Flame Holding: Selected Engine Combustion Problems

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FLAME SPREADING FROM BLUFF-BODY FLAMEHOLDERS

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Introduction

Flame stabilization and flame spreading are two processes of paramount importance in the design of combustion chambers. Sufficient experimental work has been carried out to make clear the mechanism of stabilization;[1] however, understanding of the process of flame spreading in a duct is still imperfect. This is perhaps not surprising because, in technically interesting cases, the spreading is turbulent and the behavior of even the simplest turbulent flame is still controversial. Furthermore, studies that have been made of flame spreading[2-5] have been primarily directed at solving the practical problem of the determination of combustion efficiency rather than providing insight into the physical phenomena involved in the spreading process.

The present investigation was undertaken to define the influence of certain chemical and fluid dynamic parameters on the spreading of a simple flame in a duct, with the view that the results would yield some understanding of the mechanism of flame spreading.

Apparatus and Experimental Techniques

Flame spreading is being studied in long rectangular ducts, extending at least two and a half duct heights downstream from the flameholder. Water-cooled flameholders span one dimension of the rectangle and the stabilized flame is observed through transparent side walls.[6]

Fuel is a gasoline-like hydrocarbon, Standard Oil Company Thinner No. 200, and it is injected into a heated air stream sufficiently far upstream from the flameholder to insure that a homogeneous gaseous mixture enters the test duct. Normal mixture temperature is 373°K. The flow enters the combustion duct through a nozzle which has a large area ratio and hence the axial velocity is uniform and the turbulence level is low. Because the aim of the experiments is to study spreading of a simple flame (laminar or turbulent) in a low turbulence stream, flow conditions for which the flame is distorted by pressure and velocity oscillations are unacceptable. The smooth flow requirement restricts duct length and fuel:air ratio ranges that can be studied, but has not proved to be a serious limitation.

Nevertheless, even when the flow is apparently smooth, the flame must be monitored to ensure that no flame distortions influence the results. Monitoring is accomplished by taking instantaneous schlieren photographs which also provide the primary data for the present investigation. Flame widths and flame spreading rates are measured directly from the schlieren pictures, of which Figures 1a, 1b and 1c are examples. These photographs show that the outer edges of the flame are serrated. The outer crests of the small waves on the flame surface are chosen to define the outer edge of the flame, because this definition yields flame widths that agree with widths measured on time exposure photographs, as for example, Figures 2a, 2b and 2c, and with widths obtained from total pressure measurements. Although the exact boundary is subject to personal interpretation, different observers agree on the boundaries to within a few per cent of the flame width.

Mean temperature, pressure, velocity, and composition measurements supplement the photographs. These auxiliary measurements serve especially to define the flow outside the flame and in the burned gas at the center of the wake where fluctuations are nearly absent and time-averaging instruments give reliable results.

