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Abstract

We present results from an experimental and theoretical investigation into the liftoff and blowout mechanisms in turbulent diffusion flames. The blowout stability limits of coflowing turbulent jet diffusion flames are formulated in terms of a recently proposed flame stabilization mechanism based on the large scale organization of entrainment and mixing observed in turbulent shear flows. In contrast to the linear similarity scaling of the more commonly studied simple turbulent jet flames, the nonlinear scaling of coflowing turbulent jets allows an essential element of this stabilization mechanism to be investigated. Results show that when the flame stability criterion is evaluated for the last large scale structure in the flame, consistent with the underlying physical picture for this stabilization mechanism, a large reduction in the blowout limit is expected for even a small coflow velocity. This phenomenon is experimentally verified and good quantitative agreement is demonstrated with a set of measurements for the blowout limits of coflowing turbulent jet flames. We also document the liftoff characteristics of such coflowing turbulent jet diffusion flames and discuss a possible relationship between the liftoff and blowout mechanisms.

I. Introduction

Two particular aspects of turbulent combustion that have received renewed attention in recent years are the liftoff and blowout stability limits of jet diffusion flames. Much of this attention has been directed at attempts to identify the underlying physical mechanisms responsible for these stability limits and to develop predictive techniques for these phenomena. Several very different physical mechanisms have been proposed to account for the observed liftoff and blowout limits of such flames. For example, a widely held view treats liftoff and blowout in terms of a premixed flame propagating at an apparent turbulent flame speed through the mean fuel concentration field against the mean velocity field. Various interpretations of this mechanism, based largely on differing models for the turbulent flame speed, have been considered by Vanquickenborne and van Tiggelen[1], Eickhoff et al[2], Takahashi et al[3], Kalghatgi[4-6] and numerous others. An entirely different picture based on local extinction of the flame sheet by sufficiently large strain rates in the flow has been proposed by Peters and Williams[7]. Broadwell et al[8] have described yet a different mechanism by which blowout can result from the quenching of reactions when the molecular mixing rate in the flow becomes sufficiently large.

Most of these investigations have been based solely on the liftoff and blowout limits of simple fuel jets issuing into a quiescent medium. It appears likely, however, that the physical mechanisms responsible for these flame stability limits will be common over a wide range of turbulent reacting shear flows. This suggests that the combustion stability limits in other turbulent flows for which the fluid dynamical scaling laws are sufficiently well understood may yield additional information about the underlying liftoff and blowout mechanisms and may help to distinguish among the various mechanisms proposed.

This paper focuses primarily on the blowout mechanism in turbulent diffusion flames, though we also discuss briefly its relation to the liftoff mechanism. In particular, we examine the blowout limits of a turbulent jet diffusion flame in a coflowing stream. Despite the importance of such flames for combustion applications and for studying the flame stabilization mechanisms in turbulent combustion, their liftoff and blowout limits have not previously been reported, although Takeno and Kotani[9] and Karim et al[10] describe some related phenomena. The principal aim here is to document the liftoff and blowout limits of such flames and to determine the extent to which the mixing rate mechanism can account for these limits. Section II begins with a brief description of the mixing rate mechanism for blowout. The scaling laws for coflowing turbulent jets are reviewed in Section III, from which the blowout limits are then formulated in Section IV. We compare these blowout limits with results from experiments in Section V. In Section VI we present measurements for the liftoff heights of such coflowing turbulent jet flames and comment on the possible relationship between the liftoff and blowout mechanisms.

II. Mixing Rate Mechanism for Blowout

The Lagrangian description of a physical mechanism by which a turbulent jet diffusion flame can maintain itself, as well as the conditions under which this local flame stabilization mechanism fails, was recently given by Broadwell et al[8]. We give here only the essential elements of this picture for the stabilization mechanism in jet diffusion flames; additional details can be found in Ref. 8. During the entrainment process in a turbulent diffusion flame, fresh ambient air is brought into the flow and in contact with a mixture of hot reaction products and excess fuel, as indicated in Fig. 1. This cold entrained air and the hot mixture of products and fuel intertwine as they proceed down the inviscid cascade until reaching the Kolmogorov scale. During this cascade, molecular diffusion of species and heat, accompanied by chemical reactions, occurs across the strained interface between the cold entrained air and

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the hot mixture of products and fuel. Once the cascade reaches the Kolmogorov scale, molecular diffusion homogenizes the remaining cold air and the mixture of hot products and fuel. At early stages in the flame, the resulting homogeneous mixture will still be fuel rich and as a consequence the reactions occuring during homogenization will be rapidly quenched. Correspondingly, early in the flame combustion occurs primarily in the strained flame sheets. At later stages, after successive repetitions of this process, the homogenized mixture becomes decreasingly fuel rich and increasingly more combustion occurs during homogenization. Near the flame end, combustion occurs both in the strained flame sheets and in the homogenized mixture. The flame ends when this homogeneous mixture is completely combustible.

