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RECENT STUDIES ON FLAME STABILIZATION OF PREMIXED TURBULENT GASES[1]

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I. INTRODUCTION

FLAME stabilization is of importance in the practical design of ramjets and afterburners. It has been studied extensively in recent years, particularly with reference to bluff-body flame-holders. In the present survey we describe the investigations relating to flame holding by bluff bodies as well as new techniques (e.g., flame holding by the use of reverse jets) which may prove to be of practical importance in new engine configurations.

In Section II we consider the flow field downstream of a bluff-body flame-holder which includes the recirculation zone behind the body and a region of flame spreading farther downstream. Explicit reference is made to crucial experiments which illustrate the nature and magnitude of the velocity field, the physical extent, the temperature, and the gas composition of the recirculation zone. Experimental studies and theoretical predictions of the angle of flame spreading, as well as some observations on unstable flow and the onset of blowoff, will be reviewed.

The variation of blowoff velocity with flame-holder design, pressure, and mixture composition is considered briefly in Section III both for single and for adjacent bluff bodies. Also included is a summary of results for blowoff velocities obtained with a reverse-jet flame-holder and with wall recesses.

Theoretical studies on the mechanism of flame stabilization form the subject of Section IV. We shall indicate the points on which various proposed models agree and disagree with experiment and attempt to formulate a composite description which is consistent with most of the currently available experimental data both for bluff-body and for reverse-jet flame-holders.

II. FUNDAMENTAL STUDIES RELATING TO THE RECIRCULATION ZONE BEHIND BLUFF BODIES AND WAKE SPREADING

A. *Schematic Representation of a Fully Developed Turbulent Wake Behind a Bluff Body*

In Fig. 1 we present a schematic summary of the recirculation zone and downstream flame-spreading region which is consistent with the experimental results which will now be described in greater detail.

B. *The Recirculation Zone*

The existence of a region immediately behind the flame-holder (see Fig. 1), in which almost completely burned fluid performs a vortex-type motion (which includes recirculation and reverse flow near the axis), has been demonstrated by a number of experiments. The recirculation zone differs in its essential features from the alternate vortex shedding for cold flow which is a well-known phenomenon and is referred to as the Kármán vortex street.

A number of ingenious methods have been devised to observe the flow in the recirculation zone.

Nicholson and Field (1)[2] have used several different techniques for observation of propane-air mixtures passing a two-dimensional bluff-body flame-holder both with and without combustion. Some of the methods applied are the following: (a) Aluminum powder was mixed with the gas so that the

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[1] Supported by the Office of Ordnance Research, U. S. Army, under contract DA-04-495-Ord-446.

[2] Numbers in parentheses refer to the references at the end of the paper.

streamlines became visible and could be photographed. This procedure revealed the effect of the flame on the flow field. An increase in flow blockage and the absence of vortex shedding were demonstrated. (b) High-speed schlieren and shadow motion pictures of steady and unsteady combustion were taken with ordinary light sources as well as with sparks lasting only a few microseconds. The schlieren motion pictures were more effective than the shadowgraphs and indicated the sequence of ignition and blowoff (see Section II D for details). (c) By introducing sodium acetate or carbonate into the wake region, the flow pattern within the wake could be identified through emission of the yellow light characteristic for the sodium D lines. The emitted intensity was sufficient to allow photography at 5000 frames per second. These tracer studies showed the recirculation zone immediately behind the flame-holder. Thus fluid particles travelled from perhaps two baffle lengths downstream all the way upstream to the base of the flame-holder. This upstream motion was observed to occur randomly throughout the wake for a flow velocity of 200 ft/sec and a ¼ inch wide flat-plate baffle (Reynolds number ≃ 10,000). The reverse-flow velocity was found to be as high as 65 ft/sec in some cases. The residence time of a small volume element of fluid in the recirculation zone was about 0.008 sec. (d) Direct high-speed photography of the flame front was made possible by augmenting the brightness of the flame through the addition of vaporized sodium salt to the combustible mixture.

Westenberg et al. (2) have recently described another method for tracing the flow pattern in the wake region. Sampling of the gases in the recirculation zone, with helium injection from a conical one-inch flame holder, was used to indicate the flow pattern for very lean pentane-air flames at the exit of a 6-inch pipe with flow velocities from 20 to 53 m/sec. The concentration profile of the helium tracer, which was measured as a function of position, showed absence of violent mixing in the recirculation zone but verified the hypothesis of reverse flow near the middle of the wake region. Mixing occurred near the edge of the baffle; the mixing zone thickened and became more turbulent downstream. No evidence of alternate vortex shedding was observed. The length of the recirculation zone was found to vary with equivalence ratio but to be independent of approach stream velocity. The ratio of recirculation zone length L to flame-holder diameter D was found to be different for disks and cones. Possibly the Reynolds numbers were too low to produce a fully developed turbulent wake.