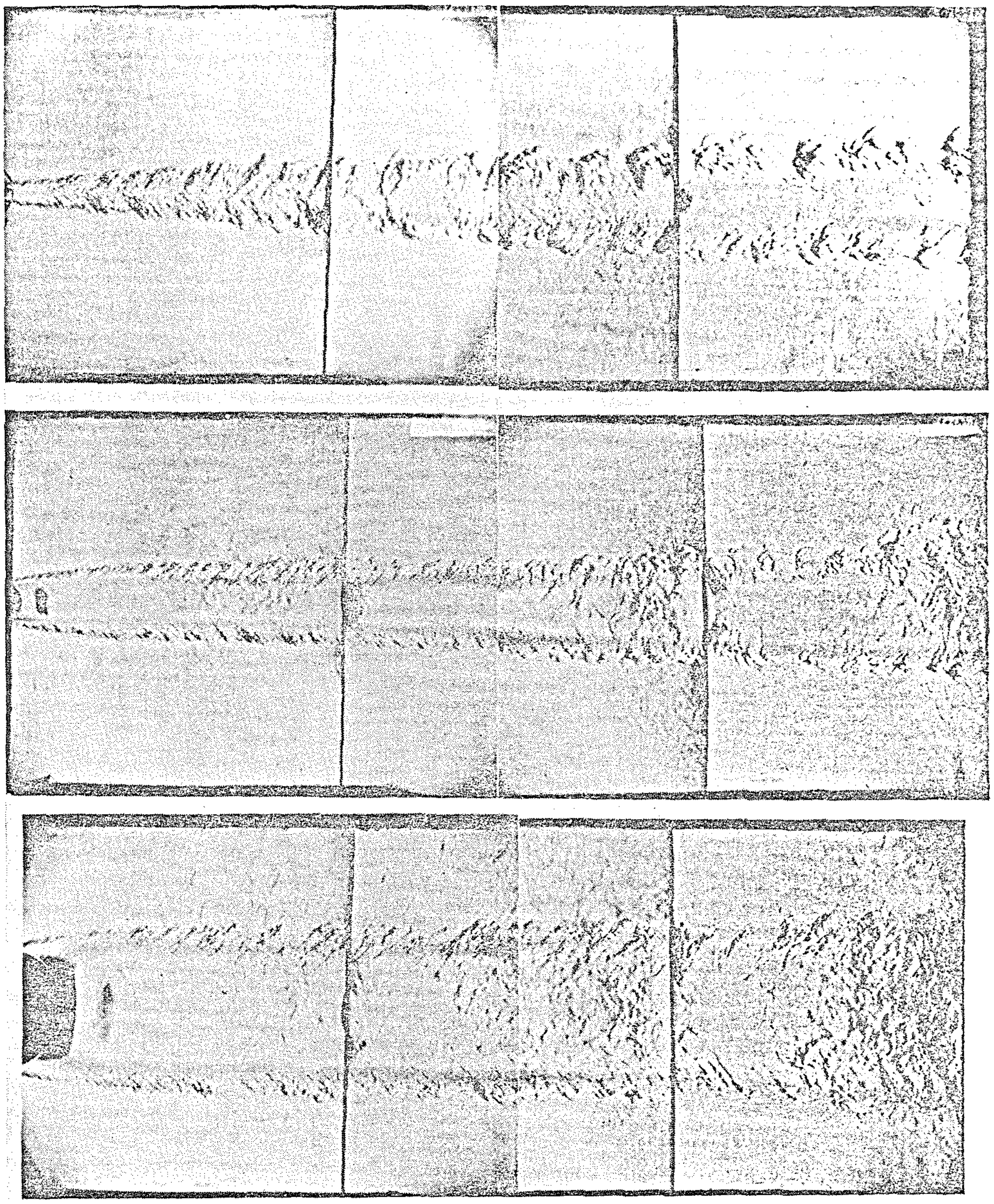

FIG. 1. Instantaneous schlieren photographs of flames held by circular cylinders in 3 x 6" duct. V = 300 ft/sec, ϕ = 1.0. Top picture: $\frac{1}{8}$" holder, Middle picture: $\frac{1}{2}$" holder, Bottom picture: 2" holder.

Description of the Flame and the Flow Field

The flame and the flow field downstream from a bluff-body flameholder are complex and involve many interesting fluid dynamic and chemical processes. A general description of some of these important features will provide a background for a later discussion of flame spreading rates.

THE FLAME

The time-exposure photos (Figs. 2a, 2b and 2c) are easily interpreted if it is remembered that vigorously burning gas has high actinic value and that hot burned gas is nearly invisible in a photograph. Hence, the bright regions of the photographs represent regions of active combustion and the dark areas are regions of no reaction and must consist of either burned or unburned

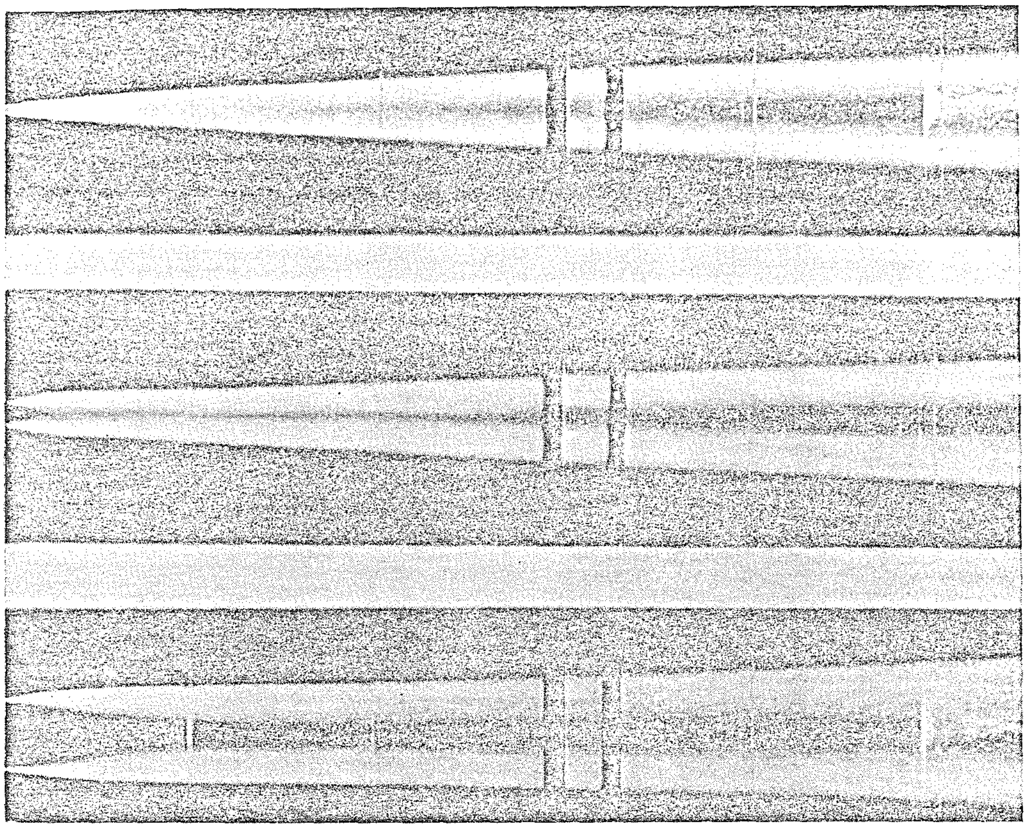

FIG. 2. Time exposure direct photographs of flames held by circular cylinders in 3 x 6″ duct. V = 300 ft/sec, ϕ = 1.0. Top picture: $\frac{1}{8}$″ holder; middle picture: $\frac{1}{2}$″ holder; bottom picture: 2″ holder.

material. All of these features may be seen in the side view photograph (Fig. 2a) of a flame stabilized on a one-eighth in. cylinder. (The holder is partially obscured at the left side of the photograph.) Just downstream from the holder is the dark inner part of the recirculation zone consisting of burned gas and bounded by brilliant white regions of active combustion. These regions thicken rapidly until they join at the downstream end of the recirculation zone and then thicken more slowly. Finally, for the last two-thirds of the picture they have nearly constant width, whereas the flame spreads linearly leaving a wedgeshaped area of burned gas at the center of the flame. The active combustion zones constitute a large part of the flame even far downstream from the holder.

