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ASSESSMENT OF THEORIES FOR THE BEHAVIOR AND BLOWOUT OF LIFTED TURBULENT JET DIFFUSION FLAMES

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Many competing theories have been published to describe the characteristics and blowout of lifted turbulent jet diffusion flames. The assumptions which are made as to the physical processes responsible for these behaviors vary widely. In this paper these assumptions are summarized for each model and compared with the actual turbulent behaviors of unignited fuel jets. As part of this discussion, recent unpublished measurements of real-time concentration fluctuations along a line in a turbulent fuel jet are introduced. To the extent possible, each theory is also assessed as to its capabilities to accurately predict experimentally observed lift off and blowout behaviors. The conclusion of these analyses is that none of the currently-available theories for flame stabilization are satisfactory. Further experimentation is required before the actual physical processes responsible for flame stabilization can be identified and models which are capable of accurate prediction of lift off heights and blowout velocities developed.

Introduction

The liftoff and blowout behaviors of turbulent jet diffusion flames have been the subjects of numerous research efforts[1–16] recently. Some of these studies have questioned the validity of the once widely-accepted flame stabilization theory of Vanquickenborne and van Tiggelen.[17] As a result, the physical mechanisms responsible for flame stabilization have become the subject of considerable confusion and controversy.

In this paper the principal experimental findings and physical models for liftoff behavior and blowout are summarized. Particular attention is focused on an empirical calculational procedure developed by the author[14,15] which provides extremely accurate correlations of experimental data for liftoff heights and blowout velocities. Unpublished experimental results are presented which provide new insights into the mixing behavior of unignited fuel jets flowing into air.

The various flame stabilization models are critically assessed for their ability to provide predictions which are in agreement with experimental observations and for the validity of their assumptions concerning the mixing processes responsible for flame stabilization. The conclusion is that none of the theories currently available are totally satisfactory and that the current experimental characterization of flame stabilization is insufficient to determine the actual physical processes which determine liftoff behavior and blowout.

Flame Stability—Experimental Findings and Models

The following discussion briefly summarizes the experimental findings and models for liftoff behavior and blowout which have appeared in the literature. Due to length requirements, complete discussions are not possible. Readers are strongly encouraged to consult the cited papers for further details and additional references.

Experimental Findings for Liftoff and Blowout:

Liftoff:

The phenomenon of liftoff has been experimentally investigated for many decades. Flow visualization studies[4,7,18,19] provide useful insights. For positions upstream of the flame base a turbulent mixing region exists which is very similar to that for the unignited flow. Combustion at the flame base takes place in a donut-shaped ring and results in an immediate thermal expansion of the flow and an apparent change in the turbulent structure.

Vanquickenborne and van Tiggelen[17] provided extensive experimental measurements for unignited and ignited turbulent jets of methane having a range of jet exit diameters, d_o, and velocities, U_o. Values of lift off heights, h, as a function of U_o and blowout velocities, $(U_o)_b$, are reported. Their findings[17] show that lifted flames are stabilized near the radial position where the time-averaged methane mass fraction of the unignited jet is equal to that required for stoichiometric burning, Y_s.

Similar experimental results are available in works published by Hall et al.[1] and Günther et al.[2] These authors investigated liftoff for jets of mixtures of natural gas and hydrogen. The most likely radial position for combustion at the flame base is shown to be along the mass fraction contour, Y_l, for which the fuel-air mixture has its maximum laminar flame speed, $(S_b)_{max}$. For hydrocarbon fuels Y_l and Y_s are very nearly equal, but for hydrogen the two values differ substantially.

The most extensive experimental investigation of liftoff is provided by Kalghatgi.[3] Results are reported for four fuels and wide ranges of d_o and U_o. The findings can be summarized as follows:

1) h increases linearly with U_o.
2) For a given U_o, h is independent of d_o.
3) Values of h are inversely proportional to $(S_b)^2_{max}$.

