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THE INFLUENCE OF TURBULENCE ON THE STRUCTURE AND PROPAGATION OF ENCLOSED FLAMES.

by

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INTRODUCTION

Although it has long been established that burning rates can be appreciably increased by turbulence, the actual extent of this increase and the precise mechanism involved are still far from clear. The object of the present research was to examine the effects of turbulence on burning velocity and on the physical structure of the flame surface under flow conditions similar to those experienced in turbojet afterburner systems.

TURBULENT FLAME CONCEPTS

A comprehensive review of current turbulent flame concepts would demand a more thorough treatment than is possible here. In any case several useful reviews already exist, of which a notable recent example is that due to Burgess.[1] The following comments are therefore brief and are confined to considerations of large-scale turbulence only.

The first, and still the most important contribution to the study of turbulent flames, was made by Damkohler.[2] He visualized a turbulent flame as being essentially the same in structure as a laminar flame, and attributed the observed increase in burning rate to the effect of turbulence in wrinkling the flame front and thereby increasing its specific surface and hence also its ability to consume fresh mixture. Damkohler proposed the following equation for large-scale turbulence

$$S_T = S_L + u' \qquad (1)$$

where S_T = turbulent flame velocity, ft/sec

S_L = laminar " " , " "

u' = r.m.s. fluctuation velocity, ft/sec

In due course several more theories embodying the wrinkled flame concept emerged, differing from Damkohler and from each other mainly in the methods employed to relate turbulence properties to the increase in specific surface of the flame. Schelkin's[3] approach led to a relationship of the form

$$S_T = S_L \left[1 + B \left(\frac{u'}{S_L} \right)^2 \right]^{0.5} \qquad (2)$$

in which B is a constant of the order of unity.

At high velocities Eqs. (1) and (2) both become

$$S_T \simeq u' \qquad (3)$$

The first serious doubts on the validity of the models proposed by Damkohler and Schelkin were expressed by Bollinger and Williams[4] whose experimental data were quite incompatible with Eqs. (1) and (2). Attempts to resolve these differences, and to find mechanisms whereby turbulence could augment burning velocities beyond the levels predicted on the basis of stream turbulence alone, led to the proposal that additional turbulence was generated by the combustion process itself. According to Karlovitz, Denniston and Wells[5] the maximum increase in turbulence attributable to this effect may be expressed as

$$u' = \frac{S_L}{\sqrt{3}} \left(\frac{\rho_u}{\rho_b} - 1 \right)$$

where ρ_u and ρ_b are the densities of the unburned and burned gas respectively. Scurlock and Grover[6] also derived a similar expression to account for the effect of flame generated turbulence. However, since then a number of workers[7, 8, 9] have obtained results which throw grave doubts on the whole concept of flame generated turbulence. Westenberg[9], in particular, showed that for lean propane-air mixtures the level of turbulence in the flame was not significantly greater than the approach stream turbulence. As a result the notion of flame generated turbulence no longer finds widespread support.

Quite apart from the apparent need to invent new theories, such as flame generated turbulence, to account for the wide differences between actual measurements of turbulent flame velocity and predictions based on Eqs. (1) and (2), other and more fundamental objections to the wrinkled laminar flame concept have been raised. Using a stirred reactor, Longwell[10] obtained volumetric heat release rates that were far too high to be explained on the basis of a combustion zone composed of a multitude of wrinkled laminar flames. Based on this evidence and their own experimental findings, Summerfield et al[11] concluded that the wrinkled laminar flame description should be abandoned and the turbulent flame brush treated as a combustion zone "in depth".

Spalding[12], on the other hand, put forward the view that, over an important range of conditions, the rate of flame spreading in an enclosed duct is independent of laminar flame speed and is governed entirely by the rate of entrainment by the flame region of the surrounding fresh mixture. The main conclusions drawn from these various theories are summarized in table 1.

PREVIOUS WORK ON ENCLOSED FLAMES

The first major experimental study of enclosed turbulent flames was reported by Williams, Hottel and Scurlock[13]. In their apparatus a combustion chamber of constant, rectangular cross section was supplied with homogeneous mixtures of gaseous fuel and air at atmospheric pressure and temperature. Fuel-air ratio and inlet velocity could be varied independently over a wide range. After flowing through a calming section terminating in a 25:1 contraction ratio nozzle, the mixture emerged with very low turbulence and a flat velocity profile. The subsequent level of stream turbulence was controlled by means of screens and grids located at the chamber entrance. Opposing side walls of the chamber were constructed of Vycor glass to permit visual observations and photographic recordings. Flame stabilization was achieved on bluff-body flameholders of various size and shape. The range of test conditions is shown in table 2.

At inlet velocities below 50 ft/sec it was found that turbulent flame velocity varied with fuel-air ratio in accordance with the behaviour of laminar flames. However, at inlet velocities higher than 100 ft/sec the turbulent flame velocity was almost independent of fuel-air ratio, and increased in a roughly linear manner with velocity. Approach stream turbulence had little effect below 2·3 percent, but at a level of 6·5 percent a substantial increase in flame width was obtained at velocities ranging from 25 to 100 ft/sec.

Wohl et al[14] also examined the effect of approach stream velocity and turbulence on the flame velocity of propane-air mixtures. They employed a horizontal duct of rectangular cross section fitted with side walls of Vycor glass. The turbulence level of the approach stream was normally below 0·4 percent but could be raised to 9 percent by the insertion of screens. Turbulent flame speeds were measured by dividing the volume flow rate by the upstream surface area of the flame. Experimental data obtained with stoichiometric propane-air mixtures at inlet velocities up to 82 ft/sec fitted quite well the equation

$$\frac{S_T}{S_L} - 1 = 26{\cdot}2\,\frac{u'}{U} + 1{\cdot}40\left(\frac{U}{24}\right)^{1{\cdot}12} \qquad (4)$$

or, since T = percentage turbulence = $100\,\frac{u'}{U}$

$$\frac{S_T}{S_L} - 1 = 0{\cdot}262T + 1{\cdot}40\left(\frac{U}{24}\right)^{1{\cdot}12} \qquad (5)$$

These equations, which are fully consistent with a wrinkled flame model, are of special interest since they demonstrate a result which is not postulated by any of the various theories, namely the important and independent effect of velocity in increasing the specific surface of the flame.

Wright and Zukoski[15] employed a similar apparatus to study flame spreading rates in gasoline-air mixtures at inlet velocities up to 440 ft/sec and gas temperatures ranging from 373°K to 520° K. Hydrogen was also used to increase laminar flame speeds by a factor of about 10. The experiments showed that "the rate of flame spreading from a bluff body is remarkably independent of the approach stream speed, temperature, fuel-air ratio and fuel type, as long as the flame is turbulent and the flow is everywhere subsonic". Since laminar flame speeds are well known to be very dependent on temperature, fuel-air ratio and fuel type, Wright and Zukoski's conclusions may be interpreted as stating that turbulent flame velocity is independent of laminar flame speed and proportional to inlet velocity.

PRESENT EXPERIMENTS

Uniform propane-air mixtures were supplied to a combustion chamber 12 ins. long and of 4-inch square cross section. The system incorporated a large calming section containing a number of screens whose purpose was to remove large-scale turbulence and to ensure that any remaining turbulence was isotropic, small-scale and of low intensity. At the downstream end of the calming section the mixture entered the chamber via a nozzle of 25:1 contraction ratio. Investigations of the flow at exit from the nozzle, using a pitot tube and a hot wire anemometer, confirmed that inlet velocity and turbulence intensity were practically uniform across the entire flow. Control over the turbulence level was achieved by means of grids located at entry to the chamber. Traverses made with a hot wire anemometer revealed that, above 50 ft/sec, the percentage turbulence was independent of velocity. The values obtained for the four grids employed in the tests were 2, 5, 9 and 14 percent. Unfortunately the available equipment was incapable of measuring turbulence scale.

Apart from differences in dimensions, the apparatus was basically the same as that employed by Scurlock. However, instead of a bluff-body flameholder a pilot burner was used to initiate combustion and anchor the flame. This had the advantage of eliminating the flow disturbances created by the presence of a bluff-body. The pilot burner consisted of a 3/4 inch diameter tube, containing a small circular flame stabilizer, and connected to separate supplies of propane and air. Ignition was accomplished by means of a high tension spark. It was found that fairly wide variations in the heat release of the pilot burner had no discernible effect on the main combustion process.

The combustion chamber was fitted with glass side walls to permit flame studies by direct and schlieren photography. Schlieren photographs were taken at turbulence levels ranging from 2 to 14 percent and at inlet velocities up to 250 ft/sec. These photographs provided the basic data for the investigation. Turbulent flame velocities were derived as the product of the inlet velocity and the sine of the angle between the flow direction and the surface of the flame. Because of the irregularities that were always present in varying degrees, definition of the flame surface was inevitably subject to personal interpretation. However, the flame surface was assumed to correspond to a line drawn through the mid-heights of the flame protuberances. Taking into account possible errors in the measurement of inlet velocity and fuel flow, it is believed that turbulent flame velocities were measured to an accuracy of between 5 and 15 percent, depending on the degree of roughness of the flame surface.

RESULTS

The critical value of Reynolds Number occurred at an inlet velocity of about 50 ft/sec. Results obtained at a slightly lower velocity (43 ft/sec) are presented in figure 1. They show that turbulent flame velocity increases with percentage turbulence in the approach stream and exhibits the same variation with equivalence ratio that characterizes a laminar flame. This result is in broad agreement with the findings of Williams et al[13] at a similar low velocity. Complementary to figure 1 are the schlieren photographs of figures 2 and 3. Figure 2 illustrates the effect of varying equivalence ratio at an inlet velocity of 43 ft/sec and a turbulence level of 2 percent. It is apparent from this figure that the structure of the flame is unaffected by changes in equivalence ratio. In all three photographs, corresponding to equivalence ratios of 0•87, 1•0 and 1•4, the flame has a smooth laminar appearance, the surface comprising an agglomeration of round swellings which gradually increase in size as the flame expands downstream. Figure 3 shows three photographs taken at the same velocity, but at a constant equivalence ratio of 1•0 and at turbulence levels of 2, 5 and 14 percent. These photographs reveal that, as the turbulence is raised, each small element of flame surface remains smooth, but the flame as a whole becomes more disrupted and its specific surface is thereby increased. The conclusion to be drawn from these tests is that at low velocity the process of flame propagation is by means of a wrinkled laminar flame in which the degree of wrinkling is governed by the turbulence level of the approach stream.

