Structure of Propane Jet Diffusion Flame in a Cross Flow*

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An experimental study was made of the structure of the propane jet diffusion flame discharged normal to a free stream of air with a uniform velocity profile. The velocity profile in the flame was measured by application of the forward scattering LDV system. A gas chromatograph was used to measure the concentration profile of the major species in the flame. The results showed that the flame configuration were correlated well with the ratio of fuel jet to cross-flow velocity. The transition from an elliptic to a kidney shape was observed in the contour of constant velocity in the transverse cross section normal to the jet axis of the flame. A peak in the CO concentration profile was observed below the jet axis where the C_3H_8 concentration showed a maximum, and above the location at a minimum O_2 concentration. The CO_2 concentration profile had dual peaks which bore a resemblance to the temperature profile.

Key Words: Combustion, Jet Diffusion Flame, Turbulent Flame, Cross Flow, Velocity Profile, Concentration Profile

1. Introduction

A turbulent jet diffusion flame penetrating and spreading transversely into a uniform stream of fluid is of great relevance to a wide variety of engineering applications including the industrial furnace and the internal combustion engine. Understanding the combustion mechanism in such a flame and its structure would lead to the improvement of the thermal efficiency and a reduction in the undesirable pollutant emissions from those industrial facilities. A number of experimental and theoretical works were carried out on an isothermal jet entering into a cross-flow of air with the interest in solving the problems arising from fluid waste disposal, dispersion of effluents from chimney stacks, V/STOL aircraft in transition flight and the secondary air jets in gas turbine combustors^{(1)~(5)}. The ranges of parameters investigated by past researchers are large and they include jet nozzle diameter, jet incident angle, jet to cross-flow velocity

ratio, jet to cross-flow momentum flux ratio, temperature and density difference between jet and cross-flow fluid. The behavior of an isothermal jet in a cross-flow is fairly well characterized. A lot of works have also been done on the jet diffusion flame in a stagnant ambient gas and co-flowing air stream⁽⁶⁾. On the other hand, not much is known about the jet diffusion flame in a cross-flow⁽⁷⁾ which is inherently more complex than such cases as to the isothermal jet in a cross-flow or the jet diffusion flame in a stagnant ambient gas.

The primary objective of the present study is to obtain the fundamental information on the structure of a steady turbulent jet diffusion flame of propane in a cross-flow of air with a uniform velocity profile. The temperature, velocity and species concentration profiles in the flame were measured by applying a thermocouple, a laser doppler velocimeter and a gas chromatograph, respectively. A photographic observation was also done to determine the flame configuration.

2. Experimental Procedure

Figure 1 shows the schematic diagram of the experimental apparatus I which was used to measure the temperature and the velocity profiles in the flame and to determine the configuration of the flame. A steady horizontal free stream of air with a uniform velocity profile was established in the test section

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behind the outlet of an open circuit wind tunnel. As described in the previous report on the structure of a droplet-laden air jet in a cross-flow⁽⁵⁾, the dimensions of the outlet of the wind tunnel are 200 mm wide and 640 mm high. A fuel nozzle was placed 100 mm downstream from the sharp leading edge of a horizontal flat plate installed 50 mm above the bottom wall of the tunnel. The fuel nozzle consisted of dual coaxial stainless steel pipes. Propane fuel of 98% purity was allowed to issue from the exit of the inside pipe of inner diameter 2 mm. An annular space between the outside and the inside pipes of the fuel nozzle was used to discharge hydrogen at low velocity for stabilizing the flame at the fuel nozzle exit. Surplus unburned hydrogen was carried away by the cross-flow. The propane which was fed from a tank was allowed to pass through a control valve, a flow meter and a particle seeder, and to effuse from the fuel nozzle exit. The discharge of the propane jet flame was vertically upward normal to the uniform stream of air.

A laser doppler velocimeter (LDV) was provided to measure the velocity profile in the flame. The LDV optics was based on the DISA LDA03 system and set up in a forward scatter configuration. A 10-mW He-Ne laser emitting monochromatic radiation at a wavelength of 632.8 nm was provided as a light source. The beam intersection angle was 11.42 deg. and the probe volume dimensions were 0.31 mm in diameter and 3.2 mm in length with a fringe spacing of 3.2 μm . The axis of the LDV optics was in the horizontal

plane and perpendicular to the direction of cross-flow. Various velocity components were measured by rotating the beam plane. The propane jet flame was seeded with talc particles of the diameter approximately 2 μm . The particle seeder was vibrated by the application of a variable speed electric motor for stable seeding. The output electrical signal from a photomultiplier (RCA 4526) was processed with a doppler frequency tracker (DISA 55 N 20). Flame temperature was measured by applying a Pt-Pt/Rh 13% bare thermocouple of the diameter 0.1 mm. A 35-mm camera was also provided for the photographic observation to determine the flame configuration.

