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Thermal Performance Analysis of an Underground Passive Cooling System in Dezful, Iran: Shavadan

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Abstract

This paper presents a case study research of the thermal behavior of a type of Iranian underground living space, called Shavadan. Shavadan is part of building typology in the city of Dezful, southeast of Iran. The focus of the study is to introduce the passive design approach in Shavadan, which has been one of the main strategies of architects and building construction practitioners to increase the indoor thermal comfort of buildings. Shavadans were built under houses, schools, mosques and public spaces at depths of 6 to 10 meters, where the thermal behavior of the earth is almost stable. But this approach is totally forgotten in today's buildings and people do not know how to use it, even if they desire to. Based on a study of ambient air temperatures, in this paper the thermal behavior of five settings in different parts of Dezful is studied, from June to December. Moreover, the temperature stability of various Shavadans were compared to evaluate the architectural effectiveness of Shavadans in terms of their passive systems. The results show that it is useful to consider passive strategy as an auxiliary system to reduce domestic energy use in hot semi-arid climates where there is considerable electricity demand for air conditioning in the over 40 degree-Celsius-heat of these zones.

Keywords: Shavadan; thermal behavior; underground space; passive cooling, energy efficiency

1. Introduction

Traditionally, passive design has been one of the main strategies for improving thermal comfort in Iranian buildings, where the majority of the country has desert climate (hot and cold) and semi-arid climate (hot and cold). While increasing thermal comfort, passive design saves energy to a great extent (Hacene, Sari, & Amara, 2011). In modern architecture, passive design strategies increasingly gain interest and popularity; and the passive approach is becoming one of the key design strategies in low and zero energy buildings (Scognamiglioa et al, 2014). While the Urban Underground Space (UUS) is regarded as a renewable resource for geothermal energy in the major cities of developed countries (Sterling *et al.*, 2012), underground spaces in Iran have been built as a living space to escape from the heat.

Focusing on passive innovative techniques used in the modern era, some environmental footprints rely on traditional performance designs, which have been applied since the ancient time (Zhai & Previtali, 2010). Design characteristics of the residential buildings provide passive strategies for heating and cooling that could respond to domestic energy demands.

In the desert and semi-arid climate regions of Iran, traditional buildings employ a variety of passive cooling and heating techniques, including natural ventilation, underground spaces (underground living spaces and urban underground spaces), solar systems, and thermal mass design (Tavassoli, 2002). Examples for each technique are as followed:

- Natural ventilation: wind-catchers (widely being used in central and southern of parts of Iran)
- Underground living space: Shavadan, Shabestan, Sardab (typologies of habitable basements that differ in depth)
- Urban underground space: Abanbar (underground water reservoir), Sardab (ventilated basement), Payab (cistern), Yakh-Chaal (ice keeper)
- Solar systems: summer-area and winter-area in courtyard houses (Memarian, Sadoughi, 2011)
- Thermal mass design: massive walls in public or residential buildings

The current literature contains only a few experimental studies about the thermal performances of Iranian underground living spaces. The study of Roaf (1988) regarding the wind-catchers of Yazd can be considered as one of key studies of the traditional passive design in Iran. Although the underground passive cooling systems including cistern, underground stream of wind towers, and ice makers have been categorized for the arid zone of Iran (Bahadori, 1978), they can also be found in the hot and semi-humid climate zones of Iran. In the south-west of Iran, the most common type of underground living spaces based on passive design approaches is Shavadan in Dezful, Khuzestan. A recent study on Shavadan focused only on one case study and recorded the data for two months of the year, August and February (Hazbei et al., 2015). This paper evaluates the thermal behavior of Shavadan in six months from June to December. The present study differs from the previous ones due to the fact that this is the first long term field examination of thermal behavior of Shavadan, with short monitoring intervals. The results are discussed in section 4.3.

2. Background

Over the past decades, there has been a growing focus on sustainability and sustainable design concept and great literature is produced in this regard (Sterling *et al.*, 2012 and Bobylev, 2010). Also, underground space use is tied to the sustainability of an urban area (Sterling *et al.*, 2012) and the use of Urban Underground Space (UUS) has been growing significantly in the world's biggest and wealthiest cities (Bobylev, 2016). Yet Earth Architecture is a centuries-long construction method, and troglodytic man-made architecture and earth-covered building are its typologies (Mohammadifar, 2017). Kandovan and Meymand in Iran and Cappadocia in Turkey are some samples of troglodytic architecture (Mohammadifar, 2017). For Earth-Covered or Earth-Sheltered building, there is a variety of samples, including primitive dwellings discovered in Africa, China and the United States (Oliver, 1969) and Skara Brae in Orkney show stone-built Neolithic settlements in UK (Farmer, 1996). The main feature of these dwellings is their passive design. The passive design of various types of buildings in different regions have been studied to indicate the potential benefits of these design strategies in terms of thermal comfort and saving energy. Some of these studies include: the comparison of thermal performance of historical dwellings and modern architecture in France (*Cantin et al*., 2010), assessing hostel buildings in India in a semiarid zone (Srivastava, Nayak, Tiwari, & Sodha, 1984), vernacular residential architecture in Kerala, India (Dili, Naseer, & Varghese, 2010), and courtyard style cave dwellings in China (Wang & Liu, 2002) and Turkey (Gulyaz, 1995). These studies concluded that the traditional passive designs are effective in providing thermal comfort and in saving energy; therefore, they have potentials to be considered in modern building designs. In addition, these studies showed that the thermal performance of traditional passive underground spaces is better than that of a typical building without passive features.

The main advantages of the traditional underground spaces such as wine cellars in Spain are the stable indoor temperature and lower indoor temperature compared to the outdoor temperature during hot seasons (Carmody & Sterling, 1993; Golany, 1989). Another study regarding the thermal behavior of traditional wine cellars proved that the thermal performance of wine cellars is more effective during one whole year than their seasonal thermal behaviors (Mazarrón & Cañas, 2009). Underground dwellings with passive features are used in many countries around the world. For instance, a study of Korean traditional earth-sheltered dwellings found that the diurnal indoor temperature range and the relative humidity were significantly lower than those of typical buildings (Lee & Shon, 1988).

3. Study area: Dezful, Iran

3.1 Dezful: a historic city in Iran

The city of Dezful, on a 32.24 latitude and a 48.23 longitude, has an elevation of 143 meters. With a population of 444,000 and an area of 40 km^2, Dezful is in the province of Khuzestan the south-west of Iran (see Figure 1). Based on a limited number of historical evidence, its formation dates back to the time of the Sassanid Empire AD 224–c. 670 (Kasravi, 1977). Some historical evidences such as the Sassanid famous bridge and residential areas have remained in Dezful from the Sassanid period. Despite the unknown age of the historic communities, the maps show the basic pathways; the residential boundaries, and the location of important settings such as Jome-Mosque and Bazaar. The modernization of Dezful began at 1950s, including construction of new urban roads and infrastructures. The population of the city increased, and as the vernacular buildings were no longer responsive, new houses and apartments were built since 1961, in western style. With the introduction of modern materials such as concrete, industrial brick, cement and stone in constructions, traditional materials such as unbacked or backed brick were not needed. The city expanded slowly. However, some parts of the city including Shavadans remained intact through the years, despite being forgotten or changing into underground storage spaces. Many of the Shavadans are destroyed due to negligence. The historic part of Dezful has an area of 2 km^2, with about 3000 to 3600 old buildings. It is estimated that about half of them have Shavadans, and about 30% of these Shavadans can be still utilized, which makes it about 500 to 600.