Data obtained at higher inlet velocities are shown in figures 4, 5 and 6. At flow conditions where a high inlet velocity was combined with a high degree of turbulence, the flame surface was usually too irregular to permit accurate determinations of flame angle. This accounts for the paucity of data at these conditions in figures 5 and 6. It is clear from these figures that turbulent flame velocity increases with inlet velocity and approach stream turbulence. They also show, in contradiction to the findings of Williams et al[13] and Wright and Zukoski[15], that flame velocity varies with equivalence ratio at all levels of velocity.

The effect of equivalence ratio on flame structure at high velocity is illustrated in figure 7, which shows three photographs obtained at an inlet velocity of 140 ft/sec, a turbulence level of 2 percent, and equivalence ratios of 0·6, 1·0 and 1·2. As at low velocities, these pictures show no evidence of any effect of fuel-air ratio on flame structure. It follows, therefore, that the observed variation of flame velocity with fuel-air ratio is not a surface phenomenon but stems from processes occurring within the combustion zone, of which the flame surface is merely a boundary.

The influence of turbulence at high inlet velocity is illustrated in the photographs of figure 8. These show the effect of increasing the turbulence level from 2 to 14 percent in four steps while maintaining the inlet velocity and fuel-air ratio constant. These photographs indicate that, as at low velocities, the effect of turbulence is to lacerate and disrupt the flame, the degree of disruption increasing with thelevel of turbulence.

The influence on flame structure of velocity acting alone is illustrated in figure 9. This contains photographs taken at an equivalence ratio of 0·8, a turbulence level of 5 percent, and at inlet velocities of 30, 43, 72 and 218 ft/sec. All four photographs show flames of irregular profile due to the fairly high level of turbulence. The flame surface itself has a cellular structure, and it is evident from the photographs that the average cell size diminishes with increase in flow velocity.

Although the influence of inlet velocity on turbulent flame speed can be deduced from figures 1, 4, 5 and 6, it is shown directly in figures 10, 11 and 12 for equivalence ratios of 0•6, 0•8 and 1•0 respectively. These graphs demonstrate that, for constant values of percentage turbulence and fuel-air ratio, the turbulent flame speed increases linearly with inlet velocity. Another significant feature of all three graphs is that, for each level of turbulence, lines drawn through the experimental points all converge at zero velocity at a flame speed corresponding to the laminar value. This is certainly true of figures 10 and 11, although figure 12 is less convincing in this respect.

Inspection of these figures suggests at once a relationship of the form

$$\frac{S_T}{S_L} = 1 + (C_1 \ T + C_2) \ U$$

and a satisfactory correlation of the experimental data was, in fact, achieved by the equation

$$\frac{S_T}{S_L} = 1 + (\cdot 0043 + \cdot 04) \ U \qquad (6)$$

In figure 13 turbulent flame velocities calculated from Eq. (6) are shown plotted against actual experimental values. The data relate to values of $\emptyset$ of 0•6, 0•8 and 1•0, for which the corresponding laminar flame speeds are 0•58, 1•0 and 1•47 ft/s.[16] In view of the inherent limitations of the methods employed in measuring turbulent flame velocities the correlation achieved is regarded as satisfactory.

The relationships between the flow properties investigated and flame spreading rates are illustrated in figures 14 and 15. Figure 14 was constructed from data extracted from figures 1, 4, 5 and 6, the actual experimental points being omitted for the sake of clarity. It demonstrates the significant effect of fuel-air ratio on flame spreading rates and the much smaller effect of inlet velocity. Figure 15 shows the influence of turbulence on flame spreading rate and also confirms the minor role of velocity.

The conclusion drawn from figures 14 and 15 is that, for any given combustible mixture at constant inlet pressure and temperature, the rate of turbulent flame propagation is determined by the percentage turbulence and fuel-air ratio, and is practically independent of velocity.

DISCUSSION OF RESULTS

The most striking feature of the experimental results is the dominant influence of laminar flame speed on turbulent burning velocity. This became very apparent during the process of data correlation as evidenced by Eq. (6) in which S_T is expressed as the sum of three separate terms, all of which are directly proportional to S_L. Particularly noteworthy is the strong dependence of S_T on fuel-air ratio, even at high velocity, a result which conflicts sharply with the findings of Williams et al[13] and Wright and Zukoski[15]. A possible explanation of this variance is that, whereas the present study was primarily concerned with the initial stages of flame propagation, the conclusions of references 13 and 15 were based on observations made at an appreciable distance downstream of the flameholder.

It is of interest to compare Eq. (4) due to Wohl et al with Eq. (6). At high velocities Wohl's equation becomes

$$\frac{S_T}{S_L} = 26{\cdot}2 \frac{u'}{U} + 1{\cdot}40 \left(\frac{U}{24}\right)^{1{\cdot}12}$$

$$\text{or,} \quad \frac{S_T}{S_L} = 0{\cdot}262\,T + 1{\cdot}40 \left(\frac{U}{24}\right)^{1{\cdot}12}$$

Thus the ratio of turbulent to laminar flame speed is expressed as the sum of two terms, one of which is independent of velocity and another which depends solely on velocity. However, at high velocities, equation 6, which describes the present experimental data, becomes

$$\frac{S_T}{S_L} = (0{\cdot}0043\,T + 0{\cdot}04)\,U \qquad \text{—————} \quad (7)$$

In this equation the ratio of turbulent to laminar flame speed is again given as the sum of two terms, but with an important difference in that both terms are directly proportional to velocity. It is of interest to note that the two terms inside the brackets are about equal in value where T is 9 percent. This suggests that the effectiveness of the velocity component in augmenting flame speed is roughly equivalent to 9 percent turbulence in the approach stream.

A better physical picture of the relevant factors may perhaps be gained by rewriting Eq. (7) as

$$\frac{S_T}{S_L} = 0{\cdot}43\ u' + 0{\cdot}04\ U$$

in which u' is the mean fluctuation velocity and U is the flow velocity.

CONCLUSIONS

The results of this investigation, carried out on enclosed flames at atmospheric pressure, fully support the wrinkled laminar flame concept of turbulent flame propagation. Turbulent flame speed is found to increase with increases in laminar flame speed, turbulent velocity and flow velocity, in a manner which is described by the equation

$$\frac{S_T}{S_L} = 1 + 0{\cdot}43\ u' + 0{\cdot}04\ U$$

Under turbulent flow conditions the flame surface is characterized by a cellular structure, the average cell size diminishing with increases in approach stream velocity and turbulence. However, the main effect of turbulence is in lacerating and disrupting the flame and thereby increasing its surface area.

The results of previous investigations are confirmed in regard to the very slight dependence of flame spreading rate on inlet velocity. However, flame spreading rate was found to vary appreciably with fuel-air ratio, a result which is consistent with the wrinkled laminar flame model, but which contradicts previous findings on enclosed flames.

LIST OF SYMBOLS

S_L - laminar flame velocity, ft/sec.

S_T - turbulent flame velocity, ft/sec.

U - inlet flow velocity, ft/sec.

u' - turbulent velocity, or r.m.s. fluctuation velocity, ft/sec.

T - percentage turbulence $= 100 \frac{u'}{U}$

α - angle between flame surface and gas flow direction

ϕ - equivalence ratio of combustible mixture

l' - turbulence scale

ρ_u - density of unburned mixture, lb/ft^3

ρ_b - density of burned products, lb/ft^3

B - constant of order of unity

C_1, C_2, C_3 - constants

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Table 1. Turbulent Flame Theories

Investigator	Postulated structure	Equations	Main conclusions
Damkohler[2]	Wrinkled laminar flame	$S_T = S_L + u'$ At high velocities this approaches $S_T = u'$	S_T is independent of scale of turbulence. At low velocities S_T is determined by laminar flame speed and turbulent velocity. At high velocities S_T is determined solely by turbulent velocity, i.e. S_T is independent of fuel type and fuel air-ratio.
Schelkin[3]	"	$S_T = S_L\left[1 + B\left(\frac{u'}{S_L}\right)^2\right]^{0.5}$ At high velocities this approaches $S_T = u'$	Broadly in agreement with Damkohler
Karlovitz et al[5]	As above but with augmentation by flame generated turbulence	For weak turbulence $S_T = S_L + u'$ For strong turbulence $S_T = S_L + (2\,S_L\,u')^{0.5}$ where $u' = \frac{S_L}{\sqrt{3}}\left(\frac{\rho_u}{\rho_b} - 1\right)$	S_T is independent of scale of turbulence. Laminar flame speed is a more important factor than turbulence even at very high levels of turbulence.
Scurlock and Grover[6]	"	$S_T = S_L\left[1 + C_3\left(\frac{\overline{y}}{l}\right)^2\right]^{0.5}$ $\overline{y}$ is dependent on approach stream turbulence and flame generated turbulence	S_T is dependent on scale of turbulence and on laminar flame speed. For confined flames, in which $U \gg S_T$, approach stream turbulence is outweighed by flame generated turbulence.
Summerfield[11]	Distributed reaction zone	None	Argues that wrinkled laminar flame description of turbulent flame should be abandoned in favour of a distributed reaction zone model. Offers little convincing physical evidence in support of this view.
Spalding[12]	Flame propagation determined by rate of entrainment of cold mixture by hot gases	None	Flame spreading dictated by laws of jet entrainment. S_T independent of scale of turbulence and percentage turbulence and proportional to inlet velocity. S_T independent of laminar flame speed except indirectly through relationship between S_L and density ratio ρ_u/ρ_b