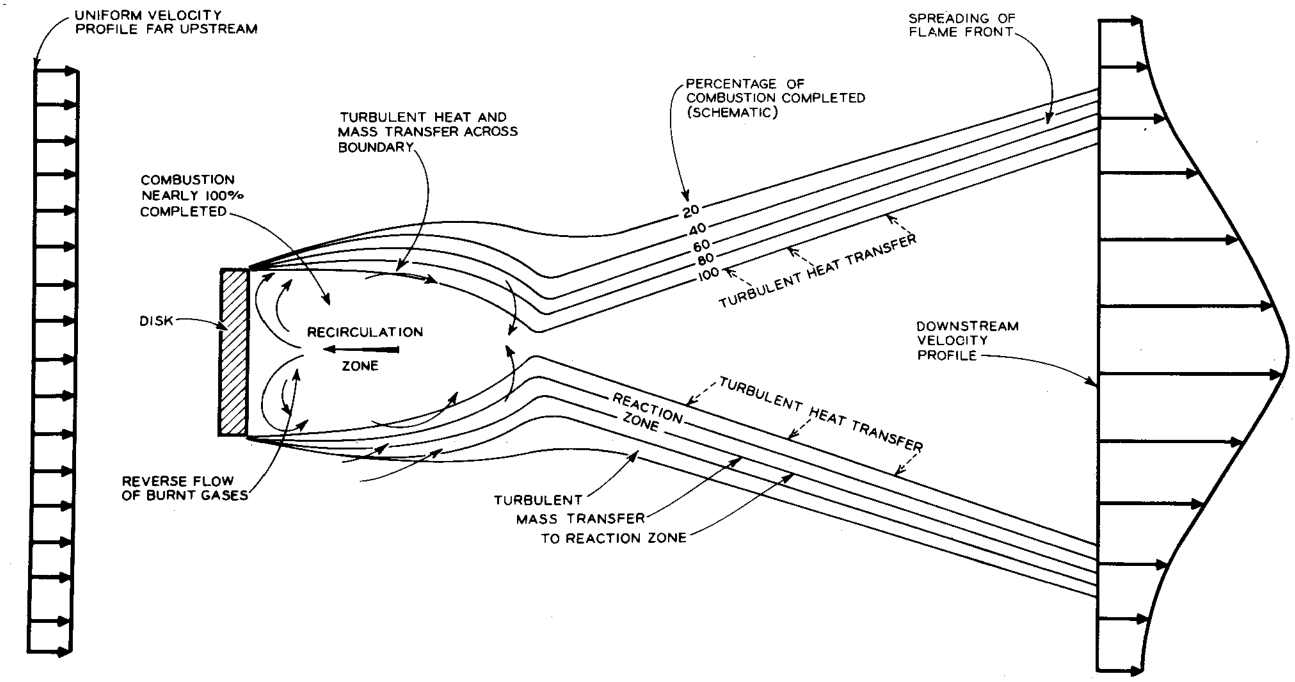

FIG. 1. RECIRCULATION ZONE AND FLAME-SPREADING REGION FOR A FULLY-DEVELOPED TURBULENT WAKE BEHIND A BLUFF-BODY

Illuminating studies of the flame-holding mechanism have been performed by Zukoski and Marble (3, 4, 5). These authors have shown that the temperature of the gases in the recirculation zone, as determined from line-reversal studies using the sodium D lines, remained practically constant and close to the adiabatic flame temperature as flame blowoff was approached. The blowoff conditions were shown experimentally to correspond to the critical value unity for the first Damköhler similarity group, i.e.,

$$D_I = (L/V_{BO})(1/\tau) = 1. \qquad [1]$$

Here L is the wake length and τ represents an effective chemical (combustion) conversion time; the ratio L/V_{BO} equals a minimum convection (residence) time for chemical conversion if V_{BO} is the blowoff velocity. For $V > V_{BO}$ blowoff occurs, whereas for $V < V_{BO}$ a stable recirculation zone and flame holding are observed. The chemical time τ is a characteristic of the fuel-air mixture under study.

Schlieren photographs obtained by Zukoski and Marble (3, 4) illustrate the change to fully developed turbulent wakes for the experimental conditions in which L/D was observed to become independent of approach stream Reynolds number. This phenomenon is similar to the well-known transition from laminar to turbulent wakes occurring for cold flow with increasing Reynolds number (6). The length of the recirculation zone was defined experimentally (4) within 5% by salt injection. While the ratio of wake length to flame-holder diameter was found to be constant for Reynolds numbers exceeding about 10^4 on cylindrical flame-holders, the wake length was found to vary roughly as the square root of the flame-holder dimension for lower Reynolds numbers. This last result is to be ascribed to fluid-dynamical blockage effects of the walls.[3]

Early schlieren photographs were taken by Scurlock (7) who found that the extent of wake turbulence increased with increasing flame-holder dimensions, with increasing free-stream velocity, and with increasing turbulence in the approach stream.

C. The Wake Combustion Profile

Sampling of combustion products and reactants in the wake (2) has indicated that the gas in the recirculation zone is essentially completely burnt, an observation which is in agreement also with flame-temperature measurements made by the sodium D-line reversal technique (3, 4). The contours of the combustion efficiency curves (see Fig. 1) show that burning becomes more complete as the axis of the flame-holder is approached. The physical region in which combustion occurs therefore appears to include the entire space between the outside flame region and the recirculation zone. Furthermore, for the experimental conditions described in reference (2), the rate of increase of combustion efficiency with linear distance appears to be substantially uniform. Increase in the upstream turbulence level did not affect stability to an important extent.