Several additional papers provide observations for lifted flames. Eickhoff et al.[4] report time-averaged concentration measurements as a function of radial position immediately upstream and downstream of two flame stabilization positions of a lifted natural gas jet. Their results indicate that between forty and fifty percent of the fuel reacts over very short flow distances. Time-averaged temperature measurements are also described. Temperature measurements in the stabilization region have also been reported by Sobiesiak and Brzustowski.[5,6]

Savas and Gollahalli[7] investigated the liftoff behavior of a turbulent propane jet for which the flame base lies near the jet exit. They conclude that combustion does not occur within the turbulent structures of the flow, but that the combustion region lies in a laminar region well outside of the jet.

Blowout:

Vanquickenborne and van Tiggelen[17] have shown that blowout occurs for liftoff heights which lie well upstream of positions in the flow field where the fuel-air mixture becomes too lean to support combustion. In fact, their measurements indicate that blowout takes place when the lifted flame is forced to a downstream position where the Y_s contour reaches its maximum radial distance. Hall et al.[1] confirmed these observations for natural gas jets and observed that $(U_o)_b$ is proportional to the jet nozzle diameter (d_o). This should be contrasted to the liftoff height velocity dependence which has been shown[3] to be independent of nozzle diameter.

The most complete experimental investigation of blowout is that of Kalghatgi.[8] $(U_o)_b$ values are reported for wide ranges of d_o and different fuel gases. His findings confirm that values of $(U_o)_b$ are linearly dependent on d_o and demonstrate that $(U_o)_b$ varies as $(S_b)^2_{max}$ and the inverse of the jet to ambient density ratio, R_ρ.

Theoretical Treatments of Flame Stabilization:

Liftoff:

In their landmark paper, Vanquickenborne and van Tiggelen[17] suggested that the stabilization of lifted turbulent jet diffusion flames can be understood by assuming that the fuel and air along the Y_s contour are *fully premixed* and that a local flame speed (S_t), determined by the local turbulence structure of the unignited flow, is associated with this mixture. Flame stabilization occurs at the position where the local time-averaged axial velocity, U_s, along the Y_s contour equals S_t. Turbulence measurements in unignited jets support these assumptions.[17]

Hall et al.[1] and Günther et al.[2] proposed an identical model. Utilizing measurements in the corresponding unignited jet flows, it was demonstrated that the assumption that the local time-averaged axial velocity along the Y_l contour, U_l, is equal to S_t results in a dependence for S_t on local turbulence properties which is identical to that observed for premixed fuel and air mixtures.[20] An important conclusion of their analysis is that

$$S_t/S_b = k\mathrm{Re}_t. \quad (1)$$

where k is a constant and Re_t is the turbulent Reynolds number formed from the velocity fluctuations, microlength scale, and local kinematic viscosity. Note that Eq. (1) requires that h scales as the inverse of S_b.

Kalghatgi successfully correlated his experimental results[3] by assuming the flame stability model of Vanquickenborne and van Tiggelen[17] and using dimensional analysis. His correlation can be approximated as

$$h \approx C_h(U_o \nu_o/(S_b)^2_{max})(R_\rho)^{1.5}. \quad (2)$$

ν_o is the fuel kinematic viscosity and C_h is a constant. The dependence of h on the inverse of $(S_b)^2_{max}$ differs from the linear dependence suggested by Hall et al.[1] and Günther et al.[2] Kalghatgi[3] did show that the resulting values of S_t are comparable to those observed in premixed fuel-air mixtures.[20,21]

Results of other experiments reported in the literature[4–6] have been cited as supporting the premixedness model.

The flame stability model of Vanquickenborne and van Tiggelen[17] has been challenged by several new theories[9–13] which propose that the stabilization of lifted flames results from flame extinction processes which occur in turbulent structures of the nearby unignited flow. Many different types of extinction processes have been suggested.

Peters and Williams[9] argue that the degree of *molecular* mixing in axisymmetric turbulent jets is insufficient to support the concept of premixed combustion. These authors analyze the problem in terms of the laminar flamelet model[22] in which flamelets are extinguished when the local turbulence-induced concentration gradients (characterized by the time-averaged scalar dissipation, χ) are sufficient to quench combustion. Flame stabilization occurs at the point where combustion extinction and propagation are balanced. Their analysis predicts liftoff behavior which is consistent with the experimental observations of Günther et al.[2] Recent measurements[23] of χ in a turbulent jet are consistent with those observed for laminar flame extinction, but have raised uncertainties concerning the assumed forms of χ used in the analysis.[9] Janicka and Peters have considered the effects of assumptions concerning the scalar dissipation on calculated values of liftoff height.[10] Peters[11] has extended the flamelet model to the case of partially premixed diffusion flamelets. He concludes that the extinction of laminar flamelets remains the relevant stabilization mechanism.

