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CHARACTERISTICS OF LIFTED FLAMES IN NONPREMIXED TURBULENT CONFINED JETS

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Characteristics of lifted flames in nonpremixed jets were studied experimentally with emphasis on the effects of the entrained flow field which was varied by placing a plate near the nozzle and by confining the jet. Results show that lifted flame behavior in a confined jet is drastically different from that of a free jet. In the confined jet, the liftoff height is linearly proportional to the nozzle diameter and the flow velocity, while the liftoff height is independent of the nozzle diameter in the free jet. The ratio of the liftoff height at blowout to the nozzle diameter maintains a near-constant value of 50 for both the free and confined jets. The blowout velocity is linearly proportional to the nozzle diameter in the free jet, whereas it is independent of the nozzle diameter in the confined jet. The jet velocity at liftoff maintains a near-constant value for the free jet, while the liftoff velocity decreases with the increase in the nozzle diameter for the confined jet. The blockage effect of the plate near the nozzle exit systematically reduces the liftoff height, and a criterion is proposed to include such an effect in interpreting liftoff behavior.

Introduction

Nonpremixed jet flames are one of the important topics related to the design of practical combustion systems such as furnaces and gas turbines. Lifted flame behavior and blowout characteristics are especially interesting phenomena with regard to flame stabilization. There are several competing theories for explaining lifted flame behavior in turbulent nonpremixed jets, including theories based on the propagation of turbulent premixed flames for the lifted flame anchoring [1–3], on the large scale turbulence [4–6], and on the extinction of laminar diffusion flamelets [7,8]. In laminar nonpremixed jets, the premixed flame nature as a result of the existence of a tribrachial flame at the lifted flame base is found to be the anchoring mechanism [9,10].

For turbulent nonpremixed jets, extensive experimental studies revealed that the liftoff height is linearly proportional to the nozzle exit velocity. The effect of nozzle diameter, however, has not been clearly demonstrated. Some studies suggested independence of the liftoff height from nozzle diameter [2,6], while others suggested a dependence on nozzle diameter [4,8,10].

The theories mentioned above suggested the importance of the hydrodynamic flow field on the anchoring of lifted flames in a turbulent nonpremixed jet. It is found that the region between the nozzle exit and the base of the lifted flame is minimally influenced by the flame [10,11]. This means that this region can be treated as a cold jet because the influence of the premixed flame on the upstream flow is limited to a distance of the order of 1 mm in laminar flames, or the turbulent flame thickness in turbulent flames, both of which are much smaller than the typical liftoff height. Recognizing the importance of the hydrodynamic flow field, well-controlled experiments are needed to clarify its effect on the characteristics of lifted flames.

The present study, thus, focuses on the effect of the flow field on liftoff height. The nozzle exit condition was maintained as a fully developed pipe flow, and the flow field surrounding the nozzle was systematically varied. First, we investigated the role of near-nozzle flow by placing a plate near the nozzle exit. This inhibits the axial entrainment of air from upstream of the nozzle. Second, the influence of jet confinement, which prohibits radial entrainment along the axis of the jet, was investigated. The study of jet flames with a confinement wall can not only clarify the effect of the flow field on lifted nonpremixed flames but also has intrinsic importance since jet flames are bounded by combustor walls in most practical burner systems. Unique features of the lifted flames in the confined jet are reported, and differences from the free jet are discussed.