Careful observations of the luminosity from some lean mixtures[4] show that the intense CH and C_2 radiation is confined to the region between the flame front and the recirculation zone. The intense blue-green emission identifies the spacial region in which most of the chemical reactions occur.

The extent of completion of combustion can also be estimated from the measurement of axial pressure distribution in a duct in which combustion is taking place (7, 8, 9).

D. Ignition, Blowoff and Flame Spreading Downstream from a Bluff Body

Flame spreading downstream of the flame-holder has been investigated experimentally by the use of direct and schlieren photography. Steady-state burning, as well as blowoff, ignition, and unstable burning have been studied in this manner.

Ignition with a spark located upstream of or at the flame-holder starts from the wake region immediately behind the flame-holder and then propagates downstream by extending "horns" of flame alternately from the upper and lower edges of the flame-holder (1). These horns curl over, envelop and consume large volumes of combustible mixture; they suggest the existence of alternate vortex shedding before ignition.

Observations of the sequence of events (1, 7) which occur in blowoff indicate that the flame is first extinguished downstream and that the point of extinction then moves to the flame-holder. For approach velocities close to the blowoff velocity, the zone of flame spreading disappears and only a small region of burning remains immediately behind the flame-holder. As the blowoff velocity is finally approached, the flame is completely extinguished. For some experimental arrangements blowoff may be accompanied by unsteady burning and pulsations. In these cases the blowoff sequence is essentially the same as described above except that combustion oscillations occur. This phenomenon has been observed by Nicholson and Fields (1) at the rich blowoff limit.

Both theoretical and experimental investigations of steady-state flame spreading have been carried out (10–14). Williams et al. (14) found that the rate of flame spreading is largest for stoichiometric fuel-air mixtures and decreases for both lean and rich mixtures. Since increasing approach stream turbulence had no effect on the rate of flame spreading, one may infer that the wake was always turbulent in the flame-spreading region. Increasing the flame-holder diameter did not influence the rate of flame spreading until blockage effects became important; also the shape of bluff-body flame-holders had little effect on flame spreading. An increase in the approach stream velocity was found to lead to a decrease in the rate of flame spreading except for very lean mixtures where there was evidence that alternate vortex shedding had begun (14). For these lean mixtures the increase in flame width with increasing velocity was attributed to increased rate of vortex shedding; support for this last interpretation was obtained from the fact that an increase in flame-holder diameter, which increases Reynolds number and, therefore, the rate of vortex shedding, was also found to increase the rate of flame spreading.

The process of flame spreading was first studied by Scurlock (7), who assumed that the flame speeds corresponded to very high turbulence levels which increased greatly with approach stream velocity. Both theory and experiment (14) show that there are regions of high velocity gradient near the flame-holder and also downstream where the velocity of the burnt gas exceeds that of the unburnt gas. Between these two zones is a region of low velocity gradients in which the flame sometimes "necks" down. More refined theoretical treatments of flame spreading, utilizing assumptions similar to Scurlock's, have been developed (10–13).

III. EXPERIMENTALLY DETERMINED BLOWOFF VELOCITIES AND CORRELATION OF DATA

In this Section III we summarize some of the important experimental results obtained for flame stabilization behind bluff bodies (Section IIIA), stabilization by opposed and transverse fluid jets (Section IIIB) and in recessed ducts (Section IIIC), and flame stabilization behind two or more adjacent bluff bodies with engineering applications.

A. Flame Stabilization Behind a Bluff Body

As early as 1943 Wolfhard (15) observed flame stabilization on a cylindrical obstacle and showed that the blowoff velocity was dependent on cylinder diameter and pressure for a given combustible mixture. Since this time, a number of investigators have measured the variation of blowoff velocity with flame-holder dimension and design, mixture composition, pressure, etc. (3, 7–9, 14, 16–28). De Zubay (17), using (commercial) propane-air mixtures and disks with diameters of ¼ in., ½ in., and 1 in., measured the blowoff velocity for pressures varying from 3 to 15 psia and linear flow velocities between 40 and 550 ft/sec. An acceptable correlation (maximum scatter ±30%) for all of the observed blowoff data was obtained by plotting the fuel-air ratio as a function of $V_{BO}/P^{0.95}\,D^{0.85}$, where V_{BO} is the linear flow velocity at blowoff past the disk, P equals the pressure in the plane of the disk, and D represents the disk diameter.[5] This correlation is in good accord with the earlier work of Scurlock (7) and of Longwell (19). For given physical conditions, De Zubay found that the maximum blowoff velocity occurred for slightly rich gas mixtures. Variations in pressure did not appear to effect significant changes in the luminosity and shape of the combustion region. This same author reported subsequently (18) that, with the same physical apparatus but using hydrogen-air mixtures in place of propane-air mixtures, experimental data were obtained which were best correlated by plotting fuel-air ratio as a func-

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[3] E. E. Zukoski, personal communication.

[4] E. E. Zukoski, personal communication.