The time required for each repetition of this Lagrangian process consists of the time t_K required for the inviscid cascade down to the local Kolmogorov scale and the additional time t_d required for subsequent homogenization by molecular diffusion across distances of the order of the Kolmogorov scale. Broadwell and Breidenthal[11] first showed that

$$t_K \sim \frac{\delta}{u}\left[\, 1 - Re^{-1/2} \,\right] \qquad \text{and} \qquad t_d \sim \frac{\delta}{u}\, Sc\, Re^{-1/2}$$

with $\delta(x)$ and $u(x)$ respectively the local width and centerline velocity characterizing the shear at that stage in the flow. Note that when the local Reynolds number $u\delta/\nu$ is large the combined mixing time, denoted t_m, becomes independent of the Reynolds number Re as well as the Schmidt number Sc, and is simply $t_m \sim \delta/u$. (This is viewed as the explanation for the Reynolds number and Schmidt number independence of flame lengths at large Reynolds number.)

In this picture of mixing and reaction in turbulent diffusion flames, if molecular mixing in the strained flame sheets and during homogenization of the cold air and hot mixture of products and fuel at the Kolmogorov scale is sufficiently rapid, there will be insufficient time for ignition of the reactions before the temperature drops below a critical value. A characteristic time t_c for initiation of the reactions can be inferred from the laminar flame speed S and the thermal diffusivity κ as

$$t_c \sim \kappa / S^2$$

This local flame stabilization mechanism would then fail when the local mixing time t_m becomes sufficiently fast relative to the chemical time t_c, namely when their ratio

$$\varepsilon \equiv t_m / t_c \sim \frac{\delta / u}{\kappa / S^2} \tag{1}$$

falls below a critical value.

The remaining question concerns the relevant axial location in the flow at which failure of this local stabilization mechanism will lead to blowout. Note that good correlation of the blowout limits for simple turbulent jet diffusion flames was achieved by Broadwell et al[8] and by Dahm and Mayman[12] without having to directly confront this question. This was possible only because the linear growth scaling of the simple jet demands that this location must be directly proportional to the flame length L, which in that flow is in turn directly proportional to the stoichiometric ambient-to-jet fluid mixture ratio φ[13,14]. The proportionality constants were, in effect, incorporated into the value of ε at blowout, given as $\varepsilon \approx 4.3$ in Ref. 12. Indeed, the linear scaling of such simple turbulent jet flames does not permit this aspect of the blowout mechanism to be investigated. However, for coflowing turbulent jet diffusion flames the corresponding similarity scaling is not linear and therefore permits this question to be addressed directly. Aside from the obvious technical importance of this class of turbulent jet diffusion flames for combustion applications, this feature of the nonlinear scaling was the principal motivation for examining the blowout limits of such flames.

III. Coflowing Turbulent Jet Scaling

Referring to Fig. 1, the proper similarity scaling for decay of the centerline excess velocity $u \equiv (U - U_\infty)$ and growth of the lateral scale δ with increasing downstream distance x in the far field of an axisymmetric coflowing turbulent jet was first given by Maczynski[15], but does not appear to be widely known. These scaling laws can be easily obtained by considering the two asymptotic limits of such a coflowing jet. Specifically, when $(u/U_\infty) \to \infty$ the effect of the coflow should become negligible and the flow should approach that for an axisymmetric turbulent jet into a quiescent medium, for which self-similarity requires the simple power law scalings

$$\delta \sim x \tag{2a}$$

$$u \sim (J/\rho_\infty)^{1/2}\, x^{-1} \tag{2b}$$

where J is the jet momentum flux and ρ_∞ the ambient fluid density. In the other limit, as $(u/U_\infty) \to 0$ the momentum flux integral in terms of the excess velocity becomes identical to that