Experiment

The experimental setup consisted of a nozzle, a flow control system, and a measurement setup. The nozzles were made of stainless-steel tubes with inner diameter d of 0.84, 1.62, 2.10, and 2.58 mm, with a thickness of 0.13, 0.19, 0.20, and 0.16 mm, respec-

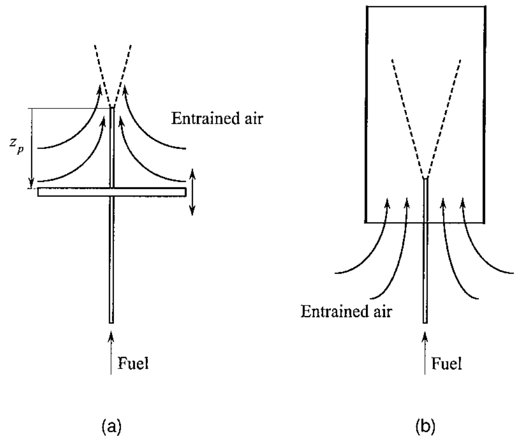

FIG. 1. Schematic showing the experimental conditions to control (a) near-nozzle flow field and (b) jet confinement.

tively. To achieve a fully developed velocity profile at the nozzle exit for all experimental conditions, the nozzle length used were 70 cm.

To study the effect of the flow field near the nozzle exit on the liftoff height, a circular plate with a diameter of 36 cm was placed near the nozzle exit, as shown in Fig. 1a. The distance from the nozzle exit to the plate z_p was varied from 0 to 50 cm, where z_p was measured upstream from the nozzle exit.

A circular cylinder with the diameter D was placed around the nozzle to investigate the effects of jet confinement on liftoff height (Fig. 1b). The lengths of the cylinders were 150 cm and the nozzles protruded 35 cm beyond the base of the cylinder. The cylinder diameters tested were D = 30, 40, 50, 75, and 100 cm.

The fuel was C.P. grade propane (>99%). Mass flow controllers (Datametrics, 825) and sonic nozzles which were used for flow rate control were calibrated with a wet-test gas meter. Liftoff heights were measured with a cathetometer. To minimize the outside disturbance, a 2 m × 2 m × 2 m housing having mesh on each side enclosed the nozzle and cylinder assembly.

Results and Discussion

To obtain basic liftoff height data, we first investigated liftoff heights in the free jets. These tests were conducted with a minimum distance to the laboratory wall of 3 m. Figure 2 shows the results together with data reported previously [2,8]. The present results show that in the range of d = 0.84 to 2.58 mm, the liftoff height is independent of the nozzle diameter and is linearly proportional to the nozzle exit mean velocity U_0. This data can be fit to

$$H_{\mathrm{L}} = -0.01663 + 0.002245\ U_0$$

where H_{L} is in meters and U_0 in meters per second. The correlation coefficient R is 0.993. The data for larger nozzle diameters up to d = 8.3 mm [2,8] agree well with the present linear dependence on U_0. Although, Røkke et al. [8] observed a weak dependence on the nozzle diameter, the overall liftoff data in the diameter range of 0.84 to 8.3 mm in Fig. 2 demonstrate the independence of the liftoff height on the nozzle diameter. This is in agreement with theoretical predictions [2,6]. The scatter of the data can be attributed to several factors such as differences in the jet flow field. This is elaborated in the following.

Effect of the Near-Nozzle Flow Field

In order to quantify the effect of the flow field near the nozzle on liftoff height, the distance be-

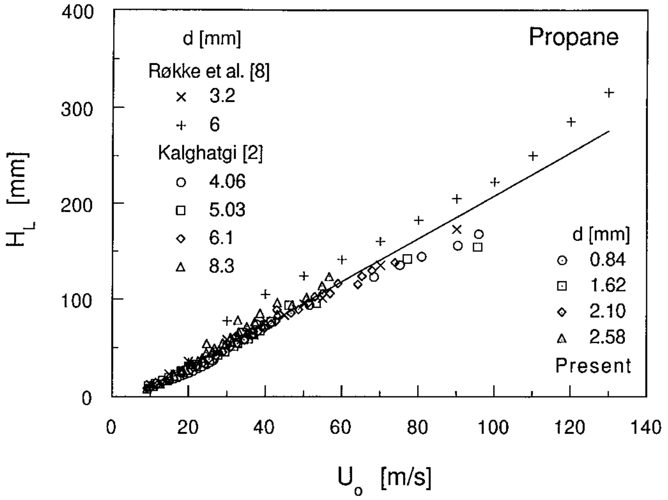

FIG. 2. Liftoff height with nozzle exit velocity in a free jet of propane fuel.

