Flow Structure in Near-Nozzle Region of Gas Jet Flames

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A flow visualization study of the near-nozzle regions of a cold jet, an attached flame, and a lifted flame of propane jet exiting a contoured nozzle with uniform velocity profile in quiescent air is presented. The observed flowfields and celerities of the coherent structures in the three cases are compared. The results show that combustion reactions occur away from both jet boundary and cores of coherent structures. The presence of flame retards the growth of the coherent structures and increases their celerity substantially.

Introduction

THE interaction of flames and flow structure in combustion systems has been the subject of several investiagations in the past. Many of these studies were concerned with premixed flames. In recent years, however, considerable effort has been devoted to understand the flame/flow interaction in reacting plane shear layers[1-3] and axisymmetric gas jets.[4-7] Such studies are motivated by the necessity to understand the roles of coherent structures in the mixing rates.[8-9] This information is needed to improve the burning characteristics of diffusion flames and to develop theoretical models for their prediction. A review of the uses of coherent structures was presented recently by Coles.[10] An understanding of the detailed flow structure and its interaction with reaction zones is also crucial to unfold the stability mechanism of diffusion flames, including liftoff and blowout phenomena, which has been a topic of controversy in recent years.[11,12] Here, we present some results from a flow visualization study in the near-nozzle region of propane gas jet flames where the flowfield is essentially an axisymmetric shear layer. The results not only confirm the presence of large-scale structures in the flames but also reveal some characteristic features of their behavior in the presence of combustion. We focused our attention on the near-nozzle region in order to understand 1) the changes in flow structure of cold jets caused by the presence of a surrounding burner-attached flame, and 2) the liftoff and reattachment processes of flames.

Experimental Details

Gas jets were produced from contoured DISA calibration nozzles with high contraction ratios. The jets were almost turbulence-free and of uniform velocity profile at the nozzle exit. The nozzles were mounted on an optical table in a draft-free room and, consequently, the jets burned in nearly quiescent air. Commercial-grade propane was the fuel gas. The uniform exit velocity U was calculated from the pressure drop across the nozzle and was checked against measurements of a calibrated rotameter. Direct color, schlieren, and shadow photography were employed for flow visualization. Both a short time exposure 35-mm camera and a 16-mm high-speed motion camera were used for recording the flowfields. A high-pressure mercury-arc lamp and a 5-mW He-Ne laser were the continuous light sources, and an externally triggerable xenon-arc lamp with a minimum flash duration of 1.3 μs was the intermittent light source. The motion pictures were analyzed with a data analysis projector.

In this investigation, the flow structure of the attached flames, the lifted flames, and the corresponding cold jets near the flame reattachment condition were studied. Photography was confined to the near-nozzle region (over a distance of about 6 diameters above the nozzle) as our interest was focused on exploring the changes in flow structure that govern the flame stabilization and its hysteresis characteristics.

Results and Discussion

Figure 1 shows schlieren photographs (2.5-μs exposure time) and their schematic representations of the vertical cold jet, the attached flame, and the lifted flame over a nozzle of diameter $D = 8.74$ mm at $U = 6.91$ m/s (47:1 contraction ratio). The flow rate was maintained the same for all three conditions (Reynolds number based on jet exit conditions was about 13,000), and the transition from lifted to attached flame was achieved by physically brushing the flame. Hence, the changes in the flow structure were due to the changes in flame conditions alone. Since only one vertically placed knife edge was employed, the darkened schlieren image appears on only the right half of the photographs. Further, because of the vertical orientation of the knife edge, it was not possible to visualize the axial density gradients on the schlieren plane. However, by slightly offsetting the film plane from the true schlieren plane, through a combination of schlieren and shadowgraph images, the circumferential rings were also recorded.

The photograph of the cold jet shows features similar to those documented by Becker and Masaro[13] and Yule.[9] The formation and rolling up of eddies, their coalescence, the development of secondary instabilities and their eventual disintegration to fine-scale turbulence in these propane jets are essentially similar to those observed by other investigators in uniform density jets.