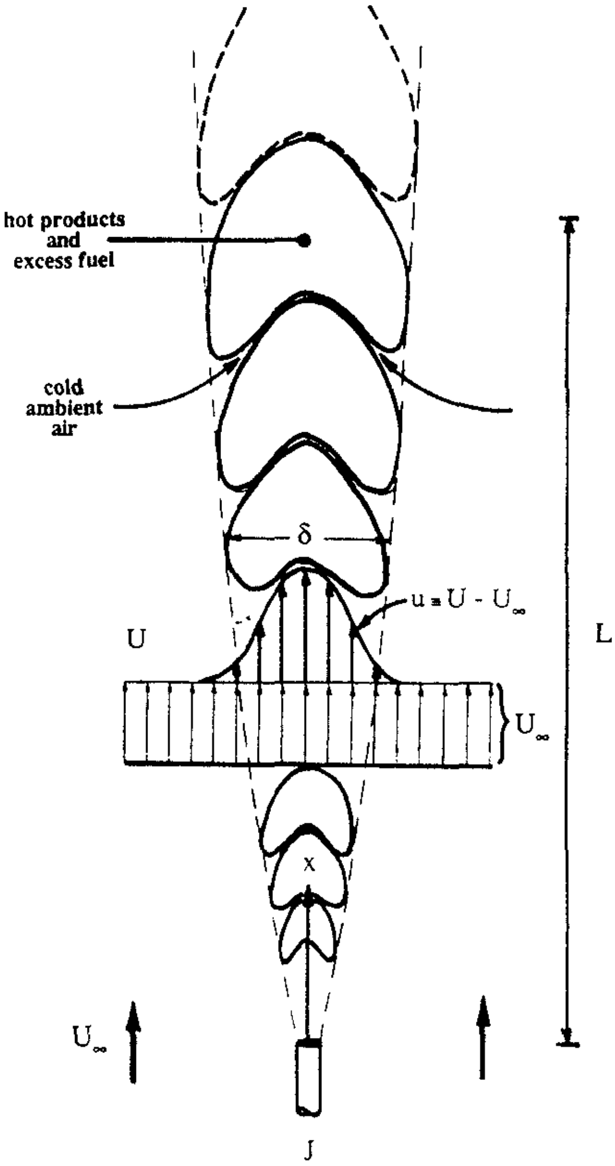


Fig. 1. Conceptual picture for large scale organization of entrainment and mixing in the far field of turbulent jet diffusion flames.

in terms of the deficit velocity for a wake. Consequently, under these conditions self-similarity requires that the axisymmetric coflowing jet should follow the same scaling as an axisymmetric wake, namely

$$(\delta/\vartheta) \sim (x/\vartheta)^{1/3} \tag{3a}$$

$$(u/U_\infty) \sim (x/\vartheta)^{-2/3} \tag{3b}$$

where ϑ denotes the momentum radius of the flow, given by

$$\vartheta^2 = \int_0^\infty \frac{u(r)}{U_\infty}\left[1+\frac{u(r)}{U_\infty}\right]2r\,dr = \frac{J}{\pi\rho_\infty U_\infty^2}$$

The wake-like limit in Eqs. (3a,b) corresponds to $(x/\vartheta)\to\infty$, while the jet-like limit in Eqs. (2a,b) corresponds to $(x/\vartheta)\to 0$, which can be written in terms of ϑ as

$$(\delta/\vartheta) \sim (x/\vartheta) \tag{4a}$$

$$(u/U_\infty) \sim (x/\vartheta)^{-1} \tag{4b}$$

This suggests that, over the entire range $0 \leq (x/\vartheta) \leq \infty$, the axisymmetric coflowing turbulent jet should follow a similarity scaling of the form

$$(\delta/\vartheta) = f_1(x/\vartheta) \tag{5a}$$

$$(u/U_\infty)^{-1} = f_2(x/\vartheta) \tag{5b}$$

with f_1 and f_2 satisfying the asymptotic limits in Eqs. (3a,b) and (4a,b). Measurements by Biringen[16] and by Reichardt[17] have confirmed this similarity scaling. The resulting similarity functions $f_1(x/\vartheta)$ and $f_2(x/\vartheta)$ are given in Fig. 2.

Although we are concerned here primarily with axisymmetric jets, it should be noted that planar coflowing turbulent jets follow very similar scaling laws. In that case, ϑ is the momentum thickness of the flow, given by $(J/\rho_\infty U_\infty^2)$ with J the momentum flux per unit span. For $(x/\vartheta)\to 0$ the flow should approach the planar jet-like limit with the corresponding simple power law scaling

$$(\delta/\vartheta) \sim (x/\vartheta) \tag{6a}$$

$$(u/U_\infty) \sim (x/\vartheta)^{-1/2} \tag{6b}$$

while for $(x/\vartheta)\to\infty$ the flow should approach the planar wake-like scaling

$$(\delta/\vartheta) \sim (x/\vartheta)^{1/2} \tag{7a}$$

$$(u/U_\infty) \sim (x/\vartheta)^{-1/2} \tag{7b}$$

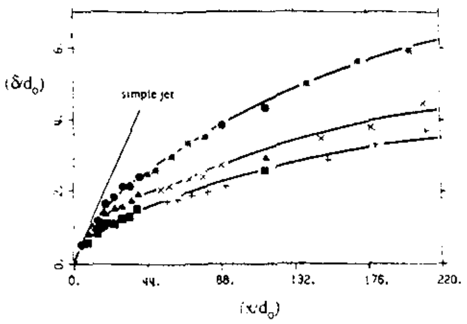
Measurements by Bradbury and Riley[18] and by Everitt and Robins[19] verify this scaling and provide the corresponding similarity functions $f_1(x/\vartheta)$ and $f_2(x/\vartheta)$ for such planar coflowing turbulent jets. A formulation of the blowout conditions similar to that given for axisymmetric jets in the following section can also be derived for planar jets.