[5] In accord with the correlations described in reference 3, it appears that De Zubay's results refer to an intermediate Reynolds number range before a fully-developed turbulent wake is obtained.

tion of $V_{BO}/P^{0.61} D^{0.74}$. Similarly, Longwell et al. (19) found that, if only the fuel-air ratio and the diameter of the flame-holder are varied, then, for hydrocarbon-air flames stabilized by circular cylinders mounted axially, V_{BO}/D depended only upon the fuel-air ratio. Scurlock (7) performed experiments in a constant-area duct with both two- and three-dimensional flame-holders; for the latter his data were correlated by plotting $V_{BO}/A^{0.45}$ as a function of fuel-air ratio where A is the area of the flame-holder normal to the flow direction.

The correlation of Zukoski and Marble (3) for fully developed turbulent flow in terms of the first Damköhler similarity group has been given in Eq. [1]. Since the wake length L was found to be a linear function of bluff-body diameter, these results clearly show a linear dependence of V_{BO} on D for a given combustible mixture. Results which are in accord with this last conclusion have been reported also by other investigators (20–22). To summarize, the available data are consistent with the idea that, for three-dimensional flame-holders, V_{BO} is a linear function of obstacle diameter for constant flow blockage provided the Reynolds number is sufficiently high.

Williams and Shipman (22) have prepared the following summary for the dependence of maximum blowoff velocity on various parameters: (a) Stability is best for systems with low ignition energy and high flame velocity. (b) Stability increases somewhat with mixture temperature. (c) Increase of flame-holder temperature increases stability (14, 23–26). (d) An increase of turbulence intensity either decreases (7) or increases stability so that the effect of entering stream turbulence is not clear. (e) Although stability increases with pressure, the detailed variation of blowoff velocity with fuel-air ratio changes (27). (f) A two-dimensional stabilizer in a rectangular duct seems to be more effective than a three-dimensional stabilizer (disk or sphere) in a duct (28). (g) For sufficiently large stabilizers, stability decreases because of wall blockage effects. (h) Increasing noise may decrease stability. Most of these summary statements are obviously in accord with the picture of the flame-holding mechanism sketched in Fig. 1 and with the correlation given in Eq. [1].

B. Flame Stabilization with Opposed and Transverse Fluid Jets

Turbulent flames have also been stabilized successfully with an opposing fluid jet (29–32). The geometric configuration of the experimental arrangement, including the recirculation zone and critical region for flame holding, is shown schematically in Fig. 2. The flame is stabilized around the stagnation region which is located at a small distance (the distance depends, of course, on the relative flow velocities of the primary and jet streams) upstream from the outlet of the jet tube.

Experimental measurements of rich and lean limit blowoff velocities (29–32) show that the observed blowoff curves depend significantly on the chemical nature of the jet stream (which contributed only about 1% to the total mass flow) under otherwise fixed experimental conditions. Since the heat release rate for hydrocarbon-air mixtures is generally greatest for mixture compositions which are nearly stoichiometric, one might expect the highest blowoff velocities to correspond to a nearly stoichiometric gas mixture in the critical region for flame stabilization (see Fig. 2). In accord with this hypothesis (and with the idea that the combustible gas composition in the critical zone is determined largely by the approach stream and jet mixture compositions), it has been shown for propane-air flames that: (a) For a stoichiometric fuel-air mixture in the opposing jet stream, the maximum blowoff velocity corresponds to an equivalence ratio close to unity (30, 32). (b) For an air jet, the maximum blowoff velocity corresponds to rich fuel-air mixtures. (c) For an oxygen jet, the lean limit blowoff curves are displaced to equivalence ratios less than unity. Quantitative calculations based on the assumption that the mixture composition in the critical region is nearly stoichiometric and that the recirculating gas contributes no combustible material will be discussed in Section IV B.

The opposing jet flame-holder provides relatively wide blowoff limits and high blowoff velocities. Furthermore, because of the pronounced effect exercised by the jet-stream composition, blowoff limit curves can be shifted significantly from one equivalence ratio to another, a fact which may be used to advantage in the operation of propulsion devices at greatly different altitudes.

Transverse fluid jets with a large range of velocities and mixture compositions have been tested for their flame-holding ability; in all cases the flame could not be stabilized (32). Also two and four opposing transverse jets were found to be ineffective. Perhaps transverse jets do not function as flame stabilizers because they are not capable of slowing down the main gas flow to form a well-defined stagnation region.

C. Flame Stabilization in Recessed Ducts (33)

Premixed turbulent propane-air flames have been stabilized in a rectangular duct by using various types of wall recesses (33). With properly designed wall recesses, the blowoff velocity versus equivalence ratio curve showed significantly wider stability limits than a relatively poor V-gutter type bluff-body flame-holder. At the same time, a significant reduction in pressure drop was achieved.

The heat transfer to the duct wall in the vicinity of a recess is greatly increased by the recirculating gases which anchor the flame. In fact, there must be a direct correlation between efficiency of flame stabilization and exaggerated convective heat transfer. The observed blowoff limits for a variety of symmetrically located wall recesses showed substantially equivalent results provided (a) the recess was sufficiently deep to support an adequate amount of recirculating gas, (b) the slope of the recess at the upstream end was great enough to produce flow separation, and (c) the geometric construction of the lip was not conducive to initiating and supporting flow oscillations, as seemed to be the case with a semicircular upstream end for the wall recess. For the symmetrically arranged recess flame-holders, the flame fronts spread across the duct and merged downstream. The rate of flame spreading was relatively smaller than for a V-type gutter, thereby necessitating the use of longer ducts. Schlieren pictures downstream from the recirculation zone revealed the presence of distorted flame fronts which may have been produced by transverse oscillations.

