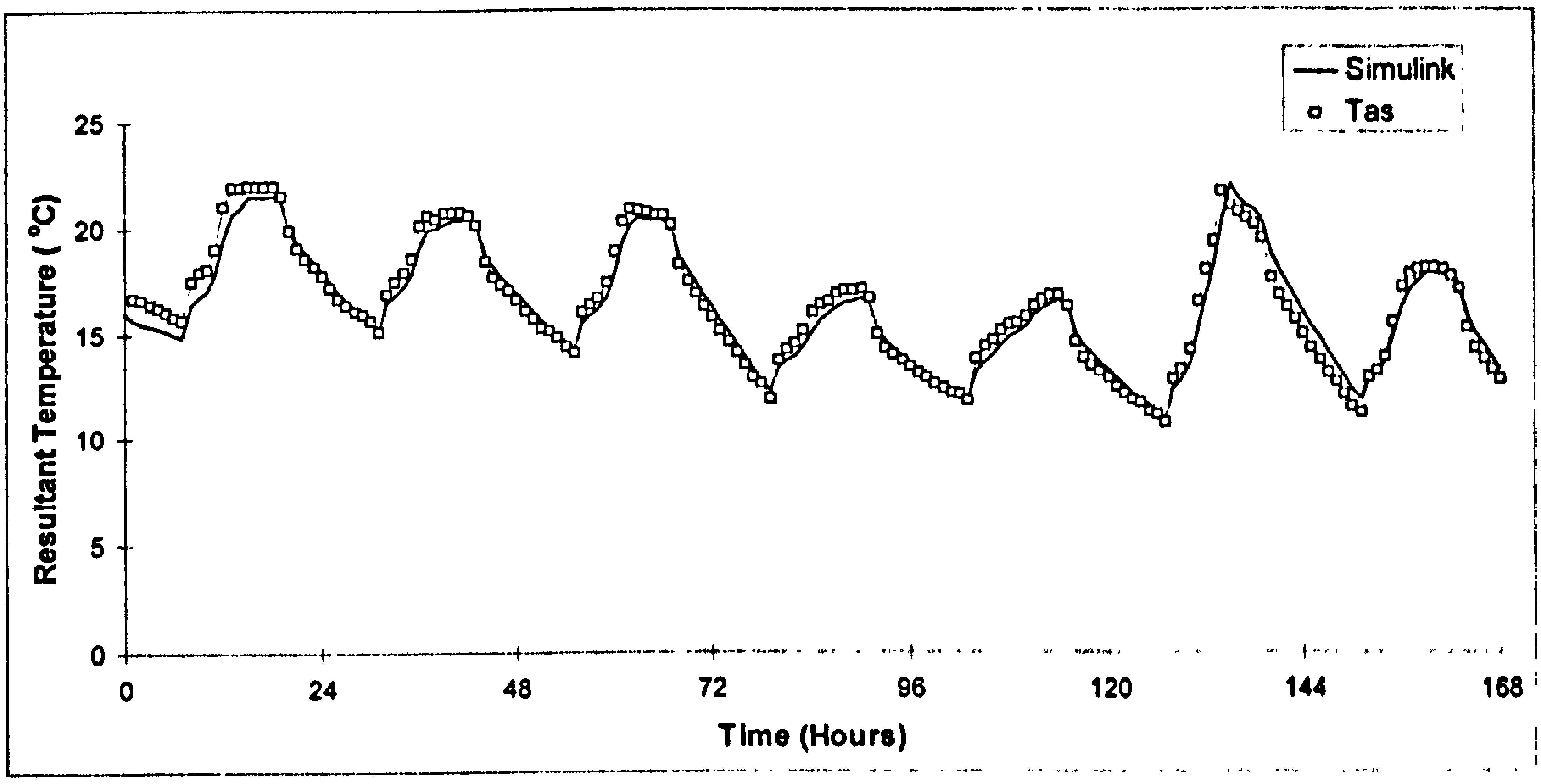

Figure 5.17. Comparison of zone resultant temperatures. Simulink and Tas simulations days 1 - 7 inclusive.

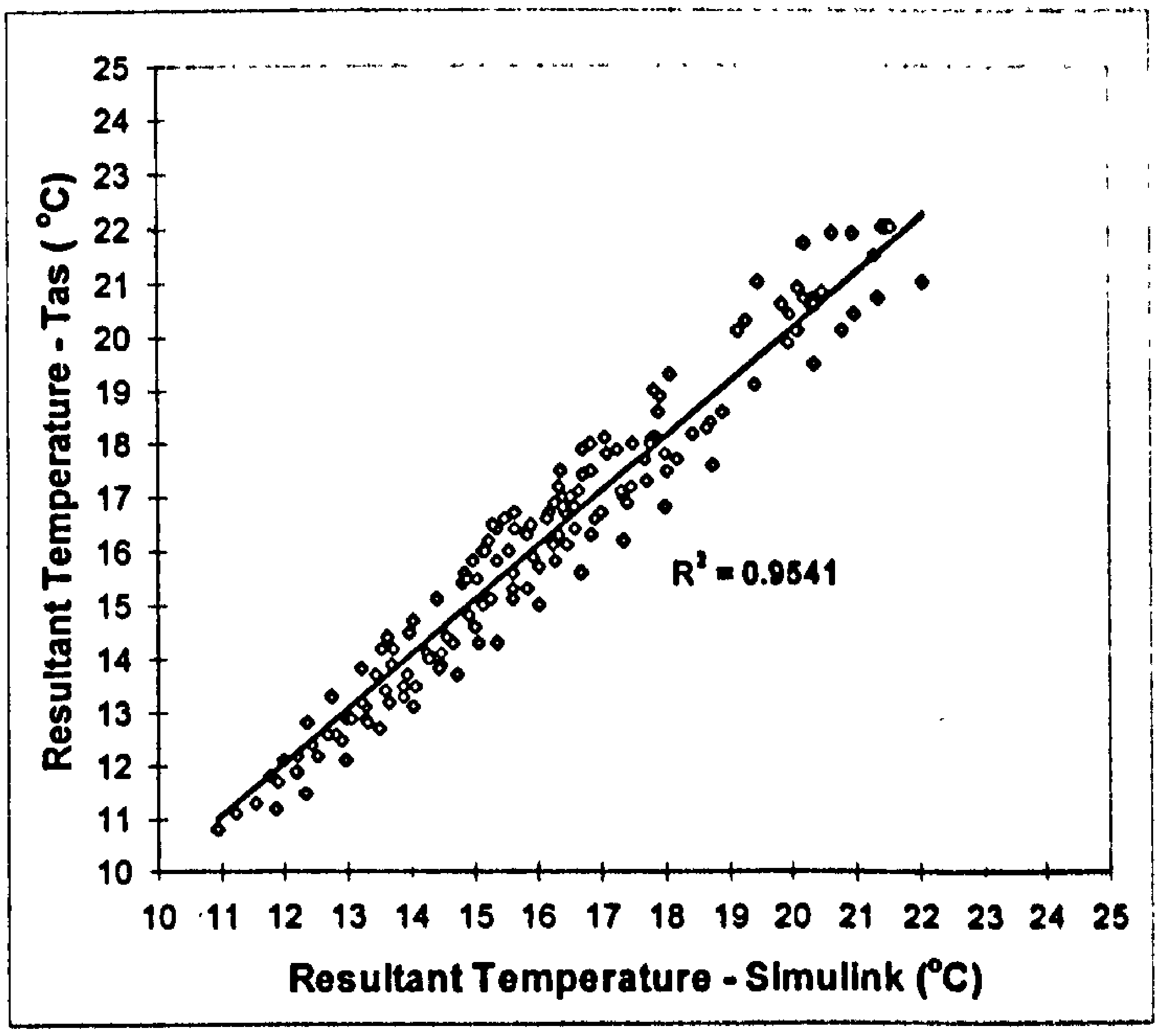

Figure 5.18. R^2 for zone resultant temperature simulated using the Simulink and Tas models. Days 1 - 7 inclusive.

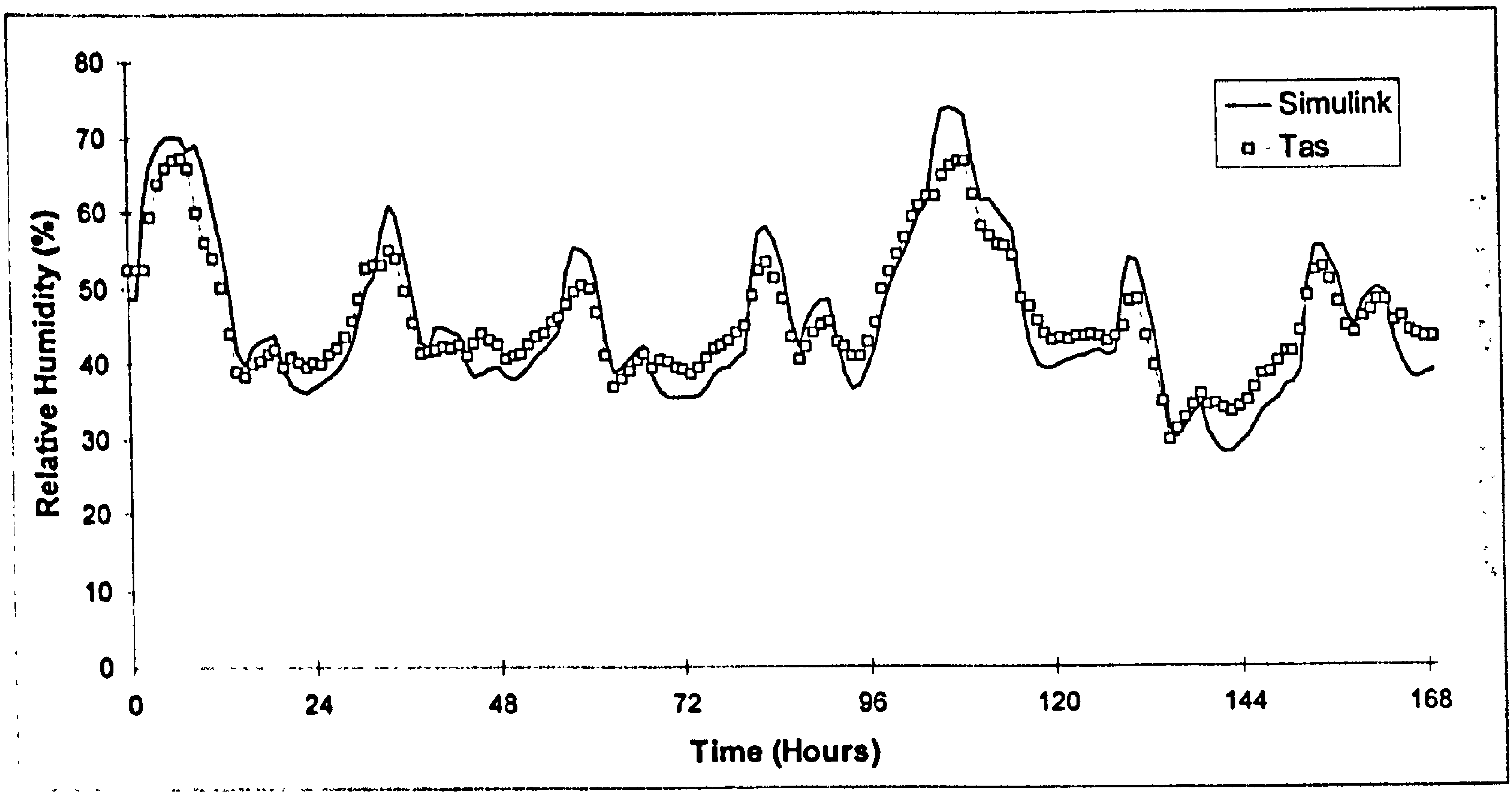

Figure 5.19. Comparison of zone relative humidity. Simulink and Tas simulations days 1 - 7 inclusive.

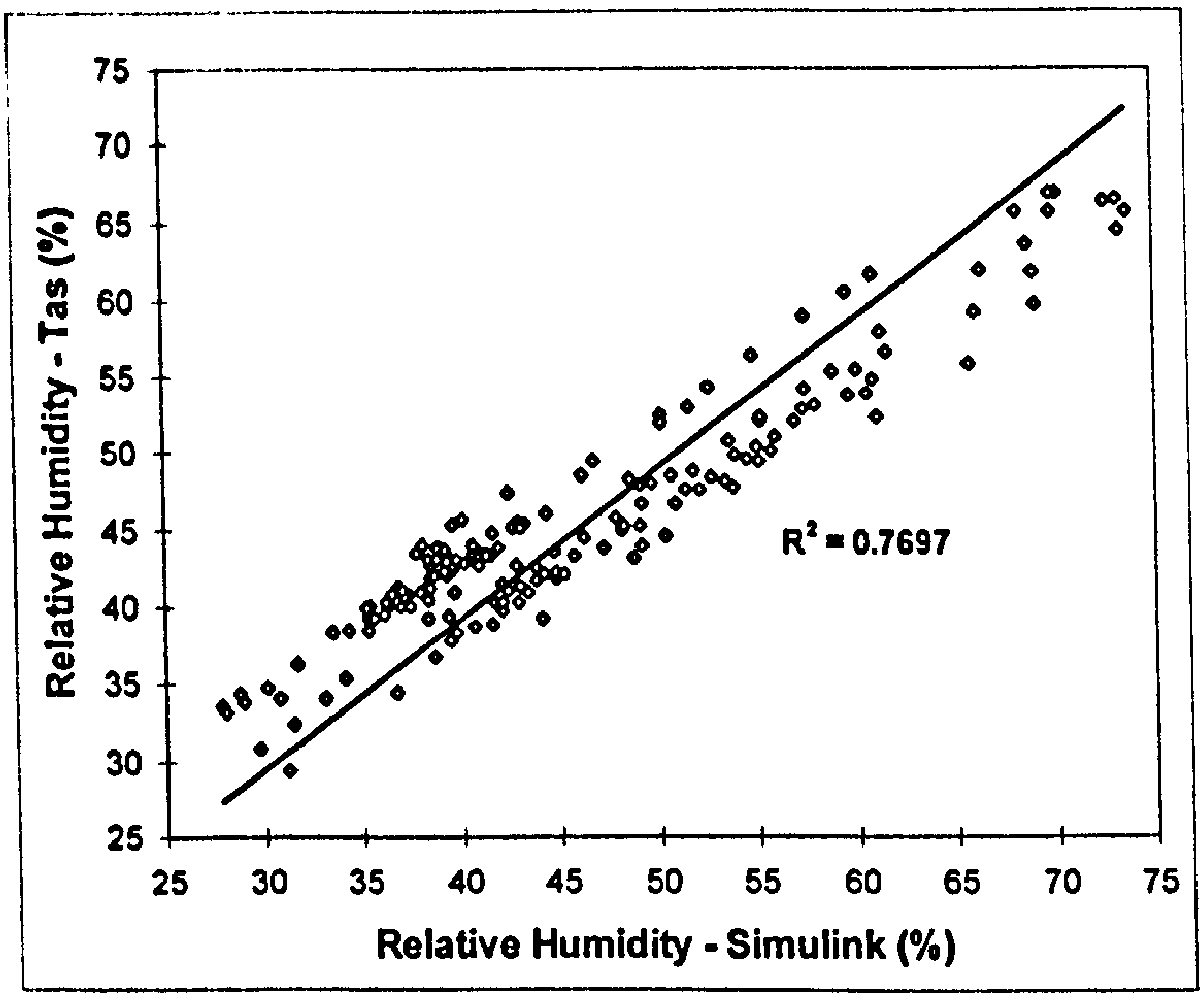

Figure 5.20. R^2 for zone air relative humidity simulated using the Simulink and Tas models. Days 1 - 7 inclusive.

The comparisons between the Simulink and Tas models for the two remaining one week periods, i.e. days 130 - 136 inclusive and days 270 - 276 inclusive were also modelled. Summaries for the three comparison periods are given in Table 5.6 in the form of R^2 values for the regression equations of best-fit lines for the relevant simulation data.

Simulation Period	Air Temperature	Mean Radiant Temperature	Resultant Temperature	Relative Humidity
Days 1 - 7	0.89	0.97	0.95	0.77
Days 130 - 136	0.94	0.98	0.97	0.68
Days 270 - 276	0.89	0.96	0.96	0.86

Table 5.6. Simulink versus Tas R^2 values for the comparison of the three selected simulation periods.

Table 5.6 indicates a good correlation between the Tas and Simulink models for the zone temperature simulations. Relative humidity correlations possessed lower R^2 values. This can be partially attributed to relative humidity calculations being dependent on zone temperature predictions. Hence, a small difference in predicted zone air temperature will be amplified as a larger difference between the relative humidity predictions for the two models. However, Figure 5.19 visually indicates that the results for the Simulink model follow the general trends in relative humidity predicted by the Tas model.

In order to assess further the suitability of the Simulink model for control modelling purposes, comparisons for solar gains to surfaces and surface temperatures were also made between the Simulink and Tas models. Results are detailed in Section 5.8.

5.8 Comparison of the Simulink and Tas Models for Surface Temperatures and Solar Gains to Zone Surfaces

The simulink model is capable of returning values for any of the calculations carried out within the model during the simulation. Tas does not make available all values calculated during simulation but does make available some specific parameter values. The rate of solar gain to exposed surfaces and surface temperatures were two such parameters the Tas model makes available to the user.

5.8.1 Solar Gains to Surfaces

The results of comparisons between the Simulink and Tas models of the solar gains to exposed surfaces are shown in Figure 5.21 to Figure 5.25.

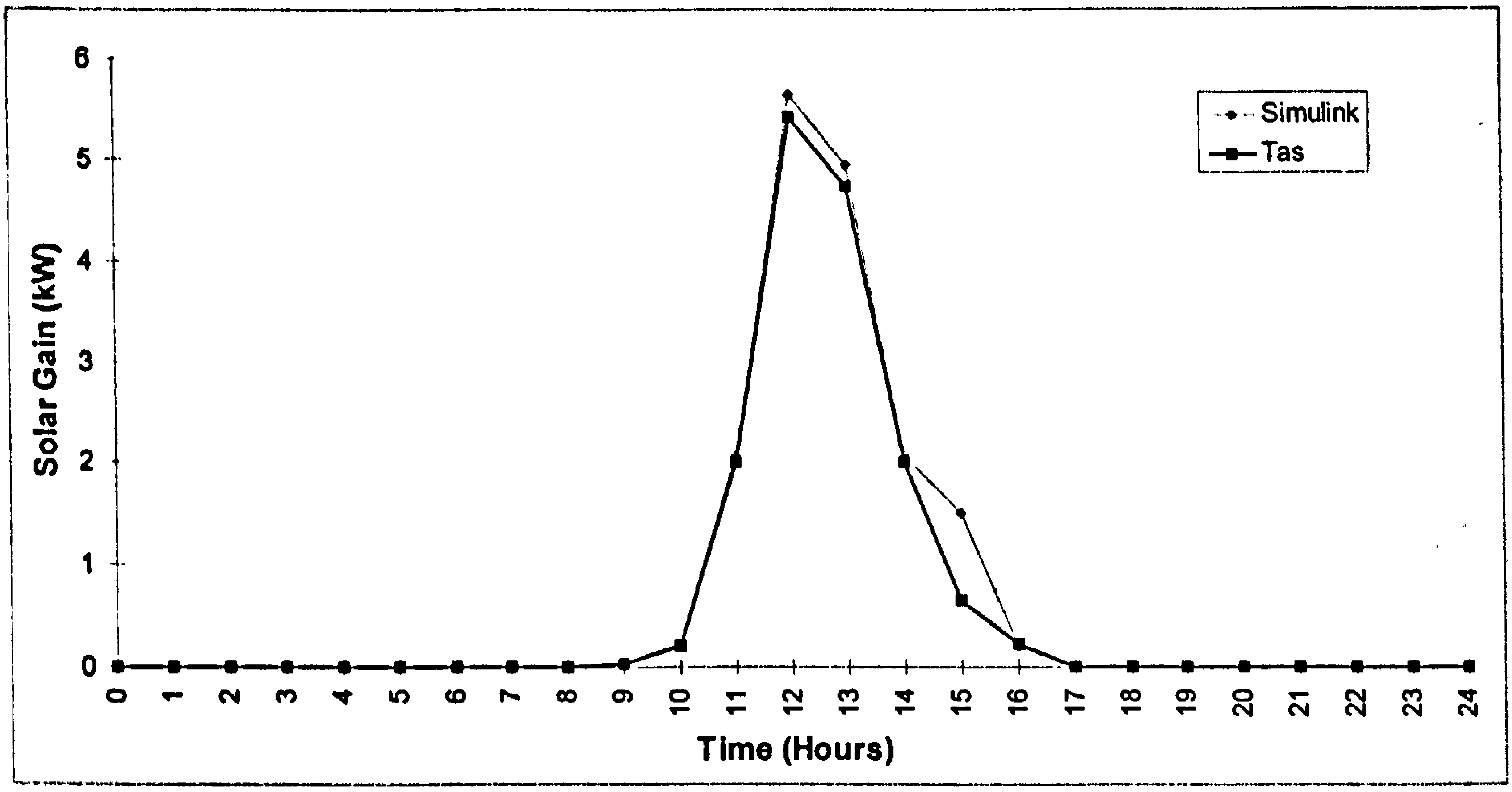

Figure 5.21. Comparison of predicted solar gains for the external wall outer surface for the Simulink and Tas models (January 1st = day 1).

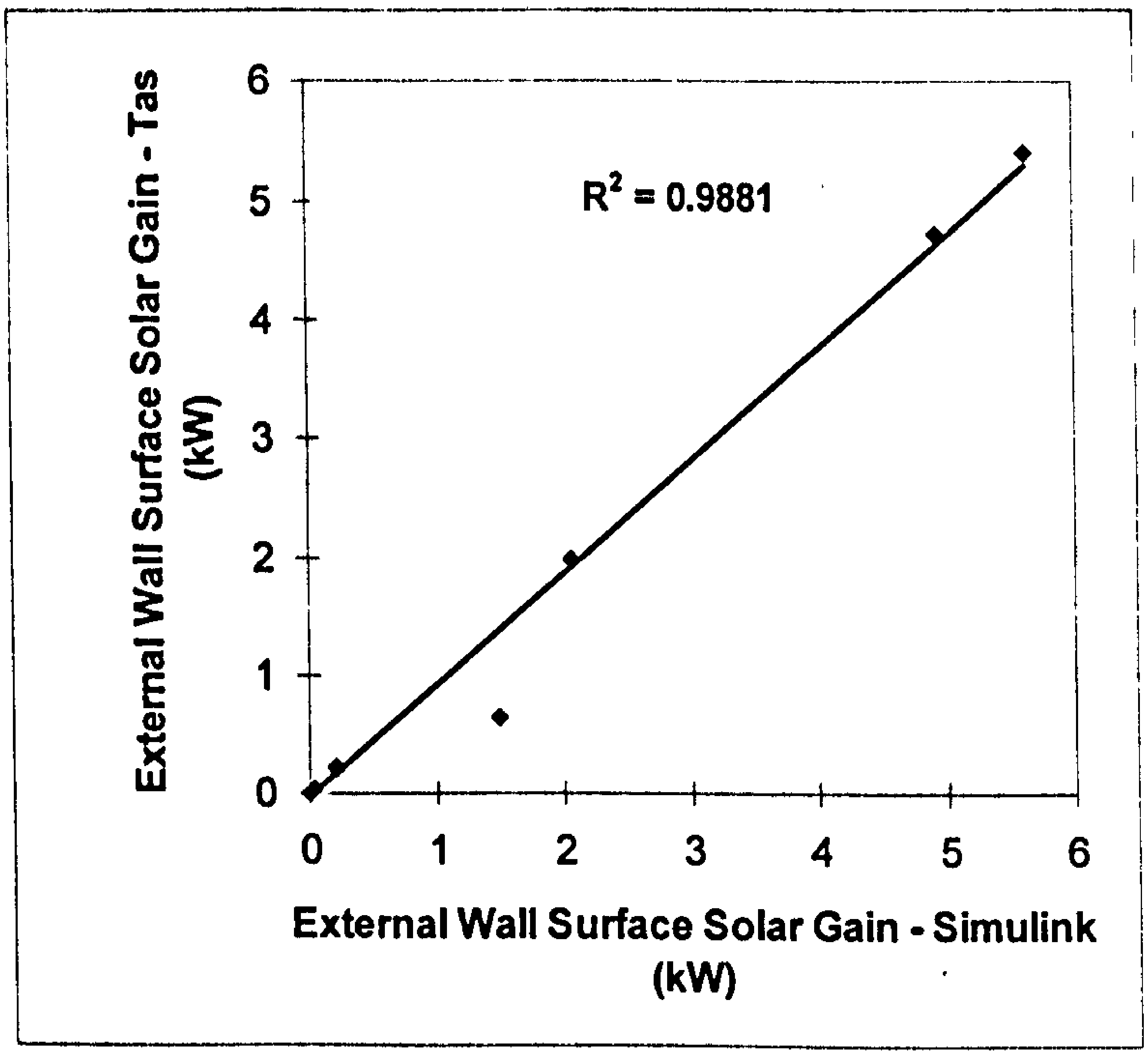

Figure 5.22. Comparison R^2 value of predicted solar gains for the external wall outer surface for the Simulink and Tas models (January 1st = day 1).

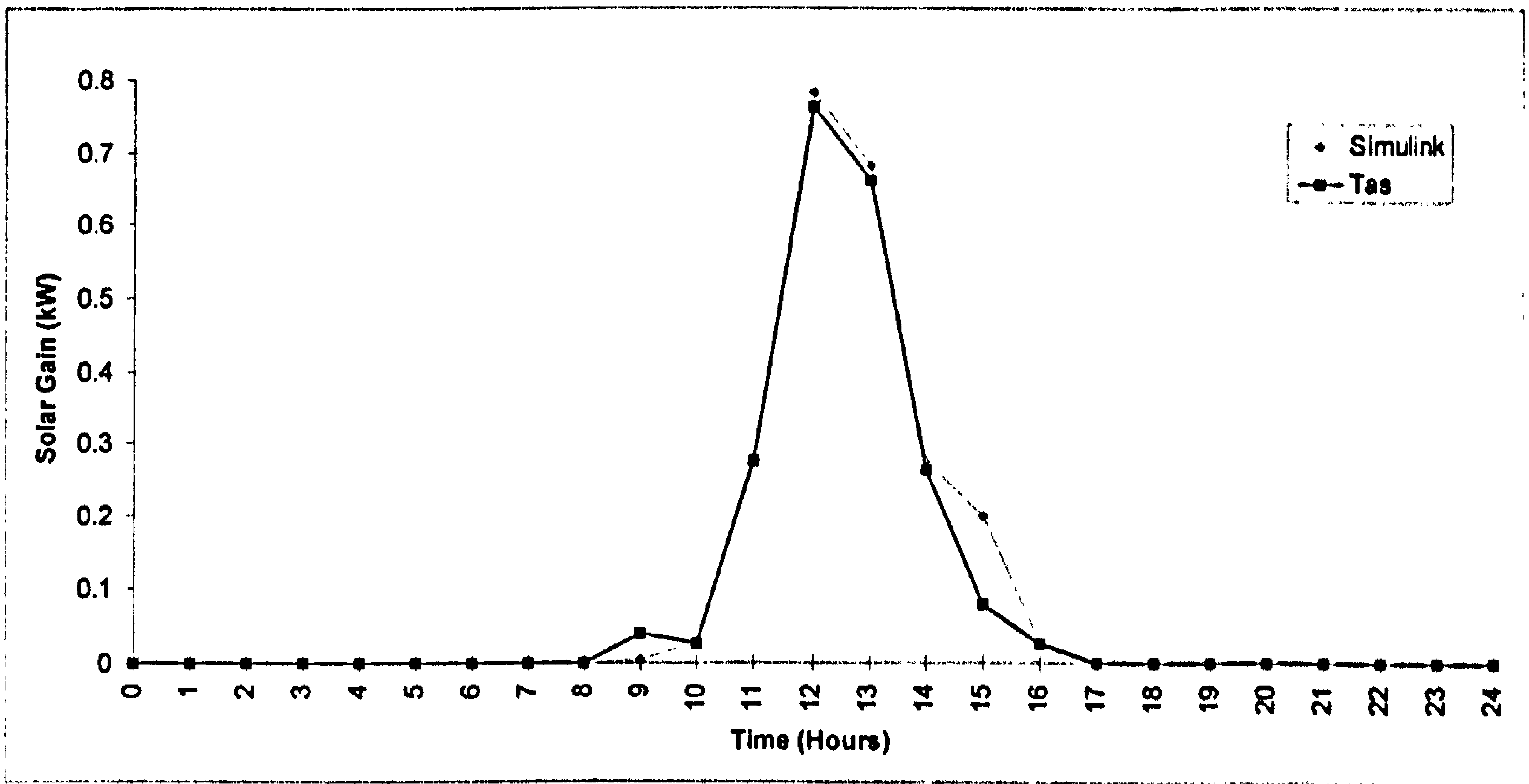

Figure 5.23. Comparison of predicted solar gains for interior wall surfaces for the Simulink and Tas models (January 1st = day 1).

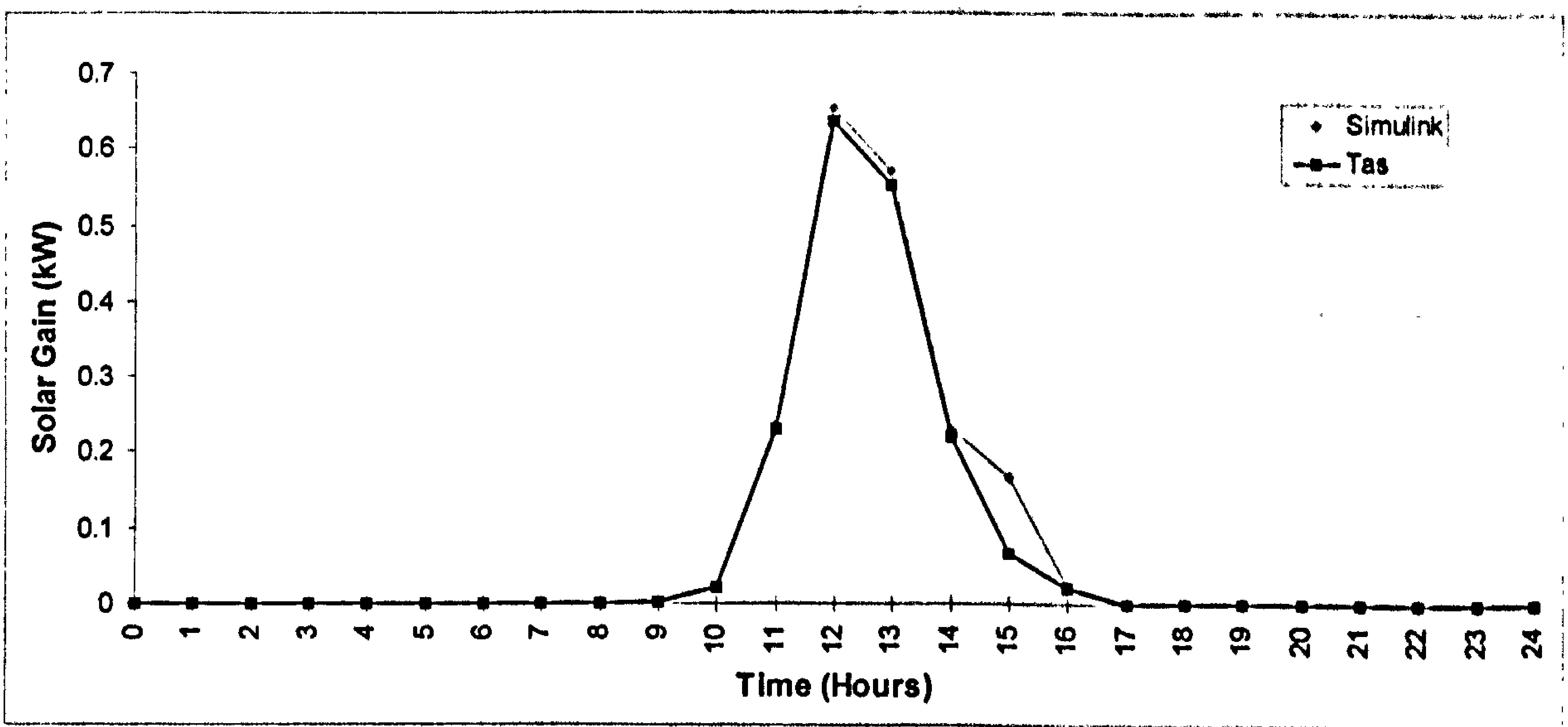

Figure 5.24. Comparison of predicted solar gains for the ceiling surface for the Simulink and Tas models (January 1st = day 1).

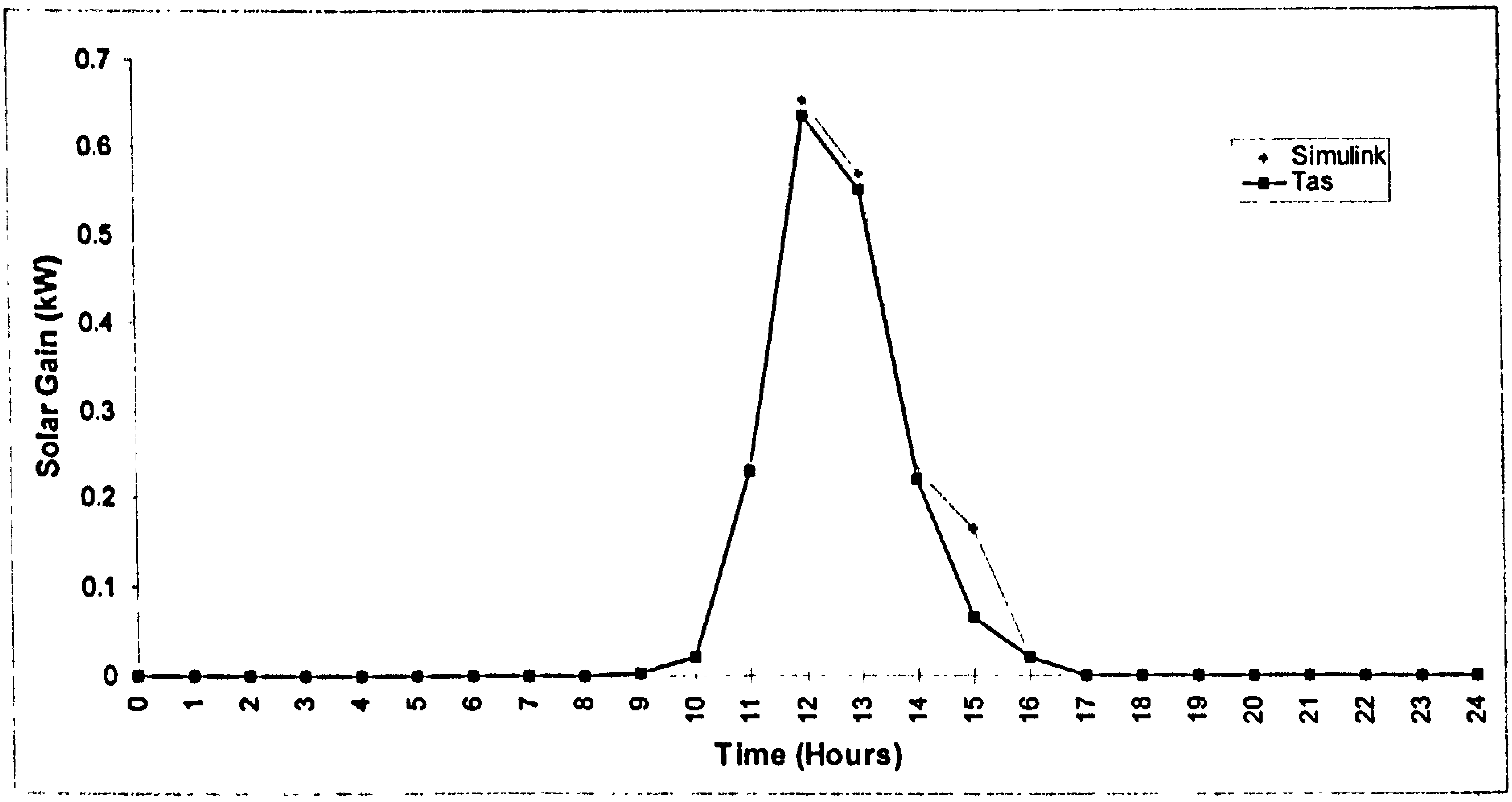

Figure 5.25. Comparison of predicted solar gains for the floor surface for the Simulink and Tas models (January 1st = day 1).

A summary of the comparisons R^2 values of predicted solar gains to exposed surfaces for the Simulink and Tas models are given in Table 5.7.

Surface	R^2 Value
Exterior Wall - Outer	0.99
Exterior Wall - Inner	0.98
Internal Walls	0.98
Floor	0.98
Ceiling	0.98

Table 5.7. Comparison R^2 of predicted solar gains to exposed surfaces for the Simulink and Tas models (January 1st = day 1).

Figure 5.21 to Figure 5.25 and Table 5.7 indicate a good fit of the predictions made by the Simulink model to the solar gains of surfaces predicted by Tas. Relatively small discrepancies are apparent at the beginning and end of daylight hours. For example, the Simulink model consistently returns a higher value approximately 3 hours before the end of daylight hours. Although the cause of this discrepancy could not be identified with any certainty, it is possible that this was due to the calculation of the ratio of direct radiation on an inclined surface to that on a horizontal surface (R_b), which is not strictly valid for times of the day around dawn and dusk. However, for the purposes of modelling the controls systems required it was deemed that the method of calculation using R_b was adequate. Care should be taken in interpreting the R^2 values as these have been calculated over the 24 hour period and hence indicate a better regression fit than if they were calculated over the period between dawn and dusk only.

5.8.2 Surface Temperatures

In order to assess whether the explicit finite difference equations used for calculating node temperatures using the Simulink model were valid, the surface temperatures predicted by the Simulink and Tas models were compared. Surface temperatures were simulated for days 1 - 7 inclusive. The results for the floor surface temperature are shown graphically in Figure 5.26 and Figure 5.27.

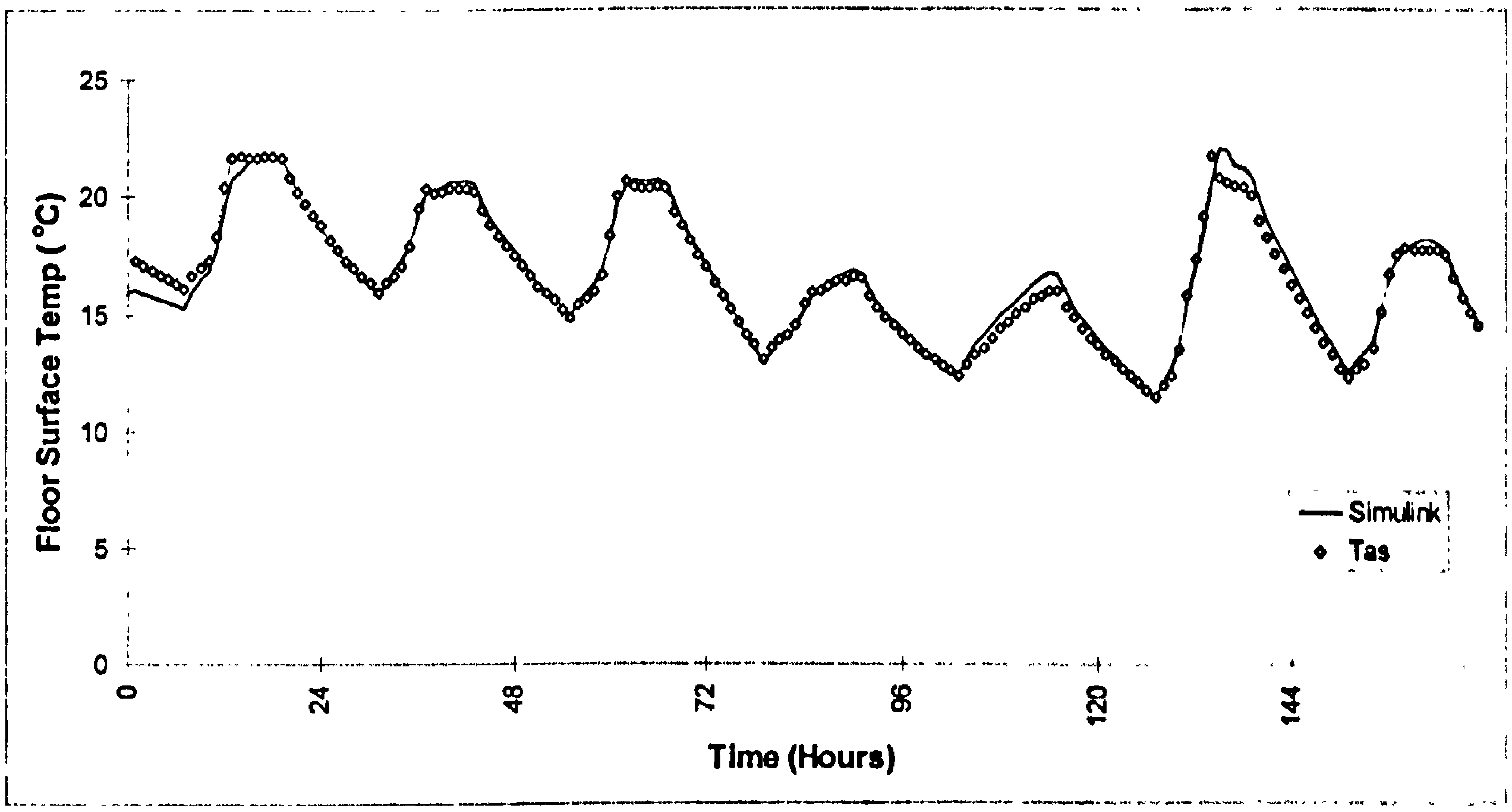

Figure 5.26. Comparison of the Simulink and Tas model predictions of the floor surface temperature, days 1 - 7.

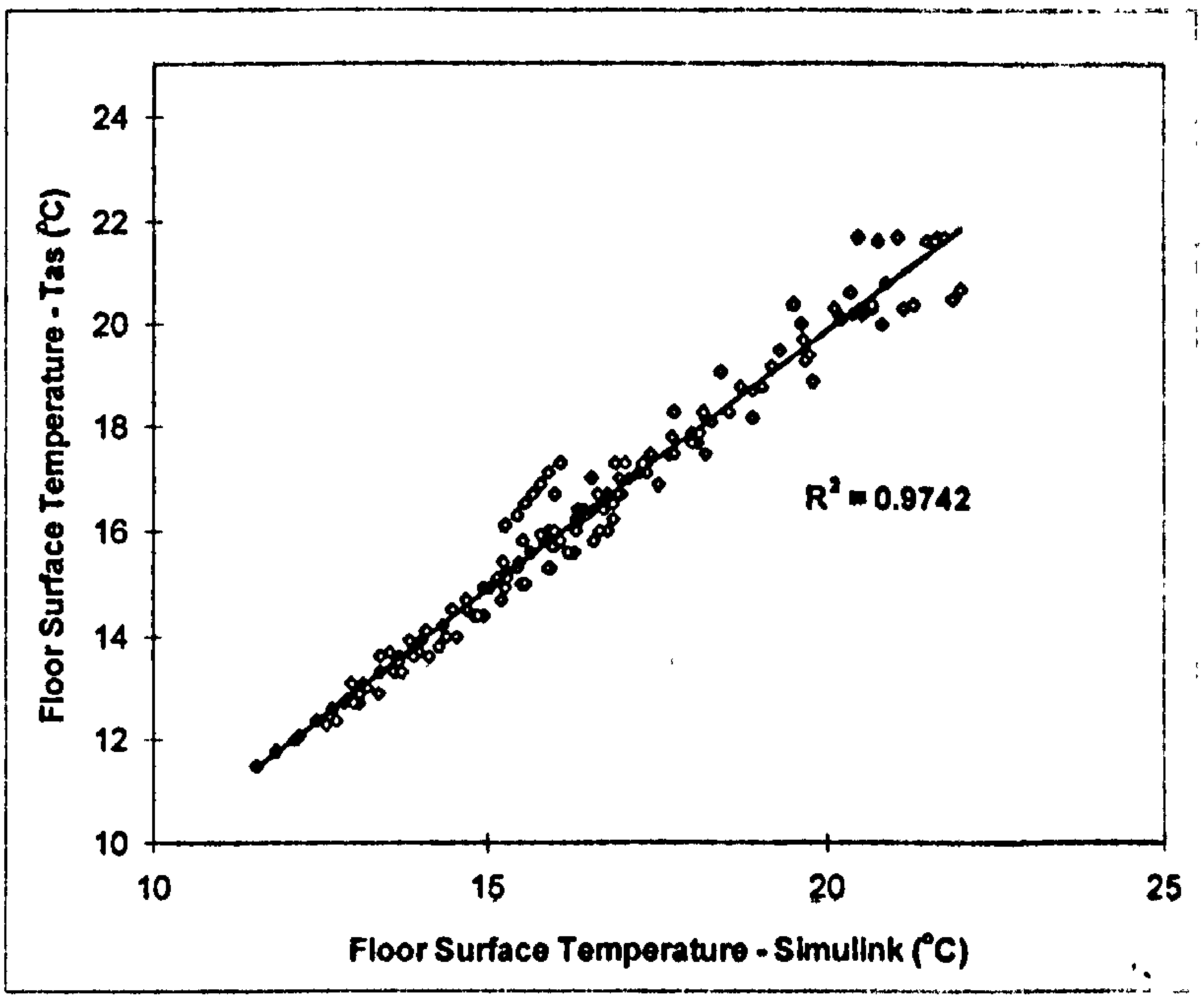

Figure 5.27. R^2 value the Simulink and Tas model predictions of the floor surface temperature, days 1 - 7.

A summary of the R^2 values obtained for the Simulink and Tas model predictions of surface temperatures are given in Table 5.8.

Surface	R^2 Value
Exterior Wall - Outer	0.91
Exterior Wall - Inner	0.99
Internal Walls	0.96
Floor	0.97
Ceiling	0.96

Table 5.8. Summary of R^2 values for the Simulink and Tas model predictions of surface temperatures, days 1 - 7.

The R^2 values for the comparison of the Simulink and Tas models for surface temperatures indicate that the Simulink model performs adequately for its intended purpose.

5.9 Conclusions and Discussion

This chapter described the theory for the simulation of the "free running" single zone building model constructed using Matlab and Simulink software. The Simulink model was compared to an identical model constructed using Tas to assess the Simulink model's appropriateness for developing fuzzy control strategies.

The Simulink model made similar predictions for a range of parameters when compared to the Tas model. Tas is a commercially available software tool that has been validated against real data. The coefficient of determination (R^2) results detailed in Table 5.6, Table 5.7 and Table 5.8 indicate that the Simulink model performs well against the Tas model. The Simulink model did not perform as well as was anticipated in terms of its predictions of relative humidity. However, this can be largely attributed to a summing of errors as the relative humidity uses air temperature in its calculation process.

For the purposes of developing the fuzzy control strategies it was decided that the model performed adequately. The comparison with the Tas model was intended to ensure that the Simulink model was giving reasonable results. The intention was to use the base Simulink model as a comparative tool to assess the performance of different control strategies. To this end the developed Simulink model accuracy was sufficient as any errors would be applicable to the different control strategies being compared.

Chapter 6 describes the theory used to implement HVAC components such as heat exchangers and dehumidifiers as well as conventional control algorithms. The integration of the free running building model, HVAC components models and conventional controls systems models would allow simulations of a complete building system. The fuzzy control theory was then developed using this model.

5.10 References

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6. One Zone Dynamic Model - Heating Ventilating and Air-Conditioning (HVAC) Component Theory

Nomenclature

ε	heat exchanger effectiveness
abs	absolute value
A_h	heat exchanger surface area (m^2)
c	equal percentage valve constant (dimensionless)
$c_{p,a}$	specific heat capacity of air (J/kgK)
$c_{p,w}$	specific heat capacity of water (J/kgK)
C_a	heat capacity rate of air (W/K)
C_{max}	maximum of heat capacity rates (W/K)
C_{min}	minimum of heat capacity rates (W/K)
$(CO_2)_1$	carbon dioxide concentration of re-circulated air (ppm)
$(CO_2)_2$	carbon dioxide concentration of fresh air (ppm)
$(CO_2)_3$	carbon dioxide concentration of mixed air (ppm)
Cr	heat capacity ratio (dimensionless)
C_w	heat capacity rate of water (W/K)
D_p	air mixing damper B position (0 = fully closed, 1 = fully open)
de/dt	rate of change of error from the set point
dp_s	circuit pressure drop (Pa)
dp'_s	design pressure drop in that part of the circuit influenced by the valve (Pa)
dp_v	valve pressure drop (Pa)
dp'_v	valve pressure drop at fully open (Pa)
dx_{PID}	incremental control effort
e	error from the desired set point (+/-)
e(i)	error at current time set
e(i - 1)	error at previous time step
G_{inh}	inherent valve flow fraction (dimensionless)
G_{ins}	installed valve flow fraction (dimensionless)
G_o	leakage flow (fraction of design flow) (dimensionless)
K	controller gain
K_u	ultimate controller gain
K_V	valve design flow rate (kg/s)
m_a	mass flow rate of air (kg/s)
m_w	mass flow rate of water (kg/s)
N	valve authority (fraction) (dimensionless)
NTU	Number of Transfer Units (dimensionless)
P	inlet port fraction (dimensionless)

P_{damp}	air mixing damper fractional flow rate (dimensionless)
q	heat transfer rate (W/m^2)
q_{max}	maximum heat transfer rate (W/m^2)
S_V	valve stem position (0 = down, i.e. fully closed; 100 = up, i.e. fully open)
T_1	air temperature of recirculated air (°C)
T_2	air temperature of fresh outdoor air (°C)
T_3	air temperature of mixed fresh and recirculated air (°C)
T_4	air temperature after cooling (°C)
T_5	air temperature after heating (°C)
T_6	air temperature after humidification (°C)
$T_{a,i}$	temperature of heat exchanger inlet air (°C)
$T_{a,o}$	temperature of heat exchanger outlet air (°C)
T_i	controller integral time
T_d	controller derivative time
T_s	simulation time step (seconds)
T_u	ultimate time (seconds)
$T_{w,i}$	temperature of heat exchanger inlet water (°C)
$T_{w,o}$	temperature of heat exchanger outlet water (°C)
W	humidity ratio (kg/kg)
W_1	humidity ratio of recirculated air (kg/kg)
W_2	humidity ratio of fresh outdoor air (kg/kg)
W_3	humidity ratio of mixed fresh and recirculated air (kg/kg)
W_4	humidity ratio of air after cooling (kg/kg)
W_5	humidity ratio of air after heating (kg/kg)
W_6	humidity ratio of air after humidification (kg/kg)
x_d	derivative control effort
$x_d(i)$	derivative term at the current time step
$x_d(i - 1)$	derivative term at the previous time step
x_i	integral control effort
$x_i(i)$	integral term at present time step
$x_i(i - 1)$	integral term at the previous time step
x_p	proportional control effort
$x_p(i)$	proportional term at present time step
x_{PID}	total control effort for a PID controller (positional and incremental)
U_h	overall heat transfer coefficient for a heat exchanger (W/m^2K)
V	circuit volume flow rate (m^3/s)
V'	circuit volume flow rate at design conditions (m^3/s)
V_{inh}	valve inherent volume flow rate (m^3/s)
V'_{inh}	valve inherent volume flow rate at fully open (design rated) position (m^3/s)

6.1 Introduction

Chapter 5 described the theory of the Simulink "free running" one zone building model. The aim of constructing the model was to enable the development of fuzzy control strategies. In order to achieve this objective a fully air-conditioned version of the free running model developed in Chapter 5 was required. Further a benchmark control system was required against which the developed fuzzy control strategies could be compared. The decision was made to develop a conventional Proportional + Integral +

Derivative (PID) control algorithm for the Simulink model as the benchmark control system. This chapter first considers the theory of the HVAC components used in the one zone Simulink model. These components include heat exchangers, valves, dampers and humidification equipment. It then describes the theory of the conventional PID control algorithms, developed as a benchmark, for the control of the HVAC components.

6.2 HVAC System Components

The basic components of the HVAC system are shown schematically in Figure 6.1.

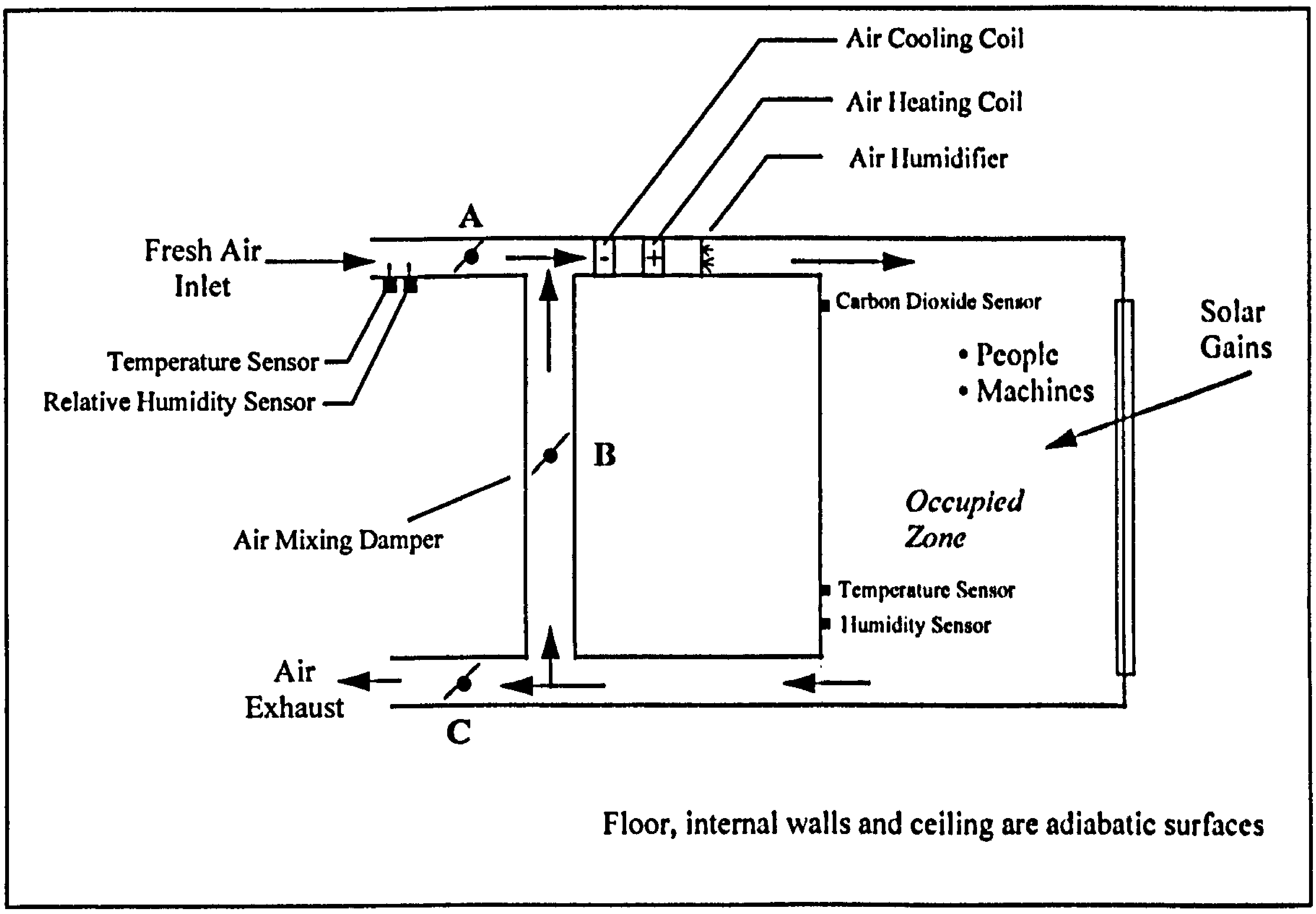

Figure 6.1. Schematic of the building zone and HVAC components used in the Simulink one zone model.

A detailed view of the HVAC components of Figure 6.1 is shown in Figure 6.2.

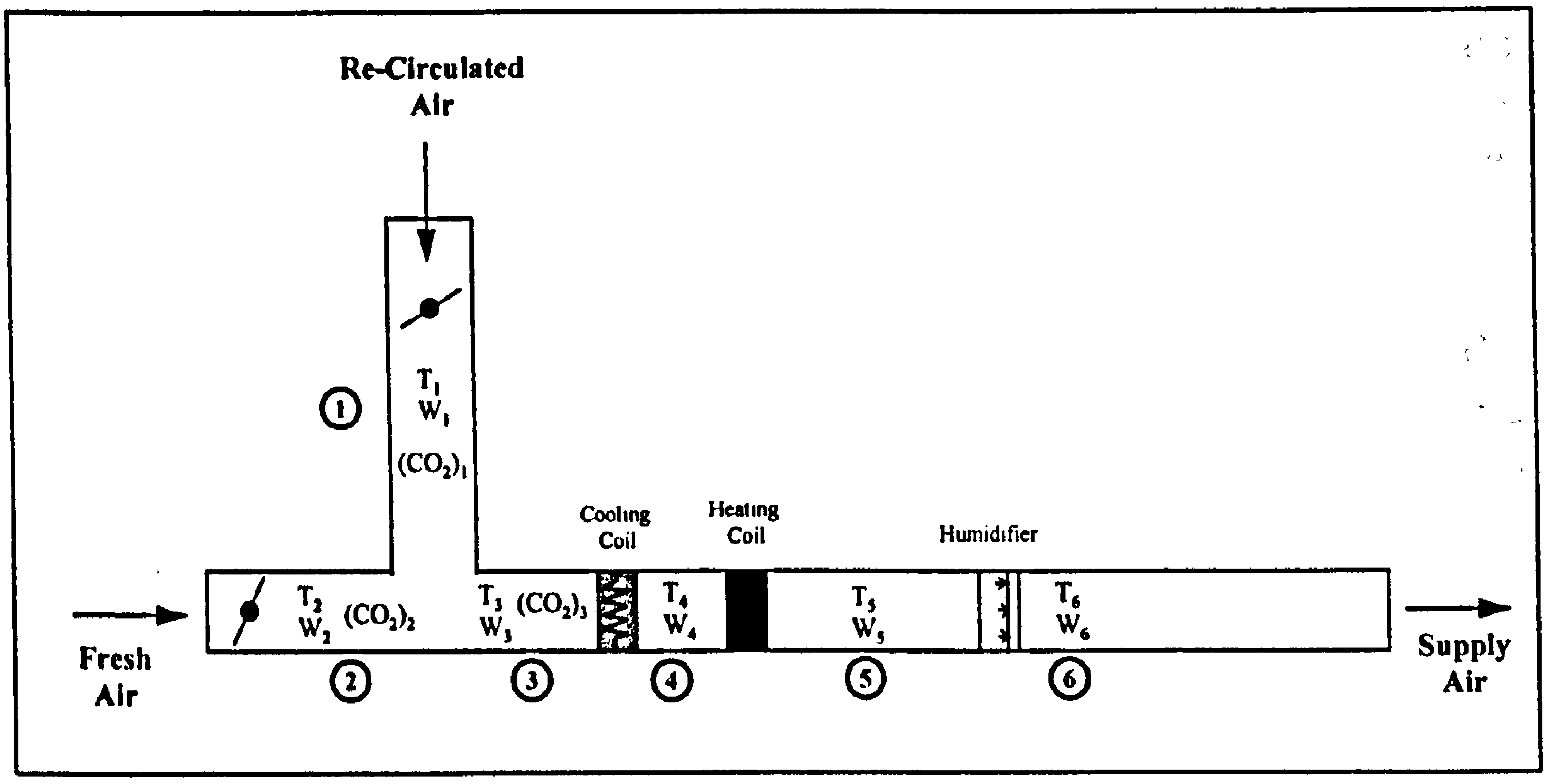

Figure 6.2. Detailed schematic of HVAC components shown in Figure 6.1.

A brief description of the components identified in Figure 6.1 and Figure 6.2 and their functions are given:-

- Air Mixing Dampers - The HVAC system model comprises a fixed volume air system in which a portion of the conditioned air from the occupied space is re-circulated. Fresh outdoor air can be introduced into the system by adjusting the three air mixing dampers. Proper control of these dampers allows the required amount of fresh air from the air inlet to mix with re-circulated air. The remainder of the re-circulated air is diverted outdoors through the exhaust outlet.
- Air Cooling Coil - Chilled water is passed through a cooling coil within the supply air duct. Sensible heat is removed from the air and the temperature of the supply air is reduced. Moisture can also be removed from the air if the air is cooled to a temperature below its dew-point. When this is the case, moisture is condensed out onto the cooling coil surface and the humidity ratio of the air is reduced. Thus the cooling coil has the dual purpose of cooling or dehumidifying the supply air.
- Air Heating Coil - Water is heated and pumped through the heating coil which is located within the supply air duct. Sensible heat is transferred to the air causing a rise in the temperature of the air with no associated change in the latent heat of the supply air. The air heating coil also serves as a reheat device when over cooling of the air has occurred for dehumidification purposes.
- Humidifier - Moisture is added to the supply air by injecting steam into the supply air. This increases the humidity ratio of the air and thus provides a method of humidifying the supply air.
- Sensors - these are used to determine the values of the controlled environmental parameters within the space and to determine the ambient conditions. For the purposes of the development of the fuzzy control strategies, the values obtained from internal temperature, humidity and CO_2 sensors and external temperature and humidity sensors were considered. The values of these parameters were used as inputs to the controllers.

The models of the HVAC systems components comprised controllers, valves, dampers, a humidifier and heat exchangers. The links between the HVAC systems components is shown graphically in Figure 6.3.

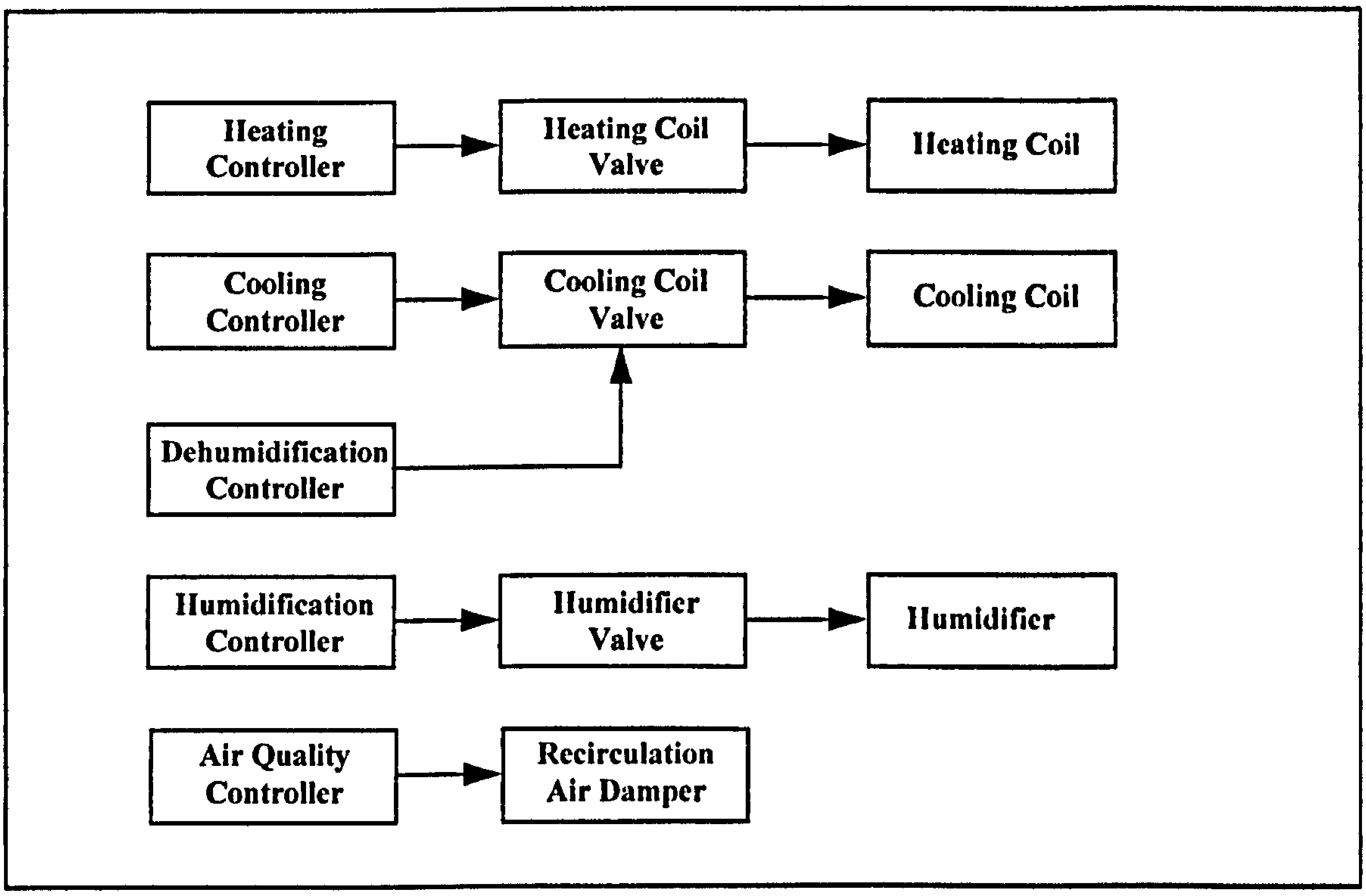

Figure 6.3 Links between HVAC system components.

Time delays were incorporated into the Simulink model to represent time delays caused by the ductwork. The model assumed that air travelling through the ductwork took 30 seconds to reach its destination. The theory used in implementing the HVAC components into the Simulink model is described in the following sections referring to Figure 6.1 and Figure 6.2.

6.2.1 Re-Circulated and Fresh Air Mixing

The HVAC system adopted for the purposes of the dynamic model is of the fixed air volume type. A controllable amount of fresh air is supplied to the zone in order to maintain levels of acceptable air quality within the zone. The amount of fresh air supplied to the zone is determined by the position of the three air mixing dampers, A, B and C, shown in Figure 6.1. For the purposes of the Simulink model it is assumed that controlling the air mixing damper B, in the duct section joining the exhaust and fresh ducts of the system, would provide a control mechanism for the amount of fresh air supplied. It was assumed that the adjustment of air mixing damper B will automatically control air mixing dampers A and C to provide the required amount of fresh air for modelling purposes.

It is therefore necessary to calculate the conditions of the air after recirculated and fresh air has been mixed.

The ratio of fresh air to recirculated air required is determined by a controller. When the two quantities of air at different temperatures, moisture contents and carbon dioxide concentrations are mixed, the resultant conditions of the air will be related to the air fractional flow rate through the damper (P_{damp}). The temperature, humidity ratio and CO_2 concentration at point 3 in Figure 6.2 are given by Equation 6.1, Equation 6.2 and Equation 6.3 respectively. The relationship between the fractional flow rate (P_{damp}) and the damper position (D_p) is given in Section 6.5.

$$T_3 = T_2 - P_{damp}(T_2 - T_1)$$

Equation 6.1

$$W_3 = W_2 - P_{damp}(W_2 - W_1)$$

Equation 6.2

$$(CO_2)_3 = (CO_2)_2 - P_{damp}((CO_2)_2 - (CO_2)_1)$$

Equation 6.3

The minimum CIBSE (1987) recommended ventilation rate for smokers (30 litres/s/p) has been used for the model as a maximum required ventilation rate via mechanical ventilation. Assuming a maximum occupancy density for the zone of 15 people, a maximum fresh air ventilation rate 450 litres/s (0.45 m^3/s) is required in the Simulink model.

6.2.2 Air Heating and Cooling - Heat Exchangers

For the purposes of simulating the heating and cooling coils within the Simulink model, cross-flow heat exchangers were utilised. The "Number of Transfer Units" (NTU) method was adopted. The theory is explained below.

Assumptions

- Negligible heat loss to surroundings and negligible potential and kinetic energy changes.
- Constant heat exchanger material properties
- Water inlet temperature is constant and known

The heat exchanger is of a cross flow type with known overall air side heat transfer coefficient. The heat transfer from the heated or chilled water to the air passing over the heat exchanger was calculated using Equation 6.4 to Equation 6.15.
First the heat capacity rates of the air and water flows are calculated using Equation 6.4 and Equation 6.5 respectively.

$$C_a = m_a c_{p,a}$$

Equation 6.4

$$C_w = m_w c_{p,w}$$

Equation 6.5

The minimum of the heat capacity rates was then selected using Equation 6.6.

$$C_{min} = \min(C_a, C_w)$$

Equation 6.6

The Number of Transfer Units was calculated using Equation 6.7.

$$NTU = \frac{U_h A_h}{C_{min}}$$

Equation 6.7

The maximum heat transfer rate from the water in the heat exchanger to the air flowing over the heat exchanger was calculated using Equation 6.8.

$$q_{max} = C_{min}[abs(T_{a,i} - T_{w,i})]$$

Equation 6.8

The actual heat transfer rate was calculated by multiplying the maximum heat transfer rate achievable by the heat exchanger effectiveness, see Equation 6.9.

$$q = \varepsilon q_{max}$$

Equation 6.9

The effectiveness of a single pass cross flow heat exchanger as used for the Simulink model is given by Equation 6.10 (Incropera and de Witt 1990) where the heat capacity ratio, Cr, is defined by Equation 6.11.

$$\varepsilon = 1 - \exp\left[\left(\frac{1}{C_r}\right)(NTU)^{0.22}\left\{\exp\left[-C_r(NTU)^{0.78}\right] - 1\right\}\right]$$

Equation 6.10

$$C_r = \frac{C_{min}}{C_{max}}$$

Equation 6.11

The outlet temperatures of the air and water flows for a heat exchanger in cooling mode are determined from the overall energy balances given by Equation 6.12 and Equation 6.13

$$T_{a,o} = T_{a,i} - \frac{q}{m_a c_{p,a}}$$

Equation 6.12

$$T_{w,o} = T_{w,i} + \frac{q}{m_a c_{p,w}}$$

Equation 6.13

The outlet temperatures of the air and water flows for a heat exchanger in heating mode are determined from the overall energy balances given by Equation 6.14 and Equation 6.15.

$$T_{a,o} = T_{a,i} + \frac{q}{m_a c_{p,a}}$$

Equation 6.14

$$T_{w,o} = T_{w,i} - \frac{q}{m_a c_{p,w}}$$

Equation 6.15

Figure 6.4 shows the Simulink representation of the heat exchanger as an example of the block representation of HVAC components within the Simulink computing environment.

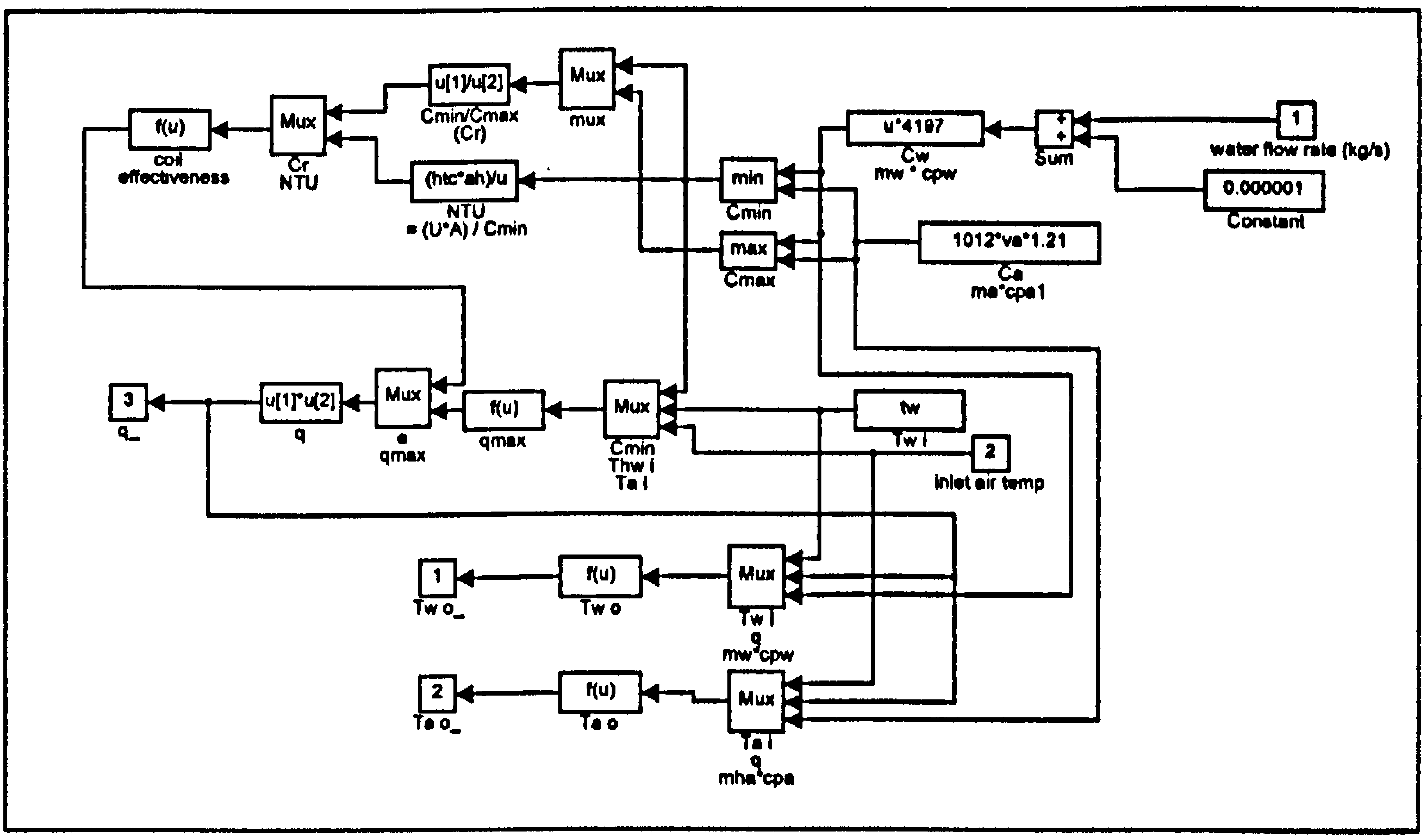

Figure 6.4. Simulink block diagram representation of the heat exchanger NTU method calculations.

6.2.3 Air Dehumidification

Dehumidification of the supply air is achieved through the control of the cooling coil to allow the air to be cooled to below its dew-point. This causes a reduction in the moisture content of the air. It was assumed that the heat transfer properties for the cooling coil when dehumidification occurred were the same as for a dry coil in order to avoid over complicating the model.

Cooling the air to below its dew-point for dehumidification purposes may result in the air being cooler than required for air temperature purposes. For this reason the heating coil was placed after the cooling coil in the Simulink model. This enables the heating coil to reheat the air so that air can continue to be delivered to the zone at the desired temperature.

6.2.4 Air Humidification

The Simulink model assumes a steam humidification unit as the last component in the air handling section of the HVAC system, see Figure 6.1 and Figure 6.2. The steam humidifier model was selected as moisture can be added to the air with virtually no effect on the air temperature. The response to control requests is also almost immediate.

The Simulink steam humidifier model is capable of adding between 0 and 0.02 kg/s of moisture to the air passing over the humidifier at 2675 kJ/kg and 100°C. The enthalpy of the air is calculated prior to humidification and after humidification. This allowed the small temperature change to be calculated.

6.3 Valves

Controllers within the Simulink model were designed to give outputs of between zero and one. The controller output signals were then used to set the valve position. A controller output of one was considered as meaning the valve was completely open while a value of zero was considered as the valve being completely closed. However, the relationship between the position of a valve and the flow of a fluid through the valve is not linear. For this reason a valve model was developed for insertion in the Simulink model which was representative of the characteristics of a real valve. The valve model developed for testing the characteristic interaction with the developed heat exchanger models was based on a paper published by Underwood and Edge (1995), the theory of which is detailed below.

6.3.1 Valve Theory

Figure 6.5 represents the valve and circuit for a three port system. The heating and cooling coils developed for the model assume this type of valve system, a constant water temperature, and a constant water flow rate in the "combined flow" part of the circuit. When heating or cooling is required the valve is opened and heated or chilled water is diverted into the "inlet sub-circuit" and through the heat exchanger. The three-port valve model was used to determine the flow characteristic of the valve, i.e. the flow rate in the inlet sub-circuit with respect to the valve stem position.

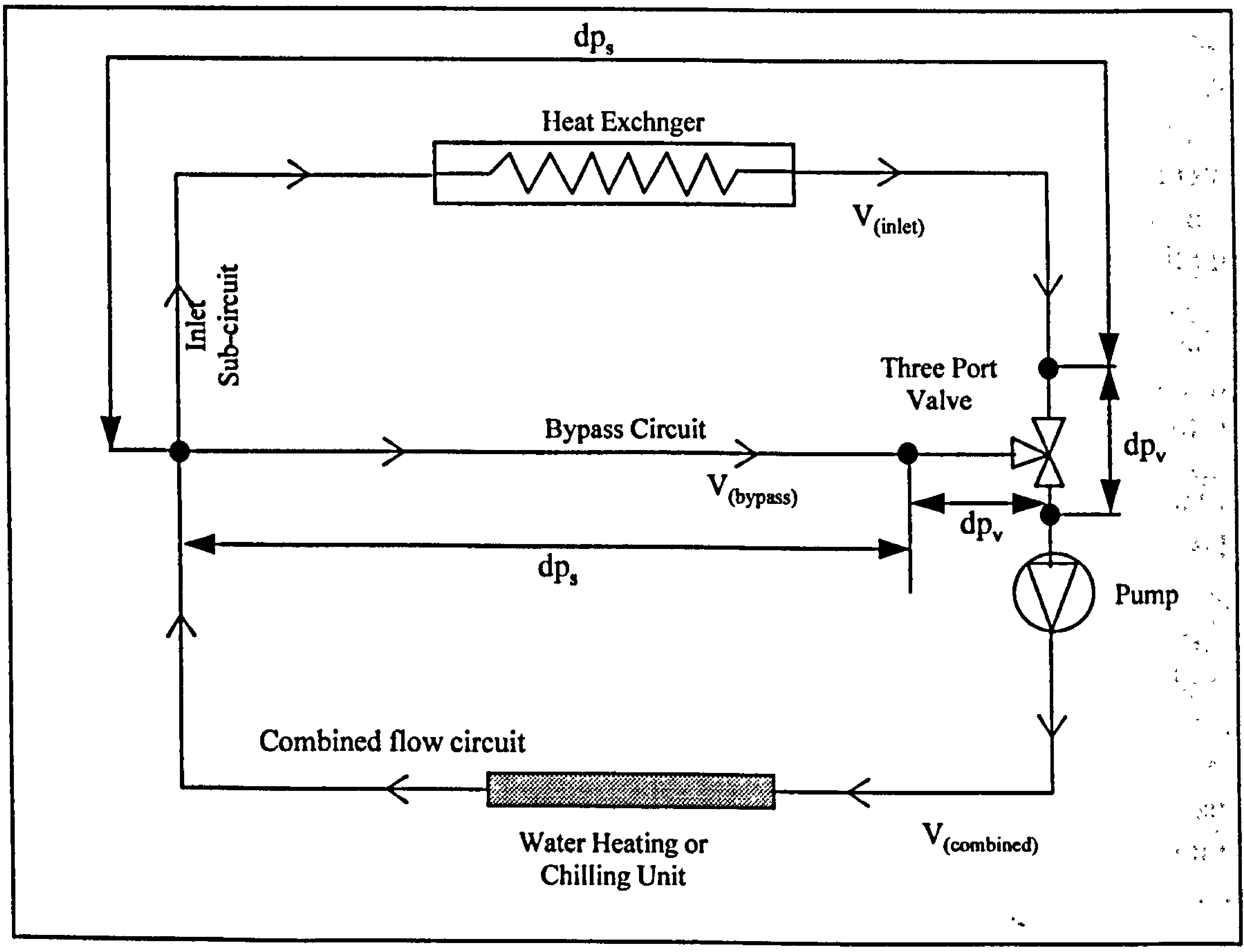

Figure 6.5. Schematic circuit layout for three port valve system.

For a linear valve the inherent characteristic can be expressed by Equation 6.16.

$$G_{inh} = G_o + P(1 - G_o)$$

Equation 6.16

For an equal percentage (=%) valve, under constant pressure conditions, equal increments will produce equal ratios of flow as described by Equation 6.17.

$$\frac{dG_{inh}}{G_{inh}} \alpha \ dP$$

Equation 6.17

By introducing a proportionality constant, c, Equation 6.17 can be rewritten as Equation 6.18.

$$\frac{dG_{inh}}{G_{inh}} = c \ dP$$

Equation 6.18

The general solution of Equation 6.18 with an allowance for leakage can be written as Equation 6.19.

$$\int_{G_o}^{G_o \le G_{inh} \le 1} \frac{dG_{inh}}{G_{inh}} = c \int_{0}^{0 \le P \le 1} dP$$

Equation 6.19

The general solution of Equation 6.19 is therefore given by Equation 6.20.

$$\ln(G_{inh}) - \ln(G_o) = cP$$

Equation 6.20

When the inlet port fraction (P) is equal to 1, and the inherent valve flow fraction (G_{inh}) is equal to 1, the equal percentage valve constant, c, is given by

$$c = -\ln(G_o)$$

Equation 6.21

Substituting Equation 6.21 into Equation 6.20 results in Equation 6.22.

$$G_{inh} = \exp[(1 - P)\ln G_o]$$

Equation 6.22

Rewriting Equation 6.22 results in an equation describing the inherent valve flow fraction as shown by Equation 6.23.

$$G_{inh} = G_o(1 - P)$$

Equation 6.23

Equation 6.16 and Equation 6.23 represent the inherent characteristic for linear and equal percentage valves respectively. The installed characteristic can be calculated from Equation 6.23.

Valves are sized with the control port open and must be sized to suit the duty with which they must cope. To size a valve correctly it is necessary to provide the correct authority in relation to the two parallel paths which it feeds. The valve authority is expressed by Equation 6.24.

$$N = \frac{dp'_v}{dp'_v + dp'_s}$$

Equation 6.24

An assumption that the pressure in any part of the circuit is related to the square of the volume flow rate as expressed by Equation 6.25 for the system and Equation 6.26 for the valve was used.

$$\frac{dp_s}{dp'_s} = \left(\frac{V}{V'}\right)^2$$

Equation 6.25

$$\frac{dp_v}{dp'_v} = \left(\frac{V}{V'}\right)^2\left(\frac{V'_{inh}}{V_{inh}}\right)^2$$

Equation 6.26

The pressure drop across the valve and the connecting circuit path remain constant under all conditions if the valve is to perform properly. Using this assumption Equation 6.27 can be written:-

$$dp_V + dp_S = dp'_V + dp'_S = \left[dp'_S + dp'_V \left(\frac{V'_{inh}}{V_{inh}} \right)^2 \right] \left(\frac{V}{V'} \right)^2$$

Equation 6.27

where the inherent valve flow fraction, G_{inh}, the installed valve flow fraction, G_{ins}, and the design pressure drop in the part of the circuit influenced by the valve, dp', are given by Equation 6.28, Equation 6.29 and Equation 6.30 respectively.

$$G_{inh} = \frac{V_{inh}}{V'_{inh}}$$

Equation 6.28

$$G_{ins} = \frac{V}{V'}$$

Equation 6.29

$$dp'_s = dp'_v \left(\frac{1 - N}{N} \right)$$

Equation 6.30

By substitution of Equation 6.28, Equation 6.29 and Equation 6.30 into Equation 6.27 it is possible to derive an equation for the installed valve flow fraction, Gins, in terms of the valve authority, N, and the inherent valve flow fraction, Ginh, see Equation 6.31.

$$G_{ins} = \frac{1}{\left[1 + N \left(\frac{1}{G^2_{inh}} - 1 \right) \right]^{\frac{1}{2}}}$$

Equation 6.31

6.4 Heat Exchanger and Valve Interaction

Both heat exchangers and valves possess non-linear characteristics between input and output values. This Section considers the non-linear characteristics inherent in the Simulink models for the heat exchangers and the valves and their interaction.

6.4.1 Simulink Heat Exchanger Model Characteristics

Heat exchangers are non-linear with respect to fluid side flow rates and heat transfer rates to the air passing over the heat exchanger. Figure 6.6 and Figure 6.7 show the relationships between inlet water flow rate and heat transfer rates to the air for the cross flow finned tube heating and cooling coil models developed using Simulink. The Simulink model assumes water in tubes at a constant temperature and adjustable flow rate and a constant rate of air flow in cross flow over tubes. The inlet air temperature is also assumed constant.

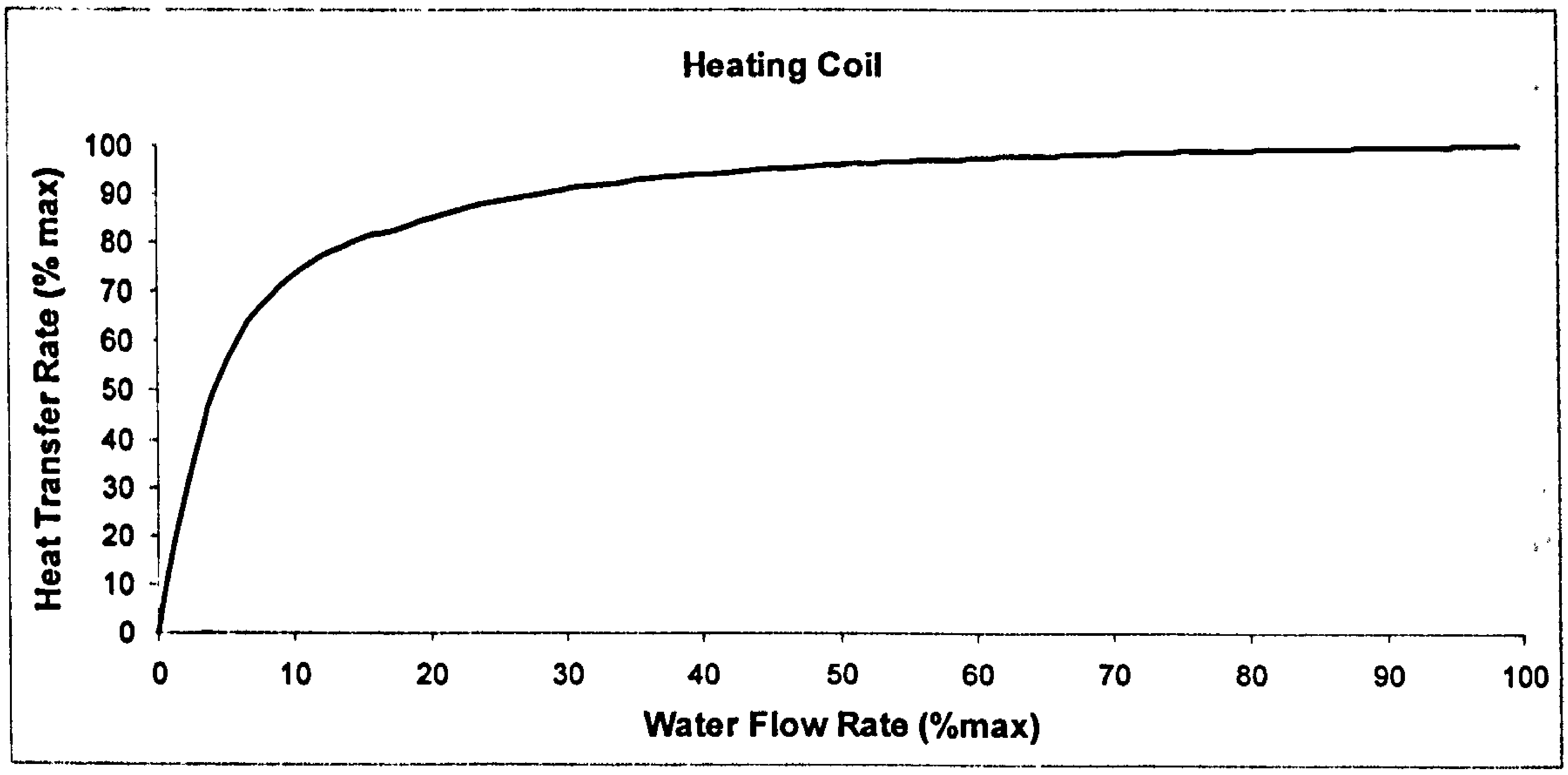

Figure 6.6. Heat transfer rate as a function of inlet water flow rate for the Simulink finned tube heating coil model.