The photograph of the attached flame exhibits the following features that contrast with those of the cold jet: 1) the formation and roll-up of eddies are delayed considerably; 2) the coalescence of vortices becomes less frequent and is moved downstream, resulting in a slower growth rate of the shear layer; and 3) the secondary instabilities causing the distortion of the vortical rings are severely inhibited. These results are in conformity with the lengthening of the transition zone described by Chigier[14] and probably can be attributed mostly to the decreased density and partly to the increased viscosity of the gases (mostly combustion products) that interface the jet fluid as discussed below.

In the attached flames, Fig. 1b, the boundary of the fuel jet is inside the flame zone (reaction zone), which lies well within the schlieren boundary. The location of the reaction zone was determined by direct photography and also by temperature traverses using a Pt-Pt/Rh thermocouple (0.4-mm bead

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diameter). As the purpose of temperature traverses was only to determine the location of the reaction zone, the measurements were not corrected for conduction, radiation, and catalytic effects. However, conduction errors were minimized by aligning the leads of the thermocouple along approximately isothermal planes parallel to the flame axis. A radial temperature profile taken at $x = 26.2$ mm ($x/D = 3$) is shown in the adjacent sketch. The sharpness of the fuel jet boundary, the orderliness of the rolled-up vortices, and the physical separation of jet and reaction zone boundaries clearly indicate that combustion does not occur inside the cores of vortices. This observation agrees with the findings of Takahashi et al.[7] but contradicts the arguments of Mungal et al.[2,3] and Breidenthal,[15] who propose that chemical reaction occurs mainly in the cores of the rolled-up vortices in the shear layer. The conflict can be attributed to the differences in the reactants and their volume ratio requirements for sustained reactions. It is known that the volume rates of the interfacing fluids drawn into the rolled-up vortices are roughly equal.[16] The hydrogen-fluorine reaction used in the experiments of Mungal et al.[2,3] is spontaneous, enabling chemical reaction in the vortex cores at any equivalence ratio. However, the stoichiometric air-fuel volume ratio for propane is about 25 and the rich flammability limit ratio is 8.8, hence the mixture in the vortex core is well beyond the flammable condition and consequently cannot support combustion. Thus, the flame zone must be located radially outward from the jet surface where the mixture is flammable. Further, almost no oxygen can penetrate inward across the flame zone of attached flames and hence the mixture in the vortex core consists mainly of