Instantaneous schlieren photographs provide detailed information concerning the structure of the flame. Examination of Figure 1 shows that the combustion zones are regions of very complex density gradients, whereas the central regions of low luminosity are comparatively free of density gradients; the gas in these regions is uniformly burned. The schlieren photographs also indicate that the regions of active combustion are zones of strong mixing between hot and cold gas, and hence they are called mixing zones.

The outer boundaries of the mixing zones spread very slowly into the external fresh stream. Far downstream the observed spreading angle of the flame is normally less than three degrees.

TRANSITION

The appearance of the mixing zones shows the character of the entire flame. At low speeds the flame is distorted only by large scale waves, and is called a laminar flame. At higher speeds above a certain transition speed whose value depends upon the flameholder, smaller scale random disturbances are superposed on the regular waves and the flame is called turbulent. Turbulent flames are found to have uniform

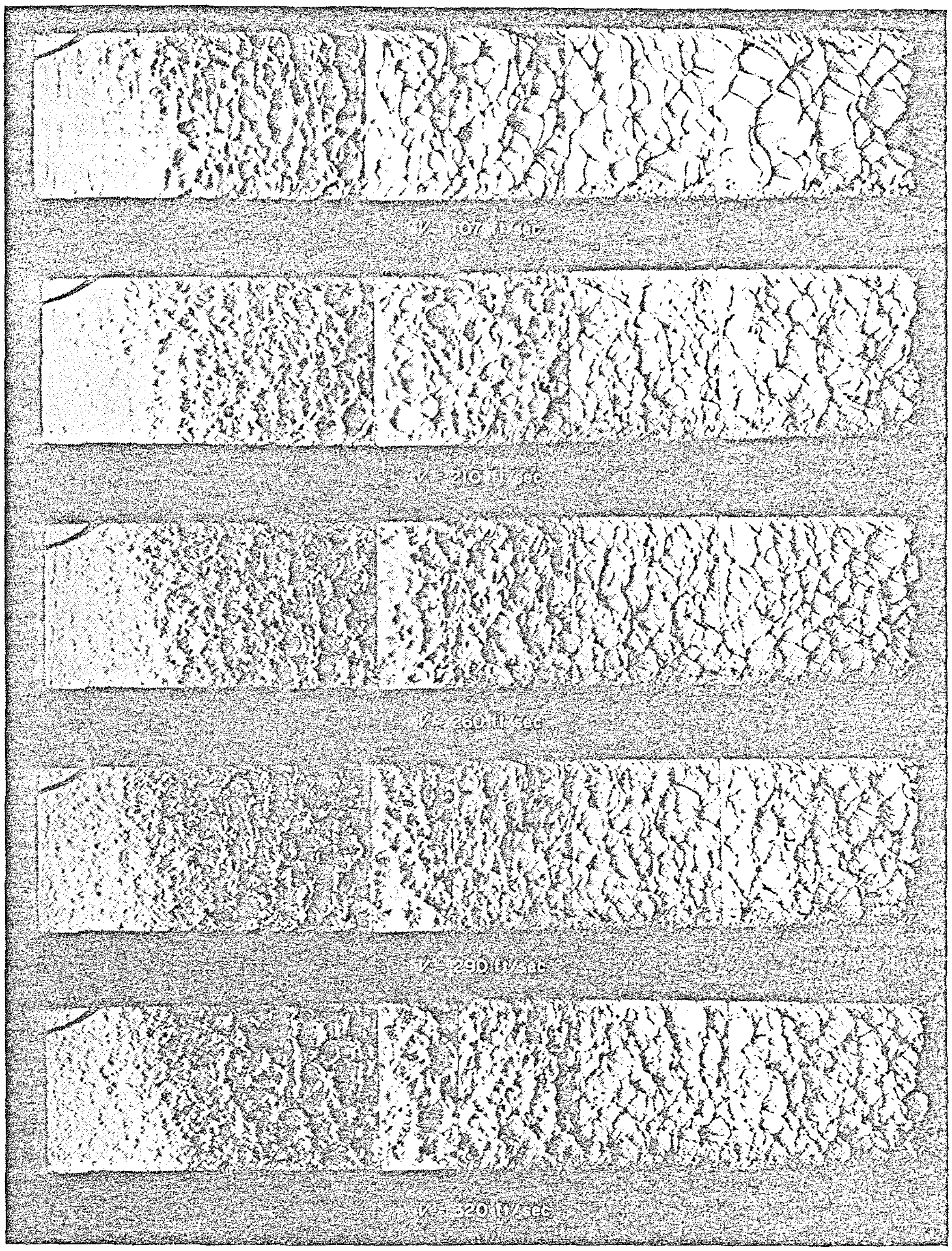

FIG. 3. Top view of flame held on $\frac{1}{2}''$ circular cylinder in 3 x 6″ duct, $\phi = 1.0$, for various flow speeds. Schlieren photograph covers 15.4 in. of 18 in. long duct.

characteristics and are the flames principally considered in this paper.