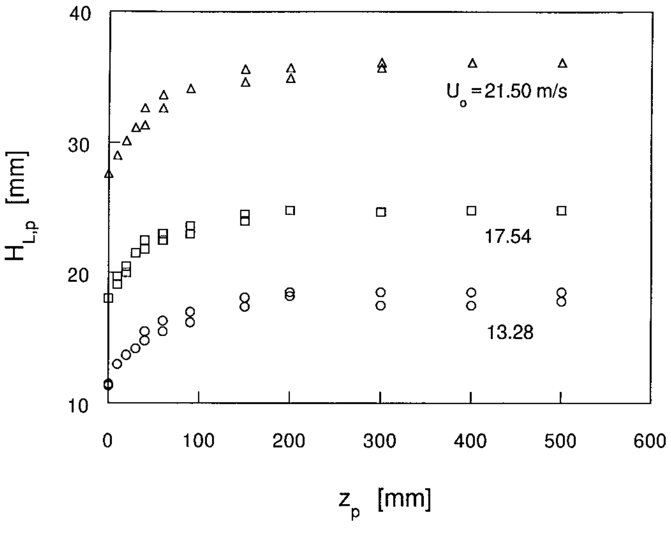

FIG. 3. Liftoff height variation with the position of the circular plate with d = 2.1 mm.

tween the nozzle exit and the circular plate is varied. The effect of a circular plate on the near-nozzle flow field is twofold. First, the circular plate prohibits axial air entrainment by the jet from upstream of the plate. Second is the effect of viscosity along the plate on the entrained air from the downstream side from the plate. In the absence of the plate, the flow field resembles that of the Squire jet [12] which allows axial entrainment of air from the upstream side of the nozzle exit. With the plate at $z_p = 0$, the flow field is close to that of a Schlichting jet [13] which allows entrainment only from the downstream side of the nozzle, with the exception that the viscous friction along the plate is not accounted for in this theory.

Figure 3 demonstrates the effect of the plate location on liftoff heights for several nozzle exit velocities. When the plate is located far upstream (large z_p), the change in the liftoff height with the plate, $H_{L,p}$, becomes negligible and approaches that of the free jet. However, when the plate approaches the nozzle exit, there is a sharp decrease in the liftoff height. The blockage effect due to the plate reduces the entrainment from upstream, and the viscous effect limits the entrainment near the nozzle. As a result, the amount of entrained air near the nozzle exit is reduced because of the plate [14]. The jet boundary is then expected to experience stronger shear with the plate, leading to an increase in the turbulence intensity. The fuel/air mixture below the lifted flame base may have a higher turbulent flame propagation speed due to the increase in the turbulence intensity; thereby, the flame anchoring position moves closer to the nozzle exit compared to a flow without a plate.

In the jet flow field, the important transport mechanisms are axial convection and radial diffusion. Based on this, we have used the nondimensional parameter $(z_p/d)/Re_d$ to characterize the plate effect on the liftoff height. This represents the ratio of the axial convection time z_p/U_0 for the influence of the existence of the plate to the radial diffusion time d^2/ν, where ν is the kinematic viscosity, and Re_d is the Reynolds number defined as $U_0 d/\nu$.

Figure 4 shows $H_{L,p}/H_{L,\infty}$ as a function of $(z_p/d)/Re_d$, where the kinematic viscosity of propane is used. The experimental data for various nozzle diameters and exit velocities correlate reasonably well. From these results, it can be estimated that $(z_p/d)/Re_d$ must be larger than 0.005 in order for the liftoff height not to be influenced by the effect of the plate, with an error margin of 5%. This result implies that nozzles should protrude a large distance from a burner assembly; if not, the effect of blockage on air entrainment should be accounted for in the data interpretation. For the present experimental conditions, $(z_p/d)/Re_d$ is larger than 0.01 when the plate is not used.

