EXPERIMENTAL STUDY OF TURBULENT LPG TURBULENT INVERSE DIFFUSION FLAME IN COAXIAL BURNER

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Abstract – The present experimental study investigates the turbulent LPG Inverse Diffusion Flame (IDF) stabilized in a coaxial burner in terms of flame appearance, visible flame length, centerline temperature distribution and oxygen concentration and NOX emission characteristics. The effect of air-fuel jet velocities on visible flame length is interpreted using global strain rate and a new devised parameter called Modified Momentum Ratio. The centerline temperature exhibits a steeper increase in the lower premixed zone of the IDF due to the enhanced premixing. Subsequently it declines gradually in the upper luminous portion owing to soot radiation and heat losses to the ambient. Further, the centerline oxygen depletes rapidly in the lower blue zone but found to increase gradually in the upper luminous portion of IDF. The centerline temperature and oxygen distribution along the flame length revealed the dual flame structure of IDF. The EINOX values exhibited a bell shaped profile and reached a maximum value around stoichiometric overall equivalence ratio.

Keywords: LPG Inverse Diffusion Flame, Modified Momentum Ratio, Global strain rate, Dual Flame Structure

I. INTRODUCTION

Most of the practical combustion systems employ non-premixed combustion due to its better stability, safety and wide operating range compared to premixed combustion. However, the presence of soot has an undesirable effect in practical combustors. These soot particles degrade the performance and life time of gas turbine engines, rocket combustors, internal combustion engines etc. Importantly, it causes potential threat to human health and environment. Inverse Diffusion Flame (IDF), a special kind of non premixed flame, is observed to produce less soot compared to Normal Diffusion Flames (NDF).The Inverse Diffusion flame can be observed in simple coaxial burner configurations when high velocity air jet is surrounded by low velocity fuel jet. The relative momentum between air and fuel jets ensures better fuel entrainment and enhanced mixing in IDF configuration as compared to Normal Diffusion flames. The effect of air–fuel velocity ratio on the characteristics of IDF was reported by several researchers [1-6]. The first detailed study was performed by Wu and Essen high [1] for laminar methane IDF stabilized in a coaxial burner. They identified six different regimes of IDF based on its visible appearance and air-fuel velocities. Glassman et al [3] investigated the effect of flame temperature, fuel structure and fuel concentration on soot formation in laminar Inverse diffusion flames of methane, propene, ethene and butene. They concluded that the effect of fuel dilution with inert has major influence on soot formation and fuel structure played only a marginal role in the soot inception. Interestingly, the comparative study on H2 IDF and NDF by Takagi et.al, [2] revealed higher flame tip temperature in IDF than H2 NDF and this was attributed to the presence of higher H2 ratio and excess enthalpy in the central region of IDF. Later, Kailasnath et. al. [6] numerically analyzed the flow field effects of exiting air–fuel jets on soot formation in laminar methane IDF and NDF configurations and observed less peak soot volume fraction in IDF as compared to NDF. Subsequently, Sobiesiak et.al, [4] performed experiments in turbulent methane IDF stabilized in coaxial burners with varying tube diameters and demonstrated the effect of nozzle geometry and air-fuel velocity ratio on visible flame length, temperature distribution and stability. Mikofski et. al. [7] conducted experiments to measure the non luminous flame heights of laminar coaxial methane and ethylene IDF at constant fuel flow and variable air velocities. The OH PLIF (Planar LASER Induced Florescence) mapping and peak luminous intensity from ICCD (Intensified Charged Coupled Device) camera were utilized to visualize the lower blue zone of IDF. The non luminous flame height of IDF was found to extend with increase in central air jet velocity. The Roper's formula for non luminous flame height estimation in laminar NDF was modified to calculate the exact non luminous flame height of laminar IDF. Recently, Sze et.al [5] conducted experiments on LPG-air IDF stabilized on two different burners' viz., coaxial (COA) and burner with circumferentially arranged ports (CAP) and reported the flame shape, visible flame length, temperature contour, centerline oxygen concentration and EINOx of two different IDFs. They observed enhanced air-fuel mixing in CAP burner compared to the COA burner. Similar to Glassman et.al [3], Eui Ju Lee et.al [8] made experimental measurements on the sooting characteristics of diluted ethene. The PAH–

LIF (Polycyclic Aromatic Hydrocarbon–LASER Induced Fluorescence) and OH–LIF together with LASER scattering were used to observe the PAH, OH radical and soot particle distribution. Their observations revealed that radial distribution of PAH and soot was qualitatively similar to that of NDF. The soot growth was found to be influenced by both flame length and temperature in nitrogen diluted ethene IDF. The present work is intended to study turbulent LPG IDF characteristics such as flame appearance, visible flame length, temperature distribution and centerline oxygen concentration at different air-fuel velocity ratio in a coaxial burner.

