ABSTRACT
An experimental study of the stability and structure of a propane gas jet flame in cross-flow at a low jet to cross-flow momentum flux ratio (0.024) is presented. The flame structure is characterized by two distinct zones. A two-dimensional flow recirculation zone attached to the burner tube in its wake forms the first zone. An axisymmetric flow follows the first zone downstream. The junction of the two zones is characterized by an intense mixing of jet and cross-flow streams. This paper deals with the structure of the first zone. The temperature and concentration profiles show that the physico-chemical processes and combustion in that zone are diffusion controlled.

NOMENCLATURE
\(d\) Jet exit diameter
\(J\) Jet to cross-flow momentum flux ratio
\(M\) Momentum flux
\(MW\) Molecular weight
\(P\) Pressure
\(Re\) Reynolds number
\(T\) Temperature
\(U\) Velocity
\(x\) Cross-stream coordinate
\(X\) Mole fraction
\(y\) Vertical coordinate
\(z\) Transverse coordinate
\(\rho\) Density

subscripts
\(j\) jet fluid
\(l\) species
\(\infty\) cross-stream

INTRODUCTION
A turbulent gas jet flame subjected to an air stream flowing perpendicular to its axis has been shown to be stable over a wide range of operating conditions (Gollahalli et al. 1975). Turn-down ratios of the order of 1000 have been proposed for the burners operating in cross-flow environments. Hence, a concept of exploiting the interaction of intersecting flows appears attractive in designing burners for gas turbine operation. Because of intense mixing that occurs at the base region of the flame, a turbulent gas flame in cross-flow (TGFCF) has been shown to produce shorter flames and reduce soot production as well as flame radiation emission, which features are attractive for gas turbine combustion chambers. A number of studies on the characteristics of TGFCF have appeared in the literature (Rao and Brzustowski, 1982; Kalghatgi, 1983; Birch et al., 1989; Askari, et. al, 1990; Ellzey, et al., 1990; Iiung et al., 1992). Most of these studies, however, have been conducted at a value of jet to cross-flow momentum flux ratio, \(J = (p_j U_j^2)/(p_{\infty} U_{\infty}^2)\), much greater than unity. At very low turn-down ratios, such as those that exist during low load operation of gas turbines, it is conceivable that this momentum flux ratio would be less than unity. A previous study (Gollahalli et al., 1975) has shown...
that the flame structure of the TGFCF at a momentum flux ratio less than unity is substantially different from the structure at a momentum flux ratio greater than unity. A recirculation zone stabilized in the wake of the burner has been shown to be the dominant feature of the TGFCF at low momentum flux ratios. Also, at some conditions a two zone structure has been noticed in these flames (Huang, 1993). The recirculation zone, which is primarily responsible for the enhanced flame stability, also increases the residence time of reactive gases in the vortex cores and consequently could affect the emission of pollutants. This study, therefore, is aimed at the pollutant concentration field (NOx and CO) in a TGFCF at momentum flux ratios less than unity. Attention is focused on the structure of the near-burner region where recirculation is dominant.

An electronic differential pressure manometer (barocell) in conjunction with a pilot tube was used to measure the fuel jet velocity. The volume flow rate of the fuel exiting the burner tube was measured with a calibrated rotameter. A chromel-alumel (type K) thermocouple with a hot junction diameter of 0.25 mm was used to measure flame temperature. Thermocouple was inserted through a two-holed ceramic tube which was housed in a stainless steel tube. Thermocouple was inserted through a hole in the top sliding plate of the tunnel.
The output of thermocouples was measured with a recorder. Color photographs of the flame were taken with a panchromatic film for recording geometrical features of the flame and to measure flame length.

A water-cooled stainless steel tube (0.75 mm ID) was used for drawing gas samples from the flame. The probe was connected to various analytical instruments with flexible teflon tubing. Fiber filters were used to remove particulate matter in the gas samples and ice-chilled water traps were used to remove moisture. The sampling probe was mounted on a three dimensional traversing mechanism capable of a space resolution of 0.25 mm. The volumetric concentrations of CO and CO₂ were measured with nondispersive infrared analyzers. The volumetric concentration of O₂ and NO were measured with a polarographic analyzer and a chemiluminescent analyzer respectively. The analytical instruments were calibrated with standard gas mixtures of the specific gas in nitrogen (3% CO₂, 1.69% CO, 21% O₂, and 510 ppm of NO) frequently.