Table 2. Experimental Data on Enclosed Flames

Investigators	Variables studied	Test conditions	Apparatus	Results
Williams, Hottel and Scurlock [13]	Percentage turbulence Turbulence scale Inlet velocity Stabilizer size and shape Fuel-air ratio Fuel type	Turbulence - 0·4 to 80% Turbulence scale - 0·01 to 0·08 in. Inlet velocity - 20 to 350 ft/sec. Inlet temperature - 300 to 340° K Pressure - atmospheric Fuel - City gas and propane	Horizontal duct 17 ins long of rectangular cross section 3 x 1 in. Duct fitted with windows for direct and schlieren photography. Bluff-body flameholders in form of single and multiple rods, 30° Vee gutters and flat plates.	At all velocities flameholder dimensions had negligible effect on flame propagation except at limit mixtures. No effect of turbulence up to 2·3%. Higher turbulence level produced appreciable effect At low velocity ($U \ngtr 50$ ft/sec) S_T varied with fuel-air ratio At high velocity ($U > 100$ ft/sec) S_T was independent of fuel-air ratio and roughly proportional to inlet velocity.
Wohl et al [14]	Percentage turbulence Inlet velocity Stabilizer size	Turbulence normally 0·4% Increased by screens to 9% Inlet velocity - 24 to 82 ft/sec Room temperature and pressure. Fuel - stoichiometric propane/air	Horizontal duct 10 ins long of rectangular cross section 2 x 1·5 in. Duct fitted with glass windows for direct and schlieren photography. Flat plate flameholders of thickness 0·117, 0·247 and 0·478 ins.	S_T increased with both percentage turbulence and inlet velocity as described by the equation $\frac{S_T}{S_L} = 1 + 0{\cdot}262\,T + 1{\cdot}40\left(\frac{U}{24}\right)^{1{\cdot}12}$ or $\frac{S_T}{S_L} = 1 + 26{\cdot}2\,\frac{u'}{U} + 1{\cdot}40\left(\frac{U}{24}\right)^{1{\cdot}12}$ This form of equation supports wrinkled flame concept.
Wright and Zukoski [15]	Inlet velocity Inlet temperature Stabilizer size and blockage. Fuel-air ratio Fuel type	Very low turbulence Inlet velocity - up to 440 ft/sec Inlet temperature - 373 to 520° K Pressure - atmospheric Fuels - gasoline and hydrogen	Horizontal duct 15 ins long of rectangular cross section 6 x 3 ins. Fitted with transparent side walls for direct and schlieren photography. Cylindrical flameholders of 0·125 to 2·0 ins diameter.	Rate of flame spreading from a bluff body was found to be "remarkably independent of approach stream speed, temperature, fuel-air ratio and fuel type, as long as flame is turbulent and flow is everywhere subsonic". * "Results strongly indicate that the local flame speed is proportional to flow speed". * This result is in conflict with the wrinkled flame model and all other theories.
Present work	Percentage turbulence Inlet velocity Fuel-air ratio	Turbulence - 2 to 14% Inlet velocity - 30 to 250 ft/sec Inlet temperature - 378°K Pressure - atmospheric Fuel - propane	Horizontal duct 12 ins long of 4 in. square cross section. Transparent side walls for schlieren photography. Flame stabilization provided by pilot burner 0·75 ins in diameter.	S_T increased with both percentage turbulence and inlet velocity as described by the equation $\frac{S_T}{S_L} = 1 + (\cdot 0043\,T + \cdot 04)\,U$ or $\frac{S_T}{S_L} = 1 + 0{\cdot}43\,u' + \cdot 04\,U$ The results fully support the wrinkled laminar flame concept. In particular S_T and flame spreading rate varied with percentage turbulence and fuel-air ratio at all velocities.

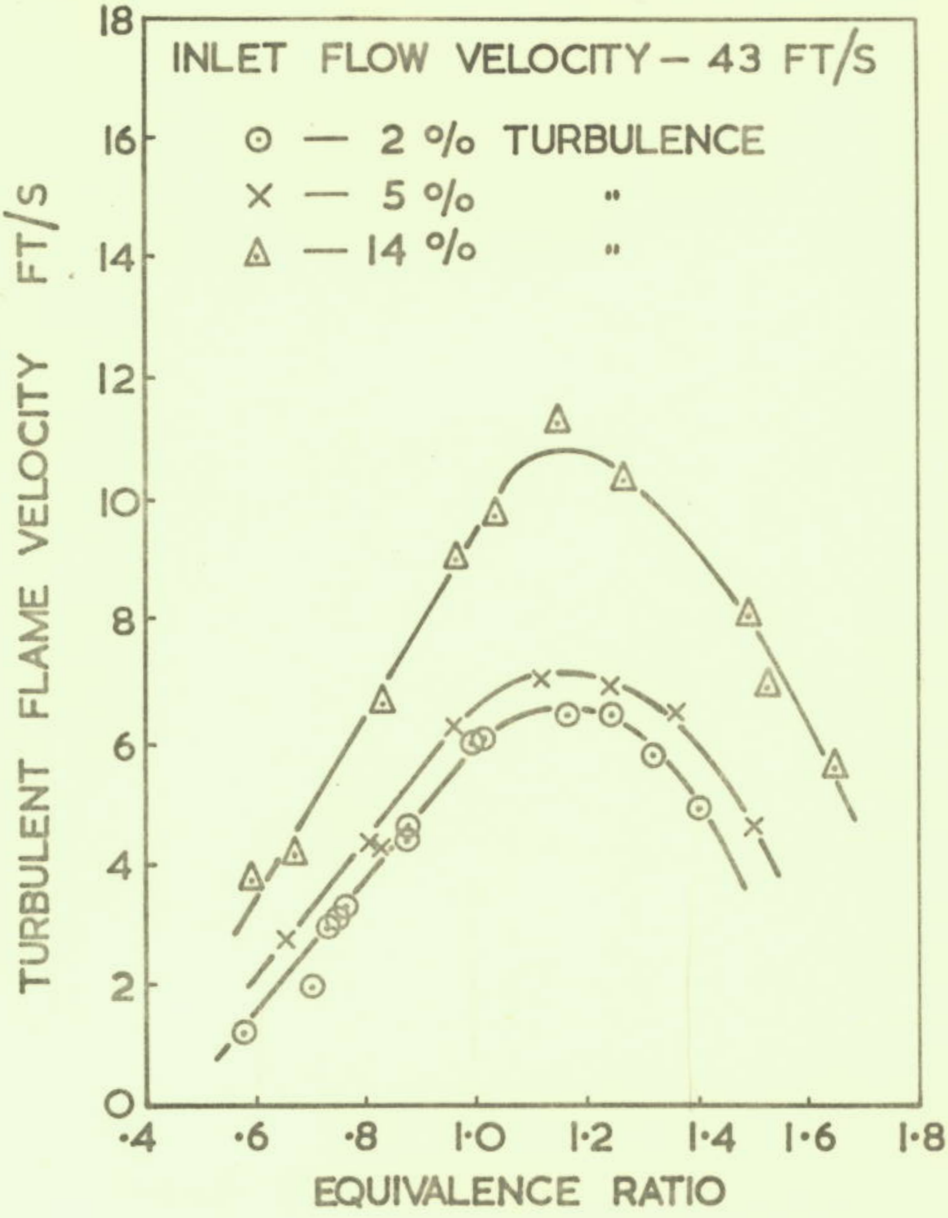

Figure 1. Influence of turbulence and equivalence ratio on turbulent flame velocity at low Reynolds Number.

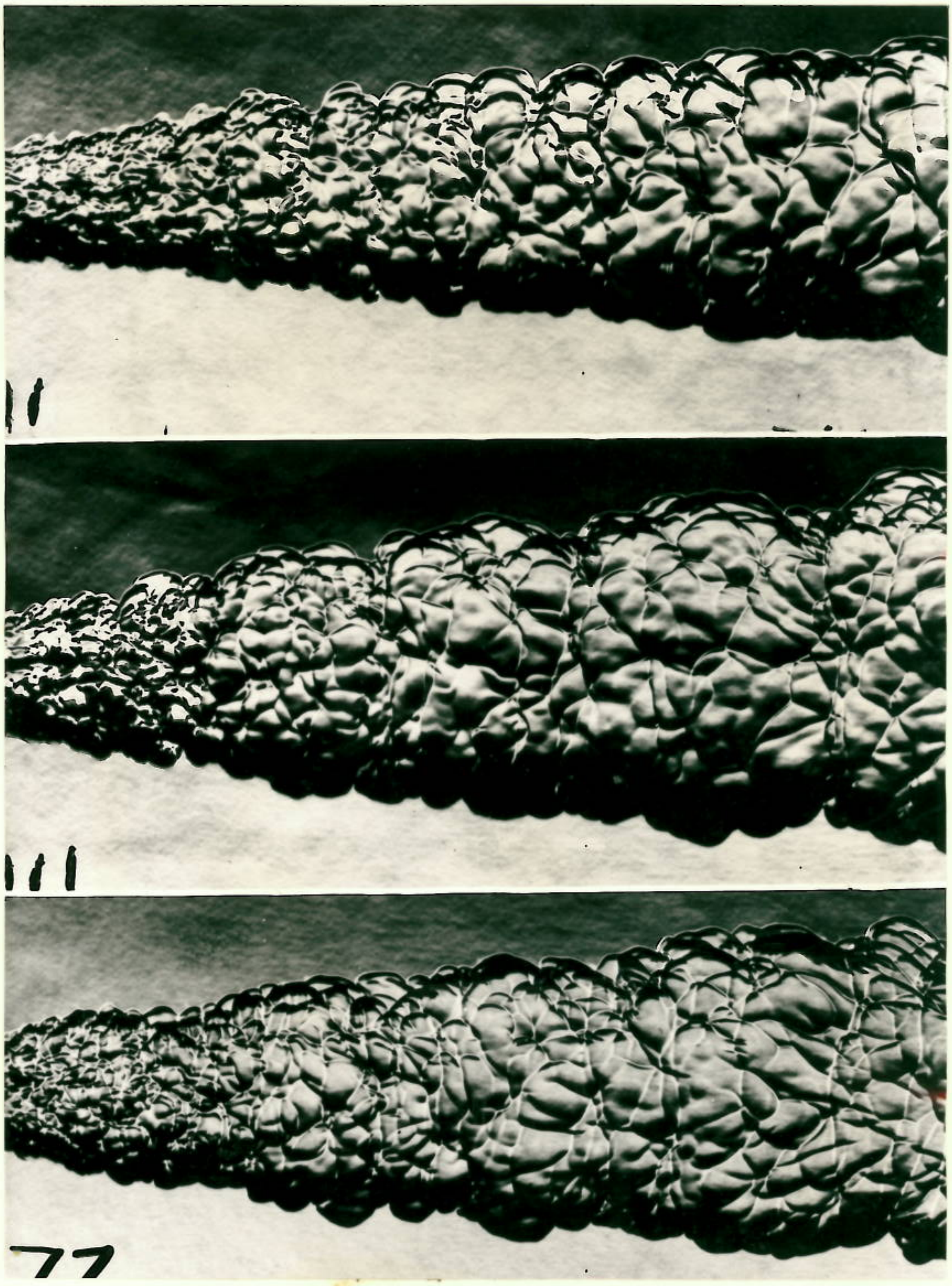

Figure 2. Schlieren photographs illustrating the effect of fuel-air ratio on flame structure at low Reynolds Number and a constant level of turbulence. Reading from top to bottom, $\emptyset$ = 0·87, 1·0 and 1·4. U = 43 ft/sec and T = 2%