Effect of Jet Confinement

Jet confinement conditions are frequently encountered in practical applications since most jet flames are surrounded by combustor walls. In a laboratory experiment, nearby walls or other equipment setups can also act as a jet confinement. To study the effect of jet confinement on liftoff height, we placed 150-cm-long cylinders with open ends over the nozzle setup.

Figure 5 shows the liftoff characteristics of the confined jets. Here, the liftoff height normalized by the nozzle diameter is plotted for various cylinder diameters. The results clearly demonstrate a nozzle diameter dependence for the liftoff heights in con-

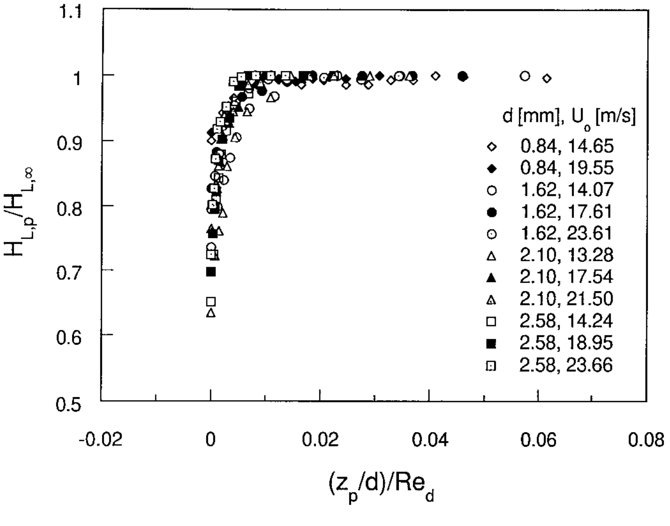

FIG. 4. Relation between dimensionless circular wall position and normalized liftoff heights.

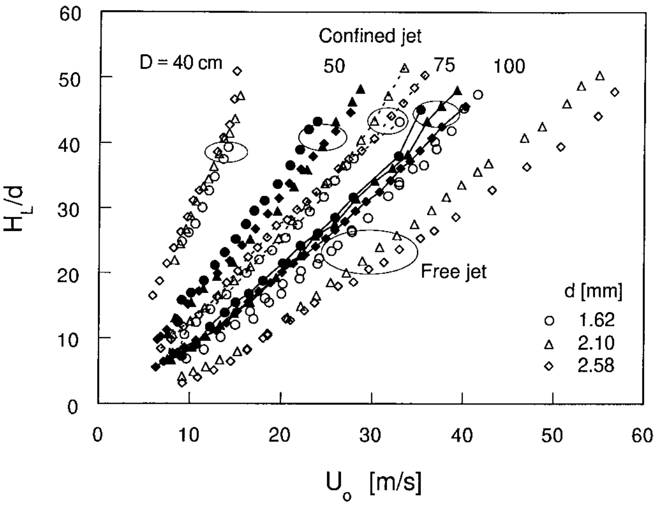

FIG. 5. Dimensionless liftoff height with nozzle exit velocity in confined jets.

fined jets. Unlike the data for free jets shown in Fig. 2 and replotted in Fig. 5, where the liftoff height is independent of nozzle diameter, the confined jets demonstrate the linear dependencies of the liftoff height on the nozzle diameter and also on the jet velocity, meaning that H_L is proportional to the Reynolds number Re_d. The maximum diameter ratio of D/d is 620 for $d = 1.62$ mm and $D = 100$ cm. This large value of the diameter ratio still influences the liftoff height behavior even though H_L is smaller than 8 cm for $d = 1.62$ mm. This implies that in order to collect meaningful liftoff data, extreme care should be used in a laboratory experiment.