Table 1
Experimental Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burner diameter (ID)</td>
<td>0.467 cm</td>
</tr>
<tr>
<td>Fuel</td>
<td>Propane</td>
</tr>
<tr>
<td>Fuel MW</td>
<td>44</td>
</tr>
<tr>
<td>Fuel Density (@ T=25°C, P=730 torr)</td>
<td>0.00175 kg/liter</td>
</tr>
<tr>
<td>Cross flow vel. U∞</td>
<td>95.1 kl/liter</td>
</tr>
<tr>
<td>Fuel jet exit vel. UJ</td>
<td>5.6 m/s</td>
</tr>
<tr>
<td>Jet Reynolds number Rej</td>
<td>735 and 1931*</td>
</tr>
<tr>
<td>Velocity ratio UJ/U∞</td>
<td>0.13 and 0.34*</td>
</tr>
<tr>
<td>Momentum flux ratio Mj/M∞</td>
<td>0.024 and 0.17*</td>
</tr>
<tr>
<td>Density of Air (@ T=25°C, P=730 torr)</td>
<td>1.2 kg/m³*</td>
</tr>
</tbody>
</table>

* For conditions 1 and 2 respectively

Table 1 shows the summary of experimental conditions. Some experiments were repeated 5 to 6 times to estimate the measure of uncertainty in results. The maximum uncertainty levels at 95% confidence level in temperature, XNO, XCO₂, XCO were estimated to be within 2%, 3%, 5%, and 5% of the reported values.

RESULTS AND DISCUSSION

Flame Configuration and Stability

Figure 3 shows the outlines traced from color photographs (exposure time=one second) of the propane flame at different jet to cross flow momentum flux ratios. At J=0.27, when the flame bent enough to just reside entirely below the exit plane of the burner, the flame exhibited a clearly distinct two-zone structure. A luminous yellow flame was seen to attach to the lee side of the burner tube and the attachment length extended to about 20 d below the burner exit plane. This zone was dominated by the burning of soot particles. Soot deposit was seen to build up on the burner tube on its lee side at this value of momentum flux ratio. A dark zone was noticed for about 2 d immediately below the burner exit on the lee side. Fuel heating and pyrolysis were probably occurring in this region. These two regions correspond to a planar diffusion flame formed by the fuel entering the recirculation region and the cross-flow wind stream. In fact, a view from the top indicated that there were two planar flame sheets in the x-y plane located at the interfaces of fuel in the wake of the burner tube and air from the cross-flow stream. Huang (1993) also reports this feature in a separate study. A long axisymmetric flame followed this planar flame in the downstream direction. The tail of this zone was luminous yellow in color. The region near the junction of these two regions, where a transition from a planar flame to round cross-section flame occurred, was intense blue indicating large air entrainment into this region and the dominance of gas-phase reactions. As the momentum flux ratio, J, was reduced by decreasing UJ the planar flame zone became larger in size and more luminous. The axisymmetric flame zone became narrower,
shorter, and more bluish. Fig. 3b shows the outline of the flame traced from a color photograph (exposure time = one second) at \( \text{J}=0.11 \). When \( \text{J} \) was further decreased, the axisymmetric flame became extinct and all the burning and heat release occurred in the planar flame zone. When \( \text{J} \) was decreased further, the size of this zone decreased. However, even at a very low momentum flux ratio of 0.01, (Fig. 3c) a small flame resided in the wake of the burner tube. The flame eventually extinguished when the fuel flow rate was reduced to such a low value that the fuel diffused into the cross-stream before being drawn into the wake of the burner tube. Hence, it was possible to operate the burner based on this configuration over a very wide turn-down ratio. In this case, the ratio of \( \text{U_j} \) at which the flame bends over to reside completely below the burner exit plane to that at which the flame blew out was about 10.

Figure 4 shows the range of jet velocity from the value at which the flame was detached from the burner to the value at which the flame completely resided below the plane of the burner tube. The structure of such flames have been studied by Huang et al. (1992, 1994). The point of interest here is that the ratio of \( \text{U_j \ high} \) to \( \text{U_j \ low} \) is about 20. Combining this turn-down ratio with the turn-down ratio for the flame entirely residing below the plane of the burner exit discussed above, one can see that the turn-down ratio for the operation of a gas burner with burner attached flame would exceed 200. It was shown that flames in cross flow could be operated in the lifted condition over a turn-down ratio exceeding 5 (Gollahalli et al., 1975). Hence, the turn-down ratio for a burner operating in a cross-stream (from the highest \( \text{U_j} \) to the lowest \( \text{U_j} \) at which flame blows out) could be as high as 1000.