Figure 1. Aerial view of Dezful, old and new fabric

3.2 Climate information of Dezful

The province of Khuzestan, with a generally very hot and occasionally humid climate, has three different climates but hot semi-arid climate (Köppen climate classification BSh) is dominated. Throughout history, people in this province have mostly settled along the riverside to get access to the fresh and clean water. Dezful is settled on rocky cemented earth along a narrow river called the Dez River. Because of its location, the high temperature of

Dezful is accompanied with high relative humidity. The annual relative humidity of Dezful is higher than the temperate regions and lower than the humid areas. From 2001-2005, mean air temperatures, mean maximum and mean minimum were 5.42°C, occurring mostly in January, and 46.3°C, occurring mostly in July, respectively. The hot season spans the months of April through late October with a relative humidity from 20% to 45%. When the temperature is higher than 25°C, and the upper relative humidity level is also high, the subjects sense differences in the environment (Givoni, 1998). In addition to air temperature, subjective sensation of humidity depends on the air speed. However, the thermal zone can be determines based solely on historical air temperatures. The average range of temperature and the mean relative humidity of 33% during the hot summer days indicate that the thermal zone in Dezful from May to September can be identified as overheated, which is above the comfort zone of bio-climatic. Figure 1 displays an Olgyay diagram representing the Bio climatic charts for Dezful from historical measurements. Other climate data of Dezful is shown in Table 1.

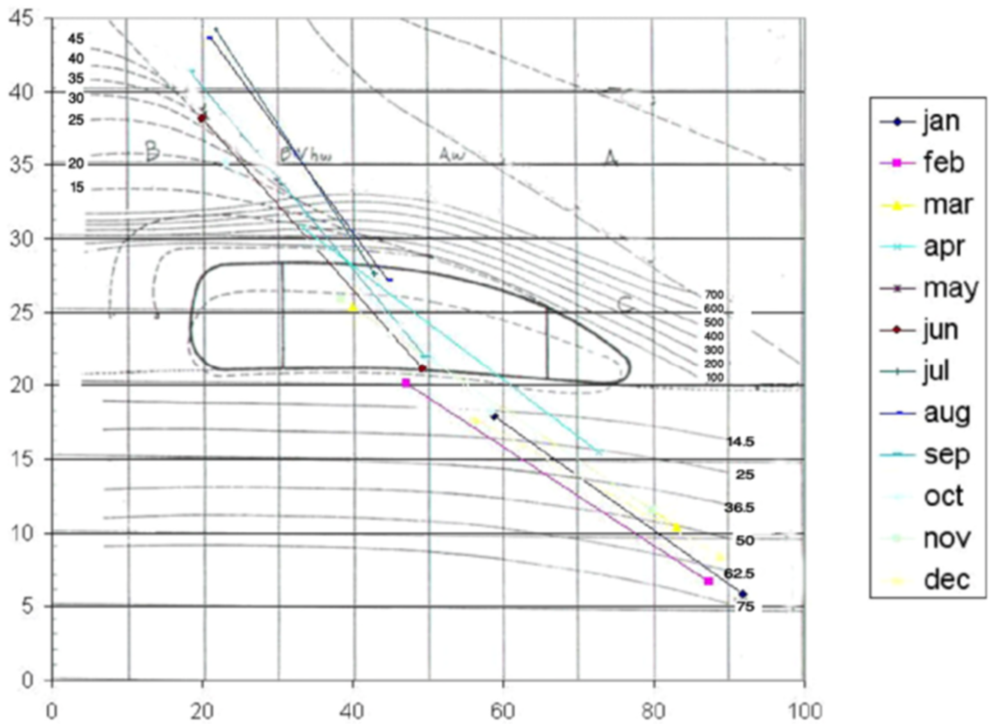

Figure 1. Bio climatic charts of Olgyay for Dezful. Drawn based on archived meteorological data 2000- 2005

Table 1. Average Monthly Data (Mean 1961-2005) – Source: IRAN METEOROLOGICAL ORGANIZATION (IRIMO)

Indicator	Jan	Feb	March	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual	Unit
Mean daily temperature	11.5	13.2	17	22.7	29.2	34	36.3	35.6	31.5	25.7	18.5	13.3	24	℃
Highest temperature records	28.5	29	36	40.5	47.5	50	53.6	52	48.5	43.5	35	30.2	53.6 (1983)	℃
Lowest temperature records	-9	-4	-2	3	10	16	19	16.5	10	6	1	-2	-9 (1964)	℃
Relative Humidity	76	68	61	50	32	23	25	28	30	41	60	74	47	%
Number of Days with maximum temperature equal to 30 and higher	0	0	1.6	17.5	30.1	30	31	31	30	28.5	6.1	0	205.8	Days
Number of Days with minimum temperature equal to 0 and lower	2.1	0.8	0.3	0	0	0	0	0	0	0	0	0.7	3.9	Days
Total Precipitation	104.2	57.3	60.6	34.5	7.6	0.1	0.1	0	0	8.9	45.2	86.1	404.6	mm
Number of days with thunder storm	2.2	1.9	3.3	3.7	2.3	0.2	0.1	0.1	0.1	1.6	3.1	2.9	21.5	Days
Number of days with snow or sleet	0	0	0	0	0	0	0	0	0	0	0	0	0	Days
Number of days with dust	2.1	4.1	7.3	9.2	14.3	15.8	18.5	15.6	10.1	8	3.7	2	110.7	Days
Wind speed	2.6	3.2	3.9	4.4	5.4	5	4.2	3.9	3.4	3	2.4	2.4	3.7	Knots

3.3 Traditional residential building in Dezful

In Iran, all of the spaces in a vernacular building can be categorized in one of these groups: open, semi-open and closed. The hierarchy of spaces provides thermal comfort for the occupants who switch between these spaces during diurnal or nocturnal hours based on the season, indoor and outdoor temperature. Since these spaces are located on the four sides of a central courtyard, the amount of received sun-light or shade alternates during the year, and thus different spaces are used in each season.