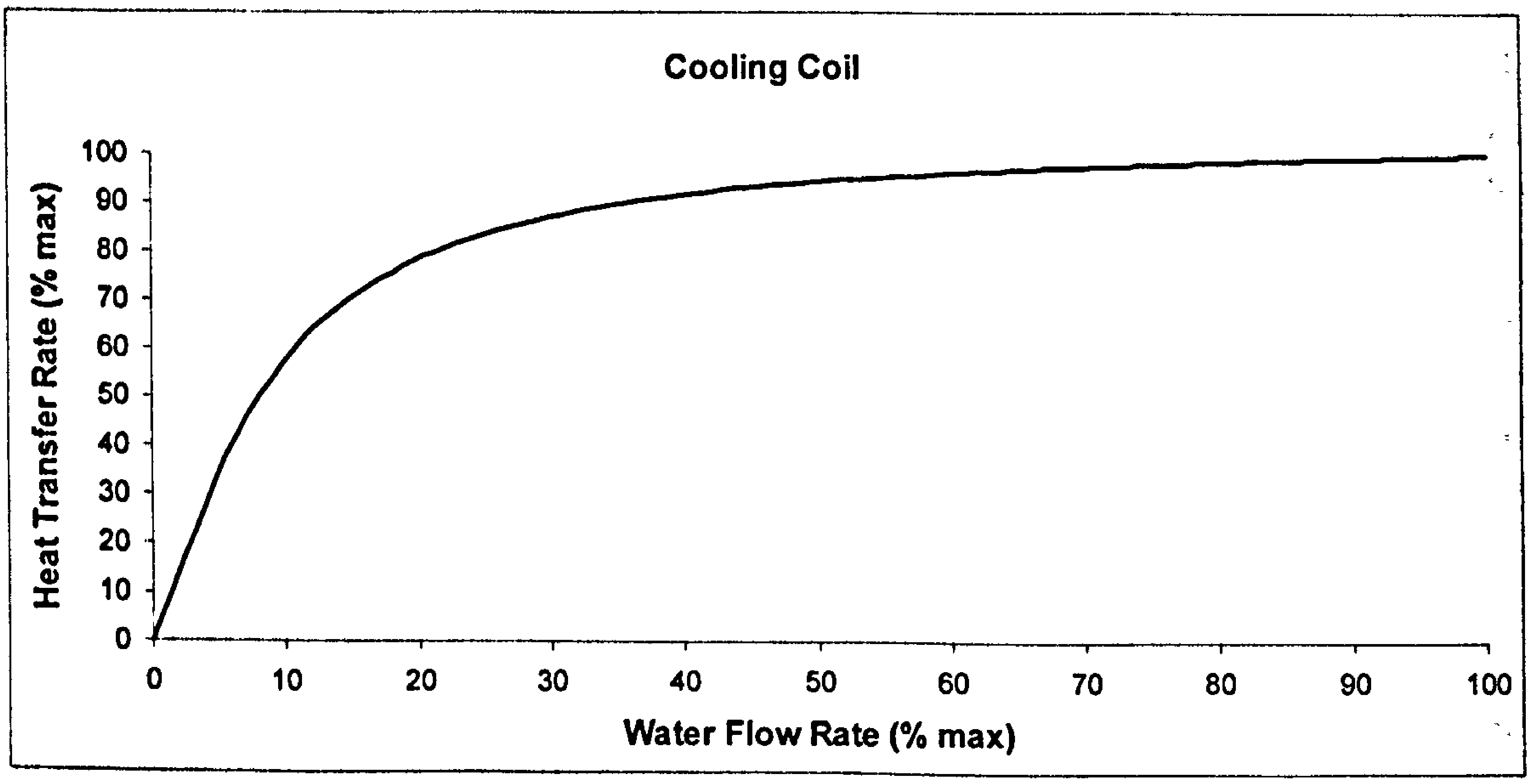

Figure 6.7. Heat transfer rate as a function of chilled fluid flow rate for the Simulink fin tubed cooling coil model.

The parameters used for the simulations of the heat exchanger models are given in Table 6.1.

Simulation Parameter	Heating Coil	Cooling Coil
Mechanical ventilation rate	0.3 m^3/s	0.3 m^3/s
Overall heat transfer coefficient	30 W/m^2K	30 W/m^2K
Heat exchanger surface area	8 m^2	25 m^2
Inlet water temperature	85 °C	5 °C

Table 6.1. Heat exchanger model parameters used during Simulink simulations.

6.4.2 Simulink Valve Model Characteristic

Valves are also non-linear with respect to valve position and fluid flow rate through the valve. Two valve models were considered.

The relationship between valve stem travel and fluid flow rate through the valve for the Simulink model developed using the theory of Underwood and Edge (1995) is shown in Figure 6.8. Port 2 of the three port equal percentage valve was the port of interest in terms of fluid flow rate through the heat exchanger.

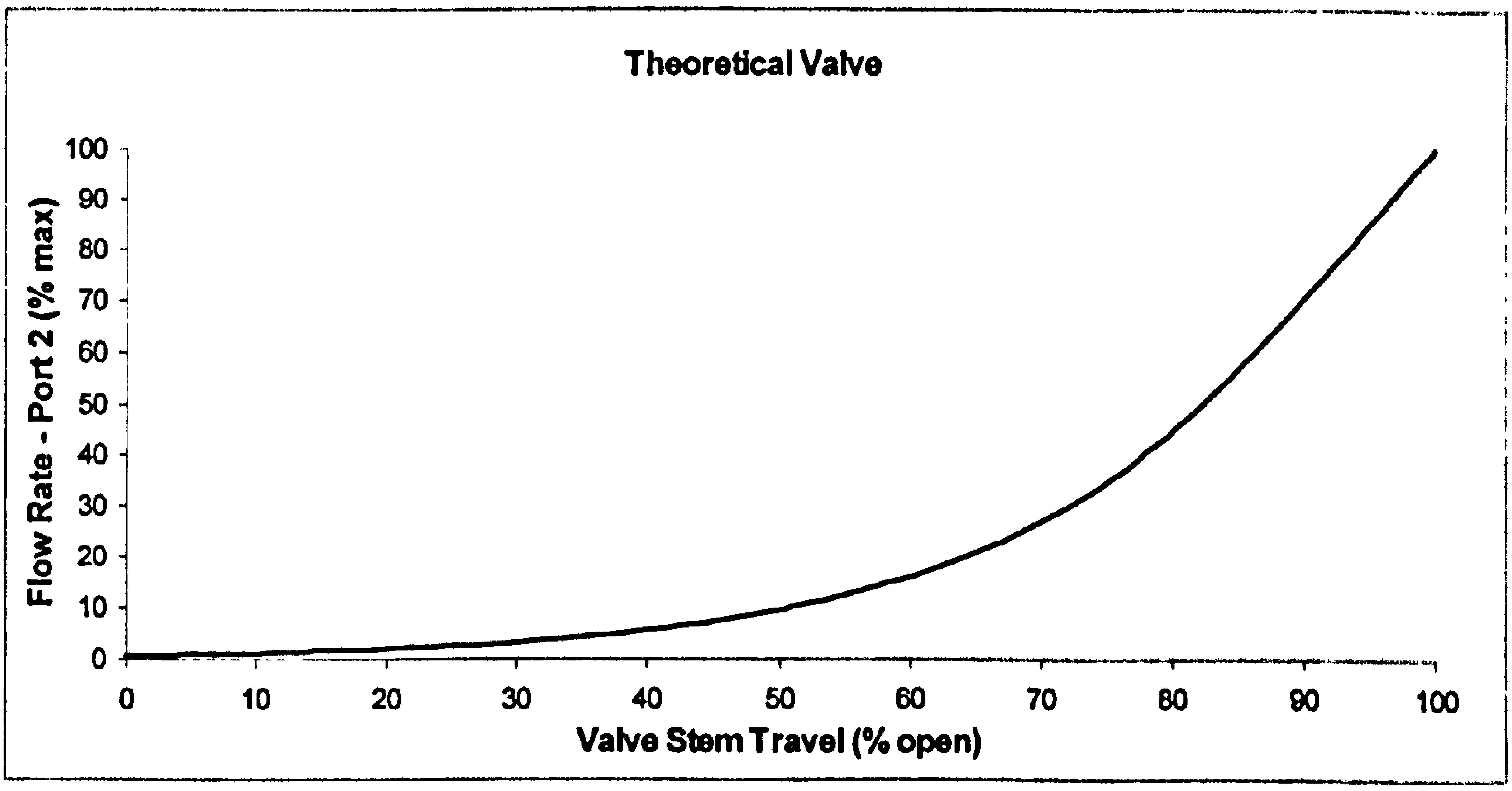

Figure 6.8. Fluid flow rate as a function of valve stem travel for the valve model based on Underwood and Edge (1995).

A characteristic of the valve developed using the theory of Underwood and Edge is the leakage flow when the valve is completely closed. This presented problems in terms of the Simulink HVAC systems model in that the heat exchangers could not be made inactive by simply setting the valve to completely closed. For this reason an empirical valve characteristic was used. The valve used for this purpose was the Satchwell MB 1402 (Satchwell 1996).

The fluid flow rate for the Satchwell MB 1402 valve is described by the empirical relationship given by Equation 6.32 (Satchwell 1996).

$$\%K_V = \frac{\%S_V^{\,2}}{100}$$

Equation 6.32

The relationship between valve stem travel and fluid flow rate through the valve for a Simulink model of the Satchwell MB1402 three port valve is shown in Figure 6.9.

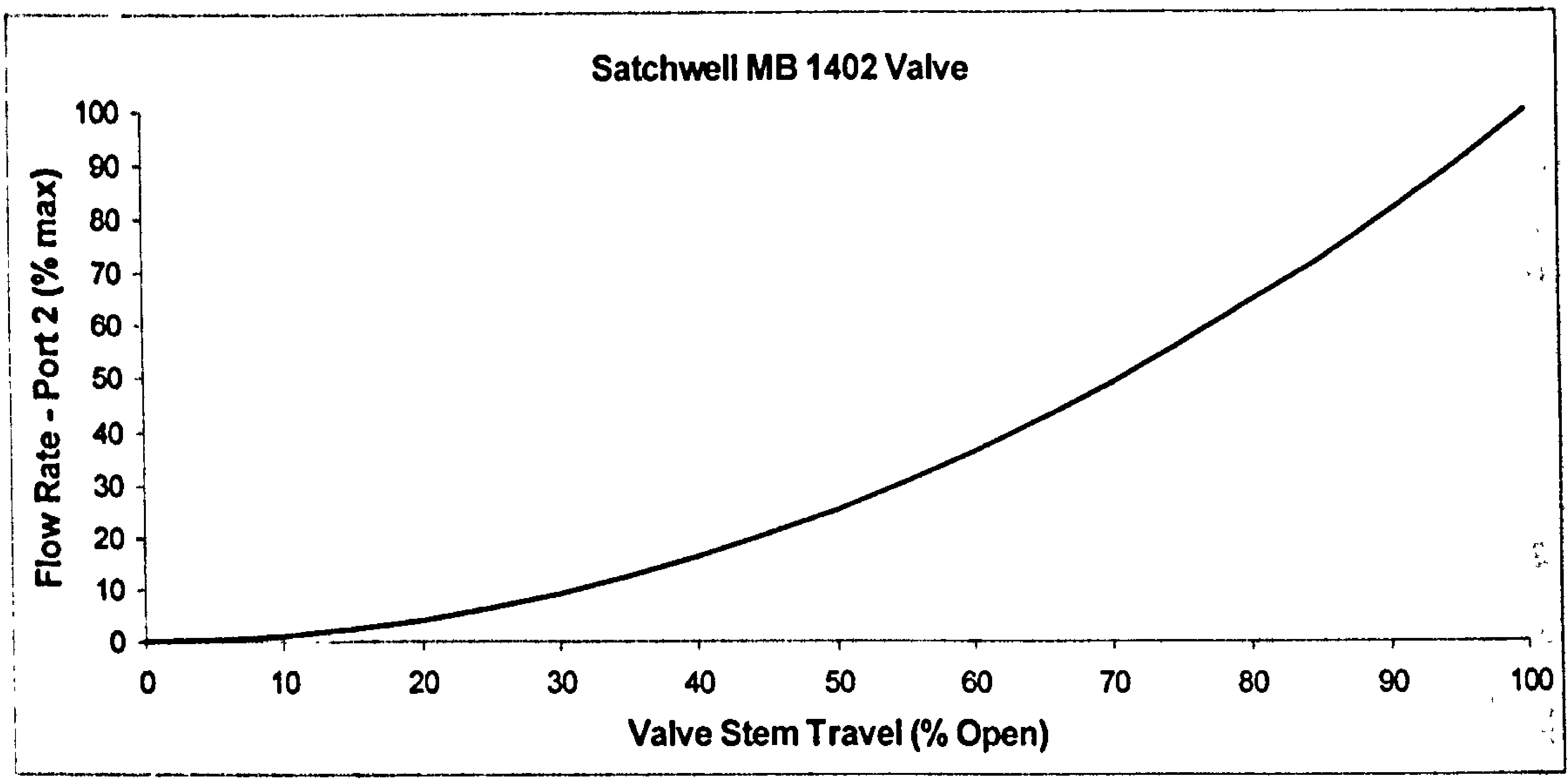

Figure 6.9. Fluid flow rate as a function of valve stem travel for the Satchwell MB 1402 three port valve as modelled using Simulink.

The Satchwell MB 1402 three port valve has a design flow rate (K_V) of 0.515 kg/s and a leakage flow rate of less than 0.5% K_V. For the purposes of the Simulink model it was assumed that there was no leakage flow rate when the valve was fully closed.

Both the valve and heat exchanger input to output relationships are highly non-linear. However, the interaction of a heat exchanger and a valve improves the situation and creates a more linear relationship between valve stem position and heat exchanger rate of heat transfer. This is discussed in Section 6.4.3.

6.4.3 Heat Exchanger and Valve Characteristics

Although the heat exchanger and valve models mimic real characteristics which exhibit high non-linearities, these characteristics are suppressed when the heat exchanger and valve operate in conjunction with each other. The stem travel versus heat transfer rate characteristics become more linear as shown in Figure 6.10 to Figure 6.13.

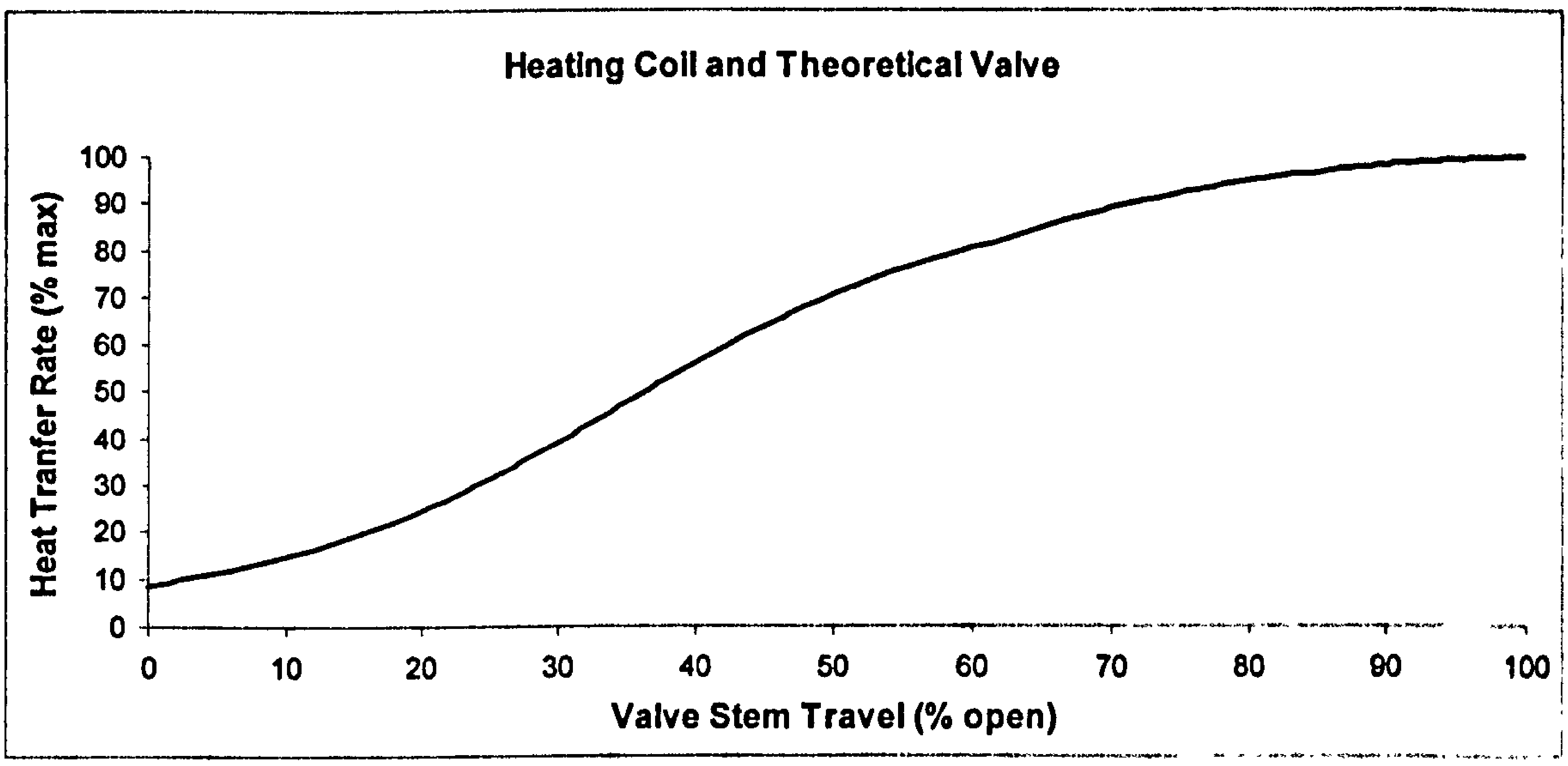

Figure 6.10. Combined valve and heating coil characteristic using the Underwood and Edge (1995) theoretical valve model.

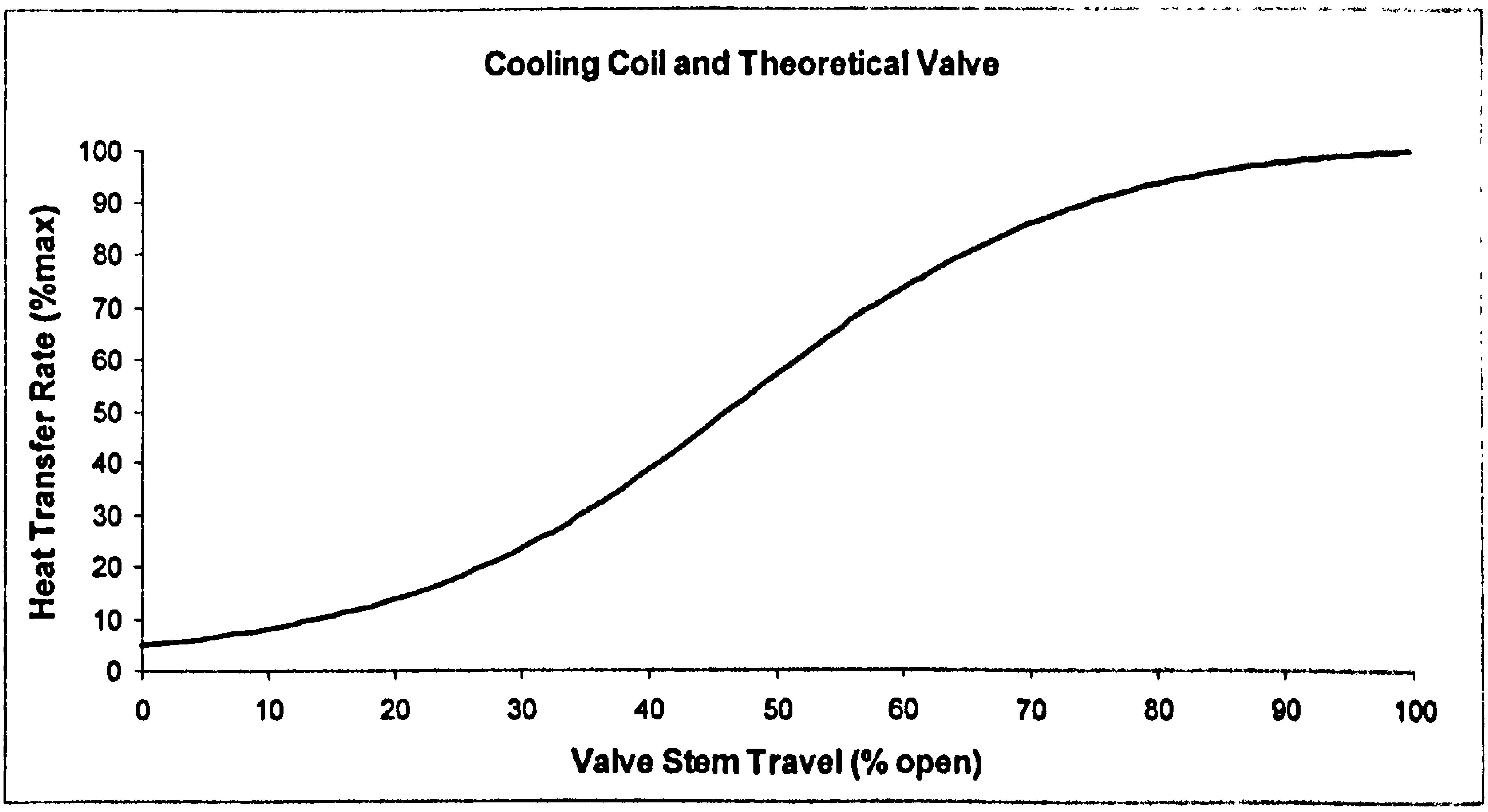

Figure 6.11. Combined valve and cooling coil characteristic using the Underwood and Edge (1995) theoretical valve model.

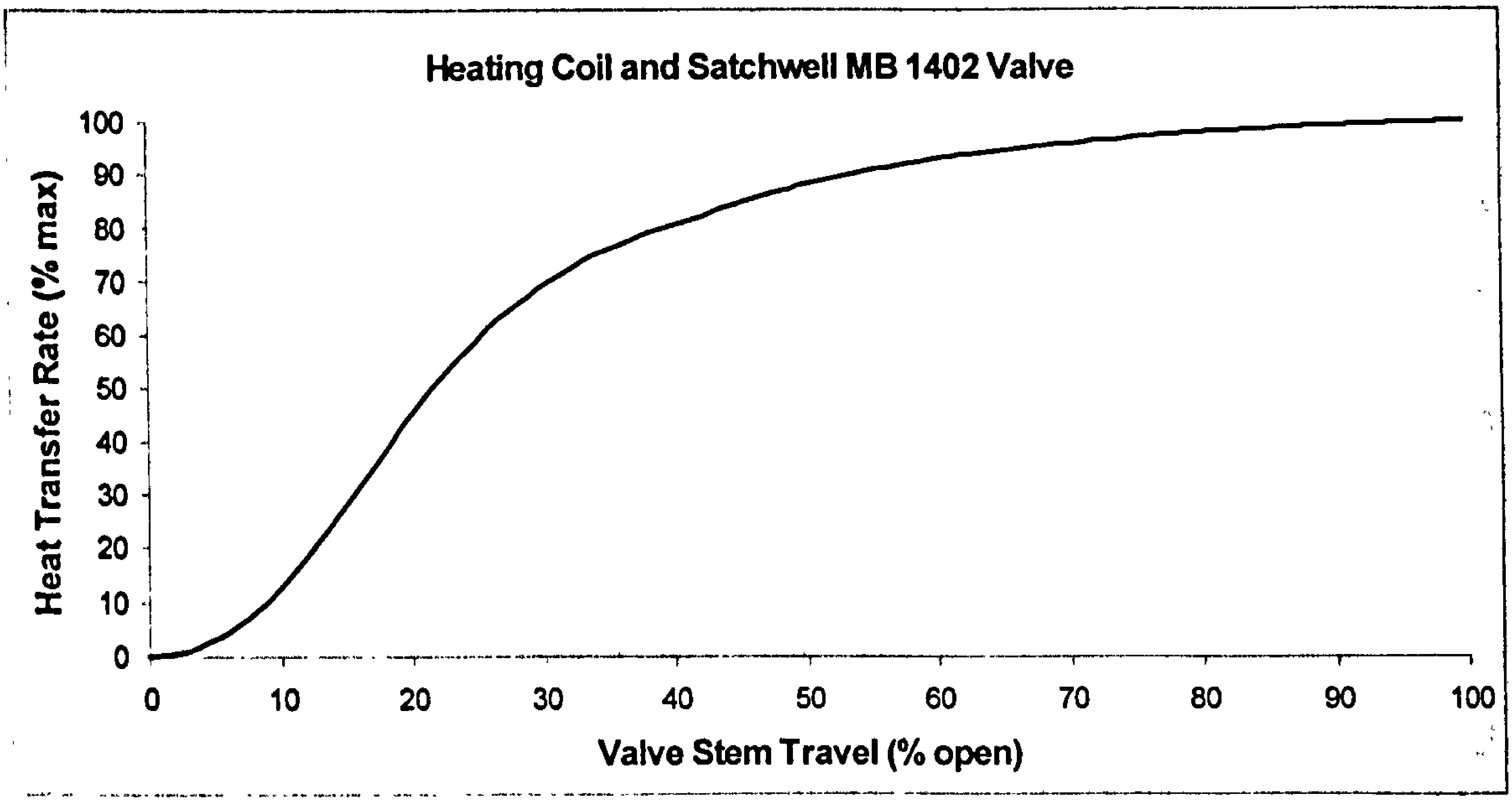

Figure 6.12. Combined valve and heating coil characteristic using the Satchwell MB 1402 valve model.

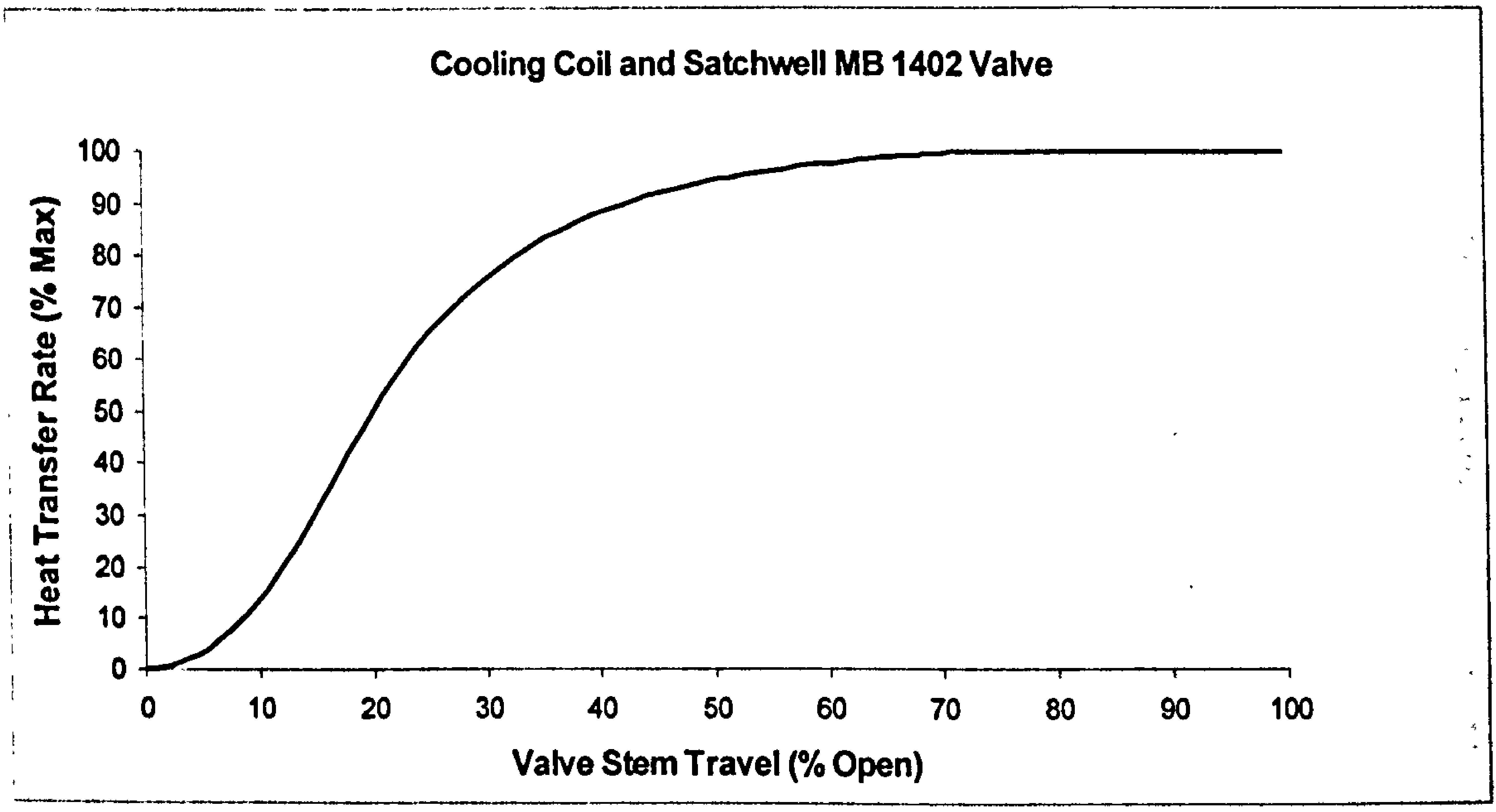

Figure 6.13. Combined valve and cooling coil characteristic using the Satchwell MB 1402 valve model.

The simulink model of the combined Satchwell valve and heat exchanger combined has a less linear characteristic than the theoretical valve model and heat exchanger. However, the real valve has linearised the heat exchanger characteristic to a large degree.

6.5 Simulink HVAC Damper Component Model

The air re-circulation damper within the Simulink one zone model was used to control the proportion of fresh outdoor air entering the constant volume HVAC system. An opposed blade air damper was assumed with the characteristic shown in Figure 6.14.

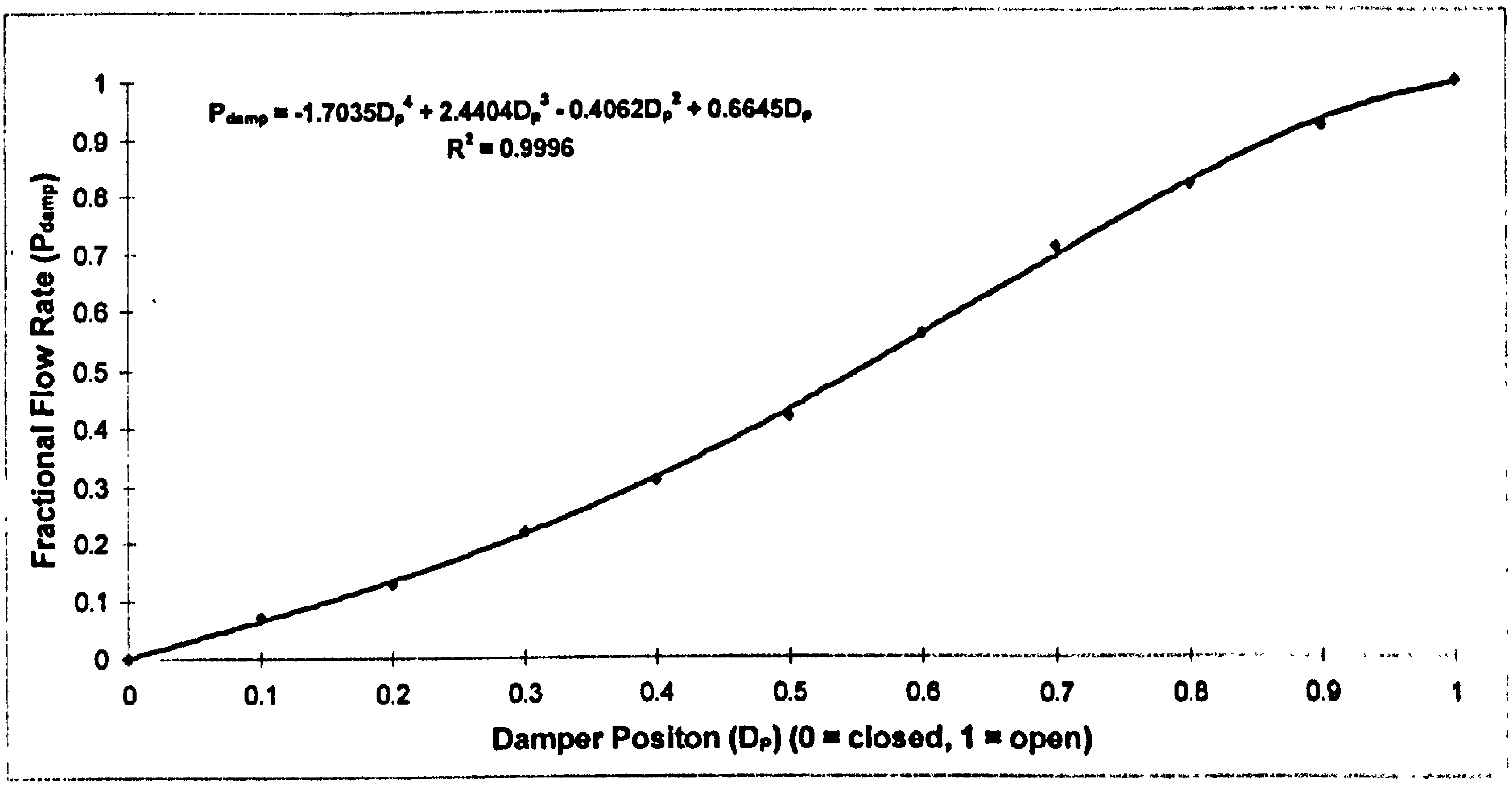

Figure 6.14. Flow rate as a function of damper blade rotation for the Simulink one zone model damper model component (Harvey 1992).

The relationship between the damper blade position and the fractional flow rate is described by the equation given in Figure 6.14.

6.6 Proportional Integral Derivative (PID) Control Theory

PID controllers were used in the Simulink one zone dynamic model as a benchmark against which to compare the developed fuzzy control strategies described in Chapters 8, 9 and 10. The PID algorithms were constructed using standard Simulink blocks which were "masked" to create PID controller blocks. Masking is a facility available in the Simulink environment by which the components of a model sub-system are hidden to the user and form a single Simulink block with a user interface for changing block parameters.

6.6.1 Integration of PID Controllers Within Building Services Systems

A schematic of a PID controller integrated into a buildings HVAC system is shown in Figure 6.15.

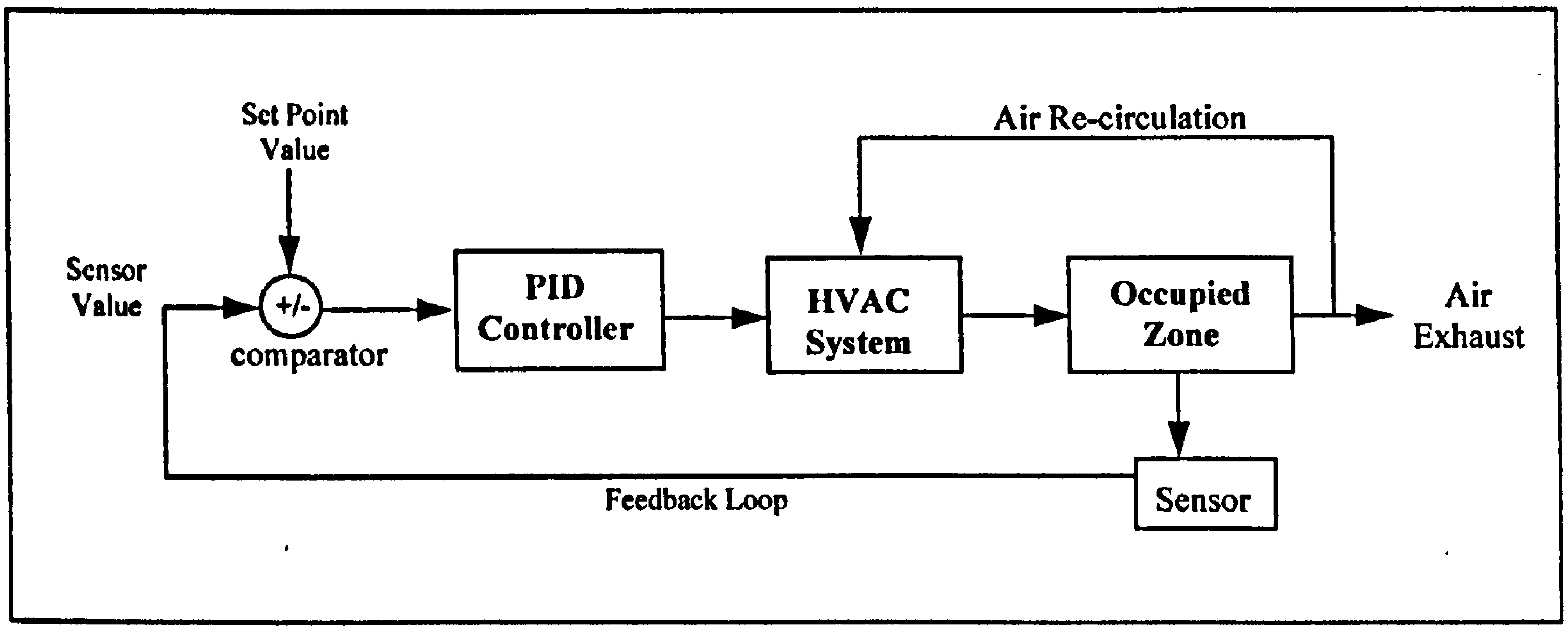

Figure 6.15. Schematic of a PID Controller integrated into a buildings HVAC system.

The operation of the control system shown schematically in Figure 6.15 is described briefly below:-

1. A sensor located in the occupied zone measures the desired environmental parameter to be controlled, e.g. temperature.
2. The comparator compares the value of the measured parameter to the desired "set point" value.
3. The difference between these values, that is the error from the set point, is calculated by the comparator and fed forward to the controller.
4. The controller uses pre-programmed algorithms and the information gained from the error signal to produce a control output in order bring the value of the zone parameter under consideration closer to the desired set point.
5. The output control signal of the controller is sent to the HVAC plant actuators which change the output of the plant, e.g. by changing the amount a valve is opened or closed.
6. The sensor monitors the zone condition and the process is repeated - hence a control feedback loop is completed. This is known as a closed system.

6.6.2 PID Control Algorithm

PID algorithms are composed of a proportional, an integral and a derivative term. Each of these is considered in the following sections.

6.6.2.1 Proportional Term

The control action of the proportional term adjusts the plant output in direct proportion to the error from the set point. The control effort, x_p, of the proportional term is described by Equation 6.33.

$$x_p = K e$$

Equation 6.33

The proportional action responds immediately to changes in error from the set point but inherently results in an off-set from the desired set point. It is also insensitive to how rapidly the error is changing. For these reasons an integral term, see Section 6.6.2.2, and a derivative term, see Section 6.6.2.3, are used in the algorithm.

6.6.2.2 Integral Term

The control action of the integral term adjusts the plant output in proportion to the integral of the error from the set point. The control effort, x_i, of the integral term is described by Equation 6.34.

$$x_i = \frac{K}{T_i} \int e\, dt$$

Equation 6.34

The integral action eliminates offset that is inherent with proportional only action controllers.

6.6.2.3 Derivative Term

The control action of the derivative term adjusts the plant output in proportion to the rate of change of the error from the set point. The control effort, x_d, of the derivative term is described by Equation 6.35.

$$x_d = K T_d \frac{de}{dt}$$

Equation 6.35

The derivative term responds rapidly to disturbances in the system and adjusts the controller action accordingly.

6.6.2.4 Proportional Integral Derivative (PID) Control Algorithm

The overall PID control algorithm is derived from the sum of the individual terms of the control modes and is described by Equation 6.36 and Equation 6.37.

$$x_{PID} = x_p + x_i + x_d$$

Equation 6.36

$$x_{PID} = K\left[e + \frac{1}{T_i} \int e\, dt + T_d \frac{de}{dt} \right]$$

Equation 6.37

6.6.3 Integration of the PID Control Algorithm in the Simulink Model

The simulation time step of the one zone model is specified before the simulation is commenced and was normally set to five seconds. Simulation time steps greater than this cause components of the model to become unstable.

Two types of PID control algorithm block were constructed for use in the Simulink model. These were:-

1. ***Positional Algorithm*** - the output of the controller specifies the desired position of the valve at each simulation time step, i.e. the controller calculates the absolute position of the valve.
2. ***Incremental Algorithm*** - the controller specifies the amount by which the valve should be moved from its present position at each simulation time step, i.e. the controller is in effect unaware of the valve's position but makes a decision on whether its position should be changed.

6.6.3.1 Positional PID Algorithm

The individual terms of the positional algorithm are given by Equation 6.38, Equation 6.39 and Equation 6.40 (Golten and Verwer 1991).

$$x_p(i) = Ke(i)$$

Equation 6.38

$$x_i(i) = x_i(i-1) + \frac{KT_s}{2T_i}[e(i) + e(i-1)]$$

Equation 6.39

$$x_d(i) = \frac{KT_d}{T_s}[e(i) - e(i-1)]$$

Equation 6.40

The complete positional PID algorithm is described by Equation 6.41.

$$x_{PID} = Ke(i) + \left\{x_i(i-1) + \frac{KT_s}{2T_i}[e(i) + e(i-1)]\right\} + \left\{\frac{KT_d}{T_s}[e(i) - e(i-1)]\right\}$$

Equation 6.41

The Simulink model representation of the positional algorithm described by Equation 6.41 is shown in Figure 6.16.

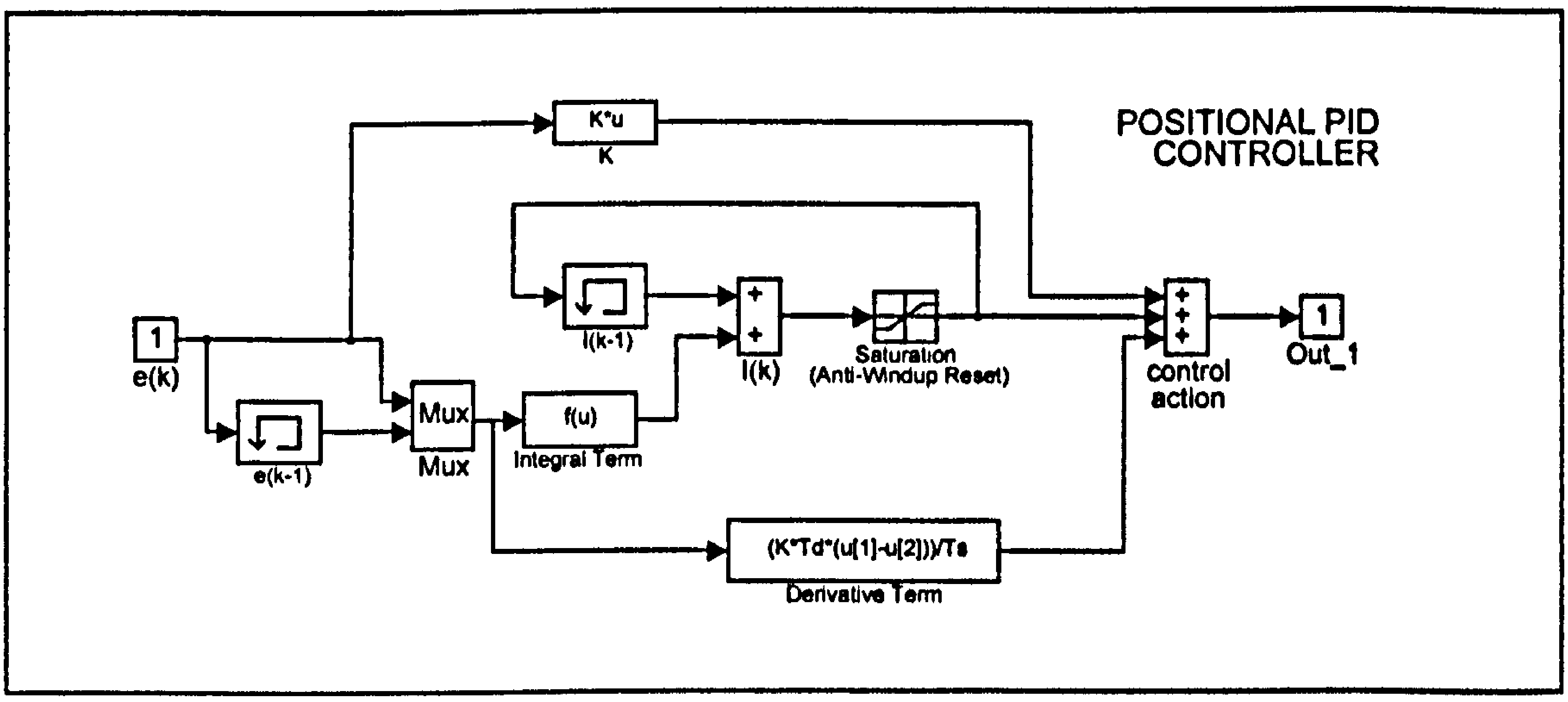

Figure 6.16. Simulink block representation of the positional PID control algorithm described by Equation 6.41.

The positional PID control algorithm has an "Anti-Windup Reset" limiter placed in the integral forward path, see Figure 6.16. This is to prevent a relatively large build up in the integral term when the controlled parameter is not able to reach the desired set point for a period of time, e.g. when the plant is operating at full capacity but not reaching the required set point for the zone parameter under consideration. Anti-windup reset is achieved by setting the limits on the forward path of the integral term between the maximum and minimum values for the control output effort (for the one zone Simulink model this is between zero and one). This is an inherent problem with the positional algorithm which is not present with the incremental algorithm. However, by using the "Anti-Windup Reset" term this problem is eliminated.

6.6.3.2 Incremental PID Algorithm

The incremental PID algorithm is described by Equation 6.42 and Equation 6.43.

$$dx_{PID}(i) = K[b_2e(i) + b_1e(i - 1) + b_0e(i - 2)]$$

Equation 6.42

$$x_{PID}(i) = x_{PID}(i - 1) + dx_{PID}(i)$$

Equation 6.43

The individual terms used in Equation 6.42 are defined by Equation 6.44, Equation 6.45 and Equation 6.46.

$$b_o = \frac{T_d}{T_s}$$

Equation 6.44

$$b_1 = \left(\frac{T_s}{2T_i} - \frac{2T_d}{T_s} - 1\right)$$

Equation 6.45

$$b_2 = \left(\frac{T_s}{2T_i} + \frac{T_d}{T_s} + 1\right)$$

Equation 6.46

The Simulink model representation of the incremental PID control algorithm is shown in Figure 6.17.

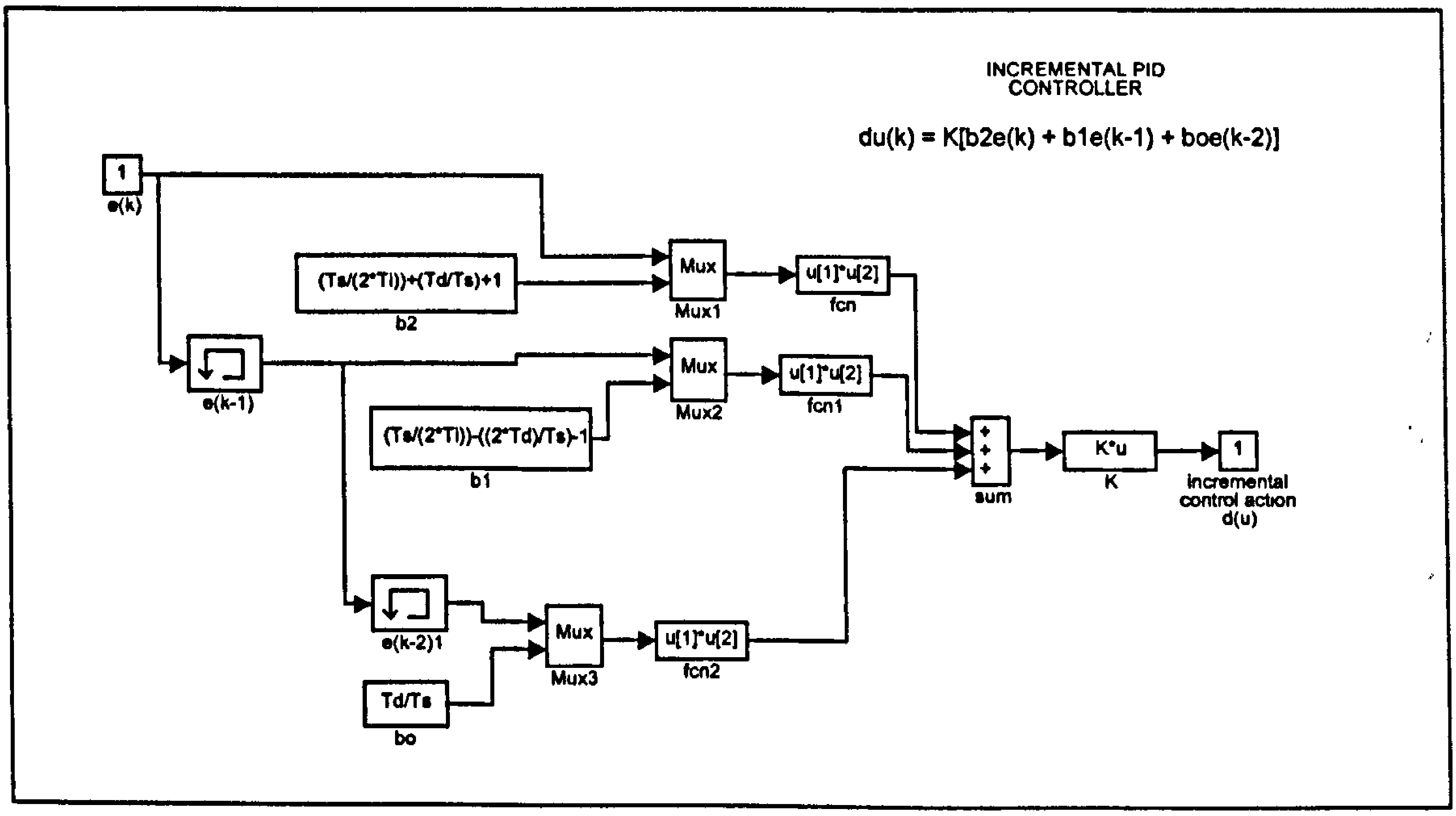

Figure 6.17. Simulink block representation of incremental PID control algorithm described by Equation 6.43.

The "masked" PID control algorithm blocks are shown in Figure 6.18. The masked Simulink blocks created for the control algorithms allows them to be copied to different parts of the model effortlessly. By double clicking on a block the user can enter values for the controller gain, integral time, derivative time and simulation time step desired.

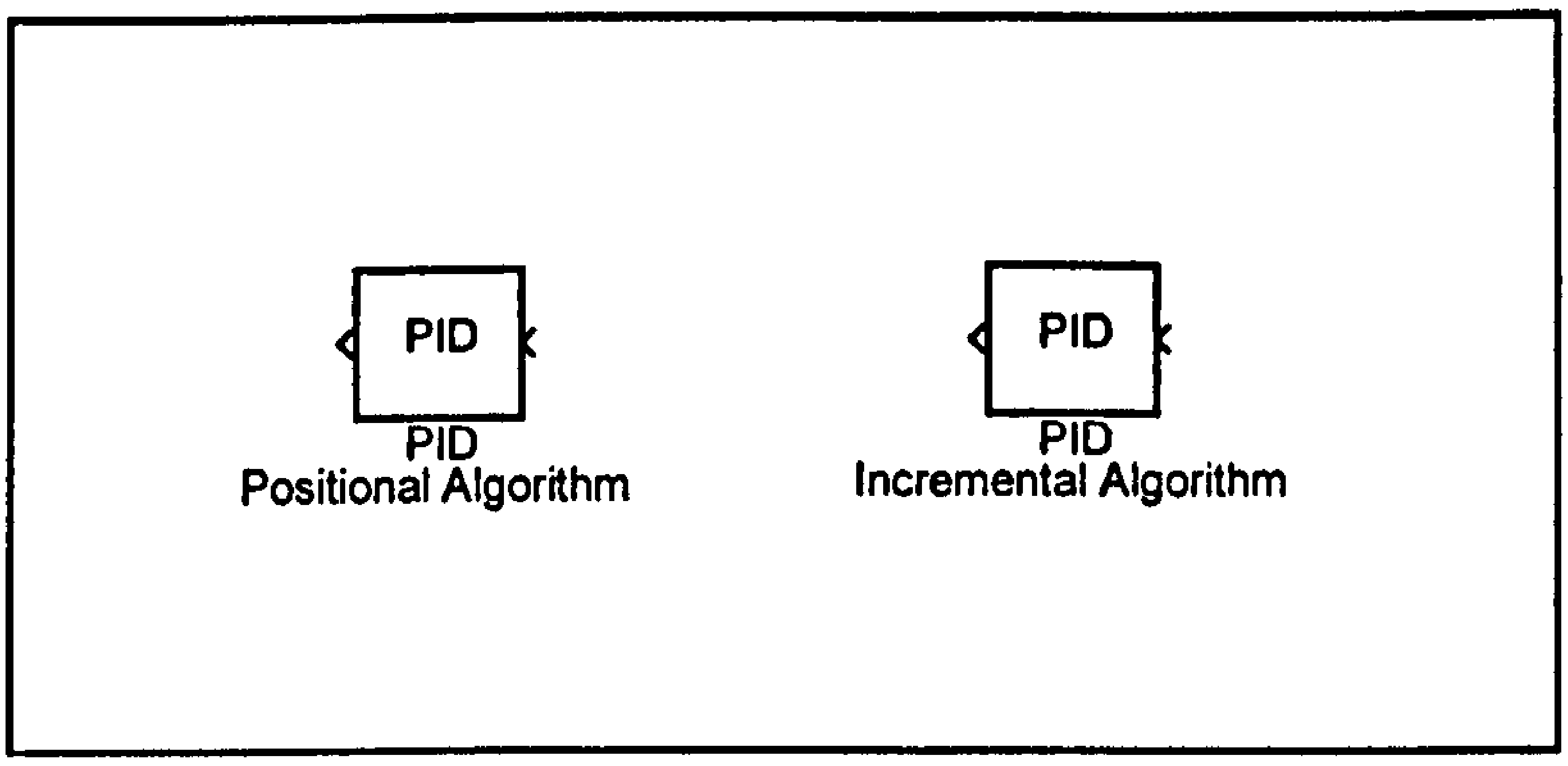

Figure 6.18. Masked Simulink PID control algorithm blocks for positional and incremental type controllers.

6.6.4 PID Controller Tuning

To ensure that the PID controllers perform correctly, the values for the controller gain (K), the integral time (T_i) and the derivative time (T_d) were deduced using an appropriate tuning method. The tuning parameter values used depend on the characteristics of the building structure and fabric, the HVAC plant and spatial arrangement. Therefore the PID controllers needed to be tuned for their specific purposes. Any changes in the building or HVAC plant characteristics cause the controller to become detuned. Where a controller becomes detuned with respect to its application the controller may cause under performance of the building services system or loss of stability in HVAC plant operation.

Two PID controller tuning methods that are commonly used were devised by Zeigler and Nichols during the 1940s (Golten 1991). These methods are commonly referred to as (i) the continuous cycling method and (ii) the reaction curve method. The method used for tuning the PID controllers used in the Simulink model was that of continuous cycling. The reaction curve method is therefore not considered further in this text.

Tuning of a PID Controller using the Continuous cycling method:-

1. Set the tuning parameters for the integral and derivative times so that they have no effect within the control algorithm, i.e. T_i = infinity, $T_d = 0$.
2. Settle the plant near to its normal operating condition, i.e. within the Simulink model set up input data files which require the plant to operate at nominal load conditions, e.g. if the heating controller is being considered set the outdoor temperature to a low value so that the heating plant is required to operate.
3. With the controller in proportional mode only and the plant settled introduce a set point change (5% - 10% for example). This will cause the plant and the controlled zone parameter to start oscillating. If it does not, increase the proportional gain until this effect is obtained.
4. With the plant valve position oscillating, one of three situations will occur (i) the amplitude of the oscillations will become smaller as the simulation proceeds, see Figure 6.19 - the proportional gain should be increased or (ii) the amplitude of the oscillations will remain constant, see Figure 6.20 - this means the controller gain is at or near the value of the controller ultimate gain (K_u) or (iii) the amplitude of the oscillation increases as the simulation proceeds, see Figure 6.21 - the system has

become unstable and the controller gain is too large. In this case the controller gain should be reduced slightly.

5. The desired value of the controller gain is the ultimate gain (K_u). It is controller gain value that is obtained just before the system starts to become unstable as the controller gain is increased during tuning.
6. The desired value for the ultimate time (T_u) is the period of the oscillations at the point just before the system becomes unstable, see Figure 6.20.
7. The actual values for the controller gain, the integral time and the derivative time that should be used for the tuned PID controller are calculated from the ultimate gain (K_u) and the ultimate time (T_u) as given in Table 6.2.

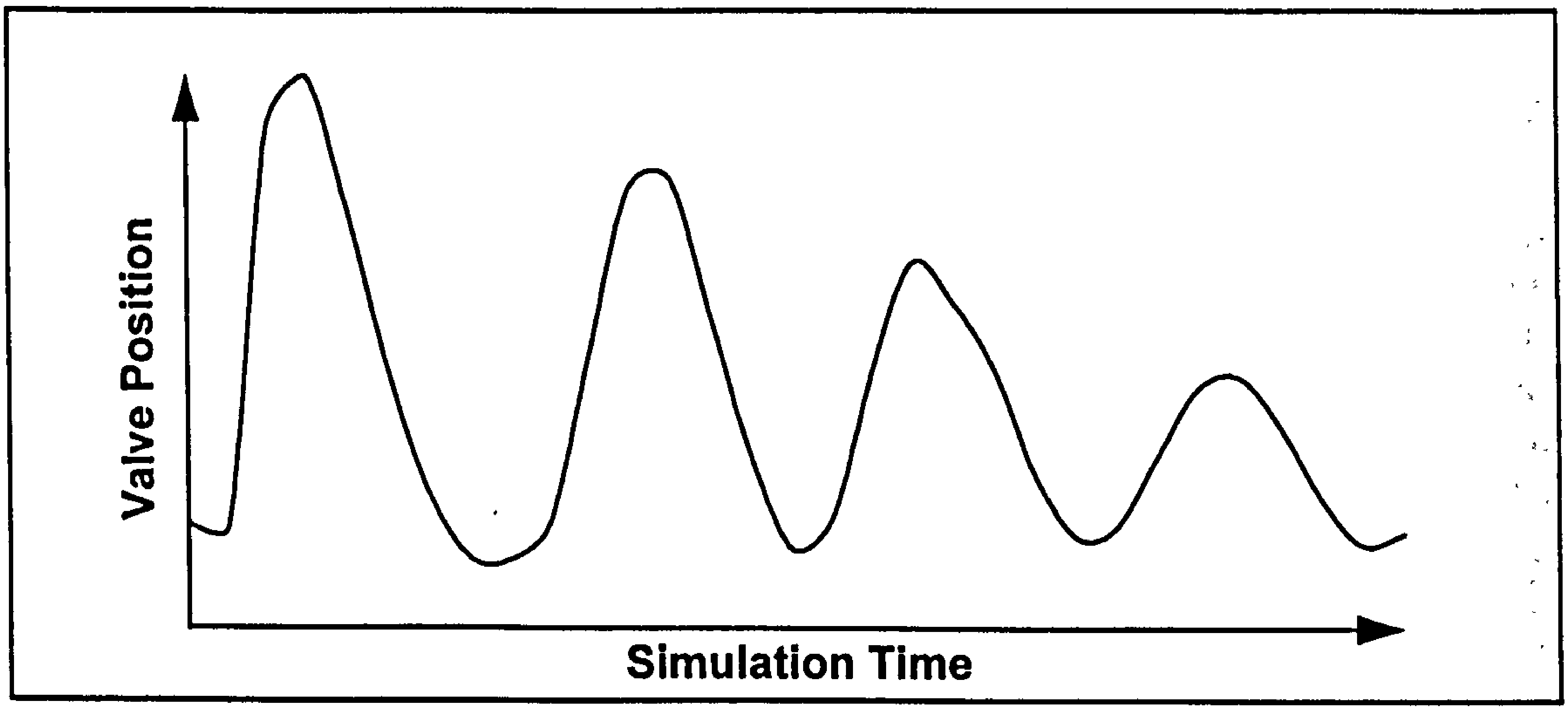

Figure 6.19. PID controller tuning using the continuous cycling method - amplitude of oscillations becoming smaller.

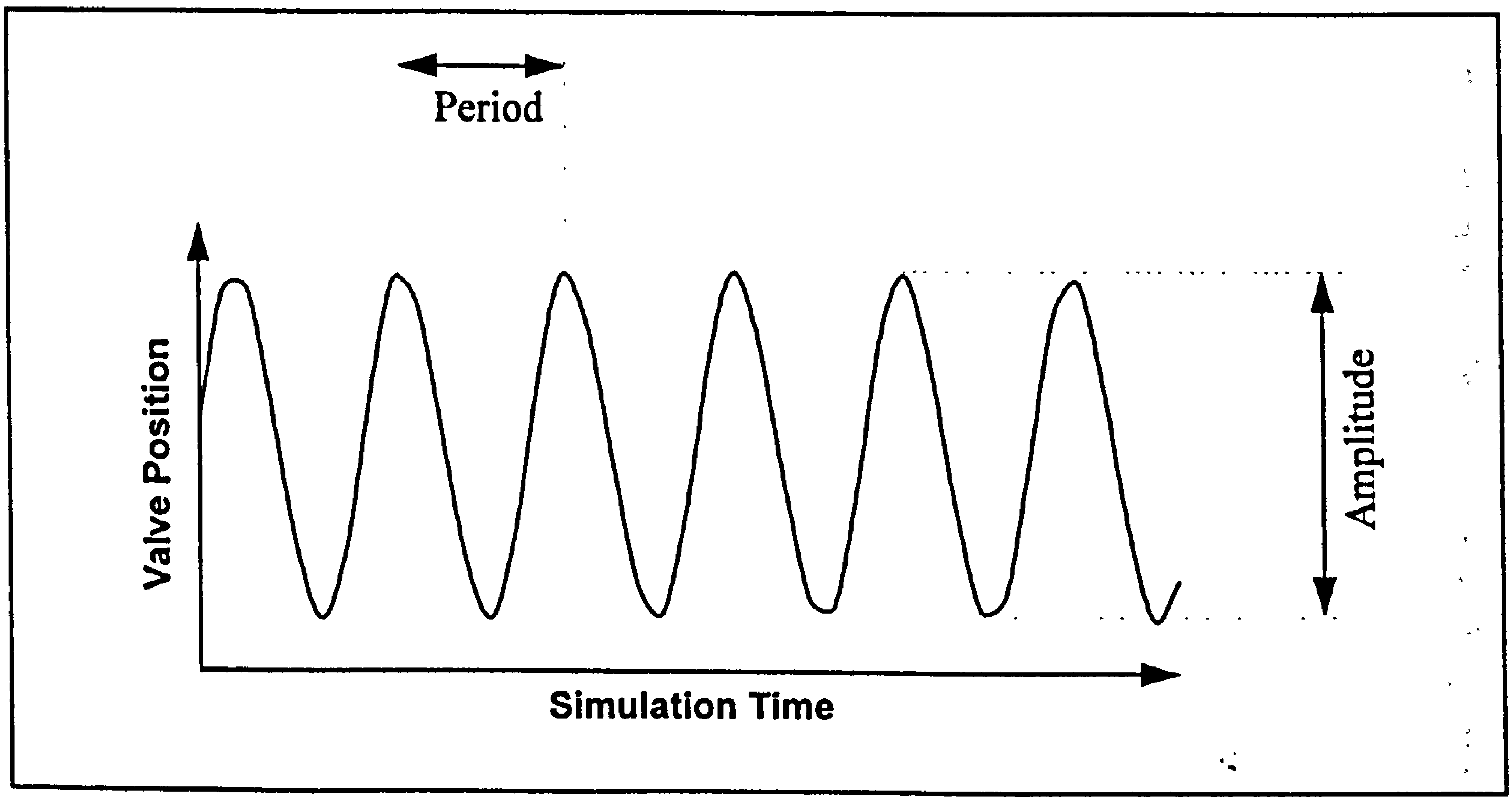

Figure 6.20. PID controller tuning using the continuous cycling method - amplitude of oscillations remains constant.

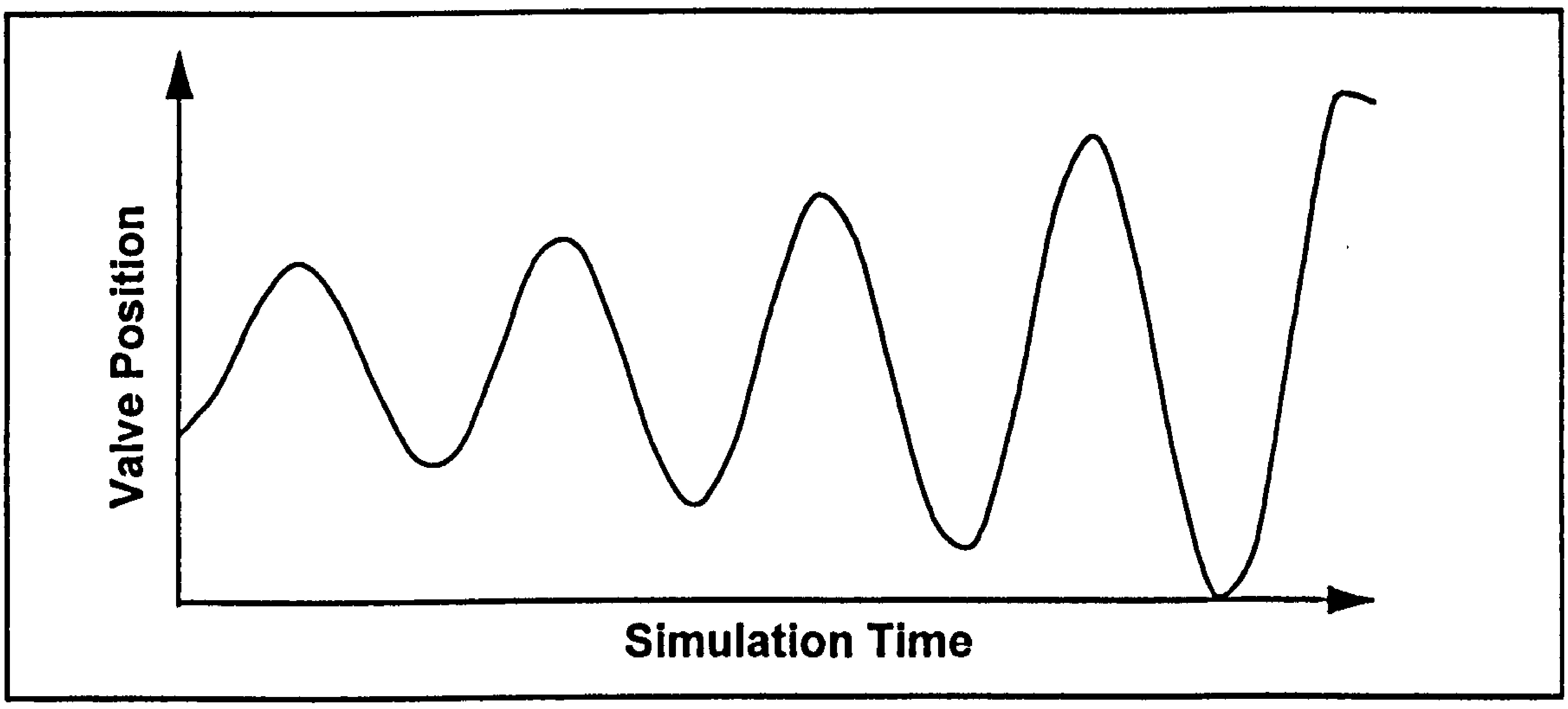

Figure 6.21. PID controller tuning using the continuous cycling method - amplitude of oscillations becoming larger.

Controller Type	Controller Gain (K)	Integral Time (T_i) (seconds)	Derivative Time (T_d) (seconds)
P	$0.5K_u$	-	-
PI	$0.4545K_u$	$0.83T_u$	-
PID	$0.6K_u$	$0.5T_u$	$0.125T_u$

Table 6.2. Recommended Zeigler-Nichols tuning parameters for positional and incremental PID controllers tuned using the continuous cycling method (Golten 1991).

For the purposes of PID controller tuning using the Simulink one zone model, an adapted PID controller block was constructed which allowed the controller gain to be varied while the simulation was in progress. This considerably reduced the time taken to tune the controllers as the simulation did not have to be restarted every time the controller gain needed adjusting to obtain the value of the ultimate gain (K_u).

It should be noted that only the positional algorithm can be used when tuning the PID controller using the continuous cycling method as the integral term in the incremental algorithm is necessary for that type of controller to function, i.e. the integral time cannot be set to infinity which is necessary for continuous cycling tuning.

Once the ultimate gain and ultimate time have been determined for the positional controller it can operate as (i) a proportional controller (ii) a proportional integral controller or (iii) a proportional integral derivative controller by using the tuning parameters given in Table 6.2 based on the ultimate gain and ultimate time.
The incremental controller can be used as (i) a proportional integral controller or (ii) a proportional integral derivative controller by using the values given in Table 6.2 where appropriate.

6.7 Conclusions and Discussion

This chapter described the theory of the HVAC system components models which were integrated with the Simulink "free running" one zone building model described in Chapter 5. The HVAC component models described included heat exchangers, valves, dampers and humidification equipment. Further, Proportional + Integral + Derivative (PID) controls models have been described which were used as a benchmark control strategy to compare the performance of the fuzzy controllers developed in Chapters 8, 9 and 10.

The HVAC system was based on a fixed air volume system. A Number of Transfer Units (NTU) method was used as the calculation method for the heating and cooling heat exchangers. Heat exchangers provided heating and cooling capacity within the Simulink model. The cooling coil also served the purpose of providing dehumidification by cooling the air to below its dew-point temperature. Both theoretical and empirical valve models were constructed. The empirical valve was used in the final Simulink building model due to problems caused by the theoretical valve model due to the inherent leakage flow. This was not desirable in the building model as the heat exchangers could not be made inoperable simply by setting the valve position to closed. Trial simulations showed how the interaction of the valve and heat exchangers linearised the relationship between the valve stem position and the heat transfer rate from the heat exchanger. This is desirable in real situations as control is made easier. The damper used to vary the amount of fresh air entering the zone was based on an opposed blade arrangement and an empirical algorithm.

Incremental and positional control algorithms were used to construct two PID control models within the Simulink environment. These were tuned using the Zeigler Nichols method and were used to provide well tuned, high performance controllers against which to compare the developed fuzzy control strategies described in Chapters 8, 9 and 10. The positional algorithm was used during later simulations as this algorithm was easier to tune due to being able to use the continuous cycling method.

It was not possible to assess the performance of the developed HVAC components and PID controls models against validated systems models as no comparable models were available. Instead, the developed Simulink models were tested by observing their characteristic performances and judging whether they performed adequately on a qualitative basis using knowledge of how the components would be expected to perform. Any inaccuracies in the performance characteristics of the simulink HVAC components models are however largely unimportant due to the model's intended use as a comparative tool. Therefore any inaccuracies that existed were inherently present in all the models that were used to assess the performance of the developed fuzzy control strategies.

This chapter concludes the development of the one zone dynamic simulink model. The following chapters use this base model to develop fuzzy control strategies for the improvement of energy efficiency, cost efficiency and comfort provision within the single building zone.

6.8 References

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7. Fuzzy Control Strategy Development Methodology

7.1 Introduction

This chapter is intended as a precursor to the following chapters:-

Chapter 8.	Proportional Derivative Fuzzy Control (Pure Fuzzy Control)
Chapter 9.	Fuzzy Ventilation Control
Chapter 10.	Fuzzy High Level Control

Section 7.2 of this chapter first considers the human comfort considerations that were taken into account during the selection of the environmental parameters suitable for control. Section 7.3 describes the objectives of the fuzzy control strategies developed. Section 7.4 briefly introduces the three types of fuzzy control strategy developed during the research project. Finally, Section 7.5 describes the fuzzy control strategy development methodology used in achieving the objectives of the research project.

7.2 Human Comfort Criteria Considerations Used During the Development of the Fuzzy Control Strategies

For the purpose of developing the fuzzy control strategies, the literature review on human comfort, see Chapter 2, identified the three following key physical environmental parameters.

- Air Temperature
- Air Relative Humidity
- Air Carbon Dioxide Concentrations

These were selected due to their relatively large influences on occupants' perceived quality of the internal environment. They can also be measured practically with regard to the implementation of environmental control systems. Temperature and relative humidity were considered to be representative of thermal comfort (Fanger 1972) while carbon dioxide concentrations were considered a good indicator of indoor air quality within an occupied space (Potter and Booth 1994).

The adaptive approach (Humphreys 1976) to thermal comfort was considered a useful approach to take during the development of the fuzzy control strategies. The majority of thermal comfort research has focused on the thermal comfort heat balance model of Fanger (1972) and is now embedded into comfort standards. However, this assumes steady state conditions and does not allow occupants to carry out options available to them by adaptation; for example by changing clothing levels. Field studies have consistently shown differences between climate chamber and field study results. Much of this discrepancy is almost undoubtedly the result of adaptive and psychological aspects coming into play. It is difficult to say which are the main parameters causing these discrepancies.

For the development of the fuzzy control strategies an approach where temperature and relative humidity ranges were considered rather than strict set values was adopted. This approach assumes that occupants have some control over their personal comfort, e.g. able to add or remove items of clothing; open or close windows. This allows the provision of comfort while enabling energy and cost efficient control strategies to be sought within a relatively large comfort band.

Carbon dioxide (CO_2) concentrations were considered a good indicator of indoor air quality as it is feasible to measure this parameter more cost effectively and instantaneously than other indicators of indoor air quality.

Noise and lighting can have considerable affects on occupant satisfaction within a given internal environment. However, problems of noise are difficult to resolve and require either refurbishment or fundamental structural modifications and are generally outside the remit of control systems. Research also suggests that lighting and noise do not interact directly with perceptions of thermal comfort or indoor air quality (Oseland 1996).

On the basis of these findings it was decided not to include noise and lighting parameters within the bounds of the current research project.

7.3 Fuzzy Control System Objectives

The example of temperature control given in Chapter 4 indicates the manner in which fuzzy logic theory can function. The research project aimed to build on the capabilities of temperature control by including the zone parameters of relative humidity and air quality within the overall control objectives. This presented the opportunity of using fuzzy logic control systems that were capable of making decisions on the HVAC plant control actions while taking into account interactions between the environmental parameters to provide a comfortable, energy and cost efficient environment.

Figure 7.1 represents hypothetical control volumes for the environmental variables representing indoor environmental quality and building systems performance. The control system objective was to be able to (i) maintain indoor environmental quality within a pre-defined control volume, i.e. within pre-determined ranges for each of the environmental parameters considered, and (ii) decide on the best course of action with regard to overall building systems performance, e.g. the fuzzy control system may decide that it is more energy efficient to cool using ambient rather than re-circulated air or requirements for air quality may demand a greater fresh air input, and (iii) attempt to provide improved indoor environmental conditions when possible without any energy penalties for doing so.

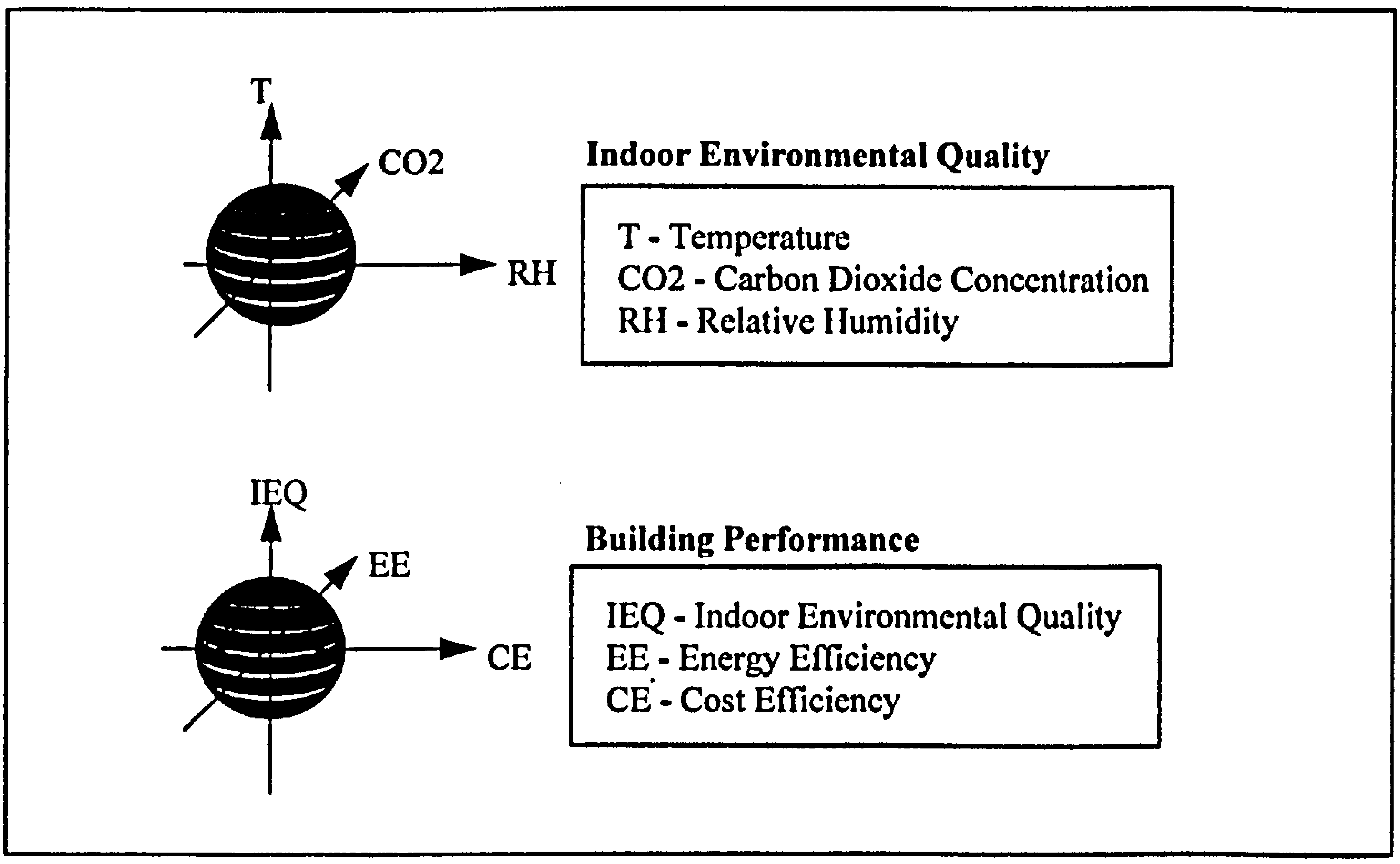

Figure 7.1. Hypothetical control volumes for Indoor Environmental Quality (IEQ) and Building Systems Performance.

Chapter 2 identified naturally ventilated buildings as lending themselves to the adaptive approach more than mechanically ventilated buildings. However, the adaptive actions of occupants can still be taken advantage of during the consideration of control strategies suitable for mechanically ventilated buildings. The definition of control set points and ranges is described in Chapters 8, 9 and 10.

7.4 Fuzzy Control Strategies

Fuzzy logic has been used to control HVAC plant with claims of performance improvements when compared with conventional PID controllers, see Chapter 3. However, fuzzy logic controllers have not been used to their full potential by taking advantage of their capabilities to deal with multi-variant control problems by utilising their decision making capabilities while controlling the various parameters simultaneously. The research project aimed to develop fuzzy building controls strategies which could provide a high quality, comfortable, energy and cost efficient internal environment.

Three types of fuzzy control were developed using the dynamic Simulink model. These were:-

1. Fuzzy Proportional Derivative Control (Pure Fuzzy Control)
2. Fuzzy Direct Ventilation Strategy Control
3. Fuzzy High Level Ventilation Strategy Control

Each of the control strategies was compared to tuned conventional Proportional + Integral + Derivative (PID) controllers, see Chapter 6, as benchmark assessment tests. For all simulations the input parameters used for the fuzzy control models and the PID control model remain identical, i.e. weather conditions, building construction and HVAC components. The only differences between the comparative models were the actual controller strategies used.

7.5 Control Development Methodology

The control development methodology used throughout the research project was essentially the same for each of the fuzzy control strategies. During the initial development of the control strategies, relatively short simulation time periods were considered. Model input parameters were manipulated in order that the control systems were active. For example, when developing a simple modulating control strategy to regulate zone temperature to a specified set point, ambient temperatures were set to below the required zone temperature in order that a heating requirement from the HVAC plant was required. If the ambient temperature was greater than the zone temperature, then it would be unlikely that any heating would be required and therefore the control output will remain at zero.

After satisfactory performance of a controller was achieved using the manipulated input parameters over short simulation periods it was tested over longer simulation periods using realistic input parameters. Three periods of one week duration were generally used starting at days 1, 130 and 270. A seven day period simulated with a 10 second time step required between 10 minutes and 30 minutes, depending on the control strategy complexity, to complete the simulation. Testing of the control strategies using these three periods of the year allowed problems with the control strategies to be identified when they were required to respond to varying conditions. This method of testing was useful when multiple controllers were in use within the model. For example, a temperature controller may work satisfactorily in isolation but when temperature (heating and cooling), humidification, dehumidification and air quality controllers are operational conflicts may occur. These conflicts were readily identifiable using the graphical interfaces available within Simulink or from the graphics tools available in the Matlab workspace.

Once satisfactory performance of the control strategies was achieved over the relatively short simulation periods of 7 days, the fuzzy control strategies were simulated for longer periods. The Proportional Derivative Fuzzy Controllers (PDFCs) were compared with normal PID controllers for 1 week in each month of the year. This provided a diverse set of operating conditions suitable for the assessment of control strategy performance. The fuzzy ventilation and fuzzy high level controllers were more complex in their operation. For this reason simulations were carried out for a one year period for each of the control strategies to ensure a comprehensive set of results suitable for control strategy performance assessment.

Control strategy performance was assessed by energy use and a measure of the error from the desired environmental condition set point. Energy use calculations are based on 100% efficient HVAC components. In reality, the HVAC components will be less than

100% efficient. However, for the purposes of comparison between the different control strategies using the same HVAC systems models this error is cancelled out. The results of these simulations are described in Chapters 8, 9 and 10 with detailed results given in Appendix C and Appendix D.

7.6 References

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8. Proportional Derivative Fuzzy Control (Pure Fuzzy Control)

Nomenclature

$\left(\frac{de}{dt}\right)_n$	normalised rate of change of error (input to Proportional Derivative Fuzzy Controller (PDFC))
$\left(\frac{de}{dt}\right)_r$	real rate of change of error (sensor value)
e_n	normalised error (input to PDFC)
e_r	real error (sensor value)
k_d	rate of change of error gain (normalisation factor) (dimensionless)
k_o	output gain (normalisation factor) (dimensionless)
k_p	error gain (normalisation factor) (dimensionless)
K	controller gain - PID controller (dimensionless)
T_d	derivative time - PID controller (seconds)
T_i	integral time - PID controller (seconds)
y_n	normalised output (PDFC output)
y_r	real output (output sent to actuator)

8.1 Introduction

This chapter considers the use of pure fuzzy controllers designed to act as an alternative to conventional, e.g. Proportional + Integral + Derivative (PID), controllers for the control of environmental parameters in an air-conditioned zone of a building.
The type of fuzzy controller investigated in this chapter is a Proportional + Derivative (PD) controller. Throughout the following text the term PDFC refers to a Proportional + Derivative Fuzzy Controller. This is sometimes referred to as a fuzzy proportional plus integral controller in other literature. The characteristics of a PDFCs operation and behaviour are very similar to that of conventional PI controllers and this has become an accepted way of referring to this type of controller. However, this can be misleading and for the purposes of this thesis Proportional + Derivative fuzzy controllers are referred to as PDFCs.

This chapter first considers the development and tuning of the PDFCs and compares short term simulation results to the benchmark performances of well tuned PID controllers using the one zone Simulink model. An example of the operation of a PDFC is given in a situation where it was used for controlling the zone temperature, under conditions requiring heating, to a pre-defined set point. The tuned PDFC controllers were then compared with normal PID controllers for seven day long simulation periods during each month of the year. Finally, the performances of the PDFC controllers during the longer term simulations were assessed in terms of energy use and the accuracy in providing the desired environmental conditions.

8.2 Proportional + Derivative Fuzzy Control (PDFC) Structure

A schematic of the components of a PDFC is shown in Figure 8.1.

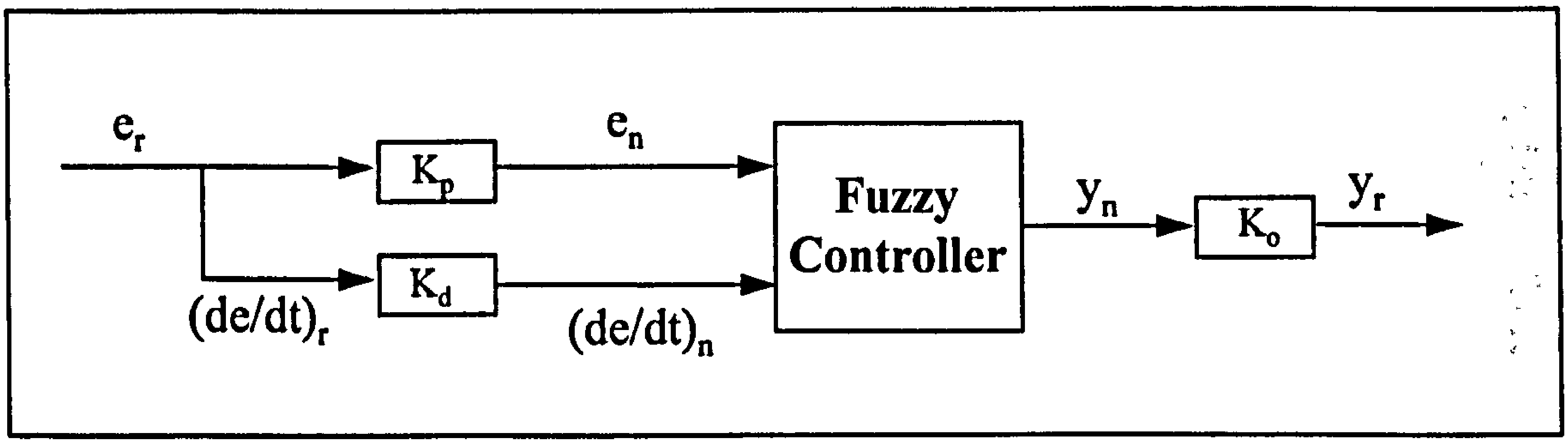

Figure 8.1. Schematic of the main components of a Proportional Derivative Fuzzy Controller (PDFC).

The inputs to the PDFC are the error from the set point (+ve above set point, -ve below set point) and the rate of change of error from the set point, de/dt (+ve increasing value, -ve decreasing value).

The output of the fuzzy controller is the desired incremental control action. For the Simulink model considered for the research project, the plant is controlled via valves and dampers operating between completely closed (0) and completely open (1). The signal, or output, from the controller therefore represents the incremental change in position from the valve or damper current position for each simulation time step; negative or positive. The valve and damper positions are limited to between 0 and 1 using saturation blocks in the Simulink model.

The controller shown in Figure 8.1 is normalised for inputs and outputs on a -1 to +1 scale. For example, if the maximum expected error from the set point was anticipated to be ±10°C a value for the error normalisation factor (K_p) of 0.1 would give an input to the controller of between -1 and +1 for this range. This allows the controller to be easily utilised for different applications by tuning the input gains, K_p and K_d, and the output gain, K_o, to suit a specific application. Tuning by altering the gain factors is an easier process than editing the membership functions for the controller.

The research project considers a fully air-conditioned building zone model and requires controllers for heating, cooling, humidification, dehumidification and air quality via fresh air provision. The inputs and outputs are normalised using Equation 8.1, Equation 8.2 and Equation 8.3.

$$e_n = k_p e_r$$

Equation 8.1

$$\left(\frac{de}{dt}\right)_n = k_d\left(\frac{de}{dt}\right)_r$$

Equation 8.2

$$y_r = k_o y_n$$

Equation 8.3

Real and normalised input and output values are shown graphically in Section 8.3.3 to give a feel for the actual quantities involved.

8.3 Fuzzy Controller Development and Tuning

The PDFCs were developed by first determining the desired controller behavioural characteristics, e.g. response, set point overshoot and stability. Secondly, knowledge of how to achieve these characteristics was incorporated into the PDFC via the definition of the membership functions and control rules.

The PDFC performances were compared to the benchmark performances of PID controllers by running simulations using the two different control strategies within otherwise identical Simulink models. Adjustments to the control rules, membership functions and controller gains of the PDFCs were then made to improve controller performances. The PID controllers were tuned using the Zeigler Nichols method as described in Chapter 6 and represented well tuned PID controllers.

8.3.1 PDFC Components

The PDFC structure developed to assess pure fuzzy control performance had 7 membership functions for each of the two inputs and the singular output universes of discourse. The rule base comprised 49 (7^2) linguistic rules to relate the input membership functions to the output membership functions.

The membership functions for the normalised error and rate of change of error (input universes) are shown in Figure 8.2.