IV. Coflowing Jet Blowout Conditions

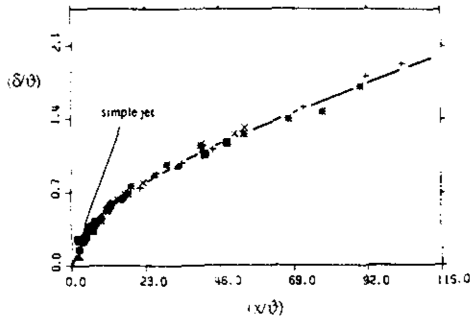
Equation (1) and the similarity functions in Eqs. (5a,b) give the blowout parameter ε for axisymmetric coflowing turbulent jet flames as

$$\varepsilon \sim \frac{\vartheta}{U_\infty}\,\frac{S^2}{\kappa}\,f_1(x_s/\vartheta)\,f_2(x_s/\vartheta) \tag{8}$$

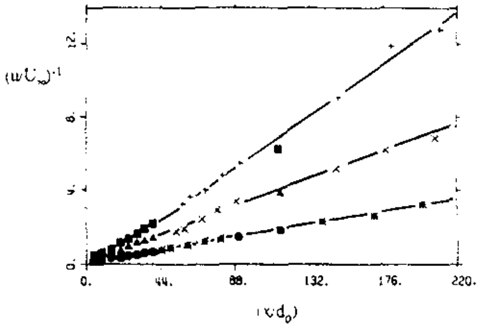
where x_s is the axial location at which failure to satisfy the stabilization criterion leads to blowout. To determine x_s we refer again to the conceptual picture in Fig. 1 of large scale organization of entrainment and mixing in the far field of turbulent jets, the elements of which are described in Refs. 13



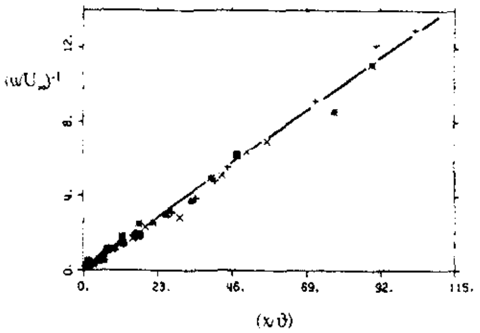
a. Local flow width $\delta(x)$, shown in simple jet variables (d_o is the jet source diameter).



b. Local flow width scaling $(\delta/\vartheta) = f_1(x/\vartheta)$, shown in proper momentum variables (ϑ is the momentum radius).



c. Centerline velocity $u(x)$, shown in simple jet variables.



d. Centerline velocity scaling $(u/U_\infty)^{-1} = f_2(x/\vartheta)$, shown in proper momentum variables.

Fig. 2. Scaling functions $f_1(x/\vartheta)$ and $f_2(x/\vartheta)$ for axisymmetric coflowing turbulent jets measured by Biringen[16].

and 14 and are summarized here only briefly. In this view, entrainment results from the dynamics of large structures whose axial and lateral scale are typically of the order of the local jet diameter $\delta(x)$ and occurs principally from the upstream end of each structure. Each structure contains mixed fluid (hot products and remaining excess fuel) intertwined over the scales of the local turbulent cascade with unmixed ambient fluid (cold air). The fuel concentration in the mixed fluid is spatially uniform throughout each structure and decreases with its Lagrangian age (as the structure progresses downstream) due to mixing with the ambient fluid as described in Section II. The flame ends when combustion is completed uniformly throughout the structure once the remaining fuel concentration has mixed to stoichiometry. This organized structure of the flow is viewed in Refs. 13 and 14 as the explanation for the relatively large and roughly periodic flame length fluctuations of turbulent jet flames.

In this picture, the farthest downstream location at which hot combustion products can be mixed with fresh reactants to stabilize the flame is in the last large structure in the flame. The average position of the center of this structure defines the mean flame tip. Following this reasoning, we propose that

$$x_s = L \tag{9}$$

where L denotes the mean flame length. The flame length can be found by recognizing that, in an Eulerian view, this corresponds to the axial location at which the highest local jet fluid concentration c_{max} reaches the stoichiometric value $1/(1+\varphi)$. Similarity suggests that c_{max} will be proportional to the local mean jet fluid concentration c. (We ignore here any presumably small change in this proportionality constant as the flow evolves from jet-like to wake-like similarity). The axial location at which c_{max} reaches stoichiometry can then be inferred from the decrease in the mean concentration c with increasing x, which in turn can be determined from the mean integral jet fluid mass balance

$$m_o = \int_0^\infty \rho(r)\ U(r)\, c(r)\ 2\pi r\, dr$$

where m_o is the mass flux at the jet source. Far field self-similarity in radial profiles of velocity and concentration then requires that

$$m_o = \rho_\infty u\, \delta^2 c \left[I_1 + I_2 \left(\frac{U_\infty}{u} \right) \right]$$

where the integrals I_1 and I_2 are given by

$$I_1 = \int_0^\infty \frac{\bar{c}(\eta)}{\bar{c}(0)}\ \frac{\bar{u}(\eta)}{\bar{u}(0)}\ 2\pi\, \eta\, d\eta$$