Transition and the turbulent character of flames at the higher speeds are more easily seen in top views, as in Figure 3, because in this view the central portion of the flame is seen free of distortions introduced by wall boundary layers. In the upper photograph of Figure 3, at a speed of 107 ft/sec, there are no small scale random disturbances outside the wall boundary layers and the flame is clearly laminar. At speeds of about 200 ft/sec, judged to be the transition

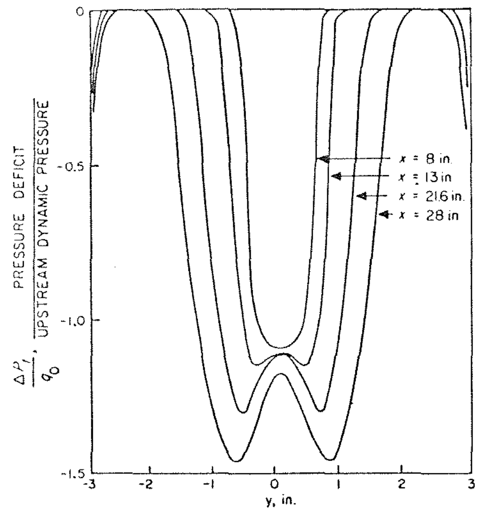

FIG. 4. Total pressure distributions at various stations in 3 x 6″ duct, ⅛″ flameholder. V = 300 ft/sec, ϕ = 1.0.

speed for the ½-in. circular cylinder used as the flameholder, random disturbances appear throughout the flame. Above the transition speed, fine-grained fluctuations are the dominant features close to the holder; farther downstream the fine-grained disturbances gradually disappear and larger scale fluctuations emerge. The mean diameter of these larger scale fluctuations or cells is about three-tenths of an inch, and this value changes little as the cells drift downstream. As the approach speed is increased farther above the transition value, the character of the flow remains unchanged. Thus, for example, the size of the large scale disturbances is independent of approach speed for turbulent flames.[a]

PRESSURE FIELD

Variation in pressure in the neighborhood of the holder is rapid due to the distortion of the flow field produced by the flameholder. However, directly behind the holder is the sheltered recirculation zone in which the pressure is nearly constant. Downstream from the recirculation zone, the static pressure is almost uniform across the duct and decreases down the duct as the flow is accelerated by the addition of heat.

The total pressure is sharply reduced as the flow passes through the flame, but remains relatively constant across the burned core of the flow (Fig. 4). The total pressure fall across the mixing zones may be estimated by examining the total pressure loss across a plane diagonal flame front. For the flow conditions studied here, this loss may be shown to be approximately proportional to and very nearly equal to the local dynamic pressure. This result indicates that the pressure loss should increase going downstream because the local speed, and therefore, the local dynamic pressure, increases in this direction. This prediction is confirmed by the data of Figure 4. The figure shows another interesting fact: the total pressure loss remains nearly constant along the center line; this result indicates that the center line flow, which enters the flame far upstream, close to the recirculation zone, is little influenced by mixing with flow that enters the flame farther downstream.

Because the total pressure losses are close to those predicted, it may be inferred that other factors influencing total pressure loss, such as mixing and dissipation, are of secondary importance. More important, the effect of flameholder drag appears to be negligible. Direct evidence is available to support the latter inference. A study was made of the total pressure profiles in the wake of a ⅛-in. diam cylindric holder with and without a stabilized flame. In the latter case, a flat plate was placed in the wake parallel to the flow direction to prevent the formation of a Kármán vortex street, and hence to make this wake as nearly similar to the flame as possible. A comparison of the total pressure deficit (Fig. 5) shows the overwhelming

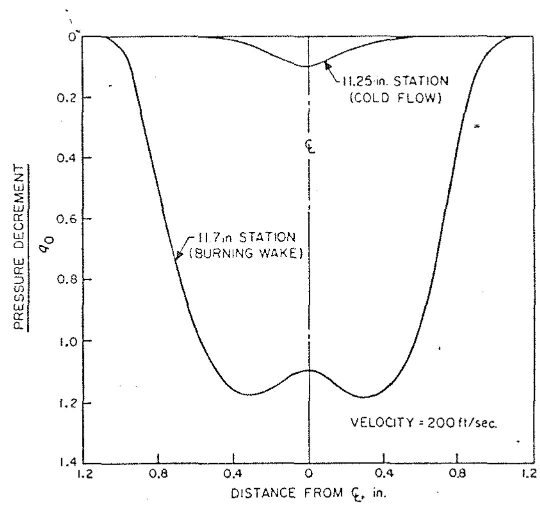

FIG. 5. Pressure profiles of burning wake and cold flow at same velocity and same station.

[a] The development of turbulence in the mixing zone is discussed more fully in References 1 and 6.

importance of combustion effects in fixing the magnitude of the total pressure loss. These data demonstrate that flame spreading is an entirely different process than isothermal wake spreading and show that the spreading flame is not confined to the isothermal wake.

TEMPERATURE AND VELOCITY FIELDS

Temperature is another important parameter of a flow field that includes a spreading flame. Measured values of the temperature rise rapidly through the mixing zones and are almost constant in the central region of the flame. These results were obtained with thermocouples, and in the hotter parts of the flame, with the sodium line reversal technique. Both methods rely on time-averaging, and hence their accuracy is suspect in the mixing zones which are regions of strongly fluctuating flow. However, the measurements clearly define general trends and also demonstrate that the gas on the center line where the flow is smooth is nearly completely burned and has a temperature approaching the adiabatic flame temperature.