We do not include the liftoff data for $d = 0.84$ mm in Fig. 5. For $D = 40$ cm and $d = 0.84$ mm, we were unable to create a stable lifted flame, since the flame blows out directly from a nozzle-attached flame. This phenomena occurs for all d when the $D = 30$ cm cylinder is used. For cylinders with $D > 40$ cm, the liftoff from the $d = 0.84$ mm nozzle undergoes a transition from laminar to turbulent flow as U_0 increases. At liftoff, which occurs over a velocity range of 10–12 m/s for $d = 0.84$ mm, Re_d is in the range of 2000–2300, and the flame lifts off to a laminar tribrachial flame structure at the flame base and undergoes transition leading to a sharp decrease in H_L. This phenomenon has been observed previously [10] and the data are not included in the figure because it is not in the turbulent regime.

Figure 5 demonstrates several interesting features. First, the slopes and values of H_L/d rapidly increase as D decreases. Second, the experimental data are bounded by $H_L/d \approx 50$ for all d and D tested. And third, the velocity at liftoff is bounded

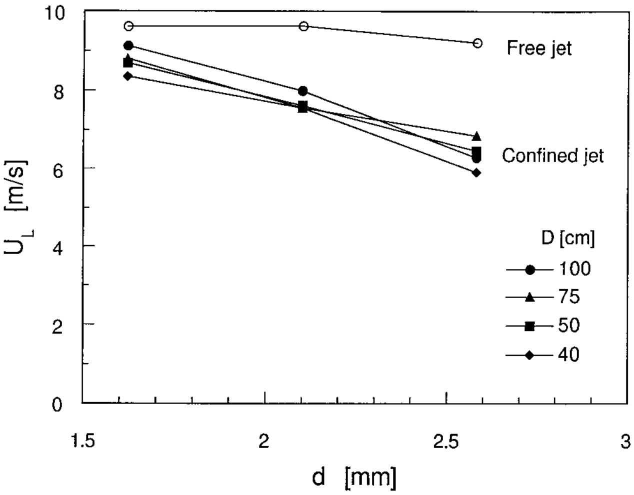

FIG. 6. Liftoff velocity with nozzle diameter in confined and free jets.

near $U_0 \approx 6$ to 10 m/s. The rapid increase in the slopes together with the boundness in U_0 and H_L/d indicates the minimum D for which turbulent lifted flames cannot exist. In this regard, we have a curve that fits the slope S of H_L/d to the hyperbolic function $S = a + b/(D - c)$. It is found that $a = 1.02$ s/m, $b = 0.0976$ s, and $c = 0.35$ m. This implies that the slope becomes infinity at $D = 35$ cm, and for smaller D, lifted flames are not expected to exist. This agrees with the experimental result that all flames blow out directly from the nozzle-attached flame when $D = 30$ cm.

Using the slopes determined above, the liftoff heights for the confined jets can be correlated as

$$\frac{H_L}{d} = U_0\left(1.02 + \frac{0.0976}{D - 0.35}\right)$$

where U_0 is in meters per second and D is in meters. This result is compared with experiment, and the agreement yields a correlation coefficient of $R = 0.978$. It is to be noted that the correlation for the confined jet indicates $H_L \propto dU_0$ as $D \rightarrow \infty$ while $H_L \propto U_0$ for the free jet.

Earlier correlations of liftoff height in nonpremixed free jets demonstrate the importance of the cold flow characteristics of jets [6,11]. In general, the entrainment of air is from both the axial and radial directions. However, radial entrainment is blocked for the confined jets by the cylinder wall. Therefore, conservation of jet mass along the axial direction should be satisfied in the confined jet, whereas jet mass conservation is not satisfied in the free jet due to continuous entrainment of air in the radial inward direction along the jet axis. Axial momentum conservation, which is obeyed for a free jet, is no longer valid for a confined jet due to friction at the boundary layer along the confinement wall.