$$I_2 = \int_0^\infty \frac{\bar{c}(\eta)}{\bar{c}(0)}\ 2\pi\, \eta\, d\eta$$

with $\eta \equiv r/\delta(x)$. These integrals can be evaluated for the simple jet limit from measured radial profiles of concentration and velocity given, respectively, by Dahm and Dimotakis[14] and by Wygnanski and Fiedler[20] to yield $I_1 \approx 0.103$ and $I_2 \approx 0.254$. (In view of the essentially identical form of the self-similar $c(\eta)$ and $u(\eta)$ profile shapes for the jet-like and wake-like limits, we take I_1 and I_2 as invariants and ignore any presumably small changes in them as the flow evolves between jet-like and wake-like similarity.) The flame tip is then reached when $c_{max} = 1/(1+\varphi)$, giving

$$(L/\vartheta) = g^{-1} \left[\left(\frac{c_{max}}{\bar{c}} \right) \frac{m_o}{\rho_\infty U_\infty \vartheta^2} (1+\varphi) \right] \tag{10}$$

where

$$g(x/\vartheta) \equiv \Big[I_1 + I_2 f_2(x/\vartheta) \Big] \frac{f_1^2(x/\vartheta)}{f_2(x/\vartheta)} \tag{11}$$

From direct measurements in Ref. 13, the ratio $(c_{max}/c) \approx 2$. The proportionality constant in Eq. (8) can be determined as $(2/\pi^2)\, I_1^{-2}\, [f_1'(0)/f_2'(0)]^3\, (c_{max}/c)^{-2}$ from the requirement that, in the simple jet limit given by Eqs. (4a,b), this entire formulation must become identical to that in Ref. 12.

Equations (8) through (11), give the complete formulation for the blowout parameter ε with no free parameters. Consistent with Ref. 12, blowout is expected when $\varepsilon \approx 4.3$. To illustrate the resulting dependence of the jet blowout velocity U_j on the coflowing stream velocity U_∞, Fig. 3 shows contours of ε for a typical case. Here, and in all subsequent calculations, the thermal diffusivity κ, the laminar flame speed S and the stoichiometric mixture ratio φ are as given in Refs. 8 and 12. Note that the contour for $\varepsilon = 4.3$ indicates a dramatic decrease in the jet blowout velocity with increasing coflow velocities, even for relatively small coflow velocities. For example, in the case shown, coflow velocities of the order of 1% of the jet velocity lead to more than 50% reduction in the jet blowout velocity. In the following section, we compare this result with measurements of the blowout limits.

V. Comparisons with Blowout Experiments

To assess this conceptual picture for the underlying stabilization mechanism governing turbulent diffusion flame blowout and the resulting formulation for the blowout limits given in the preceeding section, we conducted a set of measurements of the blowout limits for axisymmetric coflowing turbulent jet diffusion flames. These experiments were performed in the Turbulent Diffusion Flame Tunnel at the Combustion Research Facility at Sandia National Laboratories. The facility is a forced draft vertical wind tunnel with an axisymmetric fuel jet located at the upstream end of a 30 cm × 30 cm × 200 cm test section. In these experiments, the test section was equipped with solid walls on three sides and a quartz glass window on the remaining side. The fuel jet issued from a round nozzle attached to a 0.95 cm diameter straight cylindrical tube originating in the settling section and entering the test section through a 9:1 area ratio contraction. Two different nozzles were used; one having an inner diameter of 3.3 mm and a 0.9 mm wall thickness, the other with a 5.2 mm inner diameter and a wall thickness of 1.4 mm. Undiluted technical grade methane and propane were used as fuels. The free stream velocity in the tunnel and the jet exit velocity were both set by mass flow meters.

Figure 4 shows the measured blowout limits for the three cases investigated, together with contours of the blowout parameter ε as formulated above. Note that in each case the present blowout formulation predicts the large reduction in the jet blowout velocity with increasing coflow velocity noted in Section IV. The experimental results confirm this phenomenon and show good quantitative agreement with the $\varepsilon = 4.3$ contour. These results support the notion that the local molecular mixing rate in the flow may be the underlying mechanism controlling blowout in turbulent diffusion flames.

It seems at first surprising that such an apparently small coflow velocity can have such a large effect on the jet blowout velocity. However, based on this view of the physical blowout mechanism and the scaling relationships for coflowing turbulent jet flames the explanation is that, even though the coflow may be small in comparison with the jet exit velocity, at the structure defining the flame tip the local jet velocity u can have decreased considerably. For example, for a non-coflowing methane flame ($\varphi = 17.2$) the jet velocity at the flame tip is only of the order of 3% of the jet exit velocity. As a