Byggstøyl and Magnussen[12] also propose that flame stabilization is the result of combustion extinction. However, they suggest that the extinction occurs in the smallest vortices of the flow. A framework is provided for the prediction of h as a function of U_o. Predicted values are in excellent agreement with experiment.

In a publication concerned primarily with blowout, Broadwell et al.[13] hypothesize that lifted flames result from flame extinction in large scale turbulent structures. Their model is discussed in the following section. An expression for the dependence of h on U_o, d_o, R_ρ, and $(S_b)_{max}$ is provided,[13] but it has been shown[14,15] that the predicted dependencies are inconsistent with experimental findings.[3]

Blowout:

The most widely accepted model for blowout is due to Vanquickenborne and van Tiggelen.[17] In their view, blowout results from differences in the variations of S_t and U_s with downstream distance. As the liftoff distance moves downstream with increasing U_o, the stabilization region moves into a region where increases in S_t can no longer match the more rapidly increasing values of U_s. The combustion region is carried downstream and the flame blows out. The same model has been adopted by other groups.[1,8,12]

Kalghatgi[8] utilized this model, dimensional analysis, and the known mixing behavior of isothermal flows to derive an accurate correlation for his experimental findings which can be written as

$$(U_o)_b = \frac{0.136 r_\epsilon (S_b)^2_{max}}{Y_s \nu_o R_\rho^{3/2}} \quad (3)$$

r_ϵ equals the jet radius, r_o, times $R_\rho^{1/2}$. Note that $(U_o)_b$ is proportional to $(S_b)^2_{max}$. The original model of Vanquickenborne and van Tiggelen[17] predicts a linear dependence on $(S_b)_{max}$.

Broadwell et al.[13] propose that flame stabilization results when hot gases, which have been expelled to the edge of the jet by earlier large scale turbulent structures, are reentrained and ignite noncombusting eddies of the jet. If the mixing time of the reentrained gases is too short, the gases cool rapidly and ignition becomes impossible. The ratio of the turbulent mixing time, τ_m, and the chemical time required for ignition, τ_c, is the important parameter for this model. By assuming $\tau_m \sim U_m/d$ and $\tau_c \sim \kappa/(S_b)^2_{max}$ an expression for $(U_o)_b$ is derived which accurately predicts the experimental findings.[8] U_m is the centerline velocity and d the local jet diameter at h, and κ is the gas diffusivity.

Some Recent Observations Concerning Liftoff and Blowout:

Recently, the author of this paper has reported additional analyses of liftoff and blowout.[14-16] An important impetus for this work was the realization that the liftoff results of Kalghatgi[3] can be accurately correlated by writing

$$h \sim U_o/(S_b)^2_{max}. \quad (4)$$

Note that this observation implies that liftoff heights are independent of R_ρ, d_o, ν_o, and blowout Y_s or Y_l.

The simplicity of Eq. (4) suggests that it should be possible to calculate h in terms of the known similarity profiles for velocity[24] and concentration[24,25] in the unignited flows. Indeed, an empirical form has been found[14,15] for the local flow velocity along the Y_l contour,

$$U_l = C''_h h^2 (S_b)^2_{max} Y_l^2 / r_\epsilon, \quad (5)$$

which along with the similarity expressions yields highly accurate predictions of h as a function of U_o. C''_h is a constant parameter having units of s/cm^2.

This calculational procedure is extended to blowout behavior[14,15] by making the reasonable assumption that extinction occurs when the local flow velocity along the Y_l contour exceeds a well-defined velocity, $(U_l)_b$. Very good agreement of experimental[8] and calculated values of $(U_o)_b$ is found with

$$(U_l)_b = C_b (S_b)^2_{max} r_o. \quad (6)$$

It was noted[16] that jet flows are highly intermittent for the radial positions where combustion occurs in the flame base. Furthermore, values of h for which blowout occurs are very close to the downstream positions where the intermittency factor goes to one. These observations have major implications for the understanding of liftoff behavior and blowout.