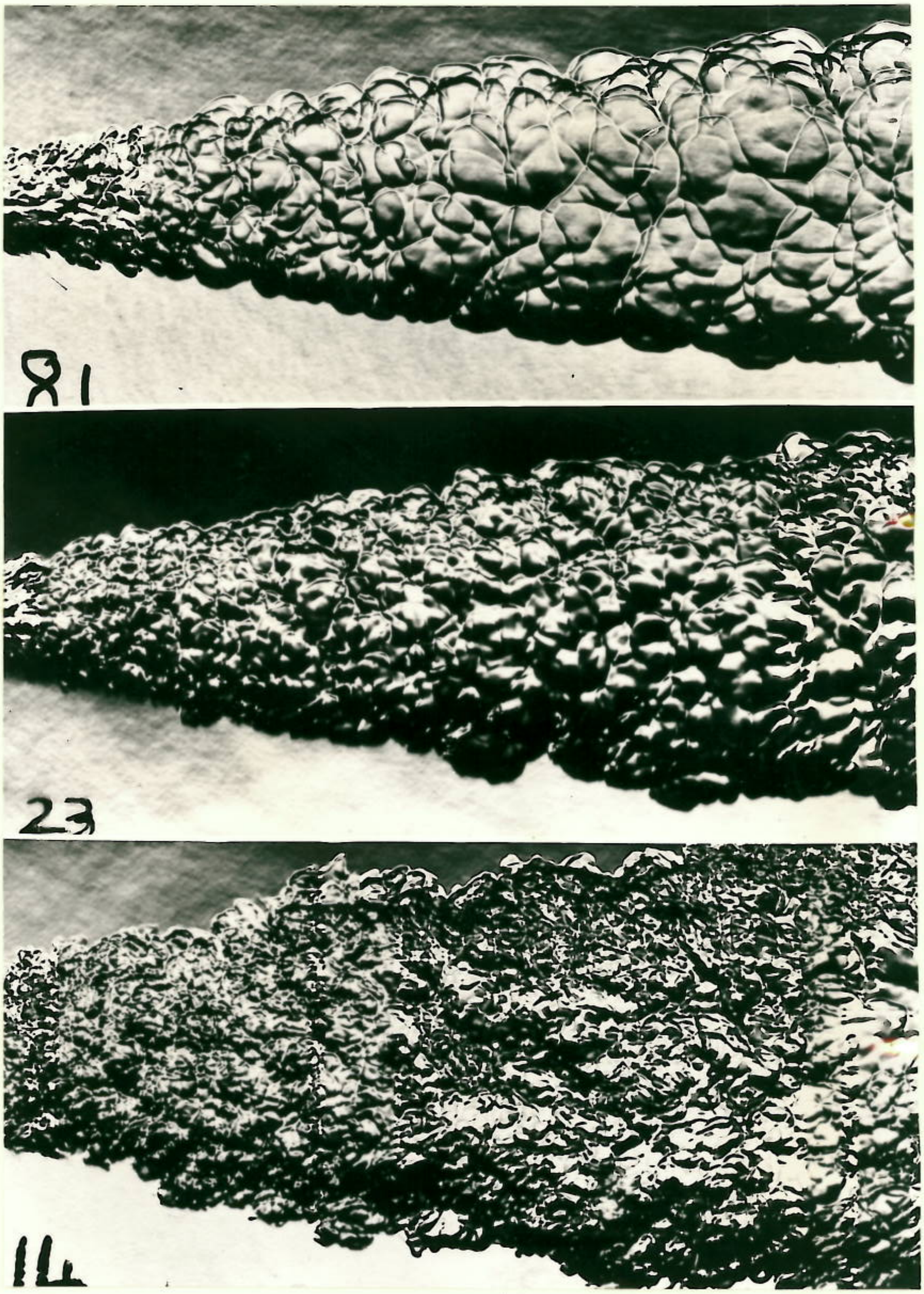

Figure 3. Schlieren photographs illustrating the effect of approach stream turbulence on flame structure at low Reynolds Number and constant fuel-air ratio. Reading from top to bottom, T = 2, 5 and 14%. U = 43 ft/sec and ϕ = 1·0.

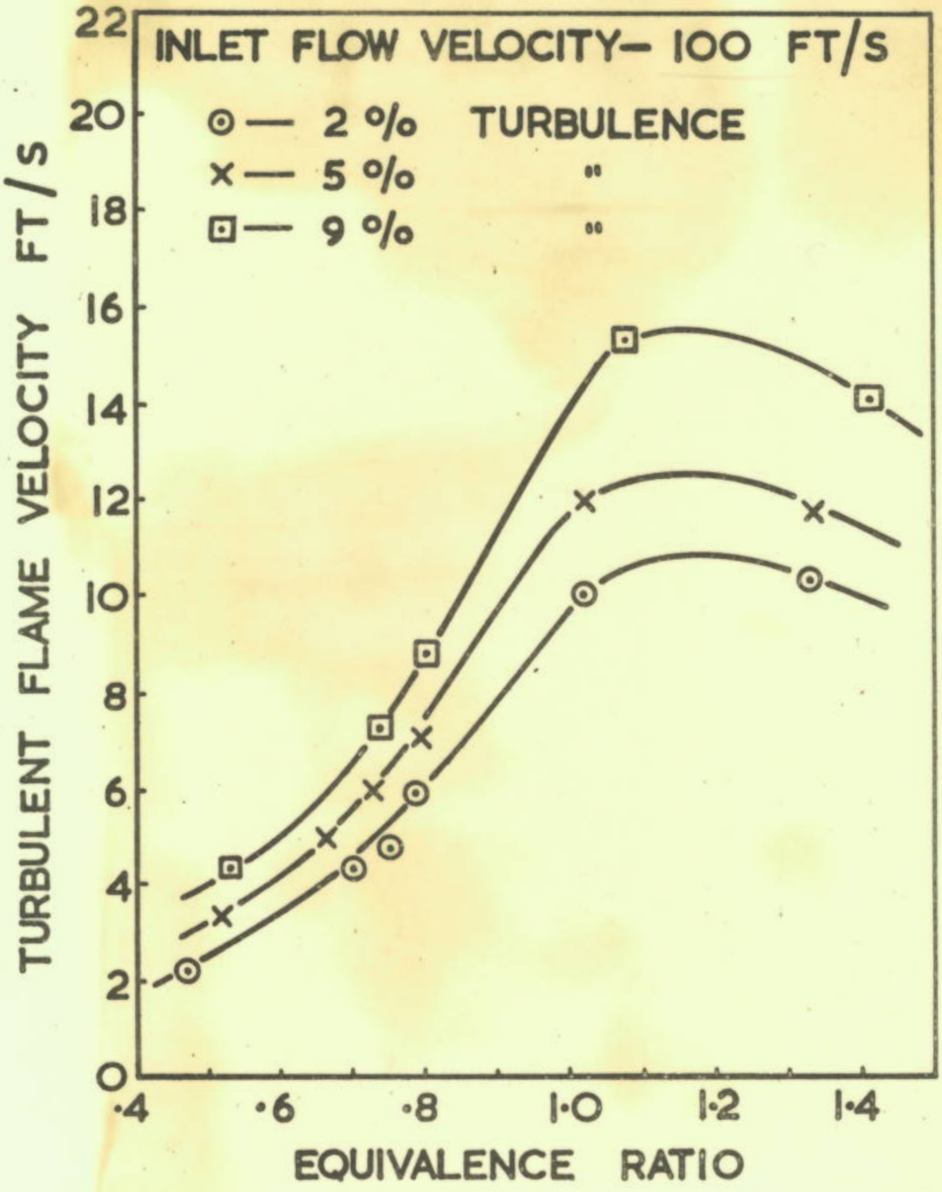

Figure 4. Influence of turbulence and equivalence ratio on turbulent flame velocity at a constant inlet velocity of 100 ft/sec