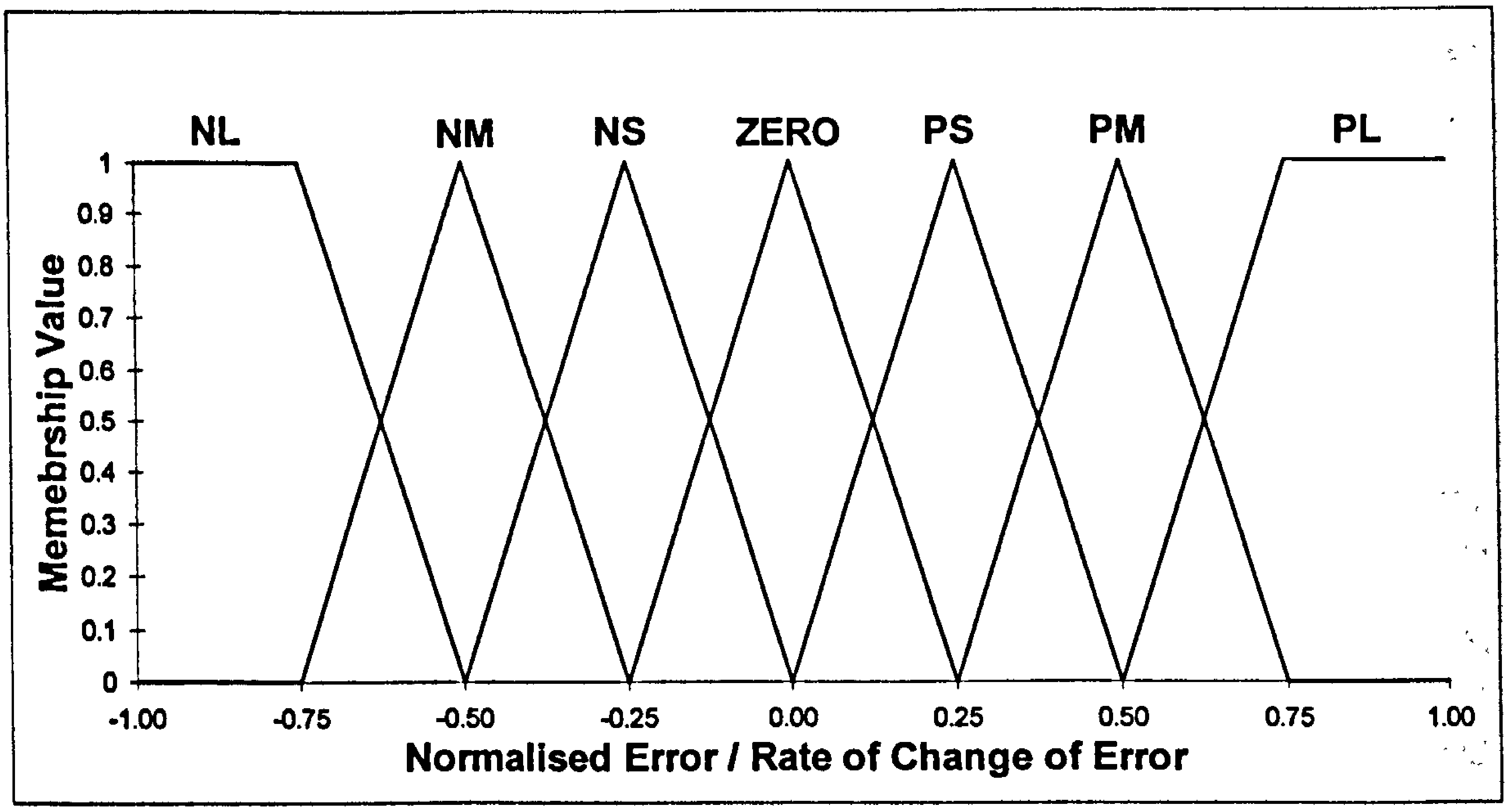

Figure 8.2. PDFC normalised membership functions for the inputs of error and rate of change of error.

The membership function linguistic descriptors were defined as follows:-

NL - Negative Large
NM - Negative Medium
NS - Negative Small
ZERO - Zero
PS - Positive Small
PM - Positive Medium
PL - Positive Large

Similarly, the membership functions for the normalised output (control action) are shown in Figure 8.3.

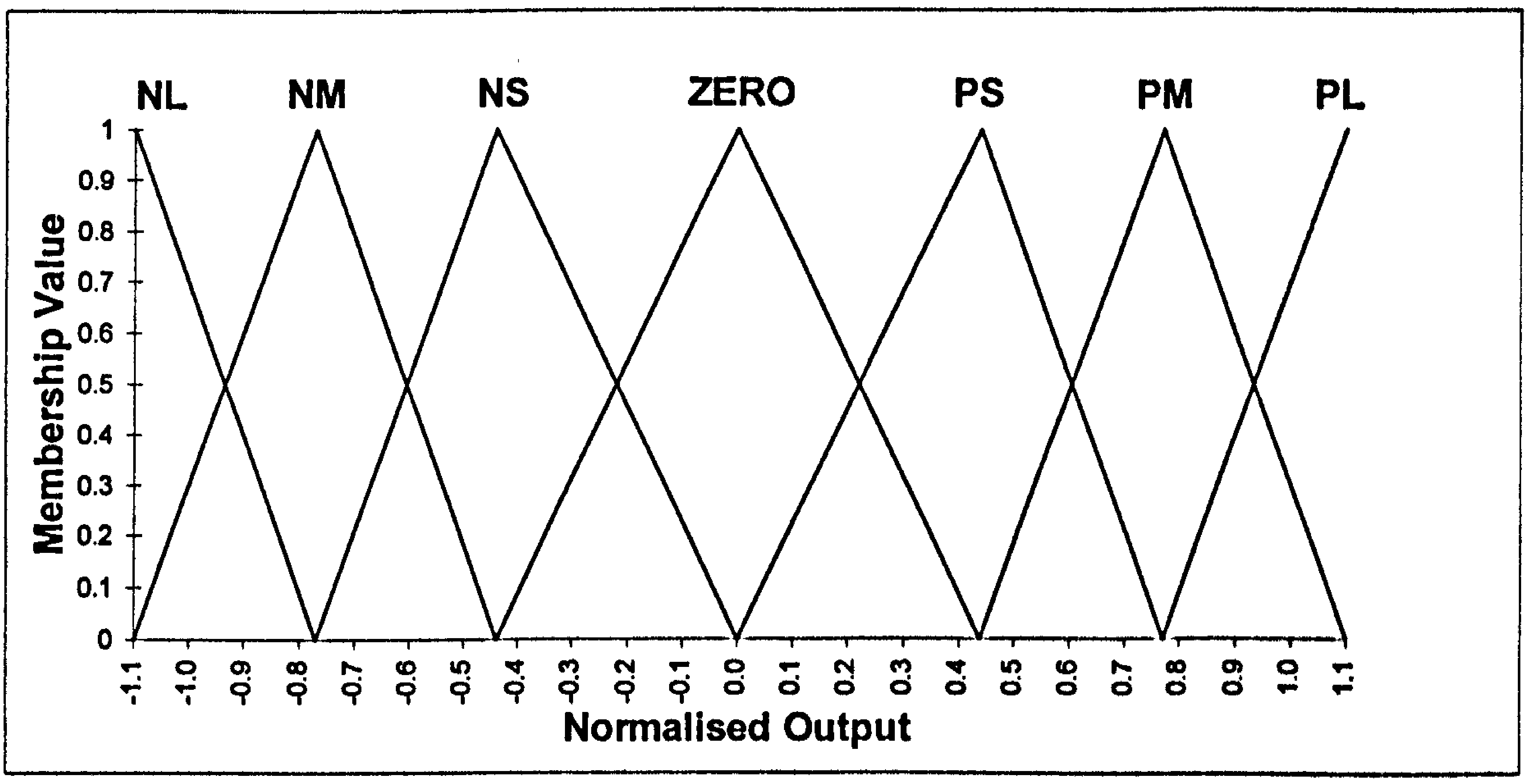

Figure 8.3. PDFC normalised membership functions for the output.

The 49 control rules were of the form:

IF (Error is PL) **AND** (Rate_of_change_of_error is PL) **THEN** (Output is NL)

The 49 control rules are summarised in a control rule table, see Table 8.1.

	Rate of Change of Error (de/dt)						
Error	NL	NM	NS	ZERO	PS	PM	PL
NL	PL	PL	PL	PL	PM	PS	ZERO
NM	PL	PL	PL	PM	PS	ZERO	NS
NS	PL	PL	PM	PS	ZERO	NS	NM
ZERO	PL	PM	PS	ZERO	NS	NM	NL
PS	PM	PS	ZERO	NS	NM	NL	NL
PM	PS	ZERO	NS	NM	NL	NL	NL
PL	ZERO	NS	NM	NL	NL	NL	NL

Table 8.1. PDFC control rule table.

The normalised control surface generated for the input membership functions, output membership functions and the control rules is shown in Figure 8.4.

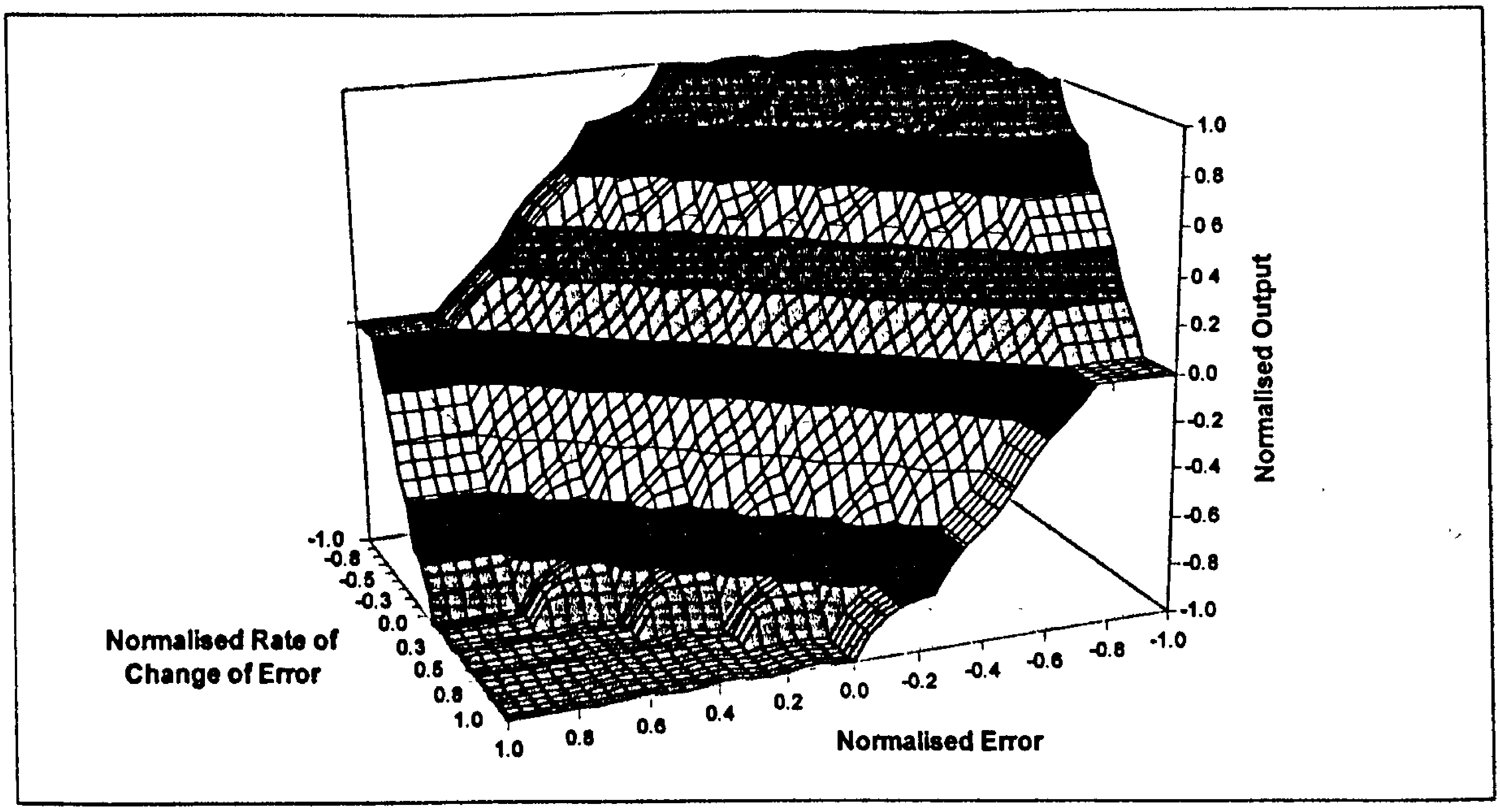

Figure 8.4. Normalised PDFC control surface.

The fuzzy control structure with normalised inputs and outputs was used to control the heating, cooling, humidification, dehumidification and air re-circulation within the Simulink model. The controller gains were adjusted for each controller to ensure the real input and output values were suitable for the PDFC normalised structure. This was an iterative process and is described in the following sections.

8.3.2 Fuzzy Controller Tuning

As with conventional control techniques the PDFC requires tuning. However, unlike the PID tuning process for which tuning techniques such as the Zeigler Nichols are appropriate, there are no such techniques for tuning fuzzy controllers. PDFCs need to be tuned using an iterative process of trial and error, and user intuition of how the tuning parameters affect the PDFC performance. The steps involved in the tuning of the PDFCs are outlined in the following text.

1. Plant operation for controllers not under consideration were made inoperable. For example, if the heating coil and temperature set point were under consideration, the cooling, humidification, dehumidification and air quality controllers of the HVAC plant were made inactive.
2. A stepping set point for the environmental parameter under consideration, e.g. zone temperature, was then provided. This gave the effect of instantaneous disturbances for the PID and PDFC controllers to react to. The step changes of set point allowed a graphical comparison to be made between the PID and PDFC controllers in terms of response time, overshoot and stability. This is a commonly used method for comparing controller performance.
3. Conditions, such as the ambient conditions, were set to ensure that the plant component and associated controller were required to operate during the controller tuning process. For example, the initial settings, i.e. outdoor temperature, zone

temperature and wall temperatures, for the model during the tuning of the controller for the heating plant were set at low values. This ensured that there was a consistent heat requirement from the heating plant.

4. A conventional PID controller was tuned for the plant component and set point, e.g. heating coil and temperature, under consideration using the Zeigler-Nichols method. This was used as a bench mark comparison control technique. The tuning parameters of the PID controller under consideration was then set to those acquired during the tuning process.
5. In an identical Simulink model, the PID controller was replaced with the PDFC to be tuned. This ensures that the models are identical in every respect with the exception of the control strategy.
6. Initial tuning gains for the PDFCs were selected from tuning experience. The controller gains for the PDFC were then adjusted until the performance of the controller was deemed satisfactory or further improvements could not be achieved. An opportunity also existed at this stage to modify the structure of the membership functions and the control rules. This enabled further improvements in PDFC performance to be achieved.
7. The PID and PDFC one zone building models were then run for a predetermined simulation time and the results compared.
8. The above steps were then repeated for all the HVAC plant components and controllers.

The tuning values for the PID and PDFC controllers determined by the above process for the Simulink one zone building model are given in Table 8.2 and Table 8.3 respectively.

Controller	Proportional Gain (K)	Integral Time (T_i) (seconds)	Derivative Time (T_d) (seconds)
Heating	0.100	170	42.50
Cooling	0.360	180	45.00
Humidifier	0.700	235	58.75
Dehumidifier	0.005	250	62.50
Air Quality (CO_2)	0.022	210	52.50

Table 8.2. Tuning parameters for the PID controllers.

Controller	Error Gain (k_p)	Rate of Change of Error Gain (k_d)	Output Gain (k_o)
Heating	0.60	100	0.00075
Cooling	0.85	120	0.0014
Humidifier	0.30	125	0.0030
Dehumidifier	0.01	6	0.0020
Air Quality (CO_2)	0.01	6	0.0020

Table 8.3. Tuning parameters for the PDFCs.

8.3.3 Tuned PDFC Performance

The performances of the PDFCs, after the iterative tuning process, were compared to the well tuned PID controllers using the step change in controlled variable set-point benchmark test method. The performances of the controllers with regard to maintaining the zone temperature at the desired set point are shown in Figure 8.5, to allow a comparison between the performances of the controllers.

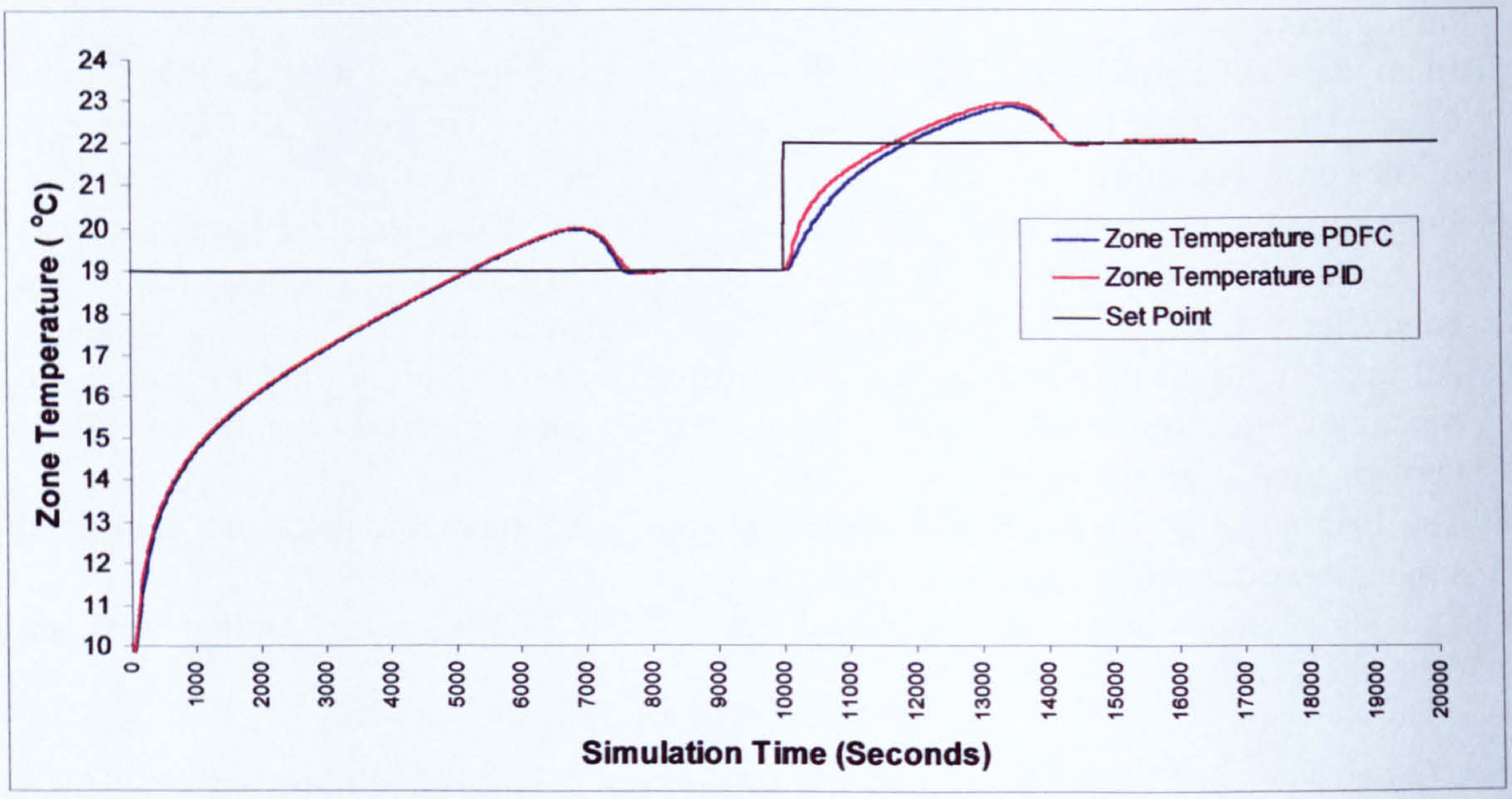

Figure 8.5. PDFC and PID controller zone temperature response after controller tuning.

Figure 8.5 indicates only a small difference between the control exercised by the PDFC and PID controllers. Energy use for the PDFC and PID controllers were 19.4898 kWh and 19.4991 kWh respectively during the 20,000 second (approximately 5.5 hour) simulation period. These results represent a negligible overall performance difference between the PDFC and PID controllers.

The operation of the PDFC shown in Figure 8.5 can be considered in more detail by examining the error and rate of change of error as recorded during the simulation, see Figure 8.6 and Figure 8.7 respectively.

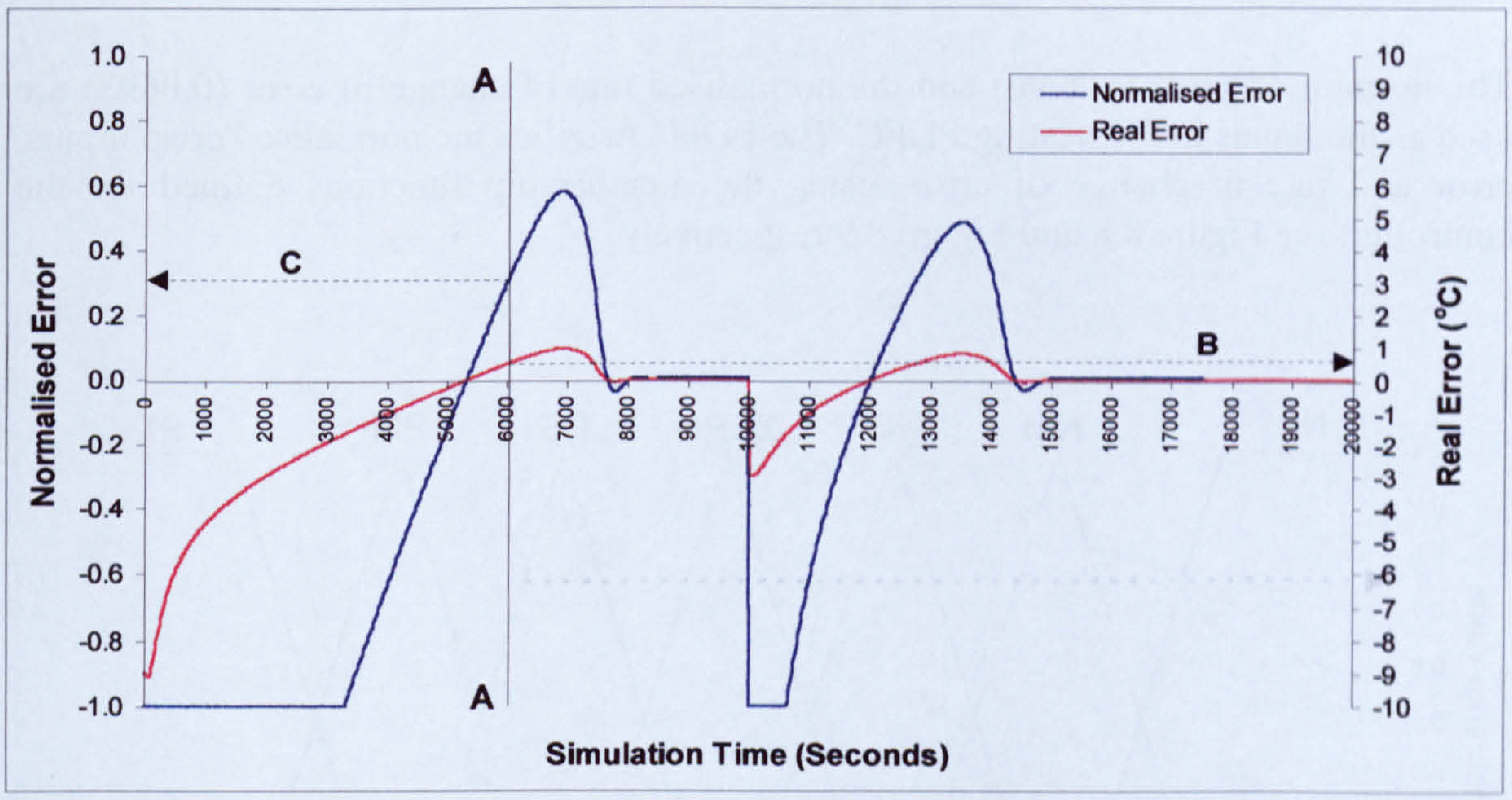

Figure 8.6. Normalised and real error for the PDFC simulation shown in Figure 8.5.

Considering the simulation time t = 6000 seconds in Figure 8.6, see line AA, the real error was 0.5°C, see broken line arrow B. Using Equation 8.1 the normalised error was 0.5 x 0.6 = 0.2990 °C, see broken line arrow C.

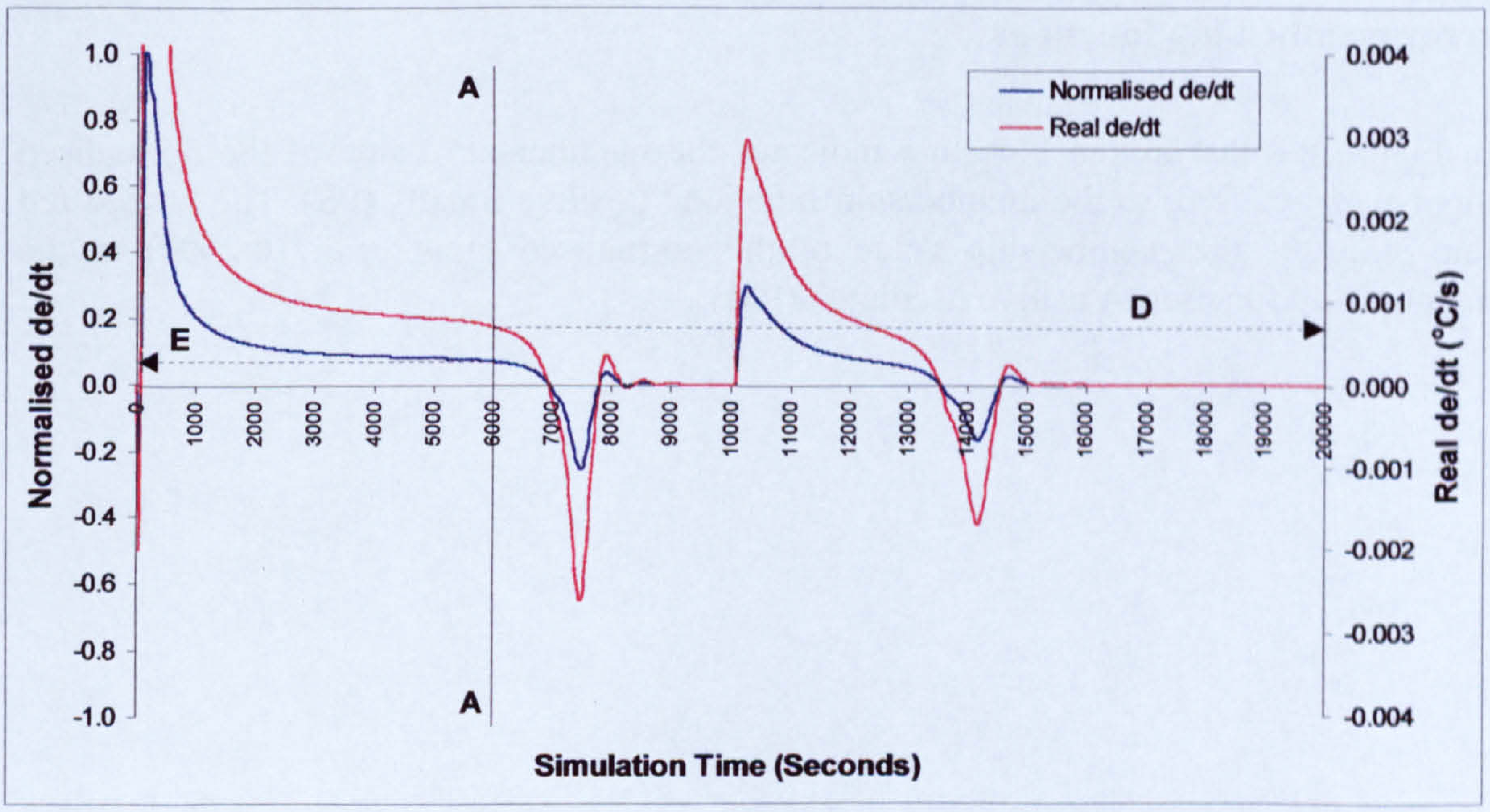

Figure 8.7. Normalised and real rate of change of error (de/dt) for the PDFC simulation depicted in Figure 8.5.

Considering Figure 8.7 at t = 6000 seconds, see line AA, the real rate of change of error is 0.000693 °C/s, see broken line arrow D. Using Equation 8.2 the normalised rate of change of error is 0.000693 x 100 = 0.0693 °C/s, see broken line arrow E.

The normalised error (0.2990) and the normalised rate of change of error (0.0693) are used as the inputs to the heating PDFC. The PDFC fuzzifies the normalised crisp inputs, error and rate of change of error, using the membership functions defined for the controller, see Figure 8.8 and Figure 8.9 respectively.

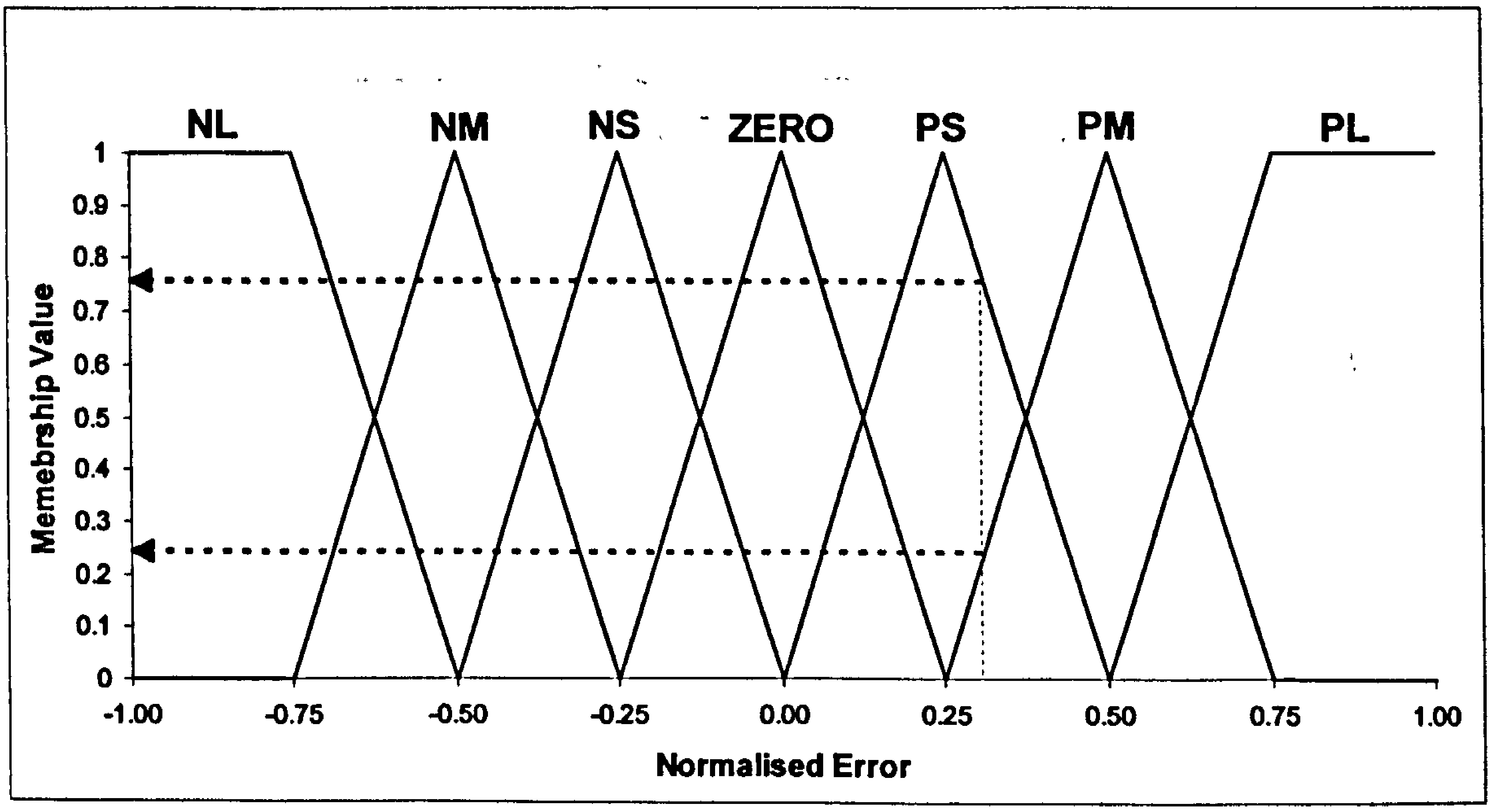

Figure 8.8 Membership values for a normalised error of 0.299 (dotted lines) for the error membership functions.

In Figure 8.8 the broken blue line indicates the membership value of the normalised input error (0.2990) to the membership function "Positive Small" (PS). The broken red line indicates the membership value of the normalised input error (0.2990) to the membership function "Positive Medium" (PM).

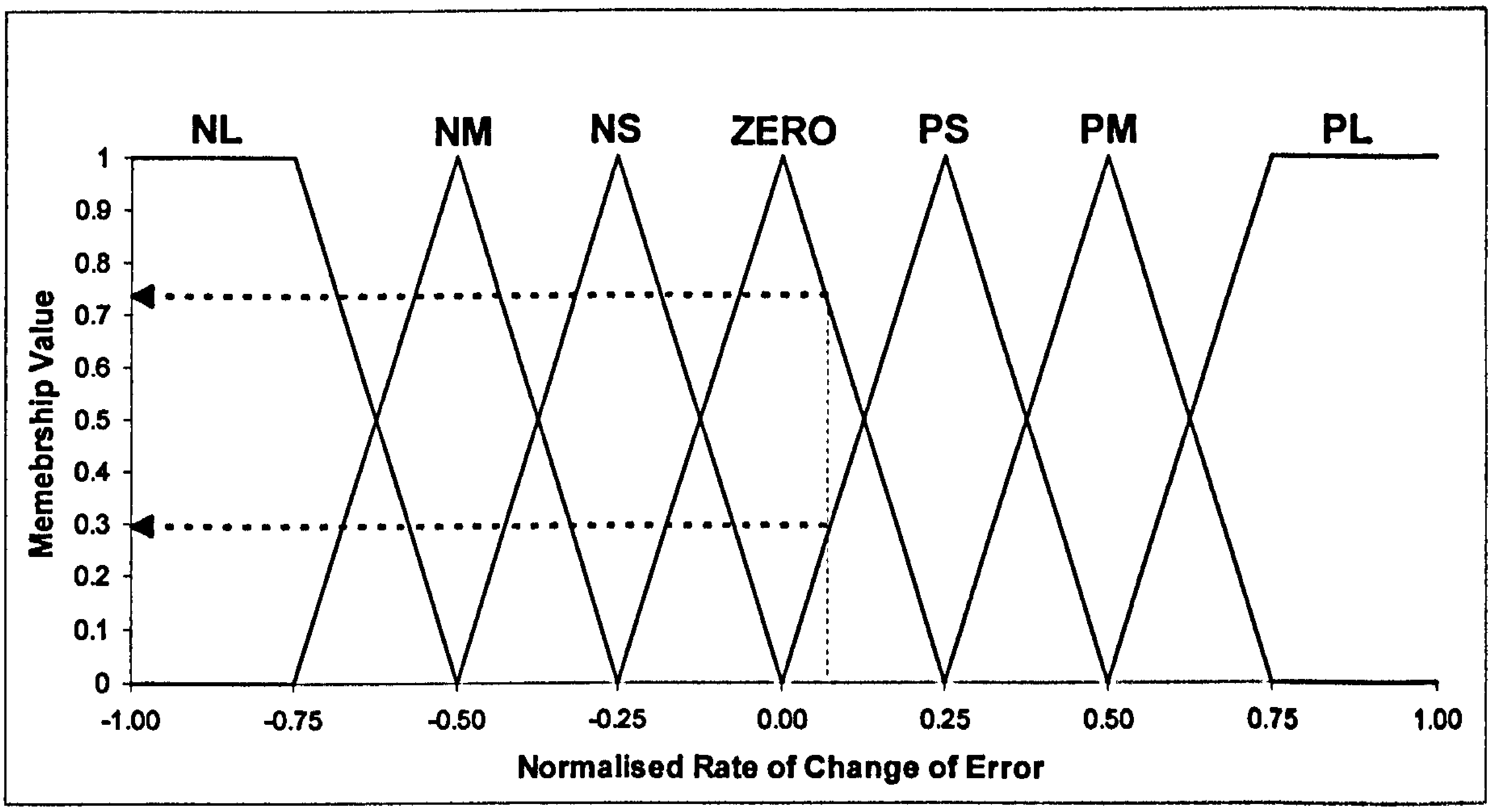

Figure 8.9. Membership values for a normalised rate of change of error of 0.0693 (dotted lines) for the rate of change of error membership functions.

In Figure 8.9 the broken blue line indicates the membership value of the normalised input rate of change of error (0.0693) to the membership function "Zero" (ZERO). The broken red line indicates the membership value of the normalised input rate of change of error (0.0693) to the membership function "Positive Small" (PS).

The fuzzy membership values for each of the membership functions for the normalised inputs under consideration are given in Table 8.4.

Membership Function	Error (μ)	Rate of Change of Error (μ)
Negative Large (NL)	0	0
Negative Medium (NM)	0	0
Negative Small (NS)	0	0
Zero (ZERO)	0	0.73
Positive Small (PS)	0.76	0.29
Positive Medium (PM)	0.24	0
Positive Large (PL)	0	0

Table 8.4. Membership values (μ) of each membership function shown in Figure 8.8 and Figure 8.9 for the normalised inputs under consideration.

The inference engine uses the PDFC rule base, see Table 8.1, and the knowledge base to infer the fuzzified output. This is done using the maximum-minimum method as described in Chapter 4.

All the rules of the PDFC are activated. However, the majority of the rules are activated to a zero degree. For example, considering the ongoing example, and applying the maximum-minimum principle to the rule:-

IF (error is NL) **AND** (rate is ZERO) **THEN** (output is PL)

results in Equation 8.4.

$$\mu_{output,PL} = \min(\mu_{error,NL}, \mu_{rate,ZERO}) = \min(0, 0.73) = 0$$

Equation 8.4

In words, Equation 8.4 can be written:-
The degree of membership of the fuzzy output value to the output membership function "Positive Large" is equal to the minimum of a) the degree of membership of the error value to the membership function "Negative Large" on the universe of discourse "error" and b) the degree of membership of the rate of change of error value to the membership function "Zero" on the universe of discourse "rate of change of error". This is equal to the minimum of the membership values 0 and 0.73. Therefore, the degree of membership of the fuzzy output value to the output membership function "Positive Large" is equal to 0.

Any rule with a membership function that has a zero membership value is activated by a zero degree where the maximum minimum principle is used.

The rules that are of interest in determining the fuzzy output for the time t = 6000 in the considered example are:

IF (error is PS) **AND** (rate is ZERO) **THEN** (output is NS)
IF (error is PS) **AND** (rate is PS) **THEN** (output is NM)
IF (error is PM) **AND** (rate is ZERO) **THEN** (output is NM)
IF (error is PM) **AND** (rate is PS) **THEN** (output is NL)

The values of the fuzzy consequents, i.e. fuzzy output, are determined using the two steps of the maximum-minimum method:

Step 1: minimum
Applying the minimum principle to each of the four rules results in Equation 8.5, Equation 8.6, Equation 8.7 and Equation 8.8 respectively.

$$\mu_{output,NS} = \min(\mu_{error,PS}, \mu_{rate,ZERO}) = \min(0.76, 0.73) = 0.73$$

Equation 8.5

$$\mu_{output,NM} = \min(\mu_{error,PS}, \mu_{rate,PS}) = \min(0.76, 0.29) = 0.29$$

Equation 8.6

$$\mu_{output,NM} = \min(\mu_{error,PM}, \mu_{rate,ZERO}) = \min(0.24, 0.29) = 0.24$$

Equation 8.7

$\mu_{output,NL} = \min(\mu_{error,PM}, \mu_{rate,PS}) = \min(0.24, 0.29) = 0.24$

Equation 8.8

Step 2: maximum
Two of the fuzzy rules have the same consequent ($\mu_{output,NM}$). For these two rules the maximum principle applies, see Equation 8.9.

$\mu_{output,NM} = \max(\mu_{output,NM}, \mu_{output,NM}) = \max(0.29, 0.24) = 0.29$

Equation 8.9

The final membership values on the output universe of discourse are

$\mu_{output,NS} = 0.73$
$\mu_{output,NM} = 0.29$
$\mu_{output,NL} = 0.24$

The membership values for each of the output membership functions are shown graphically in Figure 8.10.

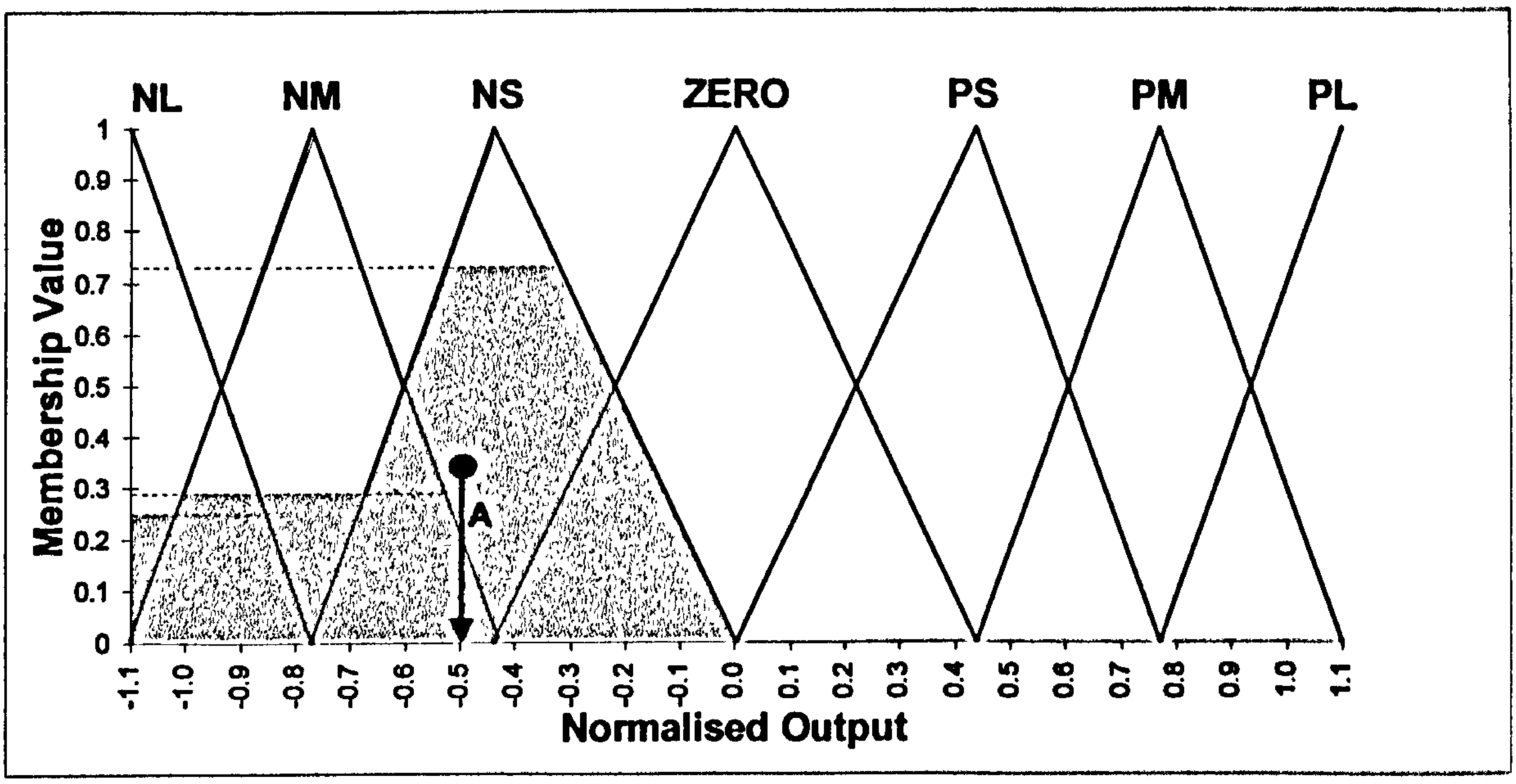

Figure 8.10. Membership values for each of the output membership functions on the output universe of discourse for the considered example.

Next the defuzzification of the output membership values is considered. The union of the consequents indicated by the shaded area in Figure 8.10 represents the fuzzified output. The method of defuzzification used during the research project was that of the centroid method. The defuzzified normalised value of the union of the membership functions calculated using the defuzzification interface within the Simulink model is -

0.5, see line arrow A, Figure 8.10. This can also been seen in the recorded outputs obtained for the heating PDFC during simulation, see Figure 8.11.

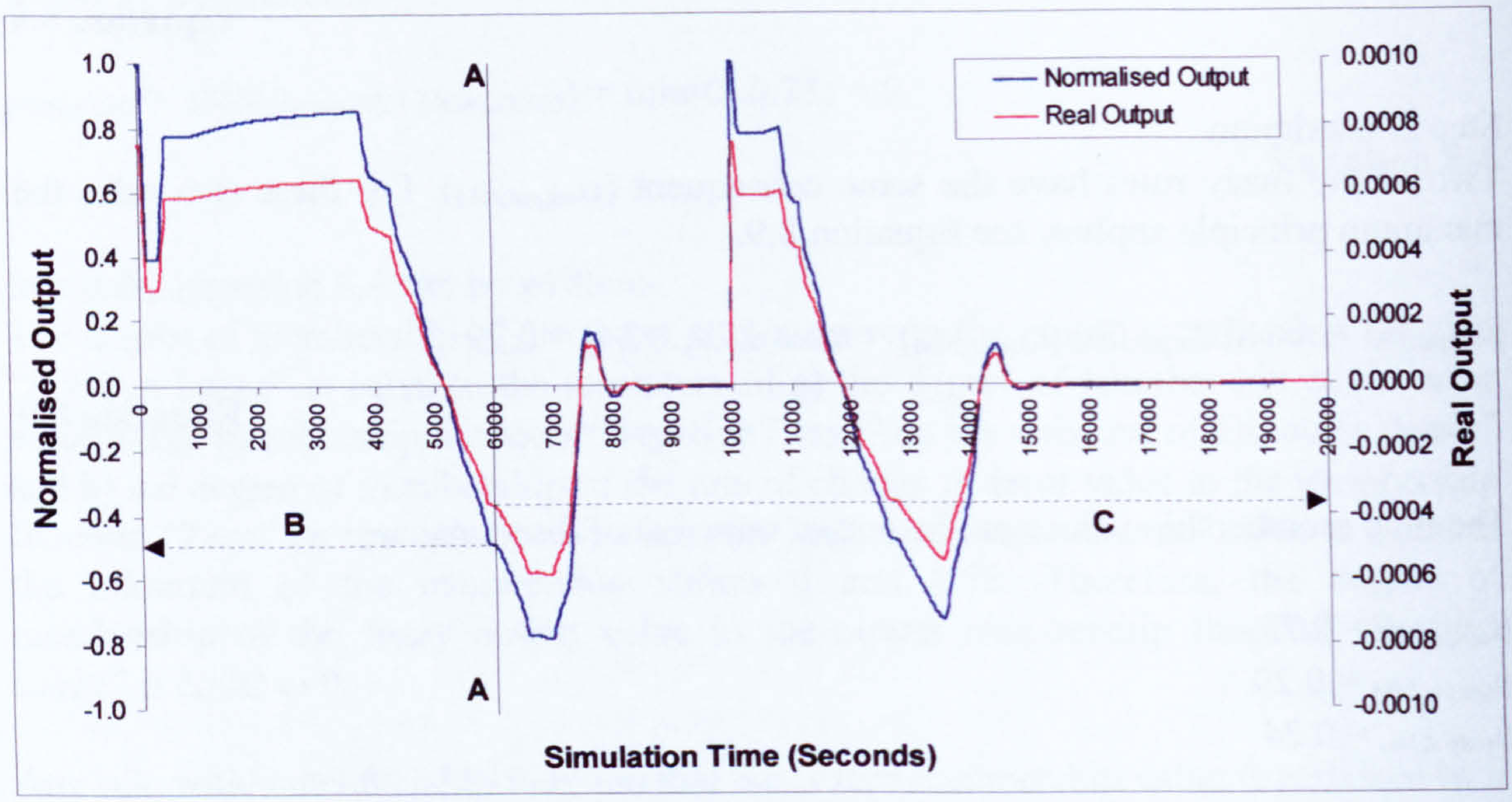

Figure 8.11. Normalised and real outputs for the fuzzy controller.

The final stage in the operation of the PDFC controller is to use the output gain factor to convert the normalised output value of the controller into a signal representing the real desired incremental movement of the heating valve. The output gain factor for the example under consideration is 0.00075. The final output of the controller utilises Equation 8.3, i.e. 0.00075 x -0.5 = -0.000375.

This implies that the controller requires an incremental movement of the heating valve in the negative direction, i.e. closing. This is similar to what would be expected from a human operator who was monitoring the plant and zone conditions to operate the plant manually. The position of the valve during the dynamic simulation is shown in Figure 8.12. The broken line in Figure 8.12 indicates the position of the valve for the simulation time t = 6000s as used in the example for the heating PDFC.

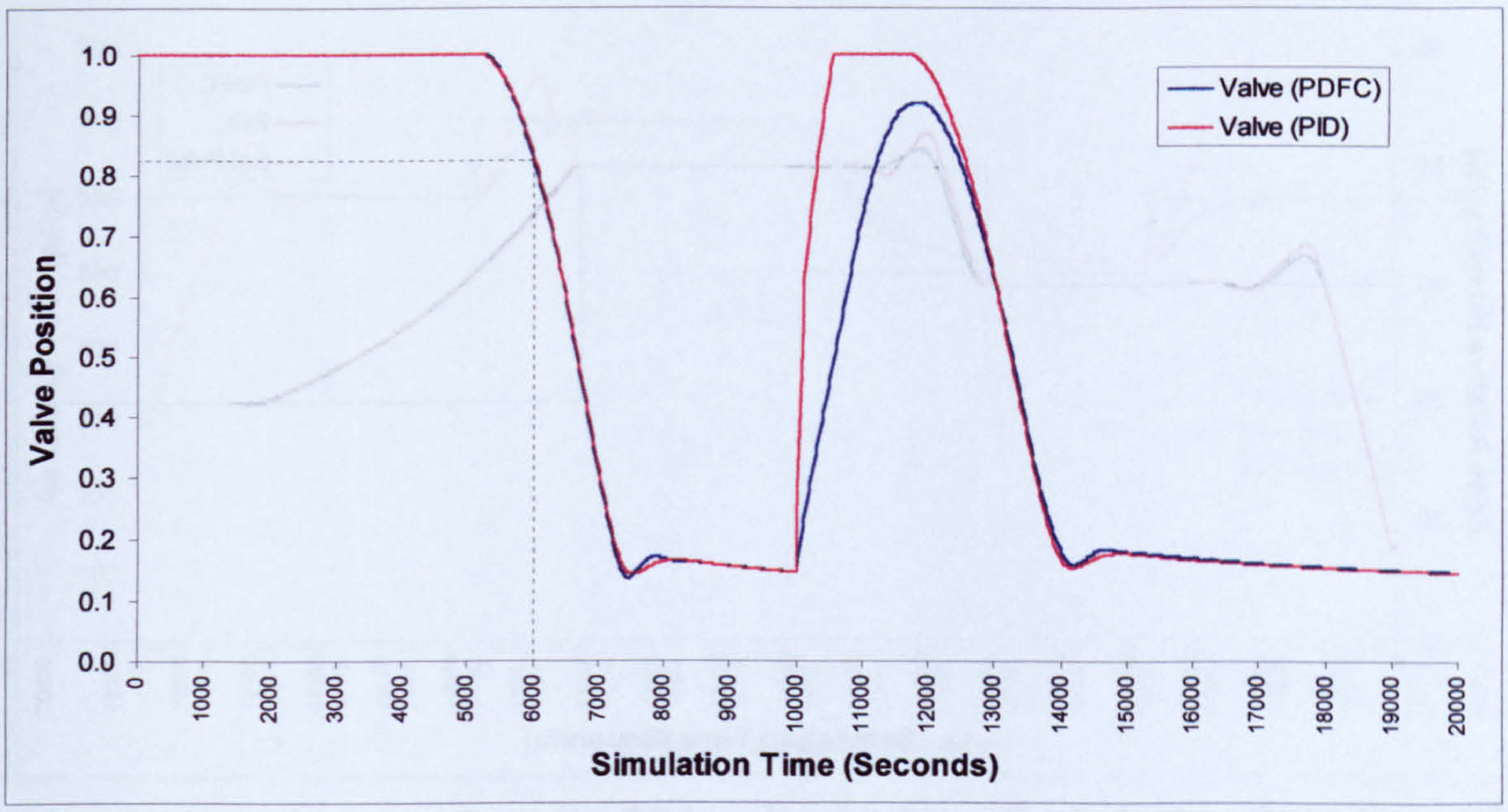

Figure 8.12. PDFC and PID controller valve positions for the example heating requirement simulation.

Similarly, the cooling, humidification, dehumidification and air quality PDFCs were tuned, see Table 8.3, and compared with conventional tuned PID controllers, see Table 8.2. Graphical performance comparisons are shown in Figure 8.13 to Figure 8.16 for the PDFC and PID controllers for the control of the cooling, humidification, dehumidification and air quality components of the HVAC system.

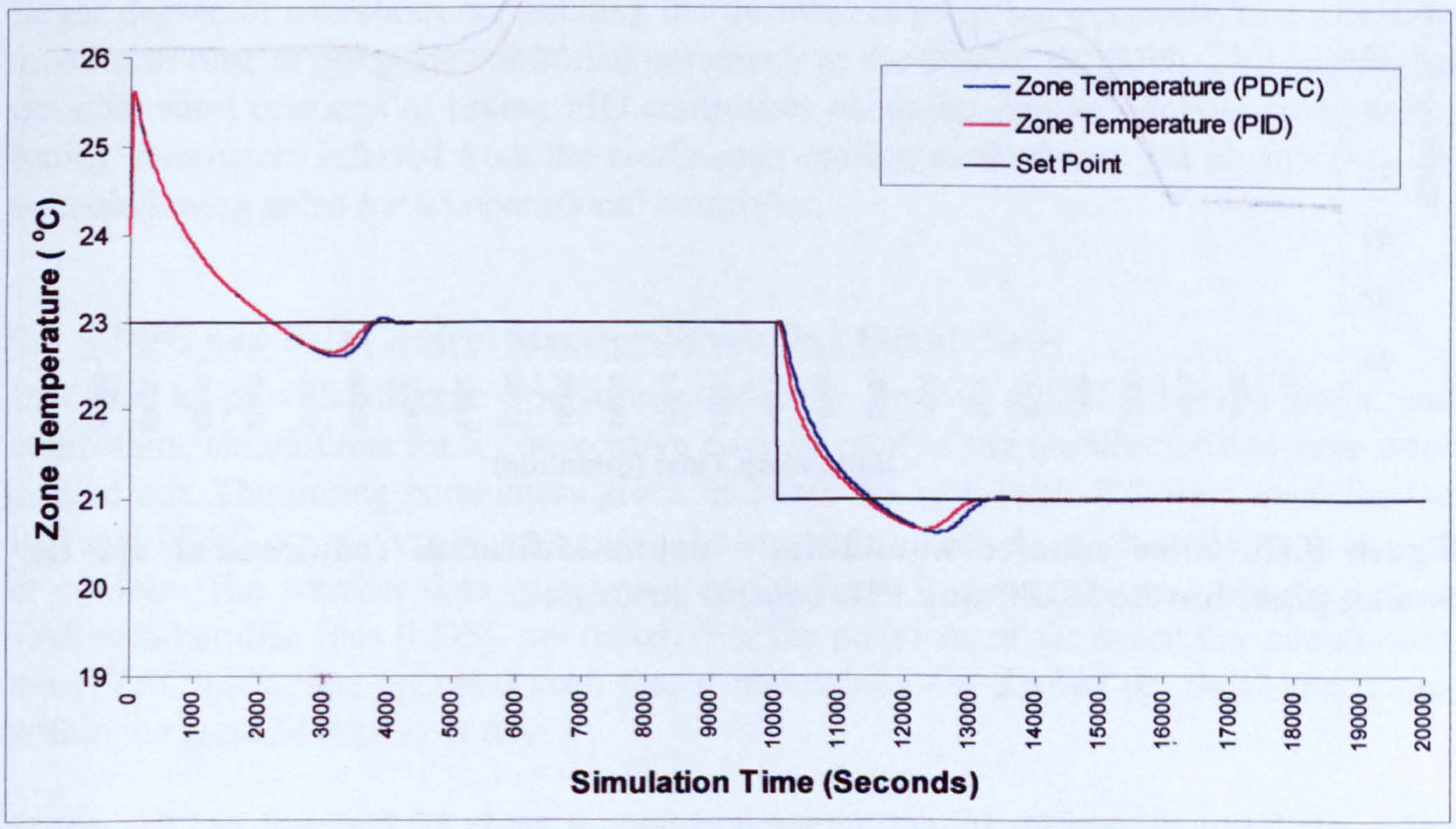

Figure 8.13. Zone temperatures - cooling plant requirement for the PDFC and PID control strategies.

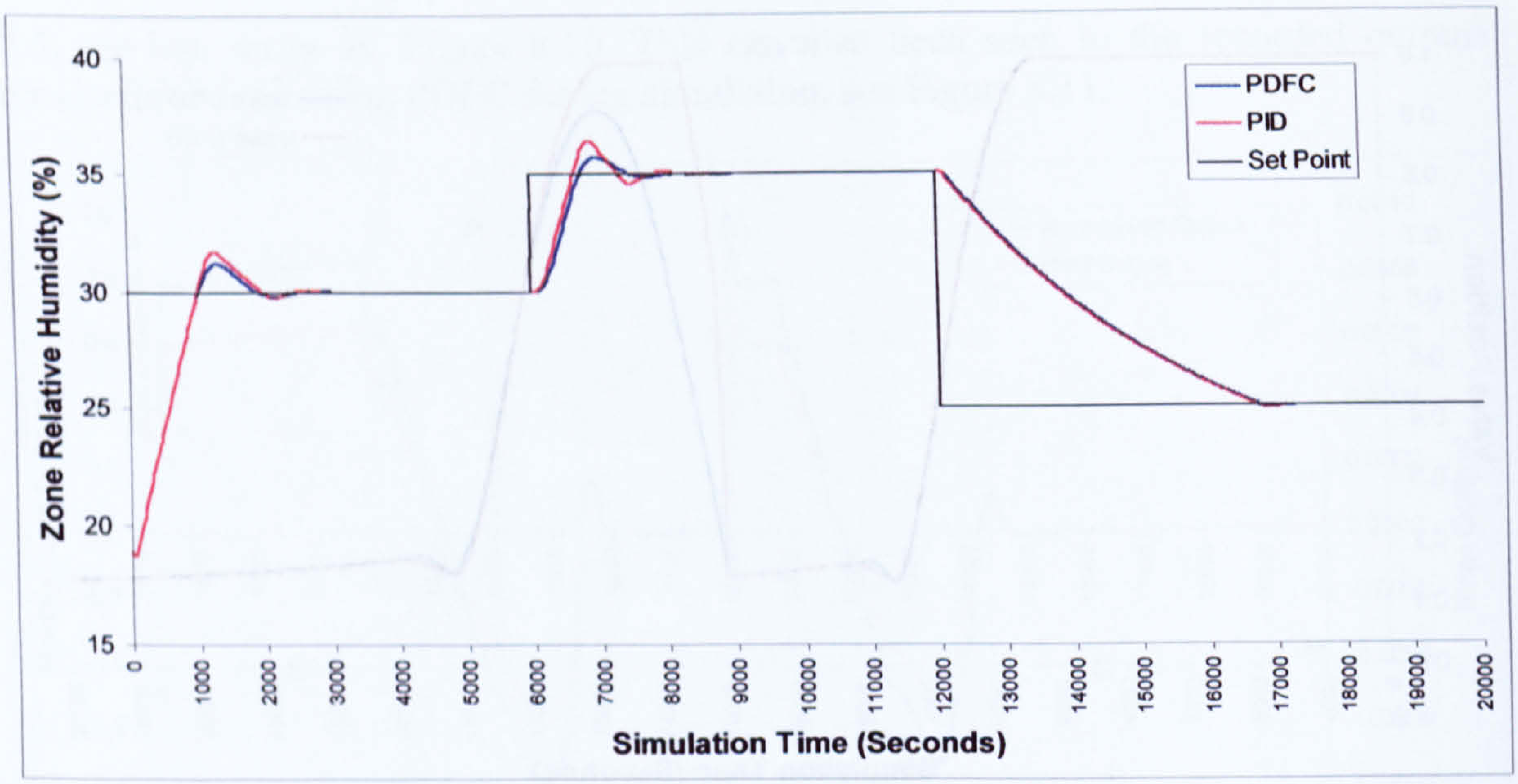

Figure 8.14. Zone relative humidities - humidification plant requirement for the PDFC and PID control strategies.

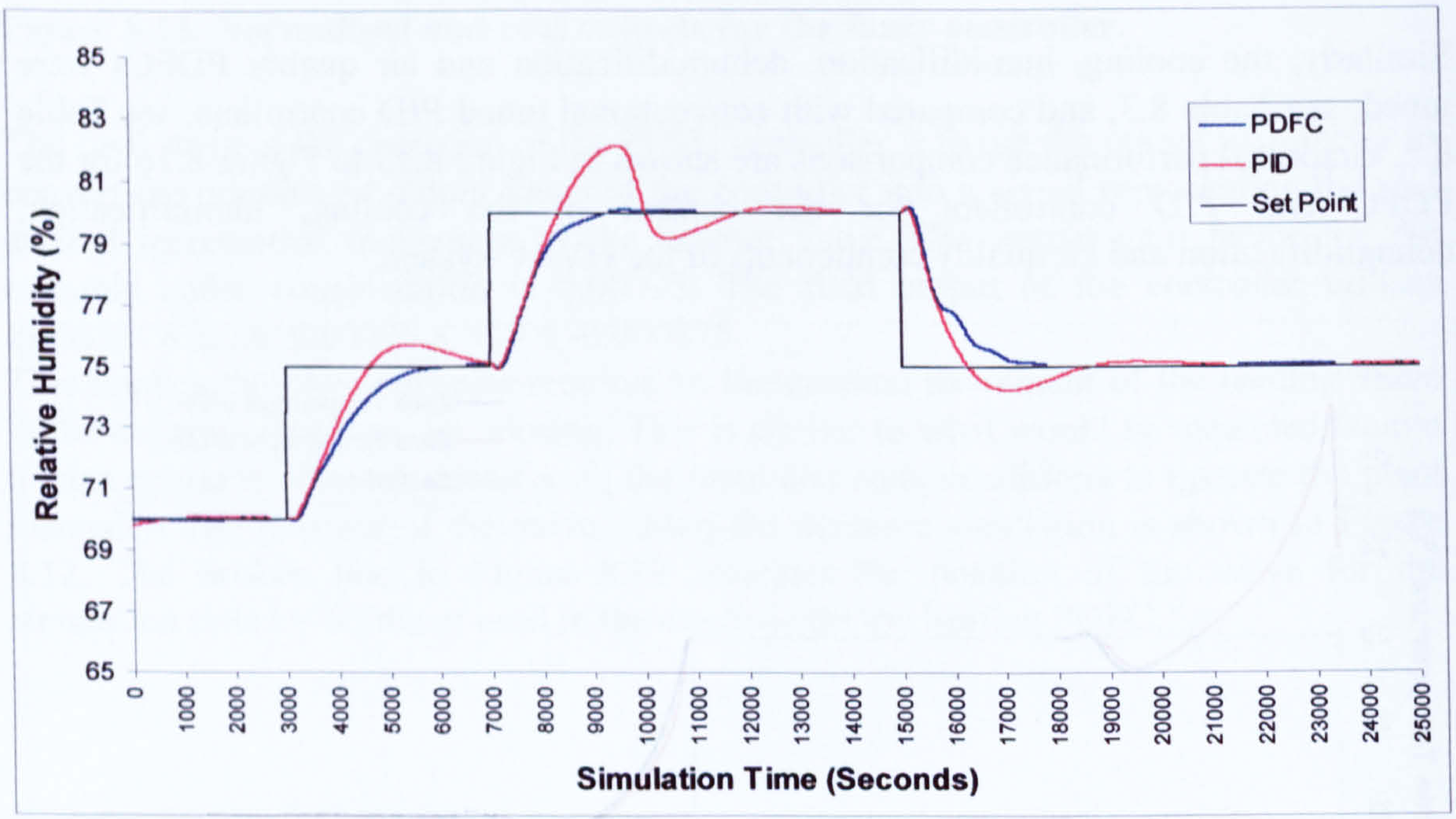

Figure 8.15. Zone relative humidities - dehumidification requirement via the cooling plant for the PDFC and PID control strategies.

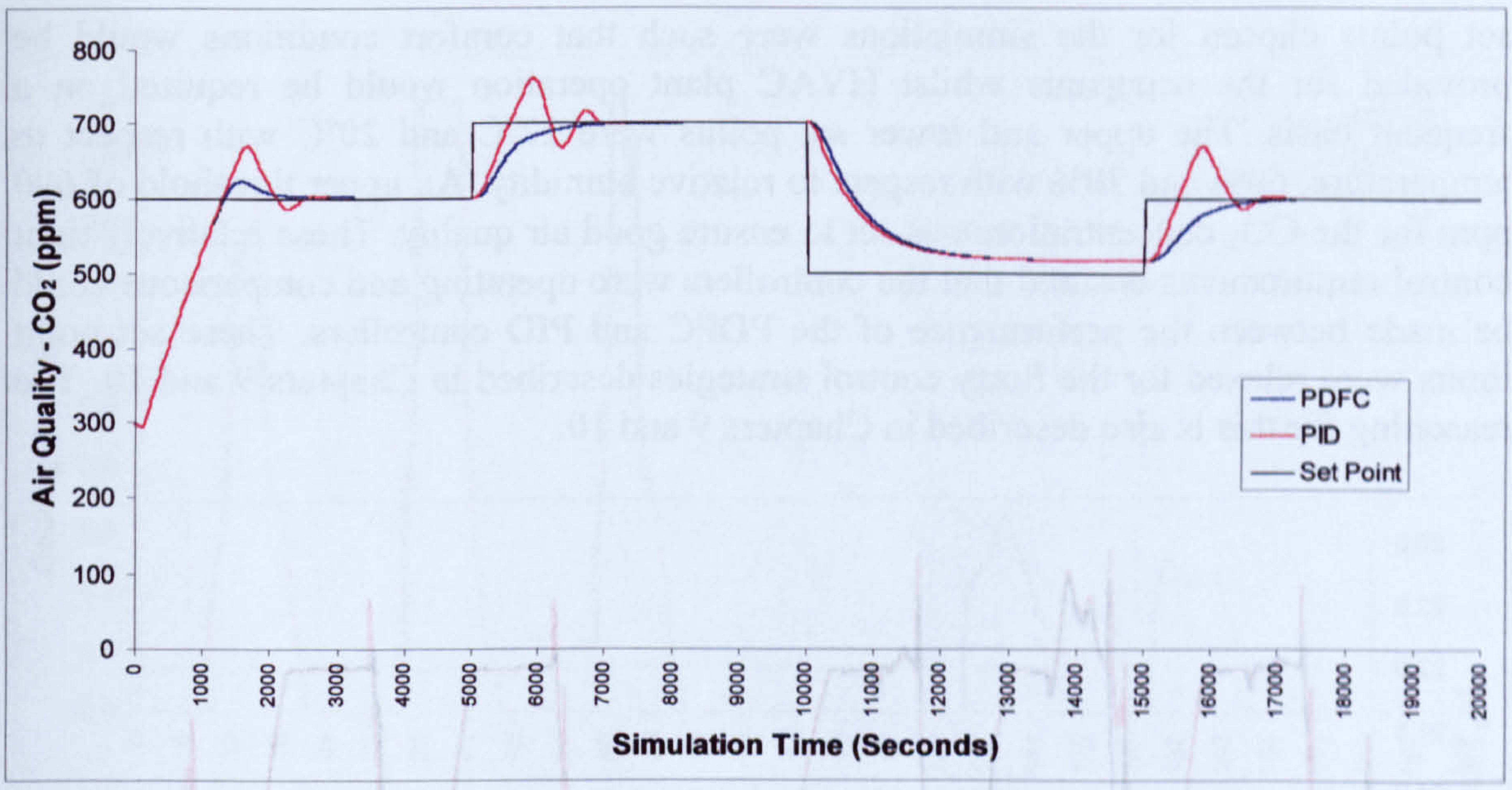

Figure 8.16. Zone air quality resulting from the use of the PDFC and PID control strategies operating the air re-circulation dampers in response to CO_2 concentrations.

The performances of the PDFC and PID control strategies assessed by graphical comparison were similar for the heating and cooling controllers. However, the humidification, dehumidification and re-circulation damper PDFCs generally showed less overshoot than for the PID controllers and hence exhibited a more desirable control characteristic. The PID results, see Figure 8.14, Figure 8.15 and Figure 8.16, show a larger degree of overshoot on reaching the desired set point but generally take a similar amount of time to bring the controlled parameter to the desired set point. This highlights possible short comings of tuning PID controllers using the Zeigler Nichols method, i.e. tuning parameters inferred from the continuous cycling method may not always provide suitable tuning gains for an operational controller.

8.4 PDFC and PID Control Strategy Seven Day Simulations

In order to provide diverse operating conditions for the model's HVAC plant and controllers, simulations for 7 consecutive days in each of the months for one year were carried out. The tuning parameters given in Table 8.2 and Table 8.3 were used for the PID and PDFC controllers respectively. The simulated week for each month was chosen at random. The weather data used was that for Kew, London, and was obtained from TAS weather data files (EDSL not dated). For the purposes of the seven day simulations the HVAC plant was operated such that it maintained the desired set point conditions within the zone 24 hours per day.

Figure 8.17 to Figure 8.23 show the environmental conditions provided and the valve positions for the HVAC plant models using PDFC and PID control for the week 2 - 8 July. The results for this simulated week were selected to show graphically because of the diverse plant operating conditions required. The broken lines in the following figures indicate the upper and lower set points for the controlled zone parameters. The set points chosen for the simulations were such that comfort conditions would be provided for the occupants whilst HVAC plant operation would be required on a frequent basis. The upper and lower set points were 22°C and 20°C with respect to temperature, 60% and 30% with respect to relative humidity. An upper threshold of 600 ppm for the CO_2 concentration was set to ensure good air quality. These relatively tight control requirements ensured that the controllers were operating and comparisons could be made between the performance of the PDFC and PID controllers. These set point limits were relaxed for the fuzzy control strategies described in Chapters 9 and 10. The reasoning for this is also described in Chapters 9 and 10.

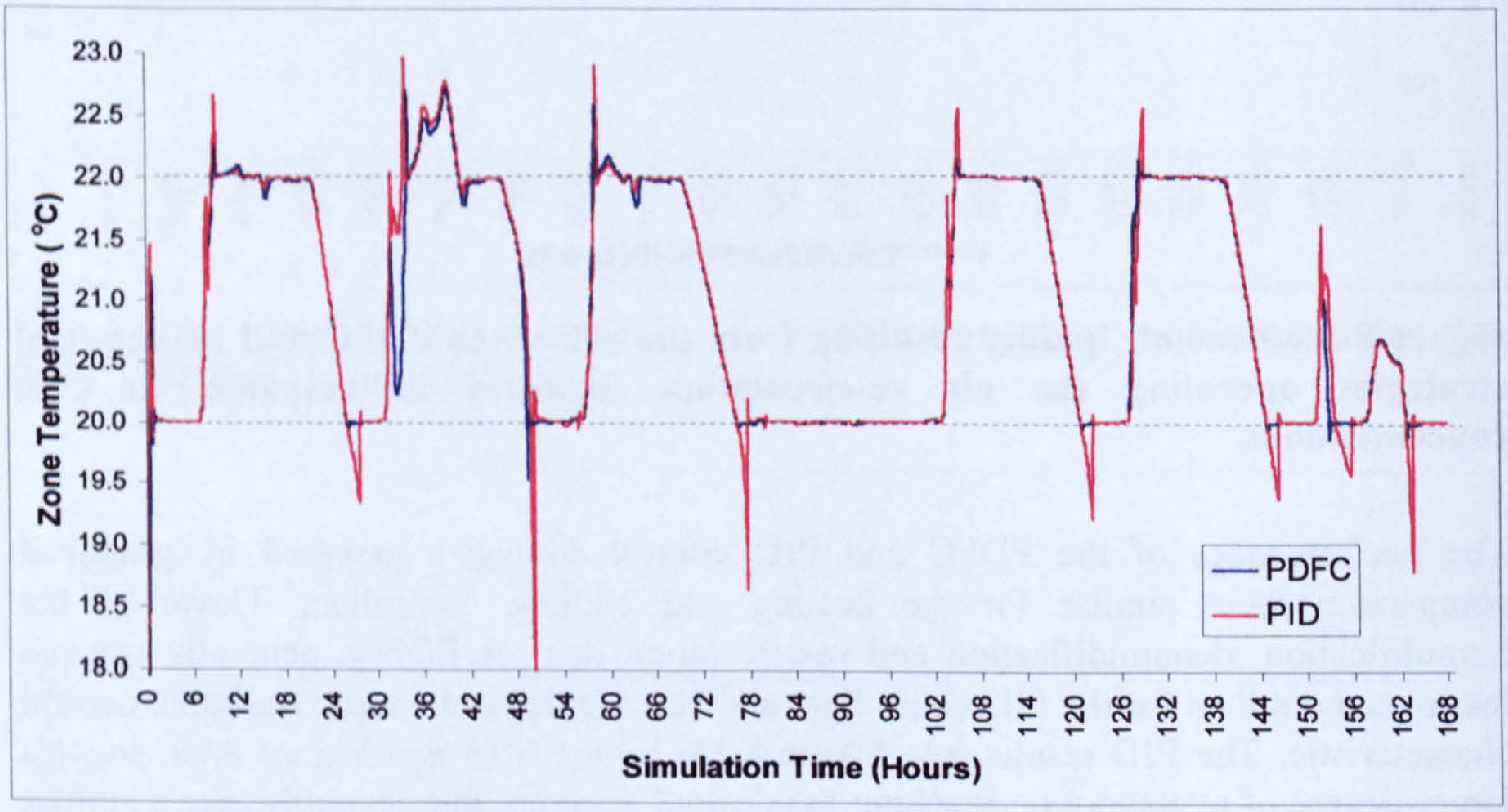

Figure 8.17. Zone temperature maintained by the PDFC and PID control strategies. Seven day simulation, July 2 - 8.

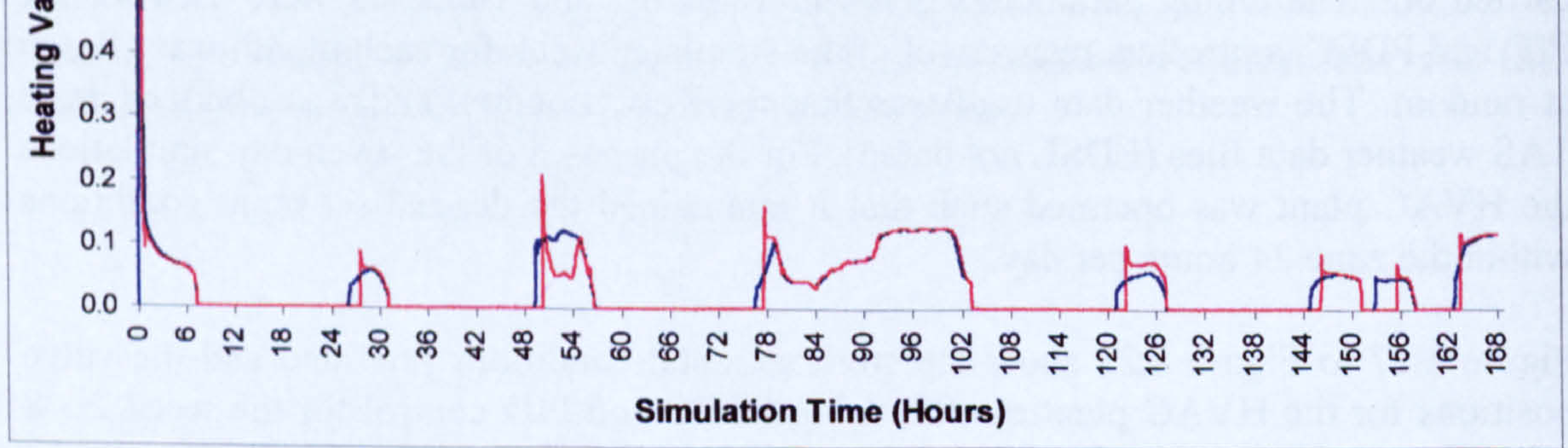

Figure 8.18. Heating valve position. Seven day simulation, July 2 - 8.

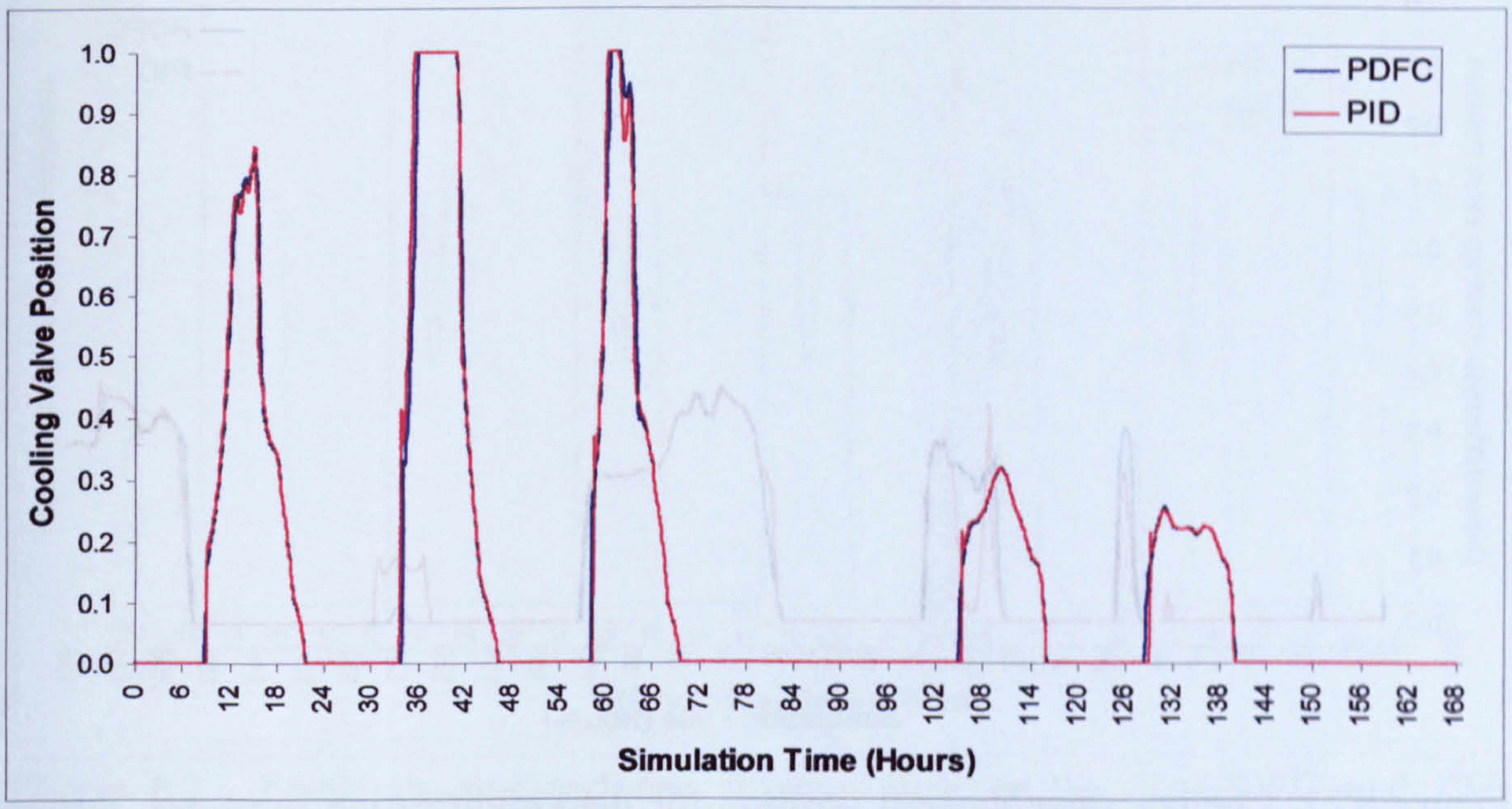

Figure 8.19. Cooling valve position. Seven day simulation, July 2 - 8.

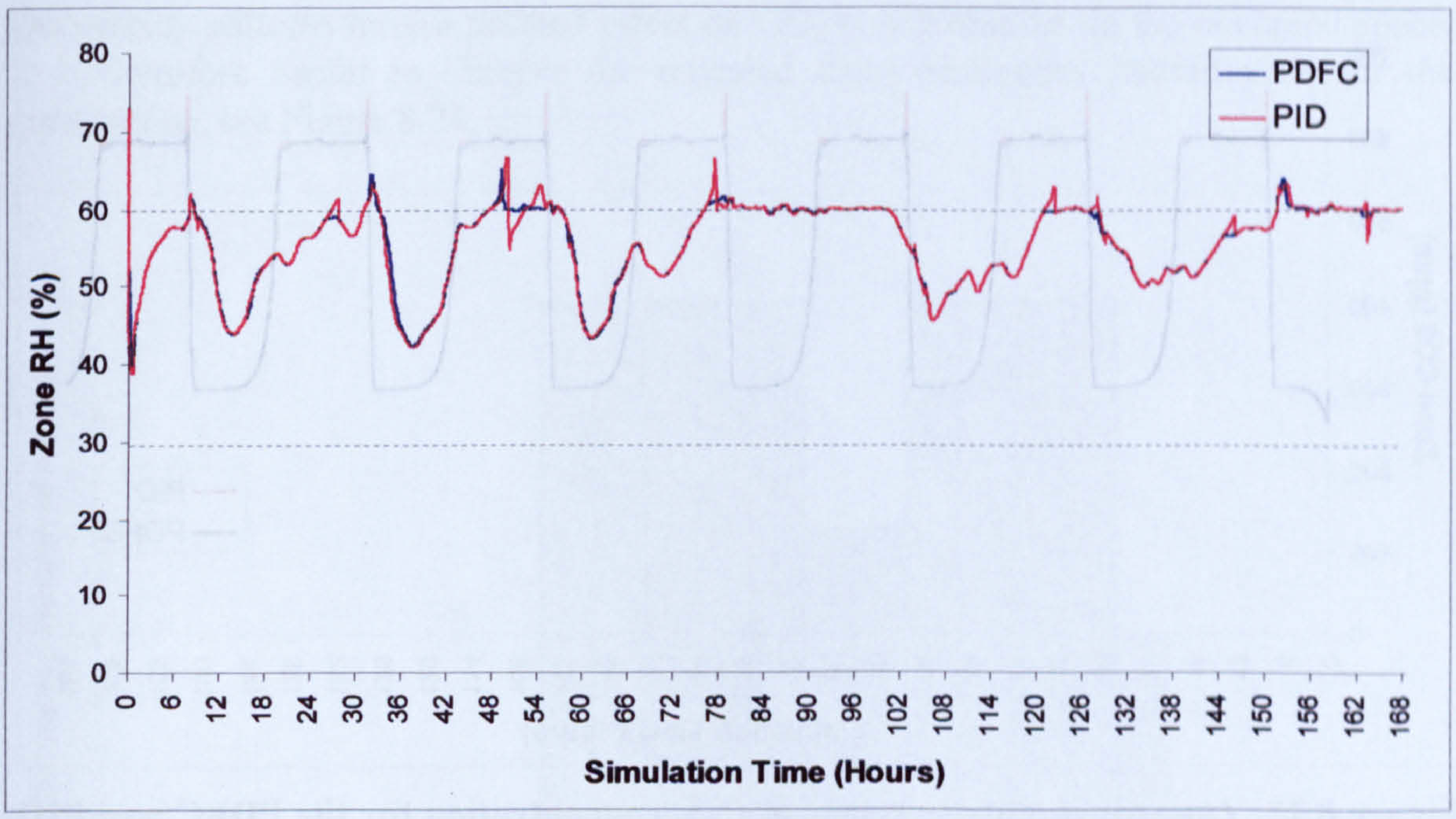

Figure 8.20. Zone relative humidity maintained by the PDFC and PID control strategies. Seven day simulation, July 2 - 8.

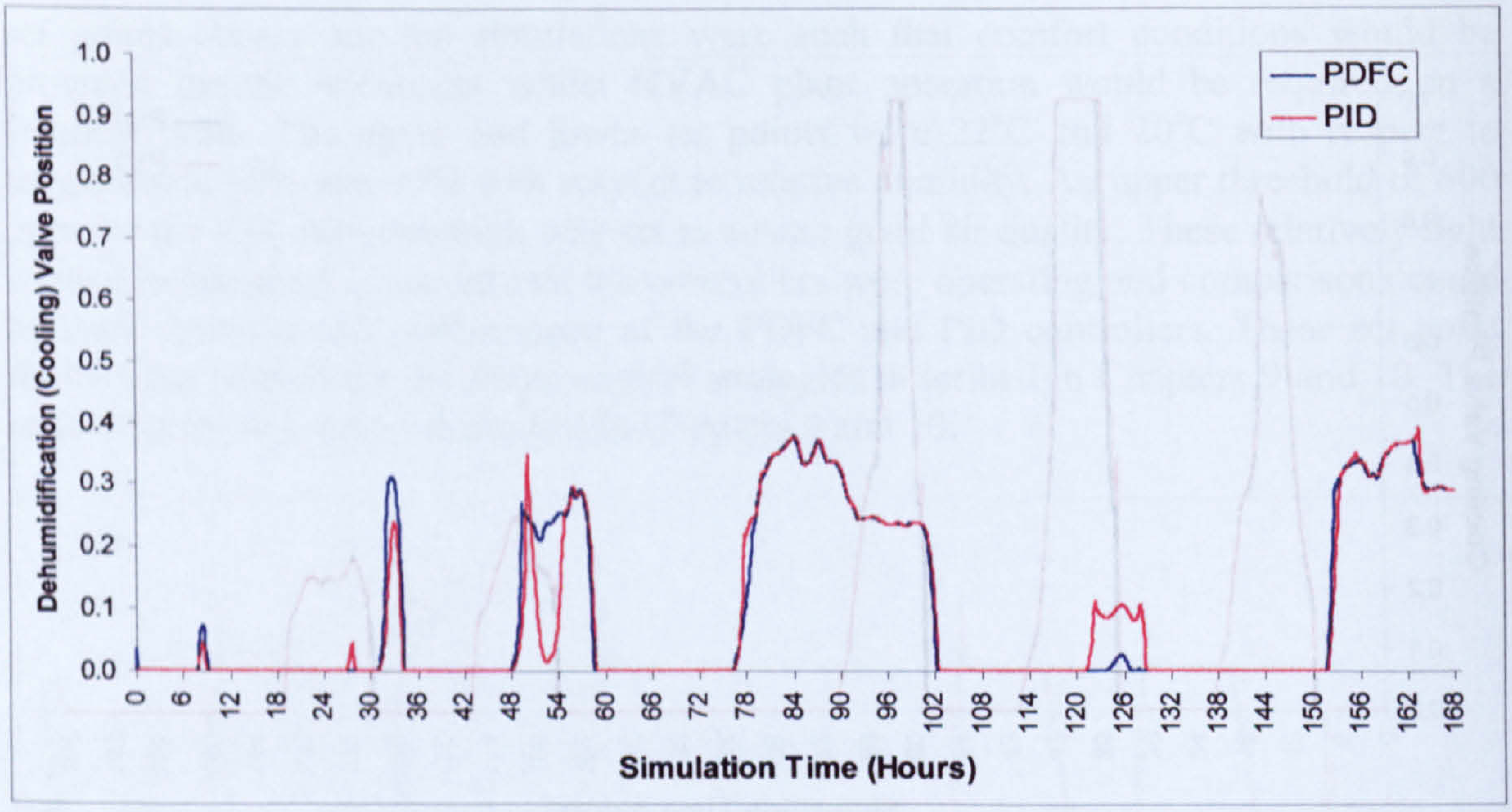

Figure 8.21. Cooling valve desired position for dehumidification purposes. Seven day simulation for PDFC and PID control strategies, July 2 - 8.