These intrinsic differences between confined and free jets significantly alter the effect of the nozzle diameter on the liftoff height characteristics. It has been demonstrated [15,16] that the centerline velocity and the jet local diameter are influenced by the Craya-Curtet number which depends on the diameters of the nozzle and the confinement duct when there is a uniform coflow around a jet. The centerline velocity and the jet local diameter have been found crucial for the prediction of the liftoff height in a free jet [6,11] and are expected to be important in a confined jet. Very little is known concerning a confined jet without a coflow, and theoretical predictions must be studied. However, the present study clearly demonstrates the importance of boundary conditions for the jet configuration on lifted flame behavior. Extreme caution is needed to avoid such an effect and causing jet confinement in laboratory experiments.

Liftoff and Blowout Conditions

Figure 5 suggests the minimum velocity at liftoff to be about 6–10 m/s. We have plotted flame liftoff velocities in Fig. 6. The liftoff velocity U_L in the free jet is independent of the jet nozzle diameter, having a value of about 9.5 m/s where we have used nearly the same thicknesses for the nozzles. The liftoff velocity in a confined jet decreases with an increase in nozzle diameter in the range of $d < 2.58$ mm, though it is insensitive to the diameter of the confinement cylinder.

As was previously mentioned, the conservation equations that can be applied are different for the two flow systems. Thus, as long as the confinement exists, it demonstrates distinct features at liftoff. The decrease in the liftoff velocity with the nozzle diameter can be attributed to several factors. In the free jet, the entrainment occurs throughout the jet

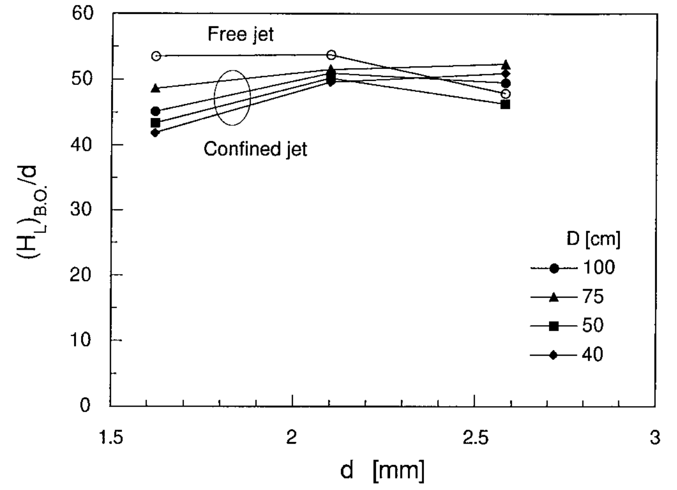

FIG. 7. Dimensionless liftoff heights with nozzle diameter at blowout.

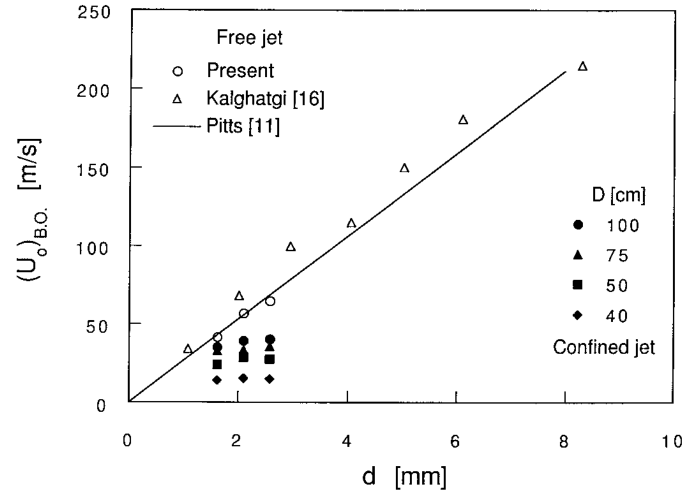

FIG. 8. Blowout velocity with nozzle diameter.

axis, thus, it is expected to be less influenced by entrainment, at least near the nozzle. On the other hand, the entrainment is restricted to the bottom area of the cylinder in the confined jet. It is conceivable that the amount of entrained air near the nozzle exit is pronounced for the confined jet compared to the free jet. This will enhance the nozzle cooling, having a tendency of promoting liftoff from a nozzle-attached flame. As the nozzle diameter is increased, the increased jet momentum, and thereby, the entrainment, is expected to promote liftoff, resulting in a decrease in U_L with the increase in d.