3.4 Shavadan: an Iranian underground living space

In the south-west of Iran, especially in the cities of Dezful and Shoushtar, people traditionally used to build Shavadan as part of their houses. Shavadan is an traditional type of architecture/construction/space that is constructed by digging out a series of connected chambers in the underground of a building. Suitable ground conditions (conglomerate soil) has made it possible for Shavadan to be statically in equilibrium with no reinforcing element, and be stabilized by its own forces. The outer surface of ceiling and walls is exposed and no plaster is used to cover it. Yet the floor is furnished with 25*25 cm tiles. Shavadan, which means a dark place in the local accent, is a traditional name for underground living spaces with a special passive ventilation feature (Roboubi & Rahimieh, 1974). Shavadan is also categorized as an underground closed space in a private sector of houses in Dezful. This underground architecture, equipped with a passive cooling system, provides a comfortable space for residential uses. Shavadans' underground depth is usually about 5 to 12 meters (Safaee, 2009) and they look like dwelling caves segregated from the main buildings. But in fact, they are not segregated from the rest of the building.

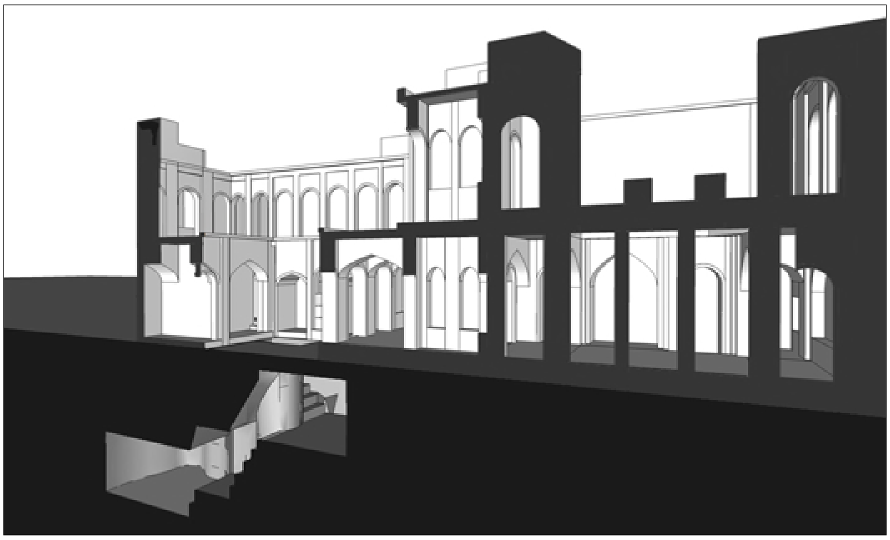

Figure 3. Nilsaz House (Bld. 04): Series of Stair access from the courtyard to Shavadan

Source: Memarian and Sadoughi, 2010

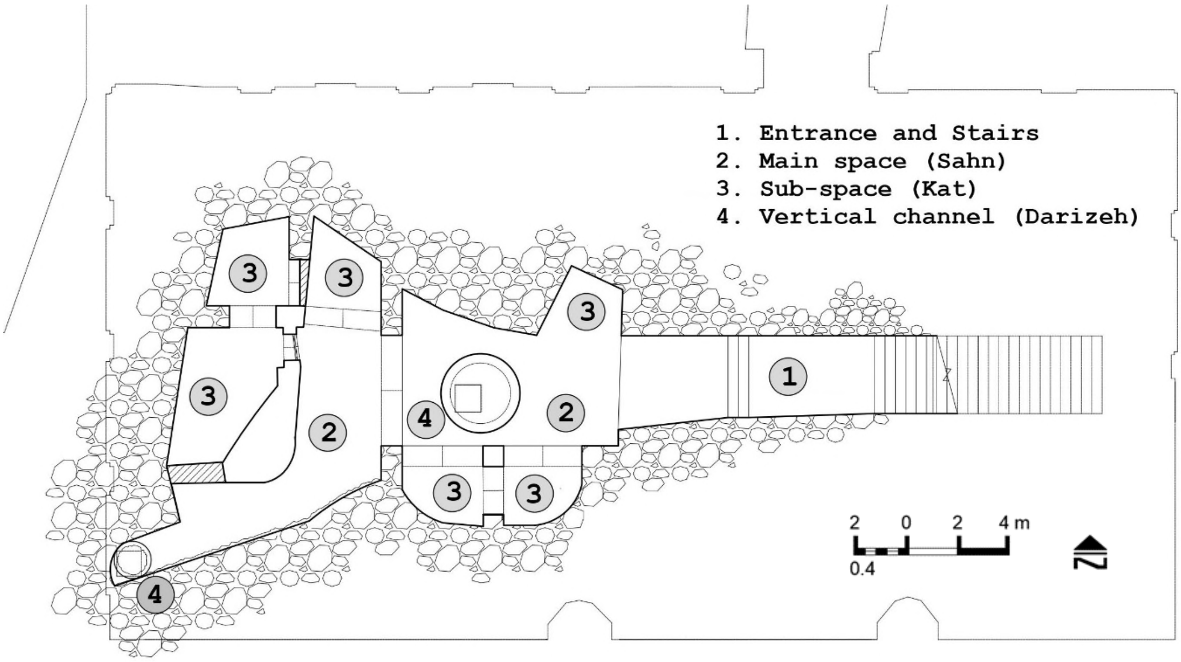

Figure 4. Shavadan of Lab-e-Khandagh Mosque (Bld. 03)

Source: Memarian and Sadoughi, 2010

Figure 5. Two examples for entrance and stairs from courtyard

Figure 6. Stairs view from the bottom

Figure 7. Main space (Sahn)

Figure 8. Sub space (Kat)

Shavadan is made of different elements as followed

- Entrance and stairs
- Main space (*Sahn*)
- Sub-space (*Kat*)
- Vertical Shaft *Darizeh*)
- Horizontal channel (*Taal*)

Shavadan's connection with the house is shown in Figure 3 and an example of its spaces can be seen in Figure 4. Detailed description of each element is given below.

3.4.1 Entrance and stairs

Since Shavadans are excavated completely in the ground, their access to the main building is provided by a series of stairs, with an average width of 1.5 meter, mostly from the courtyard (See Figure 3 and 5). Each stair has a width of 30 to 35 cm and a height of 25 to 35 cm. The number of stairs depends on the depth of Shavadan (Figure 6). The entrance supplies the majority of air exchange with the outdoor (courtyard).

3.4.2 Main Space (Sahn)

A large central space, with the width of 3 to 5, length of 5 to 9 and height of 2.5 to 5 meters, excavated in the average depth of 5 to 12 meters. Its ceiling has a cylindrical shape for statistical purposes (see Figure 7).

3.4.3 Sub-space (Kat)

Private chambers excavated on two or three sides of the main space that have a width of 1 to 3, length of 2.5 to 4 (sometimes 5.5) and height of 1.5 to 3.8 meters. Normally *Kats* are separated from *Sahn* with an elevated floor, about 30 cm upper the *Sahn*'s floor. This provides enough separation and privacy for occupants during their residence in Shavadan (Figure 8).