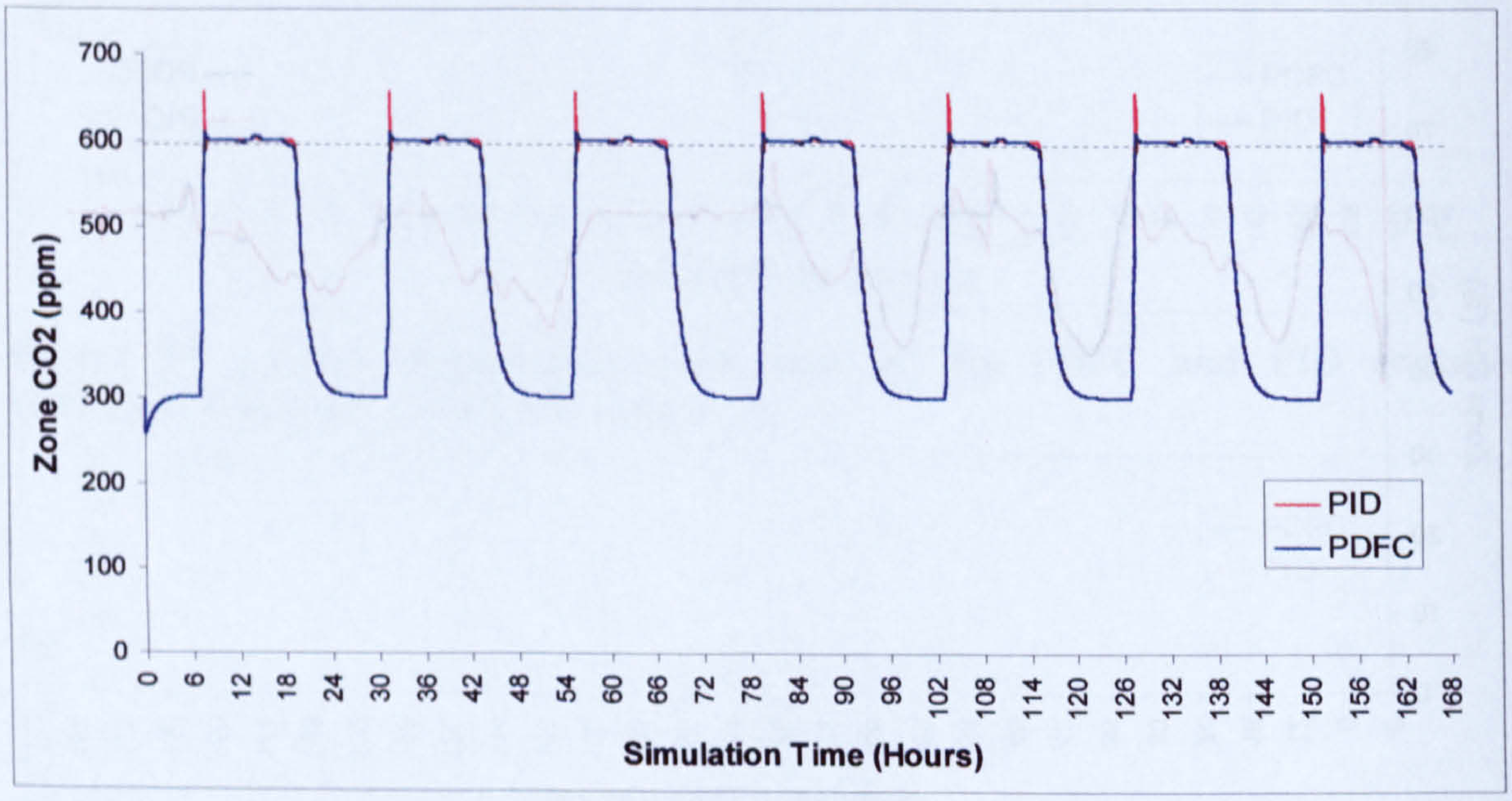

Figure 8.22. Zone air quality in terms of CO_2 concentration for the PDFC and PID control strategies. Seven day simulation, July 2 - 8.

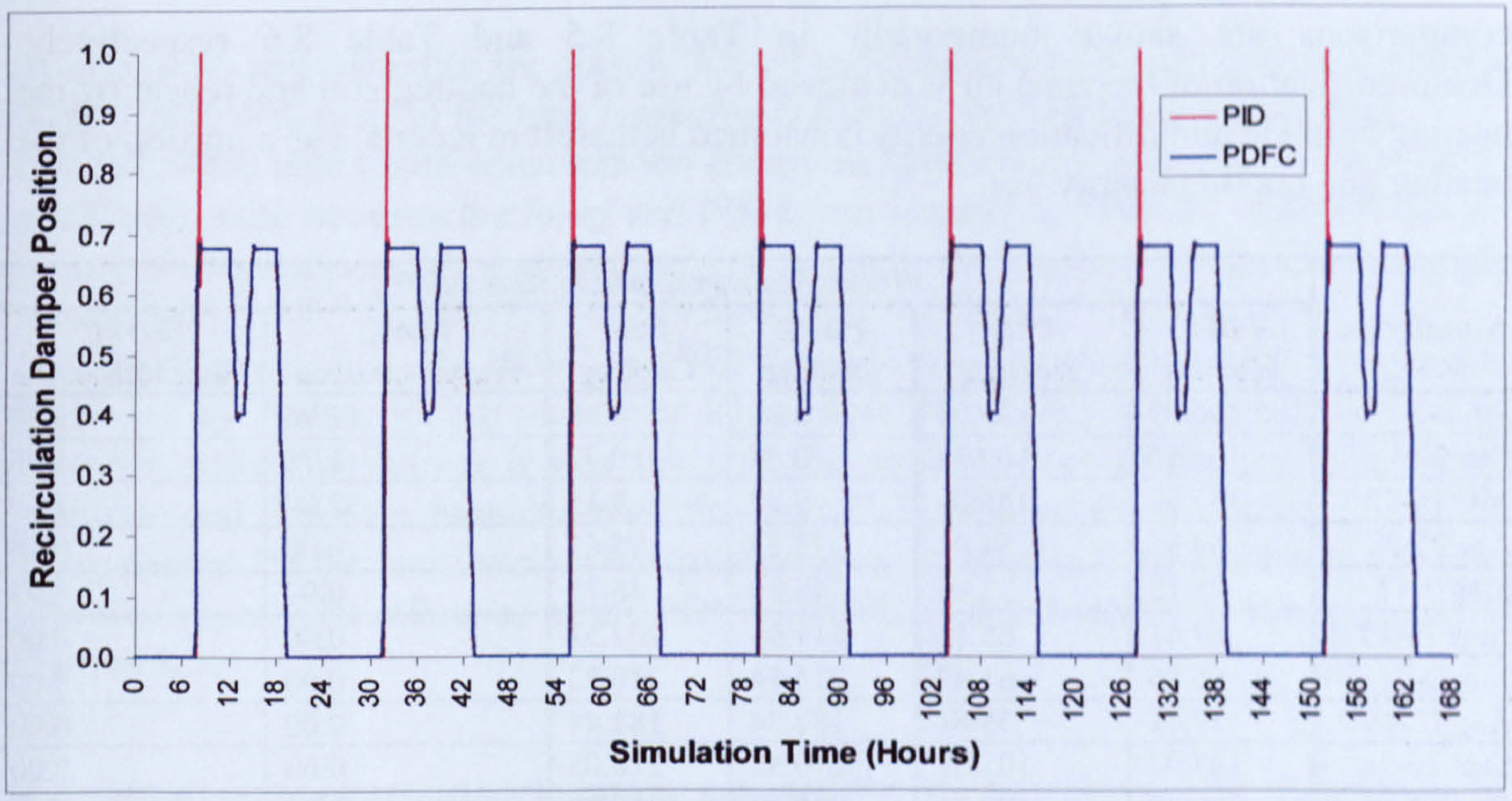

Figure 8.23. Fresh air re-circulation damper position for the PDFC and PID control strategies, seven day simulation, July 2 - 8.

Occupancy patterns have a marked effect on CO_2 concentrations in the occupied space. It is therefore useful to observe the repeated daily occupancy pattern used for the simulations, see Figure 8.24.

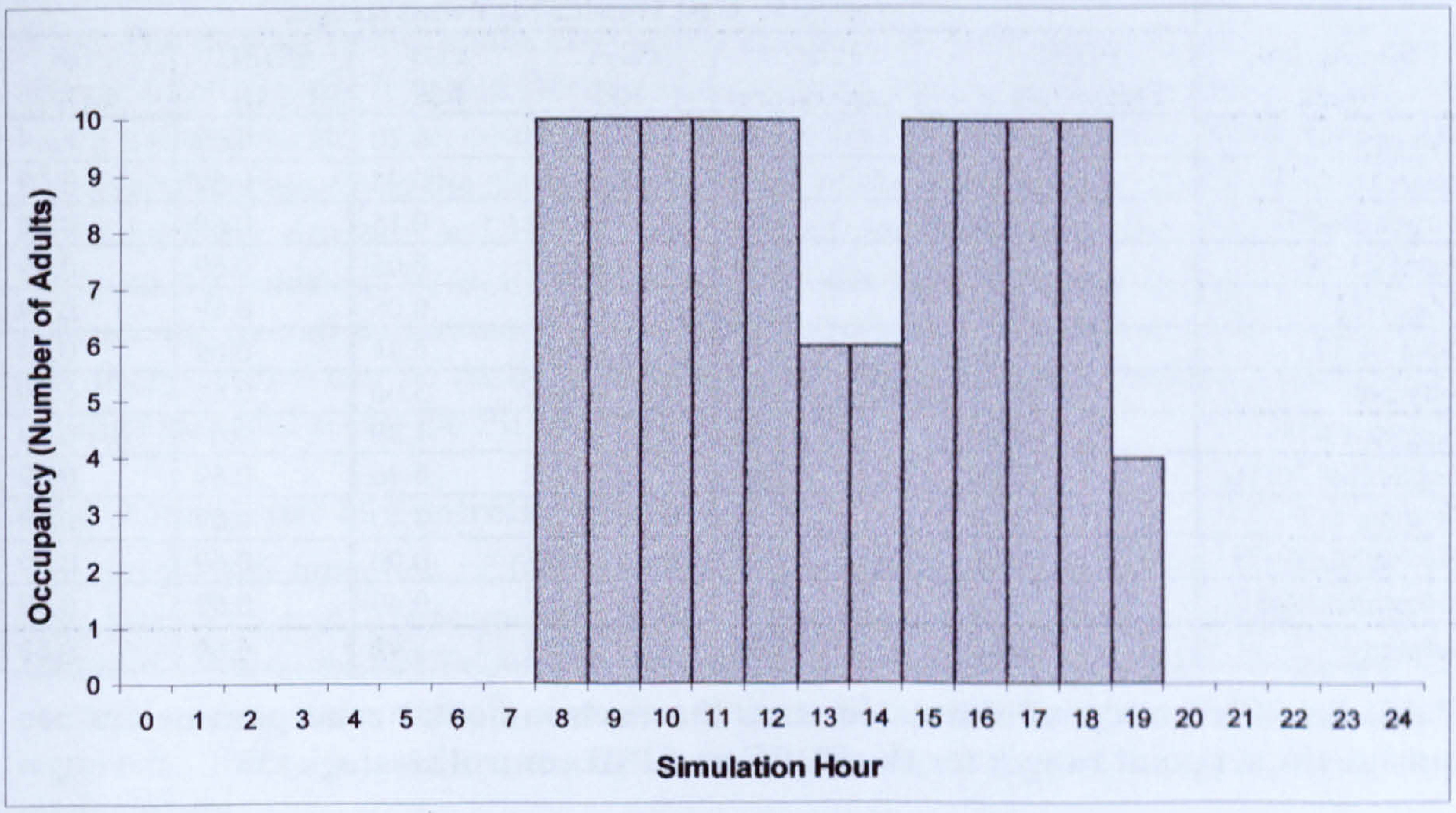

Figure 8.24. Repeated daily occupancy pattern for the seven day simulations.

For the twelve simulated weeks two types of quantitative comparisons were made between the PDFC and PID controller performances. These were energy use to maintain the desired condition and the percentage of the time the controlled parameter remained outside the pre-determined set point range for each controlled parameter. These comparisons are shown numerically in Table 8.5 and Table 8.6 respectively. Dehumidification of the zone air is achieved by use of the cooling coil and reheat by the heating coil. Dehumidification energy consumed is therefore recorded as a portion of the heating and cooling energy use.

Simulation Week	Weekly Energy Consumption (kWh)					
	PDFC Heating	PID Heating	PDFC Cooling	PID Cooling	PDFC Humidification	PDFC Humidification
Jan 1-7	196.09	195.09	0.88	0.78	13.76	13.57
Feb 5-11	161.36	160.54	0.97	0.72	1.78	1.75
Mar 19-25	157.83	156.88	9.20	9.15	32.09	31.59
Apr 23-29	54.96	54.06	75.83	75.65	0.00	0.00
May 7-13	75.12	73.95	46.89	46.75	0.99	0.97
June 11-17	67.41	65.30	211.01	207.52	0.00	0.00
July 2-8	65.16	61.42	214.14	210.23	0.00	0.00
Aug 13-19	37.11	35.81	182.34	181.45	0.00	0.00
Sept 10-16	107.07	105.51	210.98	210.05	0.00	0.00
Oct 1-7	200.87	199.71	238.69	238.29	0.00	0.00
Nov 19-25	229.13	228.09	0.01	0.01	2.72	2.67
Dec 24-30	202.71	201.65	0.53	0.32	18.87	18.63
Totals	**1554.84**	**1538.02**	**1191.49**	**1180.97**	**70.22**	**69.20**

Table 8.5. Energy use (kWh) for the twelve simulated weeks for the PDFC and PID controllers.

Simulation Week	Weekly % Time Outside Set Points Ranges					
	PDFC Temperature	PID Temperature	PDFC RH	PID RH	PDFC CO_2	PID CO_2
January 1-7	1.59	3.78	0.05	0.20	0.69	0.69
February 5-11	1.09	4.01	0.05	0.74	0.69	0.69
March 19-25	1.44	4.86	0.05	0.15	0.69	0.69
April 23-29	0.79	5.80	0.05	0.05	0.69	0.69
May 7-13	1.09	6.27	0.05	0.05	0.69	0.69
June 11-17	1.34	5.16	4.96	6.44	0.69	0.69
July 2-8	0.59	5.06	3.32	5.06	0.69	0.69
August 13-19	10.66	14.08	0.79	1.09	0.69	0.69
September 10-16	2.48	6.84	2.57	4.46	0.69	0.69
October 1-7	0.45	2.43	2.38	5.10	0.69	0.69
November 19-25	1.29	2.23	0.00	0.00	0.69	0.69
December 24-30	1.64	3.57	0.05	0.40	0.69	0.69
Average	**2.04**	**5.34**	**1.19**	**1.98**	**0.69**	**0.69**

Table 8.6. Percentage of simulated time the environmental zone parameters are outside the set point ranges for the PDFC and PID control strategies.

From Table 8.5, the total energy use for the PDFC and PID control strategies are 2816.55 kWh and 2788.19 kWh respectively. Therefore, for the 12 simulated weeks the PDFC strategy uses 1.02% more energy as compared to the PID control strategy for identical weather, occupancy, plant and building characteristics.

However, Table 8.6 reveals that the zone temperature and humidity are not controlled to within the set point ranges by the PID strategy as well as by the PDFC strategy.

Temperature and humidity are outside the set point ranges for the PID control strategy 3.3% and 0.79% more of the time respectively than for the PDFC control strategy.

Overall, when taking into consideration energy use and control accuracy, there is only a small difference between the fuzzy and PID control strategies. For the small differences observed it is not possible to determine conclusively that either of the control strategies was superior.

It is probable that both the PDFC and PID controller performances could be marginally improved by further tuning parameter adjustment. However, within the scope of the research project objectives it was felt that the performances of the controllers were adequate and that they provided realistic controllers with which to explore the use of fuzzy control for the multi-variant control strategies detailed in Chapters 9 and 10. Other relevant issues with reference to the PDFC and PID control strategies are discussed in Section 8.5.

8.5 PDFC and PID Control Strategy Issues

The performance of the PDFC and PID control strategies in terms of energy use and control accuracy indicate little overall difference in the simulations carried out. However, other positive and negative aspects should be taken into consideration for both strategies.

8.5.1 Inherent Controller Accuracy

PID controllers consider the error, the integral of the error and the rate of change of the error. The heating PDFC considered in the example used the inputs of error and rate of change of error only. It would therefore be expected that the PID controller is capable of being more accurate in its control. This was not the case in the simulations conducted. The probable cause was the slow response time of the entire system due to thermal lags in the building structure and HVAC plant. Equal performance to the PID controller is likely to be achieved by a PI controller. The derivative control actions do little to enhance the overall performance of the PID controllers. This result does however show that fuzzy control can be easily implemented to produce control performance equal to the high standard set by the PID control algorithm.

8.5.2 Complexity of Controller Design

The design and operation of fuzzy controllers is readily understood due to similarities with human thought processes and terminology. It uses human expert knowledge, i.e. common sense in terms of controller output for given controller inputs. In contrast, PID control is more mathematically complex to those who are not mathematicians or control engineers. Fuzzy control represents a more readily understood underlying design methodology.

8.5.3 Tuning of the Controllers

Two aspects concerned with controller tuning are worthy of mention.

1. Both the fuzzy and PID controllers need to be tuned in order to obtain satisfactory performance. Two points of interest arise with regard to the tuning methods. Standardised methods are available for tuning the PID controllers, i.e. Zeigler-

Nichols methods, whereas the tuning of the fuzzy controllers is carried out using an iterative process and expert operator knowledge. Using the Simulink model, the time taken to tune the PID controllers was considerably less than for the fuzzy controllers. If this is taken through to the tuning required for real HVAC plant then fuzzy tuning represents a real problem. The Simulink dynamic model allowed a simulation of 20,000 seconds, i.e. more than 5 hours, to be carried out in less than five minutes of real time. Fuzzy tuning commonly required 20 - 30 iterative tuning simulations to achieve satisfactory controller performance. In a real building this would be unsatisfactory. In contrast the tuning of the PID controllers only required 2 or 3 simulation runs to obtain the tuning parameters using the continuous cycling Zeigler Nichols method. This represents a more realistic option for real HVAC systems in real buildings. Further, using the Zeigler Nichols response method for tuning PID controllers commonly requires only one tuning run for commissioning engineers. With respect to conventional controller tuning, auto tuning controllers are readily available, e.g. CAL 3300 and 9300 Autotune Temperature Controllers (CAL 1997). Controllers such as this are capable of autotuning the PID algorithms stored within the controller. These points highlight a major drawback of pure fuzzy controllers as a replacement for conventional controllers.

2. Tuning of the controllers is carried out for representative operating conditions. As a result the control actions may become unstable under other operating conditions. However, experience of using the fuzzy and PID controllers in the Simulink model suggest that the PID controllers tuned using the Zeigler-Nichols method tended to be less stable during alternative operating conditions. The controller strategy performance comparisons described in this chapter suggest the fuzzy controllers perform with a comparable performance to the PID controllers. However, should the PID controllers be tuned using the conventional methods available and then adjusted using operator knowledge as with the PDFC controls, it is probable that it is possible to further increase their performance for that operating condition without control instability.

Improved methods of tuning PDFCs would represent a major step forward in terms of developing fuzzy controllers. Methods such as that described by Hurtta (1994), see Chapter 3, in which fuzzy logic was used as a gain scheduler for the tuning parameters of a conventional PID controller represent a possible method of improving the control performance of a PDFC. The gain factors of a PDFC could be scheduled using the same methodology. Another area worthy of exploration in this respect is the use of neural networks to tune the PDFC once the PDFCs are in use, e.g. Egilegor (1997), see Chapter 3.

8.6 Conclusions and Discussion

This chapter described the use of Proportional Derivative Fuzzy Controllers (PDFCs) as alternatives to conventional PID controllers. The PID controllers used for the benchmark comparisons were tuned using the Zeigler Nichols continuous cycling method. The tuning of the PDFC controllers was achieved by adjustment of gain factors on the inputs and outputs of the PDFCs. Intuitive reasoning and a knowledge of how the adjustment of these gain factors would affect the PDFC performance was used to satisfactorily tune the controllers. The use of gain factors as a method of tuning the

PDFCs proved useful and reduced the amount of time taken for controller tuning. From a practical view point, the PDFCs were more time consuming to tune using the iterative technique of adjusting the gain factors than using the Zeigler Nichols tuning method for the PID controllers. This could represent a major disadvantage for real PDFC control system implementation in real buildings where the tuning has to be carried out in real time. However, PDFCs provide an easy to understand control methodology based on human operator knowledge and common sense. This can make the understanding of the PDFC control methodology more attractive to the non engineer as an understanding of the control methodology can be quickly acquired. Tuning methods assisted by the use of neural networks and fuzzy gain scheduling of the PDFC gain factors were identified as methods that could improve this situation.

The comparison between the PDFC and PID control strategies investigated in this chapter suggest that there is only a small difference between the performance of the two control strategies. For the compared 7 day simulation periods for each month of one year the PDFC strategy required slightly more energy than the PID strategy (1.02%). However, PID control strategy zone temperature and humidity conditions were outside the desired set point limits for a greater percentage of the simulated time than for the PDFC strategy by 3.3% and 0.79% respectively. From these results it may be concluded that a superior overall performance cannot be conclusively attributed to either control strategy. However, the PDFCs did exhibit a better control characteristic, i.e. less overshoot, for the humidification, dehumidification and air quality controllers.

Overall, PDFC control as PID control were shown to be capable of comparative performance during the simulations. However, the commissioning time for the fuzzy controller is lengthy when compared with conventional control. A quote taken from Yen et. al. (1995) reflects the findings of this chapter:

"Using fuzzy logic to replace a PID controller is like limiting a Ferrari to drive in first gear only"

This quote would appear to be relevant as the findings of this chapter indicate that fuzzy control is capable of replacing conventional controllers, but fuzzy logic has far more to offer. The fuzzy decision making capabilities of fuzzy controllers enable multi-variant control problems to be dealt with. Chapters 9 and 10 investigate the use of these capabilities to take advantage of the possibilities offered by fuzzy control.

8.7 References

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9. Fuzzy Ventilation Control

Nomenclature

de/dt	rate of change of error from set point (°C/s) (%RH/s)
e	error from set point (°C) (% RH)
K_p	error gain factor (dimensionless)
K_d	rate of change of error gain factor (dimensionless)
K_{diff}	(zone condition - ambient condition) differential gain factor (dimensionless)
K_o	fuzzy ventilation controller output gain factor (dimensionless)
MC_{amb}	ambient air moisture content (kg/kg)
MC_z	zone air moisture content (kg/kg)
T_{amb}	ambient air temperature (°C)
T_z	zone air temperature (°C)

9.1 Introduction

This chapter investigates the use of fuzzy controllers for the control of the re-circulation air damper in the Simulink model as a means of adjusting the zone temperature and humidity. The fuzzy ventilation control strategy aims to use the free cooling and dehumidification available due to differences in zone and ambient conditions by changing the proportion of fresh air entering the HVAC system and hence the controlled zone.

Upper and lower controlled zone parameter set points were used between which fuzzy ventilation controllers and PDFC HVAC plant controllers, i.e. heating, cooling, dehumidification humidification and air quality, aimed to maintain the environmental conditions during periods when the HVAC plant was operational. For the graphically illustrated examples of the use of the fuzzy ventilation control strategies the HVAC plant was operational 24 hours per day. For the annual simulations the HVAC plant was operational between 05:00 and 17:00. When possible, the fuzzy ventilation controllers also aimed to maintain the zone conditions at a preferred set point which was between the upper and lower set points. The upper and lower set point limits and the preferred set point for fuzzy ventilation control purposes were set to ensure occupant comfort. Hence when the fuzzy ventilation control strategy was not capable of maintaining the zone conditions to within the upper and lower set-point limits the HVAC plant became operational.

Results from simulations using the fuzzy ventilation control strategy were compared with normal plant operation using PID controllers with upper and lower set point limits for each controlled parameter. This benchmark comparison was used to assess the benefits of using the fuzzy ventilation control strategy.

9.2 Fuzzy Ventilation Controller Operation

This section considers the general theory used for the fuzzy ventilation controllers.

9.2.1 General Aims of the Fuzzy Ventilation Controllers

The fuzzy ventilation controllers primarily aim to improve energy consumption and comfort conditions with respect to cooling, dehumidification and air quality. It was possible to use ambient cooling because zone temperatures often rise above outside temperatures due to solar and occupant gains within the zone. This allowed the zone temperature to be lowered by introducing cooler fresh outdoor air. Situations rarely occur where the outdoor temperature is above that of the zone and HVAC plant is required to be operational due to the zone temperature being below the required set point. Therefore ambient heating is not considered within the fuzzy ventilation control strategy.

Dehumidification using the ambient air can be achieved where humidity levels rise to undesirable levels due to occupant or process gains within the zone and was considered as part of the fuzzy ventilation control strategy. By introducing outside air to the controlled zone with a lower moisture content than the zone air, the zone relative humidity can be reduced. In contrast, humidification as part of the fuzzy ventilation control strategy was in practice unlikely to be feasible. Even though high humidity levels may exist outside while indoor levels are low, the moisture content of the air needs to be considered. A nominally high relative humidity in the outdoor air does not mean that it has a high moisture content. For example air at 5°C and 80% RH has a moisture content of 0.0044kg per kg of dry air. If this air were to be heated to 20°C without the addition of moisture its relative humidity would be 30%. Consequently, ventilating the ambient air directly into the zone will not increase the relative humidity when the air temperature needs to be raised to a comfortable level. Thus ambient humidification is not considered as part of the fuzzy ventilation control strategy.

The indoor air quality was controlled in the same way as the PDFC control strategy with the CO_2 concentration of the air used as an indicator of indoor air quality. Introducing fresh outdoor air into the zone is the only method of controlling the air quality by practical means.

With respect to zone temperature control, a fuzzy controller considered the differential between zone and ambient temperatures. With respect to zone relative humidity control a fuzzy controller considered the differential between the zone and ambient air moisture contents. The fuzzy ventilation controllers decided whether it was preferable to cool or dehumidify using ambient fresh air and then controlled the fresh air re-circulation damper to achieve the preferred set point if possible.

9.2.2 Set Point Ranges and Limits for Environmental Control using the Fuzzy Ventilation Control Strategy

Zone environmental parameter upper, lower and preferred set points are based on Predicted Percentage Dissatisfied criterion. Combinations of temperature and humidity, 20°C - 24°C and 30% - 60 % respectively, will not result in a Predicted Percentage Dissatisfied (PPD) value of greater than approximately 10% according the Fanger comfort equation as described in Chapter 2. The preferred set points for temperature and humidity are 22°C and 45% RH. This temperature humidity combination results in a 5% PPD level, the minimum PPD achievable according to Fanger. The PPD calculations used to define the set points assumed an air velocity of 0.15 m/s, a mean radiant temperature equal to the air temperature, a clothing thermal resistance of 1 clo and a metabolic rate of 1.2 met. These conditions are typical of those experienced by occupants in office type environments.

The zone temperature and humidity upper and lower set points as well as the preferred set points are shown graphically in Figure 9.1 and Figure 9.2.

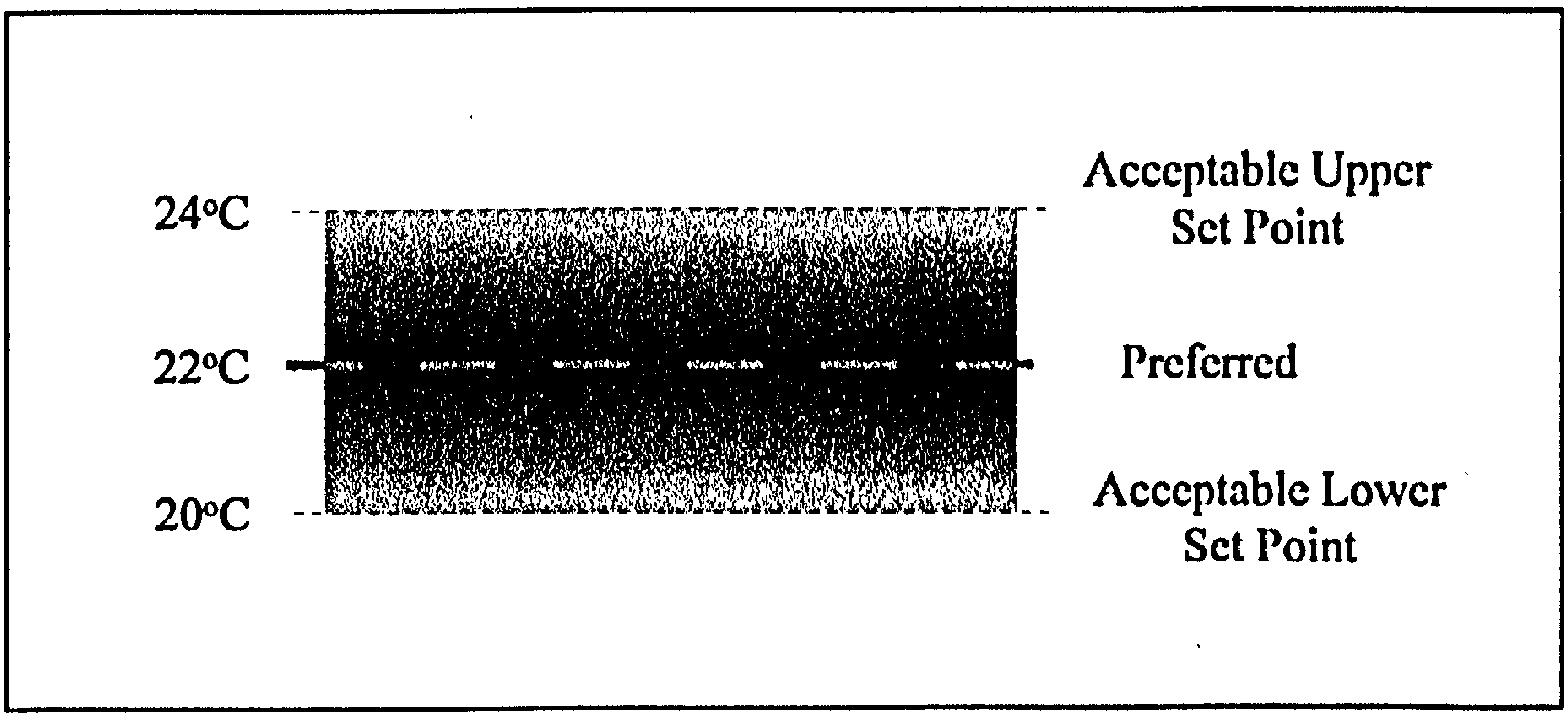

Figure 9.1. Zone temperature upper, lower and preferred set points.

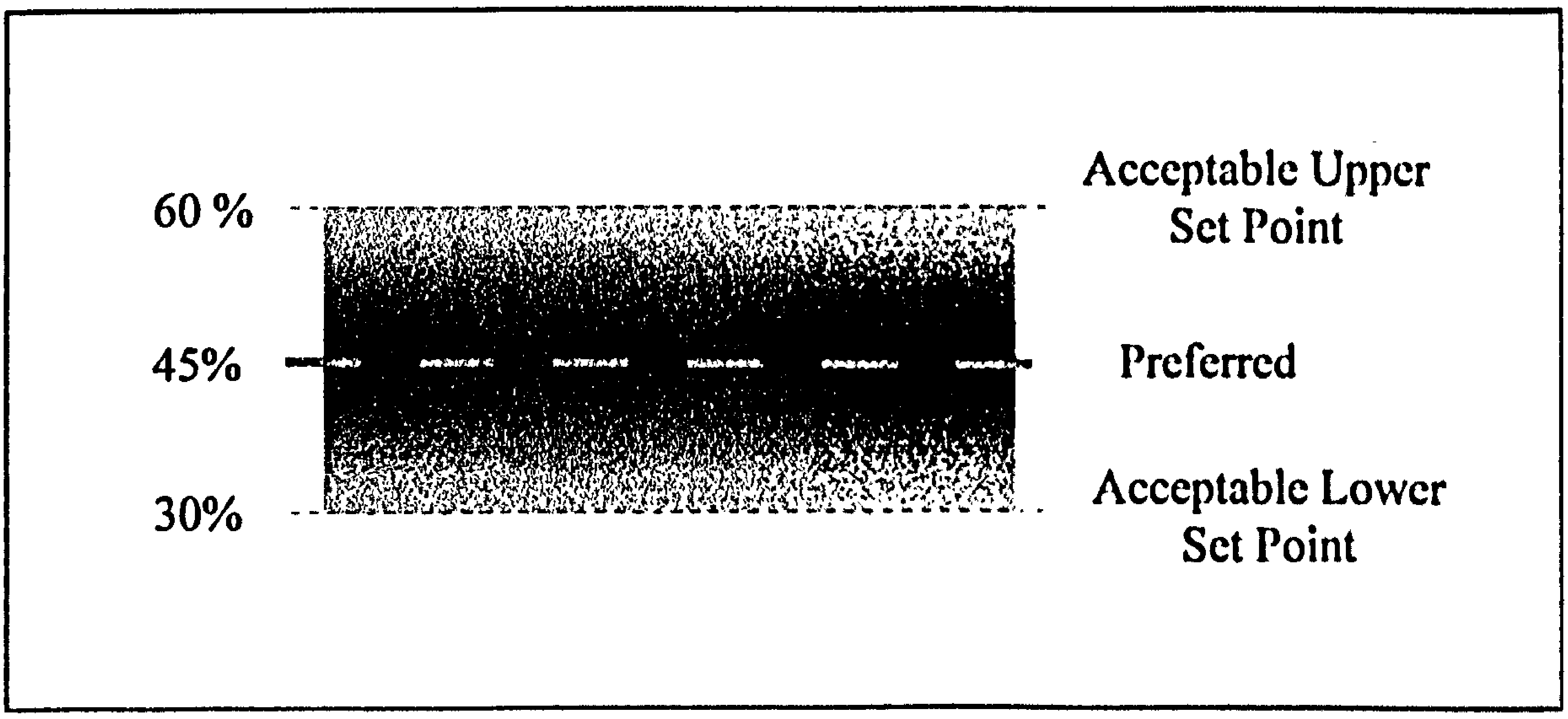

Figure 9.2. Zone relative humidity upper, lower and preferred set points.

During simulations the zone parameters were allowed to drift between the upper and lower set point limits unless the fuzzy ventilation controllers took advantage of the opportunity to bring a zone parameter towards its preferred set point. The darker shaded areas in Figure 9.1 and Figure 9.2 indicate that the zone condition is closer to the preferred zone parameter conditions.

With respect to zone air quality the upper set point limit was set at a 1000 ppm CO_2 concentration. Zone air quality considerations always took priority over temperature and humidity considerations for the control of the re-circulation damper when the desired re-circulation damper position value of the air quality controller was the largest.

9.2.3 Fuzzy Ventilation Controller Structure

A schematic of the structure of the fuzzy ventilation controllers is shown in Figure 9.3.

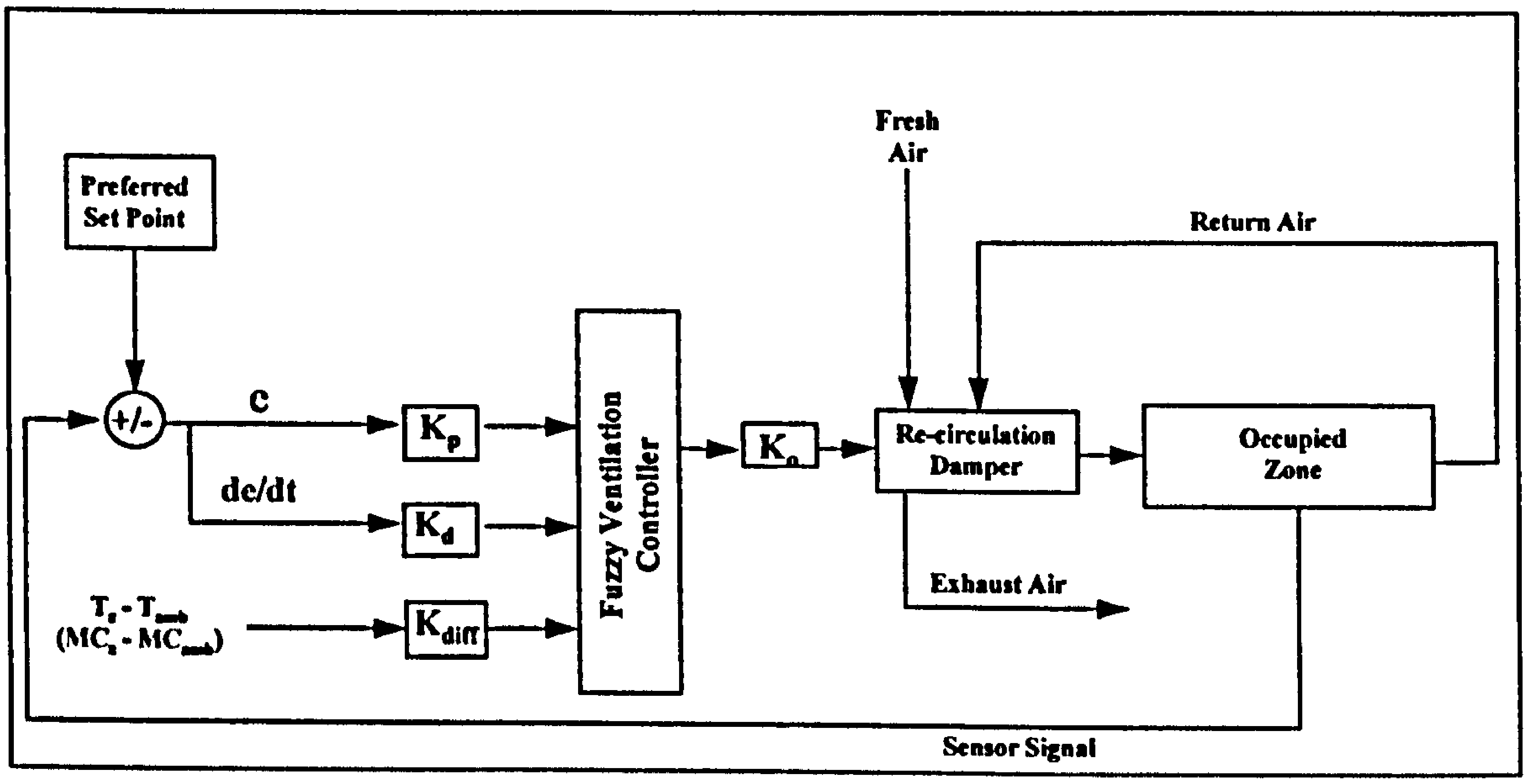

Figure 9.3. Fuzzy ventilation controller schematic.

The basic principle of operation of the fuzzy ventilation controller was that of a PDFC controller with the extra input of the ambient to zone parameter differential. The parameter differential was used to make a decision on whether it was possible to cool or dehumidify using the ambient air. Referring to Figure 9.3 the principle of operation of a fuzzy ventilation controller is as follows:-

- the error, rate of change of error and difference between the ambient and zone condition under consideration are used as the three inputs to the fuzzy controller.
- the fuzzy controller, a PDFC with the extra input information of the difference between the ambient and zone conditions, assesses the current zone condition under consideration and decides whether any benefit can be gained from altering the position of the re-circulation damper for the purposes of free cooling or dehumidification.
- PDFC controllers control the HVAC plant components as normal and are operational when the controlled zone parameter drifts beyond the upper and lower set point limits.
- the air quality requirements of the zone controlled by a separate controller has priority over the cooling and dehumidification ventilation controllers.

The membership functions for the normalised error and rate of change of error are shown in Figure 9.4. To reduce the complexity of the controller the number of membership functions on each input universe were reduced to five compared to the seven used for the PDFC in the previous chapter. Exponential, or Gauss, shaped membership functions were used to define the input and output membership functions for the fuzzy ventilation controllers. This was done in order to assess whether any noticeable control improvements could be made by having "smoother" membership functions. However, the use of the exponential membership functions had no noticeable effects on the performance of the controllers during simulations, either negative or positive. As the fuzzy ventilation controllers had been developed using the exponential membership functions, they therefore remained during the remainder of the simulations carried out for the fuzzy ventilation controller strategy assessments.

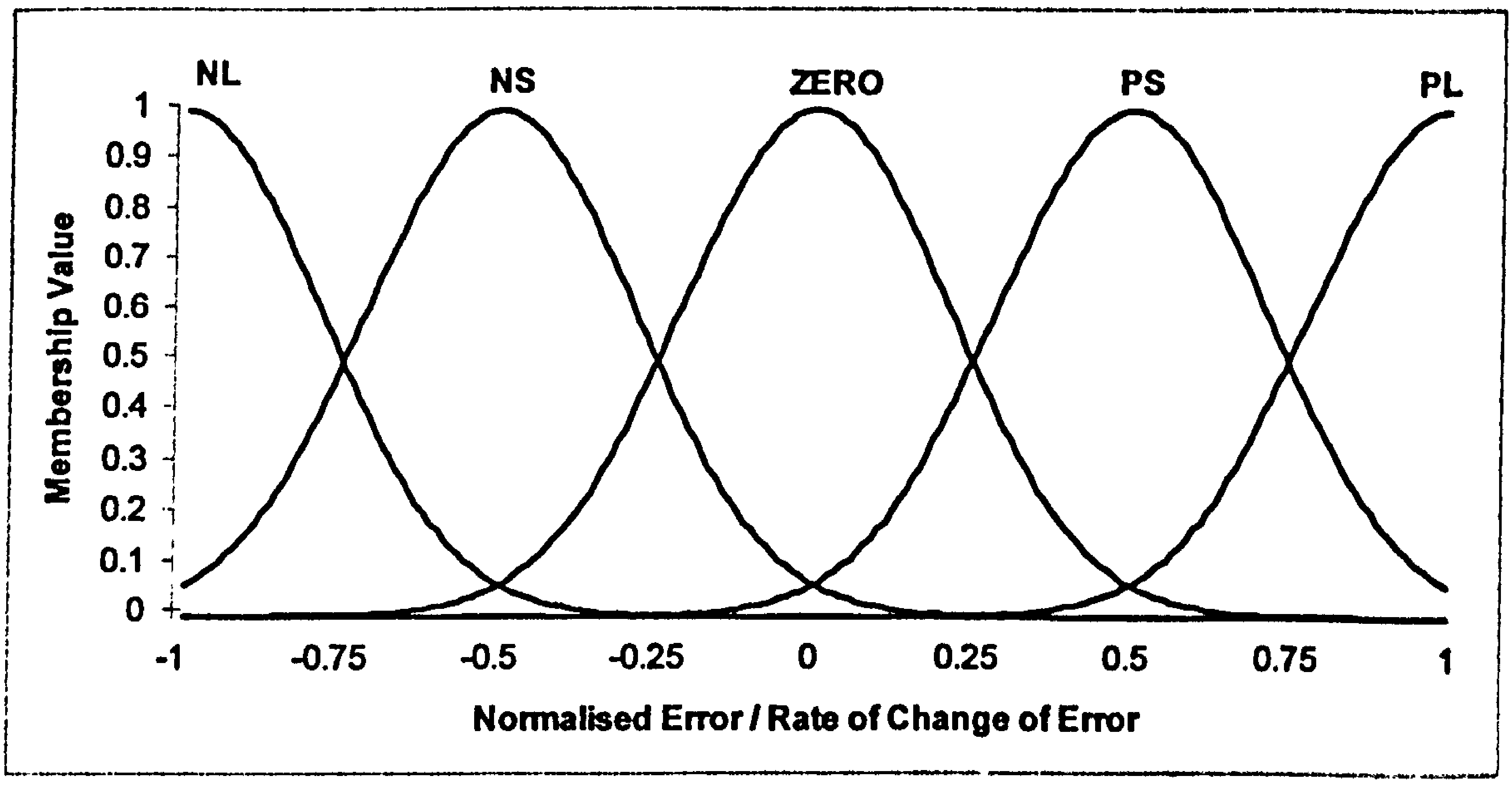

Figure 9.4. Normalised error and rate of change of error input membership functions for the fuzzy ventilation controller.

The membership functions for the zone-ambient parameter value difference are shown in Figure 9.5.

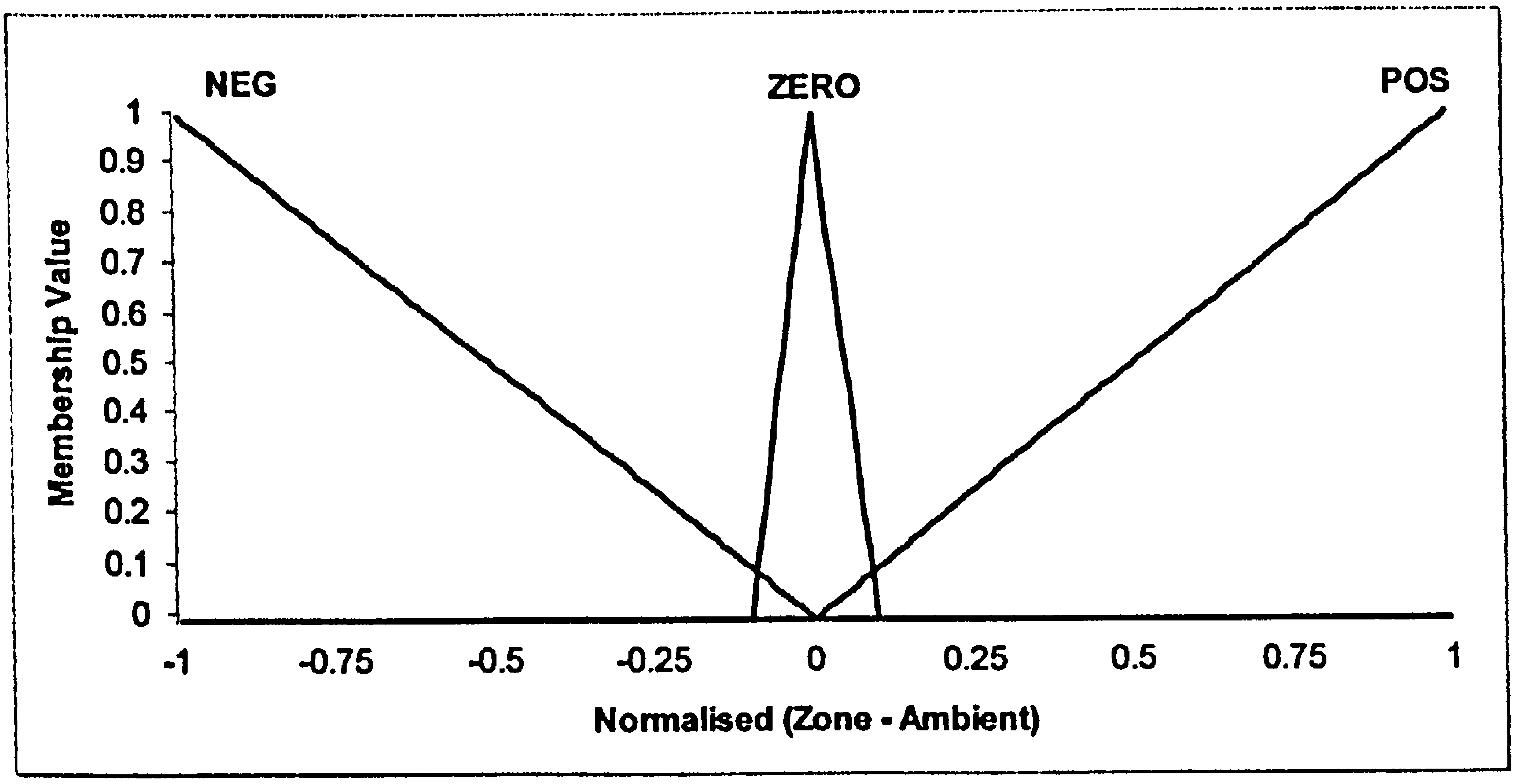

Figure 9.5. Normalised membership functions for the difference between the zone and ambient condition under consideration.

The normalised output membership functions for the fuzzy ventilation strategy controllers are shown in Figure 9.6.

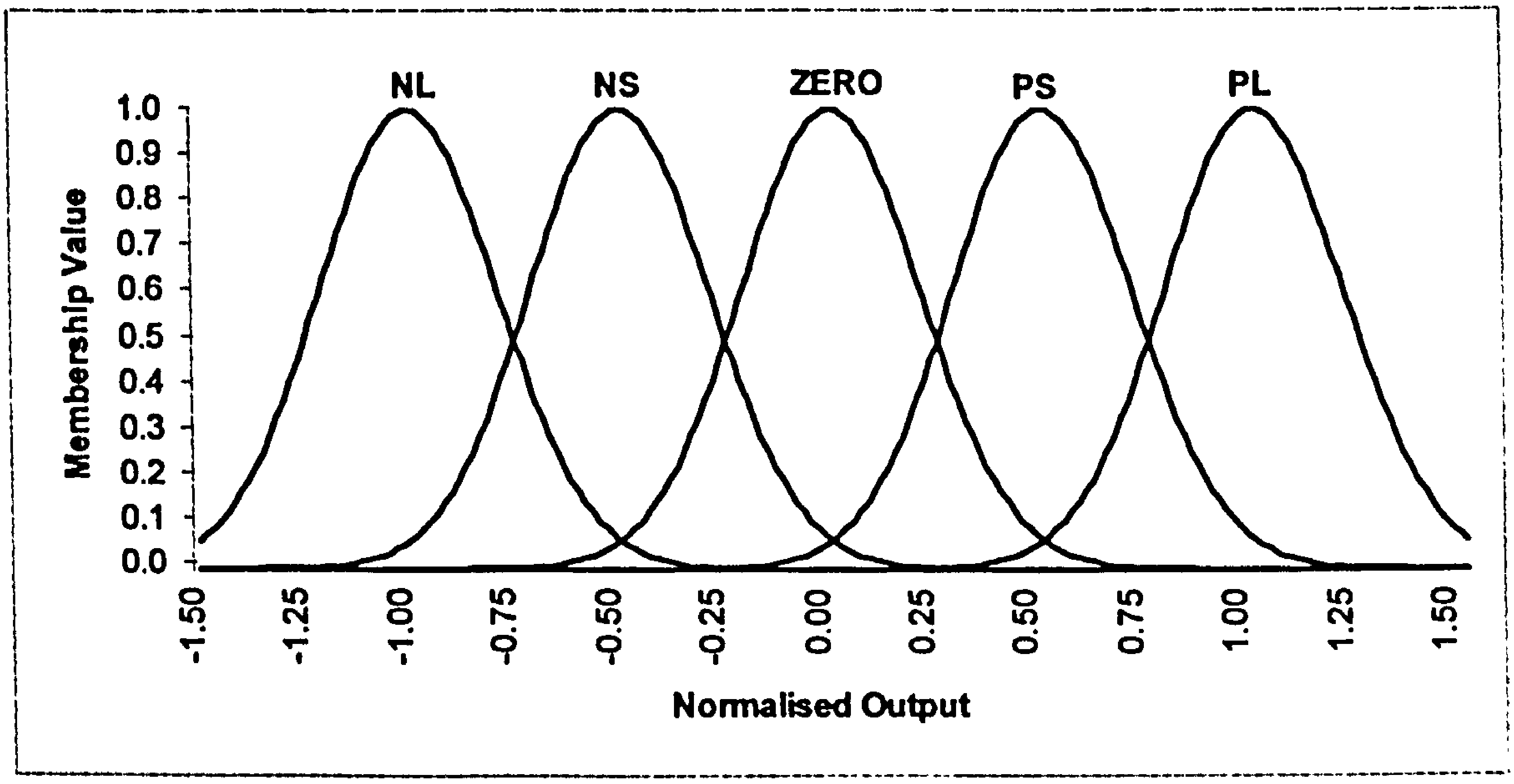

Figure 9.6. Normalised output membership functions for the fuzzy ventilation strategy controller.

Theoretically, there are 50 rules (5 x 5 x 2) for a fuzzy controller using 3 inputs and the membership functions shown in Figure 9.4 and Figure 9.5. However, the 50 rules can be reduced to 27 rules by removing redundant rules. For the fuzzy ventilation controllers under consideration increased ventilation is not required when the ambient condition is higher than the zone condition. For example, if the zone condition was 27°C and the ambient condition was 35°C, then under no circumstances should the amount of fresh outdoor air entering the zone be increased for free cooling purposes. This implies that any control rules where the "zone minus the ambient" condition is negative should result in the proportion of fresh air entering the zone being reduced. This means that 25 of the control rules can be reduced to two control rules, see rules 26 and 27 below.

The control rules relating the fuzzified input values to the fuzzy output were:-

1. **IF** (Error is PL) **AND** (Rate is PL) **AND** (Zone-Amb is POS) **THEN** (Damper is NL)
2. **IF** (Error is PL) **AND** (Rate is PS) **AND** (Zone-Amb is POS) **THEN** (Damper is NL)
3. **IF** (Error is PL) **AND** (Rate is ZERO) **AND** (Zone-Amb is POS) **THEN** (Damper is NL)
4. **IF** (Error is PL) **AND** (Rate is NS) **AND** (Zone-Amb is POS) **THEN** (Damper is NS)
5. **IF** (Error is PL) **AND** (Rate is NL) **AND** (Zone-Amb is POS) **THEN** (Damper is ZERO)
6. **IF** (Error is PS) **AND** (Rate is PL) **AND** (Zone-Amb is POS) **THEN** (Damper is NL)
7. **IF** (Error is PS) **AND** (Rate is PS) **AND** (Zone-Amb is POS) **THEN** (Damper is NL)
8. **IF** (Error is PS) **AND** (Rate is ZERO) **AND** (Zone-Amb is POS) **THEN** (Damper is NS)
9. **IF** (Error is PS) **AND** (Rate is NS) **AND** (Zone-Amb is POS) **THEN** (Damper is ZERO)
10. **IF** (Error is PS) **AND** (Rate is NL) **AND** (Zone-Amb is POS) **THEN** (Damper is PS)
11. **IF** (Error is ZERO) **AND** (Rate is PL) **AND** (Zone-Amb is POS) **THEN** (Damper is NL)
12. **IF** (Error is ZERO) **AND** (Rate is PS) **AND** (Zone-Amb is POS) **THEN** (Damper is NS)
13. **IF** (Error is ZERO) **AND** (Rate is ZERO) **AND** (Zone-Amb is POS) **THEN** (Damper is ZERO)
14. **IF** (Error is ZERO) **AND** (Rate is NS) **AND** (Zone-Amb is POS) **THEN** (Damper is PS)
15. **IF** (Error is ZERO) **AND** (Rate is NL) **AND** (Zone-Amb is POS) **THEN** (Damper is PL)
16. **IF** (Error is NS) **AND** (Rate is PL) **AND** (Zone-Amb is POS) **THEN** (Damper is NS)
17. **IF** (Error is NS) **AND** (Rate is PS) **AND** (Zone-Amb is POS) **THEN** (Damper is ZERO)
18. **IF** (Error is NS) **AND** (Rate is ZERO) **AND** (Zone-Amb is POS) **THEN** (Damper is PS)
19. **IF** (Error is NS) **AND** (Rate is NS) **AND** (Zone-Amb is POS) **THEN** (Damper is PL)
20. **IF** (Error is NS) **AND** (Rate is NL) **AND** (Zone-Amb is POS) **THEN** (Damper is PL)
21. **IF** (Error is NL) **AND** (Rate is PL) **AND** (Zone-Amb is POS) **THEN** (Damper is ZERO)
22. **IF** (Error is NL) **AND** (Rate is PS) **AND** (Zone-Amb is POS) **THEN** (Damper is PS)
23. **IF** (Error is NL) **AND** (Rate is ZERO) **AND** (Zone-Amb is POS) **THEN** (Damper is PL)
24. **IF** (Error is NL) **AND** (Rate is NS) **AND** (Zone-Amb is POS) **THEN** (Damper is PL)
25. **IF** (Error is NL) **AND** (Rate is NL) **AND** (Zone-Amb is POS) **THEN** (Damper is PL)
26. **IF** (Zone-Amb is NEG) **THEN** (Damper is NS)
27. **IF** (Zone-Amb is ZERO) **THEN** (Damper is NS)

Identical controllers were used for both fuzzy ventilation cooling and fuzzy ventilation dehumidification but with different input and output gain factors. The fuzzy ventilation controllers were tuned using an iterative process of trial and error until satisfactory performance was obtained as described in Chapter 8.

The tuned fuzzy ventilation controller gains used for simulation, see Figure 9.3, are given in Table 9.1.

Fuzzy Ventilation Controller	K_p	K_d	K_{diff}	K_o
Cooling	1	5	1	0.001
Dehumidification	0.01	20	1	0.001

Table 9.1. Gain factors used for the tuned fuzzy ventilation controllers.

Gain factors for the PDFCs controlling the heating, cooling, dehumidification, humidification and air quality remain the same as described in Chapter 8.

9.3 Fuzzy Ventilation Controller Simulation Results

The fuzzy ventilation control strategy was compared with the conventional PID strategy controlling to upper and lower set points. Simulations were initially carried out for a one week period to tune and assess the operation of the fuzzy ventilation controllers. Once their performance was considered adequate, one week simulations were carried out for each of the 52 weeks of one year based on weather data for Kew, London. This enabled a comprehensive assessment of controller performance based on provided zone conditions and energy consumption over a realistic time period while being subjected to various ambient weather conditions.

The occupancy pattern profile used for the simulations described in this chapter and Chapter 10 is shown in Figure 9.7.

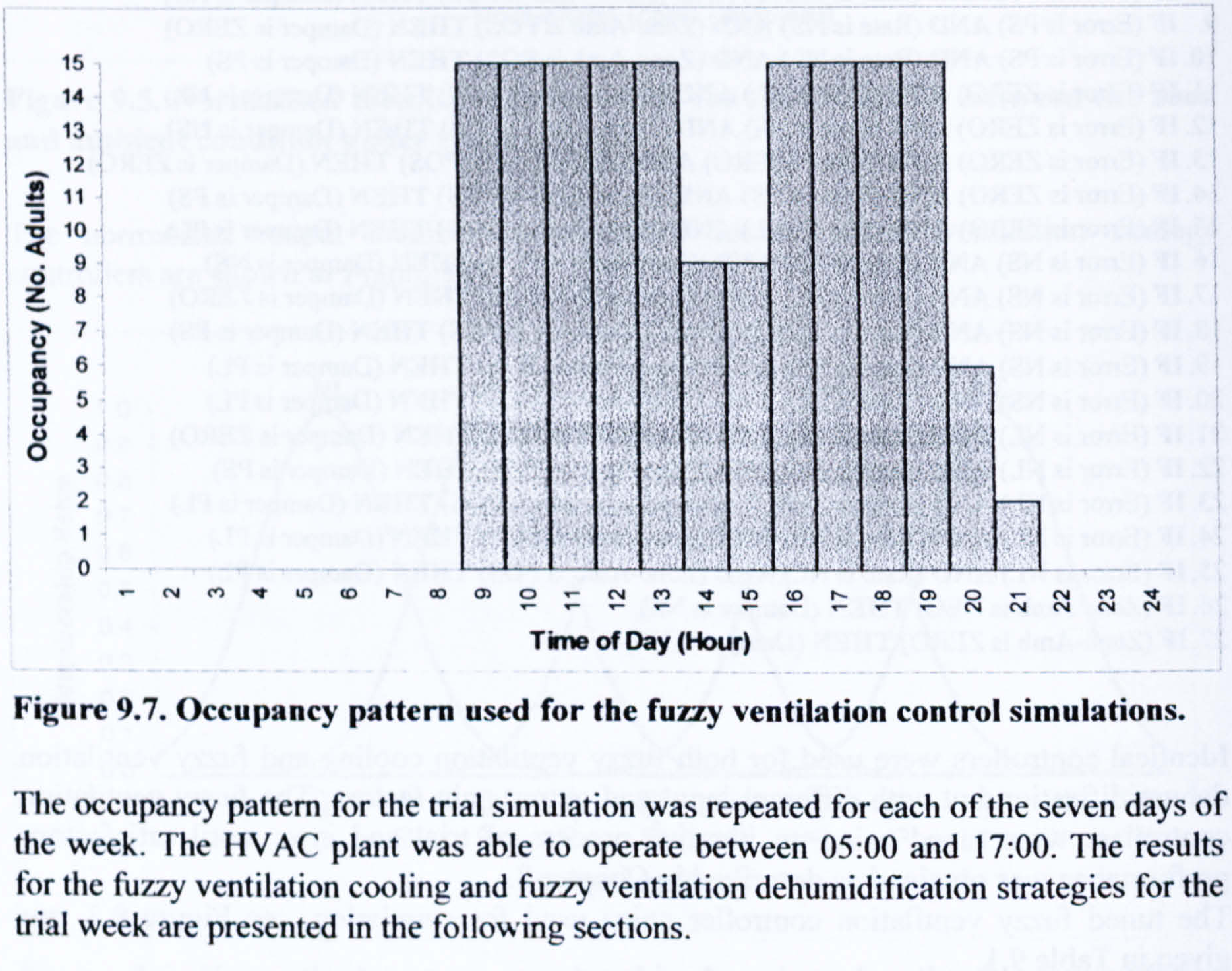

Figure 9.7. Occupancy pattern used for the fuzzy ventilation control simulations.

The occupancy pattern for the trial simulation was repeated for each of the seven days of the week. The HVAC plant was able to operate between 05:00 and 17:00. The results for the fuzzy ventilation cooling and fuzzy ventilation dehumidification strategies for the trial week are presented in the following sections.

9.3.1 Fuzzy Ventilation Cooling Control Strategy - One Week Trial Simulation

The fuzzy ventilation cooling control strategy is compared with a normal PID control strategy operating between upper and lower control set points for the week April 23-29 to give the reader a graphical view of the way in which the controller operates. Figure 9.8 shows the zone temperature and cooling valve operation for the two control strategies. Figure 9.8 shows that the result of the use of the fuzzy ventilation cooling control strategy is a significant reduction in the need for plant cooling operation. Further, it can be seen that the fuzzy control strategy maintains the zone temperature closer to the preferred set point during the occupied periods.

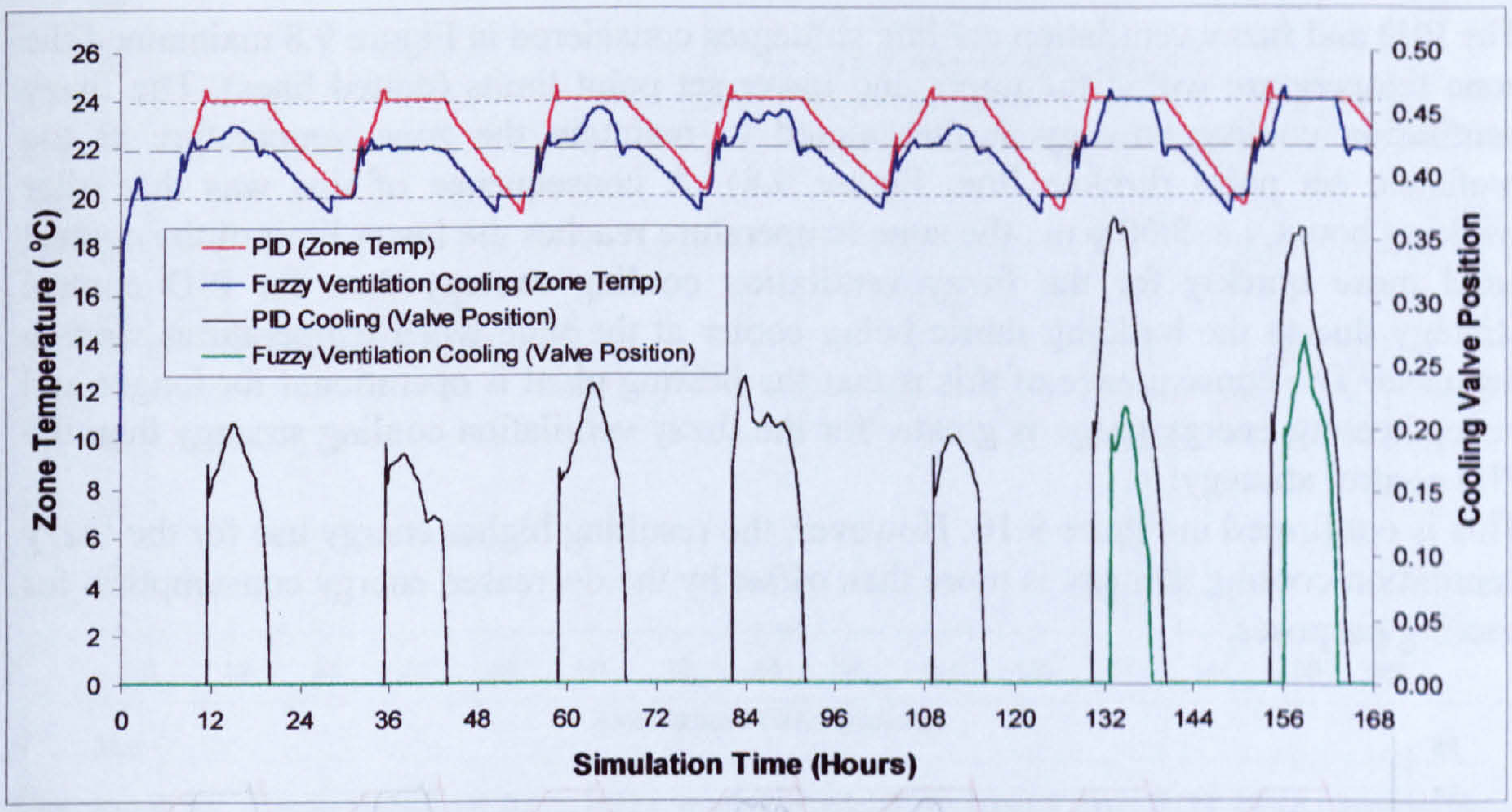

Figure 9.8. Zone temperature and cooling valve positions for the normal PID control strategy and the fuzzy ventilation control strategy (24 hour plant operation).

The PID control strategy controls the zone temperature to the bounds of the upper and lower set points. Hence, the zone temperature is often controlled to the upper set point in Figure 9.8. In contrast the fuzzy ventilation controller often manages to control the zone temperature nearer to the preferred set point using ventilation cooling, see Figure 9.8. The fuzzy control strategy achieves the improved temperature conditions within the space through the use of the re-circulation air damper for ambient cooling purposes, see Figure 9.9.

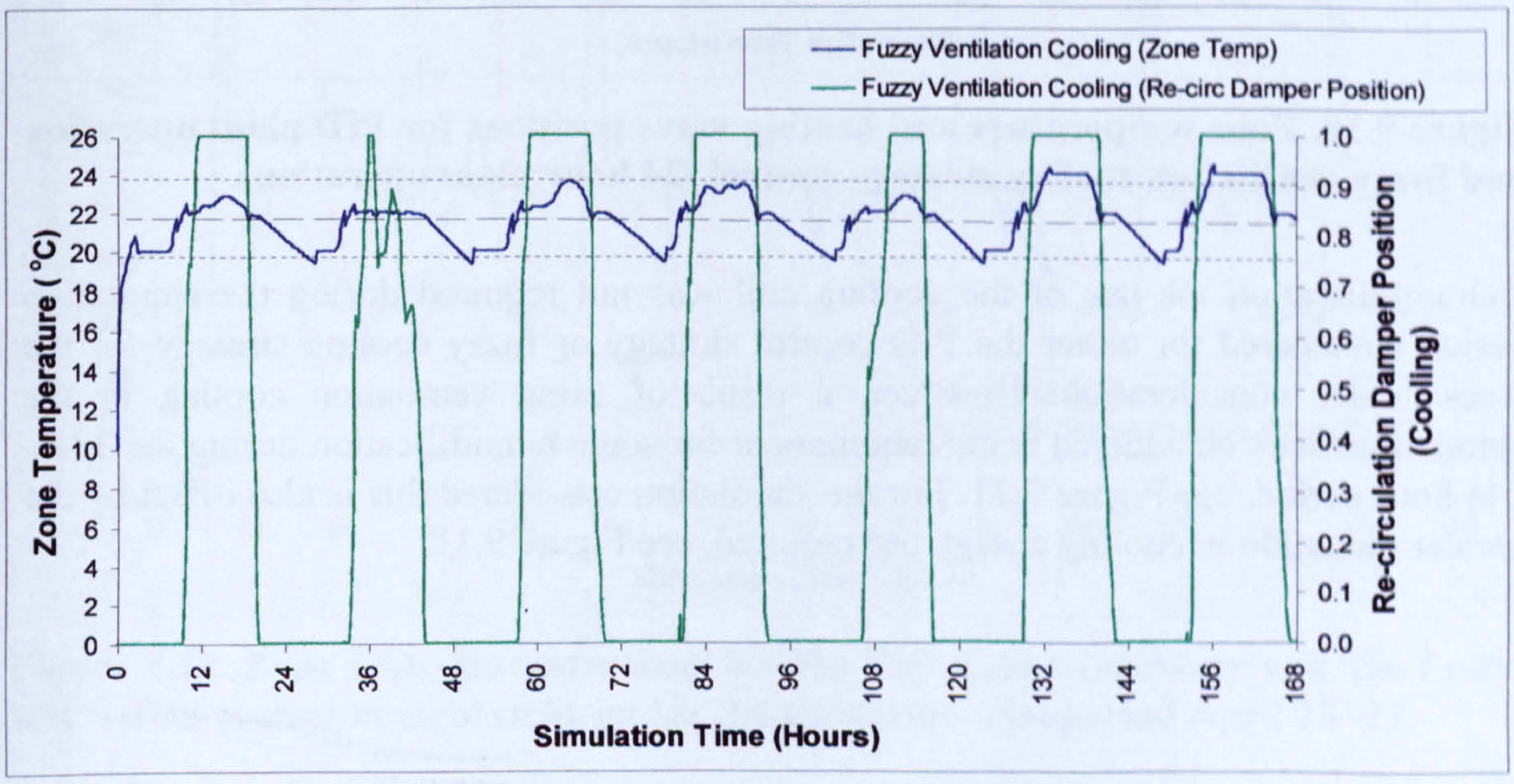

Figure 9.9. Zone Temperature and damper (cooling) position for the fuzzy ventilation cooling strategy control simulation.

The PID and fuzzy ventilation cooling strategies considered in Figure 9.8 maintained the zone temperature within the upper and lower set point limits (dotted lines). The fuzzy ventilation cooling strategy further aimed to maintain the zone temperature at the preferred set point (broken line, Figure 9.8). A consequence of this was that after working hours, i.e. 5:00 p.m., the zone temperature reaches the lower limit of the control band more quickly for the fuzzy ventilation cooling strategy than for PID control strategy due to the building fabric being cooler at the time when temperatures start to decrease. The consequence of this is that the heating plant is operational for longer and hence heating energy usage is greater for the fuzzy ventilation cooling strategy than the PID control strategy.

This is confirmed in Figure 9.10. However, the resulting higher energy use for the fuzzy ventilation cooling strategy is more than offset by the decreased energy consumption for cooling purposes.

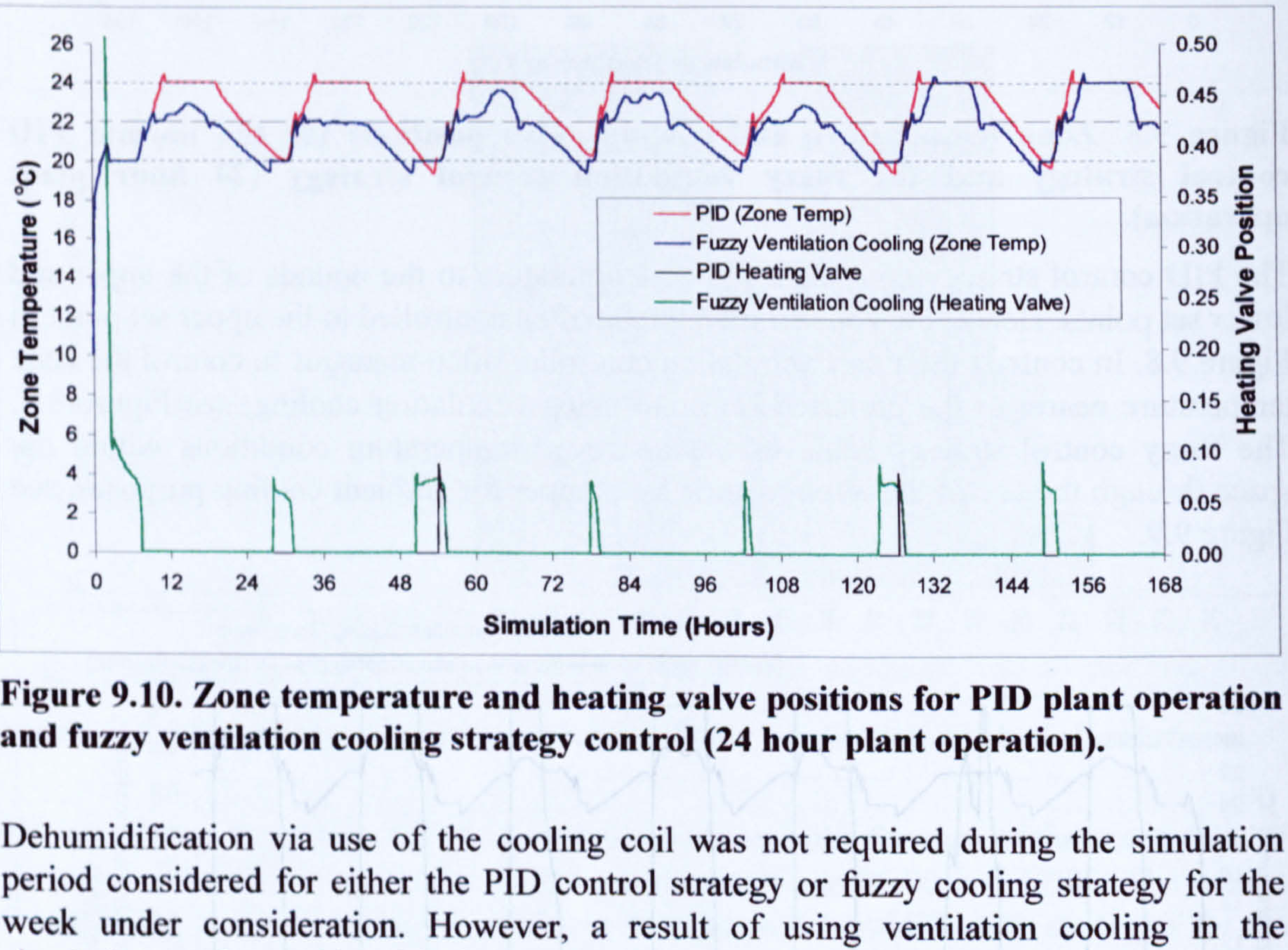

Figure 9.10. Zone temperature and heating valve positions for PID plant operation and fuzzy ventilation cooling strategy control (24 hour plant operation).

Dehumidification via use of the cooling coil was not required during the simulation period considered for either the PID control strategy or fuzzy cooling strategy for the week under consideration. However, a result of using ventilation cooling in the simulation week considered is the requirement for some humidification during the 132 - 144 hour period, see Figure 9.11. For the simulation considered this is also offset by the greater reduction in cooling energy use required, see Figure 9.11.

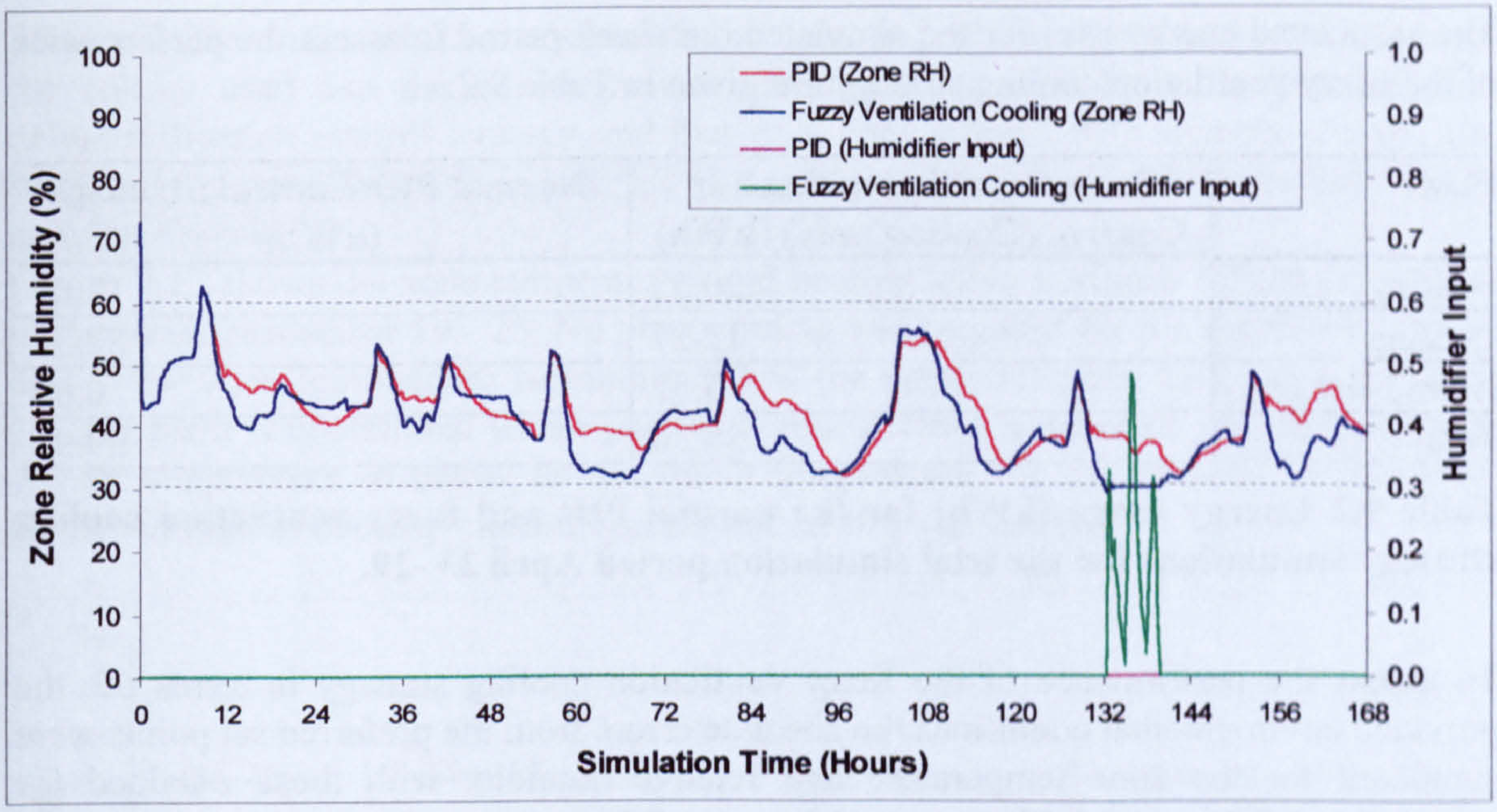

Figure 9.11. Zone relative humidity and humidifier input for PID plant operation and fuzzy ventilation cooling strategy control (24 hour plant operation).

An additional benefit of using the fuzzy ventilation cooling control strategy can be seen in Figure 9.12. Due to the increased fresh air ventilation rates associated with the fuzzy cooling ventilation strategy for free cooling purposes, the CO_2 concentrations are also reduced in the occupied zone.

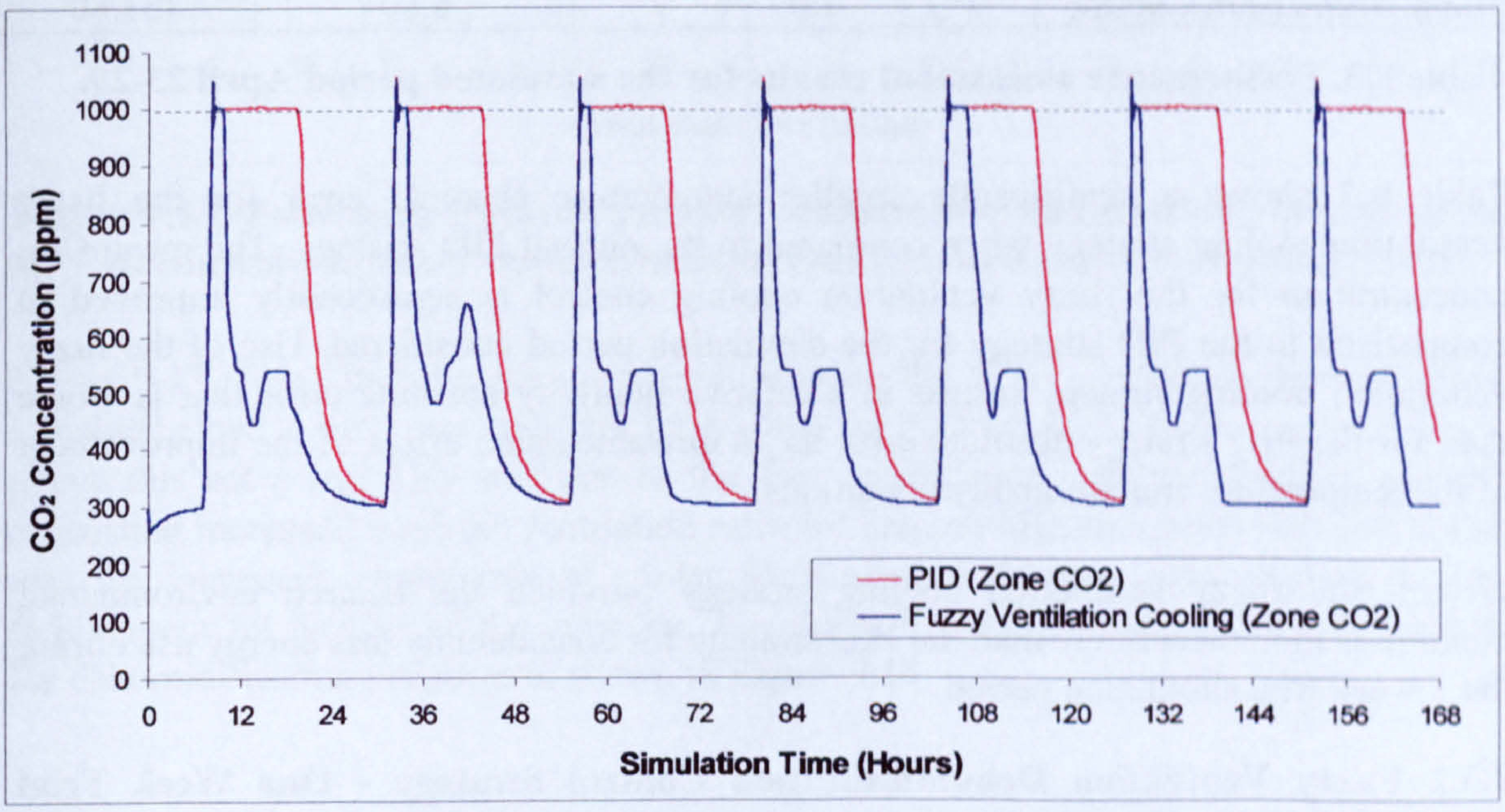

Figure 9.12. Zone CO_2 concentrations for the PID control strategy and the fuzzy ventilation cooling control strategy for the simulated trial period April 23 -29.

The associated energy uses for the simulated one week period to assess the performance of the fuzzy ventilation cooling strategy are given in Table 9.2.

Plant	**Fuzzy Ventilation Cooling Control (Cooling only) (kWh)**	**Normal PID Control Strategy (kWh)**
Heating	20.52	12.62
Cooling	12.27	87.31
Humidification	5.51	0.00
Total	38.30	99.93

Table 9.2 Energy usage (kWh) for the normal PID and fuzzy ventilation cooling strategy simulations for the trial simulation period April 23 -29.

To assess the performance of the fuzzy ventilation cooling strategy in terms of the provided environmental conditions the absolute errors from the preferred set points were compared for the zone temperature and relative humidity with those obtained for conventional PID control. The mean of the zone CO_2 concentrations were compared for the two strategies to assess the provided air quality. The calculation methods used to obtain these results are described in Appendix D. The results for the considered one week simulation period are given in Table 9.3.

Strategy	**Absolute Error**		**Mean**
	Temperature (^oC)	RH (%)	CO_2 (ppm)
PID	1.48	5.21	713.17
Fuzzy Ventilation Cooling	1.09	6.80	461.80

Table 9.3. Performance assessment results for the simulated period April 23-29.

Table 9.3 shows a significantly smaller temperature absolute error for the fuzzy ventilation cooling strategy when compared to the normal PID strategy. The mean CO_2 concentration for the fuzzy ventilation cooling control is significantly improved in comparison to the PID strategy for the simulation period considered. Use of the fuzzy ventilation cooling strategy results in a relative humidity absolute error that is worse than for the PID strategy absolute error as an unwanted side effect of the improvement of the temperature and air quality conditions.

Overall the fuzzy ventilation cooling strategy provided the desired environmental conditions more accurately than the PID strategy for considerably less energy use during the 1 week trial simulation period.

9.3.2 Fuzzy Ventilation Dehumidification Control Strategy - One Week Trial Simulation

Using a similar methodology to fuzzy ventilation cooling this strategy attempted to utilise the free dehumidification available where the zone moisture content was higher than the ambient moisture content and the zone relative humidity was above the preferred set point.

The week November 19-25 was simulated in order to provide a graphical comparison of the energy used and the environmental conditions provided by a fuzzy ventilation dehumidification control strategy and that of a conventional PID strategy. Again, the occupancy pattern shown in Figure 9.7 was used and repeated for all seven days of the simulated week.

Figure 9.13 shows the zone temperatures and heating valve positions for the simulation of the week November 19 - 25. No plant cooling was required for the simulation period due to the zone temperature remaining below the upper set point limit. However, the cooling plant is operational where plant dehumidification is required in order to reduce the air temperature to below its dew-point temperature for the removal of moisture. Fuzzy ventilation cooling was not operational for this simulation.

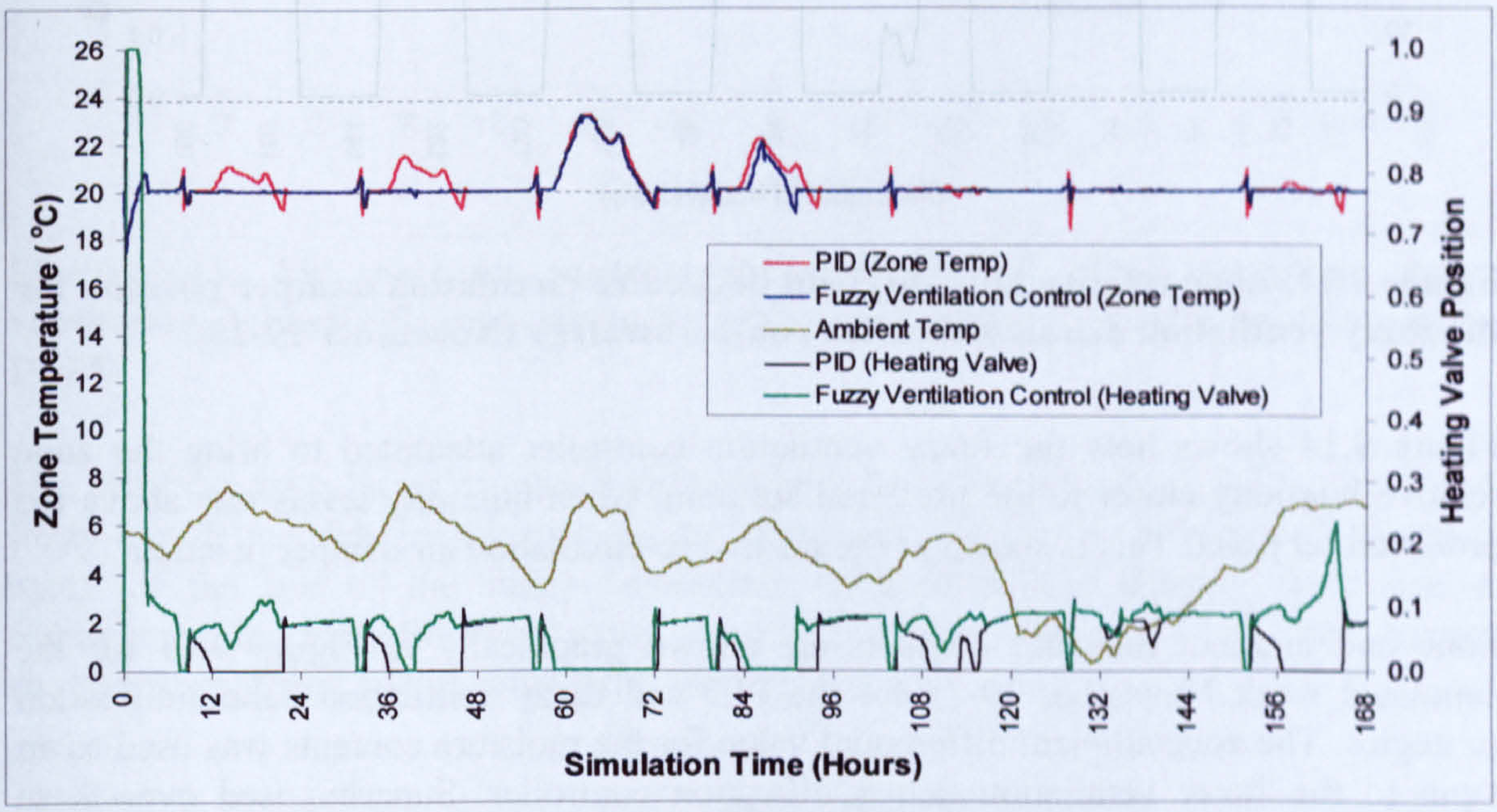

Figure 9.13. Zone temperatures, ambient temperature and heating valve position for PID control and fuzzy ventilation dehumidification control (November 19-25).

Figure 9.13 shows that the zone temperature using the fuzzy ventilation strategy often remained close to the lower set point limit while the PID strategy zone temperature rises above this set point. This was due to the fuzzy ventilation dehumidification strategy requesting increased fresh air ventilation rates for dehumidification purposes. The result was the increased supply rate of cooler fresh air and an associated increase in the requirement for heating of the zone air. The desired re-circulation air damper position for dehumidification purposes is shown in Figure 9.14.