It has been argued[14–16] that the success of these empirical calculational procedures implies that flame stability results from physical processes occurring in large scale turbulent structures. Based on observations in variable density jets, it has been proposed[16] that a realistic approximation for the turbulent mixing time is $\tau_m \sim z^2/r_\epsilon U_l$ which along with the relation for τ_c suggested by Broadwell et al.,[13] yields an expression for U_l which is similar to Eq. (5). A physical mechanism based on the intermittency behavior of the corresponding unignited flow has been suggested[16] to explain the abrupt onset of blowout. In this view, reentrained gases are mixed with nonflammable jet gases which cool and quench the entrained hot products before the hot gases can ignite the flammable mixtures existing nearer the jet centerline. The combustion is carried downstream to extinction. It must be emphasized that even though these ideas provide plausible explanations for flame stabilization behavior, no attempt has been made to investigate these models quantitatively and no experimental results are available for lifted flames which support the hypotheses utilized.

Turbulent Structure of Fuel Jets

The mixing behaviors of turbulent fuel jets with the surrounding ambient atmosphere have been extensively investigated. Time-averaged properties such as entrainment[26] and velocity and concentration contours[24,25] are characterized quite well in self-similarity flow regions. Progress has also been made on understanding the turbulence structure and the mechanism of entrainment. One of the most significant recent advances has been the recognition of the important role of large scale turbulent structures.[27–29]

A new experimental diagnostic[30] has been developed at the National Bureau of Standards which

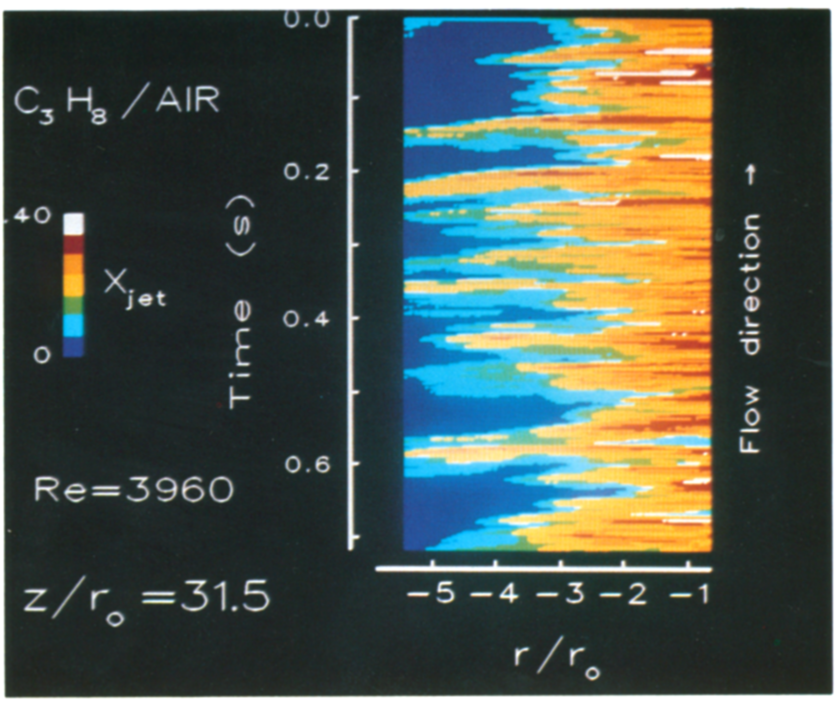

FIG. 1. Real-time concentration fluctuations along a line are shown for a turbulent jet of propane (U_o = 2.7 m/s, r_o = 3.2 mm, and Re = 3960) entering a slow coflow of air. Observations are made along the radial direction on one side of the centerline at a downstream distance of z/r_o = 31.5. The line readout rate is 357 Hz. Concentrations are represented by a seven level false-color scale where each color represents a propane mole fraction range of 0.057. It is important to remember that this is a space-time and not a two-dimensional plot of concentration.

allows the concentration fluctuations occurring along a line to be measured quantitatively. Experimental details can be found elsewhere.[30] Figure 1 shows an example for the fuel concentration behavior along the radial direction of a propane jet (U_o = 2.7 m/s, r_o = 3.2 mm, Re = 3960). The downstream distance is z/r_o = 31.5.