**Flame Structure Measurements**

Studies of the structure of the flames in cross-wind operating at values of \( \text{J}>1 \), when the flame is located above the exit plane of the burner, have been reported previously (Gollahalli et al., 1975; Askari et al., 1990). However, the flames in cross-flow with \( \text{J}<1 \) have not been studied. Nevertheless, that regime is interesting because such a condition is common for the flare stacks in chemical industries operating in high velocity wind conditions and low-load conditions of a gas turbine. Hence, two flames at \( \text{J}=0.024 \) and 0.17 were chosen for detailed structural studies (Nanjundappa, 1992). At these values of \( \text{J} \), the flame had a single planar flame zone structure and a two-zone structure described earlier. In this paper, because of space limitations, only the results pertaining to the flame with a single zone structure are presented.

**Temperature Profiles**

Figure 5 shows the temperature profiles along the vertical lines passing through \( z=0 \) plane at three downstream distances. It should be noted that the negative values of \( y \)
coordinate correspond to the locations below the exit plane of the burner. At \( x=2.72 \ d \) and \( x=5.44 \ d \) a double hump structure was noticed in the temperature profiles. The humps corresponded to the edges of the recirculation vortex in x-y plane. The humps were not symmetric about the vortex eye and the higher peak temperature occurred at the bottom edge of the vortex. The occurrence of humps at the edges of the vortex as opposed to the core of the vortex is surprising in view of the expectation that low density hot product gases move inwards to the core of the vortex. However, since the flame was diffusion-controlled in this region, combustion was confined to the interfaces of the fuel vortex with the ambient air, resulting in the occurrence of the peak temperatures in that region. The peak value of temperature on the lower edge of the vortex was higher than at the upper edge because at the upper edge, the cold fuel gas exiting the burner was drawn continuously into the vortex and at the lower edge interface was not flushed with cold fluid. It is interesting to note that at \( x=8.16 \ d \) double hump structure vanished and a single peak was noticed in the temperature profile indicating the absence of the thin flame edges of the recirculating vortex. As the color photographs indicated, this zone indeed corresponded to the blue colored well mixed region.

Figure 6 shows the temperature profiles in the z transverse direction at different values of x at the height corresponding to \( y=7.5 \ d \). Double hump structures were noticed at all three values of x/d and the peak became sharper at the larger distances downstream. Double hump structure in this profile

![Figure 6](image1.png)

**FIG. 6 TRANSVERSE TEMPERATURE PROFILE IN THE Z DIRECTION OF A PROPANE FLAME IN CROSS-FLOW**

![Figure 7](image2.png)

**FIG. 7 CARBON DIOXIDE CONCENTRATION PROFILES OF A PROPANE FLAME IN CROSS-FLOW**
indicates that exothermic reactions were dominant in the planar interfaces of the two dimensional recirculating vortex created by the burner tube in its wake. The sharpening of the peaks signify the narrowing of the width of the planar vortex with increasing downstream distance. The peak values in the temperature profiles are close to 2000 K indicating the radiant loss from the flame in this zone is small. In fact, the radiation measurements from the flame confirmed this observation (Nanjundappa, 1992).

**Composition Profiles**

Figures 7 to 10 show the concentration profiles of CO₂, CO, O₂, and NO at three downstream distances on the z=0 plane.

The CO₂ concentration profiles along the y coordinate appear very similar to the temperature profiles A double hump structure at x=2.72 d and x=5.44 d turned into a single hump structure at x=8.16 d. The peak values of CO₂ concentration at the lower edge of the flame vortex were higher than at the upper edge. Thus, the CO₂ concentration profiles support temperature data. Further, of all the major combustion products CO₂ has the highest molecular weight and hence highest density. Hence, even from the point of centrifugal effects, one expects higher concentrations of CO₂ at the edges of the vortex. At x=8.16 d, the single flame structure again indicates the absence of thin flame zones in the top and bottom surfaces.
of the region where the transition from the two-dimensional vortex structure to axisymmetric structure takes place.

Figure 8 shows that the CO concentration profile in the y direction has a single peak at all the three axial distances. Furthermore, the peak is also coincident with the location of the eye of the recirculating vortex in the wake of the burner tube. The location of the maximum value of the CO peak on the eye of the vortex can be attributed to the following: (i) the O₂ availability in the core of the vortex is limited because of the relatively lower temperature and higher density of O₂ entrained from the cross-flow stream, which tends to oppose the infusion of O₂ inwards due to centrifugal effects. The insufficiency of O₂ leads to higher rates of CO formation, and (ii) the relatively low molecular weight of CO brings it to the eye of the vortex. The peak of CO concentration becomes sharper at x=8.16 d, the transition zone, as explained earlier.