3.4.4 Vertical shaft (Darizeh)

A vertical shaft with a diameter of 0.3 to 1 and height of 6 to 19 meters, which connects the main space (*Sahn*) to the other parts of the house above the ground. *Darizeh* has various functions, including providing ventilation and light, vocal communication with the residents on the ground, and soil extraction during construction. Based on outdoor connection, *Darizeh* has four different types (see Figure 9):

- To the entrance of the house (Hashti)
- To the alley
- To the roof (through the mas of the exterior walls)
- To the courtyard

Figure 9. Vertical Shaft (Darizeh)

3.4.5 Horizontal channel (Taal)

A horizontal channel with a diameter of 0.2 to 1 and length of 4 to 16 meters that connects two neighboring Shavadans. In a group of buildings that the residents are relatives, one or more *Taals* provide horizontal connection between Shavadans as a means of ventilation and vocal communication. To maintain privacy and aesthetics, the entrance of each *Taal* is covered with porous brick wall. Not only A *Taal* provides access to both neighboring Shavadans but also it provides air circulation between two buildings. Therefore, a *Taal* is a key element in the passive cooling system of these buildings. Also, in houses in the vicinity of the Dez River, a *Taal*, with the same depth of Shavadan, connects it to the river banks to ventilate the river's cool air into Shavadan.

The volume of Shavadans ranges from 40 to 220 m^3, and the majority of them have an average volume of 120-160 m^3. Each Shavadan has between 2 to 6 channels (considering the entrance, this numbers reaches 3 to 7). With the entrance providing fresh air inflow rate, shafts and channels acting as exhausts, the natural ventilation system of Shavadan is a continuous and complex one, providing air circulation to avoid excessive moisture. Air circulation through these channels provides natural ventilation inside and plays an important role in passive cooling. Because of Shavadans' underground construction, upper layers of the earth material function as insulators; therefore, the outside temperature hardly reaches this dugout space. Since air is continuously ventilated in Shavadan, there would be no *combination* of heat in the underground in the long-term. During long hot summer days, shadowed patios; i.e., "Iwan", are not usually comfortable spaces for residents due to high temperature degrees; however, Shavadans remain well-ventilated and cool; and residents usually move to Shavadans until the heat intensity drops at about sunset (Curzon, 2012).

4. Research questions and objectives

The initial question of this study, the experimental study of Shavadan's thermal behavior, was if inconsistencies in the ambient temperature affect the indoor temperature of Shavadans. In this study, the indoor air temperatures of five Shavadans, and the outdoor temperatures of the courtyards of the connected houses to Shavadans were monitored from June to December.

The reasons of the research are as followed:

- High electricity use for cooling systems in the region resulting in high electricity bills
- Demolishing and filling in of Shavadans in new developments due to unawareness of traditional people (or authorities) of the energy efficiency and thermal value of Shavadans
- Errors made in constructing a new Shavadan (poor ventilation, high degrees of humidity and mold formation as a result of excluding *Taal* and *Darizeh* or poor thermal behavior as a result of insufficient depth)
- The possible application of Shavadan for today use

The main advantage of Shavadan is its being a net zero energy building, and its main disadvantage is the relatively deep excavation, segregating it from the buildings on the ground and rendering a strong structure necessary.

The main objectives of this study include:

- Examine the thermal behavior of Shavadans based on the ambient air temperature

- Compare the indoor and outdoor temperature fluctuations and determine the indoor temperature stability of Shavadans in comparison with outdoor temperatures
- Compare the temperature stability of different samples

To achieve the objectives of the paper, the following steps are taken:

- The Shavadan concept is briefly explained;
- The climatic condition as well as a brief history of Dezful are explained;
- The data gathering method and tools are described;
- The results obtained from the data acquisition process are presented and analyzed; and
- Finally, the concluding remarks are provided.

5. Methodology

5.1 Monitoring

To monitor the air temperature, the digital data loggers produced by TESTO company model 175-H2 and 175-T2 (with the accuracy C1: Acc: +/- 3.0 [0.100] %rH, C2: Acc: +/- 0.5 [-20.70] °C) were used. From nine data loggers that were assigned to this study, only four of them were both temperature and relative humidity loggers and the rest were temperature loggers only (See Figure 10). Considering the recording capacities of the sensors, the measurement intervals of 1 hour were set; however, two devices could not monitor the air temperatures in the intervals of less than two hours. The outdoor temperature was recorded at the height of 2 meter.

The inside data loggers were installed at an intermediate height of 120 -150 centimeter above the ground. The data loggers in the courtyards were installed in shadowed areas (southern side) at the height of 180-220 centimeters. To ensure data loggers would not interfere with the residents' activities and to minimize accidental contacts, they were installed at a height slightly higher than the standard breathing height.

Another experiment was carried out to examine the performance of the ventilation system in the Shavadans. For this purpose, the openings of the shafts to the courtyard and the other rooms were closed on a regular basis (every two days) during the experiment. Despite the fact that the shafts were built to function as ventilating systems, the recorded temperatures did not indicate any significant indoor temperature differential between two cases of shafts-open and shafts-closed. Figure 11 displays the floor plan and the section drawing of one of these shafts.

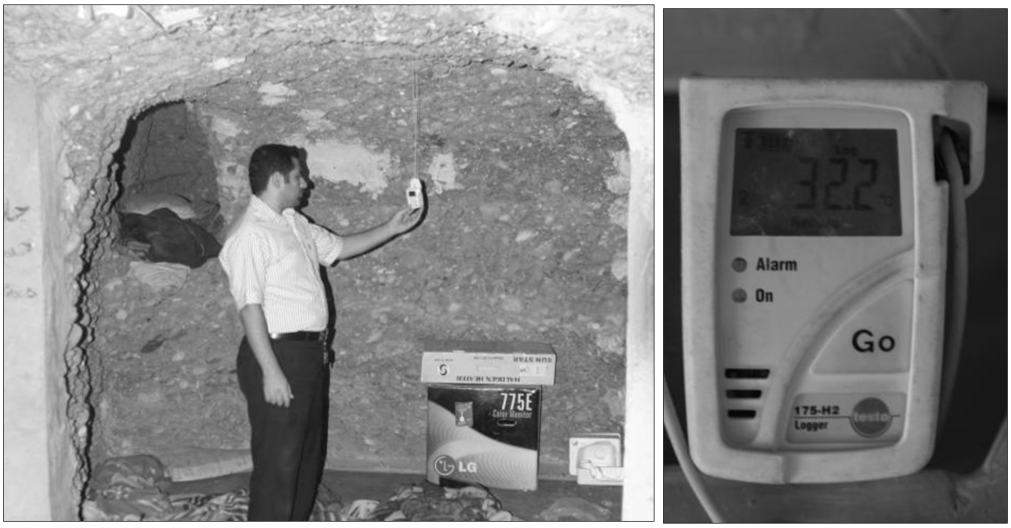

Figure 10. (Bld. 02) Left: Indoor space of Shavadan with an installed data logger, Right: Data logger 175-H2