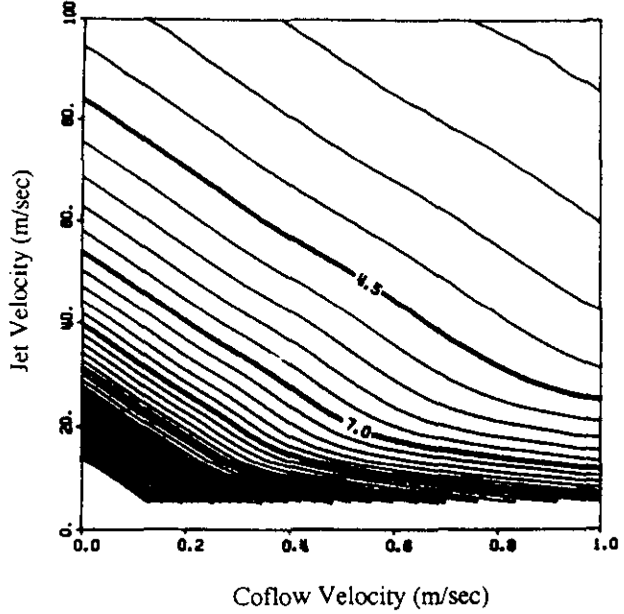
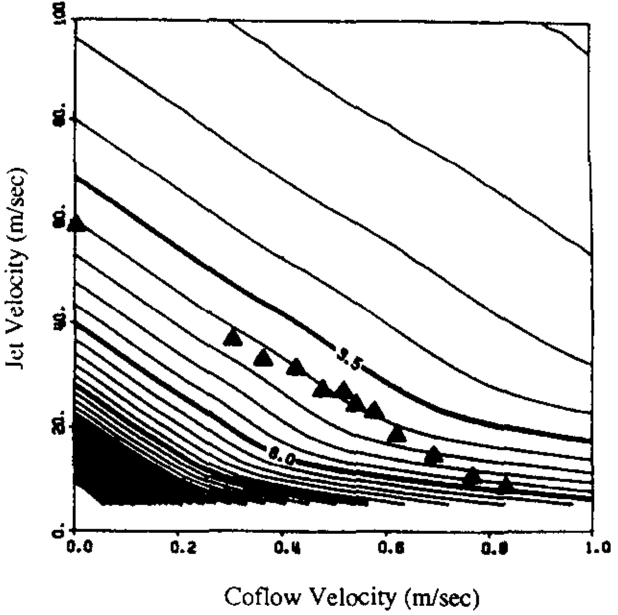
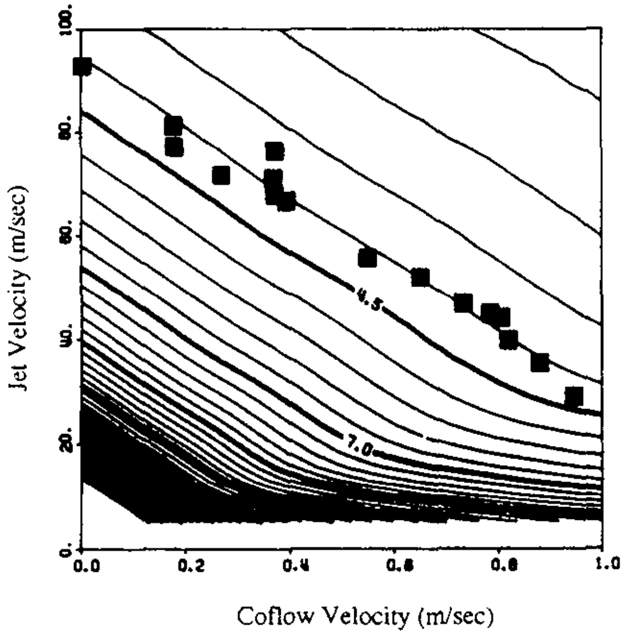


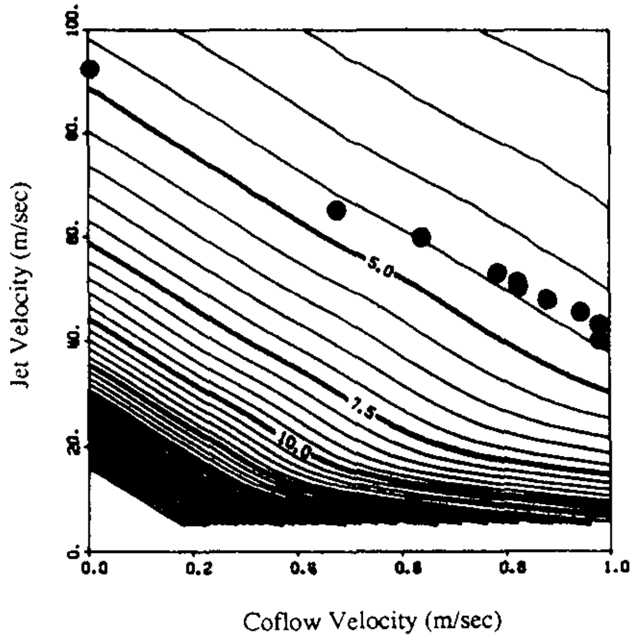
Fig. 3. Contours of the blowout parameter ε in Eqs. (8) through (11), computed for methane issuing from a 5.2mm diameter jet source. The contour interval shown is $\Delta\varepsilon = 0.5$. Blowout is expected at $\varepsilon \approx 4.3$.



b. Methane, 3.3mm diameter jet source.



a. Methane, 5.2mm diameter jet source.



c. Propane, 3.3mm diameter jet source.