II. EXPERIMENTAL SETUP

The schematic of the coaxial burner is shown in Fig.1. The burner has coaxial tubes with diameter ratio of 1.8. The burner geometry is designed such that the inner tube is submerged by δ = 4mm below burner exit for enabling better premixing of annular fuel jet by central air jet. The schematic of the experimental setup is depicted in Fig.2.The burner is fixed inside a glass fitted enclosure with the burner rim positioned at a distance of 110 mm above the enclosure base. Further, outer fuel tube is fitted with perforated disc with two layers of steel balls (5mm) to achieve uniform flow of fuel at the exit. The compressed air used for this experiment is passed through silica gel to remove its moisture content. The air and fuel flow rates are metered using calibrated rotameters. The fluctuations in airflowrate are eliminated by ensuring the steady airflow at 0.69 MPa. The flame photographs are taken using a CCD camera which has the capability of taking 21 images in intervals of 0.5 sec. The visible flame length is estimated using the image processing software ImageJ through processes such as Smoothing, Sharpening and Edge detection for exact identification of flame tip.

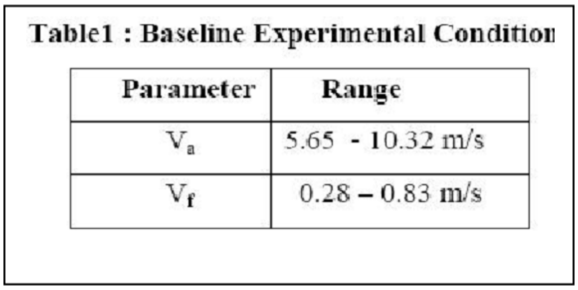
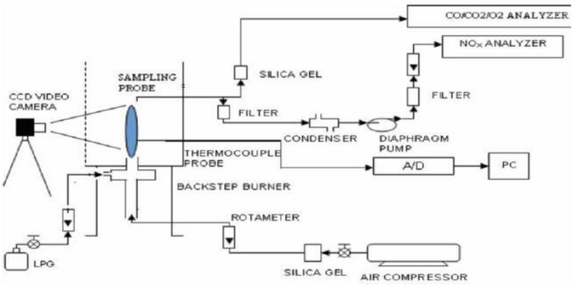
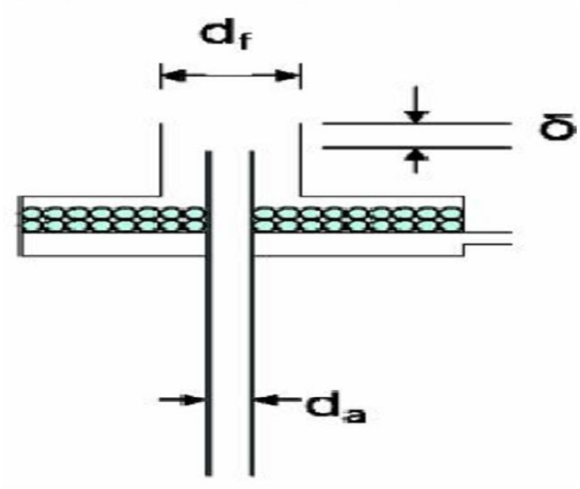