It is important to note that even though the jet velocity for the measurements shown in Fig. 1 is too low to result in a lifted flame for the downstream position where the measurements are recorded, an increase in U_o to this velocity (estimated as $U_o \approx$ 53 m/s) is not expected to significantly alter the large scale structures of the turbulent flow field.

The concentration fluctuations reveal a great deal concerning the turbulent structure and entrainment behavior of this isothermal fuel jet. The steep concentration gradients observed along the downstream edges of the large scale structures indicate that mixed propane and air are ejected radially from a core of highly concentrated jet fluid located near the jet centerline into the ambient surroundings. On the upstream side of the ejected structures large quantities of air are entrained. This view of entrainment is in agreement with the findings of Chevray and Tutu[27,28] based on single point measurements of scalar concentration and velocity.

The most probable radial location for a lifted propane turbulent jet diffusion flame with h = 31.5 r_o is calculated to be r/r_o = 5.3. This position is on the left-hand edge of the data displayed in Fig. 1. An immediate conclusion which can be drawn from the measurements is that the fuel and air are not completely premixed at this radial location. In fact, the flow is highly intermittent and only air is present during a large fraction of the time. This point can be emphasized by replotting the results of Fig. 1 to indicate spatial and temporal locations where combustible mixtures of propane and air exist based on propane flammability limits.[31] Figure 2 shows the results.

Assessment of Flame Stability Theories in Terms of Their Abilities to Predict Experimental Findings and Agreement of Mixing Assumptions with Actual Flow Behavior

All of the theories proposed for flame stability are based on turbulent processes occurring in unignited flow regions near the combustion flame base. It is

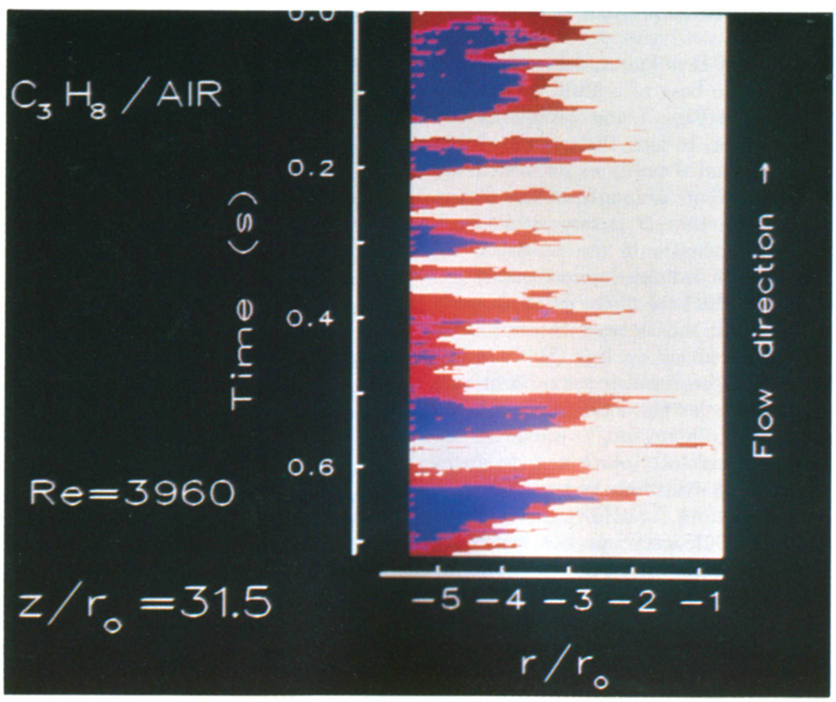

FIG. 2. The concentration measurements of Fig. 1 have been replotted to emphasize periods of time when combustible mixtures of propane (mole fractions of propane from 0.022 to 0.095) and air are present. Combustible mixtures are represented by red while blue and white represent lean and rich mixtures, respectively.