Fig. 4. Measured blowout limits for coflowing turbulent jet diffusion flames, showing contours of the blowout parameter ε in Eqs. (8) through (11). Contour interval is $\Delta\varepsilon = 0.5$. Blowout is expected at $\varepsilon \approx 4.3$.

result, a coflow of the order of 1% of the jet exit velocity would no longer be small and may have a large effect on the local mixing rate $1/t_m$ of the structure which stabilizes the flame. In effect, this demonstrates that turbulent diffusion flame stabilization is a *local* mechanism.

VI. Liftoff of Jet Diffusion Flames

The effects of various parameters on the liftoff characteristics of coflowing turbulent jet diffusion flames also do not appear to have been previously documented, although some qualitative features related to liftoff are described by Takeno and Kotani[9]. In part for this reason, we conducted a set of experiments to measure the liftoff characteristics of such axisymmetric coflowing jet flames. In this Section, we present the results of these measurements and discuss a possible relationship between the liftoff and blowout mechanisms.

Figure 5 shows the variation in absolute liftoff height with jet source velocity at a fixed coflow velocity for two different jet source diameters. Of particular interest in these data is the observation that, as is commonly seen in simple turbulent jet flames, the liftoff height in these coflowing jet flames appears to be independent of the jet source diameter. Additionally, the hysterisis in the initial liftoff point and the reattachment point, also a common observation in simple jet flames, is indicated in this figure. Although not directly confirmable from these data, it appears likely that the increase in liftoff height with decreasing jet velocities at very small jet velocities is simply an artifact of the increase in the initial laminar length of the jet with decreasing Reynolds number at these relatively low Reynolds numbers (see Dahm[13]). If measured from the breakpoint of the jet, the liftoff heights would likely continue to decrease with decreasing jet velocity. The data in figure 6 show the variation in absolute liftoff height with increasing jet source velocity at three different coflow velocities for a fixed jet source diameter. These results demonstrate a strong effect of the coflow velocity on the liftoff height even for small coflow velocities. Figure 7 shows the measured liftoff curves for two different fuels.

Although the mixing rate mechanism accurately correlates the blowout limits of these coflowing turbulent jet flames as demonstrated in the previous Section, as well as blowout of simple jet flames as demonstrated in Refs. 8 and 12, this mechanism does not appear to give the correct scaling for the liftoff heights. For example, if liftoff in the simple jet limit given by Eqs. (2a,b) were governed by the local failure to satisfy the flame stabilization criterion in Eq. (1), then the liftoff height should increase quadratically with increasing jet source velocity. However, measurements of the liftoff heights of such simple jet flames have been widely reported and suggest that this scaling relationship is instead at least approximately linear.

The physical description in Section II of mixing and combustion in turbulent diffusion flames may give some insight into the apparent distinction between the liftoff and blowout mechanisms. As noted in Section II, at early stages in the flame combustion occurs primarily in strained flame sheets, with reactions during homogenization at the Kolmogorov scale being rapidly quenched. Nearer the flame tip, however, combustion occurs both in the strained flame sheets and during homogenization. This suggests that liftoff, which typically occurs at early stages in the flame, is governed by a mechanism leading to extinction of combustion in the strained flame sheets. One such possibility is the strain-out mechanism described by Peters and Williams[7]. Indeed, the flame sheet is subjected to a spectrum of strain rates resulting from the local turbulent cascade. The strain rate σ_λ associated with any length scale λ in the cascade, with an associated velocity scale u_λ would follow a scaling of the form $\sigma_\lambda \sim u_\lambda/\lambda$. The velocity scale u_λ is in turn be related to λ through the requirement that, for the non-dissipative transfer of energy in the inertial range of the cascade the net flux of kinetic energy through every scale λ must be the same, giving $u_\lambda^3/\lambda = u^3/\delta$ where u and δ are the local width and centerline velocity characterizing the shear at that stage in the flow. This gives the strain rate associated with any scale λ as $\sigma_\lambda \sim (u/\delta)\cdot(\lambda/\delta)^{-2/3}$. With the local spectrum of length scales bounded by the local large scale δ and the local Kolmogorov scale $\delta \cdot Re^{-3/4}$, the local spectrum of strain rates is bounded by

$$\sigma_{min} \sim (u/\delta) \qquad \text{and} \qquad \sigma_{max} \sim (u/\delta)\cdot Re^{1/2}$$

Combustion at a point on the flame sheet will then be extinguished if the strain rate σ at that point exceeds some critical value σ^*. As the strain rates in the flow are increased, a larger fraction of the strain rate spectrum exceeds σ^* and more of the flame sheets are strained out. Following Peters and Williams, we hypothesize that if at least some critical fraction of the flame sheets have been strained out at any given stage in the flow, combustion in the flame sheets will be unable to sustain itself and the flame must restabilize at a downstream