The increased entrainment in the confined jet could decrease the shear at the flame anchoring position near the nozzle tip, in which case, one can expect an increased liftoff velocity compared to the free jet. On the other hand, when the entrainment velocity is increased, the velocity difference between the jet and entrainment decreases. This has an adverse effect on the formation of the wake region near the nozzle tip, which enhances the tendency to lift off. These combined effects decrease the liftoff velocity in the confined jet and, subsequently, increase the liftoff height in a confined jet as compared to the free jet, even though it is difficult to single out the dominant effect at present.

The values of $(H_L)_{B.O.}/d$ are plotted in Fig. 7 for the free and confined jets for a range of D. For the free jet, these values maintain nearly constant at about 50. The results for larger nozzle diameters [17] also fall in the range of 45–52 using the relation between H_L and U_0 [11]. This can be explained as follows. The blowout condition can be conceived to occur when the centerline mean concentration reaches a near constant value [2]. This condition can be predicted from the balance of the vertical convection time $t_c = (H_L/U_0)_{B.O.}$, with the transverse diffusion time of $t_d = d^2/D_T$, where D_T is the turbulent diffusivity. Thus, from the balance between these two time scales, we have $(H_L)_{B.O.}/d \propto (U_0)_{B.O.}d/D_T$. Noting that $D_T \propto Re_d \propto U_0 d$, a constant value of $(H_L)_{B.O.}/d$ is predicted. Combining the results of $(H_L)_{B.O.}/d =$ constant, and $H_L \propto U_0$ in the free jets, one finds $(U_0)_{B.O.} \propto d$. This result is confirmed in Fig. 8.

It should be noted that in predicting the turbulent nonpremixed flame length, the balance between t_c and t_d can also be applied. However, buoyancy influences the flame length of nonpremixed jet flames, whereas the buoyancy effect is secondary in predicting the liftoff height, since the region between the nozzle exit and the base of the lifted flame can be treated as a cold jet. In this regard, it is interesting to compare the present value of $(H_L)_{B.O.}/d \sim 50$ while the flame height to diameter ratio is ~ 290 in turbulent propane jet flames [4].

Even though there is some scatter, $(H_L)_{B.O.}/d$ remains relatively constant at about 50 for the confined jets when the fluctuations in the liftoff height near blowout are accounted for. This value is in close agreement with that for the free jets. Noting that $H_L/d \propto U_0$ in a confined jet, one can expect $(U_0)_{B.O.}$ to be independent of the nozzle diameter. This is substantiated in Fig. 8. Again, detailed hydrodynamic flow field information is needed to explain the behaviors shown in Figs. 7 and 8 for confined jets.

Finally, Fig. 8 provides an estimate for the minimum distance from a burner to a confinement wall in order for a confined jet to be treated as a free jet. From the extrapolation of the blowout velocities in the confined jets to the free jets, it can be estimated that when $D/d > 800$, liftoff heights should not to be influenced by the effect of the wall.

Concluding Remarks

Characteristics of lifted flames in nonpremixed turbulent propane jets were systematically investigated experimentally with focus on the effects of near-nozzle flow and jet confinement. For free jets, the liftoff height is independent of the nozzle diameter. The ratio of the blowout height to the nozzle diameter is maintained at a constant value of about 50. Combined with the linearity of the liftoff height with flow velocity, the blowout velocity is proportional to the nozzle diameter. By placing a plate near the nozzle, the effect of a near-nozzle entrainment flow field on the liftoff height has been investigated.