Velocities throughout the flame may be computed with some confidence because the temperature and pressure distributions are known and because previous measurements have shown good correlation between average gas temperature and average composition in these flames. Particularly along the center line where the material is burned and outside the flame in the fresh gas the speed can be computed with assurance. Close to the holder the burned material moves more slowly than the unburned. Downstream from the recirculation zone, the hot gas accelerates even faster than the cold and its speed soon greatly exceeds the cold gas speed.

The gas flow is nearly axial, but close to the flame makes an angle of 1–2° with the duct axis, a flow inclination that is important since the flame spreading angle is usually no more than 3°.

Results and Discussion

RESULTS

The principal aim of the present investigation is to determine the influence of various fluid dynamic and chemical parameters on the spreading process downstream from a bluff-body flameholder. Results will first be reported for experiments in which the flameholder-duct geometry was maintained constant, since then the flame geometry in the neighborhood of the recirculation zone is independent of the fluid dynamic and chemical parameters being studied.

Some of these parameters are known to influence laminar flame speed and as a consequence might also be expected to influence turbulent flame speed and turbulent flame spreading rate. Some of them also influence the density ratio across the flame, and hence, according to several theoretical analyses, should affect the flame geometry. Experimental results (Fig. 6), showing the influence of fuel:air ratio, temperature, and fuel types, do not confirm these expectations; these parameters have little influence on flame spreading rate when flame is turbulent.

First, Fig. 6a shows that variations in flame width caused by fuel:air ratio changes are less than 5 per cent, even though the density ratio and flame speed vary by factors of more than 1.1 and 1.5. Surprisingly, minimum width occurs near the stoichiometric value of fuel:air ratio where laminar flame speeds are highest.

Second, the temperature data of Figure 6b shows a change of only 12 per cent in flame width for a two-fold temperature increase which produces variation in density ratio and flame speeds by factors of approximately 1.6 and 2.0. Again, flame width is largest at low temperatures for which the flame speed and density ratio are smallest.

Third, fuel type has little effect. Figure 6c shows that when mixtures of standard hydrocarbon and hydrogen are used as fuel, the flame width increases only about 4 per cent as the hydrogen fraction changes from zero to one; for this fuel change, the laminar flame speed for the mixture increases by a factor of about ten.

Finally, measurements of flame width at a given downstream station for variable approach speed demonstrate (Fig. 7) that above a certain critical speed, flame width is independent of approach speed. Velocity measurements, made in the unburned flow during these experiments, show the remarkable fact that the ratio of local gas speed to approach speed is independent of approach speed above the critical speed. Further, the critical speed observed here corresponds closely to the speed at which transition to turbulence occurs. Thus, for turbulent flames, the flame geometry and the velocity field in the unburned flow (normalized by the approach speed) are independent of approach speed. This result is very important because it implies that the flame speed (*i.e.*, the speed at which the

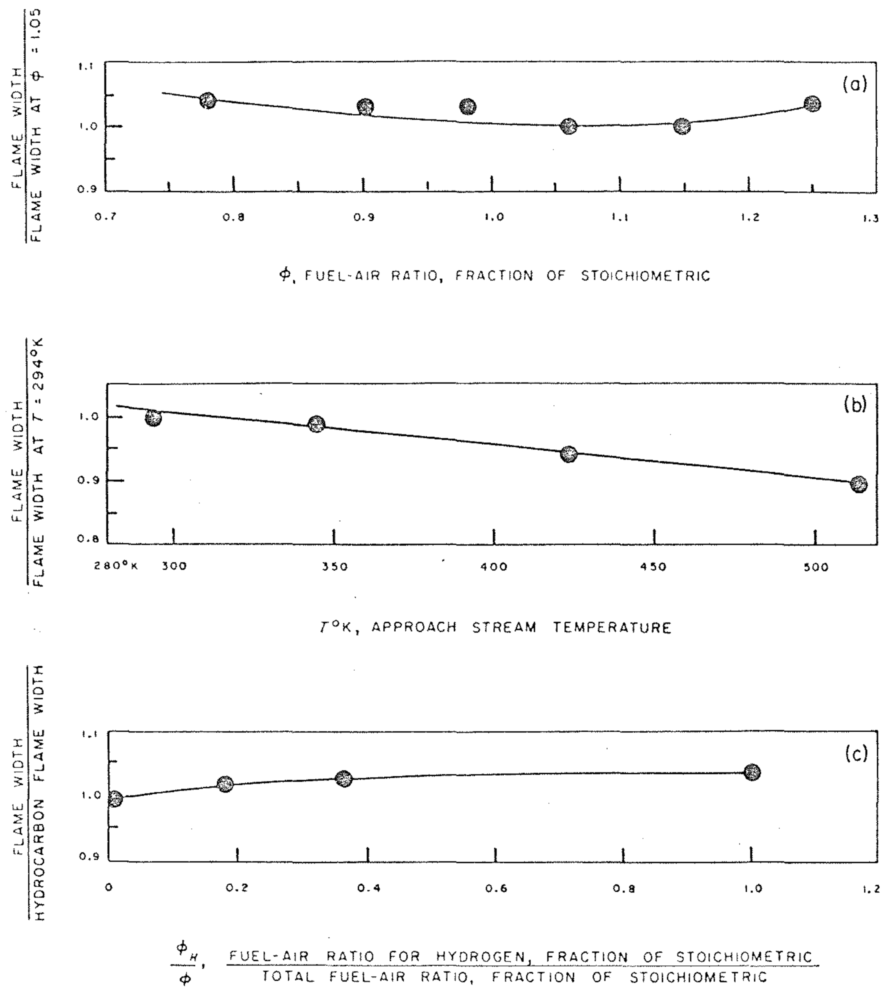

FIG. 6. Dependence of flame width on fuel:air ratio, approach stream temperatures and fuel type. Holder is a $\frac{1}{8}''$ circular cylinder and width is measured 15 in. from holder.

flame propagates into the unburned material) must be proportional to the local gas speed and is not related to the laminar flame speed.