The O₂ concentration profiles shown in Fig. 9 corroborate the arguments presented above in connection with CO and CO₂ concentration profiles. The highest O₂ concentration occurs at the edges of the vortex and the minimum occurs in the neighborhood of the eye of the vortex. A sharp decrease in O₂ concentration is noticed below the exit plane of the burner indicating a thin interfacial reaction zone. The increase of O₂ concentration from its minimum value at the vortex core to the cross flow value below the vortex is much more gradual. The gradual increase can be attributed to the wake of the burner tube in y=-10 d to -20 d region, where some of the recirculated combustion gases were also present.

Figure 10 shows the concentration profiles of NO in the vertical plane z=0 at the same three downstream locations. The concentration of NO is very small in the eye of the recirculating vortex and increases sharply towards the edges. The double hump structure is noticed at x=2.72 d and x=5.44 d locations similar to temperature profiles. Since NO formed in the flame is primarily of thermal origin, the similarity between temperature and NO concentration profiles is not surprising and indicates that NO is formed through Zeldovich type mechanisms. The higher peak value of nitric oxide concentration was approximately same at all three locations. It is also interesting to note that the higher peak value occurred on the lower side of the recirculating vortex. Again, this could be attributed to the burner tube wake effect which recirculates a significant part of the post flame gases where NO can continue to form. On the upper edge of the vortex, however, temperature is lower, as well as the post flame gases from the downstream flames are not present due to the clockwise rotation (towards burner) of the vortex. The peak value of NO concentration here is higher than the peak value of NO concentration measured in a vertical propane flame in a co-flowing air stream (Gollahalli, 1977). The longer residence time of combustion product gases associated with the recirculation is probably responsible for the higher NO concentration in the flame subjected to cross-flow.

DISCUSSION

The stability results have clearly demonstrated that a gas jet diffusion flame in cross-flow can sustain a wide range of input flow rates. A turn-down ratio of the order of 1000 is possible with this type of burner. The structure of the bent over flame with a low ratio (1<1) of the jet to cross-flow momentum fluxes is seen to be substantially different from the structure of the same flame at high values of that ratio. A distinct two zone structure consisting of a two-dimensional wake behind the burner tube and an axisymmetric jet farther downstream is the prominent feature of the low momentum flux ratio (1<1) flame. In the first zone, combustion occurs in a recirculation vortex where some of the jet fluid is mixed with the hot gases fed back from the downstream flame. The remaining jet fluid burns in the second zone. The fuel pyrolysis, soot formation and combustion, and a luminous yellow zone attached to the burner tube are characteristics of the flame in the recirculating vortex. The junction of the two-dimensional flame and the axisymmetric flame, where the transition of flow occurs, an intense mixing manifested as the blue flame is noticed. The
The initial part of the axisymmetric zone is also blue indicating an intense mixing.

The composition and temperature profiles show that the physico-chemical processes in the first zone are diffusion-controlled. The double hump structures in temperature and combustion product concentration profiles indicate that the oxidation reactions and heat release are confined to the edges of the vortex. Also, because of centrifuging action, the lighter gases are confined to the vortex core. Because of the low temperatures in the vortex core, NO concentrations are significantly lower in the vortex core of the flames in cross-flow at the low momentum flux-ratio regime.

**Practical Implications**

The burners based on the concept of using cross-flow to increase the stability range of their flames offer the potential of providing much wider turn-down ratios than the swirl burners. First, the burners in cross-flow provide good combustion at very low jet flow rates for which swirling cannot be employed effectively because of the low momentum flux of the jet fluid. Second, the recirculation vortex in the wake of the burner tube enhances the stability of the flame at low jet flow rates. At high jet flow rates (J>1), the jet fluid itself acts as an aerodynamic body to provide a wake for flame stabilization which makes the flame stable in that range of operation. Third, the attachment of the recirculation vortex to the burner tube increases the preheating of the fuel which effect could be exploited for the combustion of low calorific value gases such as coal-derived syngas or biomass-derived gas (Bhatti et al. 1982). Because of intense mixing, the soot emission and radiation emission from the flames are low because these processes are mainly confined to the recirculation vortex behind the burner. However, the designs based on the use of multiple tubes in cross-flow for use in high energy output burners have to carefully evaluate the interaction of the bent over flames produced by them and the consequent effect on pressure drop through combustors and pollutant emissions.

**Conclusions**

The hydrocarbon gas jet flame in a cross-flow at low values of jet to cross-flow momentum flux ratio exhibit a complex and distinct two zone structure. The first zone located immediately behind the burner tube is dominated by a two-dimensional recirculation vortex. The second zone, stabilized approximately at the level of the burner exit plane is characterized by an axisymmetric flow. The junction of these two zones manifests an intense mixing. The temperature and concentration profiles indicate the physico-chemical processes in the first zone are diffusion-controlled.

**References**