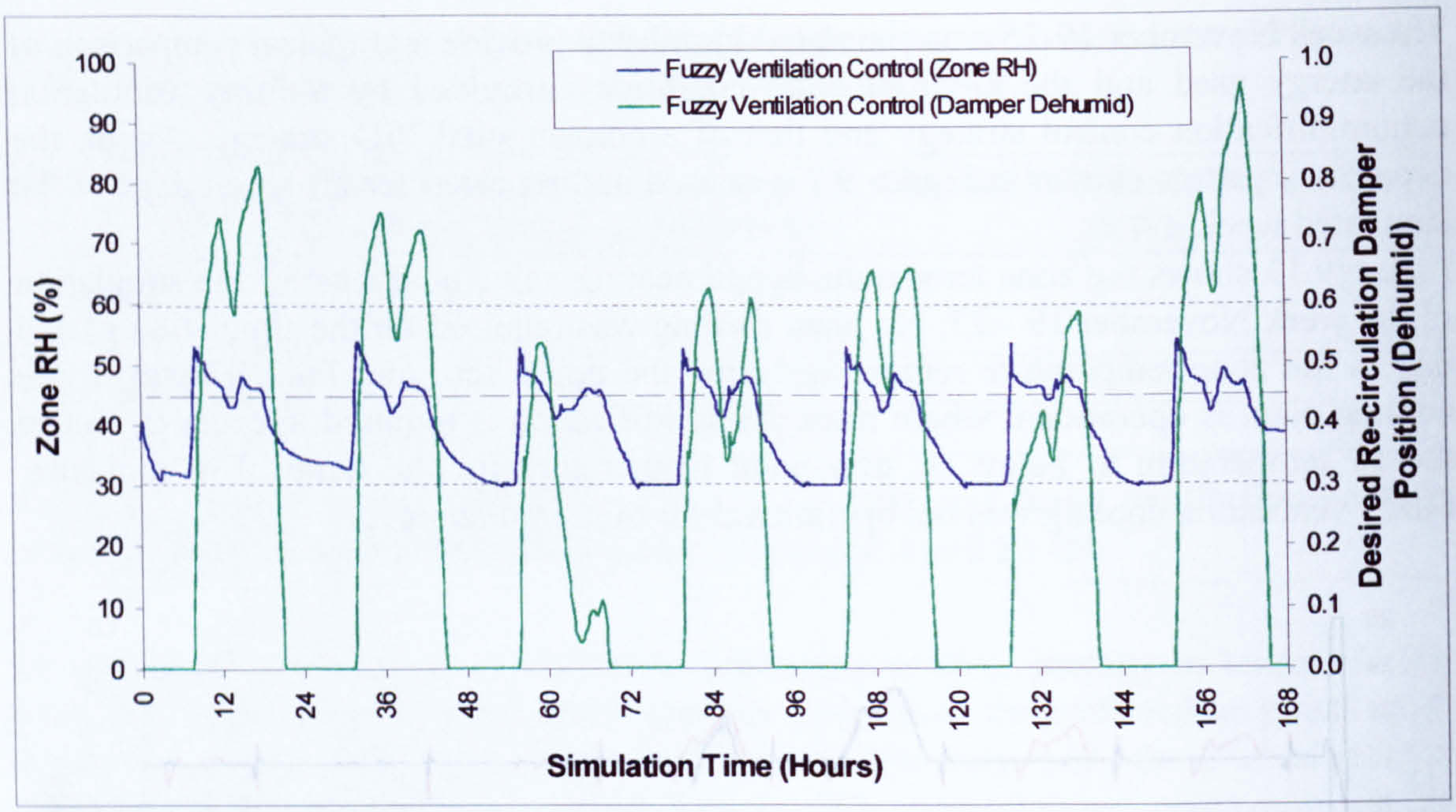

Figure 9.14. Zone relative humidity and desired re-circulation damper position for the fuzzy ventilation dehumidification control strategy (November 19-25).

Figure 9.14 shows how the fuzzy ventilation controller attempted to bring the zone relative humidity closer to the preferred set point when humidity levels rise above the preferred set point. This is shown as the desired re-circulation air damper position.

Zone and ambient moisture contents are shown graphically in Figure 9.15 for the simulated week November 19-25 for the PID and fuzzy ventilation dehumidification strategies. The zone/ambient differential value for the moisture contents was used as an input to the fuzzy ventilation dehumidification controller. Superimposed over these values is the moisture content value of the zone air for normal PID control during the same simulated week which show what the moisture content values would be if the fuzzy ventilation strategy was not operational. The zone/ambient moisture content differential value used as an input to the fuzzy ventilation dehumidification controller allows the controller to decide whether dehumidification is possible using increased fresh air ventilation rates when required.

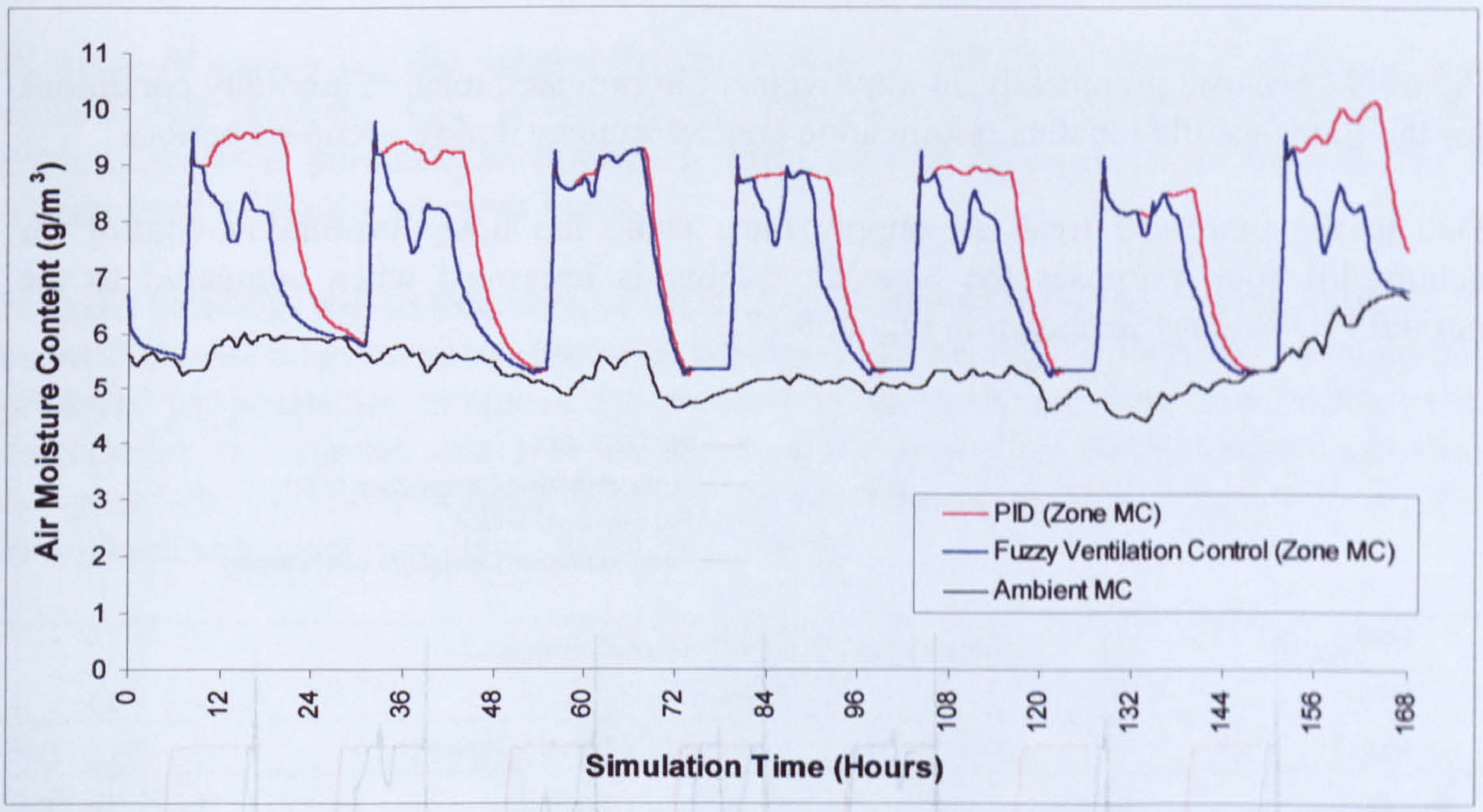

Figure 9.15. Air moisture contents for normal PID plant operation, fuzzy ventilation dehumidification strategy control and ambient conditions (November 19-25).

The resulting zone humidity conditions resulting from the use of the PID control and fuzzy ventilation dehumidification control strategies are shown in Figure 9.16. As a result of the use of the fuzzy ventilation dehumidification strategy there was a requirement for humidification using the plant slightly earlier than for the normal strategy towards the end of some days, see Figure 9.16.

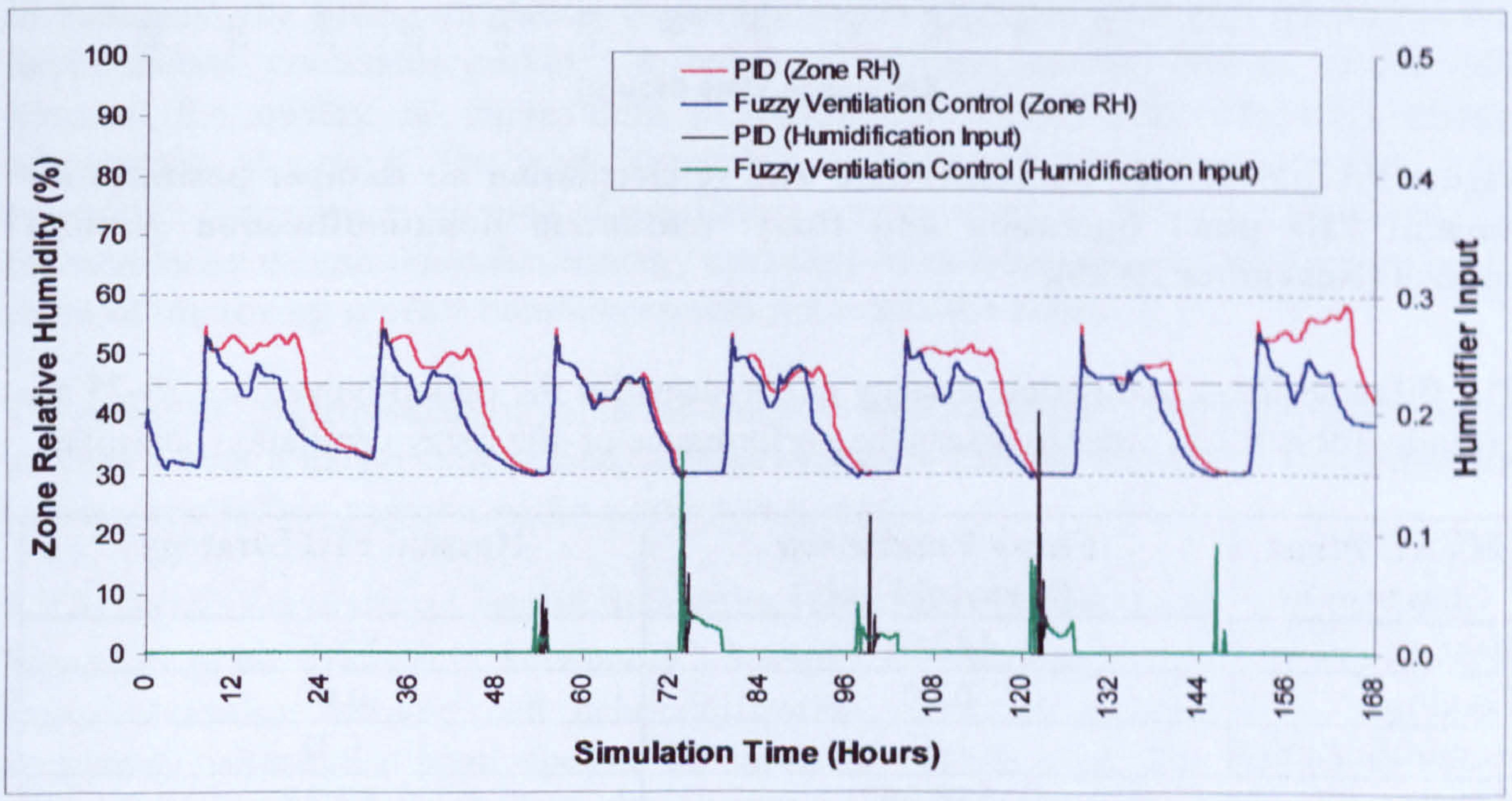

Figure 9.16. Zone relative humidity and humidifier input positions for normal plant operation and fuzzy ventilation dehumidification strategy control (November 19-25).

Figure 9.16 shows graphically an improvement in provided relative humidity conditions for the fuzzy ventilation dehumidification control strategy during occupied periods.

Due to the increased fresh air supply rates using the fuzzy ventilation control for dehumidification purposes the zone air quality is improved when compared to the normal PID strategy as shown in Figure 9.17.

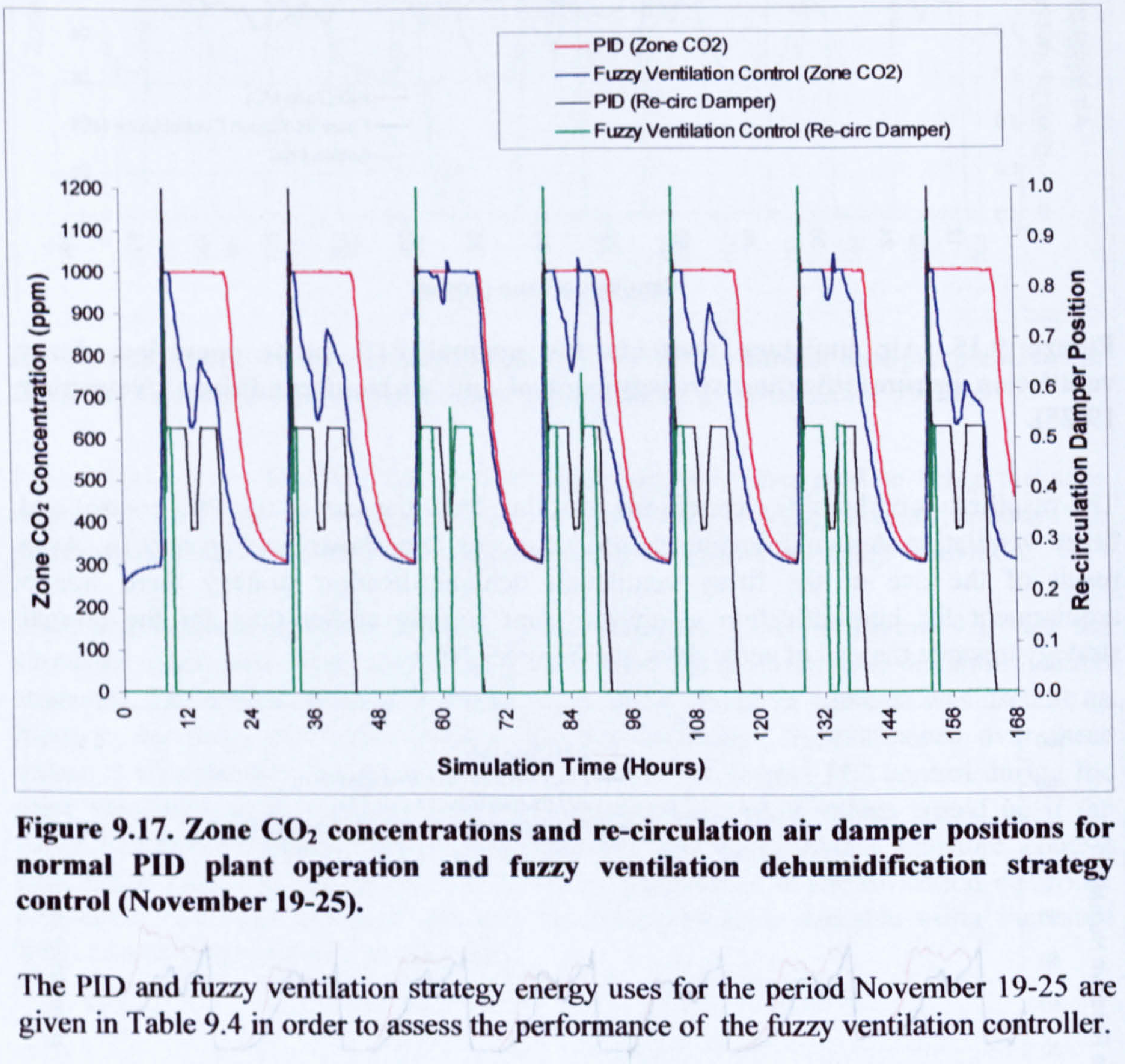

Figure 9.17. Zone CO_2 concentrations and re-circulation air damper positions for normal PID plant operation and fuzzy ventilation dehumidification strategy control (November 19-25).

The PID and fuzzy ventilation strategy energy uses for the period November 19-25 are given in Table 9.4 in order to assess the performance of the fuzzy ventilation controller.

HVAC Plant Component	Fuzzy Ventilation (Dehumid only)	Normal PID Strategy
Heating	132.61	85.83
Cooling	0.00	0.00
Humidification	1.65	1.38
Total	134.26	87.21

Table 9.4. Energy usage (kWh) for the normal PID and ventilation dehumidification strategy simulations (November 19-25).

In terms of energy use the fuzzy dehumidification strategy uses more energy than the normal PID strategy. This is due to the increased fresh air ventilation rates, for dehumidification purposes, of colder air that requires heating to maintain the zone temperature within the set point limits.

In order to assess the performance of the fuzzy ventilation dehumidification strategy in terms if provided environmental conditions within the zone, the absolute errors from the preferred set points are compared for the zone temperature and relative humidity with the normal PID control strategy. The mean of the zone CO_2 concentrations are also compared for the two strategies to assess the provided air quality. The results for the considered simulation period are given in Table 9.5.

	Absolute Error from Preferred Set Point		**Mean**
Strategy	Temperature (°C)	RH (%)	CO_2 (ppm)
Normal PID	1.80	7.47	737.32
Fuzzy Ventilation	1.89	7.23	616.50

Table 9.5. Performance assessment results for the simulated period November 19-25.

The fuzzy ventilation dehumidification strategy increases the performance marginally in terms of zone relative humidity and air quality but decreases the performance in terms of the zone temperature. The improved relative humidity provision is achieved with a significant penalty in terms of energy use.

In summary, the fuzzy ventilation dehumidification ventilation strategy improved the environmental conditions provided in terms of relative humidity and air quality but lessened the quality of temperature provision and significantly increased energy consumption as a result. The week November 19-25 highlights the problems that could potentially occur using this type of ventilation control strategy. However, the theory of the ventilation dehumidification strategy operating in isolation did obtain its objective in terms of improving relative humidity conditions within the zone.

To assess the consequences of using the fuzzy ventilation cooling and dehumidification strategies over a longer time period, simulations were carried out with both ventilation strategy controllers operational for a one year period.

9.3.3 Fuzzy Ventilation Control Strategies - One Year Simulations

The simulations detailed in Sections 9.3.1 and 9.3.2 assessed the performance of the fuzzy ventilation cooling and dehumidification strategies independently and used occupancy patterns that were repeated for seven days of the week. The HVAC plant was able to operate 24 hours per day when a zone controlled parameter drifted beyond the upper or lower set point limits.

Further simulations were carried out for all 52 weeks of a year with fuzzy ventilation cooling and dehumidification operational. Two changes were implemented in order to create more realistic operating conditions. These were:-

1. The HVAC plant was only able to operate between the hours of 05:00 and 17:00.
2. For the last day of each weekly simulation the occupancy was set to zero. The first six days of each weekly simulation used the occupancy patterns shown in Figure 9.7.

In these simulations, with the cooling and dehumidification fuzzy ventilation strategies operational, the air quality, ventilation dehumidification and ventilation cooling controllers operate the fresh air re-circulation damper simultaneously. The largest of the values returned from the three controllers is used at any instant to decide the actual position of the re-circulation damper.

The detailed results of the one year simulations in terms of energy use and environmental condition performance can be seen in Appendix C and D for South, North, East and West orientations. A yearly summary for these results are given in Table 9.6, Table 9.7 and Table 9.8.

In the following text the control strategies are designated as follows:-
Strategy 1 - normal PID controller operation
Strategy 2 - fuzzy ventilation control

Strategy / Orientation	Annual Energy Use (kWh)			
	Heating	Cooling	Humidification	Total
South Strategy 1	1579	3010	95	4684
South Strategy 2	2245	1519	171	3935
North Strategy 1	1980	2587	81	4648
North Strategy 2	2661	1324	89	4074
East Strategy 1	1842	2627	84	4552
East Strategy 2	2551	1331	97	3979
West Strategy 1	1792	2872	86	4749
West Strategy 2	2475	1489	117	4080

Table 9.6. Annual energy use summary for the PID (Strategy 1) and fuzzy ventilation (Strategy 2) control strategy simulations.

Strategy / Orientation	Energy Use as % of Strategy 1
South Strategy 1	100.00
South Strategy 2	84.01
North Strategy 1	100.00
North Strategy 2	87.65
East Strategy 1	100.00
East Strategy 2	87.41
West Strategy 1	100.00
West Strategy 2	85.91
Strategy 2 Average (all orientations)	86.25

Table 9.7. Annual energy use by strategy as a percentage of strategy 1 energy use.

Table 9.7 indicates that the fuzzy ventilation cooling and dehumidification strategies operating simultaneously consistently required less energy during the one year simulation period.

Further, analysis of the annual mean zone parameter errors from the preferred set points show that improvements in provided environmental conditions are achieved, see Table 9.8. Detailed weekly results are given in Appendix D.

Orientation	Annual Mean Absolute Error from Preferred Set Point			
	Temp 1 (°C)	Temp 2 (°C)	RH 1 (%)	RH 2 (%)
South Mean	1.91	1.73	10.30	8.67
North Mean	1.91	1.81	11.13	8.82
East Mean	1.92	1.80	10.79	8.67
West Mean	1.95	1.80	10.66	8.66
Average (all orientations)	1.92	1.78	10.72	8.71

Table 9.8. Annual mean zone temperature and relative humidity absolute error from preferred set point during periods when the HVAC plant was operational (1 = Strategy 1, 2 = Strategy 2).

Examination of Table 9.6 clearly reveals that the fuzzy ventilation control strategies use more heating and humidification energy than the normal PID control strategy. However, far less cooling is used with the fuzzy ventilation strategy leading to an overall reduction in total energy use.

In terms of energy and environmental provision performance, Appendix C and D respectively, closer examination of the weekly breakdowns indicates that the fuzzy ventilation control strategy is not always an improvement over the normal PID strategy. This is due to the resulting simultaneous control actions of the different controlled parameters considered. As with the week November 19-25, combinations of conditions such as a high indoor relative humidity and low outdoor temperatures can lead to the fuzzy ventilation controllers improving the zone condition marginally while decreasing the energy performance significantly.

Scope therefore existed to improve on the fuzzy ventilation control strategy. In order to achieve this a fuzzy high level controller (or supervisor) was implemented to make decisions on the best control actions to be taken. This was based on knowledge of the indoor environmental conditions and is described in Chapter 10.

9.4 Conclusions and Discussion

This chapter described the development and use of fuzzy ventilation control strategies for ambient cooling and dehumidification purposes. A combination of the adaptive and steady state approaches to thermal comfort were taken to define the set point ranges and preferred set points. Upper and lower set points were defined such that combinations of zone temperature and humidity would not cause a Predicted Percentage Dissatisfied (PPD) value of greater than 10% using the steady state approach. The temperature and relative humidity ranges defined using this criteria were 20°C - 24°C and 30% - 60% respectively. When the zone conditions drifted beyond these ranges the HVAC plant was used to bring the conditions to within the range. Preferred set points of 22°C and 45% RH were also defined and represented a PPD of 5% where both conditions were satisfied simultaneously. The fuzzy ventilation controllers attempted to converge the zone conditions towards these preferred set points when possible using free cooling and dehumidification through the use of the fresh air re-circulation damper.

Simulations were carried out for a one year period for the fuzzy ventilation and PID control strategies for South, North, East and West main building facade orientations. The simulations showed that the fuzzy ventilation control strategy used an average of 86.25% of the energy consumed by the PID control strategy. Further, comparisons between the two control strategies showed that the average of the mean annual absolute error from the preferred set point for the South, North, East and West building orientations were as follows:-

	Temperature (°C)	Relative Humidity (%)
PID:	1.92	10.72
Fuzzy Ventilation Control:	1.78	8.71

Overall, the yearly assessment of the fuzzy ventilation control strategies therefore showed a reduction in energy consumption and an overall improvement in the environmental conditions provided.

However, fuzzy ventilation dehumidification strategy can lead to an increased requirement for heating energy use due to the introduction of greater quantities of colder fresh air under some conditions. This was reflected in the weekly results detailed in Appendix C and Appendix D. Scope therefore existed to improve on the fuzzy ventilation control strategies. It was thought that supervision of the actions of the fuzzy ventilation controllers could lead to further improvements in their performance by suppressing their control actions where they were likely to cause detriment to the overall objectives, including energy efficiency, of using the fuzzy ventilation controllers. The investigation of the use of a high level fuzzy supervisor to improve the fuzzy ventilation control strategies is considered in Chapter 10.

10. Fuzzy High Level Control

Nomenclature

$CO2_z$	zone air CO_2 concentration (ppm)
$CO2_{error}$	zone CO_2 concentration error from set point (ppm)
$dCO2_{error}/dt$	zone CO_2 concentration rate of change of error from set point (ppm)
$dRH_{z\ error}/dt$	rate of change in zone relative humidity error from set point (%/s)
$dT_{z\ error}/dt$	rate of change in zone temperature error from set point (°C/s)
MC_z	zone air moisture content (g/m^3)
MC_{amb}	ambient air moisture content (g/m^3)
$RH_{z\ error}$	zone relative humidity error from set point (°C)
RH_z	zone relative humidity (%)
T_{amb}	ambient temperature (°C)
T_z	zone temperature (°C)
$T_{z\ error}$	zone temperature error from set point (°C)

10.1 Introduction

This chapter describes the theory and results of the use of a fuzzy supervisor to improve the performance of the fuzzy ventilation control strategies described in Chapter 9. The fuzzy supervisor and fuzzy ventilation control strategies combined are collectively referred to as the fuzzy high level control strategy.

The results of the simulations with the pure fuzzy controllers, see Chapter 8, indicated that comparable performance was achievable with PID controllers in terms of response time, overshoot, stability and energy consumption. Chapter 9 described the use of fuzzy ventilation controllers to control the fresh air ventilation strategy with the aim of utilising favourable ambient air energy and moisture contents to conserve energy and provide improved environmental conditions through variation of the fresh air supply rates to the zone. However, the simulation results indicated that scope existed to improve upon the fuzzy ventilation control strategy.

Fuzzy high level control builds on the theory of the fuzzy ventilation control strategy with the aim of further improving environmental conditions within the zone and hence occupant comfort while improving the energy and cost efficiencies simultaneously. This is achieved by supervising the fuzzy ventilation controllers to ensure they do not undermine the objective of their use under certain circumstances that arise due to specific ambient and zone environmental conditions.

The objectives and strategy used in the development of the fuzzy high level control strategy is first described. The structure of the controller is then described and a graphically illustrated example of the controller in use is given. Finally, the results of simulations over a one year period are reported and comparisons made to the normal PID and fuzzy ventilation control strategy results.

10.2 Fuzzy High Level Control Strategy And Objective

The fuzzy high level control strategy builds on the use of the fuzzy ventilation control strategy described in Chapter 9. Although the fuzzy ventilation control strategy, overall, was more energy efficient and provided better comfort provision within the zone during simulation, it was felt that the strategy could still be improved. High level fuzzy control uses the fuzzy decision making capabilities of fuzzy logic to improve the use of the fuzzy ventilation strategies further.

The fuzzy ventilation control strategy only operated the HVAC plant heating, cooling, humidification and dehumidification components when a specific controlled zone parameter could not be maintained within the defined control bands by the fuzzy ventilation control strategies alone. Where possible the fuzzy ventilation strategies attempted to converge zone conditions to the preferred set point as these were considered the most desirable conditions from a comfort perspective. It was possible for operational conflicts to arise due to the control strategies for each controlled parameter operating independently. For example, a small improvement in the humidity condition within the zone may have been achieved by the fuzzy ventilation dehumidification controller at the expense of a large energy penalty for heating the cooler outside air introduced as a result.

The fuzzy high level controller uses the fuzzy ventilation controllers described in Chapter 9 as the basic controllers within the fuzzy high level controller. Temperature, humidity and CO_2 concentrations are the zone controlled parameters considered for improvements in terms of energy consumption and the provision of indoor environmental quality. Set points defined for the fuzzy high level control strategy simulations were the same as those described in Chapter 9.

To give the reader an idea of the expert knowledge incorporated within the fuzzy high level control strategy a design philosophy example is given:-

The zone temperature, zone humidity and ambient moisture content are high. Simultaneously, the ambient temperature is below that of the zone temperature. As a result the fuzzy cooling ventilation strategy can see an opportunity to cool the zone air towards the preferred (middle) set point by increasing the fresh air re-circulation and using ambient cooling. This works satisfactorily if zone temperature control is considered in isolation. However, if the zone humidity is taken into account the following situation may result. The zone air is cooled slightly by increasing the fresh air ventilation rate in order to improve thermal comfort conditions within the zone. By cooling the air the dew point temperature of the air is decreased and the relative humidity rises. The zone humidity was initially close to the upper set point limit before fuzzy ventilation cooling commenced. This scenario is likely to result in the zone relative humidity rising above the higher dehumidification plant operating set point. As a result the cooling coil becomes operational and the air is cooled and re-heated resulting in the zone temperature being at least heated to the zone temperature lower set point. Hence, energy has been expended with little overall gain in the comfort conditions within the zone in order to keep the humidity below the upper zone humidity set point. This situation can be undesirable in terms of energy consumption and fluctuations in the zone conditions.

The fuzzy high level controller attempts to avoid situations such as the one described in the above paragraph by incorporating expert knowledge into its control structure and supervising the fuzzy ventilation control strategy.

10.3 Fuzzy High Level Controller Structure

The structure of the fuzzy high level control system incorporating the fuzzy ventilation controllers described in Chapter 9 and the fuzzy supervisor is shown schematically in Figure 10.1.

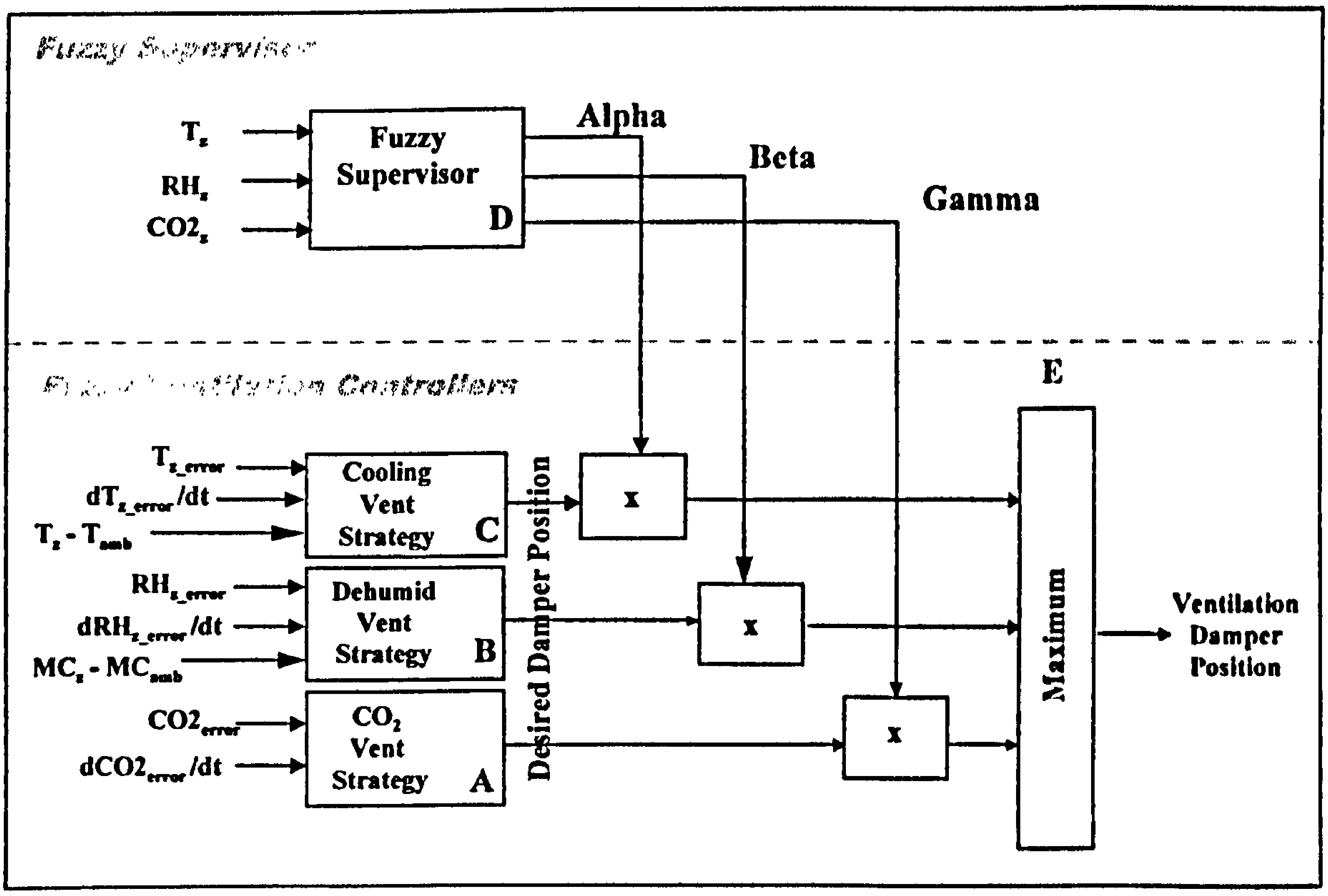

Figure 10.1. Schematic of the structure of the fuzzy high level controller incorporating the fuzzy ventilation controllers and the fuzzy supervisor.

The fuzzy ventilation dehumidification and cooling strategy controllers are shown as the components B and C respectively below the broken line in Figure 10.1. Controllers A, B and C return incremental values which alter the desired re-circulation damper position. The re-circulation damper position is referred to as "desired" as it is being controlled by three controllers. The fuzzy PDFC air quality controller (A) is shown as a component of the fuzzy ventilation control strategy as it represents the overriding ventilation controller with respect to the re-circulation damper position. The fuzzy high level supervisor, component D above the broken line in Figure 10.1, is used to control the overall controller output by the use of the weighting factors alpha, beta and gamma. The fuzzy high level controller operates by determining the most appropriate use of the plant and ventilation strategy by considering the current zone temperature, relative humidity and CO_2 concentration and suppressing the outputs from controllers A, B and C where necessary. This is achieved by multiplying the desired re-circulation damper positions by the weighting factors returned by the fuzzy high level control supervisor. The maximum of the desired re-circulation damper positions, calculated by component E in Figure 10.1, was then used to represent the actual re-circulation damper position.

The fuzzy supervisor of the fuzzy high level controller, component D in Figure 10.1, has 3 inputs and 3 outputs. Each of the inputs and outputs consisted of 3 membership functions, see Figure 10.2 to Figure 10.5.

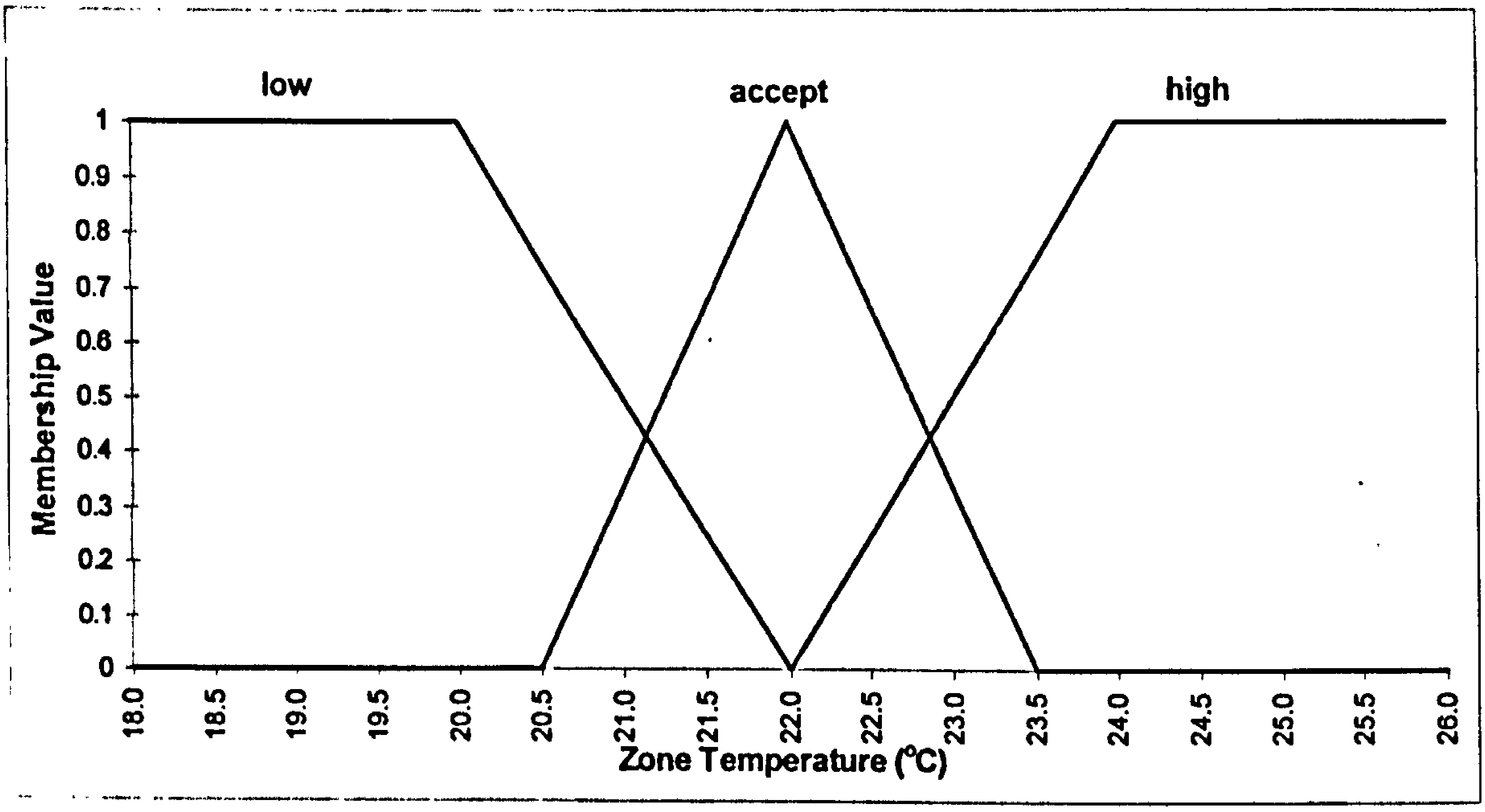

Figure 10.2. Fuzzy high level controller membership functions for the input zone temperature.

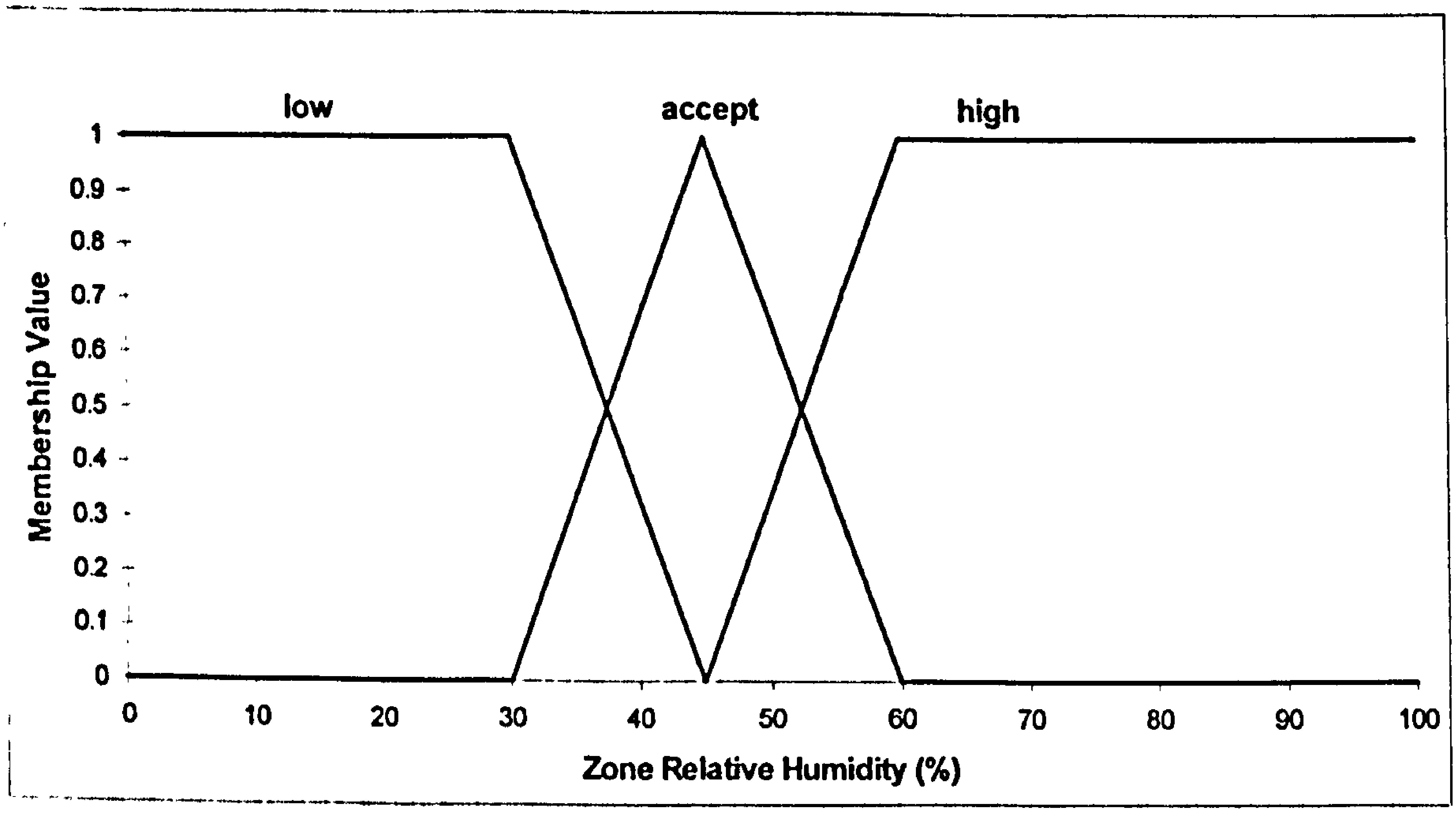

Figure 10.3. Fuzzy high level controller membership functions for the input zone relative humidity.

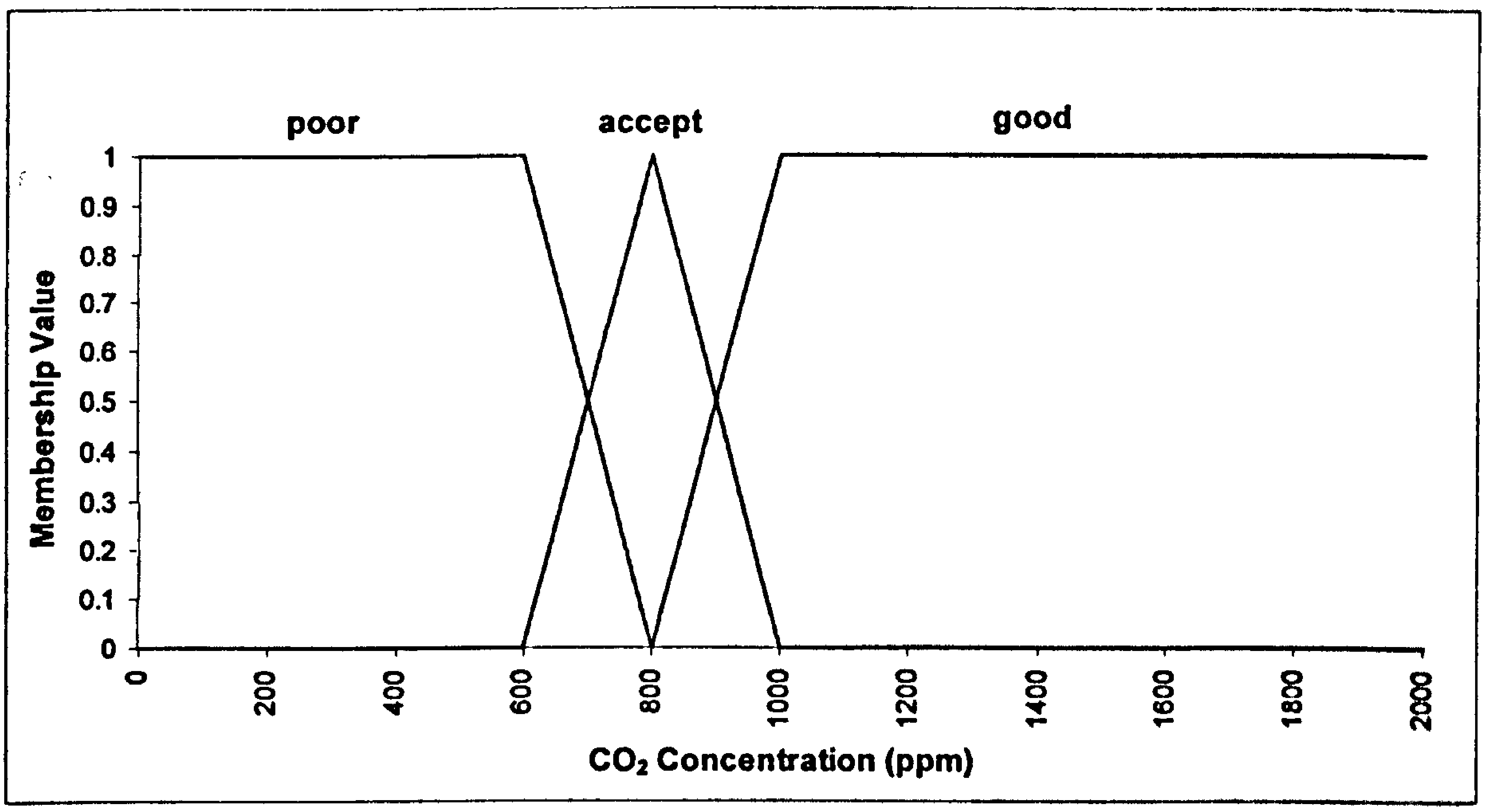

Figure 10.4. Fuzzy high level controller membership functions for the input zone air quality, CO2 (ppm).

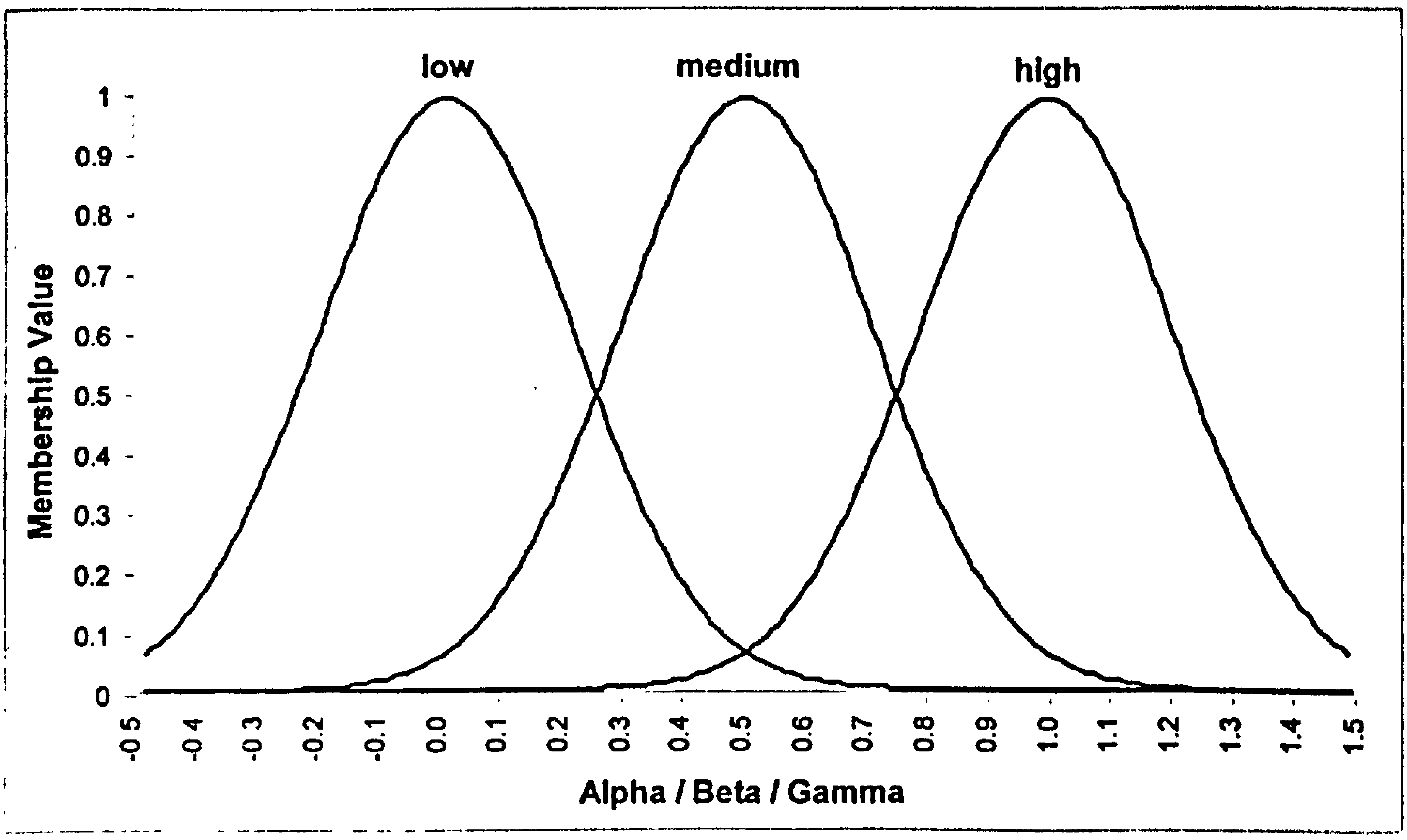

Figure 10.5. Fuzzy high level controller membership functions for the outputs alpha, beta and gamma.

The fuzzy supervisor component of the fuzzy high level controller returns an absolute rather than incremental output.

The membership functions shown in Figure 10.5 for alpha, beta and gamma are defined on the universe of discourse {-0.5, 1.5}. This effectively gives a controller output of 0 - 1 when the centroid method is used as the defuzzification method.

Twenty seven rules (3^3) were developed and used to map the fuzzy supervisors 3 sets of input membership functions to the 3 output sets of output membership functions alpha, beta and gamma.

The 27 control rules for the fuzzy high level controller are given below:-

1. **IF** (T is low) **AND** (RH is low) **AND** (CO_2 is good) **THEN** (alpha is low)(beta is low)(gamma is low)
2. **IF** (T is low) **AND** (RH is accept) **AND** (CO_2 is good) **THEN** (alpha is low)(beta is low)(gamma is low)
3. **IF** (T is low) **AND** (RH is high) **AND** (CO_2 is good) **THEN** (alpha is low)(beta is med)(gamma is low)
4. **IF** (T is low) **AND** (RH is low) **AND** (CO_2 is accept) **THEN** (alpha is low)(beta is low)(gamma is med)
5. **IF** (T is low) **AND** (RH is accept) **AND** (CO_2 is accept) **THEN** (alpha is low)(beta is low)(gamma is med)
6. **IF** (T is low) **AND** (RH is high) **AND** (CO_2 is accept) **THEN** (alpha is low)(beta is med)(gamma is med)
7. **IF** (T is low) **AND** (RH is low) **AND** (CO_2 is poor) **THEN** (alpha is low)(beta is low)(gamma is high)
8. **IF** (T is low) **AND** (RH is accept) **AND** (CO_2 is poor) **THEN** (alpha is low)(beta is low)(gamma is high)
9. **IF** (T is low) **AND** (RH is high) **AND** (CO_2 is poor) **THEN** (alpha is low)(beta is med)(gamma is high)
10. **IF** (T is accept) **AND** (RH is low) **AND** (CO_2 is good) **THEN** (alpha is high)(beta is low)(gamma is low)
11. **IF** (T is accept) **AND** (RH is accept) **AND** (CO_2 is good) **THEN** (alpha is med)(beta is med)(gamma is low)
12. **IF** (T is accept) **AND** (RH is high) **AND** (CO_2 is good) **THEN** (alpha is low)(beta is high)(gamma is low)
13. **IF** (T is accept) **AND** (RH is low) **AND** (CO_2 is accept) **THEN** (alpha is high)(beta is low)(gamma is med)
14. **IF** (T is accept) **AND** (RH is accept) **AND** (CO_2 is accept) **THEN** (alpha is high)(beta is high)(gamma is med)
15. **IF** (T is accept) **AND** (RH is high) **AND** (CO_2 is accept) **THEN** (alpha is med)(beta is high)(gamma is med)
16. **IF** (T is accept) **AND** (RH is low) **AND** (CO_2 is poor) **THEN** (alpha is high)(beta is low)(gamma is high)
17. **IF** (T is accept) **AND** (RH is accept) **AND** (CO_2 is poor) **THEN** (alpha is high)(beta is high)(gamma is high)
18. **IF** (T is accept) **AND** (RH is high) **AND** (CO_2 is poor) **THEN** (alpha is med)(beta is high)(gamma is high)
19. **IF** (T is high) **AND** (RH is low) **AND** (CO_2 is good) **THEN** (alpha is high)(beta is low)(gamma is low)
20. **IF** (T is high) **AND** (RH is accept) **AND** (CO_2 is good) **THEN** (alpha is high)(beta is med)(gamma is low)
21. **IF** (T is high) **AND** (RH is high) **AND** (CO_2 is good) **THEN** (alpha is med)(beta is high)(gamma is low)
22. **IF** (T is high) **AND** (RH is low) **AND** (CO_2 is accept) **THEN** (alpha is high)(beta is low)(gamma is med)
23. **IF** (T is high) **AND** (RH is accept) **AND** (CO_2 is accept) **THEN** (alpha is high)(beta is med)(gamma is med)
24. **IF** (T is high) **AND** (RH is high) **AND** (CO_2 is accept) **THEN** (alpha is med)(beta is high)(gamma is med)
25. **IF** (T is high) **AND** (RH is low) **AND** (CO_2 is poor) **THEN** (alpha is high)(beta is low)(gamma is high)
26. **IF** (T is high) **AND** (RH is accept) **AND** (CO_2 is poor) **THEN** (alpha is high)(beta is med)(gamma is high)
27. **IF** (T is high) **AND** (RH is high) **AND** (CO_2 is poor) **THEN** (alpha is med)(beta is high)(gamma is high)

The control surfaces generated from the membership functions and control rules for the various combinations of fuzzy supervisor inputs and outputs are shown graphically in Figure 10.6 to Figure 10.11.

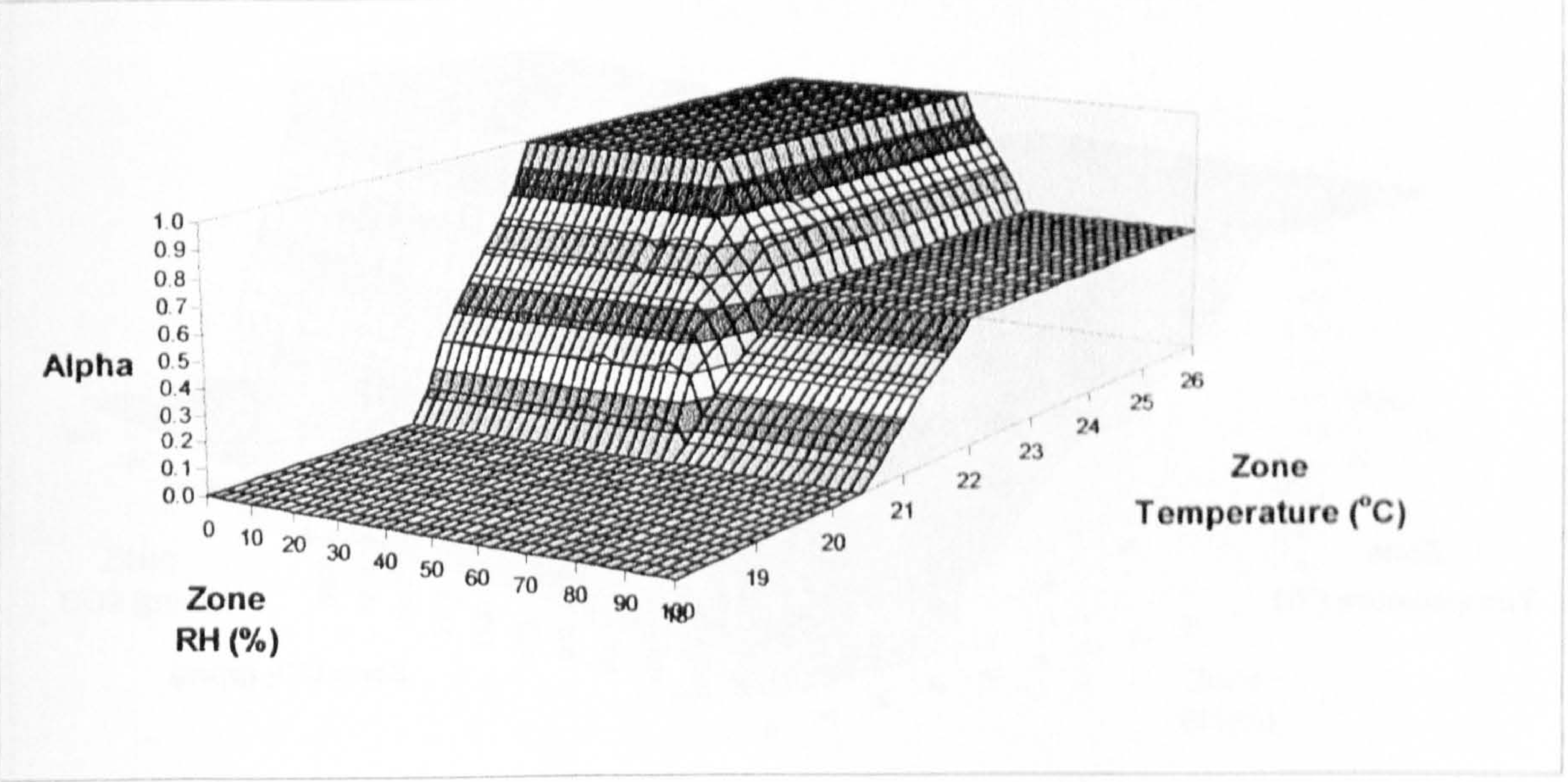

Figure 10.6. High level fuzzy supervisor control surface for inputs zone temperature and zone RH; output alpha.

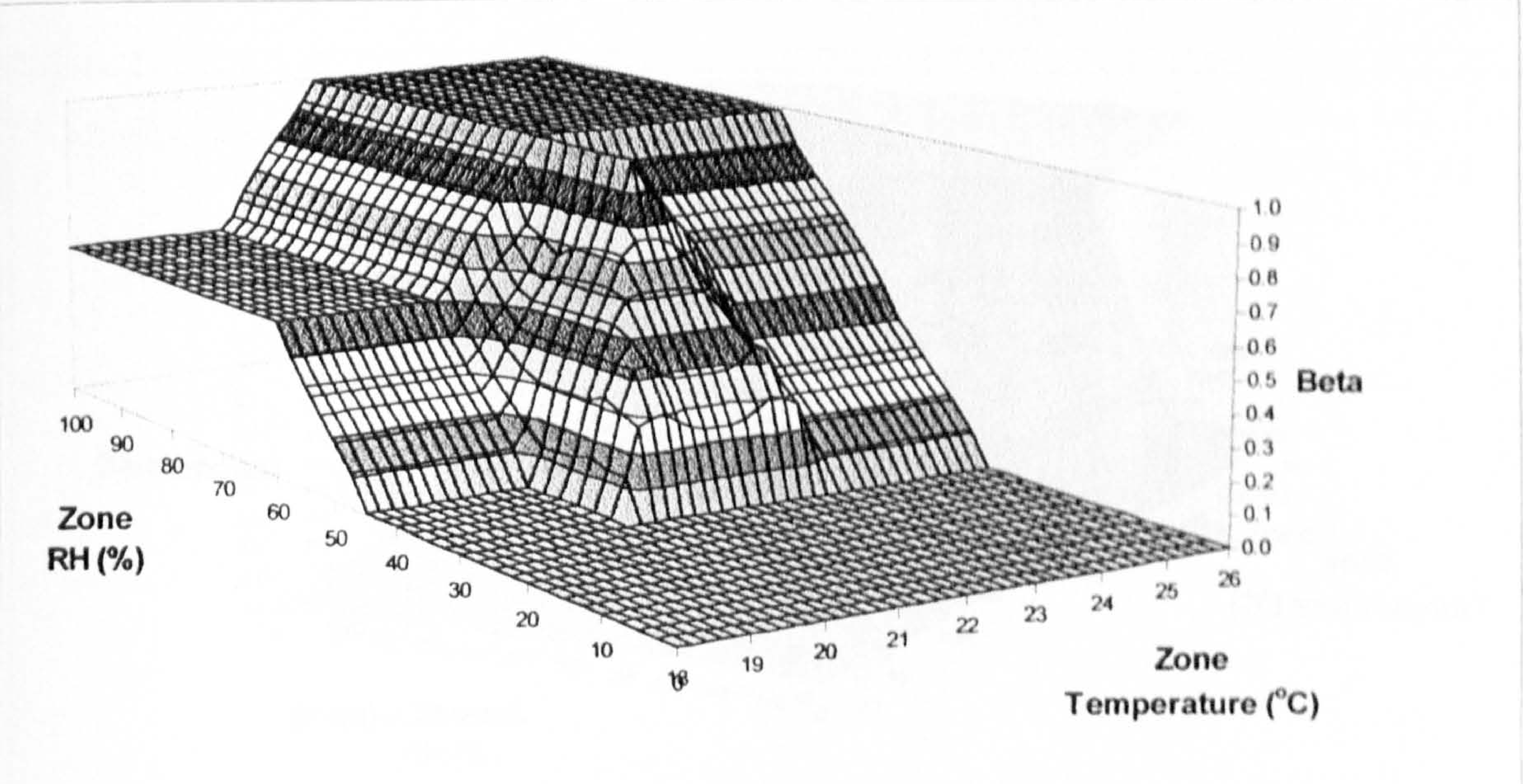

Figure 10.7. High level fuzzy control surface for inputs zone temperature and zone RH; output beta.

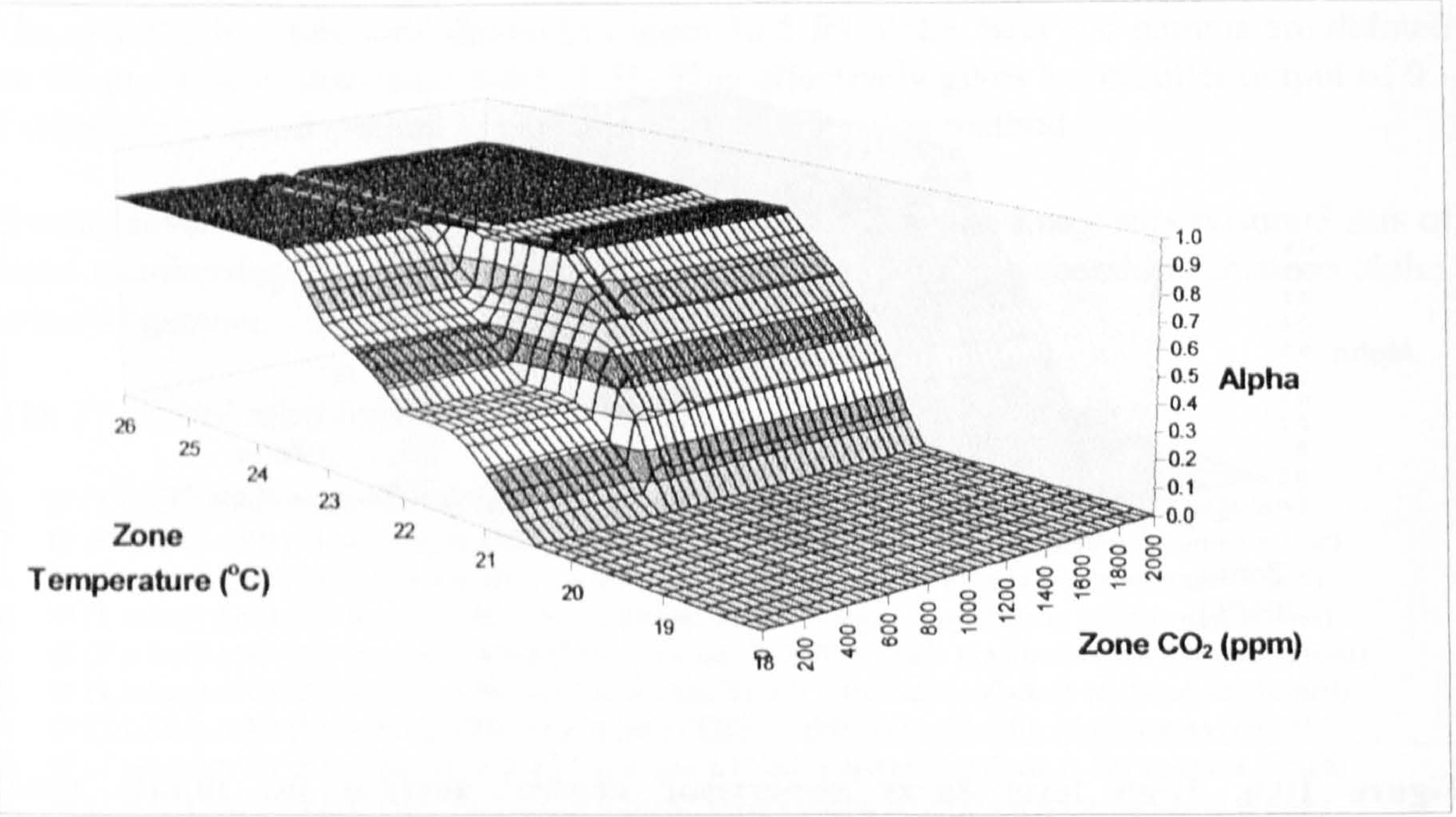

Figure 10.8. High level fuzzy control surface for inputs zone temperature and zone CO_2; output alpha.

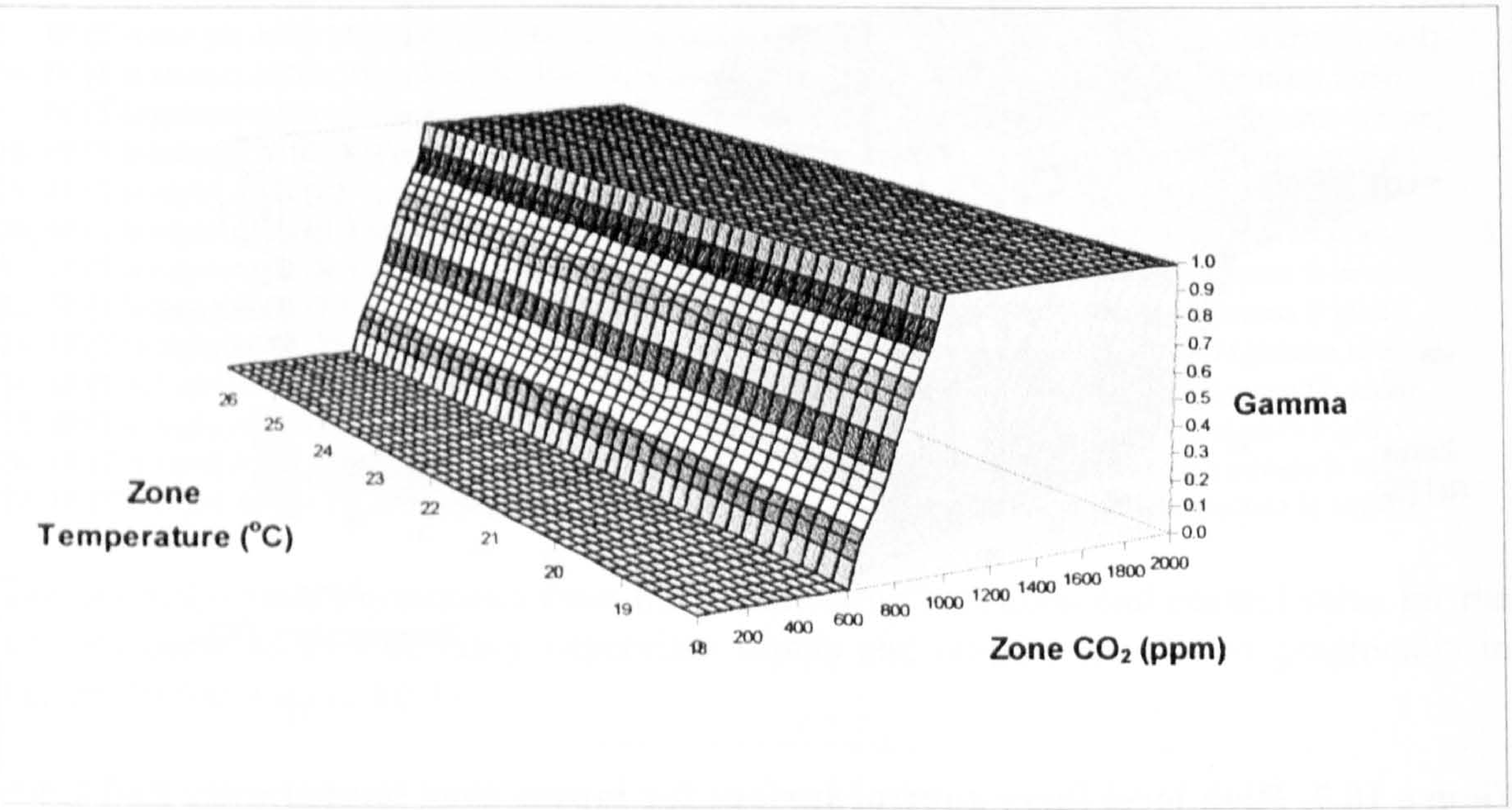

Figure 10.9. High level fuzzy control surface for inputs zone temperature and zone CO_2; output gamma.

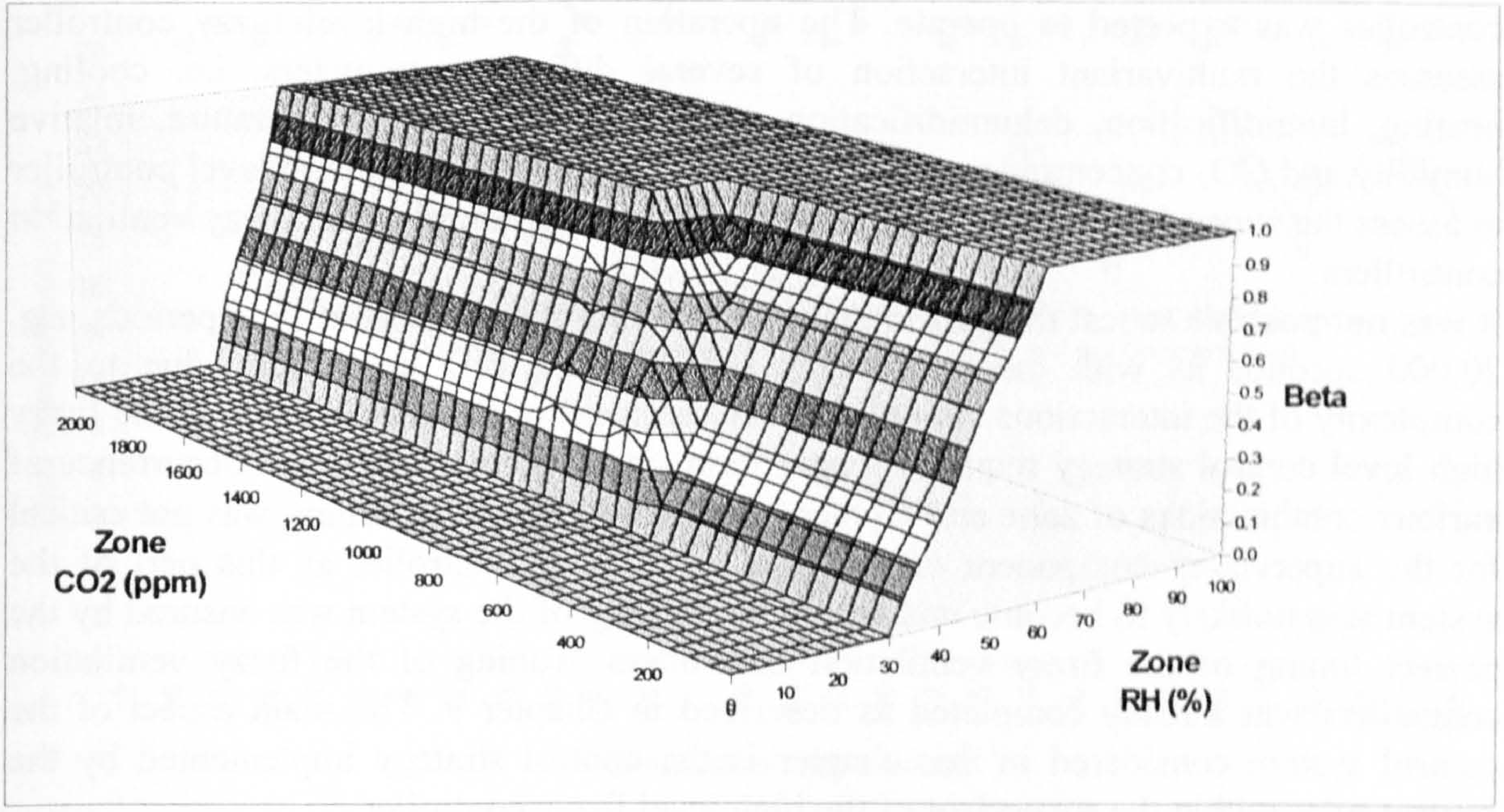

Figure 10.10. High level fuzzy control surface for inputs zone RH and zone CO_2; output beta.

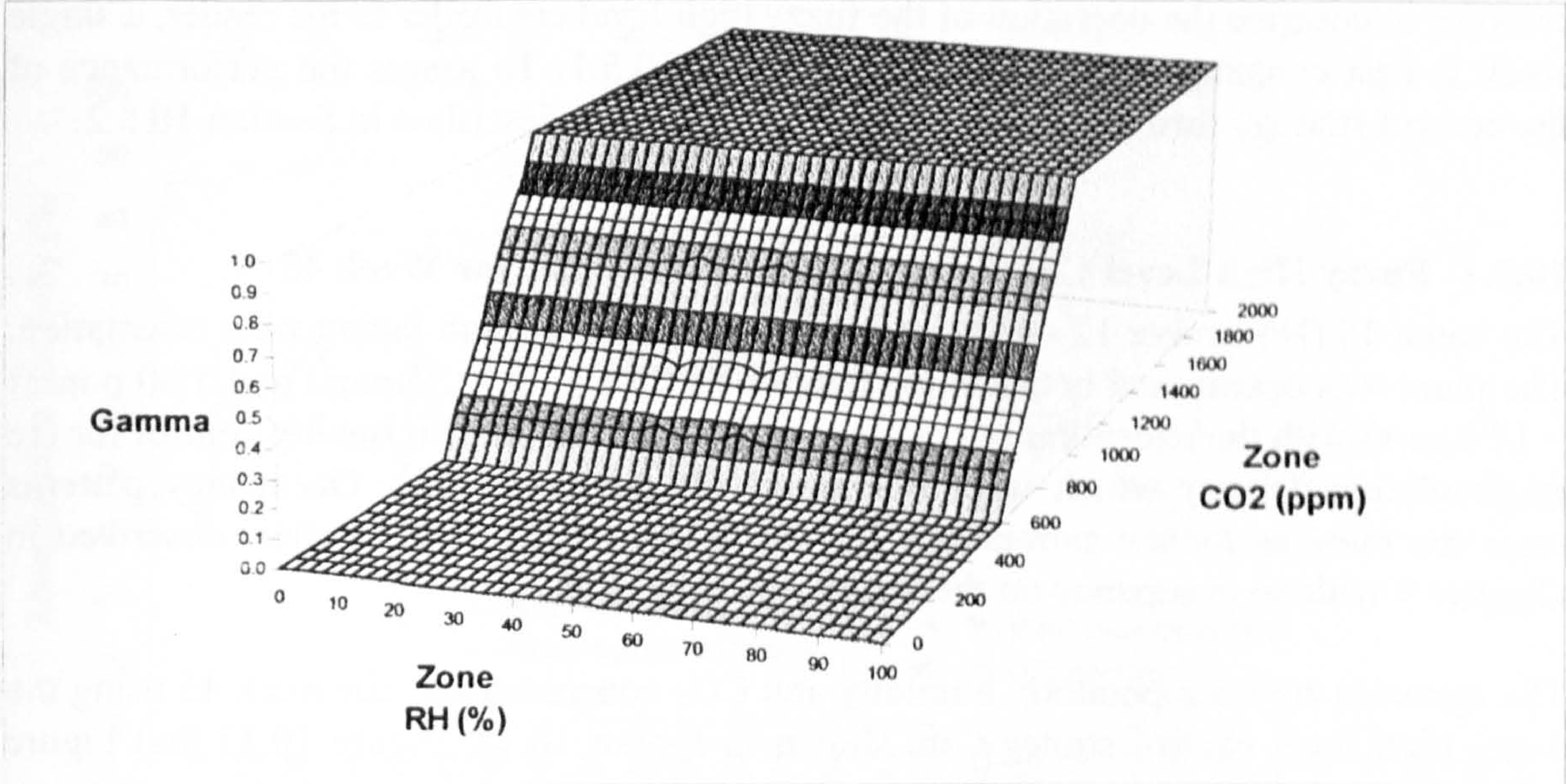

Figure 10.11. High level fuzzy control surface for inputs zone RH and zone CO_2; output gamma.

The control surfaces allow the control actions (outputs) of the fuzzy supervisor to be interpreted for given input values. It is not possible to create a single graph showing all control input / output surfaces as there are more than 3 dimensions.

10.4 Fuzzy High Level Controller Development

The high level fuzzy supervisor membership functions and control rules were developed heuristically from operator knowledge and intuition regarding the manner in which the controller was expected to operate. The operation of the high level fuzzy controller assesses the multivariant interaction of several different parameters, i.e. cooling, heating, humidification, dehumidification and air quality. Zone temperature, relative humidity and CO_2 concentration are used as the inputs to the fuzzy high level controller to assess the supervisory action that should be taken with regard to the fuzzy ventilation controllers.

It was not possible to test the performance of the controller over short time periods, e.g. 20,000 seconds as with the pure fuzzy (PDFC) and PID controllers, due to the complexity of the interactions taking place. Assessment of the performance of the fuzzy high level control strategy required longer term simulations to allow the occurrence of various combinations of zone and ambient conditions. However, tuning was not critical for the supervisory component of the high level fuzzy controller as this part of the system was unlikely to become unstable. The stability of the system was ensured by the correct tuning of the fuzzy ventilation controllers. Tuning of the fuzzy ventilation controllers was already completed as described in Chapter 9. The main aspect of the control system considered in this chapter is the control strategy implemented by the control rules within the supervisor of the high level fuzzy controller.

10.5 Fuzzy High Level Controller Operation

In order to describe the operation of the fuzzy high level controller to the reader, a single week is first considered graphically, see Section 10.5.1. To assess the performance of the control strategy further a quantitative analysis is then described in Section 10.5.2.

10.5.1 Fuzzy High Level Controller Graphical Analysis for Week 45

The week 45 (November 12 - 18) simulation is used for a south facing zone orientation. The plant was operational between the hours of 5:00 a.m. (t = 5 hours) and 5:00 p.m. (t = 17 hours) with the exception of the air re-circulation fan and air quality control for the re-circulation damper which were operational 24 hours per day. Occupancy patterns were the same as for the simulations for the fuzzy ventilation controllers described in Chapter 9 with no occupancy on the last day of each week.

The dynamic zone temperature, humidity and CO_2 concentrations for week 45 using the fuzzy high level control strategy are shown in Figure 10.12, Figure 10.13 and Figure 10.14.

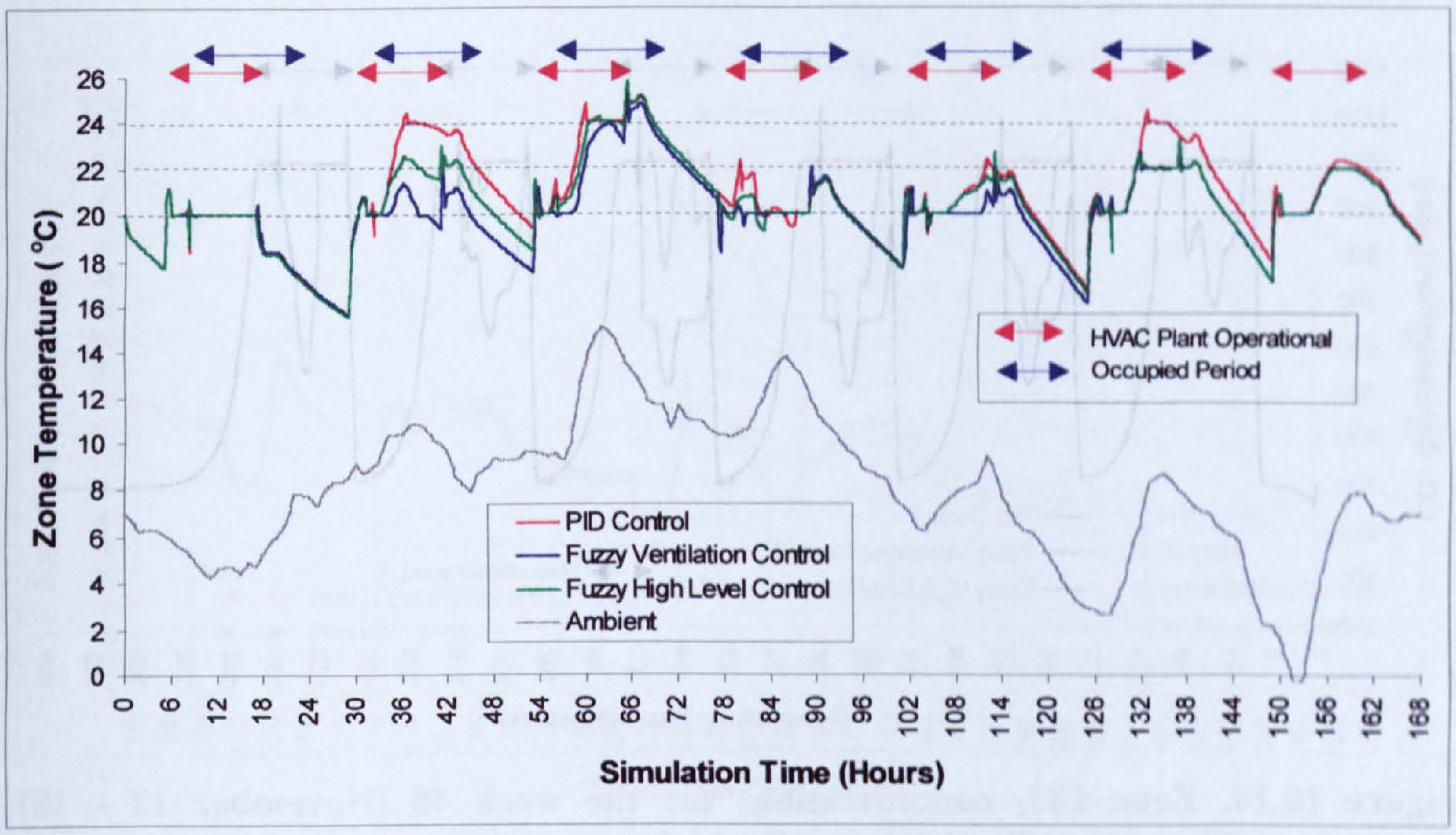

Figure 10.12. Zone and ambient temperatures for the week 45 (November 12 - 18) simulations. Broken lines indicate the upper, lower and preferred set points.

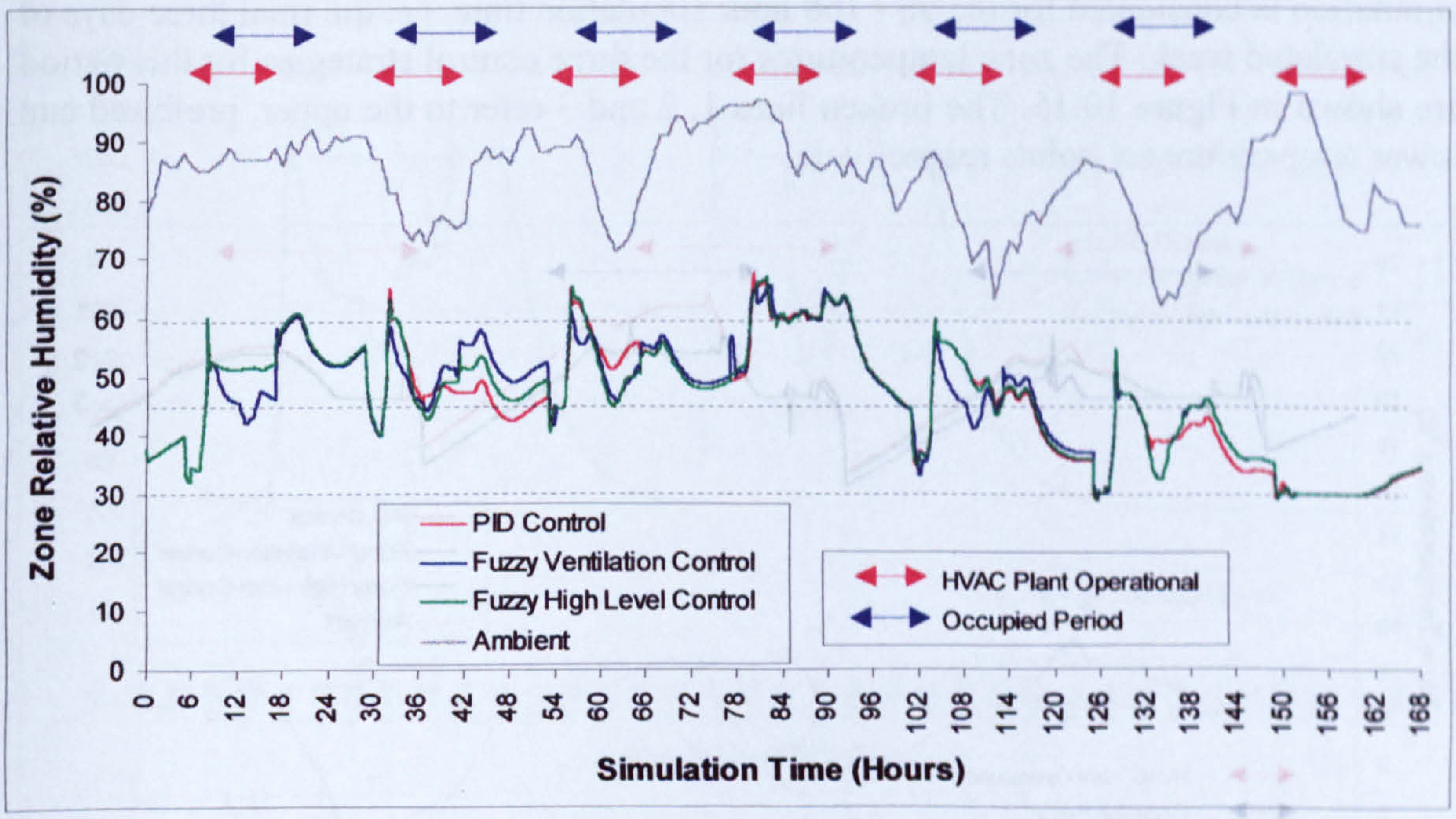

Figure 10.13. Zone and ambient relative humidity for the week 45 (November 12 - 18) simulations. Broken lines indicate the upper, lower and preferred set points.