The implication that flame speed is proportional to flow speed may be checked directly by measurements made in the external flow. The ratio of the two velocities is equal to the sine of the angle between them. This angle may be measured from particle track photographs that show the local flow directions and also include the trace of the flame, or the angle may be found by applying continuity relations to the results of mass flow, pressure distribution and flame angle measurements. Neither method of angle measurement is precise, yet both experiments demonstrate that the angle in question is a little less than 2° and is constant for turbulent flames. Hence, the flame speed must be proportional to the flow speed—at least to within the accuracy of these experiments.

The data presented in Figures 6 and 7 are typical of the results obtained under a wide range of test conditions, and demonstrate that if the flow is everywhere subsonic and the flame is turbulent, flame spreading rate is substantially independent of fuel:air ratio, temperature, fuel type and approach stream speed.

The results presented above simplify the study of the influence of the geometric parameters since they imply that tests carried out for one set of values of the chemical and fluid dynamic parameters will yield representative results as long as the flame is turbulent. Previous work,[7-16] has shown that the geometry of the outer

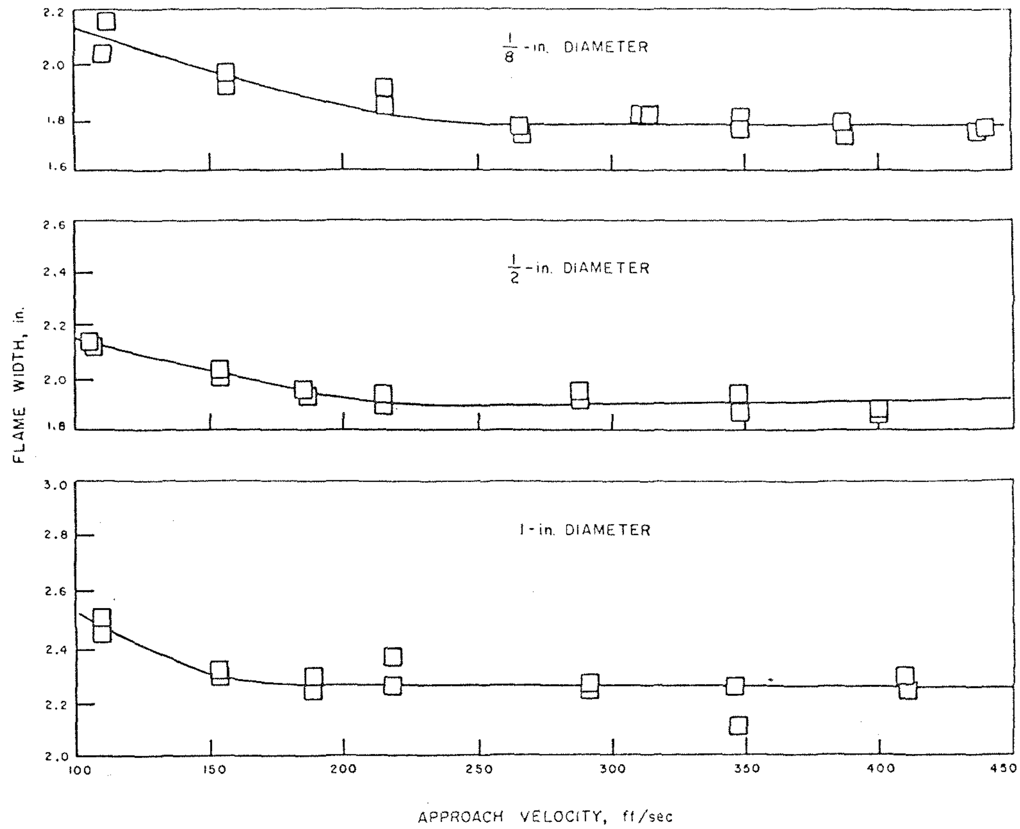

FIG. 7. Flame width *versus* flow speed for several flameholders. Station 13″ downstream from flameholder. $\phi = 1.0$.

boundary of the recirculation zone depends in a rather complicated manner on the blockage ratio, *i.e.*, on the ratio of flameholder diameter to duct height. For example, when circular cylinders are used as flame holders, the recirculation zone boundary scales directly with holder diameter up to blockage ratios of about 4 per cent; for higher blockages, the width of the boundary varies inversely as the square root of the blockage ratio. Thus, if the flame contours of circular cylinder-holders are compared for blockage ratios below 4 per cent, the effect of holder blockage ratio on the flame spreading will be particularly easy to determine. An example of such an experiment is shown in Figure 8a; here an $\frac{1}{8}$-in. circular cylinder is used at blockage ratios 1:24 to 1:48. The flame geometries appear almost identical over the entire distance investigated—over 130 holder diameters or 16 recirculation zone lengths. Flameholder blockage has no effect on flame spreading rate for these circular cylinders at low blockage ratios. Perhaps even more surprising, the flame blockage (the ratio of flame width of duct height) has no effect even when the flame occupies 70 per cent of the duct for the larger blockage and 35 per cent of the duct for the smaller.