Without the development of special techniques for efficient wall cooling, such as film cooling around recesses, the use of wall-recirculation zones for flame holding does not appear to be a practically useful technique.

D. Flame Stabilization Behind Two or More Adjacent Bluff Bodies; Engineering Applications

The stability characteristics of flames stabilized by means of a group of bluff bodies placed sufficiently far apart are, as one would expect, substantially the same as those of a flame stabilized by means of a single bluff body. In particular, the curve of blowoff velocity versus fuel-air ratio is the same (14). If, however, the bluff bodies are in close proximity, then flow blockage and interaction occur which produce narrower limits of stability (14, 34). For high flow blockage ratios we expect to obtain excessively high local flow velocities and wake interference.[6]

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[6] In this connection see also M. Ames, AE thesis, California Institute of Technology, Pasadena, June 1956.

An increase in the number of flame-holders for flow through a duct of given size reduces the distance required for complete burning. This phenomenon is of considerable practical importance in ramjet design. If one assumes that there is no interaction between the separate flame stabilizers and that the angle of flame-spreading is the same as for a single bluff body in a duct, then the distance required for complete burning should be inversely proportional to the number of flame-holders. In other words, in the absence of interaction, one would expect the chamber length necessary for complete combustion to be proportional to the flame-stabilizer separation distance. Measurements (14) with 2, 4, and 8 rod flame-holders in a rectangular duct have, however, indicated that the flame length varies roughly as the two-thirds power of the separation distance, presumably because of interaction phenomena.