Jet confinement significantly alters the lifted flame behavior. The liftoff height is linearly proportional to the nozzle diameter and the flow velocity. The ratio of the blowout height to the nozzle diameter is also maintained reasonably constant at a value of about 50. Combined with the liftoff height behavior, the blowout velocity remains independent of the nozzle diameter. Future study of the flow fields in confined jets is needed to explain lifted flame behavior in confined jets.

Acknowledgment

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COMMENTS

G. T. Kalghatgi, Shell Research Ltd., UK. About the mechanism of stabilization at the base of a lifted flame: (a) It might be possible to define a triple flame at the base of a lifted laminar flame. How would you do it for a turbulent flame? (b) The model you have developed to predict blowout implicitly assumes that at the base of the flame the mean flow velocity equals an average turbulent burning velocity. The predictions are in line with experiments. Does this not suggest that at least at large lift-off heights the assumption of a premixed flame at the base is valid?

Author's Reply. For a turbulent lifted flame base, planar imaging will be required in order to prove a tribrachial structure. The numerical and laser diagnostics results for tribrachial flames for radicals such as OH and CH do not clearly demonstrating a tribrachial structure even for laminar flames [1]. One possible way is the laser planar imaging of CH_2 [2]. It is to be noted that a smooth transition from a laminar to a turbulent lifted flame has been observed previously (Ref. 10 in paper).

The leading edge of a tribrachial flame is composed of premixed flames, thus having the characteristics of propagating upstream. Thus, the balance of a mean flow velocity with an average turbulent burning velocity can equally be applied to both the premixed flame assumption and the tribrachial flame assumption.

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A. R. Masri, The University of Sydney, Australia. You have showed results for a single fuel. How do you expect that other fuels or fuel mixture with different stoichiometric would change the correlations that you have presented?

In light of your data, can you make some comments or speculations on the prevalent mechanism of lifted flame stabilization?

Author's Reply. Factors such as fuel density, viscosity and laminar burning velocity affect the liftoff height through jet momentum [2] in the paper in free jets. For confined jets, such correlation is expected to be maintained, however, the determination of the coefficients in the liftoff height correlation with jet velocity and confinement diameter needs to be investigated.

The stabilization mechanism is conjectured to be the tribrachial flame structure: a diffusion flame, a lean premixed flame and a rich premixed flame all extending from a single location. The leading edge of a tribrachial flame has a premixed flame nature such that propagation characteristics are maintained. This propagation velocity will be influenced by flame stretch and/or flame curvature, flow redirection effects and flame interactions among these three types of flames [1,2]. It is also shown that the vortical structure in turbulent flow significantly deforms a tribrachial flame structure.

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Yung-cheng Chen, Tsing Hua University, Taiwan. In relating to the second question that Dr. Masri has asked, we have some recent experimental evidences showing that triple flame structure might be the right flame stabilization mechanism [1].

It is proposed that the stabilization mechanism is that the base of a lifted flame has a propagation velocity the same as that of the upstream unburnt mixture. However, this propagation velocity can be much higher than the laminar burning velocity of a stoichiometric plane flame. (Our data shows it can be as high as 90 cm/s for methane lifted flames.) Moreover, the propagation velocity depends strongly on the local scalar dissipation rate, as has already been shown by asymptotic analysis.

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Author's Reply. For laminar lifted flames in a nonpremixed jet, it has been demonstrated that the balance of jet velocity with a constant propagation speed of a tribrachial flame results in an excellent correlation among liftoff height, jet velocity, nozzle diameter and Schmidt number of fuel (Refs. 9 and 10 of the paper). Local scalar dissipation rate in a cold flow condition is certainly one of the important factors, however, the flow redirection effect through the interaction of gas expansion and flame curvature is also expected to be important for the stabilization of a tribrachial flame. The increase in propagation velocity for a tribrachial flame is theoretically predicted and experimentally observed previously (Refs. 1 and 2 in the Reply to Dr. A. R. Masri).