Table1 : Baseline Experimental Conditio

Parameter	Range
V_a	5.65 - 10.32 m/s
V_f	0.28 – 0.83 m/s





III. RESULTS AND DISCUSSIONS

a) Flame Appearance

The visible appearance of LPG Inverse Diffusion Flame (IDF) in the coaxial burner is investigated by varying the air jet exit velocity from 5.65 m/s to 10.32 m/s for fixed fuel jet velocities of 0.28 m/s, 0.42 m/s, 0.56 m/s respectively. For fixed fuel jet velocity of 0.28 m/s and Va = 5.65 m/s, IDF with necking zone formed due to the entrainment of low velocity annular fuel jet by high velocity central air jet is observed in the vicinity of the flame base as shown in [Fig. 3(a)]. It is interesting to observe a smaller blue (premixing) zone above the necking zone due to local air-fuel premixing. The reduction in air jet momentum in the axial direction decreases the effectiveness of fuel-air mixing. As a result, a luminous diffusion flame is formed in the upper portion of flame. With increase in air jet velocity to 6.82 m/s, the blue zone extends within the enveloped NDF as observed in [Fig. 3 (b)]. Further increment in Va to 7.98 m/s reduces the visible flame length, Hf with increase in blue zone of IDF as seen in [Fig.3(c)]. The flame shape of IDF becomes narrower with increase in air jet velocity as shown Fig. 3 (a-e). The color of lower blue zone gets intensified at Va = 10.32 m/s with significant reduction in Hf as compared to Va = 5.65 m/s. Interestingly, the increase in central air jet velocity reduces the flame luminosity in the upper portion of IDF as observed in Fig. 3 (a-e).The reduced flame luminosity with increase in air jet velocity is an indication of less soot formation in the flame. The extension of blue zone in the lower portion of IDF is attributed to higher entrainment of annular fuel jet by the central air jet and enhanced mixing that imparts partially premixed structure to IDF. Hence, it can be concluded that central air jet momentum is an important parameter to be controlled for the establishment of IDF with extended premixing zone. The increase in the height of blue zone due to enhanced fuel-air premixing was observed by Sobiesiak et.al.,[4] for coaxial turbulent methane IDF with color Schelieren technique. The similar observations were made by Sze et.al.[5] for coaxial turbulent LPG IDF.

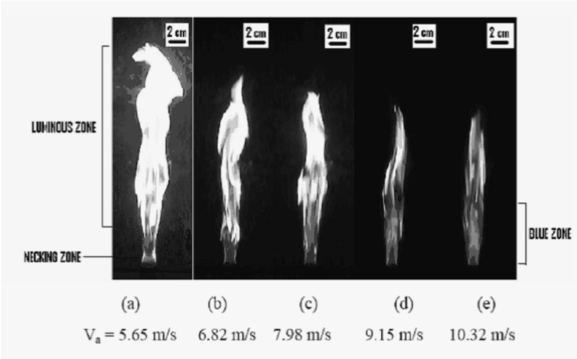


Fig. 3. Visible appearance of LPG IDF with fixed fuel jet velocity and varying air jet velocity

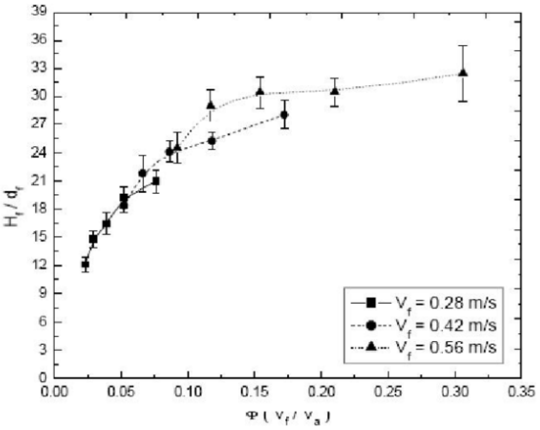


Fig.4.Variation of luminous flame length with air jet momentum for Vf = 0.28 m/s, 0.42 m/s, 0.56m/s

The luminous flame length, Hf is a useful parameter for characterizing IDF. Similar to NDF, Hf determines the fuel-air mixing and residence time flame gases qualitatively. Sobesiak et.al., [4] used air-fuel exit velocity ratio to characterize the luminous flame length in turbulent methane IDF for different coaxial tube diameters. Similarly, Sze et.al., [5] plotted the variation of Hf with overall equivalence ratio . In order to include the effect of overall equivalence ratio on the visible flame length, a non-dimensional parameter which is a product of fuel-air velocity ratio and overall equivalence ratio (modified momentum ratio) is plotted against the non-dimensional flame length.