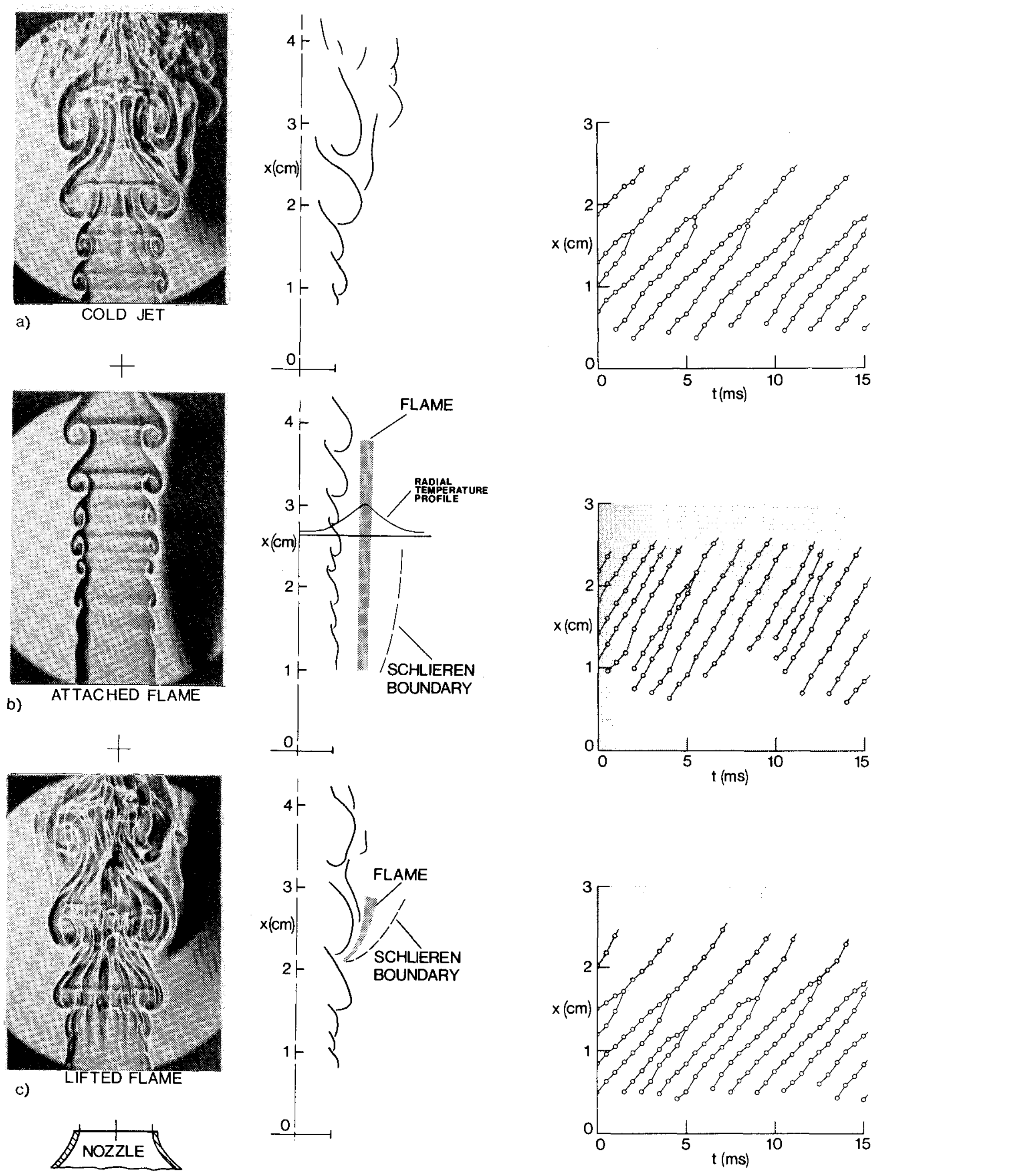

Fig. 1 Schlieren photographs (left, $U = 6.91$ m/s, 2.5-λs exposure time); schematic representations (middle); and trajectories of eddies (right, $U = 4.52$ m/s): a) in cold jet, b) attached flame, and c) lifted flame of propane in air. Shaded regions in x-t diagrams correspond to axial levels where flame is present. Nozzle diameter = 8.74 cm.

combustion products and propane. As most of the hydrocarbon fuels have stoichiometric air-fuel ratios over 10, the theoretical model of Broadwell and Breidenthal[1] proposed for mixing and chemical reactions in turbulent shear layers, which assumes reaction in the cores of the vortices, does not appear to be readily applicable for many practical combustors that use hydrocarbon gaseous fuels.

In their extensive study of the combustion/flow interactions in the transition region of a propane jet flame in a coflowing airstream, Yule et al.[6] from their schlieren pictures inferred that most of the reaction in that region occurs at or near the interfaces of the jet fluid and the outer flow. However, in our work, we found that locating the reaction surface on schlieren pictures was ambiguous and subjective. In some of our preliminary studies, in which we gradually introduced the thermocouple bead from the air side such that its tip was glowing white (indicating the location of hot reacton zone), we noticed that its image appeared considerably away from the jet interface and that the rolled-up eddies were not even perturbed by it. The radial location of the thermocouple bead, when it glowed hot, coincided with the flame region marked in the sketches in Fig. 1. The radial traverse of the thermocouple indicated approximate temperatures of 300 K on the axis of the jet, 700 K in the middle of the mixing layer, and a maximum temperature of 1950 K in the flame zone indicated in Fig. 1b. The location of the maximum temperature was displaced outward by about 3.5 mm in the region visible in Fig. 1b and thus further confirmed the presence of the reaction zone away from the mixing layer. The measurements of Yule et al.[6] also show that in the near-nozzle region ($x/D<4$), the location of the peak temperature was shifted radially outward from the location of the peak ionization current that was near jet interface. Yule et al. attribute that difference to the fluctuating nature of the inner surface causing lower mean temperatures than in the outer region, which has less fluctuations. However, if it is presumed that the reaction zone concides with the mixing layer, it is likely that the thermocouple located away from it will see a colder region for a longer time (because of the absence of flame) than the thermocouple located on the interface. Hence, the location of peak temperature in the study of Yule et al.,[6] which is in agreement with our findings, also suggests that the reaction zone does not coincide with the jet interface. That the location of the peak ionization current is closer to the fuel jet than that of the peak temperature can be traced to differences of several orders of magnitude in the equilibrium constants for dissociation and ionization reactions of fuel and air species.[17] In particular, the dissociation of hydrocarbons from carbon and hydrogen atoms and their consequent ionization of the fuel side are much more probable than ionization of nitrogen or oxygen on the air side. Hence, it is likely that the peak ionization shifts to the fuel side of the flame. Further, a comparison of the radial profiles of turbulent intensity and the mean temperature profiles by Yuel et al.[6] show that in the vicinity of the nozzle, the temperature peaks at a greater distance from the nozzle axis than the turbulence intensity and substantiates the location of the reaction zone away from the jet mixing layer.