relevant to question whether or not this is reasonable. For liftoff heights near the nozzle, Savas and Gollahalli[7] have shown that flame stabilization occurs for radial positions where there is no fuel in the corresponding unignited flow. These authors conclude that combustion does not occur in the cores of rolled-up vortices. However, for liftoff heights which are further from the nozzle, experiments clearly show that the most likely flame location lies very close to the Y_l contour.[1,2,5,6,17] Visualization studies indicate that the turbulent structure of the flow field upstream of the stabilization position is very similar to the unignited flow.[4,7,18,19] These observations strongly support the hypothesis that flame stabilization results from interactions of the combustion with turbulent structures which are essentially the same as those found in the unignited flow.

Two minimum requirements for a flame stability theory are that it accurately predict experimental behaviors and that the proposed physical mechanisms are consistent with the known turbulence structure. These two properties are used to assess available models for their applicability to the flame stabilization problem.

Theories for Liftoff Behavior:

Premixedness model of Vanquickenborne and van Tiggelen:[17]

This model assumes that fuel and air are completely premixed at the base of a lifted flame. The experimental results of Figs. 1 and 2 show clearly that this is not the case. In fact, the most probable flame locations lie at radial positions for which the flow is highly intermittent. This means that during a large fraction of the time it is impossible for a turbulent flame to propagate in the upstream direction against the time-averaged velocity field.

The value of U_l at the base of the lifted flame is assumed to equal S_t. If this is true, S_t must obey the expression for U_l given by Eq. (5). It is immediately obvious that this result is inconsistent with Eq. (1) which requires that the local value of U_l be linearly proportional to $(S_b)_{max}$.

The premixedness model[1-3] provides estimates for S_t which agree well with those observed in premixed fuel and air mixtures.[20,21] However, it should be noted that the turbulence properties which are utilized to calculate Re_t have not been corrected for the intermittency of the flow. In fact, values of the turbulence intensity and microlength scale which are used for the calculation of Re_t are expected to differ significantly from those characteristic of the periods during which combustible fuel-air mixtures are present.

It is concluded that the premixedness model does not incorporate the true physical behavior of the turbulent flow fields and fails to predict the correct experimental dependence of h on $(S_b)_{max}$. Perhaps this theory could be improved by incorporating large scale turbulent structures and allowing for both radial and axial turbulent flame propagation through regions of the flow which fall within the flammability limits.

Laminar Flamelet Model of Peters and Williams:[9-11]

One of the fundamental arguments[9,10] used to justify this model of flame stabilization is that no substantial molecular premixing of fuel and air occurs for positions upstream of the combustion region. This conclusion has been questioned by several authors,[4-6] and, in fact, the concentration measurements of Fig. 2 indicate that substantial premixing of fuel and air does take place. A model based solely on the laminar flamelet concept cannot adequately describe the physical processes responsible for flame stability.

The model developed by Peters[11] to treat the partially-premixed diffusion flame seems to be more appropriate. Unfortunately, this model has not been developed sufficiently to test predictions for lift off behavior. It does seem clear however, that large scale turbulent structure behavior should be included in future developments of this model since intermittency behavior, localization of combustible mixtures, and variation of the cross correlation of the scalar and scalar dissipation will be extremely important.

Eddy Dissipation Concept Model of Byggstøyl and Magnussen:[12]

Many of the comments made for the extinction model of Peters and Williams also apply for the application of the EDC model.[12] The model assumes that the fuel and air are essentially premixed at the base of the flame and does not incorporate the actual large scale structure of the turbulent flow field. In testing their model,[12] the k-ϵ model was used to calculate the fine structure time scales. Since the flow fields are highly intermittent at the radial positions where stabilization occurs, conditionally-averaged values should be utilized. Presumably, these are not available from the k-ϵ calculations.

At the present time insufficient experimental information is available to allow predictions of this model to be compared with experiments for a wide range of experimental conditions.