The effect of exit air-fuel velocity ratio on the luminous flame length of IDF is investigated by varying the air jet exit velocity from 5.65-10.32 m/s for constant fuel exit velocities of 0.28 m/s, 0.42 m/s, 0.56 m/s respectively. A steeper reduction in luminous flame length is observed for Vf = 0.28 m/s with increase in air jet velocity from 5.65-10.32 m/s. The Hf reduces by 43% at this fuel jet velocity. With the increase in central air jet momentum, more fuel is likely to entrain into the central air jet and can result in intense mixing within a shorter region to produce smaller flame height. However, reduction in Hf only by 34% and 24% is observed for the fuel jet exit velocities of 0.42 m/s and 0.56 m/s respectively as evident in Fig. 4. This implies that air jet velocity has to be increased for entraining higher fuel flow rate in central air stream. However, the air jet velocity cannot be increased for a certain fuel flow rate beyond flame stabilization regime due to flame blow out. The above observations indicate that both air and fuel jet velocities at the burner exit play an important role in determining the flame length of IDF. Several researchers [4,5] also made similar conclusion from their observations for both laminar and turbulent IDF.

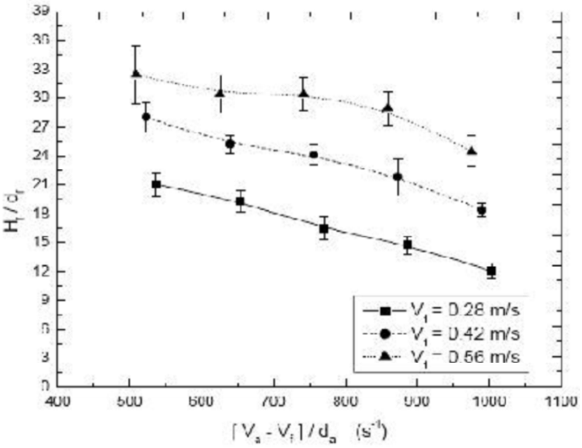


Fig.5. Variation of luminous flame length with glo strain rate in Coaxial

LPG IDF Apart from modified momentum ratio, variation in visible flame length is interpreted with global strain rate in the present study. This parameter is widely used to characterize Normal Diffusion Flames. As IDF is a special kind of NDF, it will be interesting to observe change in luminous flame height of IDF in terms of global strain rate.

The global strain rate parameter can exhibit the effect of relative velocities of exit air-fuel jets on Hf.

The decreasing trend of visible flame length is observed with increase in global strain rate in Fig.5.

The reason may be attributed to the increased shear between air-fuel jets due to their relative velocities at the burner exit. Even though the luminous flame length showed steeper decrease with increase in global strain rate for all exit fuel jet velocities, the Hf is found to increase with increase in fuel flow rate.

This is because of the ineffectiveness of central air jet in entraining higher fuel flow rate. As a result, exiting fuel jet that is not entrained by the air jet diffuse with the ambient air slowly.

The slower diffusion of fuel jet with the ambient air eventually increases the visible flame height as proposed by Kalghatgi [15] for turbulent NDF.

b) Soot Free Length Fraction

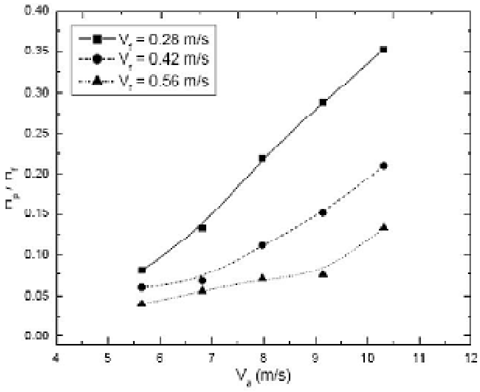


Fig.6. Variation of Soot free length fraction with air jet velocity

The soot free length fraction, SFLF is the ratio of lower blue zone length of IDF to its visible flame length. Similar to NDF, this parameter helps in determining the extent of premixing in IDF. The variation of SFLF with air jet velocity for Vf = 0.28, 0.42, 0.56 m/s is shown in Fig. 6. It can be observed that the SFLF of IDF extends with the increase in air jet velocity for all the fuel jet velocities. This is due to higher global strain rate between the air-fuel jets that enhances its premixing to produce extended blue zone in the lower portion of IDF. The increase in the height of blue zone with air jet velocity was observed by Sobiesiak et.al.,[4] for coaxial turbulent methane IDF with color Schelieren technique. However, decrease in the blue zone length of IDF with increase in fuel jet velocity is clearly evident from Fig.4.5. For Vf = 0.28 m/s, SFLF increases by 77.3% which reduces to 71.4% and 70% for fuel jet velocities of 0.42 and 0.56 m/s respectively. This is due to the ineffectiveness of the air jet in entraining higher fuel flow rate at the exit. At higher fuel exit velocities, some of the fuel that are not entrained by the central air jet diffuse with the ambient air and react slowly. This increases the luminous zone and reduces the lower premixed portion of IDF and hence leads to smaller SFLF.