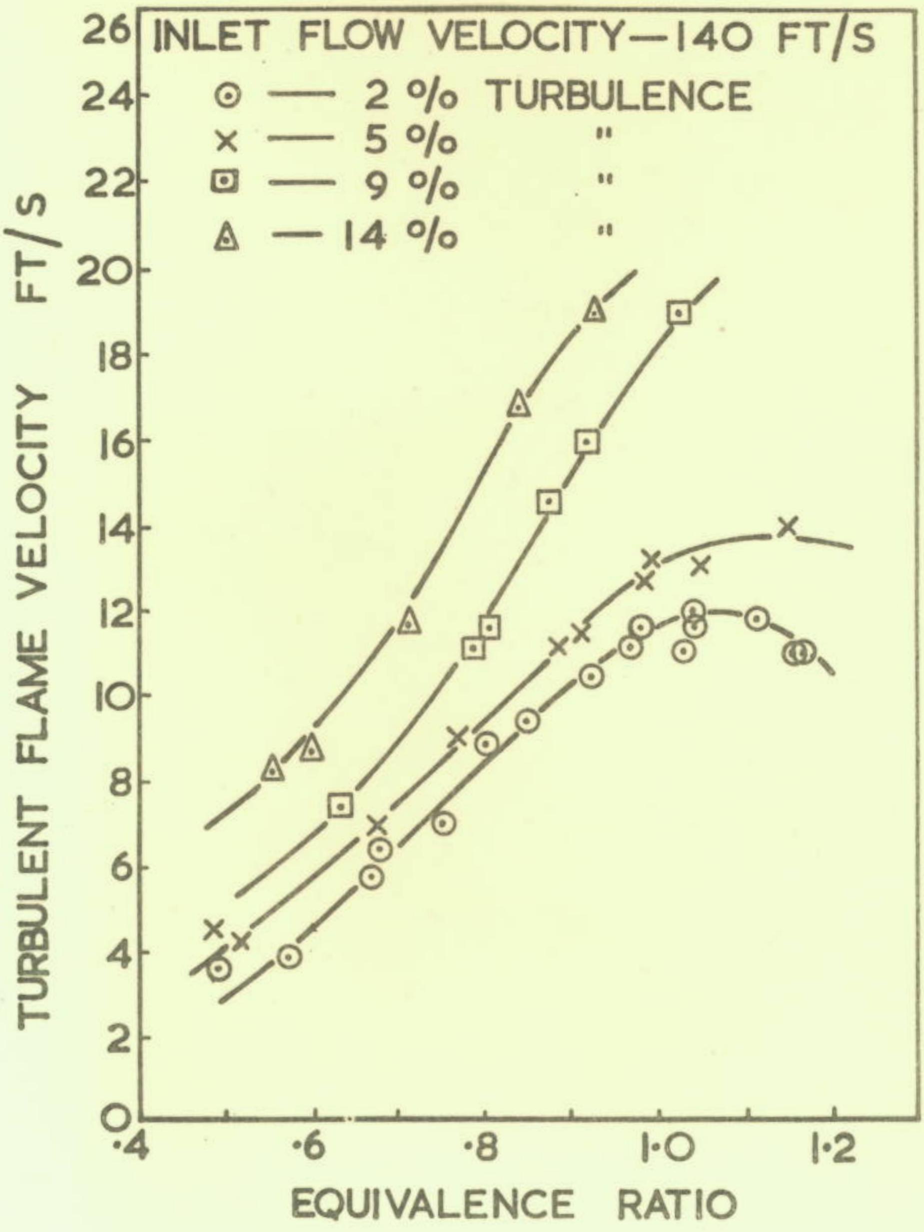

Figure 5. Influence of turbulence and equivalence ratio on turbulent flame velocity at a constant inlet velocity of 140 ft/sec

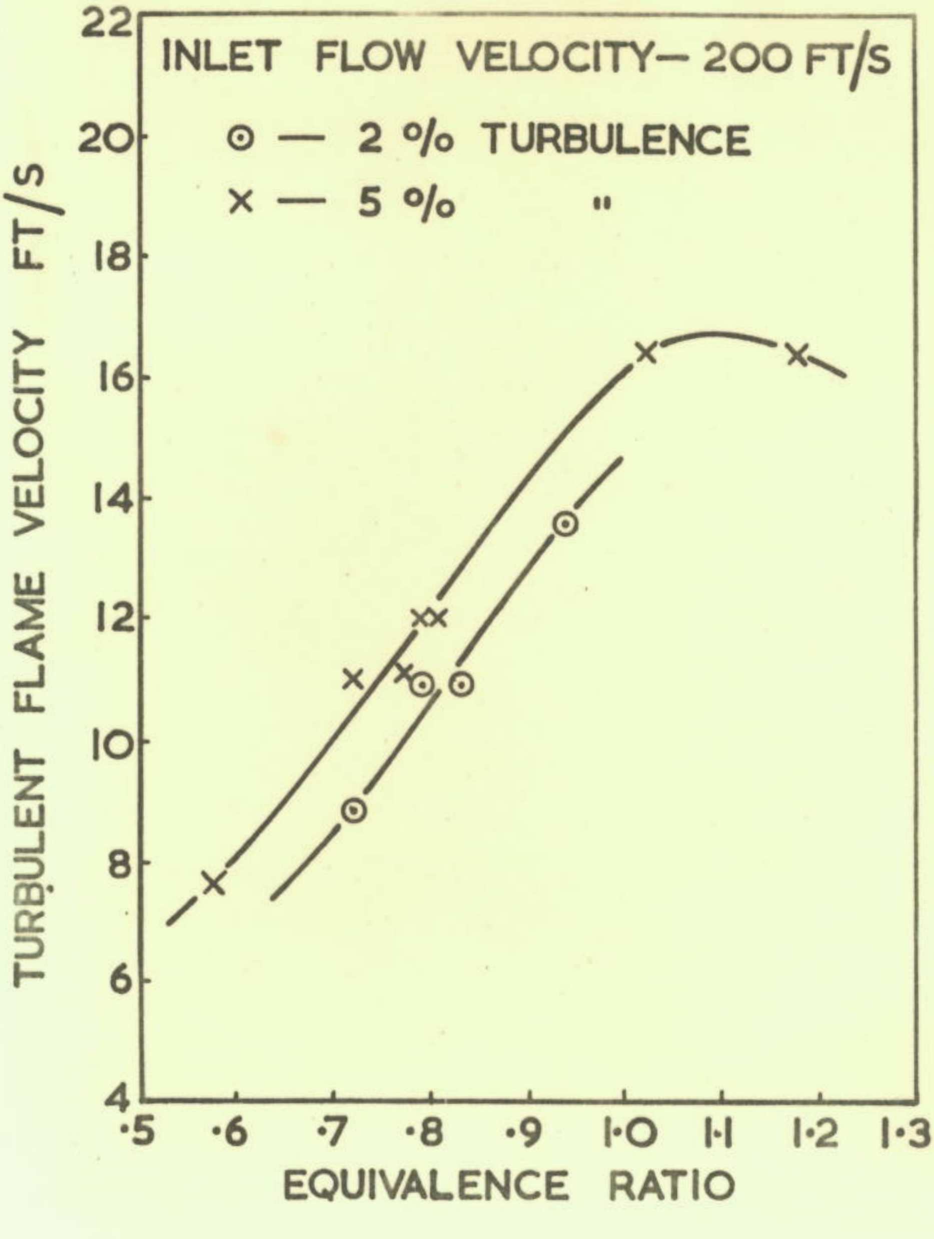

Figure 6. Influence of turbulence and equivalence ratio on turbulent flame velocity at a constant inlet velocity of 200 ft/sec

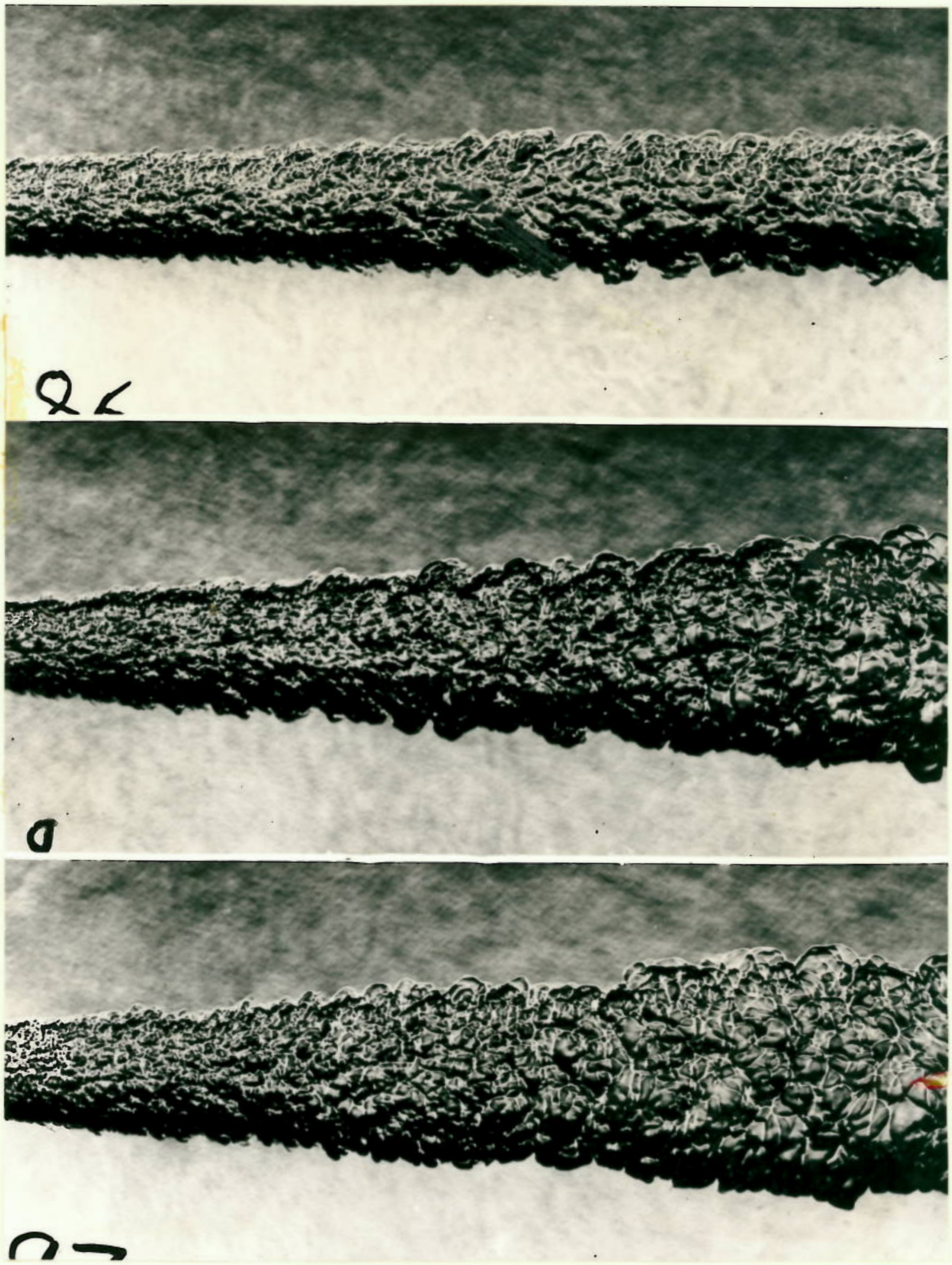

Figure 7. Schlieren photographs illustrating the effect of fuel-air ratio on flame structure at a high velocity and a constant level of turbulence. Reading from top to bottom ϕ = 0·6, 1·0 and 1·2 . U = 140 ft/sec and T = 2% .