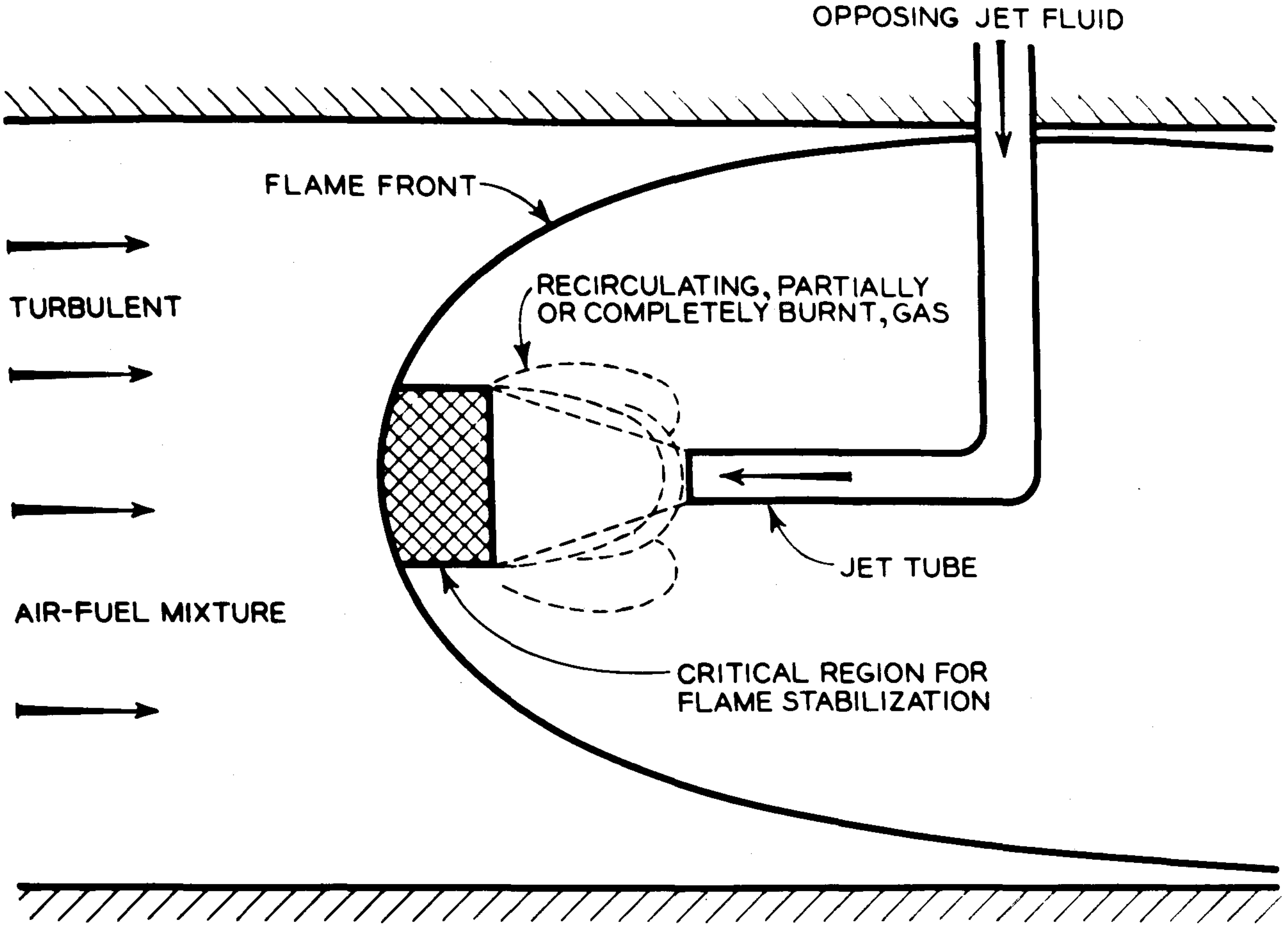

FIG. 2. SCHEMATIC DIAGRAM OF THE OPPOSING JET FLAME HOLDER

The three principal features of a flame-holder, which determine its suitability for engine applications, are: the rate of flame spreading, the flame-holder drag, and the region of flame stability (34, 35). Tests on single bluff bodies have shown that, for a given combustion chamber, the widest stability limits and lowest rates of flame spreading (i.e., lowest combustion efficiencies) are obtained with a single central baffle flame-holder. A grid-type flame-holder, on the other hand, has high combustion efficiency but relatively narrow stability limits. A reasonable compromise between these two designs is an annular baffle flame-holder (34). The flame-holder drag is determined largely by aerodynamic effects. Since streamlined bodies have low drag but narrow stability limits and bluff bodies have large drag and wide stability limits, a compromise must also be made between low drag and wide stability limits.

IV. THEORETICAL STUDIES OF FLAME STABILIZATION

The published theoretical studies on flame stabilization deal with bluff-body flame-holders. We shall survey these investigations in Section IV A. Furthermore, since useful correlations can be obtained for blowoff studies with reverse fluid jets, we conclude (Section IV B) the discussion with a critical evaluation of experimental results in terms of the simplified model for the critical flame-holding region which was mentioned in Section III B.

A. Bluff-Body Flame-Holders

The proposed theoretical models for flame holding appear, at first sight, to be very different. The assumed mechanisms range from instantaneous mixing with chemical reaction as the rate-controlling step to instantaneous reaction with mass or heat transfer as the important step. Also the geometric configuration in the flame-holding process has been idealized to one involving either transport phenomena oriented axially or normal to the tube axis. Nevertheless, the predicted variation of blowoff velocity with pressure and flame-holder dimension turns out to be practically the same in all cases and to be in accord with observations. For this reason the significance of any given model must be interpreted in terms of the validity of detailed assumptions relating to the known properties of the stabilization process (see Fig. 1 and the discussion in Section II).

1. The Stirred Reactor Model

Longwell et al. (36) assumed that the recirculation region may be approximated as a homogeneous, stirred, chemical reactor. Flame stabilization is then supposed to be determined by a balance between the rate of flow of unburned gases into the recirculation zone and the rate of burning of these gases. In the case of a second-order chemical reaction, it turns out that the mass flow into the recirculation zone at blowoff is directly proportional to both the volume of the recirculation zone and to the square of the pressure. For a given equivalence ratio, as the mass flow into the recirculation zone is increased, the combustion efficiency drops until the gas residence time in the homogeneous reactor (recirculation zone) becomes too short to maintain combustion, and blowoff occurs. The range of equivalence ratios over which a flame can be stabilized is found to depend on the parameter VP^2/m where V is the volume of the recirculation zone, P equals the pressure, and m represents the mass flow into the recirculation zone.

The volume of the recirculation zone should be approximately proportional to the square or cube of the characteristic dimension of the flame-holder for a two- or three-dimensional bluff-body, respectively. If it is assumed that the mass flow m is directly proportional to the flow velocity, density or pressure, and to some power of the flame-holder diameter, then it is found that the blowoff velocity varies linearly with the pressure and with a power of the flame-holder characteristic dimension. In order to obtain agreement with the experiments of De Zubay (17), it is necessary to assume that m is proportional to the 2.15-power of the flame-holder diameter. A curve of the dependence of blowoff velocity on equivalence ratio, which agrees approximately with the experimental results of De Zubay, may be derived by using reasonable estimates for the recirculation zone volume and for the over-all chemical reaction rate.

The postulate of flame holding by a homogeneous reactor implies that the temperature in the reactor (i.e., in the recirculation zone) is the adiabatic flame temperature if small corrections caused by heat losses are neglected. Hence, as blowoff is approached, the combustion efficiency and the temperature of the recirculation zone should both decrease. These last conclusions are contrary to the observations that the temperature in the recirculation zone (3) and the combustion efficiency (2) remain practically constant as blowoff is approached. Furthermore, on the basis of the detailed results discussed in Section II and summarized in Fig. 1 it appears, in fact, that the bulk of the chemical reactions do not occur in the recirculation zone. Thus, although the stirred reactor model can be used to correlate empirical data, it is unlikely that it provides a valid description of the mechanism of flame holding.

2. Models Depending on a Balance Between Turbulent Mass and/or Heat Transfer and Energy Absorption by Cool Gases

Several investigators have proposed that the balance between turbulent mass and/or heat transfer and energy absorption by cool gases determines the critical conditions for blowoff. The detailed description of the wake geometry is inconsequential for this analysis.