The photograph of the lifted flame in Fig. 1c at the same flow velocity as the attached flame reveals the following: 1) the structure of the flow between the nozzle and the base of the flame (flame standoff region) is essentially akin to that of the cold jet; 2) the rolled-up eddies retain their identity and integrity for some distance even above the flame base; and 3) the flame base region is much closer to the rolled-up eddies than in the attached flame. The first point is expected because the flow in the flame standoff region is not affected by the flame except for some insignificant radiant heating. The second point is interesting and corroborates the observation that combustion does not occur inside the cores of rolled-up eddies, much as in the situation in the attached flame. The third point can be attributed to the fact that the region of flammable fuel/oxygen concentrations is brought closer to the fuel jet because of the entrainment of air into the nonreacting shear layer. The motion picture films show that the flame base tends to move upstream parallel to the convex outer edges of the eddies. When the eddies coalesce and large convex outer surfaces form, the flame base tends to follow their outer contour but does not propagate into the core. Instead, it jumps over to the convex part of the next eddy. This is further evidence that the mixture inside the cores of eddies cannot sustain combustion in the case of hydrocarbon fuels.

Figure 1 also presents sample plots of the trajectories of the visual center of eddies for cold jet, attached flame, and lifted flame at $U=4.52$ m/s for all flows. These trajectories were obtained from motion pictures made at 2000 frames/s and synchronized with the xenon strobe light (flash duration 1.3 μs). The shaded regions in these figures correspond to the regions where visible flame surrounds the propane jet. Numerous interesting points are evident in these x-t diagrams. The trajectories of eddies in the flame standoff region of lifted flames and cold jets are essentially similar. The presence of flame severely retards the coalescence of eddies. The dimensionless celerity c/U for these coherent structures has average values of 0.52 and 0.79 in cold jet and attached flames, respectively, indicating an increase of about 50% in attached flames. The celerity in the cold jet agrees well with the value of 0.55 obtained from the expression $c/U=1/(1+\sqrt{\rho_0/\rho_j}$ given by Coles[10] where ρ_0/ρ_j is the ratio of the density of the surrounding gas to that of the fuel jet. Coles,[10] formula predicts a celerity of $c/U=0.77$ for the coherent structures in the attached flames for the densities of the combustion products expected in propane flame. This value also agrees well with the observed celerity of 0.79. The spacing of eddies in cold jets remains essentially unaltered by the presence of flame, and the frequency of their generation varies in proportion to the celerity. All these observations are in conformity with the preceding discussion and substantiate the findings that the flame inhibits the development and coalescence of eddies.

Conclusions

This comparative study of the flow structure of the near-nozzle region of the cold jet, attached flame, and lifted flame of propane jet has shown that 1) the behavior of the shear layer is controlled by the flame, 2) combustion cannot be sustained within the coherent structures in the shear layer of the hydrocarbon fuel jets, and 3) the presence of flame inhibits the development and coalescence of the coherent structures and increases their celerity.

Acknowledgments

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