c) Flame Temperature

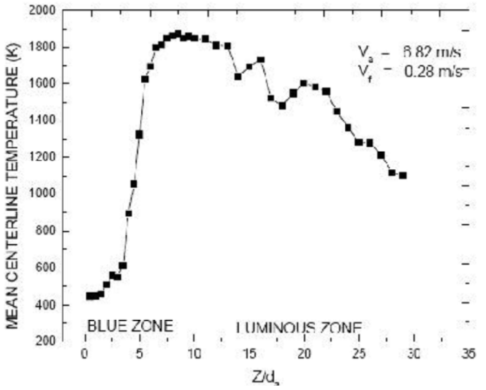


Fig.7.Variation of mean centerline flame temperature for Va = 6.82 m/s , Vf = 0.28 m/s

The centerline flame temperature of the LPG IDF is measured by R–type thermocouple [Pt13%Rh (+) Pt (-)] of wire dia 0.23mm. The thermal inertia for the wire is estimated to be 5sec. The temperature data were acquired through DAQ-PCI 6281 at a sampling rate of 1000 points/min. The thermocouple fixed to the traverse arrangement is moved in steps of 0.5 cm in the lower part (blue zone) of the flame and 1cm in the upperportion (yellow zone) of the flame. The flame temperature is measured along the centerline (r = 0) for two different air jet velocities of 6.82 and 9.2 m/s at a fixed fuel jet velocity of 0.28 m/s. From the Fig 7, gradual increase in flame temperature is observed in the vicinity of the flame base up to 4cm from the burner rim. Interestingly, flame temperature increased steeply within the blue zone from 4.5 cm from the burner surface to 10 cm along the centerline and remained uniform in the upper portion of the blue zone. This may be due to the parabolically shaped blue zone of IDF.The parabolic shape of blue zone in IDF was reported by Wu and Essen high [1]. Because of the parabolic shape of the lower blue zone, the flame sheet converges to the centerline at higher distance from the burner rim. The convergence of the flame sheet to the centerline increases the heat conduction to the central air jet and hence temperature rises steeply in the lower blue zone. However, a gradual decrease in the temperature is observed in the luminous zone of the flame. This is due to the radiation from soot particles and heat losses to the ambient due to natural convection. The peak centerline temperature obtained is around 1874K at the tip of blue zone. Further, enhanced fuel-air premixing in the lower portion of IDF results in higher flame temperature. The double flame structure of IDF is clearly identified from the centerline temperature distribution.

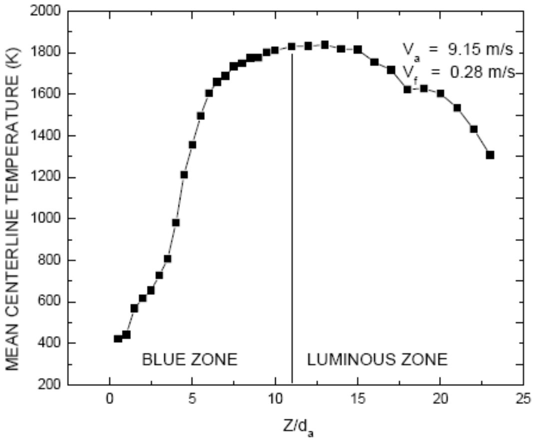
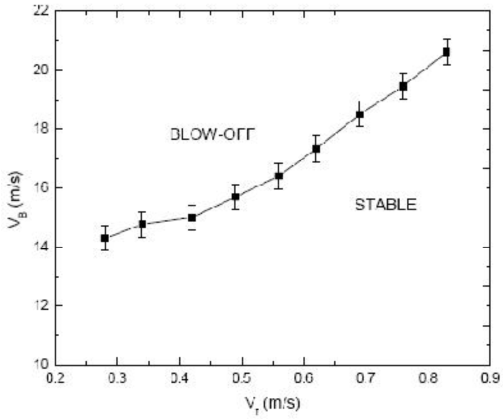


Fig.8. Variation of mean centerline flame temperature for Va = 10.32 m/s, Vf = 0.28 m/s in Coaxial burner