De Zubay (17) assumed that two recirculating elliptic toroids in the wake of the disk serve as a pilot zone for maintaining a stable flame. Unburnt gas enters the pilot zone by turbulent diffusion while the burnt gas is lost downstream at an appropriate rate. Study of De Zubay's analysis shows that the critical conditions for blowoff are assumed to be determined by a balance between the rates of heat liberation in the toroid by chemical reaction and the rates of heat absorption by unburnt gas entering the toroid at an effective ignition temperature. According to Prandtl's hypothesis, the turbulent heat transfer coefficient is equated to the square of a mixing length multiplied by the absolute value of the velocity gradient and by the temperature gradient. Introduction of a variety of additional approximations (e.g., the temperature gradient equals the ratio of the difference between the burnt gas and ignition temperatures to the flame thickness; the mixing length is proportional to the product of downstream distance and a power of the Reynolds number; the flame thickness is proportional to the quenching distance which, in turn, varies as the 0.9 power of the pressure (37); etc.) then leads to a theoretical relation which is of the same functional form as the expression used for empirical correlation of data. The toroidal recirculation eddy represents a poor approximation to the true state of affairs, as is evident from the detailed discussion of wake behavior given in Section II.

Lees (38) has developed a model for flame stabilization on the basis of the hypothesis that, at sufficiently high Reynolds numbers, the wake flow becomes fully turbulent. Although this theory predicts correctly the dependence of blowoff velocity on flame-holder diameter for turbulent wake flow, the details of the model are also not in accord with the structure of the wake zone deduced in Section II. In Lees' "wake-mixing model," flame stabilization is assumed to involve turbulent transport of some of the unburnt gas across the wake boundaries. This gas is then heated to an ignition temperature by turbulent heat conduction. At the blowoff conditions, the rates of heat liberation by chemical reaction in the wake and the rates of energy absorption for heating of the cold gases to a critical ignition temperature are just equal. Under these conditions, the approach stream velocity may be identified with the blowoff velocity and turns out to be proportional to the flame-holder breadth as well as to the square of the normal turbulent burning velocity while it varies inversely with the turbulent mass-transfer coefficient. Basic to the analysis is the statement that the mass flux in the wake is a linear function of the mass flow of the approach stream with the proportionality constant equal to the turbulent mass-transport coefficient (39).

Except for an assumed change in the wake geometry and the use of a somewhat different approximation for turbulent mixing, Lees' theory and results resemble those of De Zubay in so far as the postulated flame-holding mechanism is concerned. The geometries of the two models are opposite in that Lees assumes axial heat transfer and De Zubay assumes mostly heat transfer in a direction normal to the wake axis.

Another closely related model is one of three suggestions made by Spalding (40). This author considers flame holding by two standing vortices behind a bluff body with the critical condition for blowoff corresponding to the requirement that the heat evolved by chemical reaction in the vortices equals the heat lost downstream by turbulent heat conduction. Setting the latter proportional to $V_{BO}PD$ where D is the diameter of the flame-holder, P equals the pressure, and V_{BO} is the blowoff velocity, and stating that the critical size of the vortex equals roughly double the size of a hot gas pocket which just supports combustion, Spalding arrives at the relation

$$V_{BO} \sim DP\,Su^2 \qquad [2]$$

where Su is the laminar burning velocity. Except for the occurrence of the laminar instead of the turbulent burning velocity, Spalding's early result is seen to be identical with that of Lees.

3. Models Involving the Balance Between Convection and Chemical Times

Spalding (40) has also suggested that the critical condition for flame stabilization may correspond to the requirement that the chemical heat release rate multiplied by the contact time between the combustible and hot gases has a fixed lower limit. The critical contact time is then set proportional[7] to D/V_{BO}, whereas the chemical heat release rate is identified with the heat release rate in the premixed undiluted combustible gas. The stated conditions lead again to Eq. [2] for any order of the chemical reaction.

The correlation expressed by Eq. [1] also involves the idea that a critical minimum time is required for the combustible fluid to pass through the wake zone. The model implicit in the theory of Spalding (40) and in the correlation of Zukoski and Marble (3) is consistent with the physical picture sketched in Fig. 1. However, since it does not involve the flame-spreading pattern downstream of the recirculation zone, it is essentially incomplete.

B. Reverse-Jet Flame-Holders

As was pointed out in Section III D, the drag of a flame-holder is an important performance parameter. For this reason it is of interest to compare the drag at blowoff for reverse-jet flame-holders and for baffle-type flame-holders. Experimental results show that the drag force at blowoff varies as the fourth power of the blowoff velocity for both types of flame-holders with nearly the same constant of proportionality (41). The result that a minimum drag force is necessary to hold a flame by either technique suggests that the mechanism of flame holding may also be similar in the two cases.

1. General Remarks Relating to Reverse-Jet Flame-Holders

The detailed flame-holding mechanism for the opposing-jet flame-holder has not been worked out, although it appears likely that the concept of a critical region, with composition determined by the combustible mixture and the reverse fluid jet, forms a useful first approximation (compare Section III B).