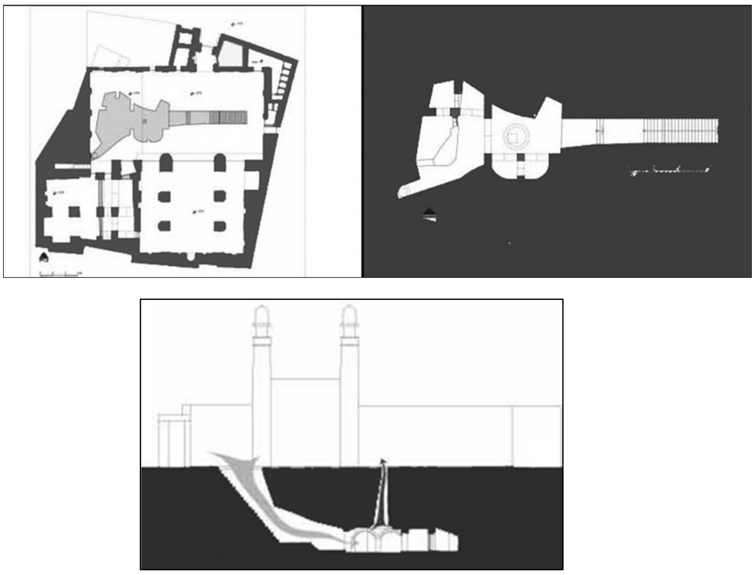

Figure 11. (Bld. 03) Lab-e-Khandagh Mosque, Left: Ground floor plan and the plan of the underground space. Right: Section. Shavadan's entrance and long narrow shaft, providing natural ventilation, circulate the air inside Shavadan to the outside (without scale)
Source: Memarian and Sadoughi 2010

5.2 Sampling

Five underground spaces with different depth, location, architectural layout in five different buildings were selected for the purpose of this study. Table 2 summarizes the main attributes of the selected Shavadans. These buildings include one occupied house, one unoccupied house, and three public buildings.

Among the selected buildings, two neighboring Shavadans, called Shah Rokn-al-Din Complex, were connected with *Taal*. In Figure 12, the plan views of the underground level of Shah Rokn-al-Din Complex are illustrated. Among the other three samples, two of them are residential underground spaces and the third one belongs to a mosque.

Some limitations in selecting appropriate spaces for this study included: not to disturb the indoor environment of Shavadans and to be able to get access to the occupied buildings.

Table 2. The buildings' specifications

Number	**Building's name**		**Shavadan's depth** (from the courtyard's level)	**Parameters**		**Building description**
				Inside	**Outside**	
1	Shah Rokn-al-Din Complex	Shah Rokn-al-Din Mosque	~ 9 m	T	T – rH	More than 400 years old
2		Shah Rokn-al-Din School	~ 8.8 m	T – rH	T – rH	The above ground building has been rebuilt after the Iran-Iraq war in 1980
3	Lab-e-Khandagh Mosque		7.25 m	T – rH	T- rH	More than 700 years old
4	Nilsaz House		~ 6.5 m	T- rH	T- rH	More than 200 years old
5	Nadali House		~ 8 m	T	T	The above ground building has been rebuilt after the Iran-Iraq war in 1980
The exact ages of the underground spaces are not clearly identified.						

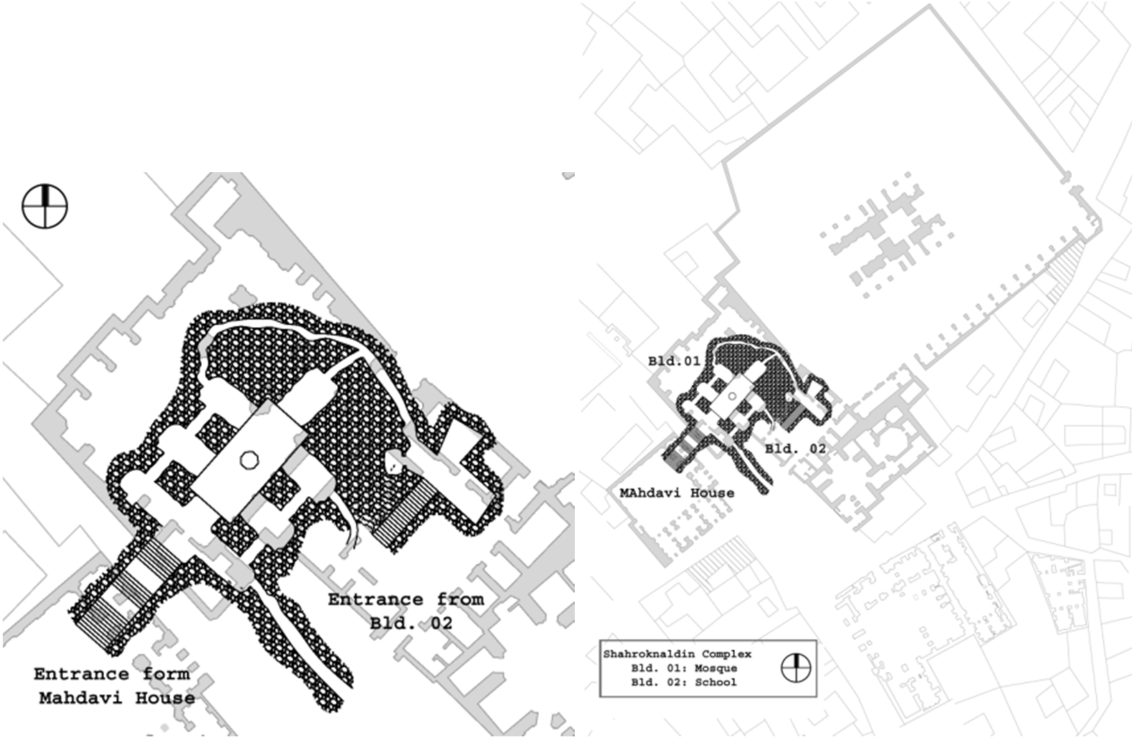

Figure 12. Shah Rokn-al-Din Complex (Bld. 01, 02). Right: Site Plan. Left: Underground Plan (without scale)

6. Results

This section provides the results obtained from the experimental study. At first, the Shavadans' indoor temperatures and the courtyards' temperatures are compared. The relationship between the indoor and outdoor temperatures for all Shavadans is then described. Finally, a comparison between Shavadans' indoor temperatures is presented.

4.3.1 Comparing the indoor temperatures of Shavadans with outdoor temperatures

Figures 13 through 17 show the results of the air temperature measurements. Based on the results, during the study, the indoor temperature of the Shavadans were almost stable compared to the outside temperature.