The centerline flame temperature variation for Vf = 0.28 m/s with Va = 10.32 m/s is shownin Fig.8. The comparison with Fig 7 makes it clear that increase in air jet velocity enhances premixing of fuel-air and hence steeper increase in flame temperature is observed close to the burner rim. In contrast to Fig.7, peak flame temperature got shifted f rom Z / da = 8.5 cm to Z / da = 10.5 cm. This may be attributed to the increase in the height of blue zone due to enhanced fuel-air premixing. The peak centerline temperature 1838 K.is obtained at the tip of blue zone. Comparatively, the fluctuations in the luminous zone have reduced. This is due to the effect of high momentum air jet which made the flame less buoyancy controlled. This can be justified by the Richardson number, Ri = 5.5. The effect of increase in air jet momentum is evidenced from the increased centerline temperature near the burner rim. Similar to the observation made by Sobesiak et.al.,[4] for turbulent coaxial methane IDF, extended region of uniform higher flame temperature is achieved with the increase in air jet momentum.

d) Flame Stability



The stability of LPG IDF in the coaxial burner at different fuel velocities is plotted in Fig.9. The experiment is conducted by varying the air jet velocity for constant fuel jet velocities of 0.28-0.85 m/s until flame blow-off is observed. The air jet velocity corresponding to the flame blow-off is termed as blow-off velocity.

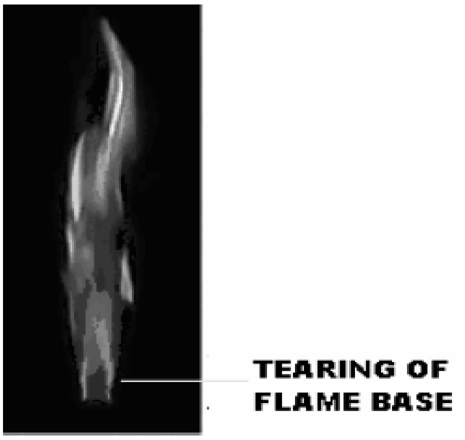


Fig.10. Tearing of flame base at higher air jet velocity close to the burner rim

The blow-off of LPG IDF in coaxial burner takes place through a series of steps. As the air jet velocity is increased for a constant fuel jet velocity, change in Hf and visible appearance is observed**.** The flame noise increases due to higher shear effect between two jets. Interestingly in IDF, the flame blow-off occurs without flame getting lifted-off from the burner rim for all the fuel exit velocities. In the present experiment, the local detachment and attachment of the flame base near the burner rim is observed close to the blow-off velocity. This may be due to the local tearing of flame base from the burner rim caused by the increased global strain rate near the burner exit as seen in Fig.10.The necking zone of IDF seen in Fig. 3(a) is likely to act as the anchoring flame that stabilizes the IDF to the burner rim. With the increase in air jet velocity, the necking zone reduces in height and becomes normal to the exiting air jet. The higher air jet velocity tears this necking zone and hence local detachment and attachment of flame base takes place leading to flame blow out.

Emission Characteristics - Centerline Oxygen Concentration

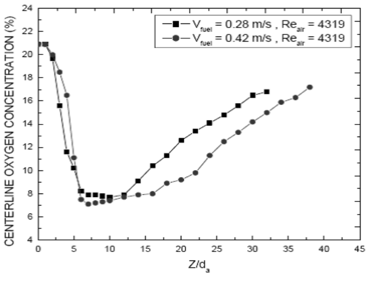


Fig.11. Variation of centerline oxygen concentration of LPG IDF in Coaxial burner

Interestingly, the blow-off velocity is observed to increase linearly with increase in fuel jet velocity. This may be due to the decrease in SFLF which extends the luminous zone of IDF. The NDF have higher flame stability and wider operating range. This causes the blowoff velocity to increase with fuel jet velocity. The presence of anchoring flame near the flame base of IDF is expected to play an important role in the stabilization of IDF to the burner rim.

Similar conclusion was postulated by Sobiesiak et.al [4] for turbulent coaxial methane IDF.