Figure 2 shows the schematic diagram of the experimental apparatus II which was utilized to measure the concentration profiles of major species in the flame. The flame gas was sampled with a water-cooled probe of the inner diameter 2 mm at its tip. A water trap was installed in a gas sampling line to eliminate a condensed water. The sampled gas was analyzed by applying a gas chromatograph. Molecular Sieve 13 X-S or Gaskuropack 54 was packed inside a column of the thermal conductivity detector of the gas chromatograph to detect C_3H_8 , CO, O_2 and CO_2 . The determination of the concentration of these species was based on the equations in Ref. (8). Experiments were done under the conditions: propane jet velocity $U_0 = 10 \text{ m/s} - 40 \text{ m/s}$; cross-flow velocity $U_\infty = 1.1 \text{ m/s} - 15.3 \text{ m/s}$.

3. Experimental Results

Figure 3 shows the sketch of flame and the coordi-

Fig. 1 Experimental apparatus I

Fig. 2 Experimental apparatus II

nate system as has been used most commonly in the studies on the isothermal jet in a cross flow. The inner diameter of the fuel nozzle, denoted by D , was maintained 2 mm throughout the present experiment. A system of axes, natural to the deflected flame, is determined from experimental measurements and pertinent flame quantities are described along these principal axes. X , Y and Z are the longitudinal, lateral and vertical Cartesian coordinates relative to the cross-flow with origin at the center of the fuel nozzle. The ξ -axis, called as a jet axis herein, is defined by the locus of a maximum velocity in the flame. The ζ -axis is in the transverse cross section of the flame normal to the ξ -axis intersected by the plane of symmetry in the X - Z plane. The η -axis is perpendicular to the ξ - and ζ -axes.

Figure 4 shows the location of the central axis of flame which is defined as the locus of a middle point between the top and bottom edges of the visible flame along the ζ -axis. The deflection of the central axis is rather slight at the initial stage of flame development. The flame subjected to the influence of the drag force exerted by the cross-flow is bent over and changes gradually its direction horizontally as the flame loses the axial momentum far downstream. It is evident that an increase in cross-flow velocity causes the enhanced deflection of the central axis. A generalized form of the expression for the location of the central axis of flame is shown in Fig. 5. The ratio of the fuel jet velocity at the nozzle exit to the cross flow velocity is called as the velocity ratio α defined by the following equation.

$$\alpha = \frac{U_0}{U_\infty} \quad (1)$$

The measured results represented by the dots in Fig. 5 are correlated well with a solid straight line expressed by

Fig. 3 Coordinate system

$$\frac{Z_c}{D} = 1.52 \alpha^{0.79} \left(\frac{X}{D} \right)^{0.39} \quad (2)$$

It is revealed that the velocity ratio is one of the important parameters controlling the location of the central axis of a flame in a cross-flow. The location of the central axis of an isothermal air jet in a cross-flow is given by

$$\frac{Z_c}{D} = 2.05 \alpha^{0.72} \left(\frac{X}{D} \right)^{0.28} \quad (3)$$

Comparison between Eq. (2) and Eq. (3) indicates that the propane jet diffusion flame in a cross-flow studied in the present experiment is less deflected than the isothermal air jet.

Figure 6 demonstrates the flame thickness which is defined as the length between the top and bottom edges of the visible flame on the ζ -axis. It is apparent that the flame thickness shows a maximum as a function of a downstream distance along the jet axis. An increased velocity ratio causes an increase in the flame thickness and the downstream distance at a maximum flame thickness. Figure 7 shows the effect of the velocity ratio on the maximum flame thickness

Fig. 4 Central axis location

Fig. 5 Central axis location

as well as the maximum flame width which is defined as the maximum length of the visible flame along the η -axis. Both of them increase almost linearly with an increase in the velocity ratio. From the results shown in Figs. 5, 6 and 7, it is concluded that the flame configuration is largely dependent on the velocity ratio.

Figure 8 gives the profile of the axial component of the time-averaged velocity in the transverse cross section of the flame. It is noted that the jet axis is located a little above the central axis which corresponds to the point C on the ζ -axis. The contour of constant velocity, as typical in the case of 2.5 m/s, is nearly of a vertically elongated elliptic shape at $\xi/D=38$ and $\xi/D=54$. A small cavity appears in the bottom of the contour at $\xi/D=81$ implying the transition to the kidney shape of the velocity profile. Figure 9

demonstrates the contour of constant velocity in an unburned propane jet in a cross-flow at the same conditions of jet and cross-flow velocities as in Fig. 8. A kidney shape appears already at $\xi/D=54$. It is also noted that the unburned propane jet has lower velocity than the jet flame at the same downstream distance.