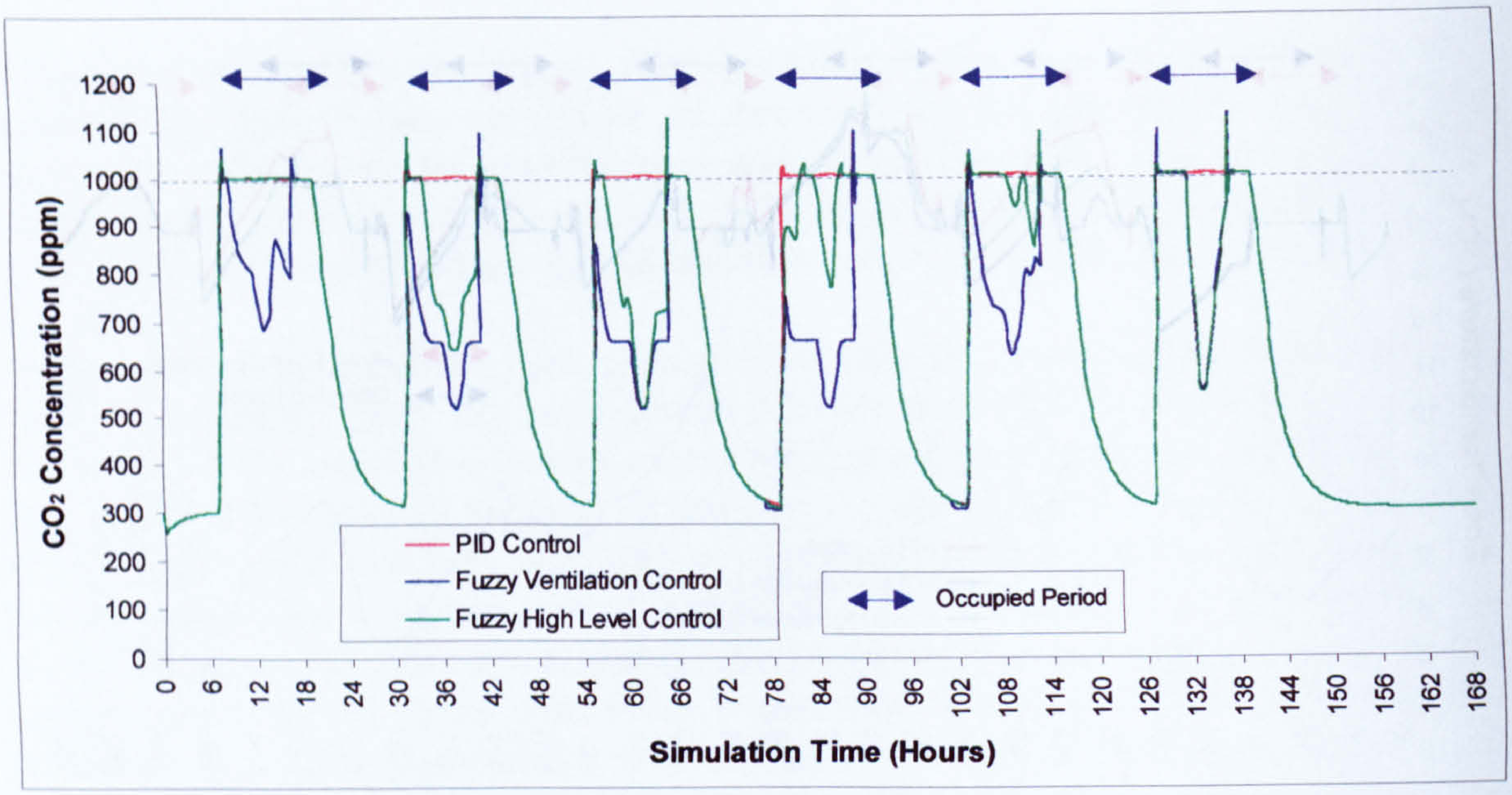

Figure 10.14. Zone CO_2 concentrations for the week 45 (November 12 - 18) simulations. The broken line indicates the higher set point.

To examine the operation of the fuzzy high level controller in greater detail the 7 day simulation is considered for the 96 - 168 hour simulation time, i.e. the final three days of the simulated week. The zone temperatures for the three control strategies for this period are shown in Figure 10.15. The broken lines 1, 2 and 3 refer to the upper, preferred and lower temperature set points respectively.

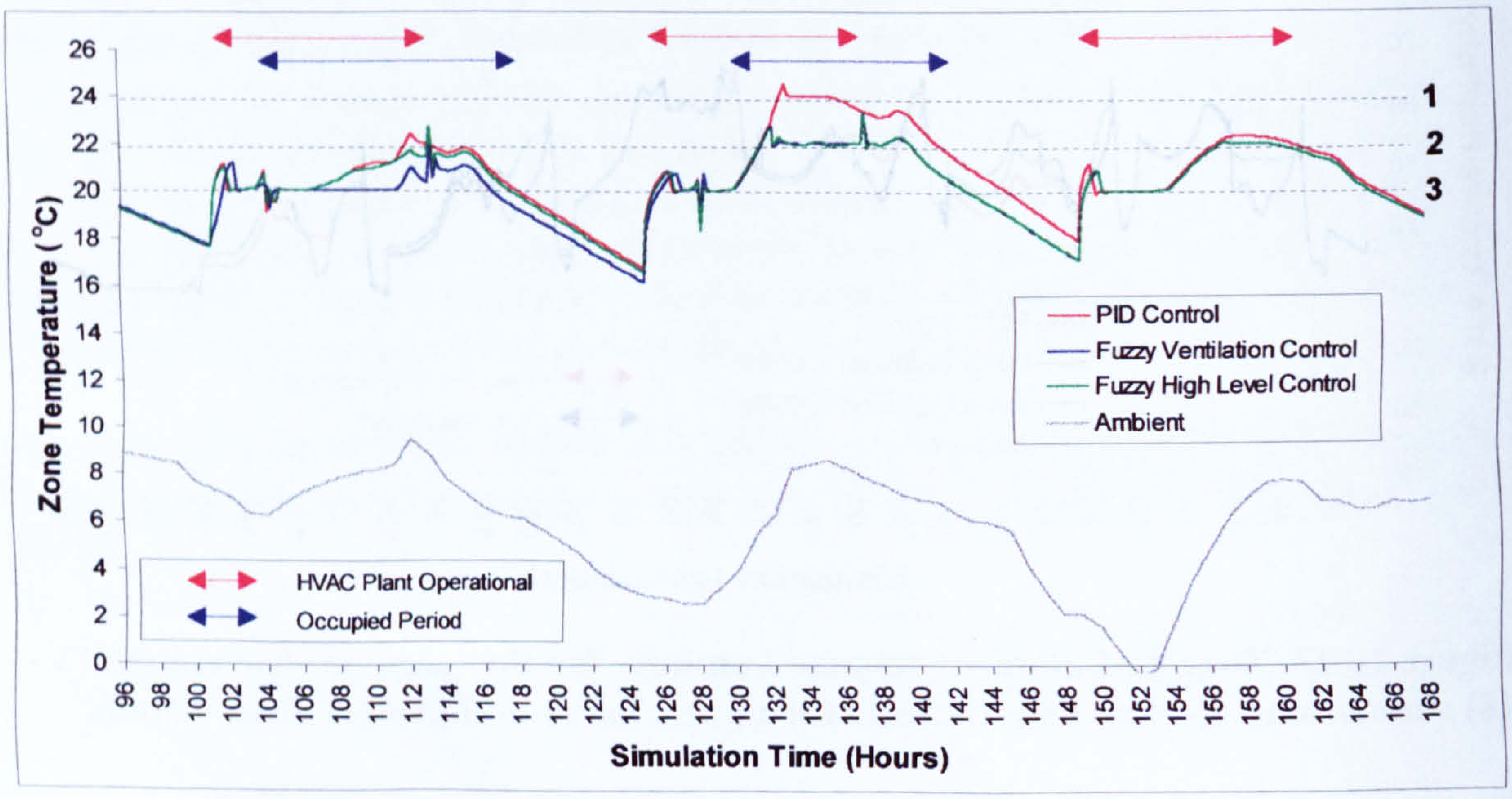

Figure 10.15. Zone and ambient temperatures for the 96 - 168 hour simulation period for the PID, fuzzy ventilation and fuzzy high level strategies (week 45).

Similarly the zone humidity and CO_2 concentrations are shown in Figure 10.16 and Figure 10.17 respectively.

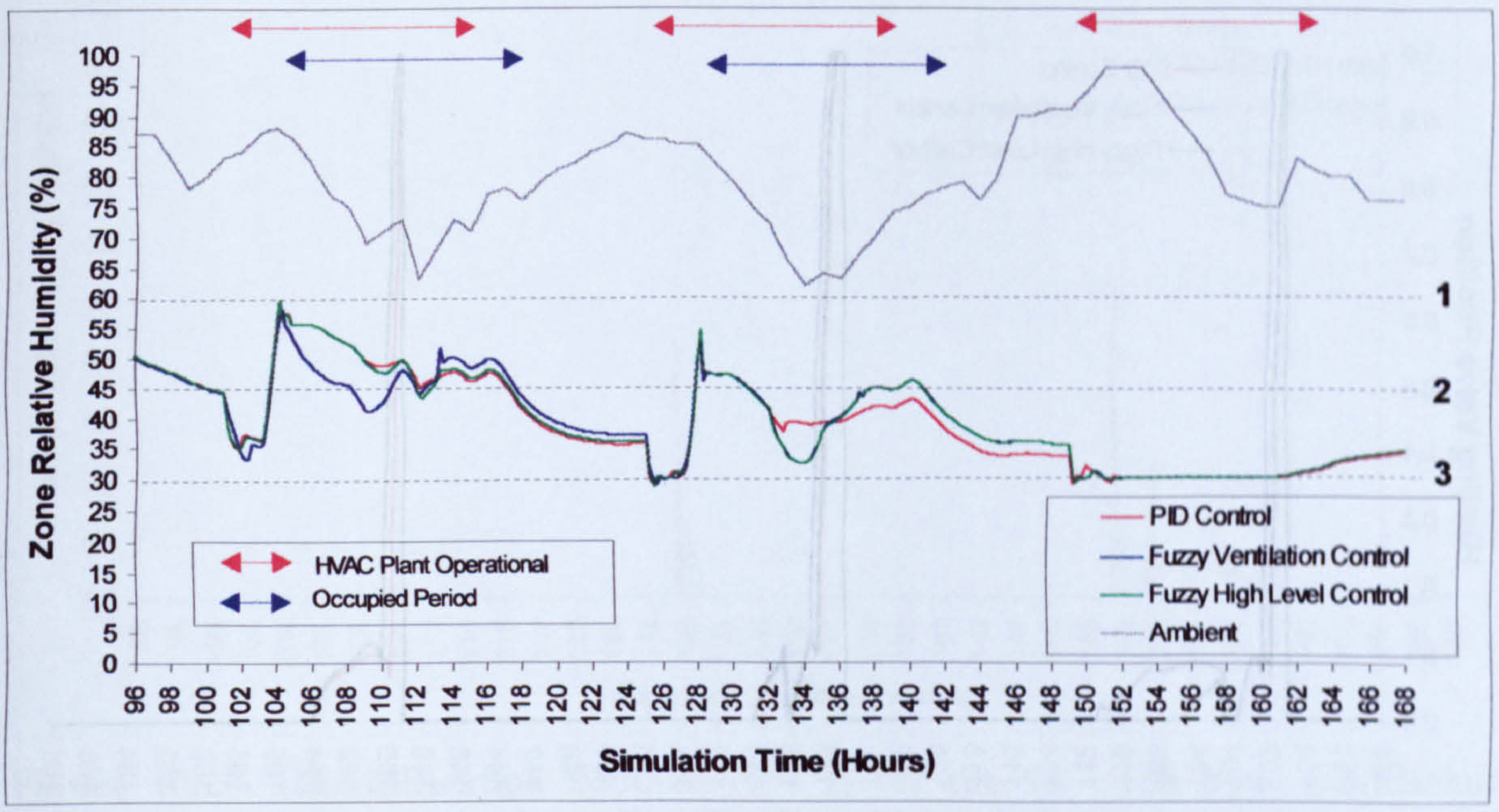

Figure 10.16. Zone and ambient relative humidity for the 96 - 168 hour simulation period for the PID, fuzzy vent and high level fuzzy strategies (week 45).

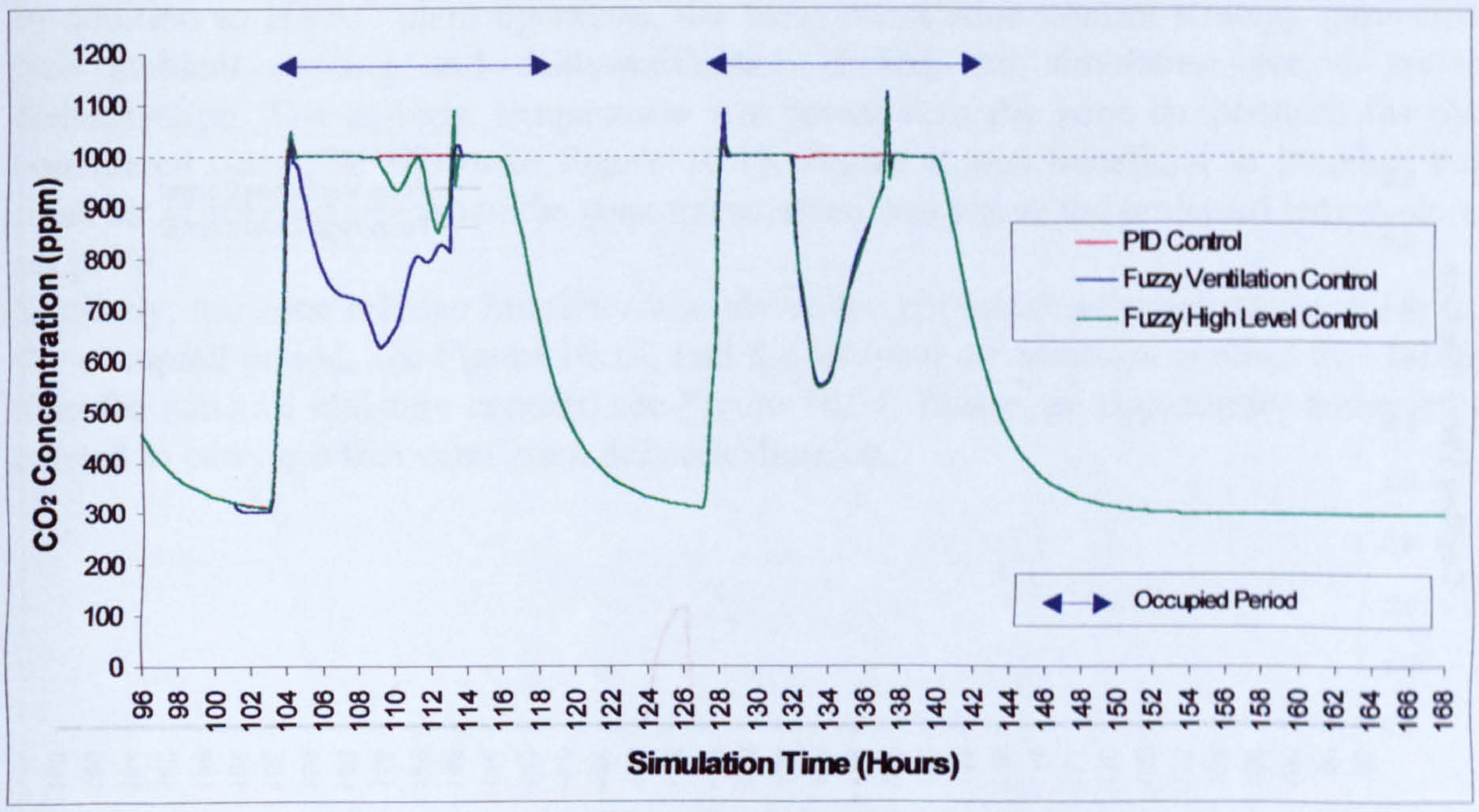

Figure 10.17. Zone CO_2 concentrations for the 96 - 168 hour simulation period for the PID, fuzzy vent and high level fuzzy strategies (week 45).

Plant dehumidification was not required during the occupied periods of the 120 - 168 hour simulation for week 45. Heating, cooling, humidification and re-circulation damper operation were required in order to maintain environmental conditions within the desired set point limits. The valve positions are shown in Figure 10.18 and Figure 10.19 for the heating and cooling plant components respectively during the simulation period week 45 96-168 hour simulation period.

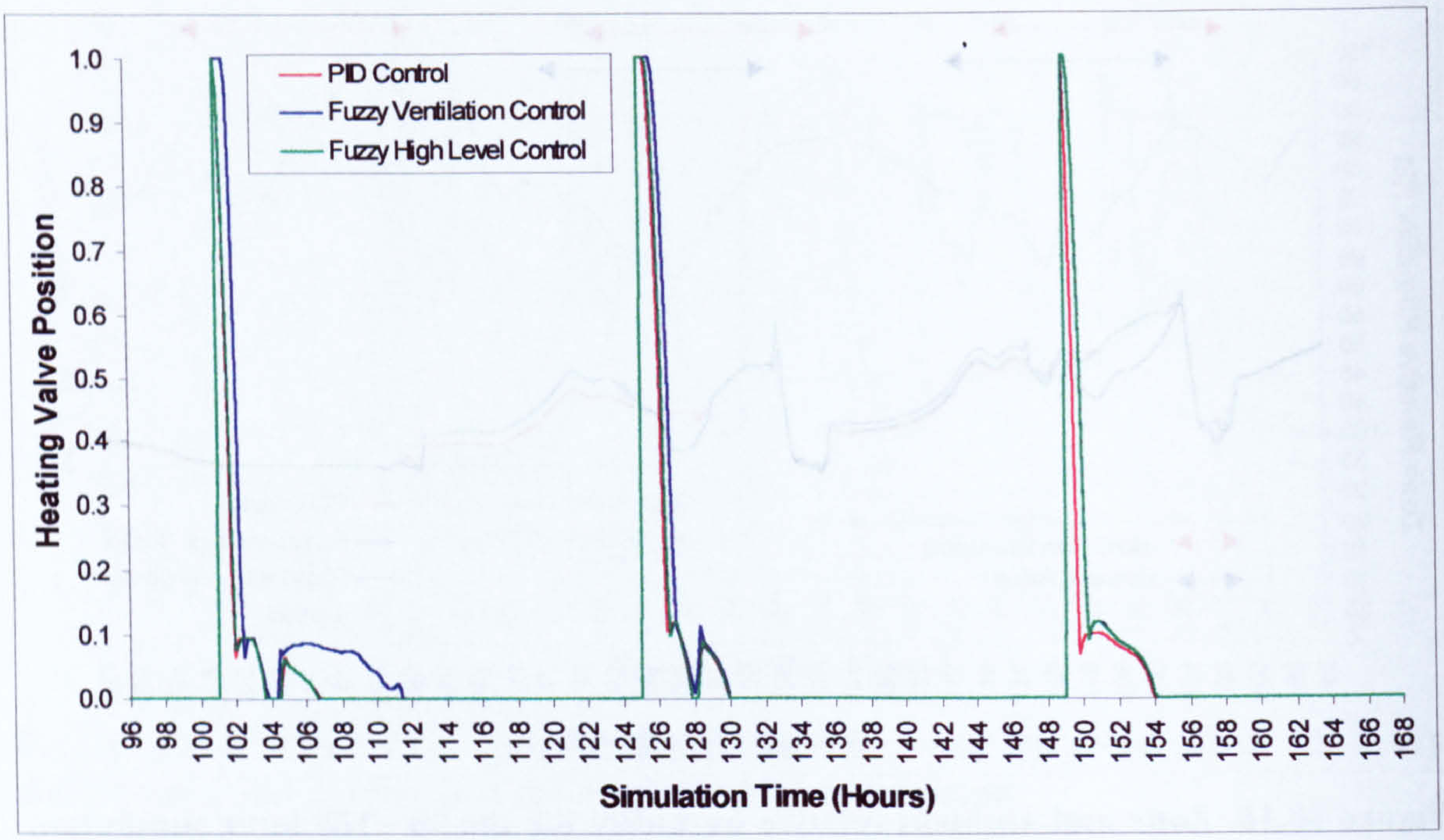

Figure 10.18. Heating valve position during the 96 - 168 simulation period (week 45) for the PID, fuzzy ventilation and fuzzy high level control strategies.

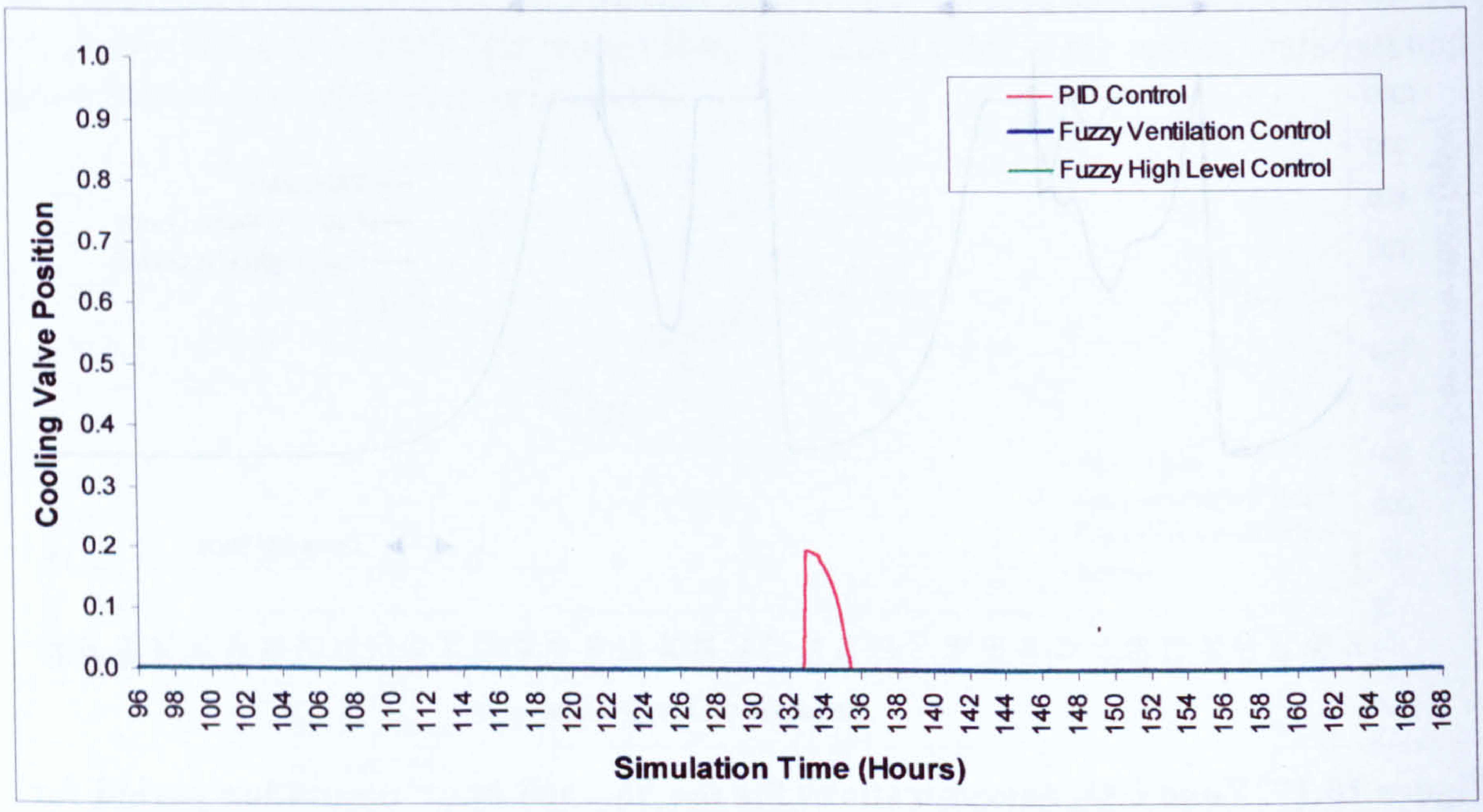

Figure 10.19. Cooling valve position for the 96 - 168 hour simulation period (week 45) for the PID, fuzzy ventilation and fuzzy high level control strategies.

The required humidification input for the 96-168 hour simulation period during week 45 is shown in Figure 10.20.

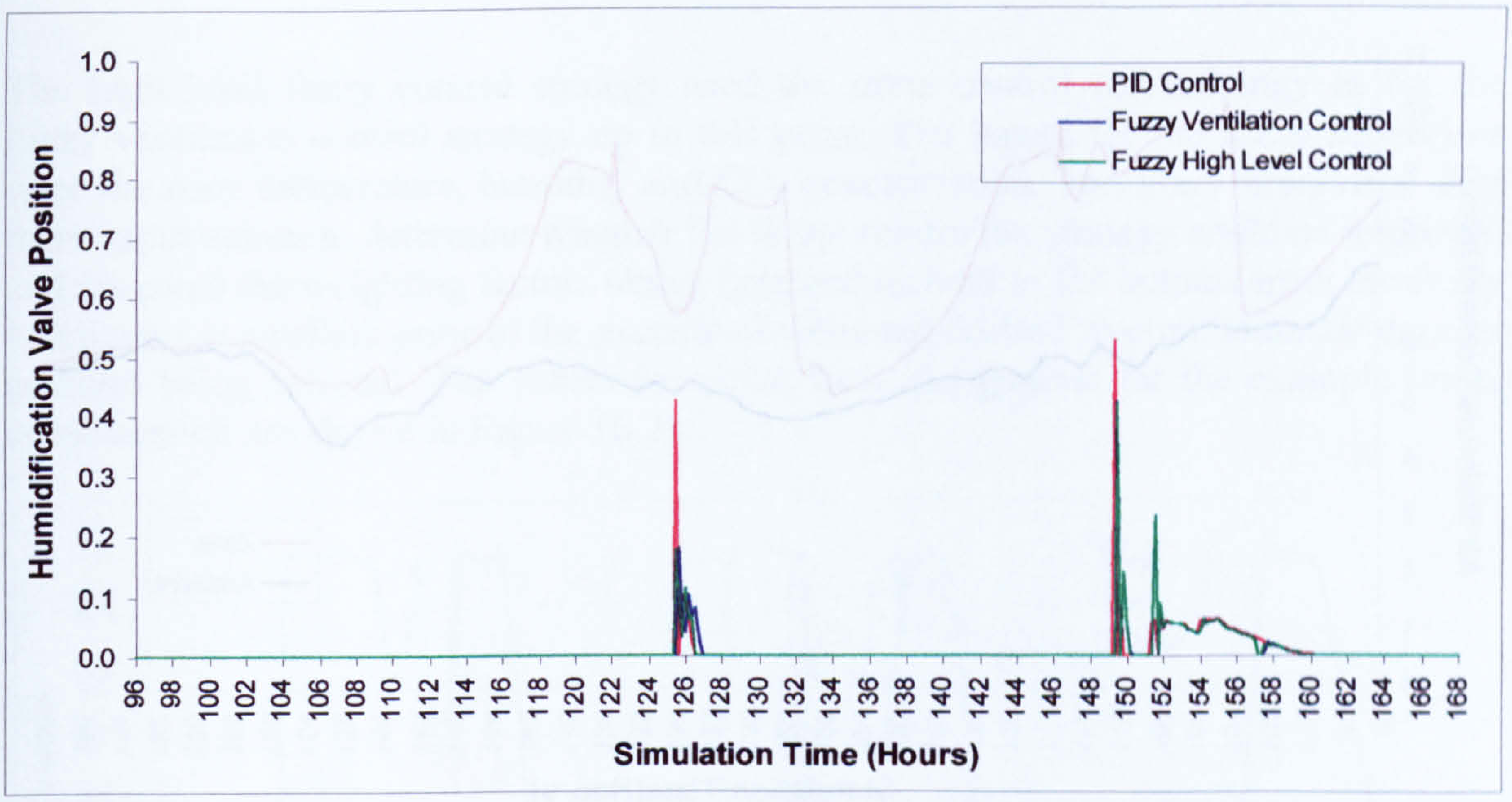

Figure 10.20. Humidification demand (0 - 1) for the 96 - 168 hour simulation period (week 45) for the PID, fuzzy ventilation and fuzzy high level control strategies.

In addition to HVAC plant operation, the fuzzy ventilation control strategy requested free ambient cooling and dehumidification during the simulation period under consideration. The ambient temperature was lower than the zone temperature for the considered period as shown in Figure 10.15. Hence it was beneficial to increase the fresh air ventilation rate when the zone temperature was above the preferred temperature set point.

Similarly, the zone relative humidity was above the preferred set point during some of the occupied period, see Figure 10.16, and the ambient air moisture content was lower than the zone air moisture content, see Figure 10.21. Hence, an opportunity sometimes existed to carry out free ventilation dehumidification.

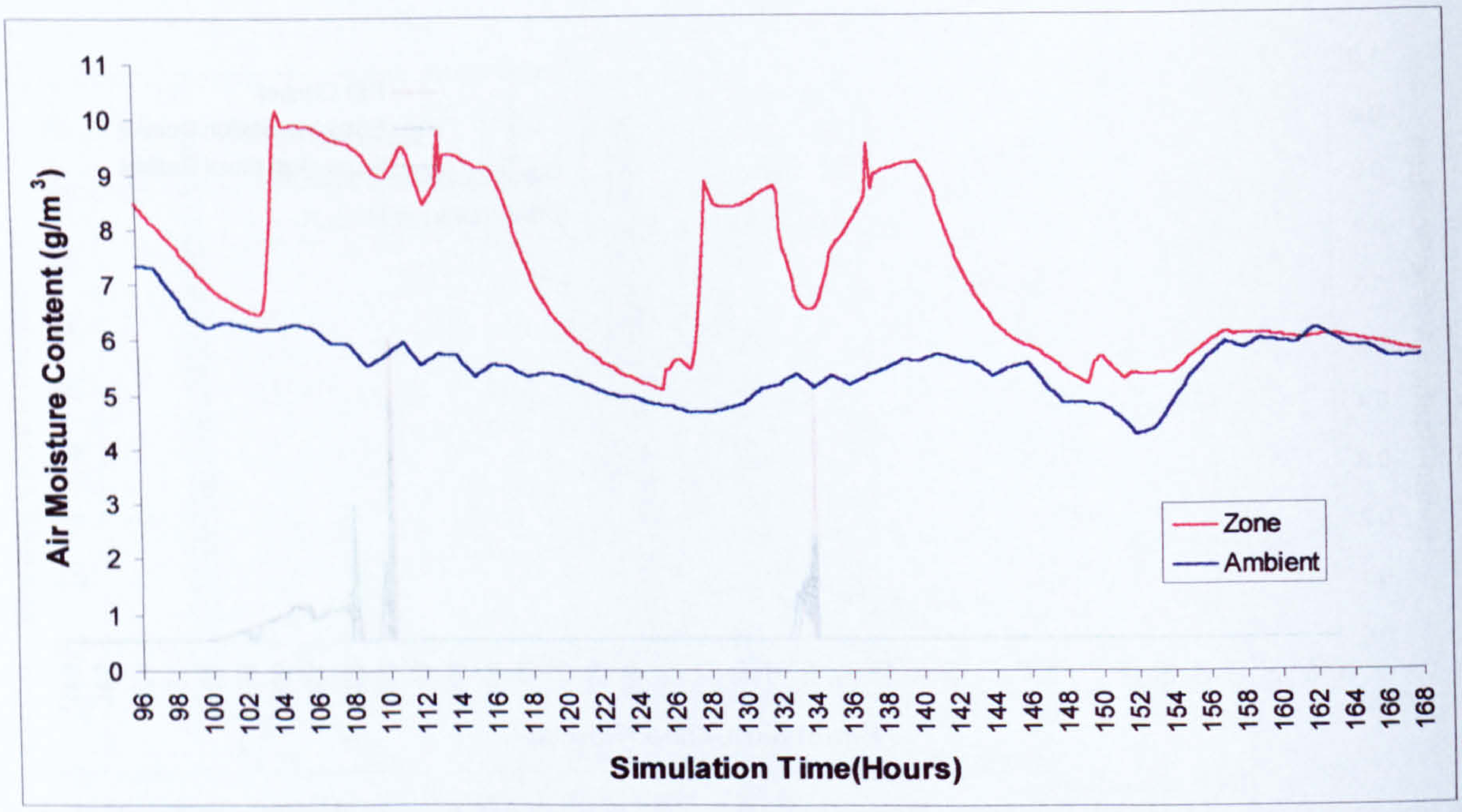

Figure 10.21. Zone and ambient air moisture content for the 96 - 168 hour simulation period (week 45).

During the simulation for the example under consideration the fuzzy ventilation control components of the fuzzy high level controller aimed to converge the values of the environmental parameters towards the preferred set points. As a result the requested positions of the re-circulation air damper for cooling, dehumidifying and air quality purposes before fuzzy supervisory control was implemented are shown in Figure 10.22.

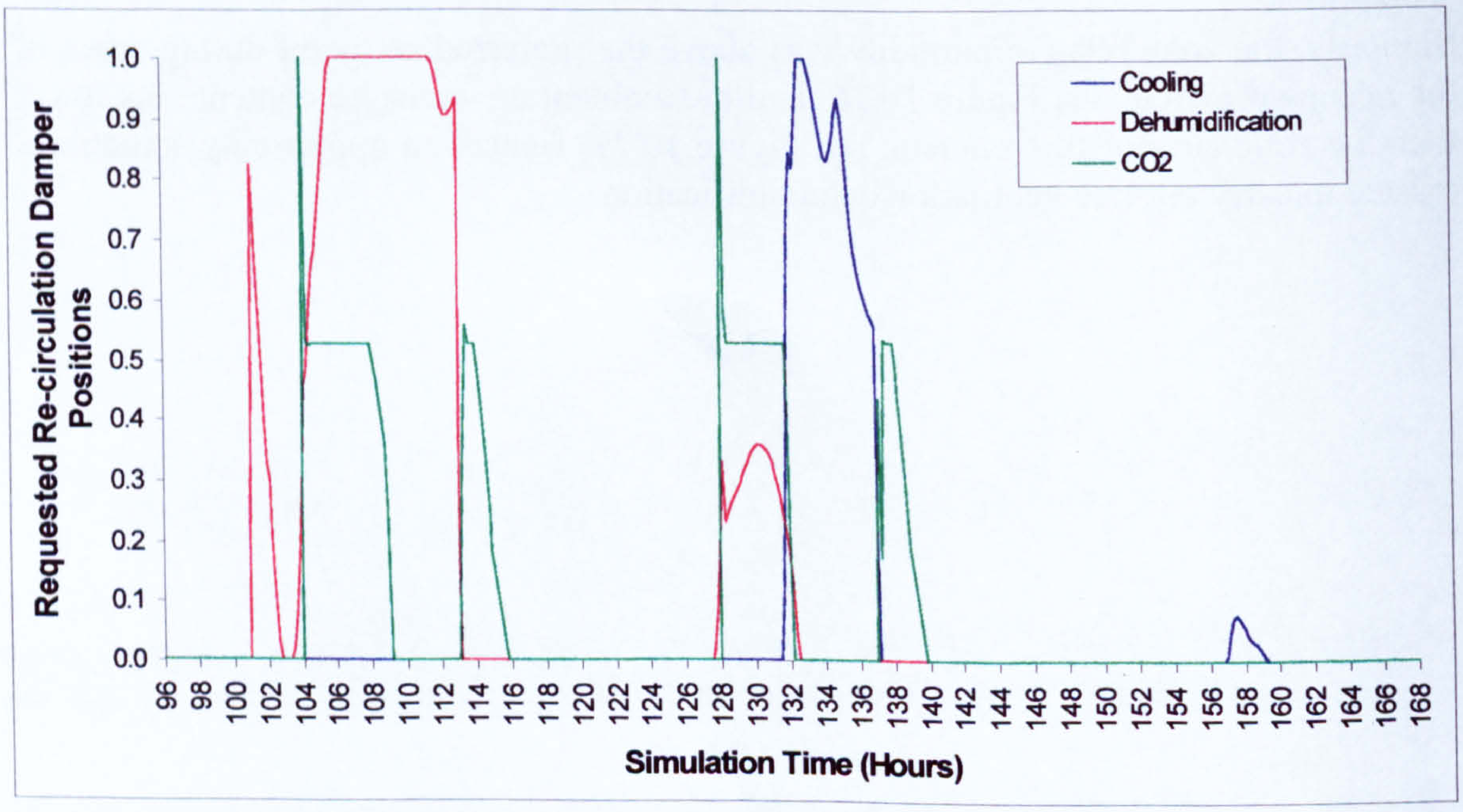

Figure 10.22. Fuzzy ventilation strategy desired re-circulation air damper positions for cooling, dehumidification and air quality purposes with fuzzy high level control operational.

The high level fuzzy control strategy used the same control methodology as for the fuzzy ventilation control strategy up to this point. The inputs for the fuzzy supervisor were the zone temperature, humidity and CO_2 concentration. The fuzzy supervisor used these input values to determine whether the fuzzy ventilation strategy could be improved and assigned the weighting factors alpha, beta and gamma to the outputs from the fuzzy ventilation controllers prior to the maximum weighted desired re-circulation air damper position being selected. The values for alpha, beta and gamma for the example under consideration are shown in Figure 10.23.

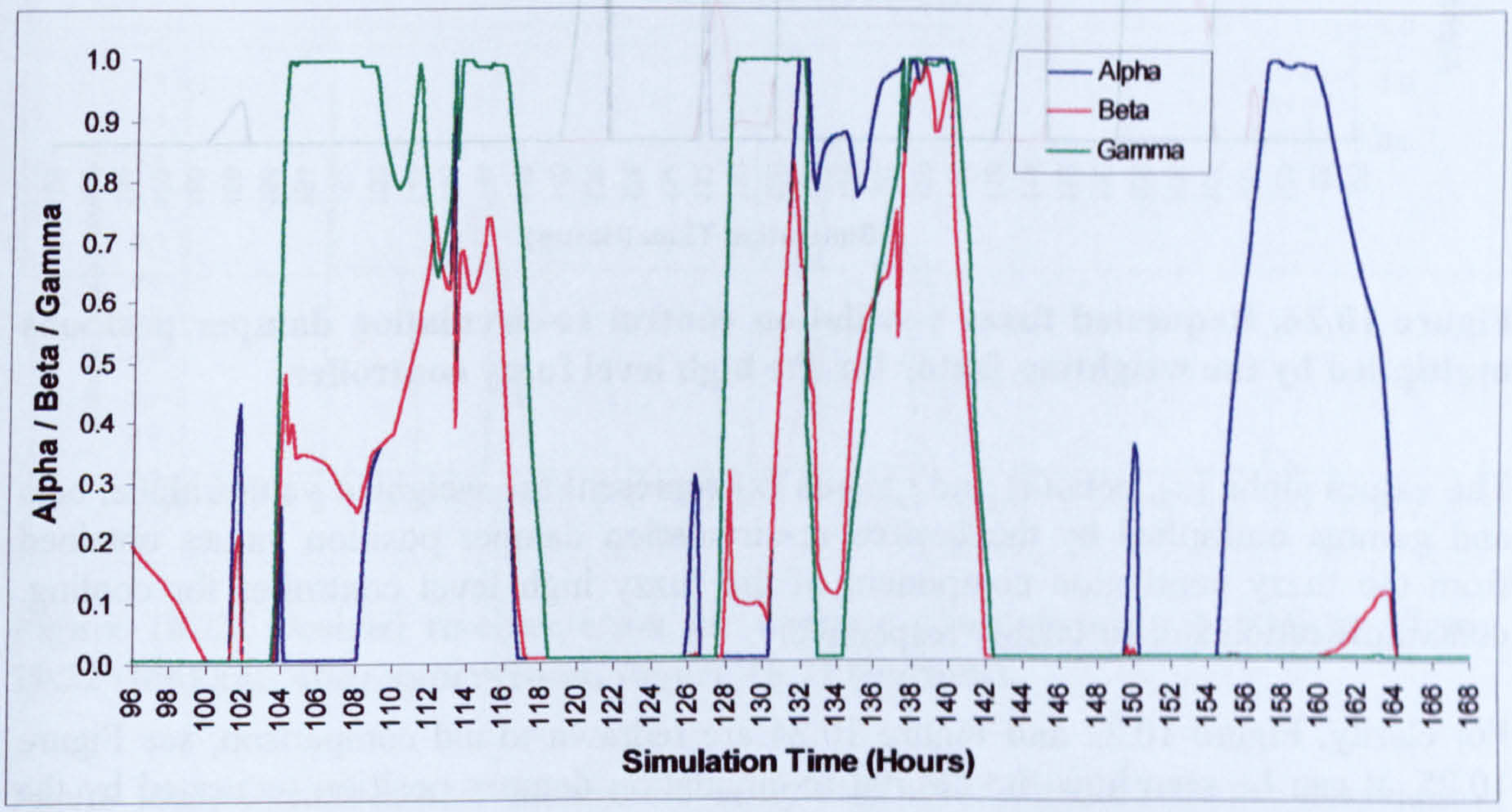

Figure 10.23. High level fuzzy controller supervisor weighting outputs alpha, beta and gamma.

The fuzzy high level controller analysed the environmental zone parameter values at each time step and provided a weighting factor to apply to the desired re-circulation air damper positions. This was implemented to ensure that theoretical energy savings or environmental condition improvements calculated by the fuzzy ventilation controllers actually provide an overall benefit after taking interactions between the environmental parameters into consideration. When the fuzzy high level controller decided a certain course of action was not beneficial overall, it suppressed the fuzzy ventilation controller desired re-circulation air damper position responsible to a lower level.

The actual desired re-circulation air damper positions for cooling, dehumidification and air quality purposes obtained from the fuzzy ventilation controllers with the fuzzy high level control operational are shown in Figure 10.24.

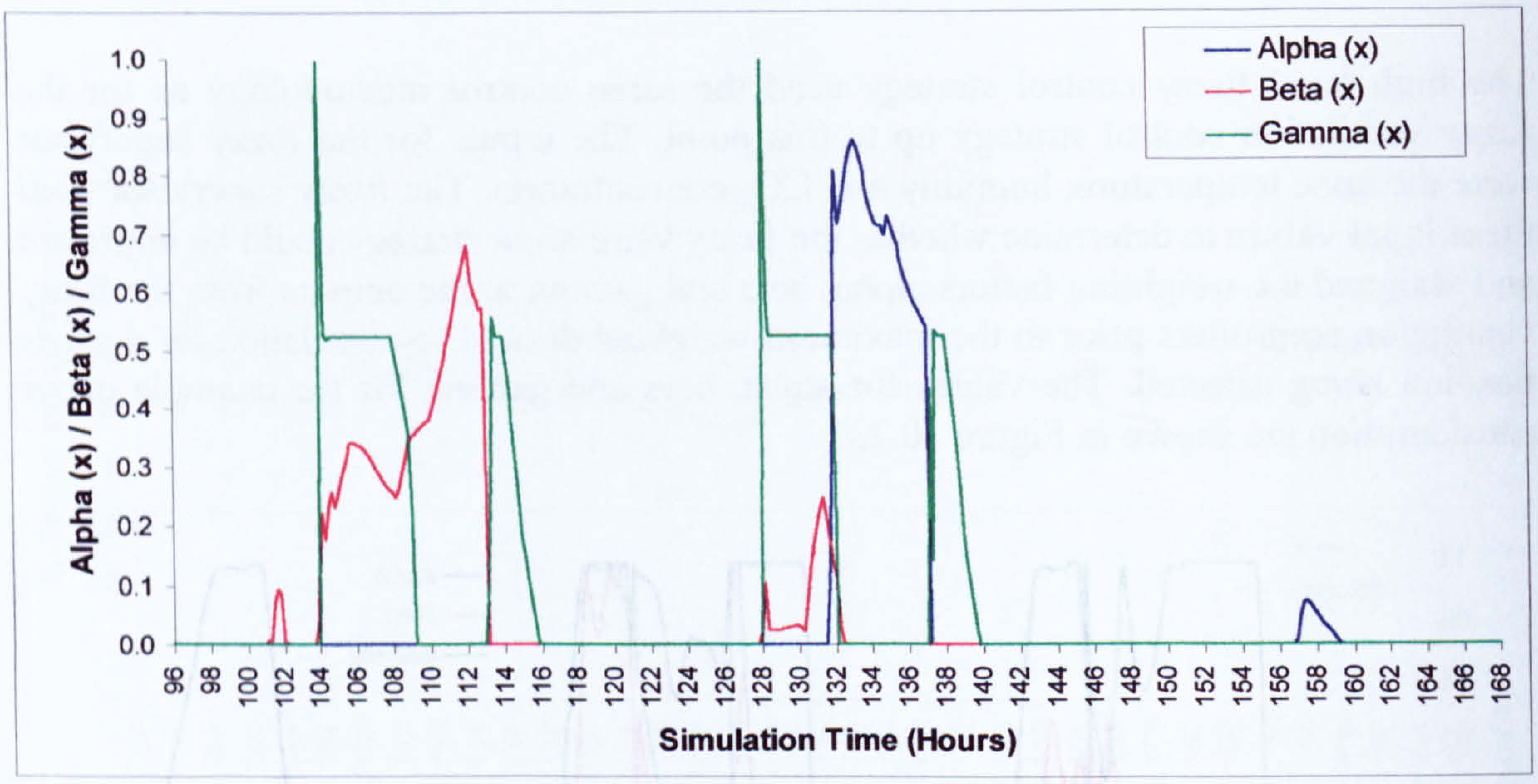

Figure 10.24. Requested fuzzy ventilation control re-circulation damper positions multiplied by the weighting factor for the high level fuzzy controller.

The values alpha (x), beta (x) and gamma (x) represent the weighted values alpha, beta and gamma multiplied by the desired re-circulation damper position values obtained from the fuzzy ventilation component of the fuzzy high level controller for cooling, dehumidification and air quality respectively.

For clarity, Figure 10.22 and Figure 10.24 are redrawn to aid comparison, see Figure 10.25. It can be seen how the desired re-circulation damper position requested by the fuzzy ventilation dehumidification controller has been suppressed during the 96-100 hour simulation period.

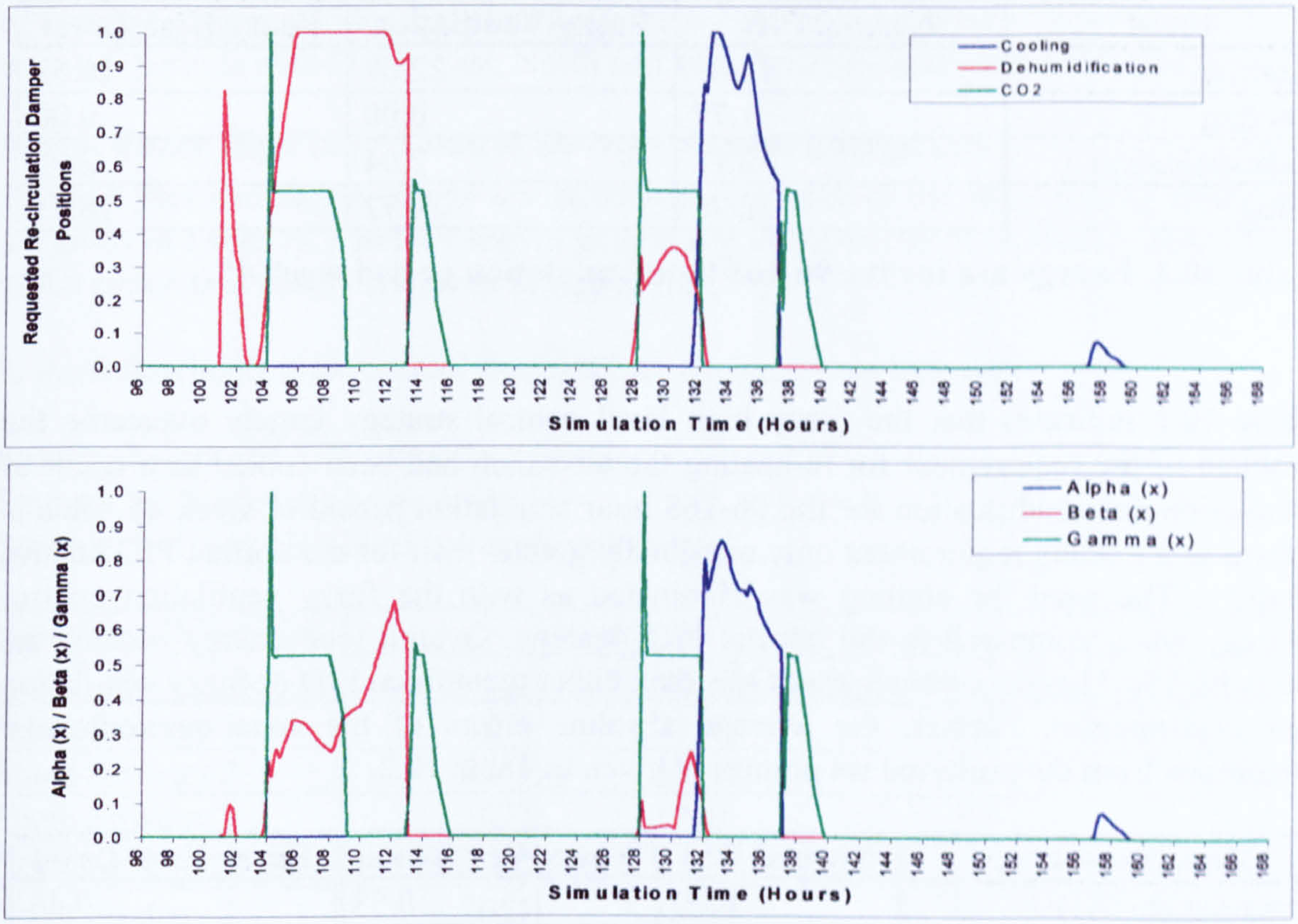

Figure 10.25. Desired re-circulation air damper position pre-supervision, Figure 10.22 (top) and after supervision, Figure 10.24 (bottom).

Figure 10.25 illustrates how each of the fuzzy high level outputs becomes dominant at some point during the simulation 96 - 168 hours of week 45. The dominance of the fuzzy ventilation control component of the fuzzy high level controller realises the potential to converge the zone temperature and humidity towards the preferred set points or the controller objectives with regard to energy efficiency.

Due to the high number of interactions taking place it is useful to analyse the performance of the fuzzy high level controller on a quantitative rather than qualitative basis. This is considered in Section 10.5.2.

10.5.2 Fuzzy High Level Control Strategy Performance Assessment for Week 45

To assess the performance of the fuzzy high level control strategy, the week 45 simulations were compared to results obtained for normal PID and fuzzy ventilation control strategy simulations as benchmark tests. With the exception of the control strategy used, all other aspects of the model remained identical. The performance of the control strategies was assessed by i) energy use (continuous), and ii) average error from the preferred set point (during periods when the HVAC plant was operational, i.e. 05:00 - 17:00). The calculation methods used for assessing the performance criteria are described in Appendix C and Appendix D.

Table 10.1 and Table 10.2 give the values for these performance criteria for the 96 - 168 hour simulation period for week 45.

Plant	Normal PID	Fuzzy Ventilation	Fuzzy High Level
Heating	14.89	22.68	16.53
Cooling	1.77	0.00	0.00
Humidification	2.12	2.04	2.00
Total	18.78	24.72	18.53

Table 10.1. Energy use for the 96-168 hour simulation period week 45.

Table 10.1 indicates that the fuzzy high level control strategy largely overcame the problem of the requirement for re-heating the air which had been cooled as a result of ventilation dehumidification for the 96-168 hour simulation period of week 45. This is shown as a heating requirement only marginally greater than for the normal PID control strategy. The need for cooling was eliminated as with the fuzzy ventilation control strategy when compared to the normal PID strategy. Overall total energy use for the fuzzy high level control strategy was less than either the normal PID or fuzzy ventilation control strategies. Further, the average absolute errors of the zone environmental conditions from the preferred set points are given in Table 10.2.

Zone Parameter	Normal PID	Fuzzy Ventilation	Fuzzy High Level
Temperature (°C)	0.60	0.53	0.45
Relative Humidity (%)	4.12	3.77	4.29
CO_2 Concentration (ppm)	767.77	640.93	707.47

Table 10.2. Average absolute errors of the zone environmental parameters from the preferred set points for the 96 - 168 hour simulation period, week 45.

Table 10.2 indicates an overall improvement in zone temperature provision, an overall decline in zone humidity provision, an improvement in air quality conditions in comparison to the normal PID strategy and a decline in air quality conditions in comparison to the fuzzy ventilation control strategy. The simulation results for the fuzzy high level control strategy therefore represent an overall performance improvement in comparison to the normal PID and fuzzy ventilation control strategies, i.e. a good compromise between comfort provision, energy efficient and cost efficiency. However, the simulations for the period under consideration were relatively short. In order to assess the performance of the three strategies, 52 weekly simulations representing a total of one year were carried out for each of the three control strategies. The results of this assessment are presented in Section 10.6.

10.6 Fuzzy High Level Control Strategy Annual Energy Use and Environmental Zone Condition Provision

To compare the performances of the PID, fuzzy ventilation and fuzzy high level control strategies, 52 weekly simulations were run for a one year period using the fuzzy high level control strategy. The results were then compared to the yearly results for the PID and fuzzy ventilation control strategies as described in Chapter 9. With the exception of the control strategies themselves the dynamic Simulink models used for the simulation of each strategy were identical. The fuzzy high level control strategy was simulated for one year periods with South, East, North and West building main facade orientations.

10.6.1 Fuzzy High Level Control Strategy Annual Energy Use

The one year simulation energy use summaries for each of the three control strategies are given in Table 10.3 and are shown graphically in Figure 10.26. A weekly breakdown of the simulation results are given in Appendix C.

In the following text the control strategies are designated as follows:-

Strategy 1 - normal PID controller operation
Strategy 2 - fuzzy ventilation control
Strategy 3 - fuzzy high level (supervisory) control

Strategy / Orientation	Annual Energy Use (kWh)			
	Heating	Cooling	Humidification	Total
South Strategy 1	1579	3010	95	4684
South Strategy 2	2245	1519	171	3935
South Strategy 3	1633	1930	172	3735
North Strategy 1	1980	2587	81	4648
North Strategy 2	2661	1324	89	4074
North Strategy 3	1988	1833	88	3909
East Strategy 1	1842	2627	84	4552
East Strategy 2	2551	1331	97	3979
East Strategy 3	1874	1750	98	3722
West Strategy 1	1792	2872	86	4749
West Strategy 2	2475	1489	117	4080
West Strategy 3	1814	1940	118	3872

Table 10.3. Annual energy use summary for the PID, fuzzy ventilation and fuzzy high level control strategy simulations.

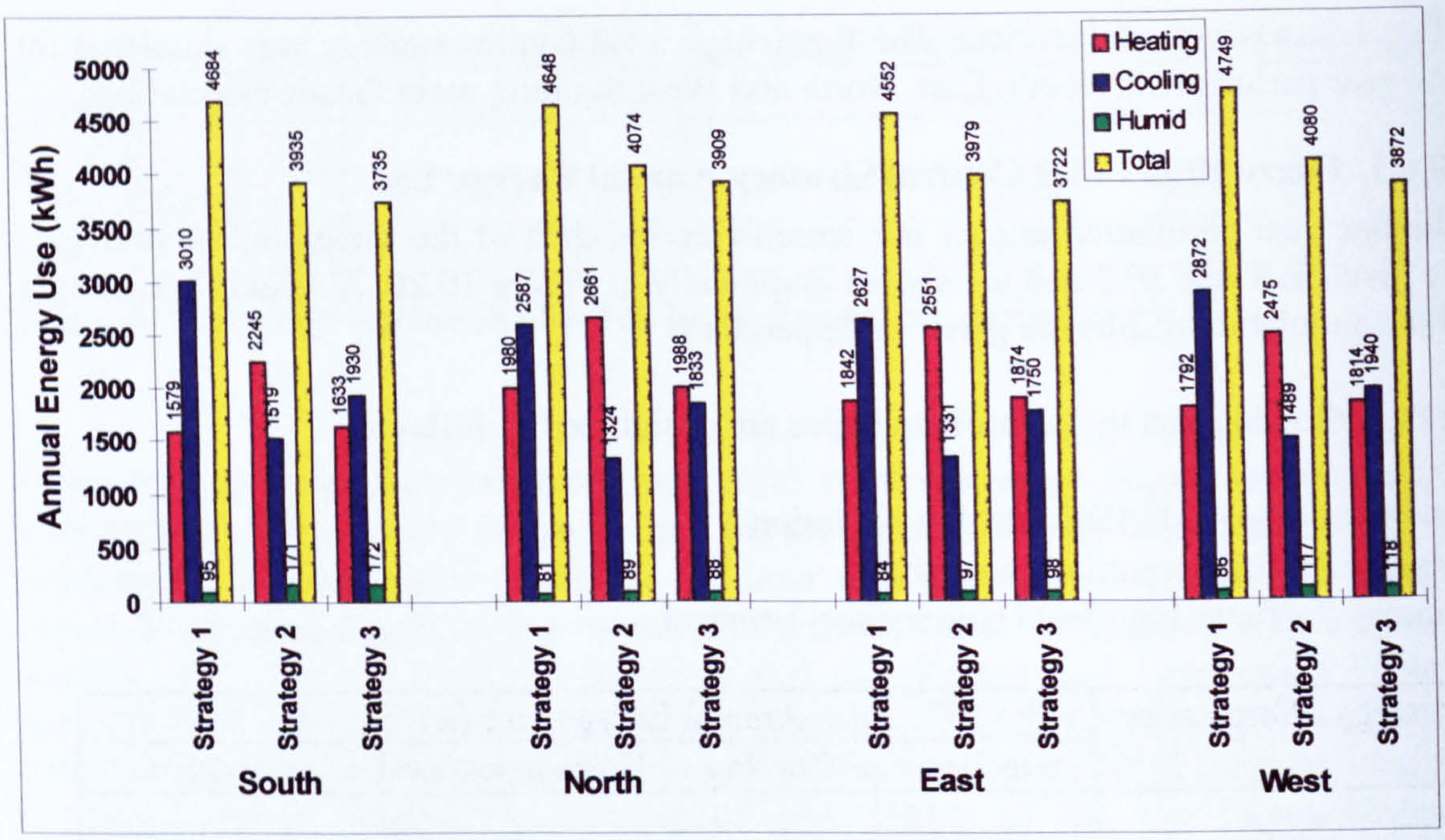

Figure 10.26. Annual energy use summary for the PID, fuzzy ventilation and fuzzy high level control strategies simulations.

Table 10.3 and Figure 10.26 clearly show that the annual total energy use decreases from strategy 1 through to strategy 3. Annual energy use as a percentage of strategy 1 energy use is given in Table 10.4.

Strategy / Orientation	Energy Use as % of Strategy 1
South Strategy 1	100.00
South Strategy 2	84.01
South Strategy 3	79.73
North Strategy 1	100.00
North Strategy 2	87.65
North Strategy 3	84.10
East Strategy 1	100.00
East Strategy 2	87.41
East Strategy 3	81.76
West Strategy 1	100.00
West Strategy 2	85.91
West Strategy 3	81.53

Table 10.4. Annual energy use by strategy as a percentage of strategy 1 energy use.

The mean annual energy consumption as a percentage of the PID control strategy for the fuzzy ventilation and fuzzy high level control strategies (all orientations) were 86.24% and 81.78% respectively.

However, the detailed breakdowns for energy use given in Appendix C reveal that strategy 3 does not always provide decreased energy consumption when compared with strategy 2 on a week by week basis. For weeks 20 - 42 inclusive (south main building facade orientation) the total energy use of strategy 3 is greater than for strategy 2. This observation is also generally valid for the other orientations. Closer analysis of the simulation results revealed that this was due to the fuzzy supervisor suppressing the desired re-circulation damper position values for the fuzzy ventilation cooling controller and hence not realising the full free cooling potential available. This can be attributed to the fuzzy high level control strategy being designed for mid-season conditions where both humidity and temperature conditions cause fuzzy ventilation controller conflicts of interest. This suggests that using strategy 3 only during the winter and mid-seasons could improve annual energy consumption further. Annual energy using this revised strategy, i.e. strategy 2 for weeks 20 - 42 inclusive (south orientation), while using Strategy 3 for the remaining weeks of the year, is 3516 kWh, i.e. 75.06% of strategy 1 annual energy use, c.f. 84.01% and 79.73% for solely strategy 2 and strategy 3 control strategies respectively.

10.6.2 Fuzzy High Level Control Strategy Environmental Zone Condition Provision Performance

To further assess the performance of the control strategies a quantitative measure of the environmental conditions within the occupied space were calculated during the periods when the HVAC plant was operational, i.e. 05:00 - 17:00:-

1. **zone temperature and humidity** - strategies 2 and 3 aim to converge the environmental conditions towards the preferred set points, i.e. the middle set points. The quantitative measures calculated were the mean weekly and annual absolute errors from the preferred set points. The analysis method and detailed results are given in Appendix D with annual summaries given in Table 10.5 and shown graphically in Figure 10.27 and Figure 10.28.
2. **zone carbon dioxide concentration** - control strategies 1, 2 and 3 consider 1000 ppm to be the threshold that the CO_2 concentration should not exceed. However, strategies 2 and 3 inherently improve the indoor air quality due to the increased fresh air ventilation rate associated with using increased fresh air ventilation rates for cooling and dehumidification. In order to assess this parameter quantitatively the mean of the CO_2 concentrations during the periods when the HVAC plant was operational was calculated, see Appendix D for detailed weekly results and Table 10.6. for annual averages. Annual averages for the CO_2 concentrations are shown graphically in Figure 10.29.

Orientation	Annual Mean Absolute Error from Preferred Set Point					
	Temp 1	Temp 2	Temp 3	RH 1	RH 2	RH 3
South Mean	1.91	1.73	1.67	10.30	8.67	9.94
North Mean	1.91	1.81	1.75	11.13	8.82	10.44
East Mean	1.92	1.80	1.74	10.79	8.67	10.11
West Mean	1.95	1.80	1.74	10.66	8.66	10.14
Average	1.92	1.78	1.72	10.72	8.71	10.23

Table 10.5. Annual mean zone temperature and relative humidity absolute error from preferred set point during periods when the HVAC plant was operational (1 = Strategy 1, 2 = Strategy 2, 3 = Strategy 3).

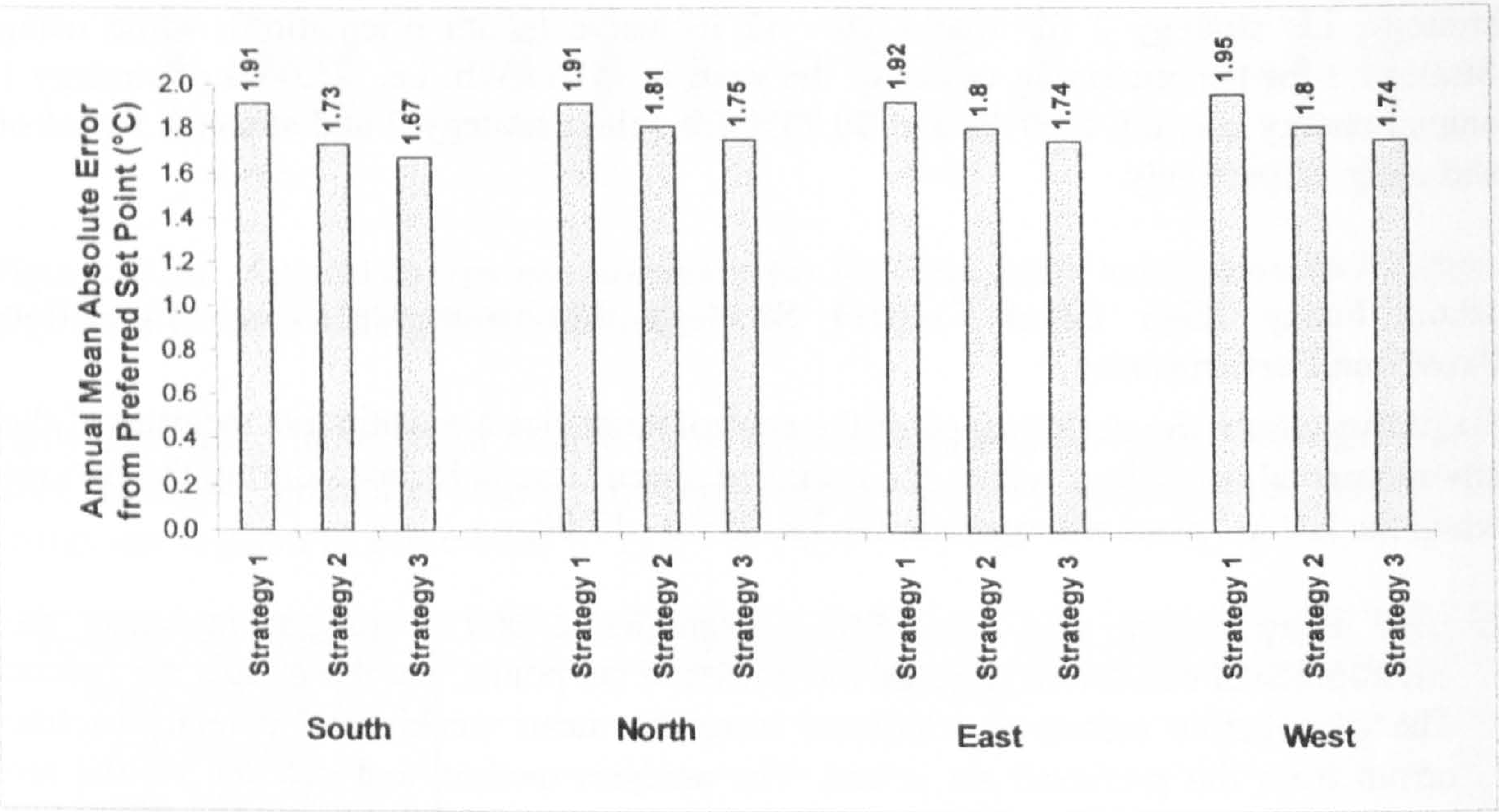

Figure 10.27. Annual mean zone temperature absolute error from preferred set point during periods when the HVAC plant was operational.

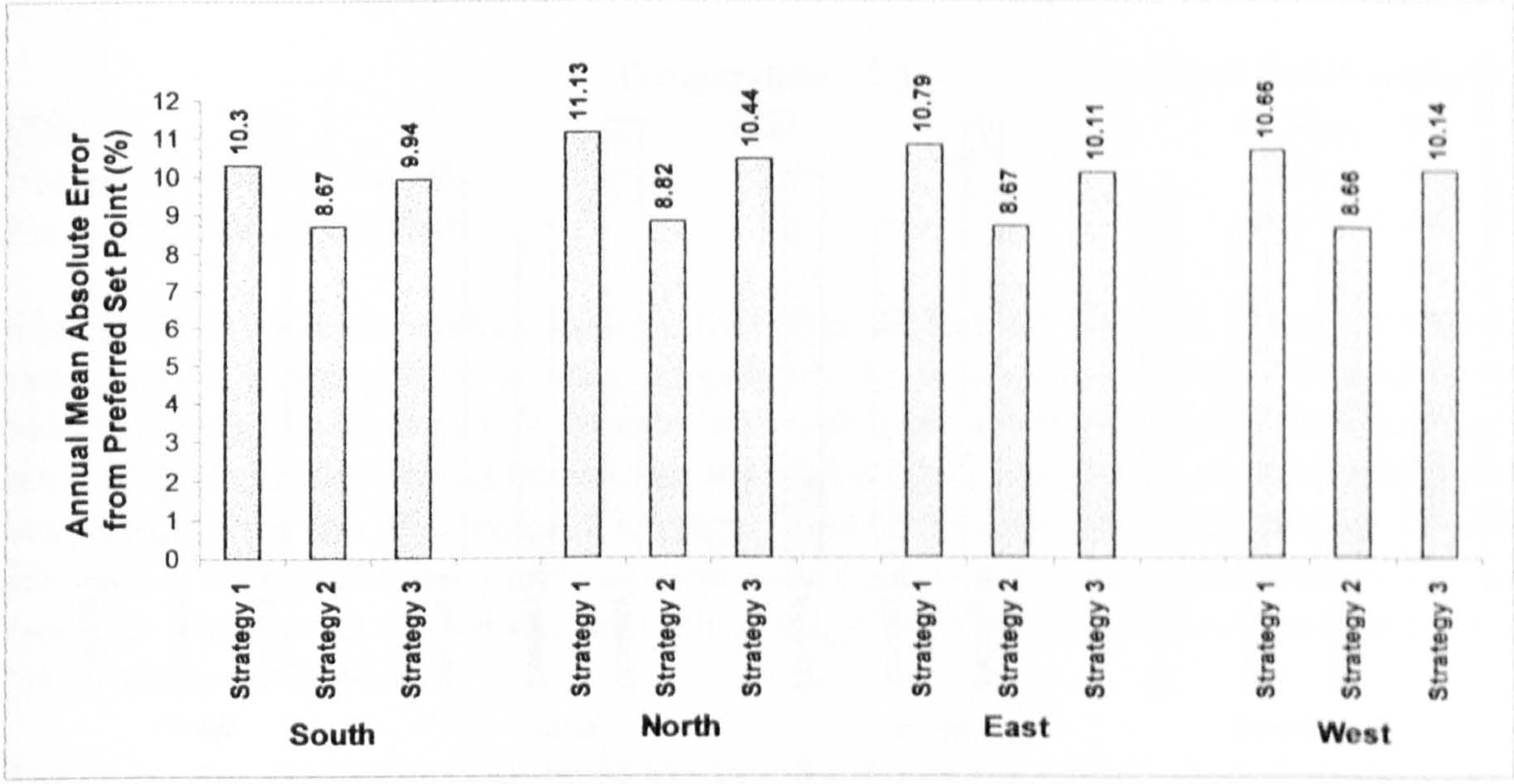

Figure 10.28. Annual mean zone relative humidity absolute error from preferred set point during periods when the HVAC plant was operational.

The mean absolute error for the zone temperature indicates that the temperature was controlled closer to the preferred set point for strategy 2 than for strategy 1. Further, strategy 3 had a mean absolute error that indicates the temperature is closer to the preferred set point than strategies 1 and 2. However, the mean absolute error for the zone relative humidity was best for strategy 2 with strategies 1 and 3 being similar. This was due to the energy considerations implemented by the strategy 3 high level fuzzy supervisor regarding dehumidification. In effect, the fuzzy supervisor has prioritised energy efficiency over relative humidity provision. The controller decided that the benefits to be gained from a slight improvement in relative humidity through fuzzy ventilation dehumidification was not prudent in the light of the imposed energy penalty. This should be considered in light of the energy consumption when comparing strategies 2 and 3, see Table 10.4.

Orientation	Mean Zone Carbon Dioxide Concentration		
	CO_2 1	CO_2 2	CO_2 3
South	901	681	769
North	901	692	797
East	901	688	786
West	901	687	785

Table 10.6. Annual mean zone carbon dioxide concentration during periods when the HVAC plant was operational (1 = Strategy 1, 2 = Strategy 2, 3 = Strategy 3).

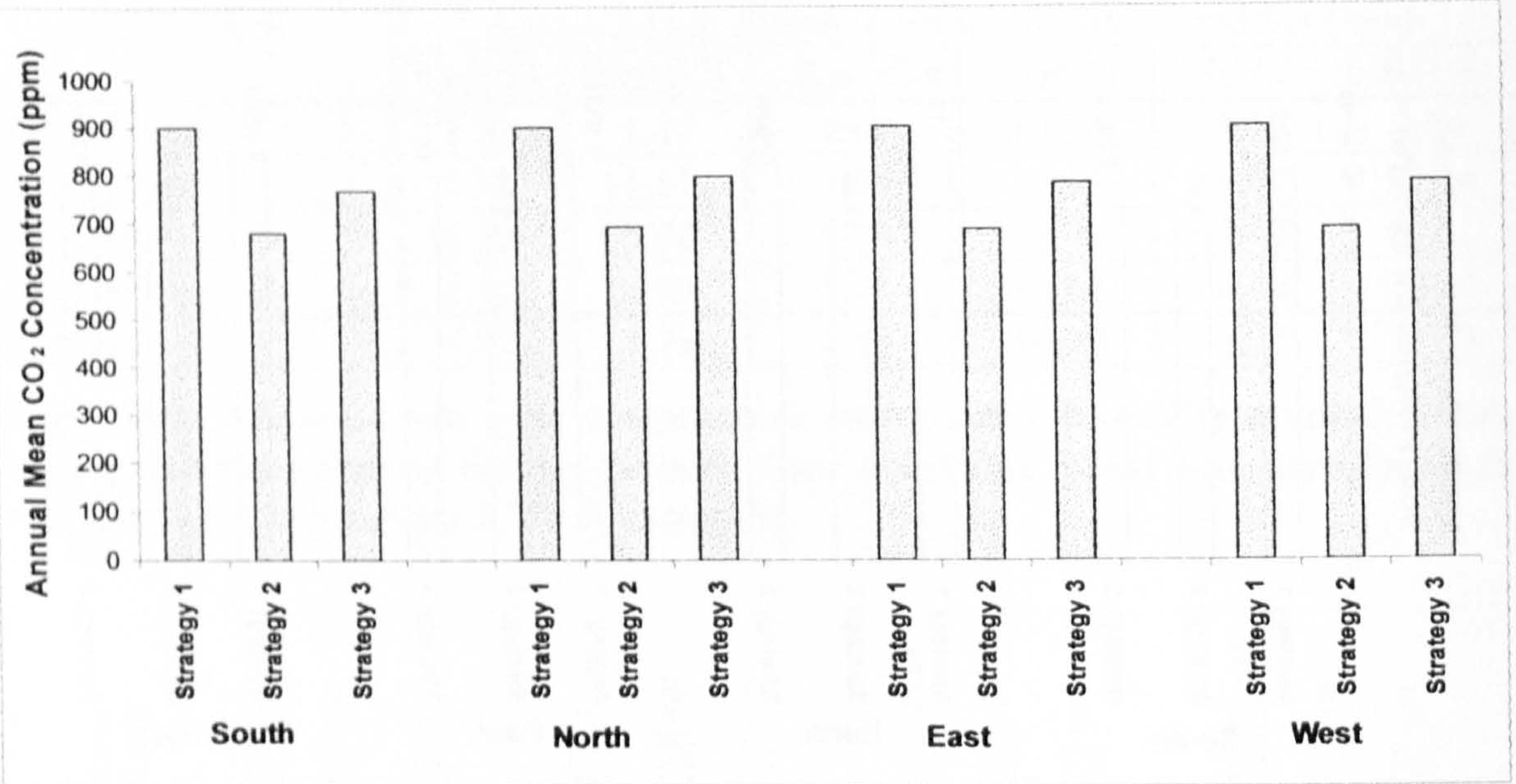

Figure 10.29. Annual mean zone carbon dioxide concentration during periods when the HVAC plant was operational.

Both strategies 2 and 3 provide improved air quality when compared to strategy 1 on an annually averaged basis. Strategy 2 provides the lowest mean CO_2 concentration. Again the strategy 3 CO_2 concentration was higher than for strategy 2 due to the energy considerations taken into account by the fuzzy high level controller.
Overall, the fuzzy high level control strategy indicates preferable performance results in terms of comfort provision, energy efficiency and cost efficiency simultaneously.

10.7 Conclusions and Discussion

This chapter considered the development and the simulation results of the fuzzy high level control strategy which used a fuzzy supervisor to improve the energy and environmental condition performance of the fuzzy ventilation control strategies. The fuzzy supervisor, an integral component of the fuzzy high level controller, made use of the fuzzy reasoning capabilities of fuzzy logic. The fuzzy supervisor used the inputs of zone temperature, relative humidity and CO_2 concentration to decide whether it was prudent to carry out the actions desired by the fuzzy ventilation control strategies. When the fuzzy supervisor considered the desired action of the fuzzy ventilation controllers not to be in the overall interests of energy efficiency and environmental comfort provision the desired re-circulation air damper position of the component in question was suppressed.

The mean annual energy consumption as a percentage of the PID control strategy for the fuzzy ventilation and fuzzy high level control strategies (all orientations) were 86.24% and 81.78% respectively. The average of the annual mean absolute errors from the preferred set points (all orientations) for the zone temperature and relative humidity conditions provided were as follows:-

	Temperature (^{o}C)	Relative Humidity (%)
PID:	1.92	10.72
Fuzzy Ventilation Control:	1.78	8.71
Fuzzy High Level Control:	1.72	10.23

The fuzzy high level control strategy therefore performed better in terms of energy consumption and provision of zone temperature when compared to the PID and fuzzy ventilation control strategies. In terms of zone relative humidity provision the fuzzy high level control strategy did not perform as well as the fuzzy ventilation control strategy but was better than the PID control strategy. Simulations therefore indicate an overall increase in energy efficiency and environmental condition provision performance for the one year simulations carried out for each strategy when all performance parameters are taken into consideration.

However, the simulations did highlight that the fuzzy high level control strategy was mainly beneficial in terms of energy efficiency and comfort provision during the mid-seasons and the winter. The energy performance of the fuzzy high level control strategy during the weeks 20 - 42 for the annual simulations generally indicated a worse energy and environmental comfort provision performance than for the fuzzy ventilation strategies operating independently with no supervisory control. This was due to the fuzzy high level control strategy being primarily designed for the winter and mid-seasons. During the summer months the suppression of the fuzzy ventilation cooling controller desired re-circulation damper position meant that more HVAC plant cooling was required than was necessary. Using the fuzzy ventilation control strategies for the weeks 20 - 42 inclusive and the fuzzy high level control strategy for the remainder of the year was identified in Section 10.6.1 as a control methodology for improving the annual energy and environmental comfort provision further.

This chapter has described a control system which takes advantage of the capabilities of fuzzy logic to deal with a multi-variant input / output control system. The simulation results indicate that improved control of the HVAC plant can be achieved when compared to normal PID control and fuzzy ventilation control. It is probable that further improvements to the control system could be implemented with regard to the fuzzy supervisor. A fuzzy supervisor with the two additional inputs of ambient temperature and moisture content would allow scope for further improvement in the fuzzy high level control strategy. However, this would increase the complexity of the control system further and represents an area suitable for further research.

11. Conclusions and Recommendations

11.1 Introduction

The research project described in this thesis aimed to improve control techniques and hence provide improved comfort and health conditions while improving building services energy and cost efficiencies.

The first objective of the research project was to determine the limits and ranges of the environmental parameters which characterised high quality internal environments. Defining a "quality internal environment" enabled the objectives of providing energy and cost efficient environments to be achieved within this constraint. The environmental conditions provided within buildings were identified as a major influence on the productivities of occupants. Improvements in building occupant comfort and hence productivity were thus identified as an objective of the research project.. However, the dependence of energy and cost efficiencies on the provision of occupant comfort were influences that were taken into consideration.

The second objective was to utilise fuzzy building services control strategies to provide a "quality internal environment" while maintaining or improving energy and cost efficiencies. Fuzzy logic control strategies were identified as a method of improving building services performance within air-conditioned and mechanically ventilated buildings. Fuzzy logic lent itself to the control of the multiple parameters affecting the provision of comfortable internal environments without compromising energy and cost efficiencies.

This chapter, Conclusions and Recommendations, brings together the main conclusions of the research project and considers potential areas for further investigation.

11.2 Building Occupant Comfort

Chapter 2 described the findings of the literature review carried out into building occupant comfort. The aim of the occupant comfort literature review was to identify and define the important parameter ranges, limits and interactions that provide building occupants with their perception of a comfortable environment. This provided a basis for developing the fuzzy control strategies for the control of internal environmental conditions and assessing any improvements in provided comfort, energy and cost efficiencies.

The environmental parameters of temperature, humidity and air quality were identified as the main influences on occupant comfort that were suitable for control purposes. The decision was made on the basis of the literature review not to consider the environmental parameters which were not totally controllable by the building services control system. Such parameters included noise, air velocity and lighting. Air temperature and relative humidity were chosen as being representative of occupants' thermal comfort and CO_2 concentrations were chosen as being representative of occupants' satisfaction with air quality provision. These environmental parameters also have the advantage that sensors for their measurement are relatively inexpensive, reasonably accurate over pro-longed periods of time and readily available. This would be important with regard to implementation of the developed control strategies within real buildings.

The literature review also identified two main approaches to considering comfort within buildings. These were the steady state and adaptive approaches. It was decided to adopt an approach where the controlled environmental parameters selected were allowed to drift between upper and lower set point limits analogous to the adaptive approach. This assumes that occupants will take actions, such as the addition or removal of clothing, within certain limits to correct slight feelings of discomfort. Simultaneously, a preferred set point was defined between the upper and lower set points based on calculations using the steady state PMV method to define preferential controlled zone parameter values. Thus a combination of the adaptive and steady state approaches was taken. For the purposes of developing the fuzzy control strategies described in Chapters 9 and 10 the set points were set at the following values.

Temperature:	20°C lower	24°C upper	22°C preferred
Relative Humidity:	30% lower	60% upper	45% preferred

Although the adaptive approach is generally recognised as being a suitable approach to the provision of comfort in naturally ventilated buildings scope still exists for its use when applied to air-conditioned buildings. However, the opportunities for adaptation are generally less within air-conditioned buildings because occupants have less control. This was reflected in the definition of the upper and lower set point limits.

11.3 Fuzzy Logic and Fuzzy Control

The research project identified fuzzy logic as a useful control method for dealing with multi-variant problems. Chapter 3 introduced the reader to a brief history of the use of fuzzy logic and its application as a control technique particularly within the field of building HVAC services control. The review of previous applications of fuzzy logic to the control of building services components suggested that fuzzy logic was capable of providing control techniques which are often simpler to implement than conventional control systems and sometimes capable of providing superior control. Where a lack of knowledge regarding system behaviour exists, the literature review identified solutions using fuzzy logic as possibilities where conventional control techniques were not suitable.

A building services control strategy that satisfied the objectives of the research project required the consideration of indoor environmental quality, energy efficiency and cost efficiency simultaneously. The literature review carried out into fuzzy logic suggested that a fuzzy control system would be capable of dealing with such a multivariant requirement.

The theory of fuzzy logic and fuzzy control was described Chapter 4. Fuzzy logic is able to handle the concept of partial truth values which lie between completely true and completely false in a similar way to human thought processes. This provided the possibility of constructing fuzzy controllers which incorporated human expert knowledge and hence the solution of the control objectives of the research project using an easily understood methodology.

An advantage possessed by fuzzy controllers was considered to be their ability to deal with multi-input and multi-output parameter systems. Control of indoor environmental quality while providing energy and cost efficiency with respect to the operation of HVAC building services equipment represents a multi-variant problem that does not have a simple "best solution" answer. The development of a computer model to assess the usefulness of applying fuzzy control to such a multi-variant problem represented a sensible platform for research into this area. Matlab and Simulink software were used to construct this model. Thermal, moisture (relative humidity) and air quality parameters were taken as the inputs to a fuzzy controller. The outputs considered were heating, cooling, humidification, dehumidification and fresh air ventilation rates. Complex interactions exist between these parameters. Conventional control algorithms would have been more difficult to implement for this multi-variant problem.

11.4 Simulink One Zone Building Model

A one zone building computer model was developed using Matlab and Simulink software. The "free running" and "HVAC components" theory of this model were described in Chapters 5 and 6 respectively. The model's suitability as a platform for developing fuzzy control strategies was assessed by comparing the "free running" part of the model to an identical model constructed using Thermal Analysis Software (Tas). The Simulink model made similar predictions for a range of parameters and varying environmental conditions when compared to the Tas model. The Simulink model did not perform as well as was anticipated in terms of its predictions of relative humidity. However, this can be largely attributed to a summing of errors as the relative humidity uses air temperature in its calculation process. For the purposes of developing the fuzzy control strategies it was decided that the model performed adequately. The comparison of the "free running" Simulink model with the Tas model was carried out to ensure that the Simulink model was giving reasonable answers. The intention was to use the base Simulink model as a comparative tool to assess the performance of different control strategies. To this end the developed Simulink model accuracy was sufficient as any errors were applicable to each of the different control strategies being compared.

Chapter 6 described the theory of the HVAC system components models which were integrated with the "free running" one zone building model. The HVAC component models described included heat exchangers, valves and dampers. Proportional + Integral + Derivative (PID) controls models were also described and were used as benchmark control strategies to compare against the performance of the fuzzy controllers developed in Chapters 8, 9 and 10. It was not possible to assess the performance of the developed HVAC components and PID controls models against validated systems models as no comparable models were available. Instead, the developed Simulink HVAC models were assessed by observing their characteristic performances and judging whether they performed adequately on a qualitative basis using knowledge of how the components were expected to perform. Any small inaccuracies in the performance characteristics of the simulink HVAC components models were unimportant in the context of the research project as the model was used as a comparative tool.

11.5 Fuzzy Controller Development

Chapter 7 introduced the reader to the development methodology and the objectives of the three fuzzy control strategies explored during the research project, i.e. Proportional Derivative Fuzzy Control (PDFC), Fuzzy Ventilation Control and Fuzzy High Level Control. Each of the control strategies was compared to the PID control strategy which was considered as a benchmark control strategy. Conclusions with regard to each of the fuzzy control strategies are given in the following sections.

11.5.1 Proportional Derivative Fuzzy Control (PDFC)

The PDFC controller was constructed with the aim of producing a controller with similar characteristics to a PID controller. The structures of the PDFC controllers used to control each of the environmental parameters via the HVAC plant were the same. Individual PDFC controllers were tuned using gain factors to ensure that they were suitable for the control of specific plant components. This provided a basis for constructing the fuzzy ventilation controllers and the fuzzy high level controller.

The use of gain factors as a method of tuning the PDFCs proved useful and reduced the amount of time taken for controller tuning compared to a method where the actual membership functions are modified for this purpose. From a practical view point, the PDFCs were more time consuming to tune using the iterative technique of adjusting the gain factors than using the Zeigler Nichols continuous cycling tuning method for the PID controllers. This could represent a major disadvantage for real PDFC control system implementation in real buildings where the tuning has to be carried out in real time. However, PDFCs provide an easy to understand control methodology based on human operator knowledge and common sense. This can make the understanding of the PDFC control methodology more attractive to the non engineer as an understanding of the control methodology can be quickly acquired.

The comparison between the PDFC and PID control strategies suggested that there was only a small difference between the performances of the two control strategies. For the compared 7 day simulation periods for each month of one year the PDFC strategy required slightly more energy than the PID strategy (1.02%). However, PID control strategy zone temperature and relative humidity conditions were outside the desired set point limits for a greater percentage of the simulated time than for the PDFC strategy by 3.3% and 0.79% respectively. From these results it was concluded that a superior overall performance cannot be conclusively attributed to either control strategy. However, the PDFCs did exhibit a better control characteristic, i.e. less overshoot, for the humidification, dehumidification and air quality controllers.

Overall, the PDFC and PID control methods were shown to be capable of comparative performances during the simulations. The modelling carried out during the research project indicated that fuzzy control was capable of replacing conventional controllers, but fuzzy logic has far more to offer. The fuzzy decision making capabilities of fuzzy controllers enable multi-variant control problems to be dealt with. Chapters 9 and 10 investigated the use of these capabilities to take advantage of the possibilities offered by fuzzy control.

11.5.2 Fuzzy Ventilation Control

Chapter 9 described the development and use of fuzzy ventilation control strategies for ambient cooling and dehumidification purposes. A combination of the adaptive and steady state approaches to thermal comfort were taken to define the set point ranges and preferred set points. Upper and lower set points were defined such that combinations of zone temperature and humidity would not cause a Predicted Percentage Dissatisfied (PPD) value of greater than 10% using the steady state approach. The temperature and relative humidity ranges defined using this criterion were 20°C - 24°C and 30% - 60% respectively. When the zone conditions drifted beyond these ranges the HVAC plant was used to bring the conditions to within the range. Preferred set points of 22°C and 45% RH were also defined and represented a PPD of 5% where both conditions were satisfied simultaneously. The fuzzy ventilation controllers attempted to converge the zone conditions towards these preferred set points when possible using free cooling and dehumidification through the use of the fresh air re-circulation damper.

Simulations were carried out for a one year period for the fuzzy ventilation and PID control strategies for South, North, East and West main building facade orientations. The simulations showed that the fuzzy ventilation control strategy used an average of 86.24% of the energy consumed by the PID control strategy. Further, comparisons between the two control strategies showed that the average of the mean annual absolute errors from the preferred set point for the South, North, East and West building orientations were as follows:-

	Temperature (°C)	Relative Humidity (%)
PID:	1.92	10.72
Fuzzy Ventilation Control:	1.78	8.71

Overall, the yearly assessment of the fuzzy ventilation control strategies therefore showed a reduction in energy consumption and an overall improvement in the environmental conditions provided.

However, the fuzzy ventilation dehumidification strategy sometimes led to an increased requirement for heating energy use due to the introduction of greater quantities of colder fresh air during some simulated weeks of the year. Scope therefore existed to improve the fuzzy ventilation control strategy. It was thought that supervision of the actions of the fuzzy ventilation controllers could lead to further improvements in their performance by suppressing their control actions where they were likely to cause detriment to the overall objectives, including energy efficiency, of using the fuzzy ventilation controllers. The use of a high level fuzzy supervisor to improve the fuzzy ventilation control strategy was investigated as a result.

11.5.3 Fuzzy High Level Control

Chapter 10 considered the development and the simulation results of the fuzzy high level control strategy which used a fuzzy supervisor to improve the energy and environmental condition performance of the fuzzy ventilation control strategies. The fuzzy supervisor, an integral component of the fuzzy high level controller, made use of the fuzzy reasoning capabilities of fuzzy logic. The fuzzy supervisor used the inputs of zone temperature, relative humidity and CO_2 concentration to decide whether it was prudent to carry out the actions desired by the fuzzy ventilation control strategies. When the fuzzy supervisor considered the desired action of the fuzzy ventilation controllers not to be in the overall interests of energy efficiency and environmental comfort provision the desired re-circulation air damper position of the component in question was suppressed.

The mean annual energy consumption as a percentage of the PID control strategy for the fuzzy ventilation and fuzzy high level control strategies (all orientations) were 86.24% and 81.78% respectively. Considering the PID, fuzzy ventilation control and fuzzy high level control strategies simultaneously the following energy uses as a percentage of the PID strategy were obtained from the simulation results.