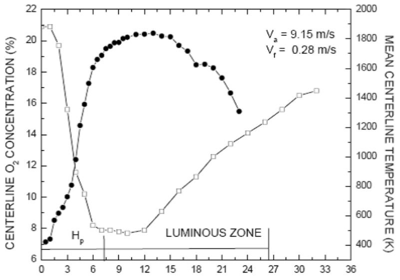


Fig.12. Variation of centerline oxygen concentration and centerline temperature of LPGIDF in Coaxial burner

In order to qualitatively observe the extent of mixing, the measurement of centerline oxygen concentration along the flame centerline is carried out for two different fuel jet velocities of 0.28, 0.42 m/s at a fixed air jet velocity of 9.15 m/s.It is observed from Fig. 11 that the oxygen concentration is depleting at a faster rate in the premixed zone of IDF because of enhanced air-fuel mixing. For a constant air jet Reynolds number of 4319 and Vf = 0.28 m/s, the steeper decrease in oxygen concentration is seen up to 5cm from the burner surface that remained at its lowest level of 8% up to Z=10 cm.The variation of centerline temperature profile and centerline oxygen level in the premixed zone of IDF at Vf = 0.28 m/s with Va = 9.15 m/s is shown in Fig 12. The enhanced premixing of fuel-air in the blue zone makes the centerline oxygen concentration to reduce at a faster rate. Interestingly, the centerline oxygen concentration increases gradually in the luminous flame zone. This may be due to the entrainment of ambient air near the burner rim that is not consumed in the blue zone of IDF. This results in increased oxygen concentration in the luminous zone of IDF. However for Vf = 0.42 m/s, the oxygen consumption increases gradually upto Z = 5cm from the burner rim and reached a lower level of 7.5% at Z = 10 cm. As the air jet velocity is kept constant, the increase in fuel jet velocity increases the overall equivalence ratio in the luminous zone and hence oxygen concentration is observed to decrease for Vf = 0.42 m/s compared to Vf = 0.28 m/s.

NOX Emission Characteristics

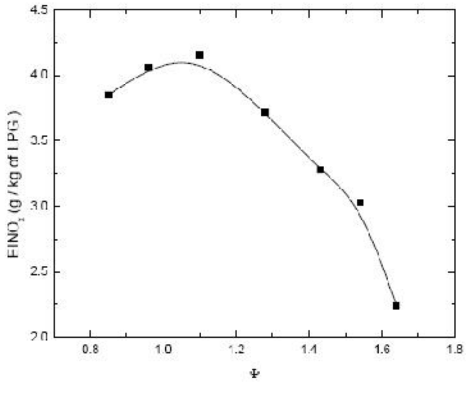


Fig.13. Variation of EINOX with overall equivalence ratio in LPG IDF

The NOX emissions from LPG IDF were analyzed using chemiluminescence analyzer to get a basic understanding on its emission characteristics. The variation of NOX with overall equivalence ratio is interpreted through EINOX. From the Fig 13, it is clearly observed that EINOX increases from 3.8 g/kg at Φ = 0.8 to 4.2 g/kg at Φ = 1.1. But it decreases gradually in the fuel rich conditions. This trend is similar to turbulent partially premixed flame observed by Lyle et.al., [16] for turbulent ethylene partially premixed flame. As IDF exhibits partially premixed structure as suggested [4], the NO emissions in IDF can be compared to that of turbulent partially premixed flame. The increase of NOx emissions in the near-stoichiometric condition can be attributed to the increase in flame temperature due to the enhanced fuel-air mixing which enhances the NOx formation. At fuel rich conditions, the IDF transforms to NDF which reduces the air-fuel mixing leading to lower flame temperature. This causes decrease in the EINOX at fuel rich overall equivalence ratio. Similar observation was made by Sze et.al [5] for turbulent coaxial LPG IDF.

IV. CONCLUSION

1.The following conclusions are made from present investigation of turbulent LPG IDF characteristics in Coaxial burner

2. Two new parameters such as global strain rate and modified momentum ratio are used to correlate the visible flame length of IDF in coaxial burner.

3. In order to quantify the soot reduction in IDF, a new parameter, soot free length fraction (SFLF) is introduced in the present study.

4. The rapid depletion of centerline oxygen in the blue zone and gradual increase in the luminous zone is observed. The steeper increase in temperature in the blue zone andgradual decrease in the luminous zone is evidenced. However, measurement of centerlineoxygen concentration did not prove to be an effective parameter in estimating the extentof premixing in IDF.

5.The EINOX shows a bell shaped profile and attains maximum value around Φ = 1.1 and decreases at fuel rich equivalence ratio.

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