Figures 8b and 8c present data obtained at larger blockage ratios for which the flame width at the end of the recirculation zone does depend on blockage. Nevertheless, the differences between flame contours are small when the blockage is changed, and appear to be entirely due to recirculation zone width changes. The spreading rates are almost identical and are independent of the flame blockage ratio.

As the holder blockage is increased, the effects of the variation in recirculation zone width predominate near the holder. In many practical applications of multiple arrays of bluff-body flameholders this will be the only region of interest, because the confining duct is frequently no longer than the recirculation zone. However, in a study of true flame spreading, conditions

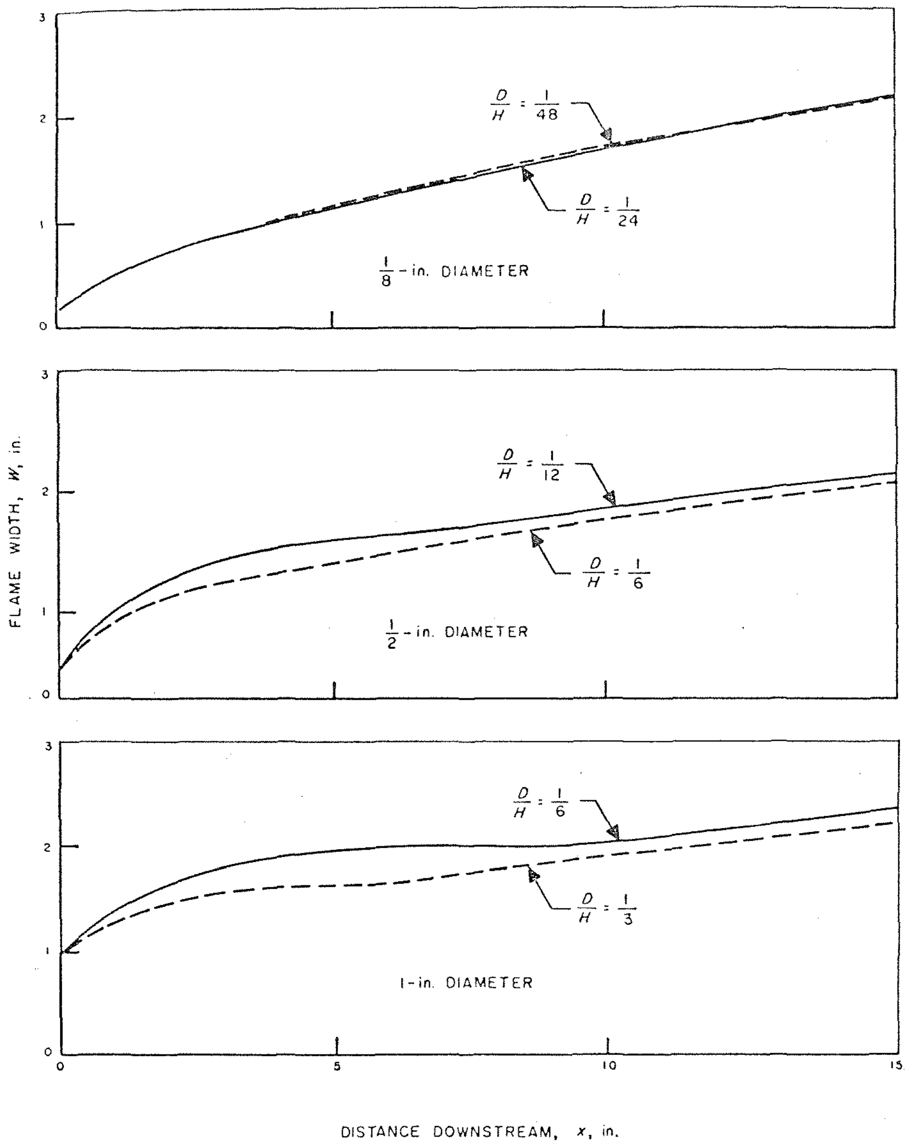

FIG. 8. Comparison of flame width at different blockage ratios for various circular cylinders. $\phi = 1.0$, $V = 300$ ft/sec.

far downstream from the recirculation zone are of primary interest, and here the flame widths are found to be nearly the same over a very wide range of flameholder size and blockage ratio. This result is strikingly confirmed in Figure 9 for holders of various sizes operating in a 3 x 6″ duct. At the 30″ station, the variation in flame width is less than 20 per cent despite the 16:1 size ratio of the holders. Both Figures 8 and 9 show that flame blockage has no effect on flame spreading until the flame comes very close to the duct walls and that flameholder blockage effects are primarily restricted to the recirculation zone.

DISCUSSION

Several experimental results should be re-emphasized. Laminar flame speed was changed by roughly a factor of ten by changing fuel from the hydrocarbon to hydrogen; at the same time, the density ratio and other parameters were not changed. The change in laminar flame speed had no appreciable effect on spreading rate and the