Large Scale Mixing Model of Broadwell et al.:[13]

It has been demonstrated[14,15] that attempts to expand this model to liftoff leads to predictions which are inconsistent with experimental findings. This failure may be attributable to assumptions concerning τ_m. Interestingly, if one assumes that τ_m ~

r_ϵ/U_m, the resulting expression for h as a function of U_o has the experimentally observed dependencies on d_o, R_ρ, and $(S_b)_{max}$. At the same time, it is clear that the original expression for τ_m suggested by Broadwell et al. is a good estimate for the average mixing time and there is no sound reason to utilize another form of τ_m within the framework of their model.

As discussed earlier, it can be argued[16] that τ_m is not the appropriate mixing time and that the value which should be utilized is the mixing time of reentrained hot products at the upstream edges of the large scale structures. Unfortunately, no experiments or theoretical treatments are available for such a mixing time.

As is the case for the other extinction models which have been proposed, it is concluded that this model does not incorporate the physical processes which are actually responsible for flame stabilization. Additional experimental information is required before a reliable test of the general model is possible.

Blowout:

Premixedness model of Vanquickenborne and van Tiggelen:[17]

This model has been used widely and is supported by a large number of groups.[1,8,12,17] Unfortunately, it is susceptible to the same criticisms as the corresponding model for liftoff—namely, a totally premixed fuel and air mixture is assumed and the predicted linear dependence of blowout velocity on $(S_b)_{max}$ is not consistent with the experimental observations.

Large Scale Mixing Model of Broadwell et al.:[13]

This blowout is the only flame stabilization model which leads to predictions of $(U_o)_b$ which are in excellent agreement with experimental results. In particular, the observed dependence on $(S_b)^2_{max}$ is incorporated correctly. However, the model suffers from the need to make the ad hoc assumption[13] that blowout occurs at a constant fraction of the flame length. The failure of the model to correctly predict the heights of lifted flames is also troubling.

The suggestion[16] that blowout may result from the intermittency of the unignited flow provides a plausible explanation and leads to the same correlation for blowout as derived by Broadwell et al.[13] However, there are no experimental results reported in the literature which suggest that such a mechanism is operative.

Conclusions

The present understanding of flame stabilization in turbulent jet diffusion flames must be characterized as poor. This is true despite the fact that experimental behaviors are fairly well-characterized, and relatively simple correlation and empirical calculational procedures are available which accurately predict h and $(U_o)_b$ in terms of such system properties as U_o, $(S_b)_{max}$, d_o, and R_ρ. Many different and competing models for liftoff behavior and blowout have appeared. All of these models have severe limitations which suggest new approaches are required in order to adequately incorporate the physical processes responsible for flame stabilization.

In this paper it has been assumed that an improved understanding of flame stabilization is possible if all of the relevant experimental findings are considered. The immediate effect of this approach has been to demonstrate that no satisfactory models currently exist. It is hoped, however, that the analyses provided herein will serve as the groundwork and impetus for new experiments and theoretical treatments which will lead to an improved understanding of this interesting and important problem.

REFERENCES

1. HALL, L., HORCH, K., AND GÜNTHER, R.: Brennst.-Wärme-Kraft 32, 26 (1980).
2. GÜNTHER, R., HORCH, K., AND LENZE, B.: First Specialist Meeting (International) of the Combustion Institute, p. 117, The Combustion Institute, 1981.
3. KALGHATGI, G. T.: Comb. Sci. Tech. 41, 17 (1984).
4. EICKHOFF, H., LENZE, B., AND LEUCKEL, W.: Twentieth Symposium (International) on Combustion, p. 311, The Combustion Institute, 1985.
5. SOBIESIAK, A. AND BRZUSTOWSKI, T. A.: Some Characteristics of the Stabilization Region of Lifted Turbulent Jet Diffusion Flames. Abstract for paper presented at the 1984 Fall Technical Meeting, Eastern Section, The Combustion Institute, Clearwater Beach, FL, December 1984.
6. SOBIESIAK, A. AND BRZUSTOWSKI, T. A.: On the Structure of the Stabilization Region of Lifted Turbulent Diffusion Flames. Abstract for paper presented at the 1986 Spring Meeting, Western States Section, The Combustion Institute, Banff, Canada, April 1986.
7. SAVAS, Ö. AND GOLLAHALLI, S. R.: AIAA J. 24, 1137 (1986).
8. KALGHATGI, G. T.: Comb. Sci. Tech. 26, 233 (1981).
9. PETERS, N. AND WILLIAMS, F. A.: AIAA J. 21, 423 (1983).
10. JANICKA, J. AND PETERS, N.: Nineteenth Symposium (International) on Combustion, p. 367, The Combustion Institute, 1983.
11. PETERS, N.: Twentieth Symposium (Interna-