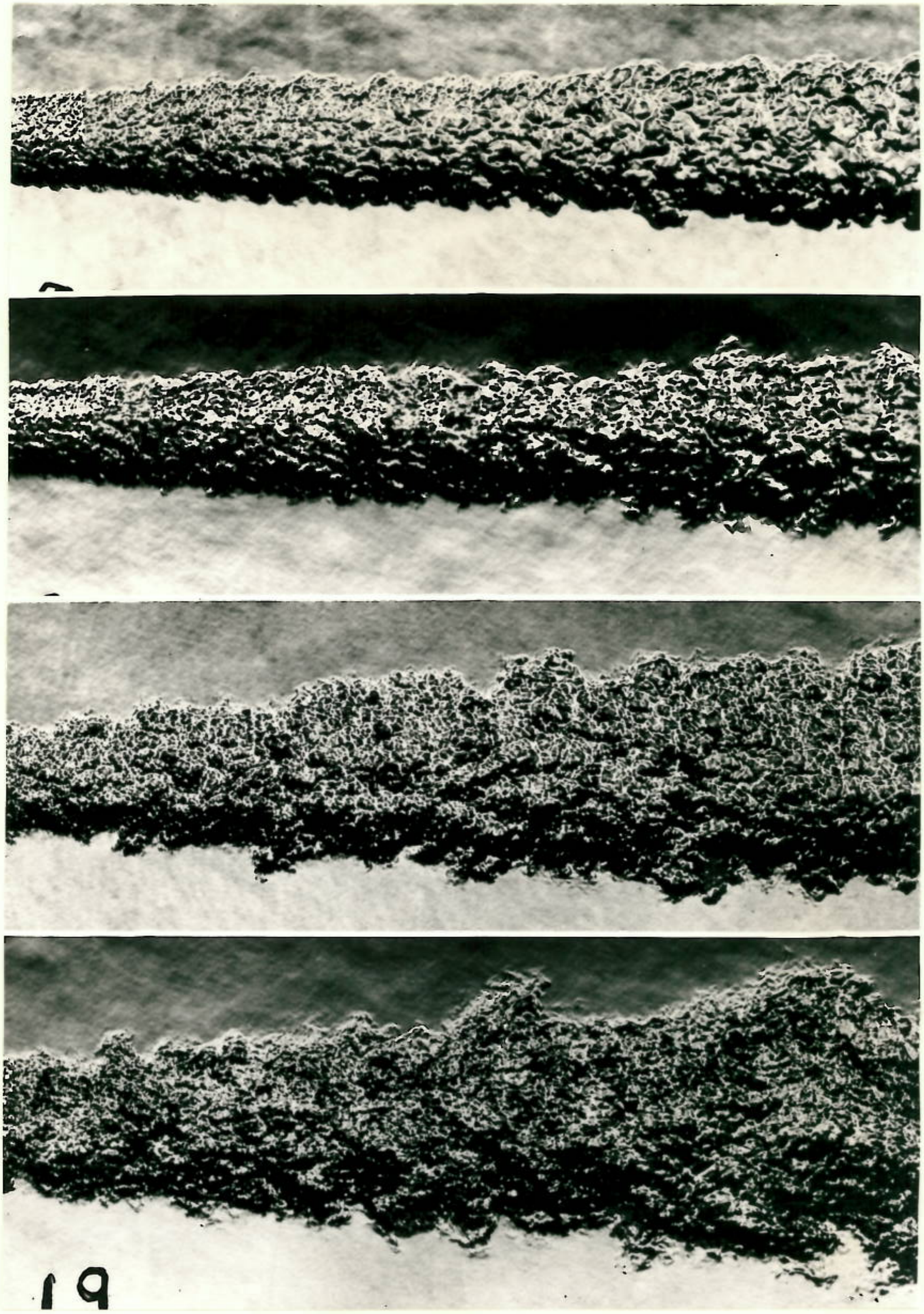

Figure 8. Schlieren photographs illustrating the effect of approach stream turbulence on flame structure at a high velocity and constant fuel-air ratio. Reading from top to bottom T = 2, 5, 9 and 14%. U = 140 ft/sec and ϕ = 0·75

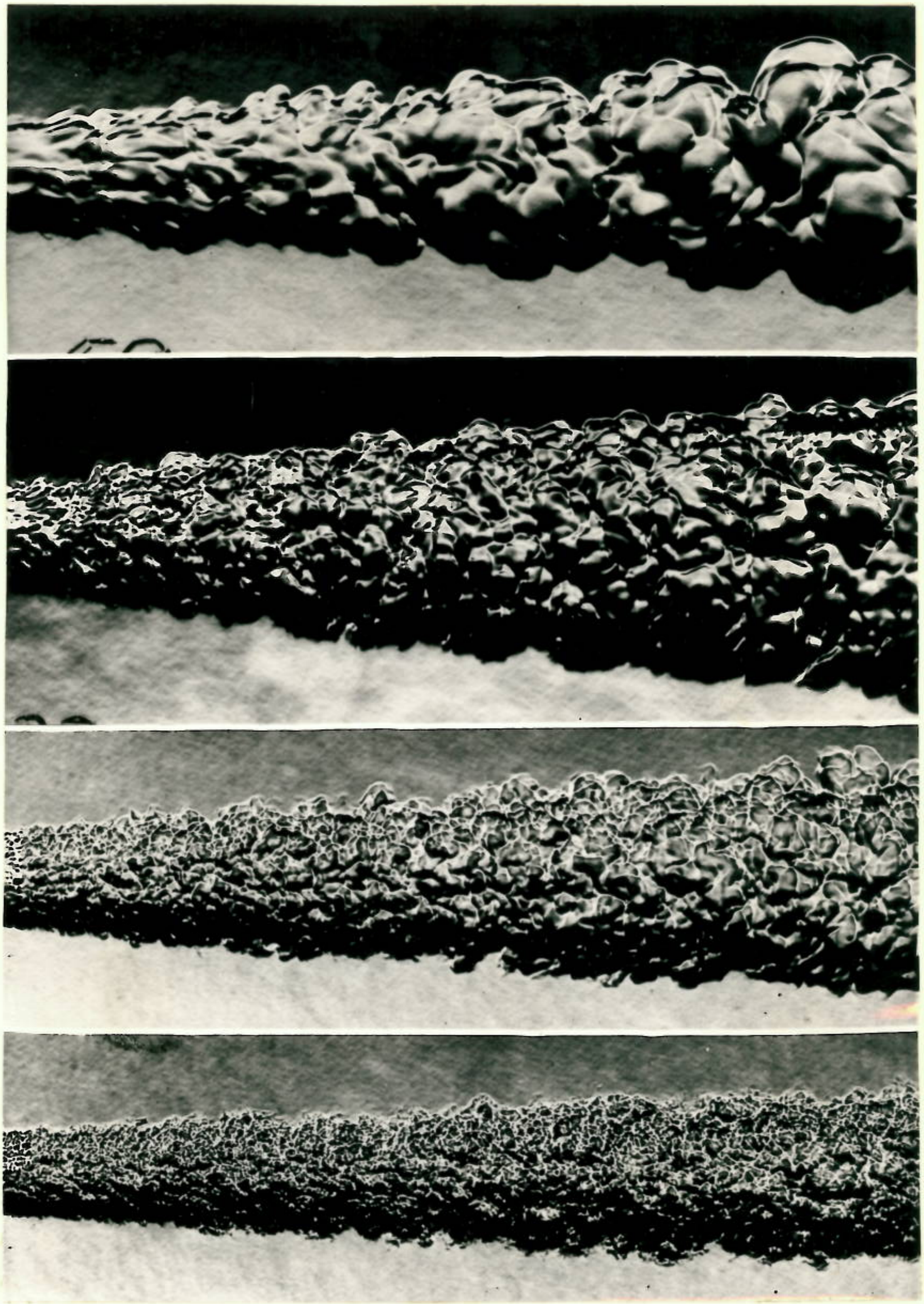

Figure 9. Schlieren photographs illustrating the effect of inlet velocity on flame structure for constant values of fuel-air ratio and percentage turbulence. Reading from top to bottom U = 30, 43, 72 and 218 ft/sec. ϕ = 0·8 and T = 5% .