As shown in the Figures 13, 14, and 15, from June 01 to December 21, the indoor air temperature ranged between 15.4 and 24.2 °C, 22.3 and 26.8 °C, and 17.3 and 26.4 °C, for Shah Rokn-al-Din Mosque (Bld. 1), Shah Rokn-al-Din School (Bld. 2), and Nilsaz House (Bld. 4) respectively; whereas, the courtyards' air temperatures (outdoor temperatures) ranged between 13.1 and 47.6 ° C for Shah Rokn-al-Din Complex (Bld. 1 and 2). The noticeable difference between the indoor and the outdoor air temperatures is not only due to conventional depths of the buildings but also a result of passive ventilation made possible by Shavadans [16].

As shown in Figures 16 and 17, the indoor air temperature ranged between 18.5 and 25.4°C from August 15, to December 21, for Lab-e-Khandagh Mosque (Bld.3). The indoor air temperature ranged between 22.3 and 24.9°C for Nadali House (Bld. 5). However, the air temperature of the courtyard area of these buildings ranged between 11.1 and 49.8°C for Lankhandagh Mosque and between 9.8 and 48.5 °C for Nadali House. The shown consistency in the indoor temperatures of Shavadans indicates that the indoor temperatures of Shavadans are insignificantly influenced by the outdoor temperature.

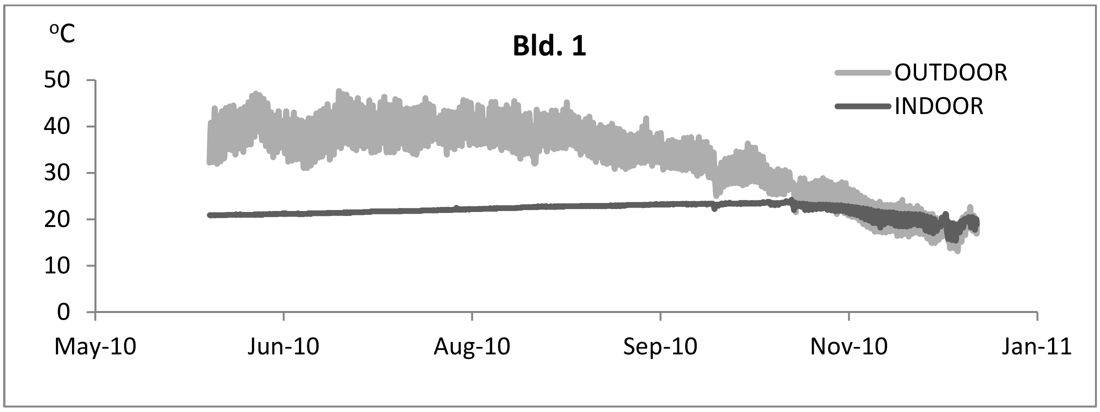

Figure 13. Air temperature fluctuation in Bld.01 from June to December

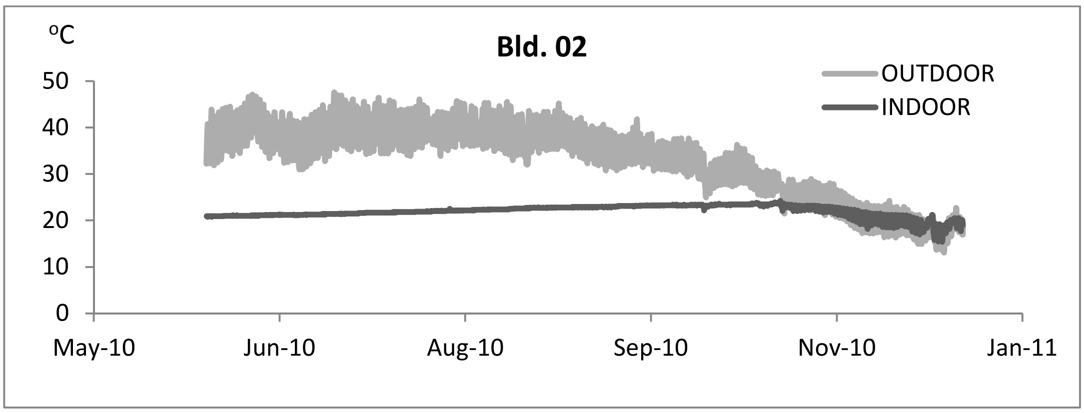

Figure 14. Air temperature fluctuation in Bld 02 from June to December

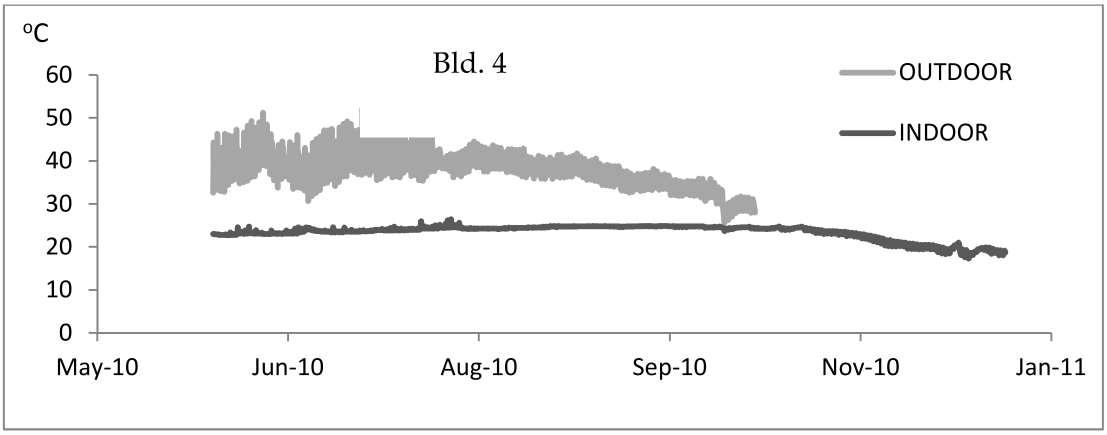

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Figure 15. Air temperature fluctuation in Bld. 04 from June to December