In this connection some preliminary experiments by E. Pohlmann on the effect of jet velocity (or jet supply pressure for fixed jet-tube diameter) are of interest (31). These studies have shown that the blowoff velocity increases with increasing relative velocity between the primary gas mixture and the jet stream. Thus the stabilization mechanism must be intimately tied up with the mixing processes between the combustible mixture and the partially or completely burnt gases entering through the recirculation zone.

2. Correlation of Reverse-Jet Flame-Holder Data

We proceed now to describe a useful method for correlating some of the performance results of reverse-jet flame-holders. Following the implications of the experimental data considered in Section III B, we shall assume that the approach flow in the duct and the jet fluid mix in the flame-holding region in such a way that, at the maximum value of the blowoff velocity V_{BO} as a function of approach stream equivalence ratio φ, the local equivalence ratio in the flame-holding region $\varphi \equiv b$ is a constant characteristic of the air-fuel mixture. Here the equivalence ratio is defined in the usual way as the mass ratio of fuel to air divided by the stoichiometric fuel-to-air mass ratio s.

Let A_j and F_j denote the mass flow rates in the reverse jet of air and fuel, respectively. Also let A_a and F_a represent the corresponding mass flow rates in the duct. Then we define the following dimensionless parameters:

$$\beta = \frac{A_j + F_j}{A_a + F_a} \text{ in the flame-holding region,} \qquad [3]$$

$$\gamma = \frac{F_j}{A_j}, \qquad [4]$$

$$\varphi = \frac{F_a/A_a}{(F_a/A_a)_{\text{stoichiometric}}} \equiv (1/s)F_a/A_a. \qquad [5]$$

Replacing F_j and F_a in Eq. [3] by the use of Eqs. [4] and [5] leads to the result

$$\beta = \frac{A_j(1 + \gamma)}{A_a(1 + \varphi s)}. \qquad [6]$$

Furthermore, according to our basic assumption, the local value of φ in the critical flame-holding region for the largest blowoff velocity is defined by

$$\begin{aligned} b &= \frac{(F_a + F_j)/(A_a + A_j)}{s} \\ &= \frac{(A_a s\varphi + \gamma A_j)/(A_a + A_j)}{s}. \qquad [7] \end{aligned}$$

From Eqs. [6] and [7] we now find that

$$\beta = \frac{s(b - \varphi)}{\left(\dfrac{\gamma - bs}{1 + \gamma}\right)(1 + \varphi s)}. \qquad [8]$$

For a pure air jet, $\gamma = 0$ and Eq. [8] reduces to

$$\beta = \frac{\varphi - b}{b(1 + \varphi s)}. \qquad [9]$$

For an approach flow consisting of natural gas and air, we find $s = 0.0555$; from the measured values (32) of V_{BO} as a function of φ it appears that $b = 0.9$. But for stabilization by a pure air jet ($\gamma = 0$) the maximum value of V_{BO} occurs (32) for $\varphi = 1.4$. Hence we find from Eq. [9] that $\beta = 0.50$. Similarly, for an air-fuel jet with $\gamma = 1.67$ it has been found (32) that $\varphi = 0.58$. Therefore, from Eq. [8], $\beta = 0.44$. In other words, for identical fluid-dynamical arrangements in which only the composition of the jet is varied, our postulate concerning the value of b shows that the relative contribution of the jet stream to the gas in the flame-holding region, β, is practically constant, as would be expected for tests in which the mixing pattern remains unchanged.

Cambel et al. (30, 31) have obtained a value of $\beta = 0.41$ for

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[7] This statement is equivalent to the statement that the chemical conversion time varies as the ratio of wake length L to blowoff velocity since the ratio L/D is practically constant for turbulent wakes and is independent of the relevant Reynolds number (3).

propane-air mixtures with a slightly different geometric arrangement and higher jet pressure (70 psig compared with 15 psig) than were used in the natural gas-air studies. This result suggests that β is relatively insensitive to pressure, a conclusion which is also consistent with the observation that b is insensitive to changes in jet pressure for otherwise fixed arrangements.

The available experimental data suggest either that the absolute maximum value of V_{BO} is a linear function of jet pressure (30, 31) or else varies with the square root of the jet pressure (32). The data leading to the former conclusion look more convincing.

Variations in jet diameter change the value of φ for which V_{BO} is a maximum. For the natural gas-air data the results are roughly correlated by the assumption that β is proportional to the jet diameter under otherwise constant conditions.

The temperature of the jet fluid has a large effect on stability. In a typical case, increasing the jet temperature from 70 F to 1030 F at constant manifold pressure increased the maximum blowoff velocity from 230 ft/sec to 310 ft/sec even though the mass flow rate through the jet decreased. For the same jet mass flow rate, increasing the jet temperature from 70 F to 1030 F increased the blowoff velocity by nearly a factor of three.

The preceding summary statements of reverse-jet performance are too sketchy to form the basis for an adequate theoretical discussion. However, the importance of the local mixture composition in the flame-holding region appears to have been demonstrated. It appears now to be desirable to perform detailed studies on the critical region in order to elucidate the physical changes and mixing processes involved in flame holding.

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"Letters to the Editor" and "Books Received for Review" appear after the reviews