	Annual Energy Use (all orientations) as a % of the PID Control Strategy
PID:	100
Fuzzy Ventilation Control:	86.24
Fuzzy High Level Control:	81.78

The average of the annual mean absolute errors from the preferred set points (all orientations) for the zone temperature and relative humidity conditions provided were as follows:-

	Temperature (°C)	Relative Humidity (%)
PID:	1.92	10.72
Fuzzy Ventilation Control:	1.78	8.71
Fuzzy High Level Control:	1.72	10.23

The fuzzy high level control strategy therefore performed better in terms of energy consumption and provision of zone temperature when compared to the PID and fuzzy ventilation control strategies. In terms of zone relative humidity provision the fuzzy high level control strategy did not perform as well as the fuzzy ventilation control strategy but was better than the PID control strategy. Simulations therefore indicate an overall increase in energy efficiency and environmental condition provision performance for the one year simulations carried out for each strategy when all performance parameters are taken into consideration simultaneously.

The overall objective of the research project was to investigate the use of fuzzy control strategies with the aim of improving the environmental comfort provided for occupants while simultaneously improving energy and cost efficiencies. The simulation results indicate overall improvements in energy efficiency and comfort provision for the fuzzy control strategies developed. In theory, the improvements in these two aspects of the provided environment would suggest improvements in cost efficiency, i.e. the expenditure on energy relative to the comfort provided for occupants.

However, the simulations did highlight that the fuzzy high level control strategy was mainly beneficial in terms of energy efficiency and comfort provision during the mid-seasons and the winter. The energy performance of the fuzzy high level control strategy during the weeks 20 - 42 for the annual simulations generally indicated a worse energy and environmental comfort provision performance than for the fuzzy ventilation strategies operating independently with no supervisory control. This was due to the fuzzy high level control strategy being primarily designed for the winter and mid-seasons. During the summer months the suppression of the fuzzy ventilation cooling controller desired re-circulation damper position meant that more HVAC plant cooling was required than was necessary. Using the fuzzy ventilation control strategies for the weeks 20 - 42 inclusive and the fuzzy high level control strategy for the remainder of the year was identified as a control methodology for improving the annual energy and environmental comfort provision further.

11.6 Recommendations for Further Research

During the research project areas were identified that are worthy of further research. These are described in the following sections.

11.6.1 Definition of Controlled Parameter Set Points

The controlled parameter upper, lower and preferred set points defined for use with the fuzzy control strategies developed during the research project were based on Predicted Percentage Dissatisfied (PPD) criteria. The assumption underlying the adaptive approach to thermal comfort that occupants would take actions to improve their comfort within certain limits was also applied. However, the set points defined for use with the fuzzy controllers remained static throughout the year. Scope therefore exists to increase energy efficiency further while maintaining comfort conditions by varying these set points throughout the year.

11.6.2 Fuzzy Controller Tuning

The fuzzy controllers developed during the research project relied on the manual tuning of input and output gain factors to ensure that the controllers work correctly. This can be time consuming and requires an iterative process of adjustment and testing within the simulation environment. With respect to real systems this would represent a problem in terms of commissioning. Methods of tuning the fuzzy controllers by automatic adjustment of the gain factors or the adjustment of the control rules and membership functions within the controller would represent an improvement in this respect. The use of fuzzy gain scheduling techniques or neural networks are possible methods for achieving these objectives.

11.6.3 Fuzzy High Level Controller with Additional inputs

The fuzzy supervisor within the fuzzy high level controller used the inputs of zone temperature, relative humidity and CO_2 concentration to make decisions on the actions of the fuzzy ventilation controllers. A fuzzy supervisor with the two additional inputs of ambient temperature and moisture content would provide the fuzzy supervisor with an increased amount of information and allow scope for further improvements in the performance of the fuzzy ventilation control strategy. However, this would increase the complexity of the control system due to the increase in the number of control rules required and was not explored in the scope of the research project. However it does represent an area worthy of further research.

Appendix A :

An Assessment of Air Quality and Ventilation Rates in School Classrooms - Part I: Air Quality Monitoring

This appendix is a copy of a paper accepted for publication in the Building Services Engineering Research and Technology journal.

An Assessment of Air Quality and Ventilation Rates in School Classrooms - Part I: Air Quality Monitoring

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Summary

Described are the findings of indoor air quality monitoring carried out at two Essex schools located on the same site. Monitoring was carried out during the week 3 - 7 November 1997. The objective of the monitoring was to assess the indoor air quality within the schools and determine whether the ventilation rates within the buildings were adequate to provide acceptable air quality to the occupants. The quality of the indoor air was assessed by determining airborne carbon dioxide concentrations using continuous infra-red detectors. A class base in each school was monitored for a two day period. Observations of occupancy patterns and window/door opening were made during the first day of each of the two day monitoring periods. Air temperature was also recorded during each of the monitoring periods in each school.

Indoor carbon dioxide levels recorded indicated that concentrations exceeded those recommended for acceptable indoor air quality for a large percentage of the occupied period. Analysis of the results also indicated that fresh air ventilation rates were below recommended guidelines.

The monitoring over short time periods (2 days) allowed a "snapshot" of the air quality conditions occurring within the school classrooms. Hence, analysis of airflow between spaces and subjective human responses were not considered during this investigation. The main objective of the monitoring was to assess air quality in densely occupied classrooms with regard to commonly used evaluation criteria for carbon dioxide within the spaces on the randomly chosen days and to indicate the ventilation rates occurring.

This air quality assessment project is presented in two papers:

Part I: Air Quality Monitoring(1)*. This paper considers the recorded carbon dioxide concentrations measured over the monitoring period in the schools in terms of provided air quality and ventilation rates.*

***Part II: Computer Modelling.** This companion paper calculates the metabolic carbon dioxide production rates of the occupants and uses the ventilation rates calculated in Part I to model the recorded CO_2 levels from the monitoring period. The model is further used to estimate the required ventilation rates in order that air quality is perceived as being acceptable to occupants.*

1. Introduction

Building designers aim to create buildings which provide high quality and energy efficient internal environments. Failure to attain these objectives can lead to poor quality internal environments in which the productivity of the building occupants is reduced and the under performance of the building results. In more extreme cases the ill health of building occupants both in the short and long terms may result. Extensive research has been carried out into thermal comfort within the internal environment(2). More recently air quality is receiving greater recognition as one of the important contributors to overall indoor environmental quality and comfort.

A range of guidelines have been in place for a number of years regarding indoor air quality. Those of the Chartered Institution of Building Services Engineers(3) (CIBSE) recommend a minimum fresh air supply rate of 8 l/s/p (litres per second per person) for non-smoking adults in offices and 8.3 l/s/p for occupants of schools. The Department for Education and Employment(4) (DFEE) recommends a minimum background fresh air supply rate of 3 l/s/p for all areas of schools. The DFEE guidelines further recommend that "all teaching accommodation, medical examination or treatment rooms, sick rooms, isolation rooms, sleeping and living accommodation shall also be capable of being ventilated at a minimum rate of 8 litres of fresh air per second for each of the usual number of people in those areas when such areas are occupied". The American Society of Heating, Refrigerating and Air-Conditioning

Engineers$^{(5)}$ (ASHRAE) recommends fresh air supply rates of 10 l/s/p and 8 l/s/p for general office accommodation and school classrooms respectively.

The terms "fresh air" or "outdoor air" are stated within these standards and guidelines as a basis for prescribing ventilation rates. However, caution should be taken with regard to the quality of outdoor or fresh air as it may not be as "fresh" as may have been assumed. Therefore, replacing indoor air with air from outdoors may not always provide an adequate solution.

In office type and school environments, the supply of adequate fresh air supply rates and hence perceived acceptable air quality, should be high on the list of priorities. This will help to ensure comfortable working conditions as well as content and productive occupants. In these types of environment no individual pollutant may present in sufficient quantities to cause immediate adverse health effects. However, a mixture of pollutants may combine to cause adverse health effects or irritation to the occupant both in the short and long terms. Further, some pollutants, such as human bioeffluents, or body odour, which have no known adverse health effects, may cause occupants to become irritated or uncomfortable with their indoor environments.

In recent design projects for school buildings a concern for indoor air quality has caused the authors to question the usefulness of the guidelines quoted in Building Bulletin 87$^{(4)}$. As stated previously these recommend a background fresh air supply rate of 3 l/s/p with the capability to supply 8 l/s/p. The manner in which the guidelines are written are open to interpretation and introduce ambiguity as to exactly what ventilation rates are satisfactory. Further it is stated "The heating system shall be capable of maintaining the required room air temperature with the minimum background ventilation of 3 litres per second per person when the outside temperature is -1 °C". This would suggest that heating systems designed to the guidelines would not be capable of maintaining comfort temperatures if adequate ventilation were provided during cold weather conditions. The DFEE guidelines are often misinterpreted to mean that the fresh air ventilation rate of 3 l/s/p is adequate in all areas and under all circumstances.

Another problem is that many schools rely upon natural ventilation through the opening of windows. Windows are often not opened during winter months when the outside temperatures are low and it is therefore unlikely that desired fresh air ventilation rates can be achieved.

This report investigates the quality of the indoor air and the associated ventilation rates in two school classrooms in order to ascertain whether air quality guidelines are maintained. The schools considered were chosen due to their location near to the development site of a new school by the same local authority. They were not chosen because they were known to experience good air quality conditions nor because they were known to suffer from poor air quality. The monitoring periods were chosen at a predetermined date which was convenient for carrying out the monitoring, i.e. weather conditions not known. The monitoring was carried out in a non-disruptive manner with staff and students using the building in a normal way.

2. Indoor CO_2 Concentrations as an Indicator of Air Quality

A practical means of determining indoor air quality is to monitor the carbon dioxide concentrations of the air. This is suitable in buildings where humans are the main sources of air pollutants. Humans produce metabolic carbon dioxide as a product of respiration. Hence the concentration in enclosed spaces, such as buildings, increases when the rate of production is greater than the rate of removal from that space. Other pollutants, such as those from building materials and processes within the enclosed space, also represent pollutant sources. However, during this investigation human bioeffluents were the main pollutant source and so carbon dioxide was considered to be the best indication of pollutant accumulation. Although variations of concentration of carbon dioxide are not directly perceived by occupants at the levels usually found in indoor air it is considered a good indicator of the concentrations of other human pollutants and human bioeffluents which are sensed and considered as a nuisance$^{(6,7,8)}$.

Where the indoor carbon dioxide concentrations become high it is indicative that the ventilation rates to the space are inadequate to provide the necessary amount of fresh air to remove pollutants produced by humans. Indoor carbon dioxide concentrations and their associated quality ratings given by various organisations are listed in Table 1.

Table 1. Carbon dioxide concentrations in indoor air and associated quality ratings.

CO_2 Concentration (ppm)	Recommended Air Quality Rating
300 - 400	Typical background (atmospheric) concentrations(9)
800	BSRIA control level for acceptable indoor air quality(9)
1000 or less	Concentration of limited or no concern(10) (short term exposure)
1000	ASHRAE limit to satisfy comfort and odour criteria(5)
≈ 1000	20% Percentage People Dissatisfied Threshold(6)
3500	Recommended threshold to avoid adverse health effects(6)
5000	8 hour occupational exposure limit(3, 11)
6600 and above	Concentration of concern(10) (short term exposures)

It is not thought that the carbon dioxide concentrations normally experienced in buildings are harmful to health in the short term. Far higher concentrations are required before they have a metabolic influence on the human body, some examples of which are given in Table 2.

Table 2. Metabolic influences of carbon dioxide(7).

Carbon Dioxide Concentration (ppm)	Metabolic Influence
less than 8500	none
8500 - 10000	tidal flow of air through lungs increased
34000 +	respiratory system becomes more rapid
40000 - 45000	sweating occurs
50000	anxiety induced
500000	narcotic used in surgery during 19th Century

The Percentage of People Dissatisfied (PPD), i.e. the percentage of people in a given space that could be expected to be dissatisfied with the environmental conditions in question, increases as the indoor carbon dioxide concentration above ambient increases, see Figure 1.

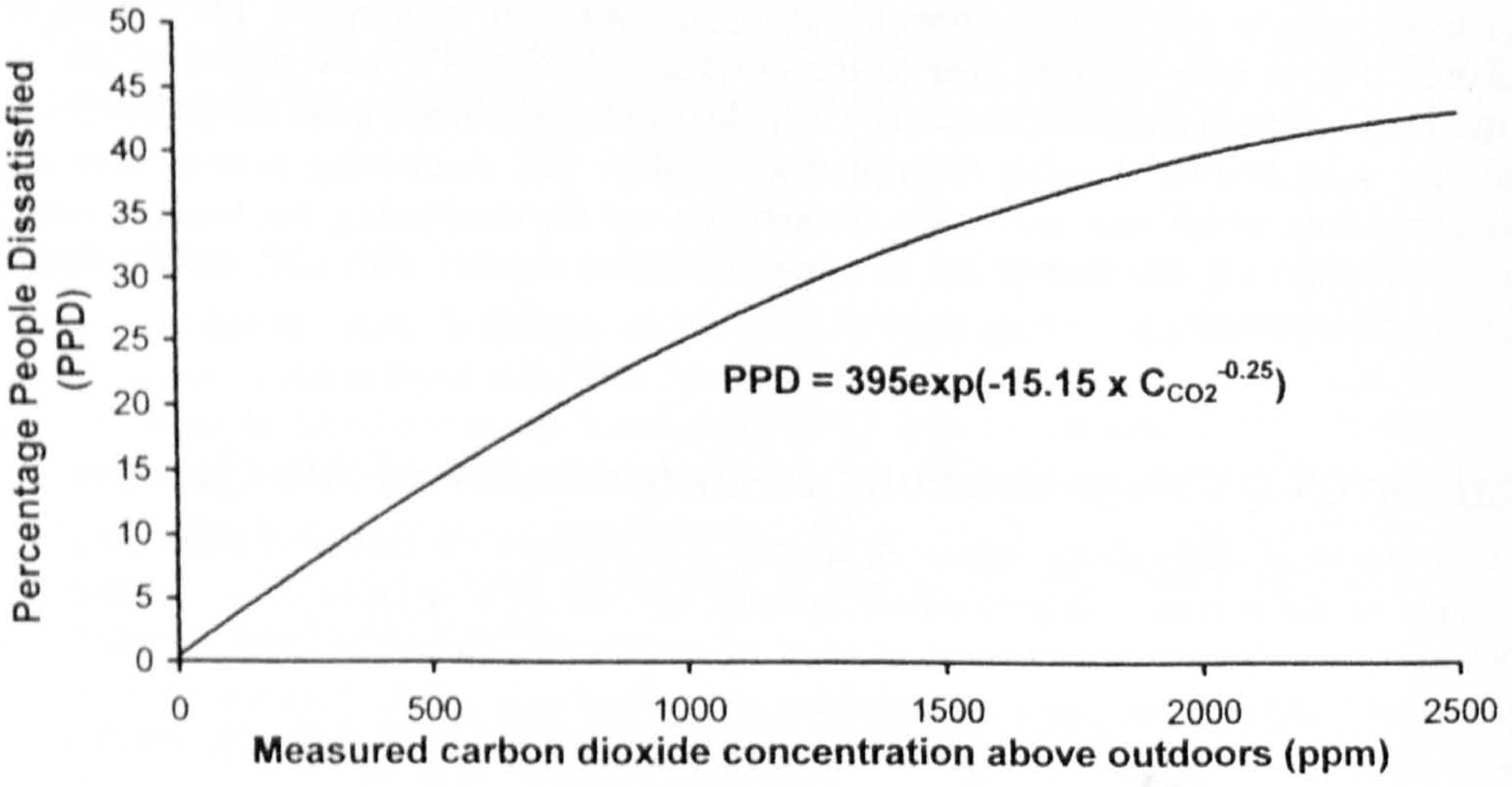

Figure 1. PPD as a function of indoor CO_2 concentration(6). (C_{CO2} = CO_2 concentration in ppm)

Figure 1 suggests that for an indoor carbon dioxide concentration of approximately 700 ppm above the outdoors concentration, 20% of the occupants will be dissatisfied with the indoor air quality. This corresponds to an absolute indoor carbon dioxide concentration of 1000 ppm assuming an outdoor concentration of 300 ppm. A maximum 20% PPD for occupants with regard to thermal comfort is the generally accepted level for temperature requirements in occupied buildings. It would therefore seem prudent to adopt a 20% PPD level with regard to indoor air quality.

3. Indoor Air Quality Monitoring in School Classrooms

Carbon dioxide concentrations were measured in each of the schools over a period of two days using Horiba (Model APBA-250E) continuous non-dispersive infra-red carbon dioxide monitors, see Table 3 for specifications.

Table 3. Horiba Model APBA-250E non-dispersive infra-red carbon dioxide monitor specifications.

Parameter	Specification
Range of measurement	0 - 3000 ppm
Repeatability	± 1.5% of full scale
Total Accuracy	± 10% of full scale / 3 months
Response Time	≤ 15 seconds (90% response to change at instrument inlet)
Operating temperature range	5 - 40 °C

The carbon dioxide monitors were calibrated using two calibration points, zero and 2500 ppm, using proprietary calibration gases to the manufacturers recommendations one day prior to the monitoring periods.

The monitoring over short time periods (2 days) allowed a "snapshot" of the air quality conditions occurring within the school classrooms. Hence, analysis of airflow between spaces and subjective human responses were not considered during this investigation. The main objective of the monitoring was to assess air quality in densely occupied classrooms with regard to commonly used evaluation criteria for carbon dioxide within the spaces on the randomly chosen days and to indicate the ventilation rates occurring.

On the first monitoring day in each school, details were noted regarding occupancy patterns and the degree to which windows were open. Two carbon dioxide monitors were used in each monitored area in order to give an indication of the air mixing efficiency. For the purposes of this report the schools are referred to as shown in Table 4.

Table 4. School designations and brief descriptions (* the school was open plan, therefore air mixing occurs with adjacent class bases)

School	Pupils	Construction	Ventilation	Max. No. Pupils in Class Base
School 1	Infants (5 - 6 Years)	Modern - Concrete	Natural	60
School 2	Middle (8 - 9 Years)	Modern - Concrete	Natural	60*

Photographs and schematic plans of Schools 1 and 2, are shown in Figures 2 through 5.

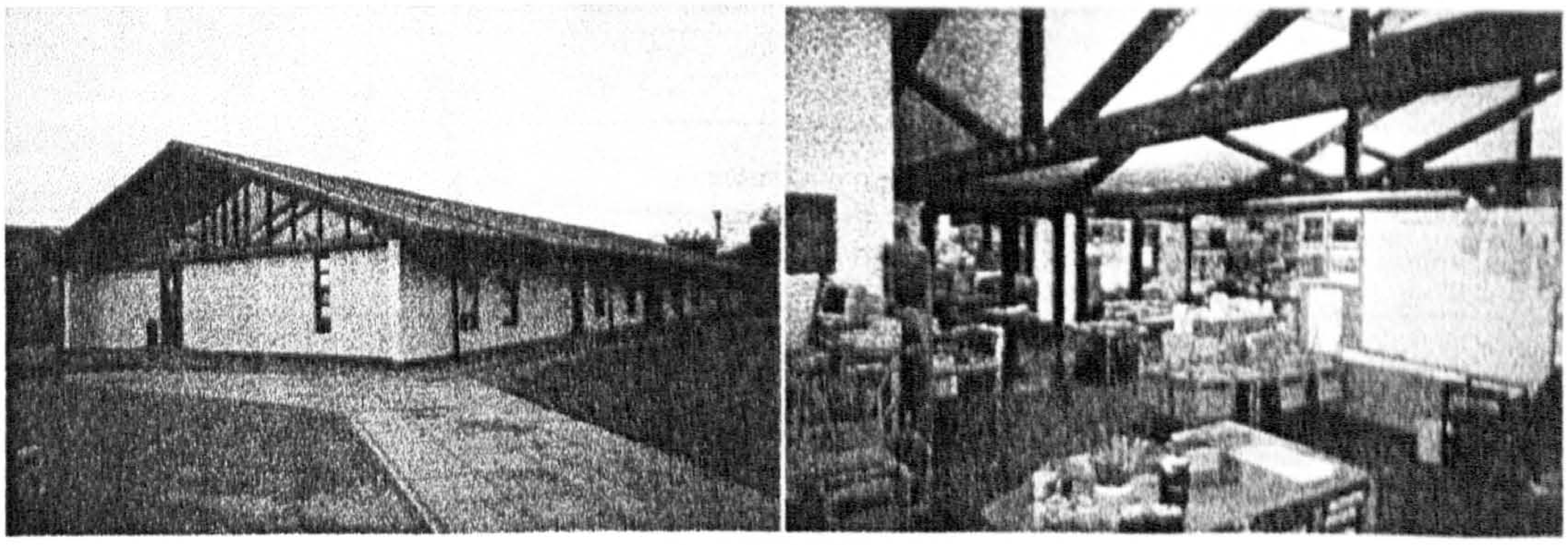

Figure 2. School 1 - Outside south facing elevation (left) and monitored twin class base (right).

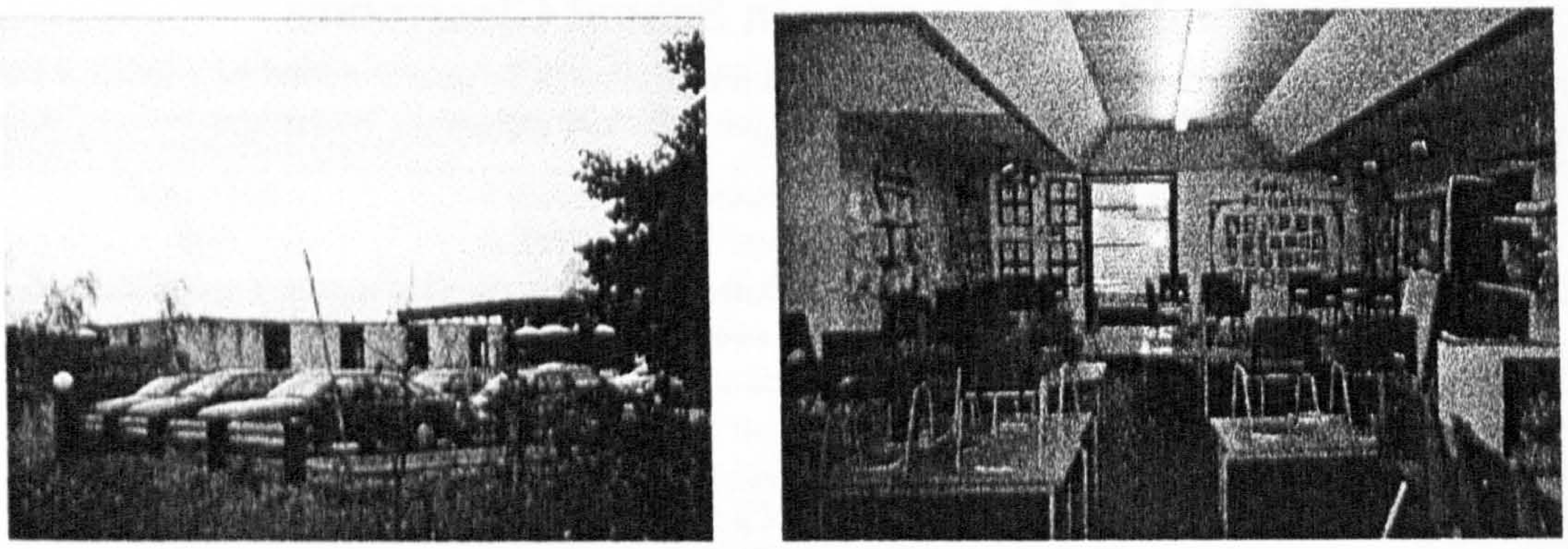

Figure 3. School 2 - outside east facing (left) and an area of a monitored class base (right)

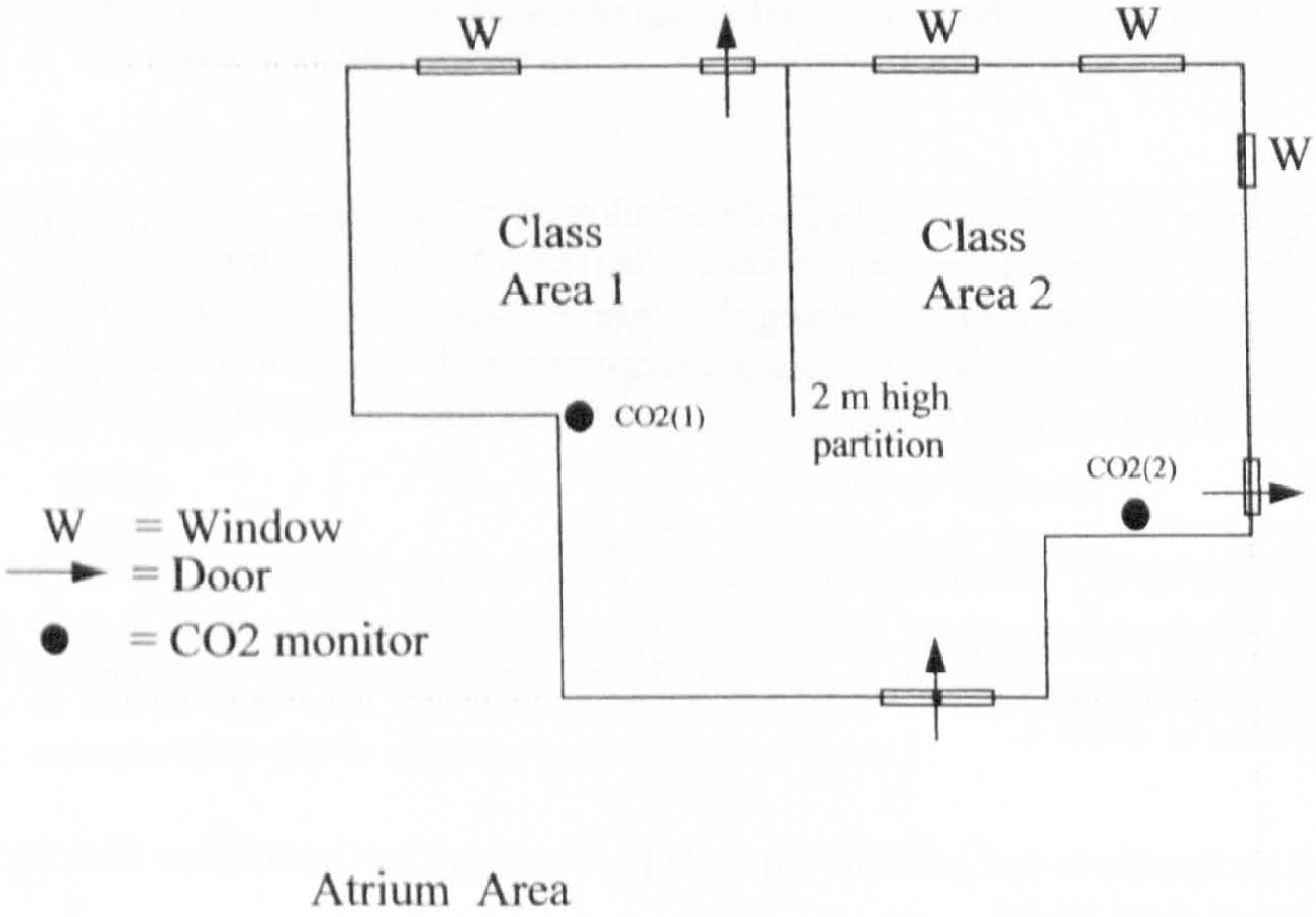

Figure 4. Plan of monitored class base, school 1. [CO2(1) and CO2(2) refer to carbon dioxide monitors 1 and 2 respectively]

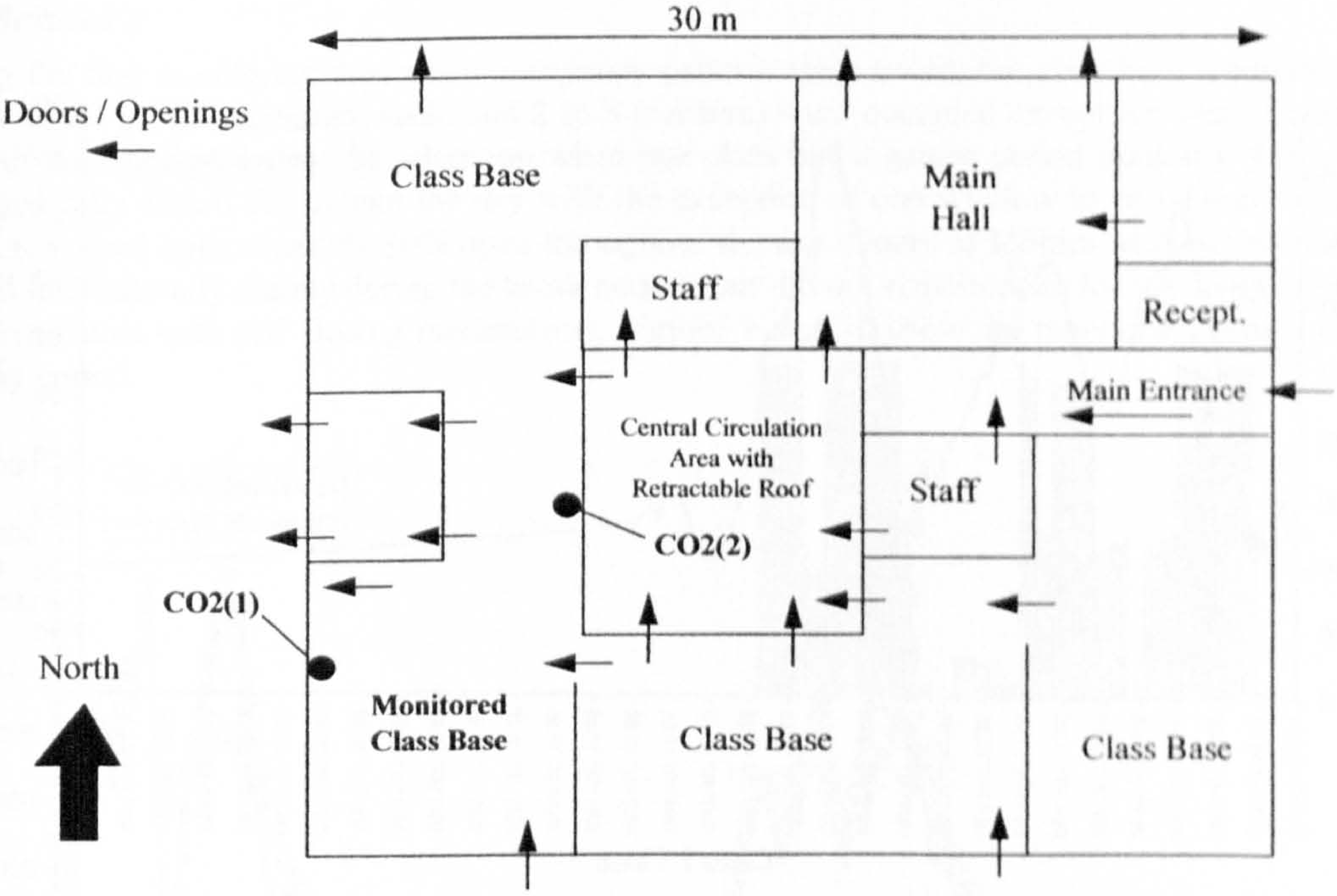

Figure 5. Schematic plan of school 2 showing monitored class base as diagonally hatched. [CO2(1) and CO2(2) refer to carbon dioxide monitors 1 and 2 respectively]

4. Results of Indoor Air Quality Monitoring

4.1 School 1

During the first monitoring day occupancy patterns were noted. The twin class base was fully occupied except for break periods. Full occupancy of the class base is 60 children and 3 to 4 adults. Three of the four windows in the external wall remained open throughout the day. External doors were opened intermittently mainly during the end of break periods to allow children to re-enter the classroom. The entrance door leading into the classroom from the atrium area was opened intermittently throughout the day especially during the beginning and end of break periods. No doors remained open for any length of time as they were fitted with self closing mechanisms. The carbon dioxide concentration and occupancy monitoring results are shown in Figures 6 and 7.

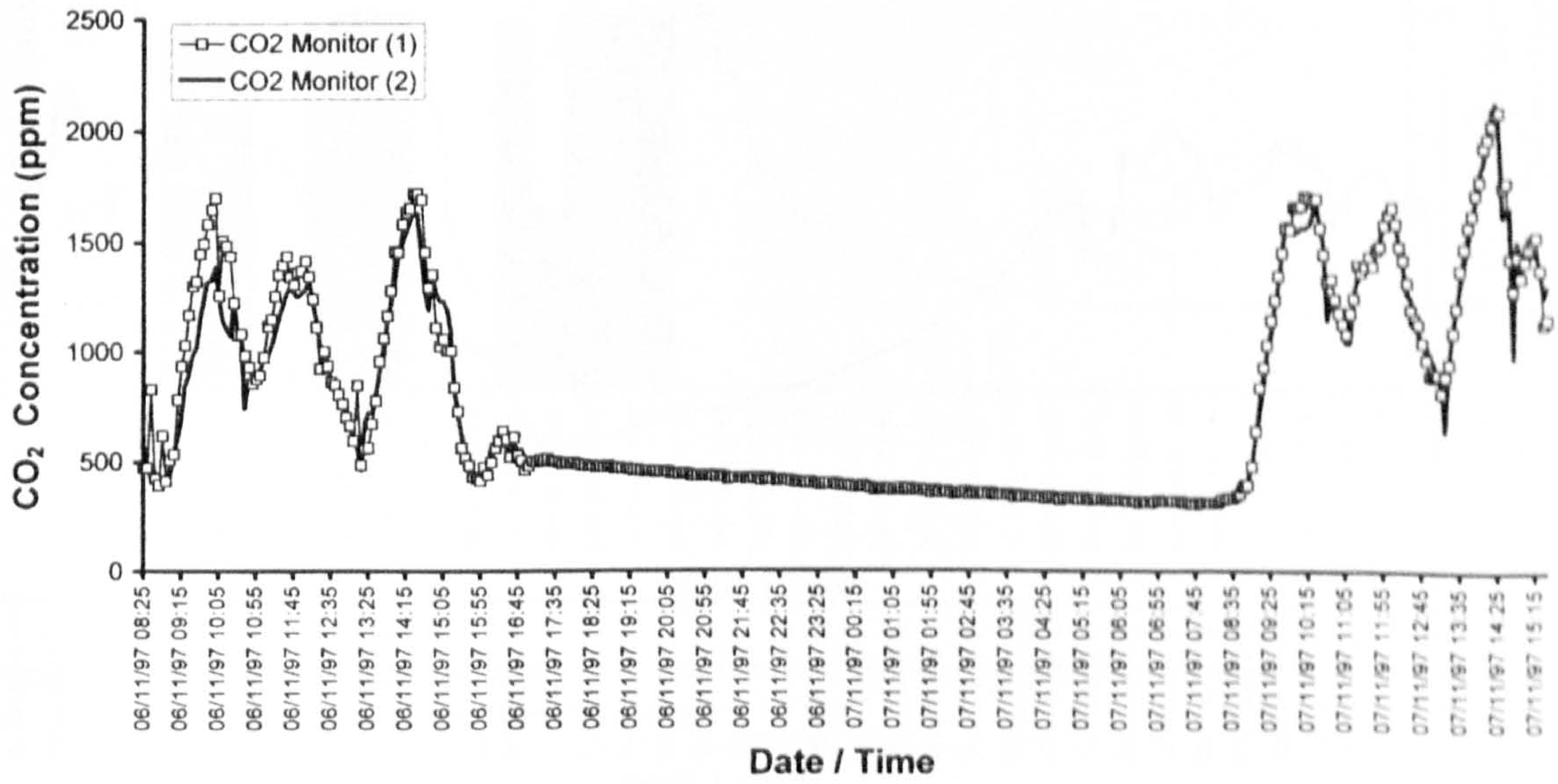

Figure 6. Carbon dioxide concentrations for school 1 over the two day monitoring period.

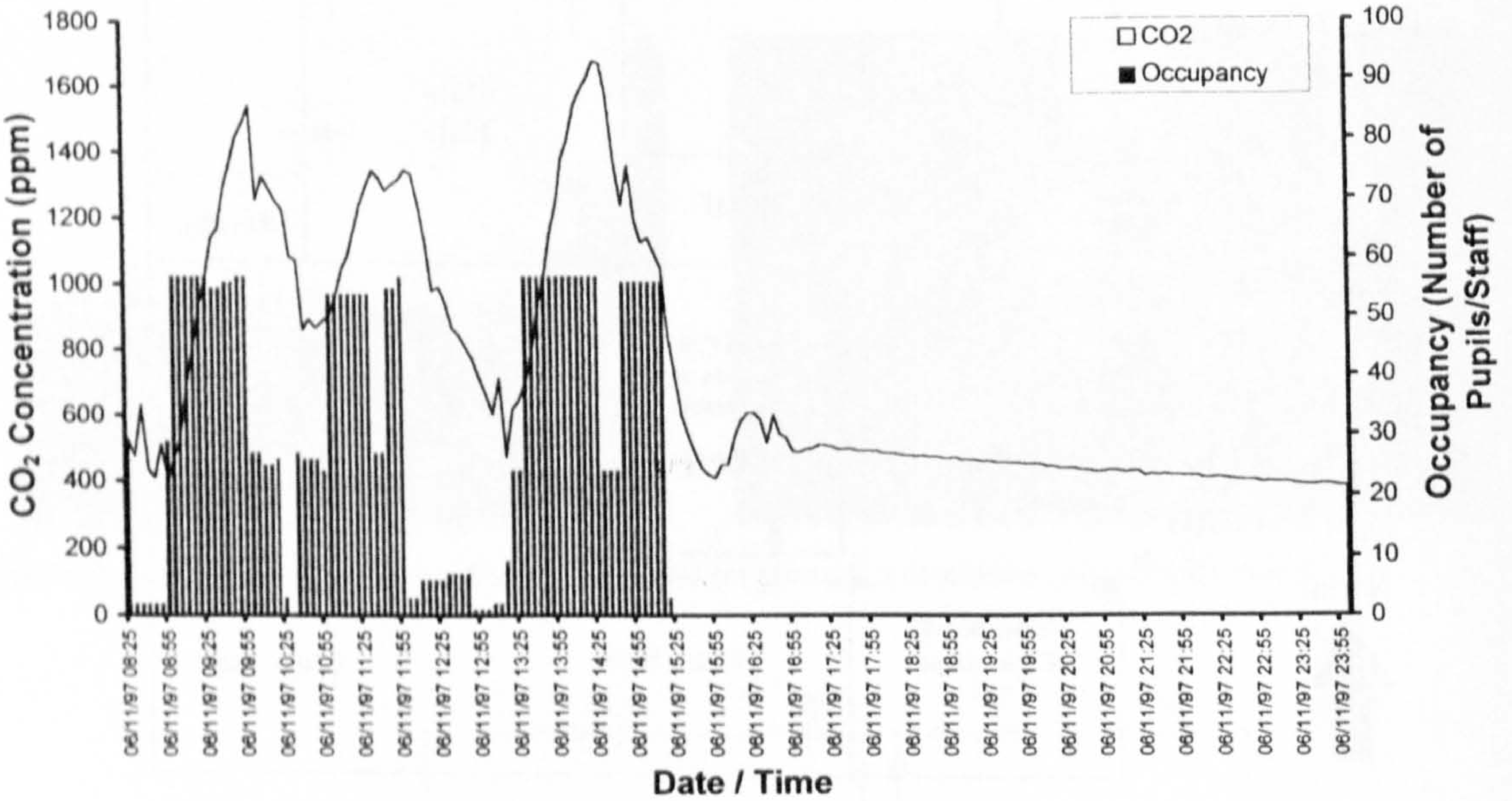

Figure 7. Averaged carbon dioxide concentrations and occupancy patterns during the first days monitoring for school 1.

In Figure 7 the carbon dioxide concentration was strongly related to the number of occupants. Carbon dioxide concentrations quickly rise and fall at the beginning and end of occupied periods respectively. However, some discrepancies are apparent in Figure 7. At 16:00 there is a small rise in carbon dioxide concentration without an apparent accompanying rise in occupancy level. This is due to the occupancy pattern being estimated after school hours and it was assumed that the class bases were unoccupied during this period. According to staff at the school, two or three teachers would normally remain after school hours, leaving work between 16:00 and 17:00. It would seem probable that this unexpected rise in CO_2 concentrations could therefore be teachers returning to the class base, after a meeting or coffee in the staff room, to prepare for the next days lessons. Cleaners entering the space during this period are another possible cause. The slow decay in carbon dioxide concentration after 17:00 is due to the windows being shut by the teachers as they leave and hence lower outside air infiltration rates existed than during the occupied period. The resultant temperature in the school 1 classroom ranged approximately from 20°C to 24°C during the occupied period, see Figure 8.

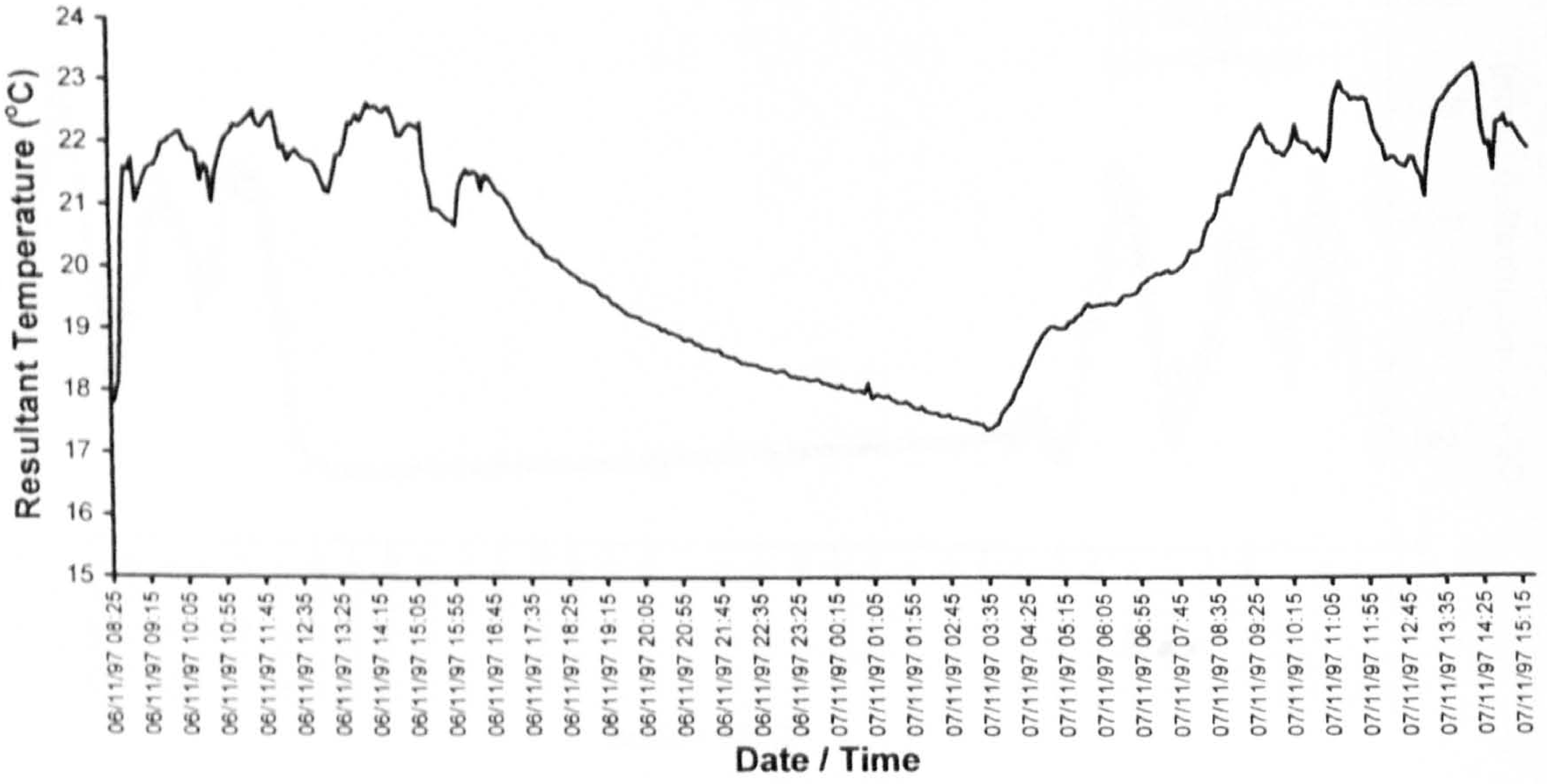

Figure 8. Resultant temperature during the monitoring period for School 1.

4.2 School 2

During the first monitoring day, when occupancy patterns were noted, the class base (comprising two classes of 30 pupils maximum each, and 2 to 3 teachers) were occupied except for break periods and one half hour period during the afternoon when one class had a games period outdoors. All windows remained fully closed throughout the day with the exception of one window in an adjacent class base which remained approximately 10% open throughout the day. Doors to lobbies leading outdoors were opened intermittently mainly during the break periods but did not remain open for any length of time as they were fitted with self closing mechanisms. Figures 9 and 10 show the monitoring results over the two day period.

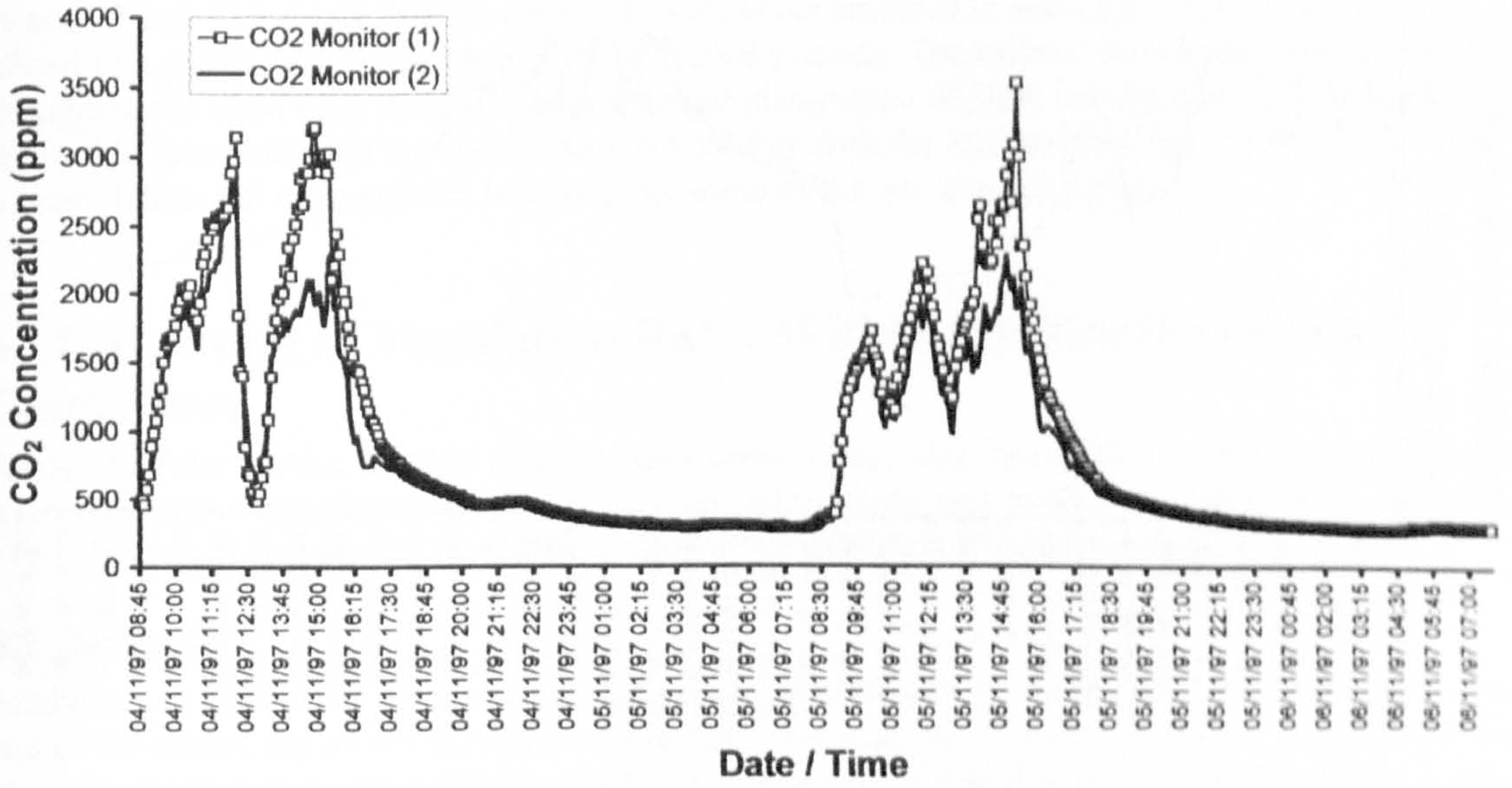

Figure 9. Carbon dioxide concentrations for school 2 during the two day monitoring period

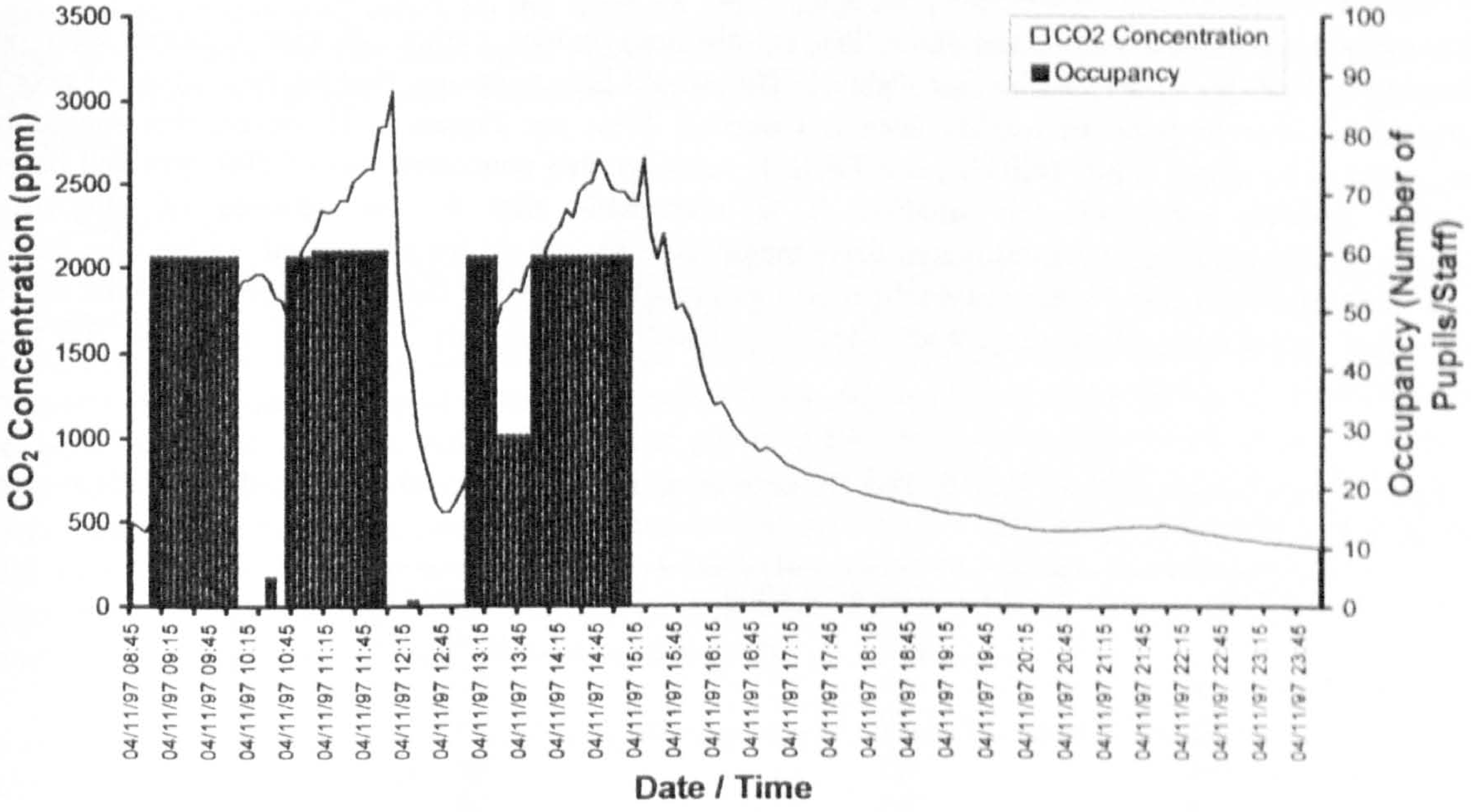

Figure 10. Averaged carbon dioxide concentrations and occupancy patterns for the monitored class areas during the first days monitoring for school 2.

Again, a small discrepancy between what would be expected in terms of carbon dioxide concentrations and the relationship with occupancy pattern can be seen in Figure 10 at approximately 12:45. The carbon dioxide concentration begins to rise before the class base becomes occupied. Examination of the data on occupancy patterns taken during the monitoring period reveals that pupils had began to re-enter the building at the end of the lunch period but not into the actual class base being monitored for air quality. School 2 is of an open plan design which would allow carbon dioxide to disperse to the monitored class base. Careful examination of Figure 10 reveals that the rate of increase in carbon dioxide concentration becomes much greater once the class base becomes occupied (approx. 13:00). During the two day monitoring period in school 2 the resultant temperature fluctuated approximately between 22 °C and 26.5 °C during the occupied periods, see Figure 11.

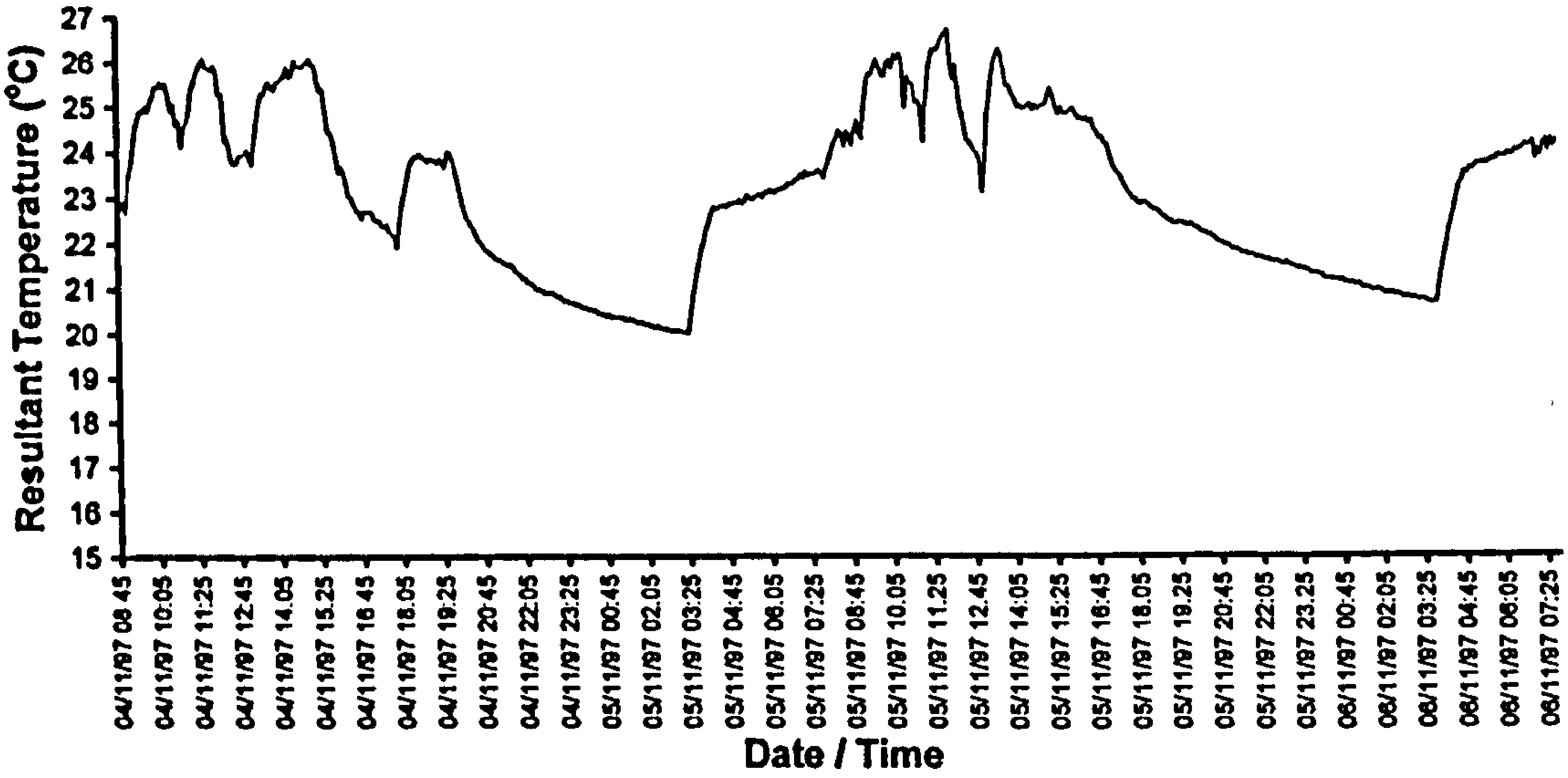

Figure 11. Resultant temperature during the monitoring period for School 2 (location 1, Figure 5).

5. Monitored Carbon Dioxide Concentrations and Their Implications for Indoor Air Quality

Previously mentioned guidelines state that an absolute indoor carbon dioxide concentration not exceeding 1000 ppm is preferable, see Table 1. This would help to ensure that the percentage of people dissatisfied due to poor air quality does not exceed 20%, see Figure 1. However, this should be regarded as an upper limit. BSRIA , see Table 1, consider that concentrations of 800 ppm and below would provide acceptable air quality. It is reasonable that in the absence of alternative recommendations that concentrations of these magnitudes are sought for the majority of the time during occupied periods. Table 5 summarises the monitored results by stating the percentage of the time during occupied periods for which the carbon dioxide concentration exceeds both 1000 ppm and 800 ppm thresholds.

Table 5. Percentage of time that carbon dioxide concentrations exceed the stated limits during the occupied period (09:00 to 15:15).

School / Date	% Time exceeding 1000 ppm	% Time exceeding 800 ppm
School 1 6/11/97	63	83
7/11/97	87	95
School 2 4/11/97	83	89
5/11/97	95	96

Table 5 clearly shows that threshold concentrations for carbon dioxide are exceeded for a large proportion of the occupied period. This is especially true of the 800 ppm threshold value and shows that the air quality in these areas was in general poor.

5.1 School 1

Figures 6 and 7 indicate that the carbon dioxide concentrations in school 1 ranged from 300 ppm after school to a peak of 2100 ppm during the occupied periods. Figures 6 and 9, schools 1 and 2 respectively, show that the carbon dioxide concentrations in the school 1 class base did not reach such high levels as in the school 2 classrooms. Three of the four windows were open all day thus providing a relatively high air change rate. Should the outdoor temperature be lower it is probable that these windows would remain closed thus creating higher indoor carbon dioxide concentrations and hence lower indoor air quality.

5.2 School 2

Figures 9 and 10 indicate that the carbon dioxide concentrations in school 2 ranged from 300 ppm after school to a peak of 3500 ppm during the occupied periods. The carbon dioxide concentrations quickly rise above the 1000 ppm threshold soon after the classrooms become occupied at 9:00 AM and remain above this threshold until the end of each school day with the exception of the lunch periods when the concentrations fall to acceptable levels during some of the unoccupied period.

6. Estimation of Ventilation Rates Within the Monitored School Class Bases

Analysis of the carbon dioxide concentration decay rates, after occupation of the class bases ended, were carried out using a carbon dioxide concentration decay rate method as described in Appendix 1. The calculations assume that complete mixing of the air occurs within the spaces.

6.1 School 1

Analysis was carried out on the monitored values immediately after the classroom was vacated at the end of the school day on the first days monitoring. This suggests that the ventilation rate in the school 1 classroom was in the region of 2.9 a.c.h. It has been assumed that this rate remained relatively uniform throughout the day as the windows were constantly open at the same position and still, mild weather conditions were experienced. The air change rate would be higher than this at the beginning and end of break periods when the main entrance door from the atrium area, and occasionally, external doors were opened. It has therefore been assumed that the intermittent opening of external doors for very short periods had little overall effect on the fresh air ventilation rate, especially considering the constantly large window area that remained open. Analysis of the carbon dioxide concentration decay rates could not be carried out at any other times for the monitored data as the classrooms remained partially occupied.

6.2 School 2

After school analyses of the decay rates of carbon dioxide concentration for both of the monitored days indicates that the background ventilation rate with all the windows closed was in the range 0.5 - 1.0 a.c.h. Analysis of the decay rate during lunch time on day 1 indicates that the air change rate, with frequent opening and closing of external doors due to the pupils leaving and entering the building, rises to between 3 and 3.5 a.c.h. Analysis was not possible for Wednesday lunch time as the occupancy patterns were unknown for this period. The data analyses for these days indicate that during normal occupancy, when the external doors are opened less frequently, the air change rate lies between 0.5 and 3.5 a.c.h.. However, during normal occupied periods, i.e. during lessons, it is probable that the air change rate is closer to that of the time immediately after school, i.e. 0.55 - 1 a.c.h., due to the window and door openings being similar for these time periods.

Elementary calculations for per capita ventilation rates within the schools based on calculated air change rates are given in Table 6.

Table 6. Per capita fresh air ventilation rates (assumed occupancy 60 Students, 2 Adults)

School	Time	Calculated a.c.h.	Equivalent Per Capita Fresh Air (l/s/p)
School 1	Day 1 - After School	2.9	4.7
School 2	Day 1 - Lunch	3.0 - 3.5	5.7 - 6.7
School 2	Day 1/2 - After School	0.5 - 1.0	1.0 - 1.9
School 2	Estimated for Occupied Periods	1.0	1.9

Table 6 suggests that the maximum possible fresh air ventilation rate provided during the monitoring period was 6.7 l/s/p. However this occurred during the beginning of the lunch time period in school 2 when the students were leaving the building and ventilation rates were higher than during the occupied period due to frequent door opening. The fresh air ventilation rates determined for the periods just after the end of the school day are more representative of those occurring during occupied periods as doors remain in the same position, i.e. closed. These values are far lower and indicate that fresh air ventilation rates are significantly less than those required to provide acceptable air quality.

7. Conclusions

The use of continuously monitored CO_2 concentrations in the two monitored class bases, each for a period of two days, provides a snapshot of the air quality provided by means of natural ventilation. Analysis of the CO_2 decay rates allows approximate air change rates to be estimated for the monitoring periods.
Carbon dioxide concentrations recorded at the schools suggest that the indoor air quality experienced by the occupants is consistently below that recognised as acceptable air quality, i.e. > 1000 ppm carbon dioxide concentrations, during the occupied periods. The results shown in Table 5 indicate that carbon dioxide concentrations exceeded this threshold for between 63% and 95% of the occupied period. Where 1000 ppm carbon dioxide concentrations are considered to represent a 20% PPD level with respect to the indoor air quality the monitoring results clearly show that unsatisfactory conditions persist within the schools.

The carbon dioxide concentrations were higher for school 2 than school 1. However, as the windows remained closed all day during the monitoring period in school 2, these results probably represent the worst case scenario regarding this school. In contrast, school 1 windows remained open throughout the occupied period mainly due to the classrooms being too warm and stuffy. During colder weather it is probable that these windows would remain shut and carbon dioxide concentrations would at least approach those experienced in school 2.

The calculated fresh air infiltration rates for the schools on a per capita basis, 1.0 - 6.7 l/s/p, were not capable of providing acceptable air quality when considered in relation to the CO_2 concentrations. CIBSE recommendations(3) of 8.3 l/s/p would improve the air quality. However, DFEE recommendations(4) of a minimum background ventilation rate of 3 l/s/p would be inadequate for the schools concerned. The DFEE does recommend(4) that the ventilation system should be capable of providing 8 l/s/p in classroom areas. Unfortunately the DFEE guidelines are easily misinterpreted and the lower air change rate is regarded as being able to satisfy air quality requirements of the occupants. The DFEE guidelines need to be clearer in order to eliminate the ambiguity of the recommendations.

The natural fresh air ventilation rates in the monitored schools were found to be inadequate to provide sufficient fresh air to the occupied spaces. This is a problem that may be difficult to overcome using natural ventilation alone because of the high occupancy densities of school classrooms. Careful consideration needs to be given at the design stage as to whether the necessary ventilation rates can be achieved or whether mechanical assistance is required in order to provide acceptable air quality.

Appendix 1. Determination of Ventilation Rates from Transient Indoor Carbon Dioxide Concentrations

List of Symbols Used in Appendix 1

C_o	initial CO_2 concentration above ambient in the space at start of decay period (ppm), $t = 0$
C_t	CO_2 concentration above ambient after time t (ppm)
t	time elapsed since start of decay period (s)
v	volume of the space (m^3)
x	volume of air leaving the space per second (m^3/s)

The air change rate in an internal space can be determined by monitoring and analysing the decay rate in carbon dioxide concentrations immediately after the occupants have vacated the space.

Procedure

1. Monitor the dynamic carbon dioxide concentration in the space.
2. When the occupants leave note the CO_2 concentration at this time (C_o).
3. Note the CO_2 concentration after a time t (C_t).
4. Use the following equations to calculate the air change rate.

Note: when using metabolic CO_2 as the tracer gas the carbon dioxide concentration of the ambient, i.e. outdoor air should be subtracted, i.e. use the difference value not the absolute value.

Where the zone internal rate of CO_2 production is zero, the zone concentration will decay to the outdoor concentration according to Equation (1) (12).

$$C_t = C_0 e^{-\frac{x}{v}.t} \quad \text{.......Equation (1)}$$

The -ve sign indicates that the CO_2 concentration is decaying. Rearranging Equation (1) :-

$$x = -\frac{v}{t} \log_e \frac{C_t}{C_0} \quad \text{.......Equation (2)}$$

In Equation (2) the -ve sign indicates that the air is leaving the space. However, air also enters the space at the same rate. Therefore the -ve sign can be removed and Equation (2) effectively gives the air change rate.

Acknowledgements

The authors would like to thank Essex County Council, W.S. Atkins and Satchwell Control Systems who made this project possible.

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Appendix B :

An Assessment of Air Quality and Ventilation Rates in School Classrooms - Part II: Computer Modelling

This appendix is a copy of a paper submitted for publication at the time of writing this thesis.

Appendix B

An Assessment of Air Quality and Ventilation Rates in School Classrooms - Part II: Computer Modelling

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Summary

Part I: Air Quality Monitoring(1), the preceding paper, considered the recorded carbon dioxide concentrations experienced in two schools in terms of provided air quality and ventilation rates.

Part II: Computer Modelling, a) calculates the approximate metabolic carbon dioxide production rates of the occupants and b) develops a dynamic spreadsheet model as a tool to corroborate the results obtained in Part I, and c) utilises the model to estimate the ventilation rates required to achieve acceptable air quality in the schools concerned.

Two methods are considered in order to calculate the metabolic rate of production of carbon dioxide of school age children; a) estimation using the monitored results, and b) calculations from knowledge of the physical attributes of the children. These two methods yield similar results and confirm that the metabolic carbon dioxide production rate of the children is not proportional to their size when compared to that of adults. An iterative model was developed with the aid of a computer spreadsheet and was used to model the dynamic carbon dioxide concentrations in the classrooms using known and estimated input variables and parameters. It was then possible to use the model to examine the effects of varying air change rates for realistic occupancy patterns. The model suggests that air change rates of 5 a.c.h. are required in the school classrooms considered in this project in order to provide acceptable air quality for the majority of the occupied period. The magnitude of this ventilation rate corresponds to per capita fresh air ventilation rate of between 8.17 and 9.52 l/s/p for the schools considered. These figures for fresh air ventilation rates are in line with CIBSE recommendations of 8.3 l/s/p for schools.

The monitoring over short time periods (2 days) allowed a "snapshot" of the air quality conditions occurring within the school classrooms. Hence, analysis of airflow between spaces and subjective human responses were not considered during this investigation. The main objective of the monitoring was to assess air quality in densely occupied classrooms with regard to commonly used evaluation criteria for carbon dioxide within the spaces on the randomly chosen days and to indicate the ventilation rates occurring.

List of Symbols

A_{Du}	Dubois surface area (m^2)
$C_{indoor}(t)$	indoor CO_2 concentration at time = t (g/m^3)
$C_{outdoor}$	outdoor CO_2 concentration (g/m^3)
d_{CO_2}	change in CO_2 concentration (g/s for total space)
G_{CO_2}	Zone CO_2 addition rate (g/s)
H	persons height (m)
M_{abs}	absolute metabolic rate (W/m^2)
$M^*_{CO_2}$	metabolic CO_2 production rate per person (g/s/person)
M_{CO_2}	total metabolic CO_2 production rate (g/s)
M_{tot}	total metabolic rate (W)
I	air change rate (air changes per second)
P	number of occupants
R_{CO_2}	Zone CO_2 removal rate (g/s)
t	time elapsed (s)
t^*	time step (s)
V	space volume (m^3)
V_{inf}	zone ventilation rate (infiltration / exfiltration) (m^3/s)
W	persons weight (kg)
$Z1_{CO_2}$	zone CO_2 concentration (g/m^3)
$Z2_{CO_2}$	zone CO_2 concentration (g/room volume)
$Zone_{CO_2}$	zone CO_2 concentration (ppm)

1. Introduction

Descriptions of the schools considered in this project are given in the preceding paper - Part I: Air Quality Monitoring(1). In that paper the air quality was assessed using continuously monitored carbon dioxide concentrations. Part I also estimated natural ventilation rates for the schools concerned by using a CO_2 decay rate method. This paper, Part II: Computer Modelling, continues by :-

1. Calculating the metabolic carbon dioxide production rates of the occupants.
2. Using the ventilation rates calculated in Part I and the metabolic CO_2 production rates calculated in Part II, to create a model capable of approximating the monitored results.
3. Using an iterative spreadsheet model to estimate the ventilation rates required to achieve acceptable air quality in the schools concerned.

2. Metabolic Carbon Dioxide Production Rates of School Aged Children

These were calculated for the occupants of the two schools using two methods.

2.1 Method 1 - Calculations of the Metabolic CO_2 Production Rates using Monitored CO_2 Concentrations in the School Class Bases

This method uses known occupancy patterns, room volumes and estimated ventilation rates calculated using the CO_2 decay rate method, see Part I(1).
Equation (1)(2) can be used to determine the carbon dioxide concentration in a space, at time t, where all values except time, t, on the right hand side of the equation remain constant.

$$C_{indoor}(t) = \frac{M_{CO2}}{VI}(1 - e^{-It}) + C_{outdoor} \quad \text{..........Equation (1)}$$

By rearranging the above equation it is possible to determine the total metabolic carbon dioxide production rate, see Equation 2.

$$M_{CO2} = \frac{VI(C_{indoor}(t) - C_{outdoor})}{1 - e^{-It}} \quad \text{..........Equation (2)}$$

This gives the value for the total carbon dioxide generation. To obtain the per capita rate this value was divided by the number of occupants.

However, certain conditions apply to the use of this equation:-
1. the occupancy must remain constant over the period in which the equation is applied
2. the initial carbon dioxide concentration in the space must be at the outdoor level
3. the air change rate must be constant over the period to which the equation applies
4. the total metabolic CO_2 production rate of the occupants must remain constant

These conditions dictated that for the monitored schools the period between the start of the school day and the first break period only were considered suitable for calculations employing Equation (2). Some caution should be applied to the results as it is difficult to estimate the air change rate precisely for the analysis periods. see Part I(1). However, these estimates do give order of magnitude values for the calculated parameters. For an example calculation using Method 1 see Appendix 1.

The metabolic carbon dioxide production rates calculated using Method 1 are shown in Table 1

Table 1. Metabolic carbon dioxide production rates of 5/6 year olds calculated for School 1 using Method 1.

School	Time	Metabolic CO_2 Production Rate (mg/s/p)
School 1	08:55 - 10:00 Day 1	10.4
School 1	13:15 - 14:25 Day 1	13.2
School 1	08:50 - 10:00 Day 2	9.5
Average		11.0

Method 1 could not be used to calculate the metabolic carbon dioxide production rate for occupants of School 2 as the air change rate for the calculation period could not be estimated with any degree of certainty, see Part I(1).

2.2 Method 2. Calculation of Metabolic Carbon Dioxide Production Rates from Knowledge of the Physical Attributes of the Occupants

This method involved the use of the knowledge of the occupants physical attributes, i.e. age, sex, height and weight, to calculate values for metabolic carbon dioxide production rate from empirically derived data, see Figures 1 and 2. In the example below the theoretical metabolic carbon dioxide production rate is calculated for 5/6 year old children. The method involved the following steps:

2.2.1 Step 1: Calculate the surface area of the child age group in question

The surface area of a person can be calculated from Equation 3(3)

$$A_{Du} = 0.202W^{0.425}H^{0.725} \quad \text{.......... Equation (3)}$$

Average weight and height statistics for the age group concerned can be obtained from Figure 1.

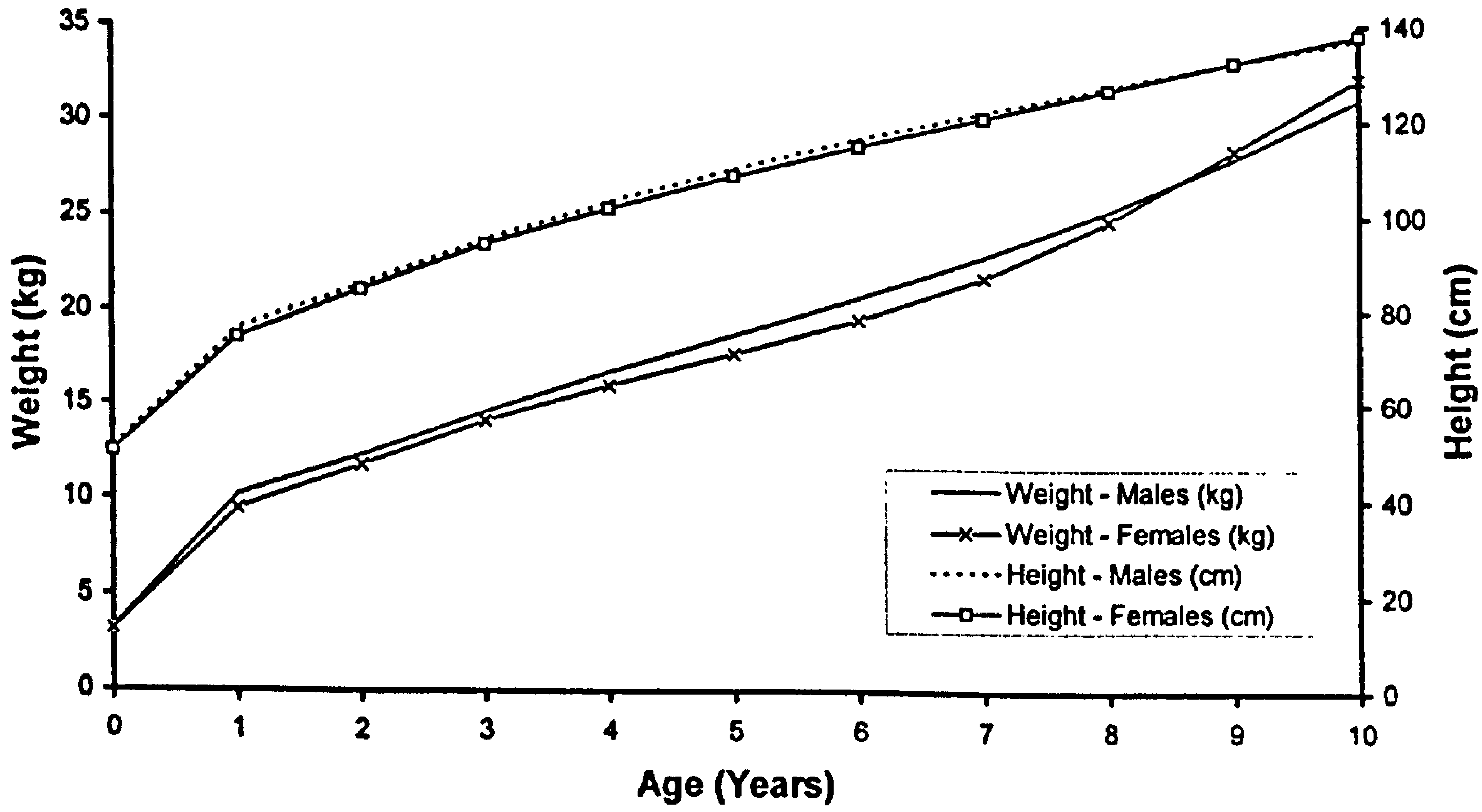

Figure 1. Average weight and height data for children up to 10 years old(4).

The weight and height characteristics of male and female children are very similar for this age group and therefore the average of these values was used for the calculation. The weight and height data for 5/6 year old children, as taken from Figure 1, are shown in Table 2.

Table 2. Weight and height data for 5/6 year old children used for theoretical carbon dioxide production calculation.

Attribute	Males	Females	Average Males / Females
Weight (kg)	19.7	18.7	19.2
Height (m)	1.13	1.11	1.12

Using Equation (3) the surface area for 5/6 year old children is:

$A_{Du} = 0.202 \times 19.2^{0.425} \times 1.12^{0.725} = \underline{0.77\ m^2}$

2.2.2 *Step 2: Calculate the metabolic rate*

The surface area calculated in Step 1 and the basal metabolic rate obtained from Figure 2 were used to calculate the total metabolic rate using Equation (4).

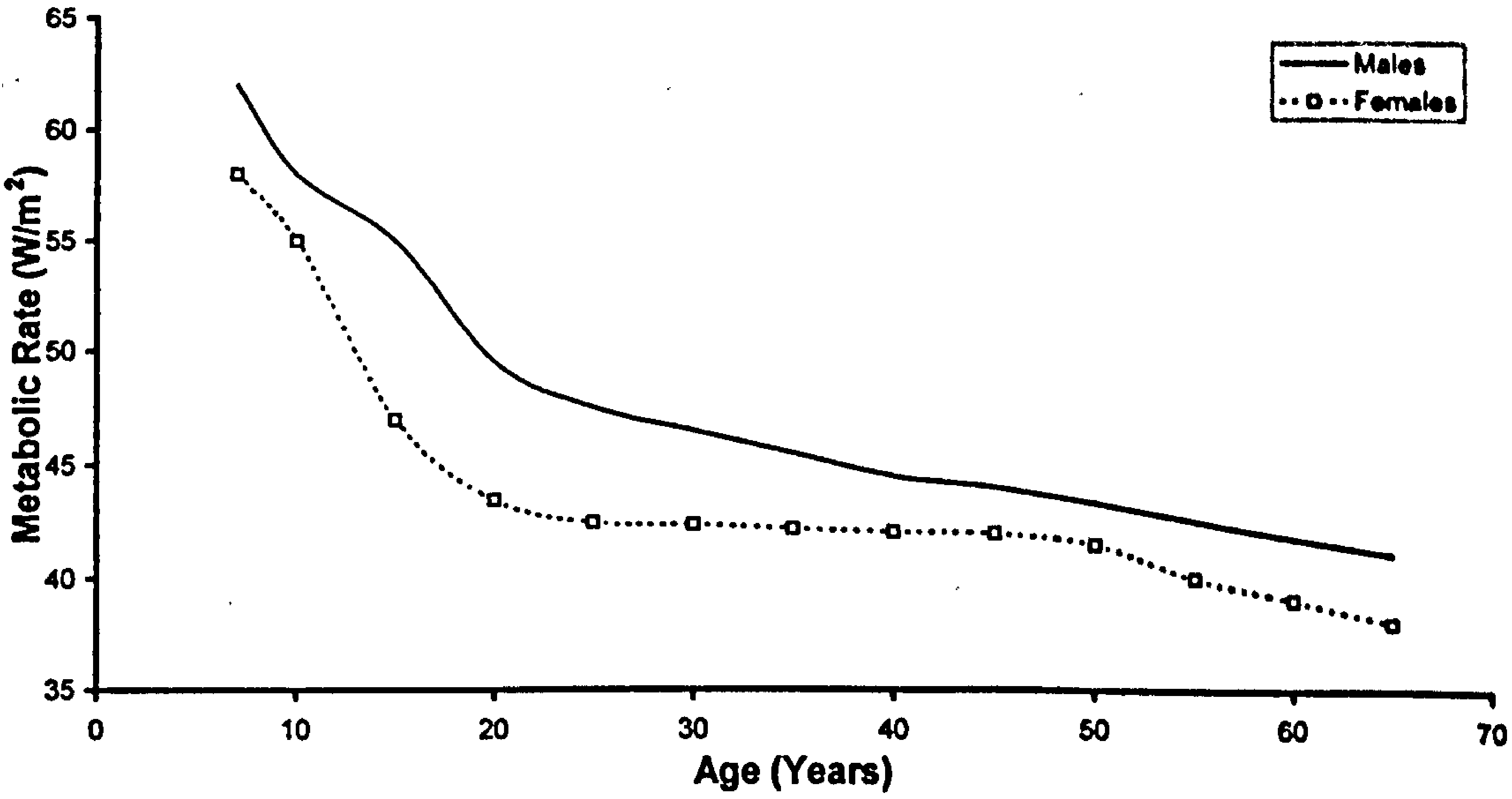

Figure 2. Average basal (i.e. completely at rest) Metabolic Rate (W/m²) as a function of age and sex(5).

From Figure 2 the average basal metabolic rates for 5/6 year old children are 62 W/m² and 59 W/m² for males and females respectively. These values are similar and for the purposes of the calculation the average value, i.e. 60.5 W/m², was used. Therefore :-

$M_{tot} = M_{abs}A_{DU} = 60.5 \times 0.77 = \underline{46.6\ W}$ ....Equation (4)

2.2.3 *Step 3: Calculate the metabolic heat production rate for different activity levels*

This was calculated from metabolic heat production data given for adults obtained from BS 5925(6) on a proportional basis for activity levels above basal. From Figure 2 it can be seen that the basal metabolic rate for adults is approximately 45 W/m² (males/females 20 - 40 years old). The surface area of a male adult is approximately 2 m² (6). Therefore, from Equation (4), the total basal metabolic rate for an adult is approximately (45 W/m² x 2 m²) = 90 W.

The metabolic heat production of an adult seated at rest, i.e. sedentary is 100 W, i.e. a factor of approximately 1.11 times the basal metabolic heat production rate. Similar calculations were carried out for other activity levels as shown in Table 3.

2.2.4 Step 4: Calculate the metabolic carbon dioxide production rate

The final two columns of Table 3 to 5 give the metabolic CO_2 production rate calculated from the metabolic heat production rate using Equation (5)$^{(6)}$.

$$M_{CO2} = 0.00004M_{HM} \quad \text{.......... Equation (5)}$$

Table 3. Metabolic CO_2 production rates for 5/6 year old children, School 1

Activity	Metabolic Heat Production Adult (W)	Factor above basal	Metabolic Heat Production Children 5/6 years old	Metabolic CO_2 Production (ml/s/p)	Equivalent Metabolic CO_2 Production (mg/s/p)
Basal	90	1	46.60	1.86	3.30
Sedentary	100	1.11	51.78	2.07	3.67
Light Work	160 - 320	1.78 - 3.56	82.84 - 165.69	3.31 - 6.63	5.88 - 11.75
Medium Work	320 - 480	3.56 - 5.33	165.69 - 248.53	6.63 - 9.94	11.75 - 17.63
Heavy Work	480 - 650	5.33 - 7.22	248.53 - 336.56	9.94 - 13.46	17.63 - 23.87

Similarly the calculations were carried out for the 8/9 year old children from School 2, see Table 4.

Table 4. Metabolic CO_2 production rates for 8/9 year old children, School 2

Activity	Metabolic Heat Production Adult (W)	Factor above basal	Metabolic Heat Production Children 8/9 years old	Metabolic CO_2 Production (ml/s/p)	Equivalent Metabolic CO_2 Production (mg/s/p)
Basal	90	1	56.53	2.25	4.00
Sedentary	100	1.11	62.61	2.50	4.44
Light Work	160 - 320	1.78 - 3.56	100.18 - 200.36	4.01 - 8.01	7.10 - 14.21
Medium Work	320 - 480	3.56 - 5.33	200.36 - 300.53	8.01 - 12.02	14.21 - 21.31
Heavy Work	480 - 650	5.33 - 7.22	300.53 - 406.97	12.02 - 16.28	21.31 - 28.86

2.3 Comparison of CO_2 Production Rates of Adults and School Aged Children

It is useful to compare the approximated metabolic CO_2 production rate calculated for children in Tables 3 and 4 to that for adults, see Table 5.

Table 5. Metabolic CO_2 production rates for adults calculated using Method 2.

Activity	Metabolic Heat Production (W)	Metabolic CO_2 Production (ml/s/p)	Equivalent Metabolic CO_2 Production (mg/s/p)
Basal	90	3.60	6.38
Sedentary	100	4.00	7.09
Light Work	160 - 320	6.40 - 12.80	11.35 - 22.69
Medium Work	320 - 480	12.80 - 19.20	22.69 - 34.04
Heavy Work	480 - 650	19.20 - 26.00	34.04 - 46.10

An adults metabolic CO_2 production rate for the activity level light work, is between 11.35 and 22.69 mg/s/p, as calculated using Method 2. However, adults working in office environments tend to be less active, i.e. sedentary. Table 5 suggests that sedentary adults with metabolic heat production rates of 100 - 160 W would have metabolic CO_2 production rates of 7.09 - 11.35 mg/s/p. Therefore, school children would appear to produce similar per capita quantities of carbon dioxide compared to adults due to their increased basal heat production rates and higher activity levels. It is also interesting to note that the European guidelines(7) suggests that the sensory pollution load of 3 - 6 year olds and 14 - 16 year olds are 1.2 and 1.3 times that of adults respectively.

2.4 Summary Metabolic CO_2 Production Rate Calculations

2.4.1 School 1

Method 1 indicates an average metabolic carbon dioxide production rate of 11 mg/s/p. This lies in the region of the calculated metabolic carbon dioxide production rate estimated using Method 2 for the activity of light work.

A difficulty arises when using method 2 as the children's activity level can only be estimated within the scope of this project. European guidelines(7) suggest that children in the age group 3 to 6 years old have metabolic heat production rates of 2.7 met which is equivalent to approximately 120 W if a body surface area of 0.77 m^2 is assumed for the 5/6 year old children. Table 3 indicates that this is equivalent to the category of light work and a metabolic CO_2 production rate of 5.88 - 11.75 mg/s/p. The European guidelines(7) also suggests a metabolic CO_2 production rate for 3 - 6 year old children of 18 l/h/occupant (8.86 mg/s/p) which is in the range calculated using method 2 for the appropriate metabolic rate. For the purposes of modelling in the remainder of this paper the figure derived from the monitored results, i.e. using Method 1, of 11 mg/s/p has been used. This value lies within the range calculated using Method 2 and has therefore been considered a reasonable value to use in the light of the information available.

2.4.2 School 2

Method 1 could not be used for school 2 due to the uncertainty in ventilation rates for the suitable calculation periods. Method 2 indicates generation rates for children in the age group 8 to 9 years as being between 7.10 and 14.21 mg/s/person for the appropriate activity level, i.e. light work. For the purposes of any further calculations and modelling in this paper it has been assumed that the CO_2 production rate for the 8/9 year old children in School 2 is equivalent to that of the children in School 1, in the absence of any actual data from the monitoring period.

Table 6 summarises the calculated ventilation rates, see Part I(1), and the metabolic CO_2 production rates calculated in this paper.

Table 6. Summary of the ventilation and metabolic carbon dioxide production rates.

School	Background Ventilation (a.c.h.)	Max. Ventilation During Monitoring Period (a.c.h.)	Metabolic CO_2 Production (mg/s/p) Method 1	Metabolic CO_2 Production (mg/s/p) Method 2	Activity Level
School 1	2.9	2.9	11	5.88 - 11.75	Light Work
School 2	0.5 - 1.00	3.5	N/A	7.10 - 14.41	Light Work

3. Determination of Ventilation Rates Required to Improve Indoor Air Quality using an Iterative Spreadsheet Model

An iterative spreadsheet model, see Appendix 2, was developed to assess whether the estimated metabolic CO_2 production rate and ventilation rates were representative of the actual values required to produce the monitored dynamic CO_2 concentrations. This was achieved by setting the ventilation rates at the estimated values derived from the monitored decay of CO_2 concentrations in the schools, see Part I(1), and utilising the estimated carbon dioxide production rate, i.e. 11 mg/s/p, calculated using Method 1 in this paper.

This modelling procedure was used to asses the base model before introducing changes to the natural ventilation rates in order to observe the effects on indoor air quality and hence determine required ventilation rates for acceptable air quality.

3.1 School 1

It was found that by using the estimated air change rate of 2.9 a.c.h. during the period of occupation and 0.5 a.c.h. after 16:00, see Part 1(1) produced the "best fit" to the monitored data for the estimated CO_2 production rate of 11 mg/s/p and the observed numbers of occupants, see Figure 3. An increase in CO_2 concentration occurred after the pupils had left school centered on the time 16:30. An occupancy of 4 adults, i.e. teachers or cleaners, between 16:00 and 16:30 was assumed in order to account for the unexpected increase in CO_2 concentrations between these times.