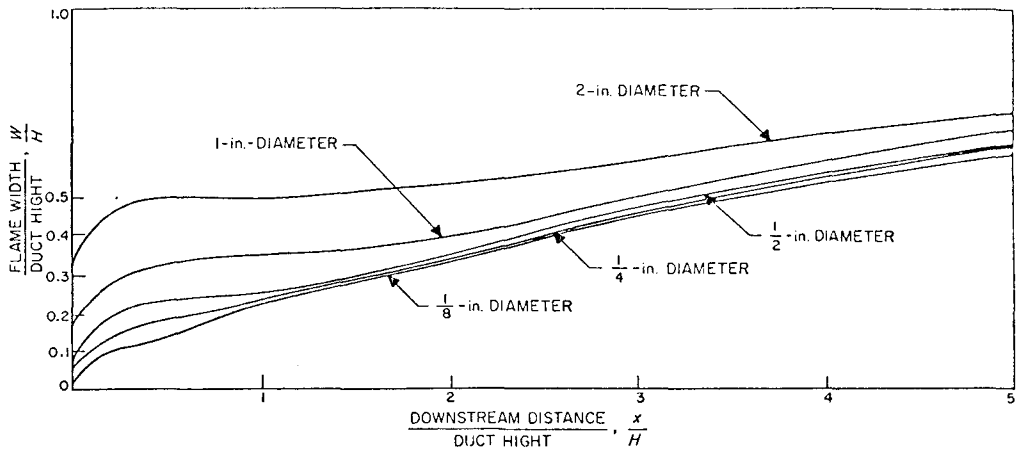

FIG. 9. Flame shapes for flameholders of several sizes in a duct of fixed size, $V = 300$ ft/sec, $\phi = 1.0$, $H = 6$ in.

implication is that laminar flame speed does not influence the spreading of a turbulent flame.

In the experiments in which fuel:air ratio or approach stream temperature is varied, flame speed and density ratio change, and the experimental result cannot be interpreted unambiguously. However, it is difficult to believe that in these experiments the effects of both parameters fortuitously cancel out, and the simplest interpretation of the experiments is that the spreading rate is almost constant because neither laminar flame speed nor density ratio is very important in fixing the flame spreading rate.

Perhaps the most striking experimental result is that the flame spreading rate is independent of approach flow speed, and further, that the angle between flame and local flow velocity is at least roughly constant; these results strongly indicate that the local flame speed is proportional to flow speed. The flame spreading process appears to be somewhat analogous to the spreading of a turbulent mixing zone. However, the spreading flame is quite different from an isothermal wake as pressure measurements in the flame and wake have demonstrated.

These experimental results may be compared with flame spreading theories. Theoretical treatments have been based,[11-13] in general, on a physical model derived from the assumption that the flame is a discontinuous surface separating gas streams of different densities and temperatures. The theory predicts that the spreading rate increases with the density ratio across the flame. Most of the calculations based on this theory have also shown a spreading rate dependent on the laminar flame speed, because they have assumed that the turbulent flame speed is proportional to the laminar flame speed. In either case, these theories do not agree with the experimental results.

More recently, Spalding[14] presented a theory of turbulent spreading based on an assumed similarity between a spreading flame and a turbulent jet. Unfortunately, this theory also predicts a strong dependence of spreading rate on the density ratio across the flame front. The present experimental work shows that this ratio is not important.

In summary, the theoretical treatments of flame spreading that have been devised to date do not account for the rather simple behavior observed experimentally. The experiments show that the rate of flame spreading from a bluff body is slow and 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. Far downstream from the flameholder the spreading rate is little influenced by flameholder blockage ratio or even by flame blockage. In the typical spreading region far downstream, flame speed is proportional to flow speed.

Nomenclature

D flame holder diameter
H duct height
q_0 approach stream dynamic pressure
V approach stream velocity
T temperature
W flame width

x distance between flameholder centerline and observation station

ϕ fraction of stoichiometric fuel-air ratio

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Discussion by T. Y. Toong

Recent experiments conducted at the Massachusetts Institute of Technology on the study of jet mixing with chemical reaction seem to shed some light on the mechanisms of flame stabilization by bluff bodies, recessed ducts and opposed or deflected jets, where the critical region is the mixing zone between a combustible stream and recirculation zone. These experiments were planned to answer some of the questions raised in an earlier paper.[a]

An apparatus was constructed to study the development of combustion in the mixing zone between two concentric gas streams. The central stream is a cold combustible mixture and the other flowing in an annulus inside a Pyrex duct surrounding the combustible gas consists of hot products of combustion and diluents. The composition, velocity and temperature of both streams can be varied. As the two streams flow downstream, chemical reaction and transfers of mass, momentum and energy occur simultaneously in the mixing zone.

Under certain conditions, a flame may develop in the stream of the combustible mixture. Although this flame resembles the usual Bunsen flame and macroscopically, seems to have a "continuous" conical surface, high-speed streak photographs distinctly show the propagation of kernels ignited at a short distance downstream of the initial contact point between the two streams. The multitude of these kernels originating at various locations around the central stream and at relatively high frequencies accounts for the seemingly continuous flame surface. These pictures thus indicate that the flames originating from the mixing zone are actually "stabilized" because of high-frequency discontinuous ignition and not (like Bunsen flames) because of stable equilibrium between flame propagation and fluid motion. It would seem to me that this fact should be borne in mind in the interpretation of the experimental results and in the formulation of a realistic theory of flame stabilization by bluff bodies, recessed ducts and the like.

Author's Reply

I agree that the experimental work reported by Dr. Toong may lead to a better understanding of the processes occurring in the mixing zones of a bluff body flameholder. Similar experiments were carried out in 1952 by F. H. Wright and J. L. Becker at the Jet Propulsion Laboratory.[b] These experiments demonstrated ignition by a hot inert stream and also indicated that the phenomenon of ignition by a hot stream shows all the features of the bluff body stabilization process.

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[a] Toong, T. Y. *Combustion and Propulsion, Third AGARD Colloquium*, p. 584. Pergamon Press, London, 1958.

[b] J. Am. Rocket Soc., November 1956, pp. 973–978.