Figure 10 gives the isotherm in the same transverse cross section as in Fig. 8. At $\xi/D=38$ and $\xi/D=54$, a low-temperature region is observed near the jet axis, which is likely to be caused by the flow of the unburned fuel. It disappears at $\xi/D=81$, implying the complete consumption of fuel. The isotherm near the maximum temperature region formed below the central axis is of an inverse kidney shape at $\xi/D=38$ and $\xi/D=54$, and becomes to be of a kidney shape at $\xi/D=81$.

Figure 11 shows the contour of constant concen-

Fig. 6 Flame thickness

Fig. 7 Maximum flame width and thickness

Fig. 8 Contour of constant velocity

tration of C_3H_8 , CO , O_2 and CO_2 in terms of mole fraction in the transverse cross section at $\xi/D=54$. The C_3H_8 concentration (X_f) shows a maximum at the jet axis. The CO concentration profile (X_{CO}) is nearly of concentric circle with its center at the central axis of the flame. The O_2 concentration (X_{O_2}) has a minimum at a location below the central axis and shows an inverse kidney shape. The CO_2 concentration (X_{CO_2}) has dual peaks and shows a maximum below the central axis. This bears a resemblance to the isotherm as shown in Fig. 10.

Figure 12 gives a simultaneous demonstration of the profiles of velocity, temperature and species concentration along the ζ -axis at $\xi/D=38, 54$ and 81 . It is evident that the peaks in the C_3H_8 concentration and the velocity profiles are observed near the jet axis at

Fig. 9 Contour of constant velocity (isothermal propane jet)

Fig. 10 Isotherm

$\xi/D=38$ and 54 . No C_3H_8 is observed at $\xi/D=81$ as presumed previously. A maximum CO and a minimum O_2 concentrations appear in turn toward the bottom edge of the flame, namely, the left-hand side of Fig. 12. As typically shown in the results at $\xi/D=54$, both the temperature and the CO_2 concentration profiles have dual peaks. Figure 13 shows the axial profiles of velocity, temperature and species concentrations. The C_3H_8 concentration decreases with an increase in a downstream distance approaching zero at $\xi/D \approx 60$ where a maximum CO and a minimum O_2 concentrations are observed. The CO_2 concentration and the flame temperature increase monotonously along the jet axis.

On the basis of the facts found in the present experiment, the essential feature of the turbulent jet diffusion flame in a cross-flow would be characterized as follows. The flame subjected to the drag force exerted by the cross-flow is bent over and changes gradually its direction toward downstream. In the periphery of the flame, the mean velocity is much lower than in either flame or cross-flow and a pair of attached vortices are likely to be formed in the wake of the flame, exactly as found in an air jet in a cross-flow. This results in the formation of a well-mixed region in the wake of the flame, where chemical reaction proceeds very actively and consequently the flame temperature is rather high. An increased cross-flow velocity, in other words, a reduced velocity ratio causes the deflection of the jet axis more remarkable. This also results in an enhanced mixing of fuel and air, and hence an increased rate of chemical reaction leading to a decrease in flame size and the prevalence of the nonluminous region. Compared with the unbur-

Fig. 11 Contours of constant concentration

Fig. 12 Profiles of concentration, temperature and velocity along ζ -axis

Fig. 13 Profiles of concentration, temperature and velocity along ξ -axis

ned propane jet, the jet flame has relatively high axial velocity resultant from the heat release in it. This is equivalent to a substantial increase in a velocity ratio which causes less deflection of the flame and an increase in the downstream distance at the first appearance of the kidney shape of velocity profile.

4. Conclusions

An experimental study was made of the structure of the propane jet diffusion flame discharged normal to a free stream of air with a uniform velocity profile. The velocity profile in the flame was measured by application of the forward scattering LDV system. A gas chromatograph was used to measure the concentration profile of the major species in the flame. The flame temperature measurement and the photographic observation of the flame were also done.

The primary conclusions reached in the present study are as follows.

- (1) The flame configuration is largely dependent on the ratio of fuel jet to cross-flow velocity.
- (2) The central axis of the flame is correlated with Eq. (2) and is located a little below the jet axis of the flame.
- (3) The contour of constant velocity in the transverse cross section normal to the jet axis is nearly of a vertically elongated elliptic shape at the initial stage of the flame development and shows a sign of the appearance of a kidney shape downstream. The first appearance of a kidney-shaped velocity profile in a flame occurs further downstream than in an unburned

fuel jet.

(4) Isotherms in the same cross section as the above also show a kidney shape around a high-temperature region which is located below the central axis of the flame. Dual peaks are observed in the temperature profile.

(5) In the transverse cross section of the flame, the C_3H_8 concentration shows a peak at the jet axis and maximum CO and minimum O_2 concentrations appear in turn toward the bottom edge of the flame. The CO_2 concentration profile has dual peaks similar to the temperature profile.

(6) The C_3H_8 concentration decreases with an increase in the downstream distance approaching zero near the location where a maximum CO and minimum O_2 concentrations are observed. The CO_2 concentration and the flame temperature increase monotonously downstream along the jet axis.

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