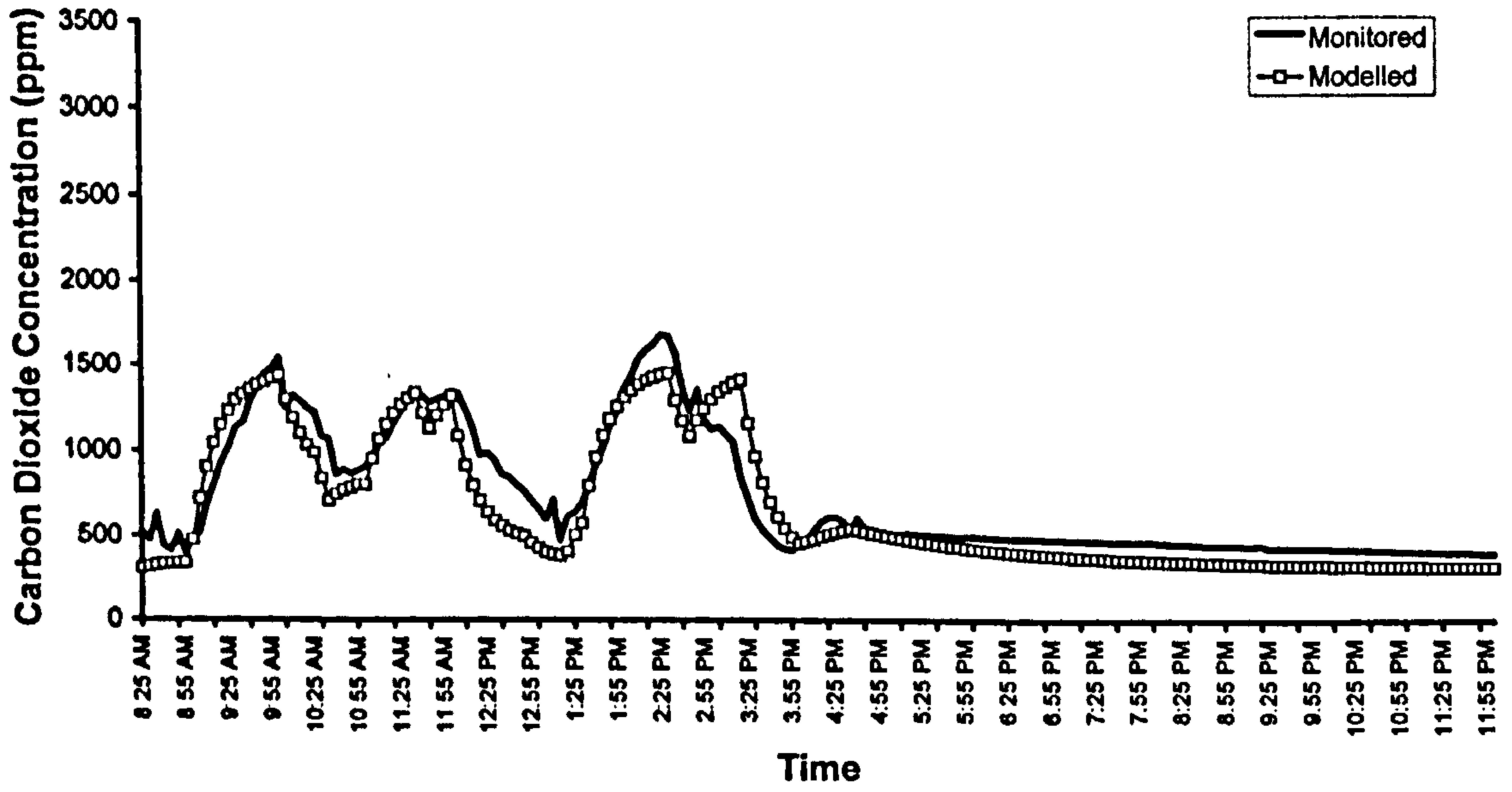

Figure 3. Best fit modelled carbon dioxide concentrations compared to monitored results, school 1.

Figure 3 shows that the model is able to predict approximately actual conditions within the classroom. Figure 4 shows that values of the modelled CO_2 concentrations compared with those of the monitored CO_2 concentrations for School 1.

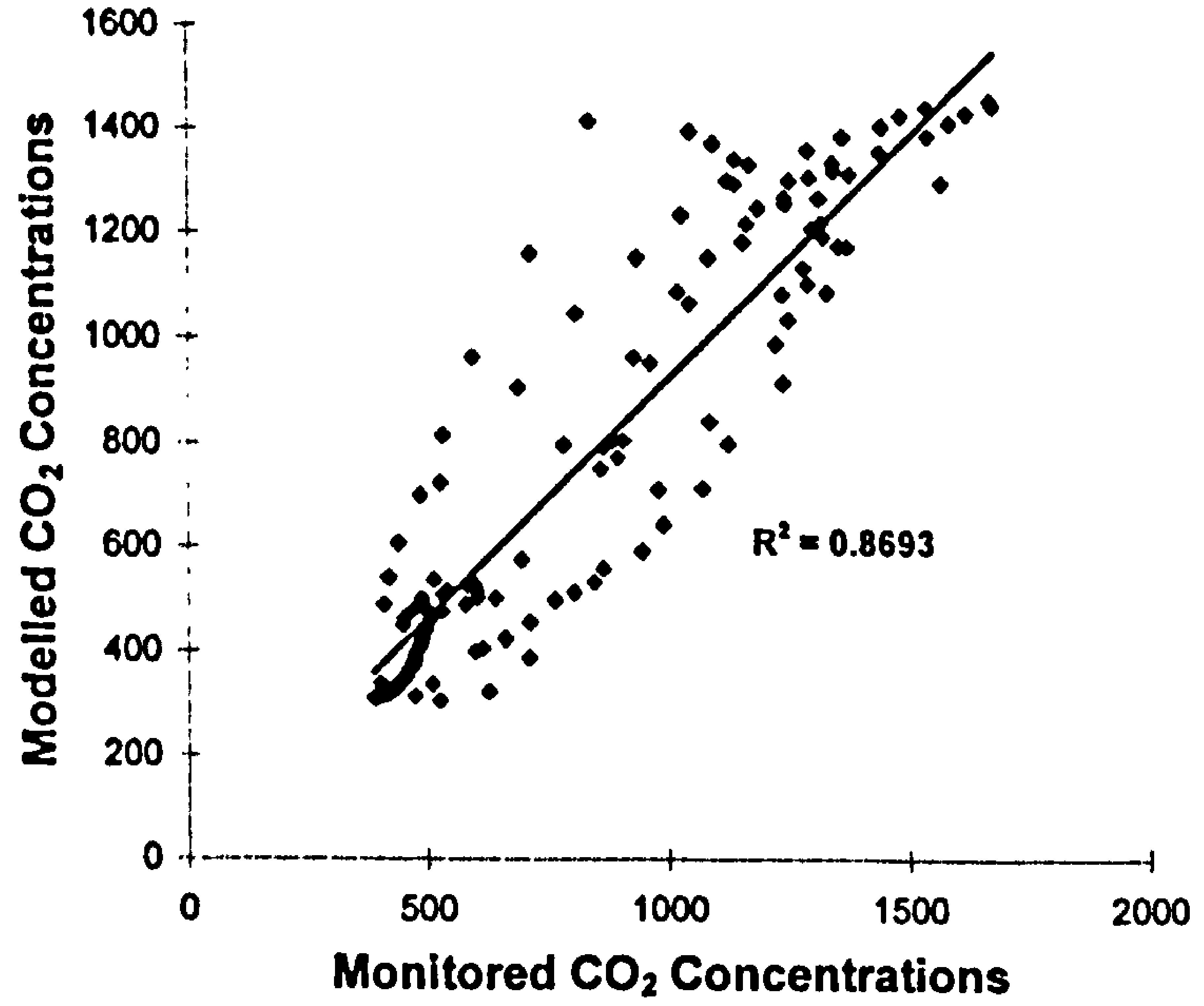

Figure 4. Modelled CO_2 concentrations against monitored CO_2 concentrations, school 1.

The degree of scatter in Figure 4 is quite large. However, the general fit of the curve, see Figure 3, mimics the monitored results. Several factors may have contributed to the model errors which are discussed here.
The model assumes a constant ventilation rate throughout the occupied period because detailed information on this aspect was unavailable. In order to improve the model more detailed information is required regarding the dynamic ventilation rates throughout the day. Ventilation rates for the occupied period were estimated using the CO_2 decay rate method and could only provide approximate averaged values. The windows of the class base were open and so small variations in wind speed and direction could induce marked fluctuations in ventilation rates. For school 2 where the windows remained closed throughout the day thus attenuating the fluctuations in ventilation rates and reducing the scale of modelling error, see Figure 7.

Nevertheless, the model does provide an indication of the general trends that can be expected in dynamic CO_2 concentration variations throughout the day.
The model was next used to examine the effect of varying the ventilation rate during the occupied period while holding all other input variables at the same values, see Figure 5.

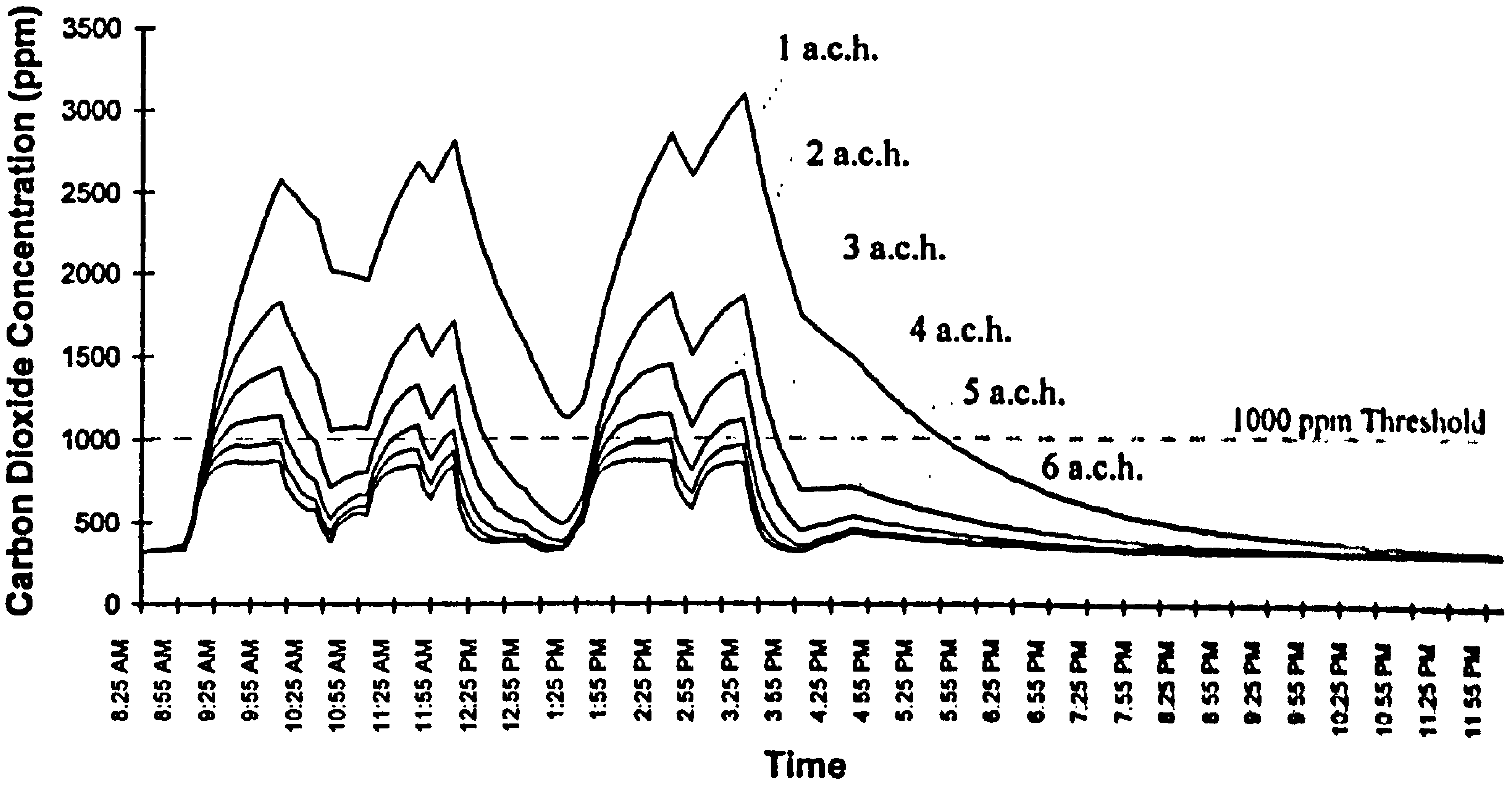

Figure 5. Simulated carbon dioxide concentrations for air change rates ranging from 1 to 6 during the occupied period - school 1.

In order to achieve acceptable air quality, i.e. carbon dioxide concentrations below 1000 ppm during the occupied period, the simulations indicated that an air change rate of 5 a.c.h was required.

3.2 School 2

Simulation using an estimated average air change rate of 1 a.c.h. during the occupied period and 0.5 a.c.h. after 16:00, see Part 1(1), represented the best fit when compared to the monitored data, see Figure 6. During the period 12:00 to 12:45 an air change rate of 3 was used to reflect the increased rate occurring during this period due to door opening by the pupils entering and leaving the building, see Part 1(1). The computer model was useful in this case to corroborate the ventilation rates calculated from the monitored data(1), see Table 6.

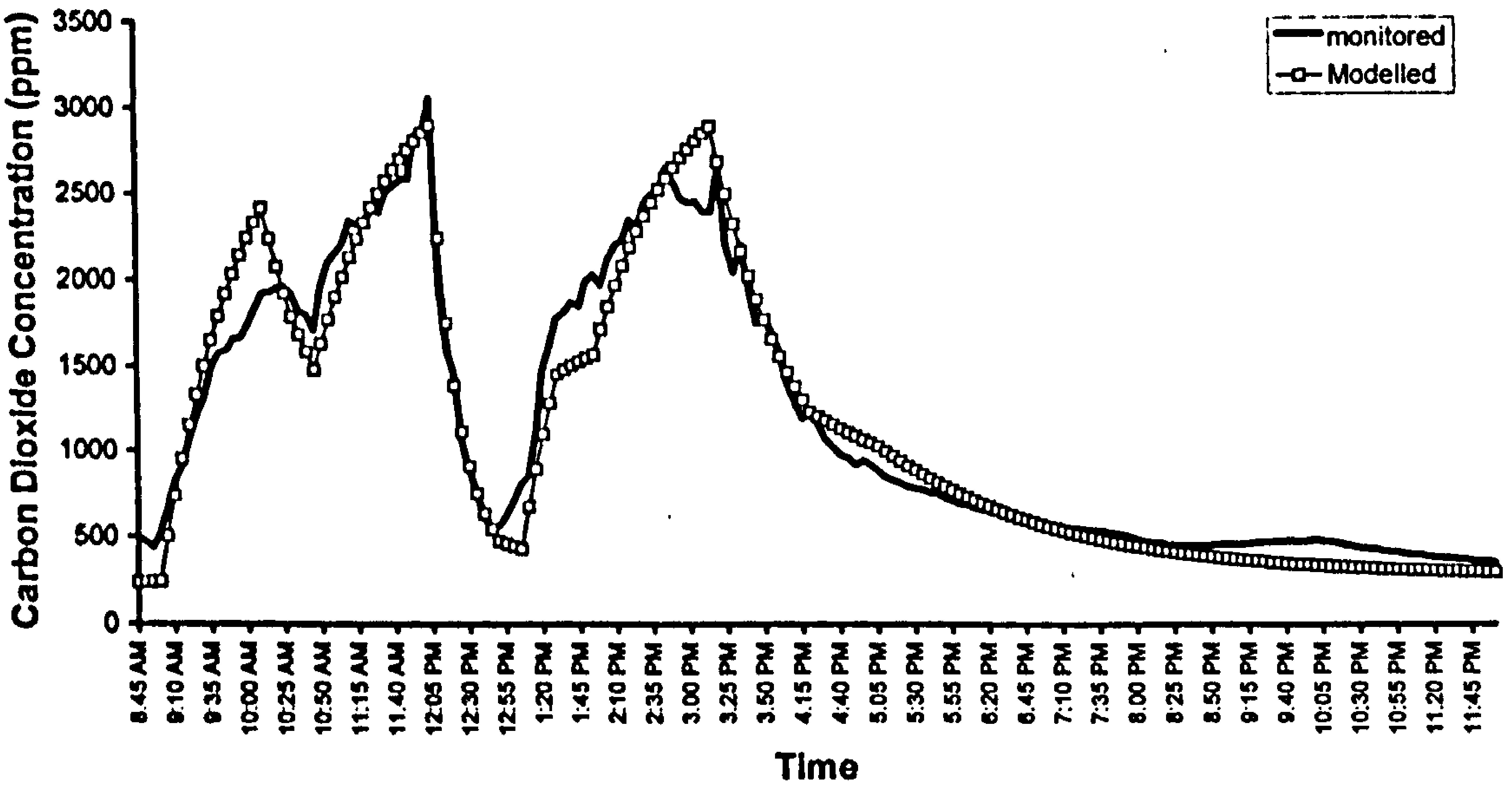

Figure 6. Best fit simulated carbon dioxide concentrations compared to monitored results, school 2.

Figure 7 shows modelled CO_2 concentrations against monitored CO_2 concentrations for school 2.

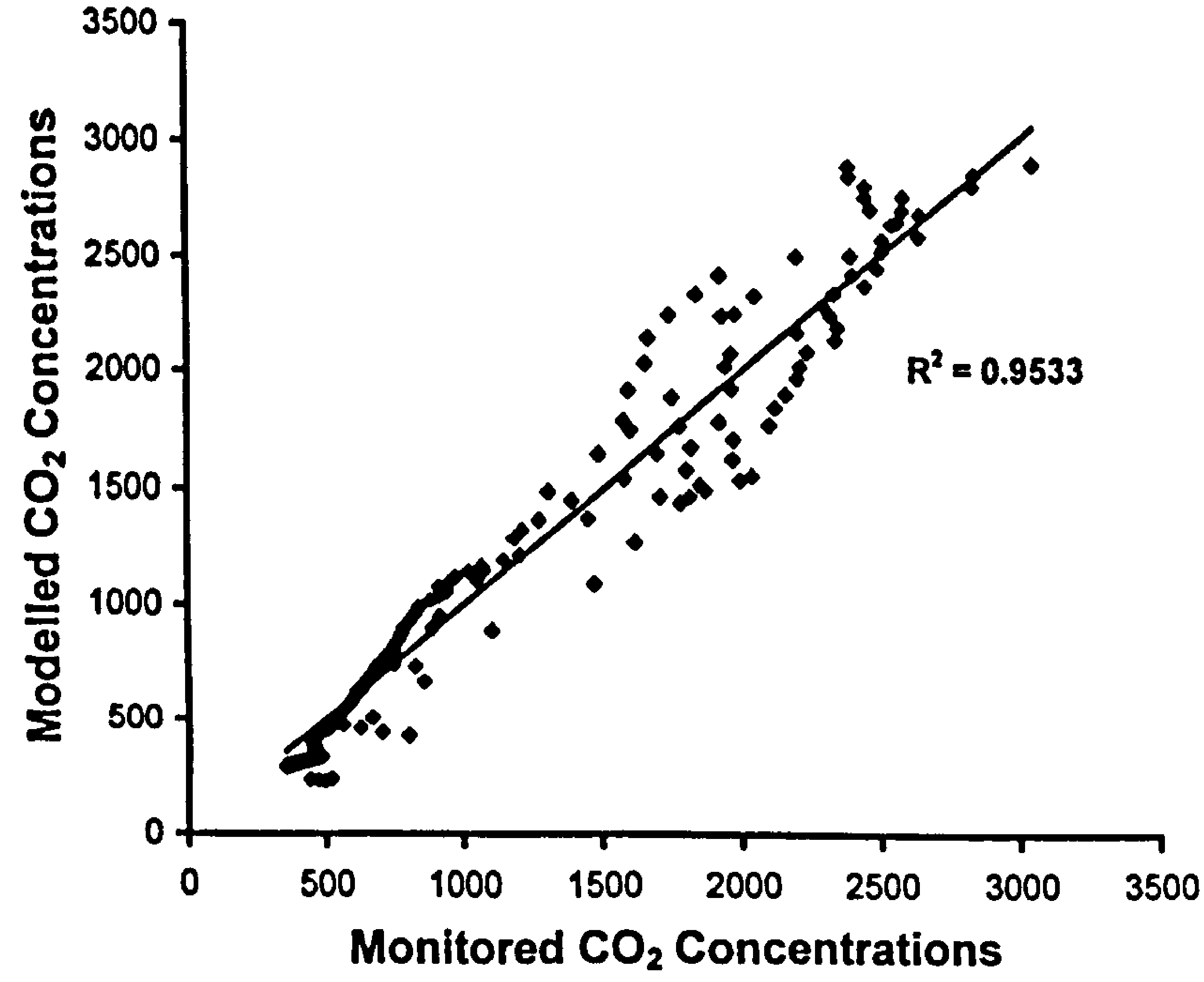

Figure 7. Modelled CO_2 concentrations against monitored CO_2 concentrations for school 2.

The model was capable of producing a better fit to the monitored data for school 2 than for school 1, compare Figures 5 and 7, for the reasons stated in Section 3.1.

Again, average air change rates of between 1 and 6 a.c.h., with lunch time and after school variations applied as for Figure 6, were modelled to examine the effects of increased ventilation rates for School 2, see Figure 8.

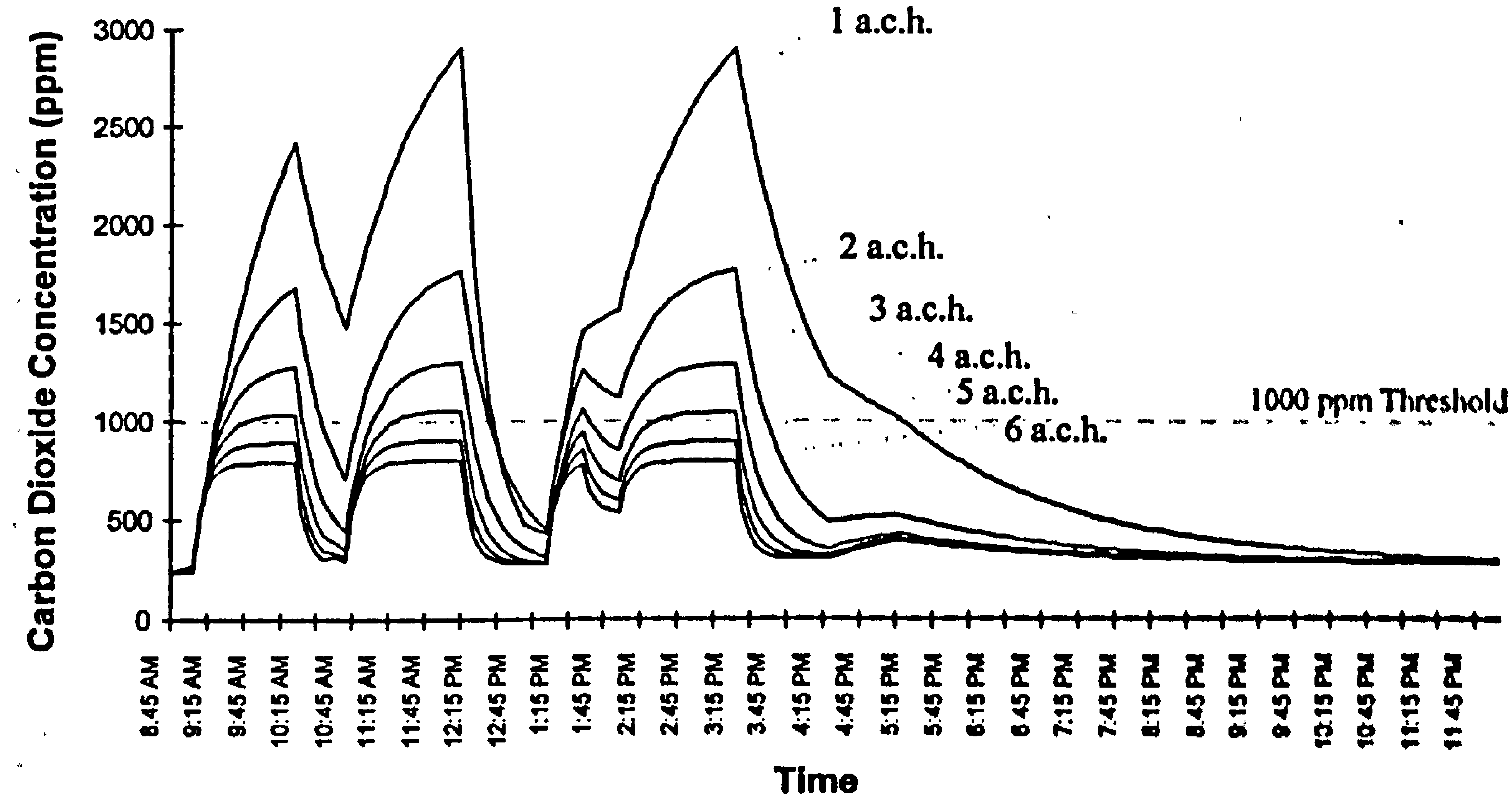

Figure 8. Simulated carbon dioxide concentrations for air change rates ranging from 1 to 6 during the occupied period - school 2.

In order to achieve satisfactory indoor air quality, i.e. CO_2 concentrations constantly below 1000 ppm, modelling indicated that an air change rate of 5 a.c.h is required. However, Figure 8 also indicates that an air change rate of 4 a.c.h. would provide air quality where the CO_2 concentration only marginally exceeds 1000 ppm during periods of occupancy. Interpolating reveals that a fresh air ventilation rate of approximately 4.2 a.c.h would prevent CO_2 concentrations exceeding the 1000 ppm threshold.

3.3 Summary of Ventilation Rate Monitoring and Requirements for the Two Schools

Table 7 shows the estimated average air change rates experienced in the two schools during normal occupancy, obtained from analysis of the monitored data and corroborated by the computer model. The equivalent per capita fresh air delivery rates estimated for each school are also shown.

Table 7. Estimates of average air change rates during occupied periods and equivalent per capita fresh air delivery rates from the monitored data and computer modelling.

School	Estimated Average a.c.h	Equivalent Fresh Air Delivery Rate l/s/person
1	2.9	4.90
2	1	1.97

Table 8 gives per capita fresh air ventilation rates required for the provision of acceptable air quality as determined using the computer model.

Table 8. Recommended air change rates in order to achieve acceptable indoor air quality estimated from computer modelling and the equivalent per capita fresh air delivery rates (assumes maximum occupancy of 60 pupils and 2 adults in each twin class base).

School	Recommended a.c.h (modelled)	Equivalent Fresh Air Delivery Rate l/s/person
1	5	8.17
2	4.2	7.99

CIBSE(8) recommends a minimum fresh air ventilation rate of 8 l/s/p for people working in offices (8.3 l/s/p in schools). The results for the schools, see Table 8, indicate that the results of this monitoring project are in close agreement with CIBSE recommendations with regard to the ventilation rates required to satisfy air quality requirements. However it does suggest that the recommendations of the DFEE's Building Bulletin 87(9), i.e. a minimum background ventilation rate of 3 l/s/p, are inadequate.

4. Conclusions

Both the observed data from the monitoring period(1) and calculations in this paper indicate that the metabolic carbon dioxide generation of children is higher than may be expected. This is due to (i) their relatively high average basal metabolic rates, see Figure 2, and (ii) their activity levels being relatively high compared to adults working in similar environments. These factors combined result in their metabolic CO_2 production rates being close to those of sedentary adults. Taking into account that the European guideline(7) also suggests a sensory pollution load for school aged children of between 1.2 and 1.3 times that of adults, the CO_2 concentration of the indoor air provides an indicator of indoor air quality that should be taken seriously.

Results obtained from the computer model indicate that air change rates of between 4.2 and 5 a.c.h. (7.99 - 8.17 l/s/p for schools 2 and 1 respectively) are required to maintain the CO_2 concentrations and hence air quality at acceptable levels (not exceeding 1000 ppm CO_2) throughout the occupied period.
The air change rate (a.c.h) values may appear high but it must be taken into account that the occupant densities in these school classrooms are high when compared to normal office adult occupant densities. The fact that the sensory pollution load of children is greater than for that of adults should also be taken into consideration.
Nevertheless, the results considered on a per capita basis are broadly in line with CIBSE recommendations(8), i.e. 8.3 l/s/p for schools. The results of this study show that when using realistic metabolic CO_2 production rates for children, fresh air ventilation rates in line with the CIBSE(8) recommendations are required and that the recommended minimum background rate of 3 l/s/p given in Building Bulletin 87(9) are inadequate.

Appendix 1. Example Calculation of Metabolic CO_2 Production Rate - Method 1
This example calculation is based on School 1 during the period from 08:55 - 10:00 of the first days monitoring. Input values indicated in [ ].
Using Equation 2:

$$M_{CO2} = \frac{VI(C_{indoor}(t) - C_{outdoor})}{1 - e^{-It}} \quad \text{.......... equation (2)}$$

For t = 3300 s
$C_{indoor}(t)$ = 1343 ppm = 2.4198 g/m^3
$C_{outdoor}$ = 305 ppm = 0.5495 g/m^3
V = 365 m^3
I = 2.9 a.c.h. = 0.8056 x 10^{-3} a.c.s.

$$M_{CO2} = \frac{365 \times 0.8056 \times 10^{-3}(2.4198 - 0.5495)}{1 - e^{-0.8056 \times 10^{-3} \times 3300}} = 0.5913 \text{ g/s}$$

The occupancy for this period is 57 (including 2 teachers), therefore

M^{*}_{CO2} = 10.4 mg/s/person

Appendix 2. Single Zone Dynamic Carbon Dioxide Concentration Model
The model uses a carbon dioxide balance method shown schematically in Figure 9.

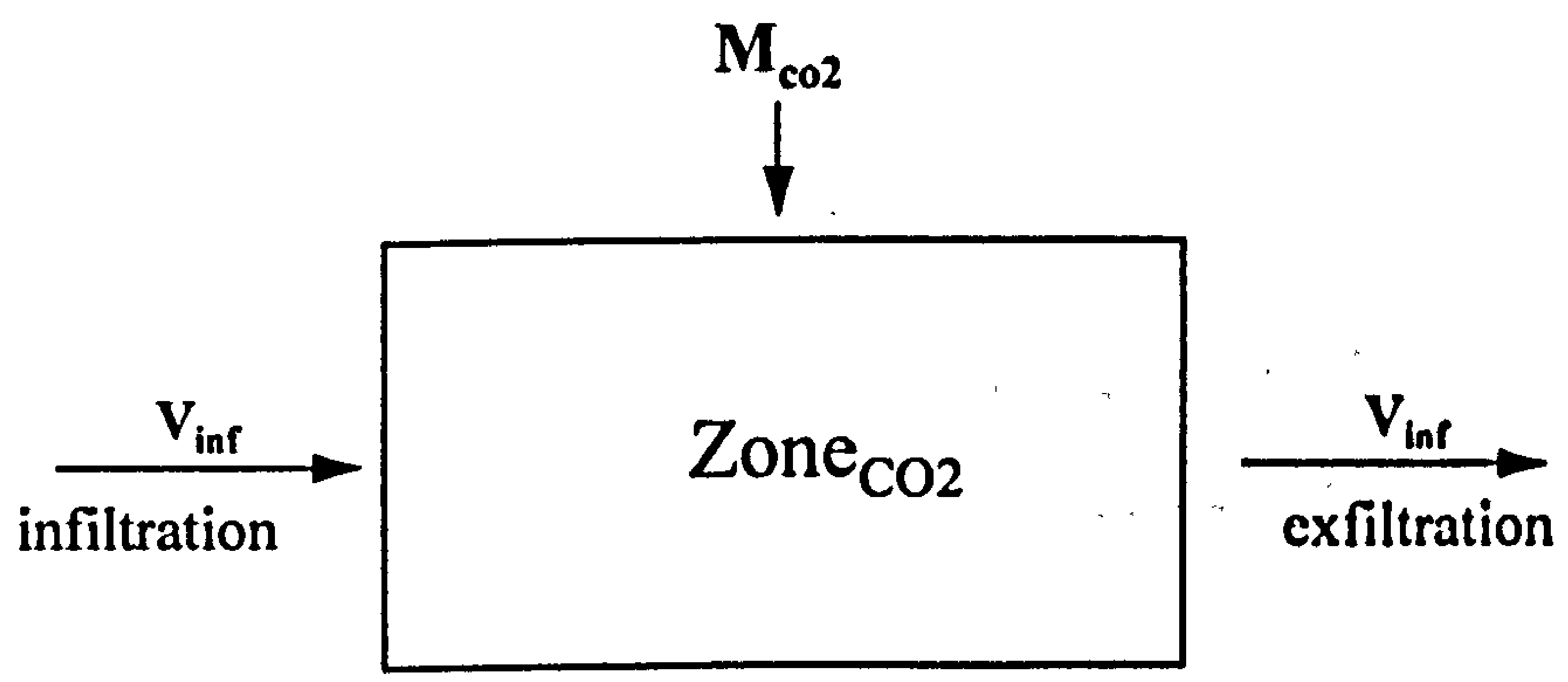

Figure 9. Schematic representation of zone carbon dioxide concentration balance model.

The zone CO_2 concentration, ZoneCO2, is calculated using Eqns. 6 to 11.

$d_{CO2} = G_{CO2} + R_{CO2}$ .... Equation (6)

where $G_{CO2} = P \times M^{*}_{CO2}$ .... Equation (7)
$R_{CO2} = V_{inf}\,(Z1_{CO2}\,(i-1) - C_{outdoor})$ .... Equation (8)

therefore substituting Equations 7 and 8 into 6 :-

$d_{CO2} = \{(P \times M^{*}_{CO2}) + V_{inf}[Z1_{CO2}(i-1) - C_{outdoor}]\}t^{*}$ ....Equation (9)
and
$Z2_{CO2}(i) = Z2_{CO2}(i-1) + d_{CO2}$ ....Equation (10)

to convert to a meaningful unit use the conversion

$$Zone_{CO2} = \frac{Z2_{CO2} \times 555}{V} \quad \text{(ppm)}$$ ....Equation (11)

Acknowledgments

The authors would like to thank Essex County Council, W.S. Atkins and Satchwell Control Systems who made this project possible.

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Appendix C :

Detailed Control Strategy Simulation Energy Use Results

The simulated energy use for the normal PID, fuzzy ventilation and fuzzy high level control strategies are presented for South, North, East and West main building facade orientations in Table C.1, Table C.2, Table C.3 and Table C.4 respectively.
The column headings referred to in the tables are:

Week = Simulated week number (e.g. week 1 = January 1 - 7)
Heat 1 = Heating energy use, PID strategy (kWh)
Heat 2 = Heating energy use, fuzzy ventilation strategy (kWh)
Heat 3 = Heating energy use, fuzzy high level strategy (kWh)
Cool 1 = Cooling energy use, PID strategy (kWh)
Cool 2 = Cooling energy use, fuzzy ventilation strategy (kWh)
Cool 3 = Cooling energy use, fuzzy high level strategy (kWh)
Humid 1 = Humidification energy use, PID strategy (kWh)
Humid 2 = Humidification energy use, fuzzy ventilation strategy (kWh)
Humid 3 = Humidification energy use, fuzzy high level strategy (kWh)
Total 1 = Total energy use, PID strategy (kWh)
Total 2 = Total energy use, fuzzy ventilation strategy (kWh)
Total 3 = Total energy use, fuzzy high level strategy (kWh)

Calculation Method

Rates of energy use for each of the HVAC components used in the Simulink model were logged every 10 minutes (600 seconds) as the simulations proceeded. Energy use was calculated by assuming that the rate of energy use remained constant until the next logged time step. The calculation method is described by Equation C.1.

$$E_{total} = T_{int} \sum_{t=0}^{t=168} E_{rate}$$

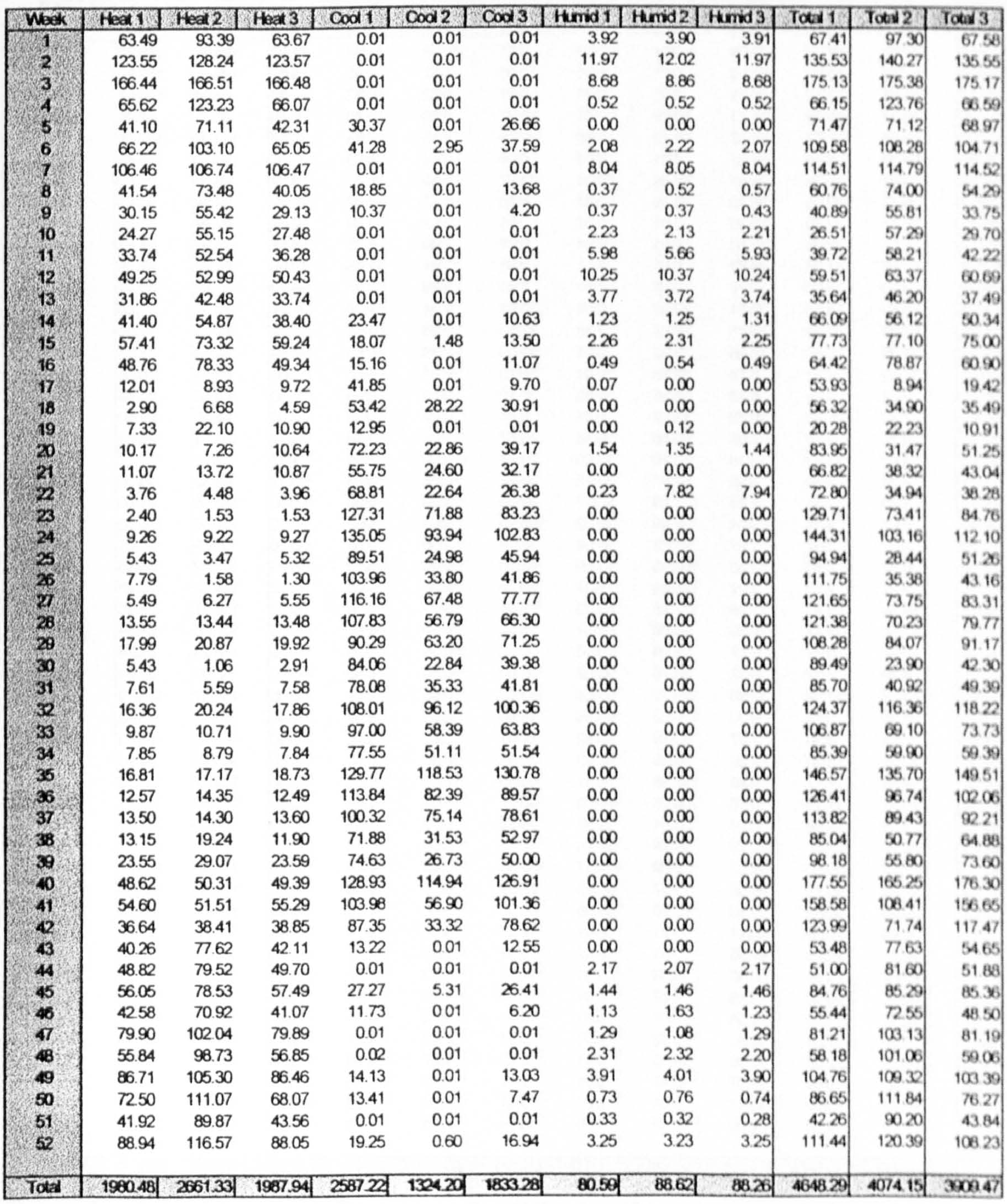
Equation C.1

where

E_{rate}	rate of energy use for the HVAC component under consideration at each logged time interval (W)
E_{total}	total weekly energy use for the HVAC plant component under consideration (Wh)
t	simulation time (hour)
T_{int}	logging time interval (seconds)

Week	Heat 1	Heat 2	Heat 3	Cool 1	Cool 2	Cool 3	Humid 1	Humid 2	Humid 3	Total 1	Total 2	Total 3
1	48.74	75.17	51.04	1.23	0.01	0.01	4.71	7.01	6.94	54.68	82.18	57.99
2	111.56	116.26	111.58	0.01	0.01	0.01	11.98	12.00	11.98	123.55	128.27	123.56
3	139.85	139.92	139.89	0.01	0.01	0.01	9.06	9.02	9.06	148.92	148.94	148.96
4	65.36	122.67	65.81	0.01	0.01	0.01	0.52	0.52	0.52	65.89	123.20	66.34
5	27.33	59.93	30.47	22.25	0.01	16.35	0.00	0.00	0.00	49.58	59.94	46.82
6	62.11	100.48	59.54	41.18	2.95	34.30	2.08	2.23	2.07	105.36	105.66	95.91
7	104.22	104.50	104.24	0.01	0.01	0.01	7.55	7.55	7.55	111.78	112.06	111.79
8	23.13	58.06	29.27	6.56	0.01	4.97	0.65	0.39	0.43	30.34	58.46	34.67
9	24.16	41.35	22.90	22.37	0.01	4.09	2.31	3.53	3.50	48.85	44.89	30.49
10	10.11	27.33	13.17	32.43	0.01	0.01	4.13	10.55	10.99	46.67	37.89	24.17
11	26.09	40.70	30.34	10.91	0.01	0.01	7.98	27.38	27.52	44.98	68.08	57.87
12	36.27	41.04	39.40	8.17	0.01	0.01	12.37	23.56	23.34	56.82	64.61	62.74
13	23.52	36.33	28.51	10.79	0.01	0.01	4.92	23.12	23.20	39.23	59.46	51.71
14	35.91	53.15	37.65	14.01	0.01	10.22	1.33	1.25	1.23	51.25	54.41	49.10
15	56.93	68.97	58.71	27.21	4.48	17.58	2.26	2.30	2.26	86.40	75.75	78.55
16	48.12	75.93	47.99	20.06	0.01	10.96	0.49	0.54	0.49	68.67	76.48	59.44
17	9.22	6.73	7.28	74.13	7.96	19.17	0.08	1.52	1.55	83.42	16.21	28.01
18	2.92	6.11	4.39	92.49	54.22	56.84	0.13	0.00	0.00	95.54	60.34	61.23
19	6.31	18.57	10.14	31.69	2.11	2.43	0.00	0.00	0.00	38.00	20.68	12.58
20	5.57	4.65	5.97	99.95	37.21	57.53	1.89	4.08	4.16	107.40	45.93	67.67
21	10.19	13.18	9.96	62.92	26.82	30.19	0.00	2.79	2.85	73.11	42.79	43.00
22	3.59	3.62	3.59	109.15	51.98	56.23	0.23	10.04	10.03	112.97	65.64	69.86
23	1.65	1.65	1.65	137.57	89.32	101.54	0.00	0.00	0.00	139.22	90.97	103.19
24	7.08	7.01	7.08	140.37	99.12	108.56	0.00	0.00	0.00	147.44	106.12	115.65
25	1.60	1.36	1.36	97.46	29.10	44.24	0.00	0.00	0.00	99.06	30.46	45.60
26	5.26	1.30	1.20	122.90	52.23	61.23	0.00	0.00	0.00	128.16	53.53	62.43
27	1.83	2.71	1.78	129.40	74.97	86.74	0.00	0.00	0.00	131.23	77.67	88.52
28	13.48	13.23	13.35	119.60	64.67	74.25	0.00	0.00	0.00	133.08	77.90	87.60
29	14.00	19.89	18.62	93.51	65.34	74.00	0.00	0.00	0.00	107.50	85.23	92.61
30	1.16	1.16	1.16	93.96	36.50	44.70	0.00	0.00	0.00	95.12	37.66	45.86
31	3.94	3.51	3.96	96.27	35.60	53.13	0.00	0.00	0.00	100.21	39.11	57.09
32	14.98	17.60	15.69	126.29	111.26	116.09	0.00	0.00	0.00	141.26	128.85	131.78
33	5.16	5.24	5.22	156.71	109.44	116.57	0.00	0.00	0.00	161.87	114.67	121.79
34	1.77	2.14	1.77	100.32	53.40	59.87	0.00	0.00	0.00	102.09	55.55	61.64
35	9.56	12.75	12.39	107.88	88.14	95.52	0.00	0.00	0.00	117.45	100.89	107.91
36	3.71	4.35	3.57	144.14	96.18	111.36	0.00	0.00	0.00	147.85	100.54	114.93
37	2.82	3.64	2.97	106.95	65.08	70.65	0.00	0.00	0.00	109.77	68.72	73.63
38	3.26	6.69	3.30	81.22	28.57	36.64	0.00	0.00	0.00	84.48	35.26	39.94
39	5.71	12.55	5.77	61.00	22.58	26.68	0.00	0.00	0.00	66.71	35.14	32.45
40	43.34	45.10	44.22	128.14	112.94	125.68	0.00	0.00	0.00	171.48	158.04	169.91
41	37.29	42.25	38.59	94.98	59.91	77.64	0.00	0.00	0.00	132.27	102.17	116.23
42	14.99	22.06	17.23	81.89	31.13	58.06	0.00	0.00	0.00	96.88	53.20	75.30
43	34.85	67.55	38.11	14.83	0.01	12.54	0.00	0.00	0.00	49.67	67.56	50.65
44	36.24	64.64	40.46	4.27	0.01	0.01	2.92	3.80	3.91	43.43	68.44	44.39
45	37.79	60.75	42.27	24.41	5.40	14.45	2.12	2.04	2.00	64.32	68.20	58.72
46	35.91	63.33	37.93	10.80	0.01	6.20	1.63	1.44	1.56	48.34	64.78	45.69
47	73.67	91.16	74.14	0.01	0.01	0.01	1.44	1.40	1.33	75.12	92.57	75.47
48	47.33	87.79	48.99	0.03	0.01	0.01	2.35	2.41	2.34	49.70	90.21	51.34
49	58.87	72.96	60.97	15.12	0.01	13.02	4.49	4.43	4.57	78.47	77.40	78.56
50	68.40	105.08	64.40	13.31	0.01	7.48	0.71	0.73	0.73	82.43	105.82	72.61
51	41.35	88.89	42.99	0.01	0.01	0.01	0.35	0.33	0.37	41.71	89.23	43.37
52	71.03	101.58	70.13	18.96	0.57	11.69	4.09	5.47	5.40	94.08	107.62	87.23
Total	1579.23	2244.59	1633.12	3009.82	1519.37	1929.53	94.77	171.43	171.88	4683.82	3935.38	3734.53

Table C.1 Detailed energy use for the PID, fuzzy ventilation and high level fuzzy control strategy simulations for South orientated main building facade.



Week	Heat 1	Heat 2	Heat 3	Cool 1	Cool 2	Cool 3	Humid 1	Humid 2	Humid 3	Total 1	Total 2	Total 3
1	63.49	93.39	63.67	0.01	0.01	0.01	3.92	3.90	3.91	67.41	97.30	67.58
2	123.55	128.24	123.57	0.01	0.01	0.01	11.97	12.02	11.97	135.53	140.27	135.55
3	166.44	166.51	166.48	0.01	0.01	0.01	8.68	8.86	8.68	175.13	175.38	175.17
4	65.62	123.23	66.07	0.01	0.01	0.01	0.52	0.52	0.52	66.15	123.76	66.59
5	41.10	71.11	42.31	30.37	0.01	26.66	0.00	0.00	0.00	71.47	71.12	68.97
6	66.22	103.10	65.05	41.28	2.95	37.59	2.08	2.22	2.07	109.58	108.28	104.71
7	106.46	106.74	106.47	0.01	0.01	0.01	8.04	8.05	8.04	114.51	114.79	114.52
8	41.54	73.48	40.05	18.85	0.01	13.68	0.37	0.52	0.57	60.76	74.00	54.29
9	30.15	55.42	29.13	10.37	0.01	4.20	0.37	0.37	0.43	40.89	55.81	33.75
10	24.27	55.15	27.48	0.01	0.01	0.01	2.23	2.13	2.21	26.51	57.29	29.70
11	33.74	52.54	36.28	0.01	0.01	0.01	5.98	5.66	5.93	39.72	58.21	42.22
12	49.25	52.99	50.43	0.01	0.01	0.01	10.25	10.37	10.24	59.51	63.37	60.69
13	31.86	42.48	33.74	0.01	0.01	0.01	3.77	3.72	3.74	35.64	46.20	37.49
14	41.40	54.87	38.40	23.47	0.01	10.63	1.23	1.25	1.31	66.09	56.12	50.34
15	57.41	73.32	59.24	18.07	1.48	13.50	2.26	2.31	2.25	77.73	77.10	75.00
16	48.76	78.33	49.34	15.16	0.01	11.07	0.49	0.54	0.49	64.42	78.87	60.90
17	12.01	8.93	9.72	41.85	0.01	9.70	0.07	0.00	0.00	53.93	8.94	19.42
18	2.90	6.68	4.59	53.42	28.22	30.91	0.00	0.00	0.00	56.32	34.90	35.49
19	7.33	22.10	10.90	12.95	0.01	0.01	0.00	0.12	0.00	20.28	22.23	10.91
20	10.17	7.26	10.64	72.23	22.86	39.17	1.54	1.35	1.44	83.95	31.47	51.25
21	11.07	13.72	10.87	55.75	24.60	32.17	0.00	0.00	0.00	66.82	38.32	43.04
22	3.76	4.48	3.96	68.81	22.64	26.38	0.23	7.82	7.94	72.80	34.94	38.28
23	2.40	1.53	1.53	127.31	71.88	83.23	0.00	0.00	0.00	129.71	73.41	84.76
24	9.26	9.22	9.27	135.05	93.94	102.83	0.00	0.00	0.00	144.31	103.16	112.10
25	5.43	3.47	5.32	89.51	24.98	45.94	0.00	0.00	0.00	94.94	28.44	51.26
26	7.79	1.58	1.30	103.96	33.80	41.86	0.00	0.00	0.00	111.75	35.38	43.16
27	5.49	6.27	5.55	116.16	67.48	77.77	0.00	0.00	0.00	121.65	73.75	83.31
28	13.55	13.44	13.48	107.83	56.79	66.30	0.00	0.00	0.00	121.38	70.23	79.77
29	17.99	20.87	19.92	90.29	63.20	71.25	0.00	0.00	0.00	108.28	84.07	91.17
30	5.43	1.06	2.91	84.06	22.84	39.38	0.00	0.00	0.00	89.49	23.90	42.30
31	7.61	5.59	7.58	78.08	35.33	41.81	0.00	0.00	0.00	85.70	40.92	49.39
32	16.36	20.24	17.86	108.01	96.12	100.36	0.00	0.00	0.00	124.37	116.36	118.22
33	9.87	10.71	9.90	97.00	58.39	63.83	0.00	0.00	0.00	106.87	69.10	73.73
34	7.85	8.79	7.84	77.55	51.11	51.54	0.00	0.00	0.00	85.39	59.90	59.39
35	16.81	17.17	18.73	129.77	118.53	130.78	0.00	0.00	0.00	146.57	135.70	149.51
36	12.57	14.35	12.49	113.84	82.39	89.57	0.00	0.00	0.00	126.41	96.74	102.06
37	13.50	14.30	13.60	100.32	75.14	78.61	0.00	0.00	0.00	113.82	89.43	92.21
38	13.15	19.24	11.90	71.88	31.53	52.97	0.00	0.00	0.00	85.04	50.77	64.88
39	23.55	29.07	23.59	74.63	26.73	50.00	0.00	0.00	0.00	98.18	55.80	73.60
40	48.62	50.31	49.39	128.93	114.94	126.91	0.00	0.00	0.00	177.55	165.25	176.30
41	54.60	51.51	55.29	103.98	56.90	101.36	0.00	0.00	0.00	158.58	108.41	156.65
42	36.64	38.41	38.85	87.35	33.32	78.62	0.00	0.00	0.00	123.99	71.74	117.47
43	40.26	77.62	42.11	13.22	0.01	12.55	0.00	0.00	0.00	53.48	77.63	54.65
44	48.82	79.52	49.70	0.01	0.01	0.01	2.17	2.07	2.17	51.00	81.60	51.88
45	56.05	78.53	57.49	27.27	5.31	26.41	1.44	1.46	1.46	84.76	85.29	85.36
46	42.58	70.92	41.07	11.73	0.01	6.20	1.13	1.63	1.23	55.44	72.55	48.50
47	79.90	102.04	79.89	0.01	0.01	0.01	1.29	1.08	1.29	81.21	103.13	81.19
48	55.84	98.73	56.85	0.02	0.01	0.01	2.31	2.32	2.20	58.18	101.06	59.06
49	86.71	105.30	86.46	14.13	0.01	13.03	3.91	4.01	3.90	104.76	109.32	103.39
50	72.50	111.07	68.07	13.41	0.01	7.47	0.73	0.76	0.74	86.65	111.84	76.27
51	41.92	89.87	43.56	0.01	0.01	0.01	0.33	0.32	0.28	42.26	90.20	43.84
52	88.94	116.57	88.05	19.25	0.60	16.94	3.25	3.23	3.25	111.44	120.39	108.23
Total	1980.48	2661.33	1987.94	2587.22	1324.20	1833.28	80.59	88.62	88.26	4648.29	4074.15	3909.47

Table C.2 Detailed energy use for the PID, fuzzy ventilation and high level fuzzy control strategy simulations for North orientated main building facade.

Week	Heat 1	Heat 2	Heat 3	Cool 1	Cool 2	Cool 3	Humid 1	Humid 2	Humid 3	Total 1	Total 2	Total 3
1	62.41	92.25	62.59	0.01	0.01	0.01	3.94	3.95	3.94	66.37	96.21	66.54
2	122.96	127.65	122.98	0.01	0.01	0.01	11.99	12.04	11.99	134.96	139.70	134.98
3	164.99	165.06	165.03	0.01	0.01	0.01	8.67	8.85	8.67	173.66	173.92	173.70
4	65.51	123.12	65.96	0.01	0.01	0.01	0.52	0.52	0.52	66.04	123.65	66.49
5	40.11	69.99	41.21	30.16	0.01	26.27	0.00	0.00	0.00	70.27	69.99	67.48
6	65.73	102.67	64.37	41.22	2.95	37.53	2.08	2.23	2.07	109.03	107.85	103.97
7	106.30	106.58	106.31	0.01	0.01	0.01	8.04	8.05	8.04	114.35	114.64	114.36
8	39.82	70.75	38.67	18.85	0.01	13.67	0.38	0.51	0.57	59.05	71.28	52.91
9	29.15	53.05	28.12	10.36	0.01	4.18	0.47	0.42	0.47	39.98	53.47	32.78
10	20.14	48.99	23.70	0.01	0.01	0.01	2.82	2.69	2.75	22.97	51.69	26.46
11	29.66	46.88	32.54	0.01	0.01	0.01	7.30	8.23	8.57	36.97	55.12	41.13
12	43.57	47.26	44.87	0.01	0.01	0.01	10.94	11.08	10.98	54.52	58.35	55.86
13	28.53	39.03	30.70	0.01	0.01	0.01	3.38	3.47	3.49	31.93	42.51	34.20
14	36.49	54.55	38.31	12.93	0.01	10.61	1.24	1.25	1.31	50.66	55.80	50.23
15	57.33	71.29	59.16	19.54	1.48	13.50	2.26	2.31	2.26	79.13	75.08	74.92
16	48.29	76.93	48.66	15.90	0.01	11.06	0.49	0.54	0.49	64.68	77.48	60.21
17	11.09	8.32	8.74	52.98	0.01	10.10	0.07	0.00	0.00	64.14	8.33	18.84
18	2.64	5.89	4.18	66.36	34.65	37.10	0.00	0.00	0.00	69.00	40.54	41.28
19	7.10	21.46	10.78	18.29	0.01	0.01	0.00	0.13	0.00	25.39	21.60	10.79
20	9.21	4.48	9.65	90.48	26.18	46.87	2.02	3.18	3.47	101.71	33.83	60.00
21	10.62	13.12	10.18	60.10	19.96	20.72	0.00	1.19	1.63	70.72	34.27	32.53
22	3.23	3.79	3.56	87.97	30.18	34.22	0.32	9.83	10.02	91.52	43.80	47.79
23	1.33	1.33	1.33	127.23	80.07	92.08	0.00	0.00	0.00	128.56	81.40	93.41
24	9.01	9.01	9.04	134.99	95.32	103.99	0.00	0.00	0.00	144.00	104.33	113.03
25	1.07	1.07	1.07	91.62	20.54	32.99	0.00	0.00	0.00	92.69	21.61	34.05
26	0.87	0.86	0.86	106.95	43.30	53.10	0.00	0.00	0.00	107.82	44.15	53.96
27	2.27	2.58	2.27	126.84	75.37	86.99	0.00	0.00	0.00	129.10	77.95	89.26
28	13.33	13.22	13.26	117.28	62.34	72.01	0.00	0.00	0.00	130.61	75.56	85.26
29	13.54	19.77	18.60	93.46	64.57	73.09	0.00	0.00	0.00	107.00	84.34	91.69
30	0.87	0.87	0.87	88.09	30.35	36.92	0.00	0.00	0.00	88.96	31.23	37.80
31	6.19	2.52	6.12	89.78	26.02	46.00	0.00	0.00	0.00	95.96	28.54	52.12
32	13.32	11.15	12.86	120.75	92.64	106.86	0.00	0.00	0.00	134.07	103.79	119.72
33	8.96	9.58	9.00	114.82	68.95	75.95	0.00	0.00	0.00	123.78	78.53	84.95
34	2.54	3.30	2.57	83.70	49.42	44.41	0.00	0.00	0.00	86.24	52.73	46.98
35	10.64	14.30	13.56	94.83	83.95	88.44	0.00	0.00	0.00	105.47	98.25	102.00
36	9.48	11.12	9.40	113.66	78.41	83.56	0.00	0.00	0.00	123.14	89.53	92.96
37	10.53	11.15	10.66	106.26	76.06	80.17	0.00	0.00	0.00	116.79	87.21	90.83
38	3.15	15.69	5.04	51.41	31.86	34.92	0.00	0.00	0.00	54.55	47.55	39.96
39	20.22	27.57	20.29	64.24	26.74	37.15	0.00	0.00	0.00	84.45	54.31	57.45
40	47.79	49.50	48.57	128.69	114.47	126.63	0.00	0.00	0.00	176.48	163.97	175.19
41	41.32	49.79	44.56	79.67	56.85	73.69	0.00	0.00	0.00	120.98	106.64	118.25
42	29.33	32.62	29.60	83.58	32.35	64.35	0.00	0.00	0.00	112.91	64.96	93.95
43	38.49	73.66	40.47	13.21	0.01	12.54	0.00	0.00	0.00	51.70	73.67	53.01
44	46.11	76.32	47.05	0.01	0.01	0.01	2.26	2.07	2.26	48.38	78.40	49.32
45	46.82	74.54	50.10	15.08	5.31	14.50	1.32	1.37	1.34	63.21	81.22	65.93
46	40.25	69.30	40.46	8.87	0.01	6.20	1.26	1.64	1.22	50.38	70.95	47.88
47	79.15	101.18	79.14	0.01	0.01	0.01	1.32	1.11	1.32	80.48	102.30	80.47
48	54.35	97.01	55.41	0.02	0.01	0.01	2.30	2.31	2.18	56.67	99.33	57.60
49	83.81	102.38	83.56	14.13	0.01	13.03	3.87	3.98	3.86	101.81	106.36	100.45
50	72.31	110.89	67.87	13.41	0.01	7.47	0.73	0.76	0.74	86.45	111.66	76.08
51	41.77	89.69	43.42	0.01	0.01	0.01	0.34	0.32	0.29	42.12	90.01	43.71
52	87.89	115.53	87.00	19.25	0.60	16.94	3.25	3.23	3.25	110.39	119.36	107.19
Total	1841.58	2550.58	1874.27	2627.05	1331.11	1749.93	83.58	97.27	97.71	4552.22	3978.95	3721.91

Table C.3 Detailed energy use for the PID, fuzzy ventilation and high level fuzzy control strategy simulations for East orientated main building facade.

Week	Heat 1	Heat 2	Heat 3	Cool 1	Cool 2	Cool 3	Humid 1	Humid 2	Humid 3	Total 1	Total 2	Total 3
1	59.46	89.06	59.80	0.01	0.01	0.01	4.13	4.13	4.05	63.60	93.20	63.86
2	118.81	123.50	118.83	0.01	0.01	0.01	11.75	11.77	11.75	130.57	135.28	130.58
3	156.06	156.13	156.10	0.01	0.01	0.01	8.67	8.77	8.67	164.74	164.91	164.78
4	65.58	122.88	66.03	0.01	0.01	0.01	0.52	0.52	0.52	66.11	123.41	66.56
5	38.03	66.96	39.96	30.63	0.01	26.36	0.00	0.00	0.00	68.66	66.97	66.32
6	65.38	102.49	63.86	41.28	2.95	37.15	2.08	2.22	2.07	108.74	107.67	103.07
7	104.90	105.18	104.91	0.01	0.01	0.01	7.52	7.52	7.52	112.43	112.71	112.44
8	34.63	67.51	35.38	16.22	0.01	11.67	0.65	0.45	0.42	51.49	67.97	47.47
9	26.79	48.99	25.51	15.68	0.01	4.19	1.17	1.16	1.23	43.64	50.16	30.93
10	14.76	40.36	17.91	12.21	0.01	0.21	3.22	5.17	5.35	30.19	45.54	23.47
11	31.85	50.06	34.48	4.19	0.01	0.01	7.29	15.42	15.54	43.34	65.49	50.03
12	42.63	47.05	44.85	2.12	0.01	0.01	10.95	12.87	12.75	55.70	59.93	57.61
13	25.65	38.03	29.95	1.24	0.01	0.01	4.61	11.37	11.42	31.50	49.41	41.38
14	40.18	54.30	38.13	22.61	0.01	10.47	1.29	1.25	1.29	64.09	55.56	49.89
15	56.78	69.98	58.49	21.30	1.75	14.46	2.27	2.31	2.26	80.34	74.04	75.21
16	48.29	76.67	48.14	18.91	0.01	10.98	0.48	0.71	0.79	67.69	77.39	59.90
17	10.56	7.73	8.81	60.92	6.77	17.84	0.07	1.29	1.23	71.55	15.79	27.88
18	2.92	6.29	4.10	80.99	43.63	47.03	0.00	0.00	0.00	83.91	49.93	51.13
19	5.29	17.57	8.20	27.15	3.13	3.71	0.00	0.00	0.00	32.44	20.70	11.91
20	7.99	6.20	8.29	90.66	34.96	51.39	1.52	1.68	1.78	100.17	42.83	61.46
21	9.34	12.62	9.64	64.04	29.46	33.39	0.00	1.47	1.73	73.37	43.55	44.76
22	3.77	4.03	3.78	112.97	54.50	58.12	0.97	9.91	10.25	117.71	68.45	72.14
23	1.99	1.65	1.65	143.66	89.51	101.43	0.00	0.00	0.00	145.66	91.16	103.08
24	7.45	7.10	7.31	159.51	109.75	124.34	0.00	0.00	0.00	166.96	116.84	131.65
25	4.08	3.66	3.96	101.26	33.69	52.28	0.00	0.00	0.00	105.33	37.34	56.24
26	7.80	1.70	1.37	126.31	52.91	60.90	0.00	0.00	0.00	134.11	54.61	62.27
27	3.83	4.84	3.87	131.09	76.16	87.86	0.00	0.00	0.00	134.92	81.00	91.73
28	13.44	13.31	13.36	116.67	62.89	72.71	0.00	0.00	0.00	130.11	76.21	86.07
29	14.66	20.04	19.11	93.11	67.10	75.97	0.00	0.00	0.00	107.77	87.13	95.08
30	3.32	1.16	1.16	93.36	33.50	45.39	0.00	0.00	0.00	96.69	34.66	46.55
31	5.02	4.64	4.81	91.27	41.28	49.23	0.00	0.00	0.00	96.29	45.92	54.03
32	15.98	18.06	16.58	117.01	102.07	106.69	0.00	0.00	0.00	133.00	120.13	123.27
33	7.40	7.54	7.43	138.00	90.42	96.38	0.00	0.00	0.00	145.40	97.97	103.81
34	5.85	6.16	5.85	89.81	45.27	50.32	0.00	0.00	0.00	95.66	51.43	56.17
35	9.39	12.44	12.13	101.78	91.24	96.64	0.00	0.00	0.00	111.18	103.67	108.78
36	6.54	8.28	6.45	124.18	89.19	93.25	0.00	0.00	0.00	130.72	97.47	99.70
37	7.34	8.65	7.97	91.45	68.94	72.70	0.00	0.00	0.00	98.79	77.59	80.67
38	7.16	9.75	6.93	67.92	23.10	31.34	0.00	0.00	0.00	75.08	32.85	38.27
39	12.12	18.91	11.84	65.86	24.86	41.13	0.00	0.00	0.00	77.98	43.78	52.97
40	45.32	47.11	46.10	128.63	114.23	126.37	0.00	0.00	0.00	173.95	161.33	172.47
41	40.79	45.16	41.46	92.13	56.32	81.00	0.00	0.00	0.00	132.92	101.48	122.47
42	25.26	32.38	27.54	81.26	33.13	64.81	0.00	0.00	0.00	106.52	65.51	92.34
43	38.73	74.66	41.05	13.22	0.01	12.55	0.00	0.00	0.00	51.95	74.67	53.60
44	44.76	74.23	46.48	0.01	0.01	0.01	2.11	2.46	2.65	46.88	76.70	49.14
45	51.34	75.21	53.27	26.91	5.32	26.05	1.50	1.35	1.38	79.75	81.87	80.70
46	38.73	68.67	39.77	7.61	0.01	6.20	1.27	1.17	1.29	47.61	69.84	47.26
47	78.12	98.63	78.12	0.01	0.01	0.01	1.18	1.33	1.18	79.31	99.96	79.30
48	53.77	95.96	54.78	0.02	0.01	0.01	2.38	2.37	2.29	56.17	98.34	57.08
49	78.01	93.46	78.20	14.13	0.01	13.03	4.17	4.05	4.22	96.32	97.52	95.44
50	70.43	108.10	66.30	13.30	0.01	7.46	0.62	0.77	0.63	84.35	108.88	74.39
51	41.71	89.53	43.35	0.01	0.01	0.01	0.37	0.33	0.36	42.09	89.86	43.72
52	81.80	109.96	80.83	19.24	0.59	16.90	2.94	2.77	2.94	103.98	113.33	100.67
Total	1791.79	2474.55	1814.18	2871.91	1488.78	1940.00	85.69	116.60	117.53	4749.40	4079.93	3871.71

Table C.4 Detailed energy use for the PID, fuzzy ventilation and high level fuzzy control strategy simulations for West orientated main building facade.

Appendix D : Detailed Control Strategy Performance Assessment Results

The simulated performances of the PID, fuzzy ventilation and fuzzy high level control strategies are presented for South, North, East and West main building facade orientations in Table D.1, Table D.2, Table D.3 and Table D.4 respectively. Absolute error from the preferred (middle) set point was used as the performance assessment criteria

The column headings used in the tables are:

Week	Simulated week number (e.g. week 1 = January 1 - 7)
Temp 1	temperature - normal PID strategy
Temp 2	temperature - fuzzy ventilation strategy
Temp 3	temperature - fuzzy high level strategy
RH 1	RH - normal PID strategy
RH 2	RH - fuzzy ventilation strategy
RH 3	RH - fuzzy high level strategy
CO_2 1	CO_2 - normal PID strategy
CO_2 2	CO_2 - fuzzy ventilation strategy
CO_2 3	CO_2 - fuzzy high level strategy

Calculation Methods

The calculation methods used to assess the environmental zone conditions provided by the control strategies are described below. Environmental conditions provided were assessed for the times during which the HVAC plant was operational.

Temperature and humidity

The logged values of the zone temperature or relative humidity during the occupied period were subtracted from the preferred set point. The absolute of these values were then calculated and the weekly average used as an indication of how well the control strategies were able to provide environmental conditions with respect to the preferred set point. This calculation method is described by Equation D.1.

$$P_{error} = \frac{\sum_{t=0}^{t=168} \sum_{t=PlantStart}^{t=PlantFinish} abs(T_z - T_{pref})}{N}$$

Equation D.1

where

abs	absolute value
N	number of logged values
P_{error}	zone parameter weekly absolute error from preferred set point (°C / %RH)
PlantFinish	HVAC plant operation finish time (hour)
PlantStart	HVAC plant operation start time (hour)
t	simulation time (hour)
T_z	logged simulation zone temperature (°C)
T_{pref}	zone temperature preferred set point (°C)

Air Quality (CO_2 concentration)

Air quality provision within the zone was assessed by calculating the average of the logged CO_2 concentrations recorded during the periods when the HVAC plant was operational. The calculation method is described by Equation D.2.

$$CO2_{av} = \frac{\sum_{t=0}^{t=168} \sum_{t=PlantStart}^{t=PlantFinish} CO_2}{N}$$

Equation D.2

where

$CO2_{av}$	average weekly zone CO_2 concentration (ppm)
N	number of logged values
PlantFinish	HVAC plant operation finish time (hour)
PlantStart	HVAC plant operation start time (hour)
t	simulation time (hour)
CO_2	logged simulation zone carbon dioxide concentration (ppm)

Week	Average Absolute Error from Preferred Set Point						Mean		
	Temp 1	Temp 2	Temp 3	RH 1	RH 2	RH 3	CO_2 1	CO_2 2	CO_2 3
1	1.60	1.75	1.54	8.44	6.01	8.56	900.99	758.90	865.30
2	2.14	2.14	2.14	7.46	6.93	7.46	900.99	879.86	901.04
3	2.10	2.10	2.10	8.44	8.44	8.43	900.99	901.07	901.02
4	1.96	2.24	2.02	9.71	4.10	9.56	900.99	686.67	889.49
5	1.83	2.02	1.56	12.35	8.73	11.78	900.99	604.60	800.56
6	2.08	2.17	2.06	16.07	10.16	15.78	900.99	605.96	870.94
7	2.19	2.18	2.19	5.63	5.64	5.63	900.99	897.70	901.03
8	1.59	1.85	1.26	9.82	7.13	9.40	900.99	645.40	792.08
9	1.59	1.70	1.15	10.25	8.26	10.52	900.99	650.72	788.77
10	1.69	1.31	1.12	8.52	9.04	10.68	900.99	657.44	743.04
11	1.53	1.46	1.00	7.20	6.26	7.42	900.99	756.74	822.40
12	1.58	1.11	1.04	6.63	7.06	7.25	900.99	817.60	831.19
13	1.58	0.99	0.86	9.17	8.55	9.87	900.99	744.63	787.85
14	1.75	1.88	1.57	9.03	6.54	8.22	900.99	708.78	845.60
15	1.80	2.14	1.79	8.81	8.37	8.94	900.99	715.46	820.12
16	1.96	1.96	1.88	9.44	6.67	9.87	900.99	699.94	850.98
17	1.95	1.19	1.33	9.33	8.99	9.75	900.99	612.97	675.13
18	2.03	1.31	1.40	7.06	6.31	6.36	900.99	626.75	662.54
19	1.66	1.31	1.00	7.12	7.72	8.29	900.99	649.60	716.59
20	2.11	1.36	1.58	8.53	7.52	8.66	900.99	591.01	660.96
21	1.75	1.09	1.06	11.74	11.99	12.01	900.99	604.12	684.21
22	2.12	1.62	1.76	4.62	7.20	7.26	900.99	619.81	635.51
23	2.14	2.08	2.18	10.03	8.20	8.22	900.99	615.89	666.00
24	2.11	1.82	2.02	12.54	12.82	12.48	900.99	679.03	723.16
25	2.11	1.73	1.91	12.92	9.57	10.23	900.99	580.16	648.34
26	2.19	1.91	2.06	9.37	6.96	7.18	900.99	580.29	616.84
27	2.10	1.89	2.04	10.20	8.81	8.72	900.99	618.36	660.32
28	2.22	1.90	2.04	11.72	9.52	9.94	900.99	633.98	671.61
29	1.92	1.73	1.74	12.02	11.99	12.01	900.99	674.53	753.47
30	2.12	1.58	1.81	10.21	8.02	7.82	900.99	584.02	626.47
31	2.17	1.42	1.82	12.29	9.95	10.17	900.99	586.53	674.57
32	2.11	1.88	1.86	13.55	12.81	13.20	900.99	706.25	748.22
33	2.19	1.83	2.01	8.01	7.28	7.21	900.99	649.50	675.50
34	2.03	1.39	1.63	8.92	9.23	9.01	900.99	620.30	654.93
35	2.14	1.51	1.57	14.24	14.95	14.73	900.99	678.01	731.82
36	2.08	1.67	1.90	10.30	9.57	9.85	900.99	642.01	688.22
37	2.05	1.48	1.60	12.49	11.04	11.16	900.99	663.14	694.65
38	2.01	1.46	1.50	9.76	8.26	8.14	900.99	591.02	641.70
39	1.42	1.42	1.32	13.07	10.59	10.21	900.99	607.58	679.24
40	1.95	1.99	1.96	17.67	17.75	17.71	900.99	791.74	873.03
41	2.01	1.89	1.92	14.88	14.33	14.15	900.99	699.53	801.91
42	1.82	1.47	1.53	15.62	13.03	13.49	900.99	618.23	771.64
43	1.68	1.88	1.43	9.98	6.73	10.13	900.99	655.92	837.31
44	1.57	1.54	1.24	8.61	6.67	8.78	900.99	727.41	827.91
45	1.73	1.71	1.44	10.53	8.67	10.15	900.99	669.84	801.59
46	1.69	1.75	1.59	11.87	8.67	12.13	900.99	709.11	842.39
47	1.90	2.01	1.91	5.91	4.24	6.01	900.99	812.37	892.95
48	1.77	2.00	1.80	10.83	6.87	10.57	900.99	725.84	875.50
49	1.81	1.79	1.66	9.43	7.22	9.54	900.99	760.48	864.37
50	2.14	2.24	2.10	9.38	4.27	9.08	900.99	706.83	890.89
51	1.70	2.24	1.85	10.79	5.80	10.37	900.99	672.44	865.85
52	1.90	1.77	1.73	13.09	9.30	12.72	900.99	715.73	865.51
Annual Mean	1.91	1.73	1.67	10.30	8.67	9.94	900.99	681.00	769.47

Table D.1 Control strategy environmental condition provision performance assessment results, South main building facade orientation.

Week	Average Absolute Error from Preferred Set Point						Mean		
	Temp 1	Temp 2	Temp 3	RH 1	RH 2	RH 3	CO_2 1	CO_2 2	CO_2 3
1	2.11	2.21	2.11	8.36	4.97	8.31	900.99	769.27	899.99
2	2.23	2.22	2.23	7.33	6.81	7.33	900.99	879.86	901.05
3	2.30	2.30	2.30	8.06	8.06	8.06	900.99	901.08	901.02
4	1.97	2.25	2.03	9.72	4.11	9.57	900.99	686.73	889.54
5	1.75	2.23	1.83	13.93	9.36	13.46	900.99	604.28	836.75
6	2.09	2.23	2.12	16.11	10.38	15.99	900.99	605.96	875.12
7	2.24	2.23	2.24	5.50	5.52	5.50	900.99	897.70	901.03
8	1.61	2.14	1.70	11.55	7.10	11.07	900.99	652.41	849.48
9	1.40	2.13	1.33	11.03	7.73	10.43	900.99	641.28	815.11
10	1.38	1.91	1.37	9.12	6.46	9.01	900.99	700.75	838.10
11	1.43	1.88	1.45	7.49	5.61	7.13	900.99	760.55	852.04
12	1.62	1.72	1.61	5.41	5.06	5.37	900.99	859.24	880.62
13	1.35	1.31	1.17	7.77	6.54	8.10	900.99	816.66	864.49
14	1.77	1.93	1.59	9.79	6.69	8.54	900.99	708.68	850.22
15	1.75	2.08	1.74	9.27	8.14	9.12	900.99	713.60	831.29
16	2.00	2.01	1.92	9.29	6.16	9.50	900.99	708.96	866.16
17	1.76	1.00	0.90	9.52	8.66	9.33	900.99	624.36	701.99
18	1.89	1.23	1.22	8.84	6.59	7.00	900.99	612.62	674.82
19	1.49	1.26	0.79	7.11	6.90	7.39	900.99	665.12	747.91
20	2.03	1.24	1.50	10.11	8.34	8.76	900.99	594.50	670.74
21	1.81	0.96	0.99	11.77	11.87	12.13	900.99	608.47	703.37
22	2.04	1.38	1.55	5.38	6.40	6.54	900.99	635.67	659.07
23	2.21	2.07	2.17	12.43	9.23	9.55	900.99	582.25	640.85
24	2.08	1.78	2.00	13.71	13.82	13.50	900.99	687.83	728.80
25	2.20	1.59	1.82	13.45	9.94	11.27	900.99	580.32	666.71
26	2.21	1.77	1.98	10.66	7.45	7.74	900.99	580.66	620.97
27	2.23	1.90	2.07	12.11	10.68	10.64	900.99	607.08	671.38
28	2.18	1.78	1.94	12.29	9.52	10.04	900.99	633.83	671.29
29	2.00	1.56	1.62	12.08	11.81	11.88	900.99	677.19	758.27
30	2.17	1.44	1.66	11.34	8.46	8.96	900.99	585.01	647.13
31	2.10	1.12	1.57	13.41	10.50	10.33	900.99	633.09	670.63
32	2.04	1.84	1.82	15.54	13.92	14.33	900.99	706.02	754.90
33	2.18	1.61	1.84	11.63	8.14	8.32	900.99	639.42	673.54
34	1.94	1.03	1.25	10.32	10.51	10.49	900.99	684.61	704.75
35	1.36	1.28	1.50	16.67	17.17	16.86	900.99	790.18	850.36
36	1.68	1.51	1.61	14.11	13.24	13.13	900.99	652.71	723.62
37	1.85	1.48	1.54	13.71	11.98	12.08	900.99	732.05	754.63
38	1.63	1.40	1.47	14.37	11.20	12.40	900.99	632.65	746.83
39	1.67	1.39	1.51	15.36	12.10	12.96	900.99	636.91	771.25
40	1.99	2.03	2.00	17.68	17.76	17.71	900.99	805.36	881.50
41	2.04	1.74	2.01	17.04	15.44	17.22	900.99	701.91	870.78
42	1.86	1.71	1.84	16.11	14.39	15.98	900.99	617.72	825.20
43	1.61	2.15	1.69	10.35	6.25	10.00	900.99	660.73	863.54
44	1.75	2.17	1.84	8.53	5.34	8.29	900.99	749.94	882.38
45	1.88	2.15	1.94	11.97	9.03	11.82	900.99	680.18	876.97
46	1.87	2.14	1.88	11.64	7.79	11.44	900.99	710.89	869.90
47	2.18	2.23	2.18	6.67	4.18	6.67	900.99	797.16	901.06
48	2.02	2.22	2.08	11.04	6.62	10.76	900.99	723.43	884.39
49	2.20	2.24	2.19	9.38	6.00	9.31	900.99	765.72	893.18
50	2.24	2.25	2.21	9.70	4.26	9.48	900.99	706.05	892.00
51	1.73	2.24	1.87	10.87	5.80	10.46	900.99	672.40	866.80
52	2.23	2.24	2.24	12.01	8.42	11.86	900.99	727.19	886.42
Annual Mean	1.91	1.81	1.75	11.13	8.82	10.44	900.99	692.47	797.31

Table D.2 Control strategy environmental condition provision performance assessment results, North main building facade orientation.

Week	Average Absolute Error from Preferred Set Point						Mean		
	Temp 1	Temp 2	Temp 3	RH 1	RH 2	RH 3	CO_2 1	CO_2 2	CO_2 3
1	2.11	2.20	2.11	8.36	4.98	8.31	900.99	769.36	899.96
2	2.23	2.22	2.23	7.33	6.81	7.33	900.99	879.86	901.05
3	2.29	2.29	2.29	8.09	8.09	8.09	900.99	901.07	901.02
4	1.97	2.25	2.03	9.72	4.11	9.57	900.99	686.74	889.54
5	1.74	2.23	1.83	13.87	9.36	13.40	900.99	604.23	835.82
6	2.09	2.23	2.12	16.12	10.37	15.99	900.99	605.97	875.02
7	2.24	2.23	2.24	5.50	5.52	5.50	900.99	897.69	901.03
8	1.56	2.05	1.61	11.30	7.02	10.82	900.99	657.51	846.07
9	1.38	2.11	1.28	10.82	7.75	10.23	900.99	641.59	810.94
10	1.22	1.76	1.13	8.76	6.55	8.79	900.99	701.16	830.84
11	1.27	1.66	1.16	7.29	5.74	7.06	900.99	759.19	843.58
12	1.37	1.43	1.33	5.71	5.44	5.70	900.99	858.02	876.68
13	1.22	1.11	0.97	8.16	7.13	8.58	900.99	812.18	857.03
14	1.70	1.92	1.57	9.03	6.65	8.45	900.99	708.67	849.35
15	1.77	2.05	1.73	9.03	8.12	8.93	900.99	714.09	826.20
16	1.97	1.97	1.88	9.26	6.25	9.48	900.99	708.26	861.81
17	1.98	0.92	1.03	9.29	8.54	9.16	900.99	609.99	681.97
18	2.00	1.21	1.28	7.96	6.51	6.56	900.99	616.56	660.77
19	1.61	1.18	0.79	7.07	6.92	7.42	900.99	655.09	733.76
20	2.18	1.30	1.61	9.64	7.83	8.73	900.99	584.68	656.42
21	1.84	0.97	1.01	11.78	12.02	11.92	900.99	596.00	665.91
22	2.11	1.58	1.75	5.20	6.74	6.80	900.99	619.33	636.60
23	2.23	2.12	2.21	10.79	8.61	8.88	900.99	589.40	661.01
24	2.08	1.79	2.00	13.63	13.74	13.46	900.99	687.60	729.39
25	2.07	1.63	1.88	13.34	8.91	9.51	900.99	580.74	628.82
26	2.24	2.07	2.18	9.71	6.85	7.35	900.99	580.54	617.19
27	2.20	1.92	2.07	11.05	10.15	9.97	900.99	605.19	670.98
28	2.25	1.91	2.05	11.87	9.48	9.94	900.99	632.25	670.28
29	2.00	1.71	1.76	11.83	11.99	11.94	900.99	670.51	748.14
30	2.23	1.60	1.85	10.60	7.86	7.81	900.99	582.73	614.41
31	2.19	1.12	1.77	12.83	9.24	9.98	900.99	583.73	662.49
32	2.07	1.73	1.82	14.36	13.18	13.64	900.99	690.96	742.36
33	2.20	1.85	2.03	10.74	7.59	7.78	900.99	636.58	670.74
34	2.05	1.16	1.55	9.77	10.34	9.83	900.99	666.26	662.89
35	2.08	1.38	1.46	15.44	16.06	15.76	900.99	683.91	728.78
36	1.92	1.60	1.88	13.14	12.49	11.95	900.99	660.90	717.99
37	1.87	1.43	1.53	13.99	11.86	11.94	900.99	731.83	750.22
38	1.45	1.35	1.35	13.28	11.02	10.92	900.99	627.06	711.42
39	1.54	1.38	1.45	14.63	11.91	11.56	900.99	637.53	739.44
40	1.98	2.01	1.98	17.68	17.76	17.71	900.99	800.96	881.01
41	1.92	1.70	1.71	15.83	15.18	15.07	900.99	701.94	816.97
42	1.85	1.57	1.53	16.01	14.32	14.86	900.99	617.63	791.96
43	1.57	2.11	1.59	10.00	6.30	9.73	900.99	661.65	858.10
44	1.70	2.15	1.79	8.49	5.41	8.25	900.99	750.38	881.60
45	1.73	2.13	1.70	11.41	9.00	11.07	900.99	680.77	848.63
46	1.77	2.13	1.82	11.56	7.79	11.33	900.99	711.36	867.76
47	2.17	2.23	2.17	6.65	4.18	6.65	900.99	797.21	901.06
48	2.00	2.22	2.07	10.97	6.62	10.68	900.99	723.55	883.48
49	2.20	2.24	2.19	9.38	6.00	9.31	900.99	765.73	893.18
50	2.24	2.25	2.21	9.70	4.26	9.48	900.99	706.06	892.00
51	1.73	2.24	1.87	10.86	5.80	10.45	900.99	672.39	866.70
52	2.23	2.24	2.24	12.01	8.42	11.86	900.99	727.19	886.42
Annual Mean	1.92	1.80	1.74	10.79	8.67	10.11	900.99	687.53	785.32

Table D.3 Control strategy environmental condition provision performance assessment results, East main building facade orientation.

Week	Average Absolute Error from Preferred Set Point						Mean		
	Temp 1	Temp 2	Temp 3	RH 1	RH 2	RH 3	CO_2 1	CO_2 2	CO_2 3
1	1.98	2.08	1.98	8.53	5.26	8.51	900.99	769.96	897.72
2	2.21	2.21	2.21	7.37	6.84	7.37	900.99	879.86	901.05
3	2.28	2.28	2.28	8.09	8.10	8.09	900.99	901.08	901.03
4	1.96	2.25	2.02	9.72	4.11	9.56	900.99	686.75	889.51
5	1.84	2.16	1.79	13.53	9.18	13.09	900.99	604.56	827.63
6	2.09	2.22	2.12	16.10	10.34	15.99	900.99	605.89	874.66
7	2.20	2.19	2.20	5.60	5.62	5.61	900.99	897.70	901.03
8	1.57	2.09	1.60	11.20	6.98	10.44	900.99	653.04	835.66
9	1.42	1.91	1.29	10.85	8.01	10.65	900.99	643.93	804.51
10	1.59	1.69	1.34	9.01	7.74	9.99	900.99	671.36	796.79
11	1.47	1.77	1.35	7.50	5.80	7.34	900.99	761.89	848.41
12	1.57	1.52	1.44	5.87	5.86	6.07	900.99	842.94	862.10
13	1.52	1.25	1.08	8.31	7.26	8.75	900.99	786.14	833.40
14	1.75	1.92	1.60	9.85	6.65	8.47	900.99	708.78	849.17
15	1.76	2.12	1.75	9.09	8.33	9.04	900.99	715.13	826.16
16	1.91	1.99	1.88	9.54	6.55	9.91	900.99	704.58	861.52
17	1.87	1.09	1.07	9.60	8.80	9.40	900.99	620.37	691.21
18	2.02	1.37	1.40	8.07	6.45	6.70	900.99	616.01	666.01
19	1.62	1.33	0.95	6.96	7.42	7.99	900.99	653.71	728.13
20	2.09	1.28	1.56	9.24	7.98	8.60	900.99	593.34	664.92
21	1.94	1.05	1.04	11.64	11.92	11.86	900.99	597.81	680.27
22	2.28	1.60	1.79	5.26	7.05	7.12	900.99	616.68	638.73
23	2.25	2.16	2.23	10.79	8.54	8.79	900.99	599.95	660.46
24	2.21	1.95	2.16	11.60	11.81	11.50	900.99	684.01	732.73
25	2.17	1.71	1.92	12.58	9.64	10.64	900.99	579.76	662.41
26	2.29	1.88	2.07	9.81	7.48	7.71	900.99	580.32	616.86
27	2.28	1.99	2.13	10.82	9.66	9.59	900.99	620.63	668.54
28	2.19	1.81	1.97	11.78	9.43	9.89	900.99	633.80	672.36
29	1.85	1.59	1.62	12.33	11.72	11.83	900.99	675.60	751.86
30	2.17	1.48	1.71	10.51	7.86	8.30	900.99	590.52	653.88
31	2.16	1.19	1.68	12.78	10.26	10.35	900.99	615.15	668.77
32	2.08	1.78	1.82	14.48	13.43	13.74	900.99	706.15	750.34
33	2.25	1.72	1.98	9.32	7.56	7.58	900.99	641.08	670.18
34	2.02	1.27	1.53	9.55	9.71	9.62	900.99	636.04	669.31
35	2.06	1.42	1.46	15.21	15.92	15.73	900.99	706.23	752.46
36	2.08	1.55	1.86	11.56	11.29	10.84	900.99	656.43	708.24
37	1.94	1.17	1.28	13.23	11.76	11.86	900.99	701.61	737.97
38	1.98	1.35	1.37	11.43	9.36	9.41	900.99	593.42	663.33
39	1.58	1.38	1.42	14.06	11.34	11.69	900.99	632.73	741.21
40	1.98	2.02	1.99	17.68	17.76	17.72	900.99	803.00	880.12
41	1.95	1.86	1.89	16.22	14.98	15.45	900.99	700.31	830.83
42	1.85	1.68	1.62	16.18	13.89	14.69	900.99	618.38	791.19
43	1.67	2.08	1.64	10.32	6.38	10.15	900.99	659.59	856.57
44	1.66	2.01	1.68	8.38	5.64	8.21	900.99	749.79	871.27
45	1.77	1.98	1.86	11.82	8.85	11.69	900.99	684.59	871.99
46	1.76	2.02	1.80	11.75	7.98	11.68	900.99	713.31	864.22
47	2.10	2.22	2.10	6.43	4.24	6.42	900.99	799.19	900.88
48	1.93	2.14	1.99	11.03	6.70	10.74	900.99	725.32	883.91
49	1.95	2.13	1.97	9.15	6.29	9.03	900.99	766.69	887.76
50	2.20	2.24	2.16	9.58	4.28	9.32	900.99	706.46	891.54
51	1.72	2.24	1.87	10.85	5.80	10.43	900.99	672.42	866.58
52	2.11	2.09	2.11	12.24	8.57	12.10	900.99	727.01	886.44
Annual Mean	1.95	1.80	1.74	10.66	8.66	10.14	900.99	686.75	785.46

Table D.4 Control strategy environmental condition provision performance assessment results, West main building facade orientation.