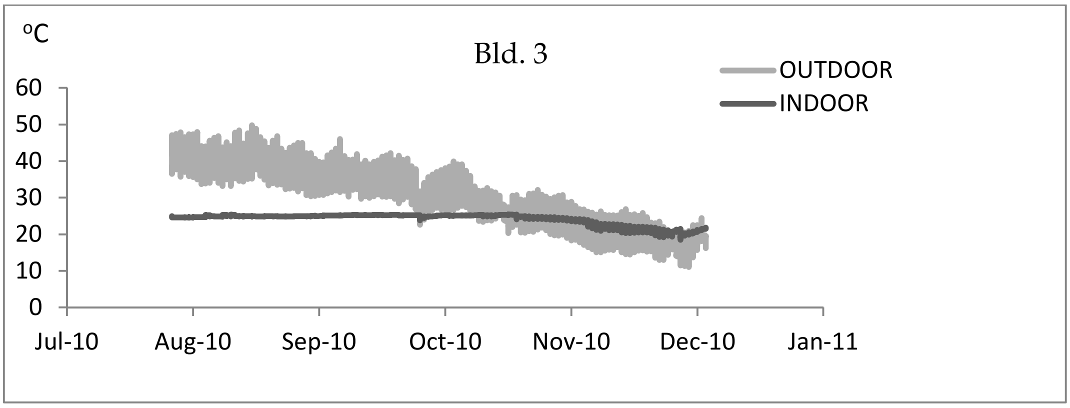

Figure 16. Air temperature fluctuation in Bld.3 from August to December

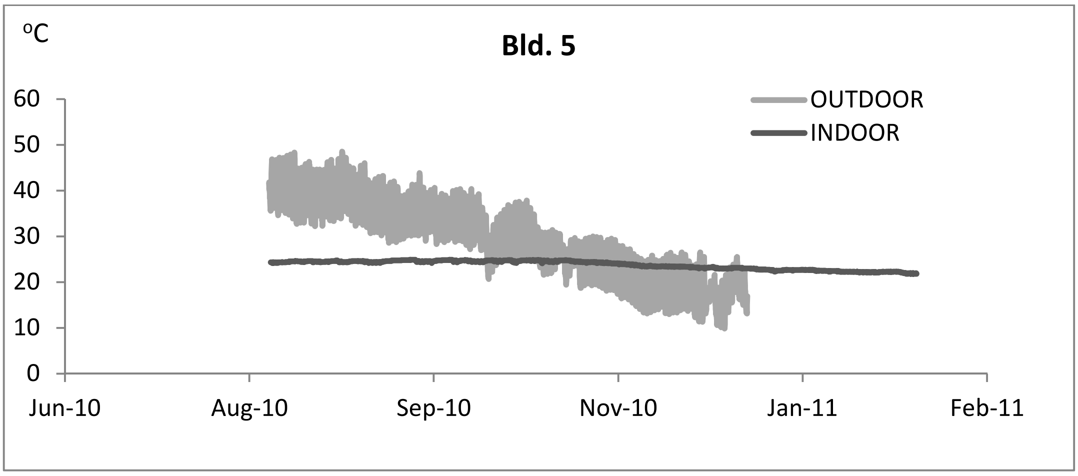

Figure 27. Air temperature fluctuation in Bld.5 from August to December

4.3.2 *Relationship between the indoor and outdoor air temperatures of the Shavadans*

In order to evaluate the effectiveness of Shavadans' architecture on their energy efficiency, this section assesses the relationship between the indoor and outdoor temperatures of all

Shavadans. For this purpose, the indoor temperature is plotted as a function of the outdoor temperature and a curve fitting procedure is used to determine their relationships. The indoor temperature of Shavadans can be related to the outdoor temperatures as follows:

- Shah Rokn-al-Din Mosque (Bld. 1): Ti =0.083 To + 19
- Shah Rokn-al-Din School (Bld. 2): Ti =0.115 To + 21
- Lab-e-Khandagh Mosque (Bld. 3): Ti=0.094To+20
- Nilsaz House (Bld. 4): Ti =0.115 To + 20
- Nadali House (Bld. 5): Ti =0.045 To + 23

Where Ti= indoor Temperature; To= Outdoor Temperature

Since all the above equations have bias ranging from 19 to 23, they indicate that the indoor temperatures of the Shavadans are less influenced by the outdoor temperature. By comparing the slope of the above-listed equations, it can be inferred that the indoor temperature of building 5 was less affected by the outdoor temperature because its equation has the minimum slope. Whereas, the indoor temperature of Bld. 04 is more affected by the outdoor temperature. In other words, the more an equation's slope is; the outdoor temperature impacts the Shavadans' indoor temperature to a greater extent.

4.3.3 Comparison of the indoor temperatures of the Shavadans

In this section, the indoor air temperature of Shavadans are compared. As shown in Figure 38, in summer times, the indoor temperature of the Shavadans ranged from 20^{o} C to 25^{o}C, which is considered a comfortable indoor temperature range for residents. The results confirmed the effectiveness of the Shavadans architecture in providing a low indoor air temperature for the buildings during hot months.

It is worth mentioning that in October, the fluctuations of the Shavdans' indoor air temperature have increased, which means that while the outdoor air temperature gets colder, the indoor temperature gets warmer. However, from the end of October until the end of December, the rate of the indoor and outdoor air temperatures are the same. This parity is an evidence to confirm the effectiveness of Shavadan for passive cooling rather than passive heating. In addition, Nadali house's architecture (Bld. 05) seems more effective since its temperature variation was lower; its temperature ranged from 22.3 to 24.9.

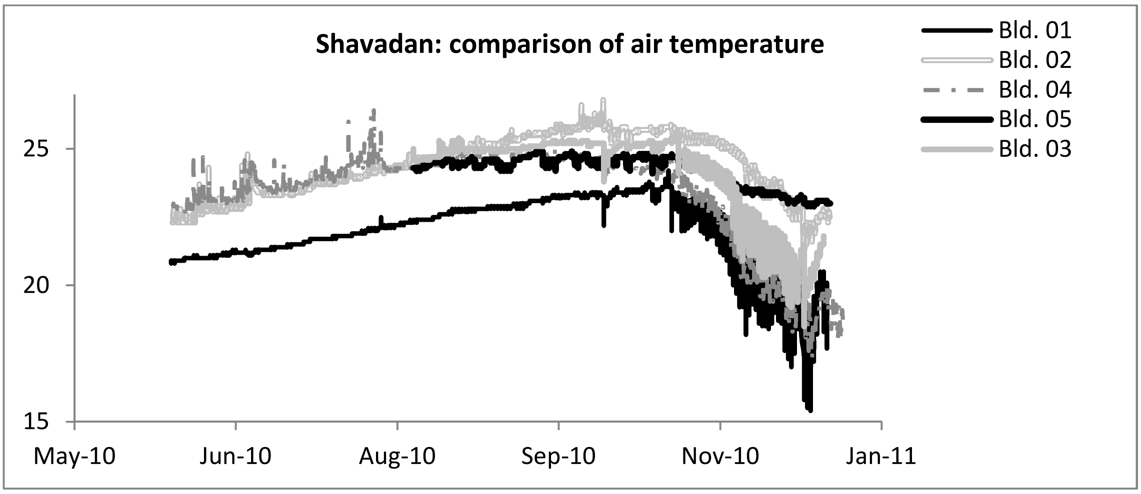

Figure 38. Comparison of the indoor air temperature fluctuations in the Shavadans

4.3.4 *The stability of the indoor air temperature of Shavadans*

The average soil temperature recorded at deepest level of 4 meter below surface is shown in table 3. The earth temperature in the deep level below surface is approximately the same as the average annual dry-bulb temperature (Florides & Kalogirou, 2004). According to Iran Meteorological Organization, the average annual dry-bulb temperature from 1997 to 2005 was 24.81, which is close to the average indoor air temperature of the Shavadans; the mean of the Shavadans' hourly temperature was 23.53. The annual average of soil temperature is almost the same as annual average of dry-bulb temperature (Table 3).