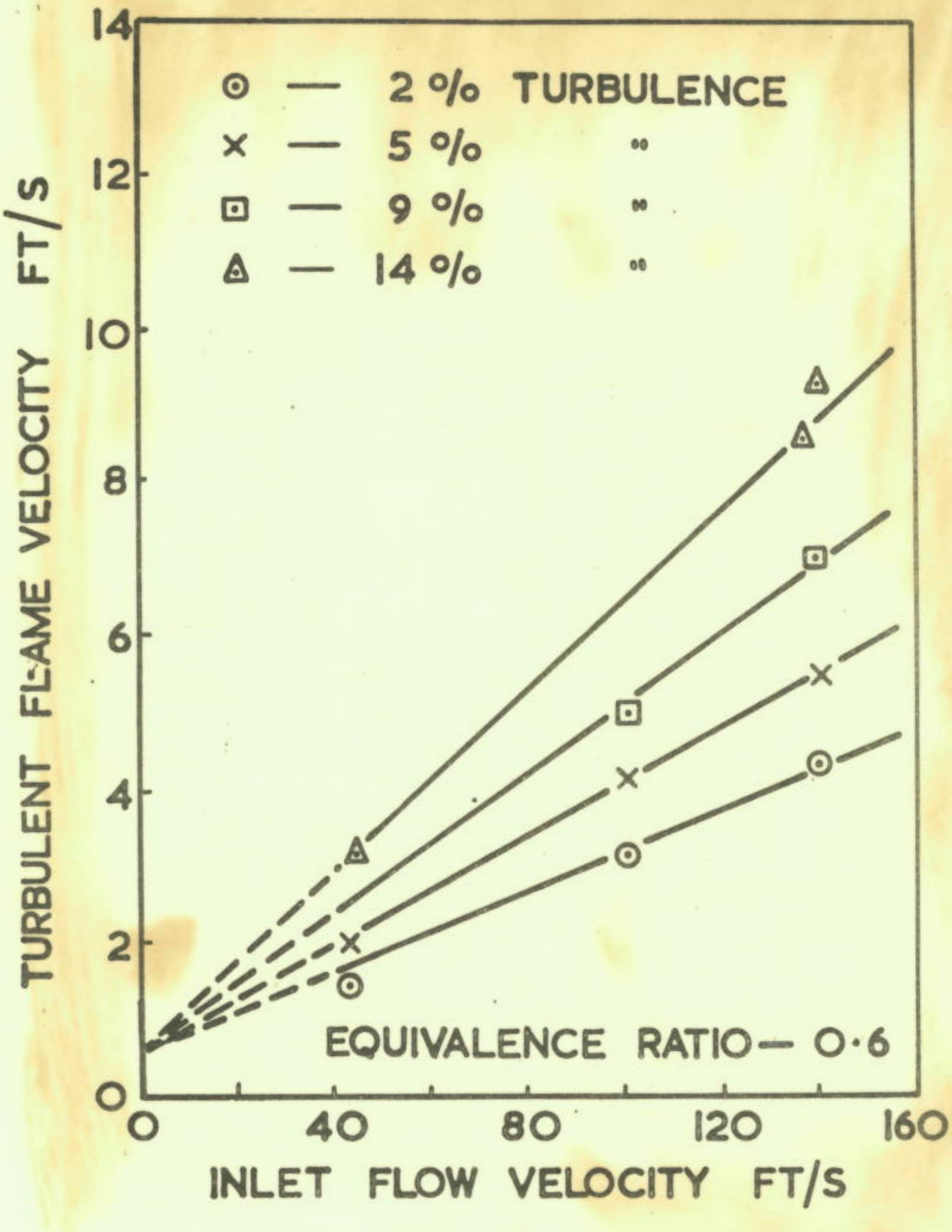

Figure 10. Influence of turbulence and inlet velocity on turbulent flame velocity at constant fuel-air ratio ($\phi = 0{\cdot}6$)

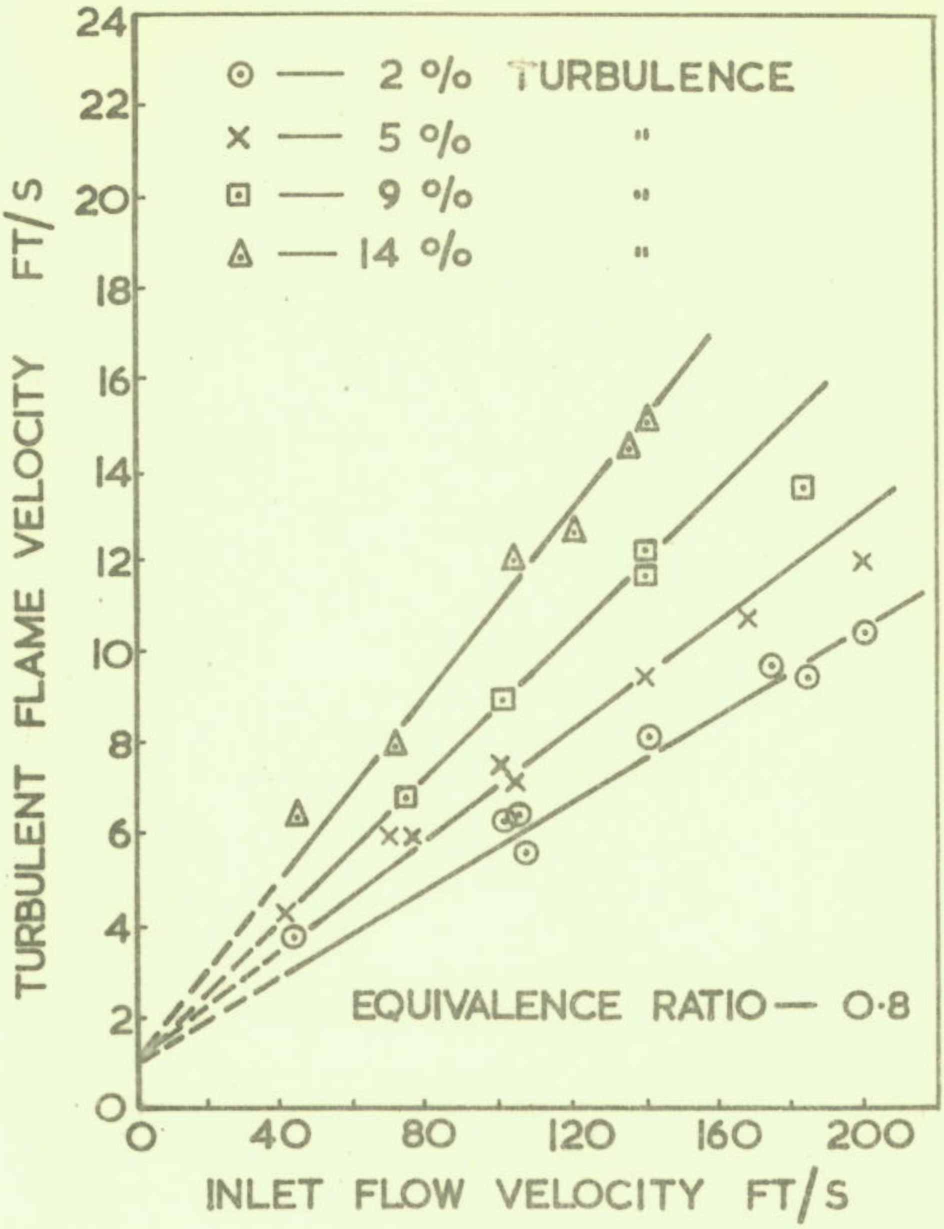

Figure 11. Influence of turbulence and inlet velocity on turbulent flame velocity at constant fuel-air ratio (ϕ = 0·8)

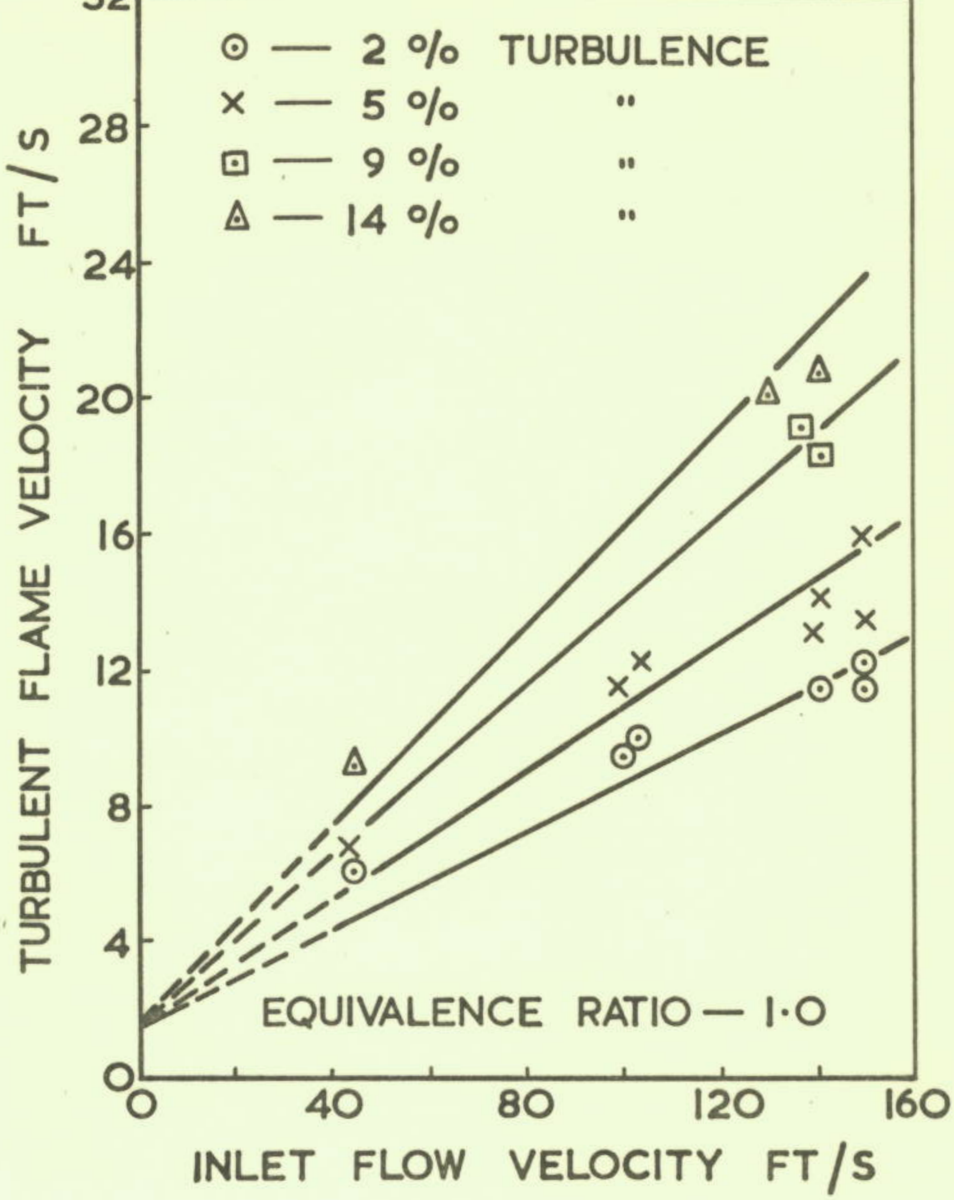

Figure 12. Influence of turbulence and inlet velocity on turbulent flame velocity at constant fuel-air ratio (ϕ = 1·0)