tional) on Combustion, p. 353, The Combustion Institute, 1985.
12. BYGGSTØYL, S. AND MAGNUSSEN, B. F.: Turbulent Shear Flows 4 (L. J. S. BRADBURY *et al.*, Eds.) p. 381, Springer, 1985.
13. BROADWELL, J. E., DAHM, W. J. A., AND MUNGAL, M. G.: Twentieth Symposium (International) on Combustion, p. 303, The Combustion Institute, 1985.
14. PITTS, W. M.: Proceedings of the 1987 ASME/JSME Thermal Engineering Joint Conference (P. J. MARTO AND I. TANASAWA, Eds.), Vol. 1, p. 123, The American Society of Mechanical Engineers, 1987.
15. PITTS, W. M.: Importance of Isothermal Mixing Processes to the Understanding of Lift-Off and Blow Out of Turbulent Jet Diffusion Flames, accepted for publication in Combustion and Flame.
16. PITTS, W. M.: Role of Large Scale Turbulent Structures in the Lift-Off and Blow Out of Turbulent Jet Diffusion Flames. Abstract for paper presented at the combined Eastern Section, Combustion Institute and Annual Conference on Fire Research Meetings, Gaithersburg, MD, November, 1987.
17. VANQUICKENBORNE, L. AND VAN TIGGELEN, A.: Comb. Flame 10, 59 (1966).
18. WOHL, K., KAPP, N. M., AND GAZLEY, C.: Third Symposium on Combustion, Flame, and Explosion Phenomena, p. 3, Williams and Wilkins, 1949.
19. SCHOLEFIELD, D. A. AND GARSIDE, J. E.: Third Symposium on Combustion, Flame, and Explosion Phenomena, p. 102, Williams and Wilkins, 1949.
20. ANDREWS, G. E., BRADLEY, D., AND LWAKABAMBA: Comb. Flame 24, 285 (1975).
21. SMITH, K. O. AND GOULDIN, F. C.: AIAA J. 17, 1243 (1979).
22. PETERS, N.: Prog. Energy Comb. Sci. 10, 319 (1984).
23. NAMAZIAN, M., SCHEFER, R. W., AND KELLY, J.: Scalar Dissipation Measurements in the Developing Region of a Jet, Sandia National Laboratories Report Sand 87-8652, 1987.
22. PETERS, N.: Prog. Energy Combust. Sci. 10, 319 (1984).
23. NAMAZIAN, M., SCHEFER, R. W., AND KELLY, J.: Scalar Dissipation Measurements in the Developing Region of a Jet, Sandia National Laboratories Report Sand 87-8652, 1987.
24. CHEN, C. J. AND RODI, W.: Vertical Turbulent Buoyant Jets—A Review of Experimental Data, Pergamon, 1980.
25. PITTS, W. M.: Effects of Global Density and Reynolds Number Variations on Mixing in Turbulent, Axisymmetric Jets, National Bureau of Standards Internal Report NBSIR 86-3340 (NTIS PB87-199956/AS) (1986).
26. RICOU, F. P. AND SPALDING, D. B.: J. Fluid Mech. 11, 21 (1961).
27. CHEVRAY, R. AND TUTU, N. K.: J. Fluid Mech. 88, 133 (1978).
28. CHEVRAY, R.: Prog. Energy Comb. Sci. 8, 303 (1982).
29. DAHM, W. J. A. AND DIMOTAKIS, P. E.: AIAA J. 25, 1216 (1987).
30. PITTS, W. M.: Proceedings of the Fifth International Congress on Applications of Lasers and Electro-Optics, Flow and Particle Diagnostics, p. 7, The Laser Institute, 1986.
31. LEWIS, B. AND VON ELBE, G.: Combustion, Flames, and Explosions of Gases, 3rd Ed., Academic, 1987.