Moreover, the range of monthly average temperature from June to December was between 23.04 and 24.38 for 3 cases. Monthly average temperature of each case from August to September is considerably close to 24.81, the average annual temperature. It is also close than the average of annual soil temperature. Average monthly temperature of Shavadan is lower compare to monthly soil temperature. This compatibility between the indoor temperatures of the Shavadans, the average annual temperature both dry-bulb and earth in depth, is another indication for the effectiveness of Shavadans' underground structures.

In this study, the annual dry-bulb temperature of Dezful is compared with the indoor temperature of Shah Rokn-al-Din Complex (See Figure 19). In this figure, the data points in each line show the monthly mean temperatures. It is worth noting that from June to December, the indoor temperatures of two of the Shavadans had similar behavior to the trend of Dezful's monthly temperature. Although the recorded indoor temperatures of Shavadans covered only 6 months of the year, the relative similarity of its trend to the trend of Dezful's temperature shows that the thermal behavior of Shavadan in summer is very close to the thermal behavior of the earth.

Besides, compatibility of stable earth temperature in depth of 10 meter with annual temperature (Heidari & Gilani, 2009), is comparably similar to Shavadan's temperature stability in 5 cases of this study (Figures 13-17). In their studies, G. Florides and S. Kalogirou indicated that the insensitive behavior of the earth temperature to the diurnal and annual cycle is related to the depth, ground characteristics, and presence of water[20]. Dry sandy conglomerated type of Dezful's earth is another factor to reduce the temperature penetration into the depth. This compatibility is another evidence that Shavadans' passive cooling system behave in a similar fashion as the earth thermal behavior during hot months.

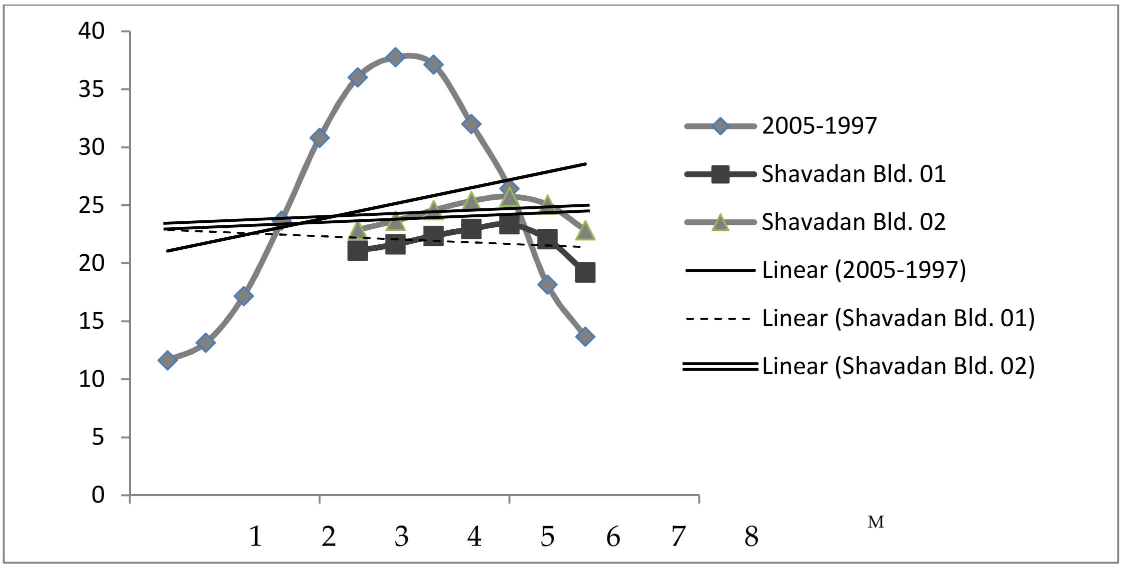

Figure 49. Comparison of Shavadan's air temperature of Shah Rokn-al-Din Complex with Dezful's annual

Table 3. The average indoor temperature of the Shavadans in comparison with average monthly dry-bulb temperatures of Dezful

	Average monthly dry-bulb temperature (Source: Iran Meteorology Organization)	Bld. 01	Bld. 02	Bld. 03	Bld. 04	Bld. 05	Average of the Shavadans	Average monthly soil temperature source: Energy Plus lat 27.13 deg N, 56.22 deg E)
June	36.02	21.09	22.89		23.29		22.42	28.9
July	37.75	21.63	23.67		23.93		23.07	30
Aug	37.13	22.36	24.58	24.83	24.46	24.43	24.13	30.3
Sep	32.01	22.96	25.37	25.04	24.78	24.55	24.54	29.7
Oct	26.42	23.36	25.75	25.13	24.47	24.63	24.66	28.3
Nov	18.17	22.09	25.06	23.86	24.47	24.06	23.9	26.4
Dec	13.67	19.2	22.86	21.11	19.41	23.16	21.14	25
Mean	28.73	21.81	24.31	23.99	23.54	24.16	23.56	28.4
Hourly average		21.94	24.38	24.09	23.04	24.2	23.53	

However, the average of Shavadans' indoor air temperature from August to December, are more compatible with the annual average dry-bulb temperature of Dezful (See Table 4).

Table 4. The average indoor air temperature of the Shavadans from June to December

Hourly average	Bld. 1	Bld. 2	Bld. 3	Bld. 4	Bld. 5	Average
June-Aug	21.69	23.71		23.89		23.09
June-Dec	22.28	24.45		24.18		23.63
Aug-Dec	22.89	25.23	25	24.57	24.53	24.44

6. Conclusion

The thermal behavior of a Shavadan as a traditional passive cooling system in Iran was analyzed and presented in this study. For this purpose, five different Shavadans, placed in Dezful, with different depth, location, architectural layout, and area were studied during the summer and autumn seasons. In this study, the indoor air temperatures of five Shavadans and the outdoor air temperatures were measured by TESTO digital data loggers.

The results showed that during the time of the experiment, the indoor air temperature of the Shavadans remained stable compared to the outdoor temperature. This stability was shown to be due to the depth of the structures below the ground and their natural ventilation systems connected to the living spaces of the Shavadans. The recorded indoor air temperature of the Shavadans, 20-23 °C, were lower than the outdoor temperature which indicates that the temperature of Shavadan is less influenced by the outdoor temperature. This stability confirmed the effectiveness of this type of passive cooling system for future designs of high performance buildings.

In the future, a sensitivity analysis process, including measurements of RH and AER, can be done to determine the exact effectiveness of the shafts on Shavadans' thermal behavior. In addition, further studies on other Shavadans in a whole year help to have more confidence in the thermal behavior of Shavadans. The comparison of the thermal behaviors of Shavadans with other types of underground structures is also recommended for future studies.

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