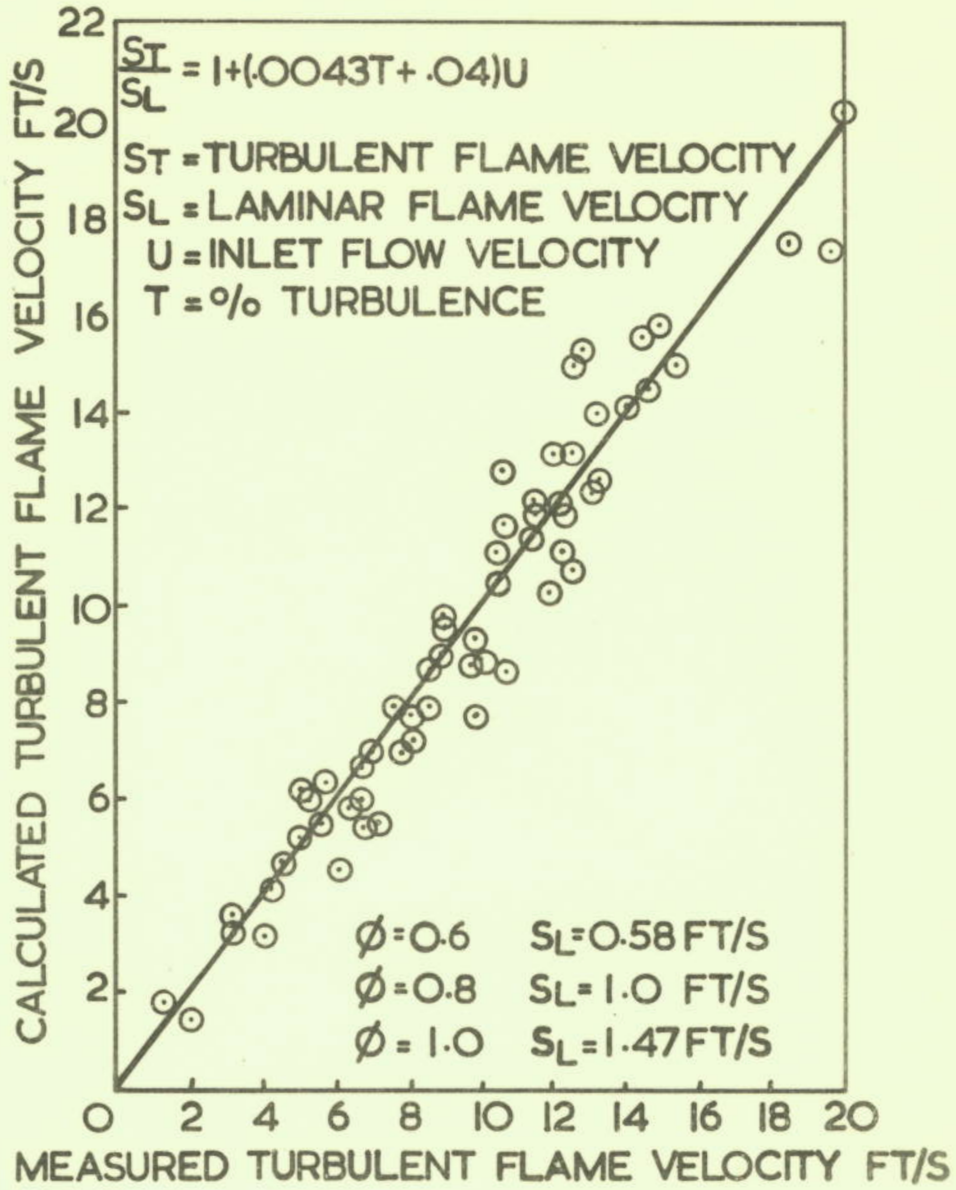

Figure 13. Comparison of measured and calculated turbulent flame velocities

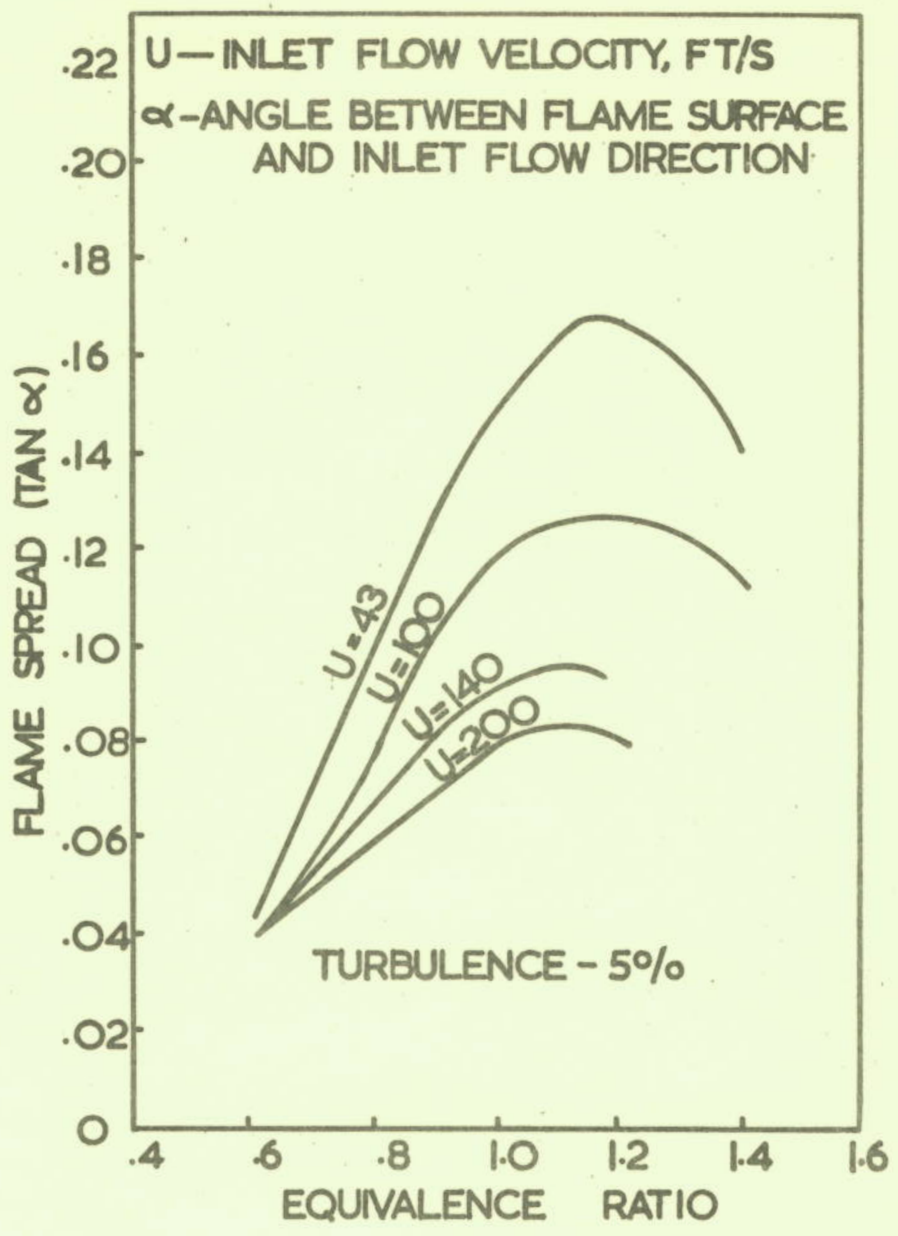

Figure 14. Flame spreading rate as a function of velocity and equivalence ratio

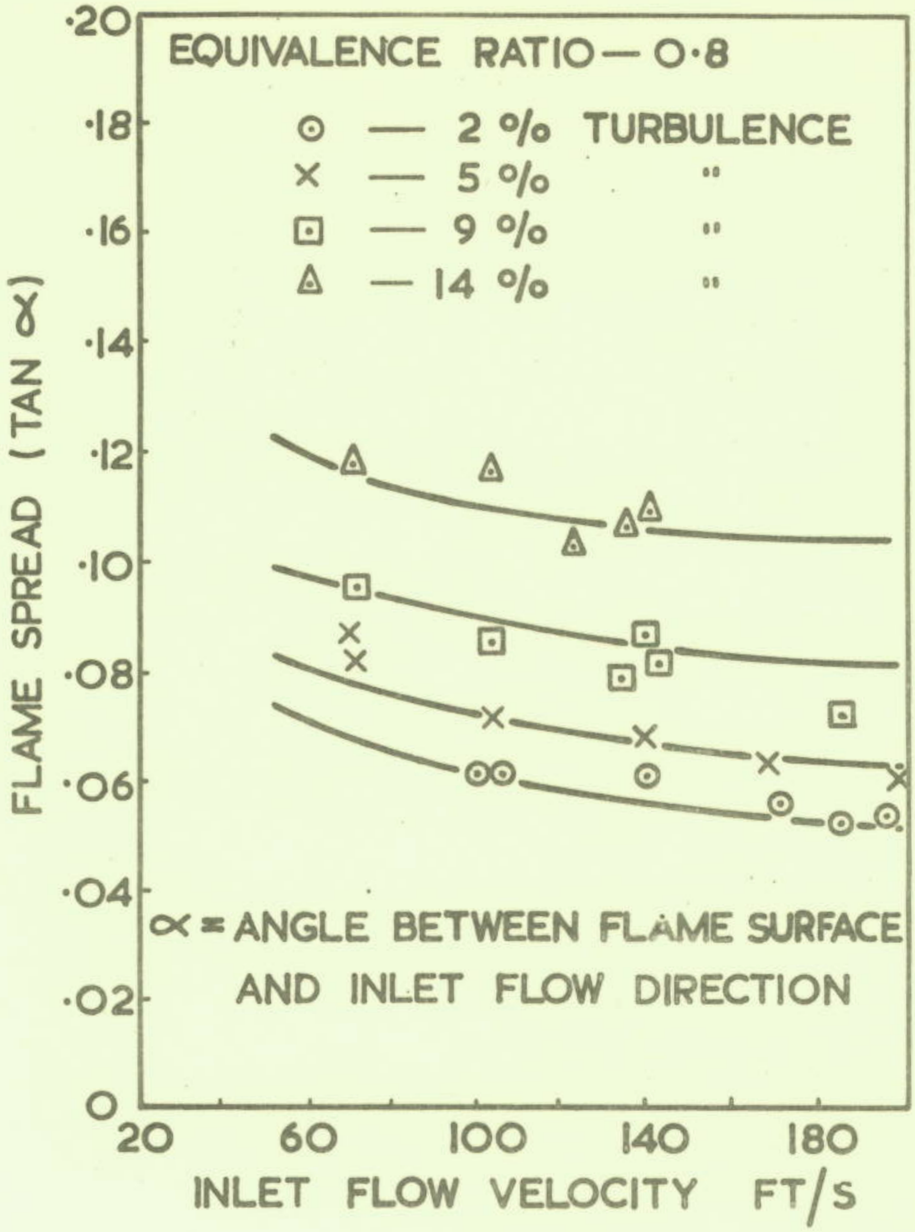

Figure 15. Graphs illustrating slight dependence of flame spreading rate on inlet velocity