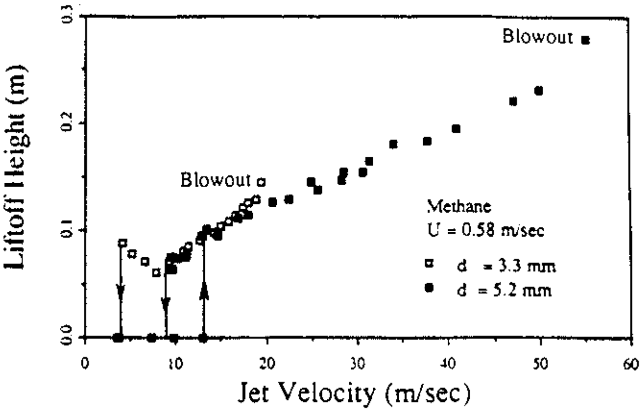


Fig. 5. Measured liftoff heights for coflowing turbulent jet diffusion flames, showing effects of varying the jet source diameter.

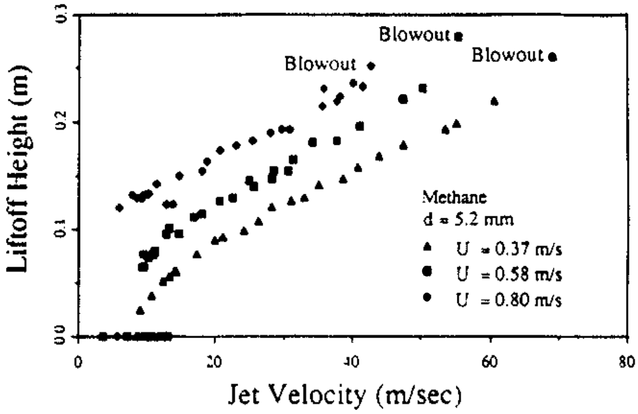


Fig. 6. Measured liftoff heights for coflowing turbulent jet diffusion flames, showing effects of different coflow velocities.

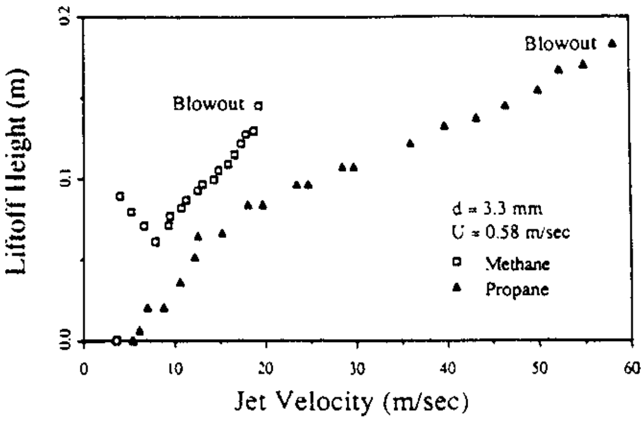


Fig. 7. Measured liftoff heights of coflowing turbulent jet diffusion flames, showing effects of varying the fuel type.

location at which the spectrum of strain rates permit the flame sheet to sustain itself. Since this critical fraction will likely be somewhat less than one, this local flame sheet extinction criterion would be reached somewhat before $(u/\delta) \approx \sigma^*$. Although this could presumably be the mechanism governing flame liftoff, similar reasoning suggests that it would probably not be the mechanism governing blowout. Specifically, near the flame end, combustion occurs both in the flame sheets and in the homogeneous regions near the Kolmogorov scale. Once the flame is stabilized in the last large structure in the flame, combustion in the flame sheets would be extinguished before $(u/\delta) \approx \sigma^*$, but combustion would still continue in the homogeneous regions at the Kolmogorov scale. The flame sheet strain-out mechanism would not be appropriate for describing extinction of these homogeneous regions. On the other hand, the mixing rate mechanism provides a physical means for extinguishing combustion in these regions and thereby blowing the flame out. In this context, it is possible that the flame sheet strain-out mechanism may be the appropriate for describing liftoff, while blowout may be governed by the mixing rate mechanism.

VII. Conclusions

The blowout stability limits of coflowing turbulent jet diffusion flames have been formulated in a simple description for a physical mechanism by which a turbulent diffusion flame can stabilize itself. Unlike the linear similarity scaling of the more commonly studied simple turbulent jet diffusion flames, the nonlinear scaling of such coflowing jets allows an investigation of the location in the flow at which failure of this local flame stabilization mechanism will lead to blowout. Consistent with the large scale organization of entrainment and mixing in the far field of turbulent jets, we propose that the resulting flame stability criterion should be evaluated for the last large structure in the flame. Results show that for coflowing turbulent jet flames this predicts a large reduction in the jet blowout velocity even for relatively small coflow velocities. This phenomenon is experimentally verified and good quantitative agreement is found with measurements for the blowout limits of coflowing jet diffusion flames. This strong effect of the coflow suggests that such coflowing turbulent jet flames provide an environment well suited for investigating the underlying liftoff and blowout stability mechanisms of turbulent diffusion flames and for examining the validity of proposed stabilization mechanisms. The present results support the notion that the local molecular mixing rate in the flow may be the mechanism controlling blowout in turbulent diffusion flames.

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