Effect of jet velocity on LPG to flame stability and flame temperature distribution on Inverse Diffusion Flame (IDF)

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Abstract. Liquid Pretolium Gas (LPG) experimental investigation used to Inverse Diffusion Flame (IDF) burners is presented. The effect of fuel jet velocity on the flame stability and flame temperature distribution of LPG Inverse Diffusion Flame (IDF) was investigated. Fuel jet speed ($V_f$) = 0.154 m/s and 0.330 m/s was chosen for analysis. Air jet velocity varies from $V_a = 7.431$ m/s to $V_a = 15.924$ m/s for $V_f = 0.154$ m/s and $V_a = 8.493$ m/s up to $V_a = 21.231$ m/s for $V_f = 0.330$ m/s. The results of the observation show that the velocity of the fuel jet affects the ratio of the velocity of the air-fuel jet which will ultimately have a significant effect on the flame. It was found that the stability of LPG IDF flame at $V_f = 0.154$ m/s occurred at $V_a = 11.677$ m/s, the equivalence ratio ($\phi$) = 1.99. The stability of LPG IDF flame at $V_f = 0.330$ m/s occurs at $V_a = 14.862$ m/s with an equivalence ratio ($\phi$) = 1.56. It was observed that the temperature along the IDF centerline increased when the distance from the burner ($Z$) exit increased. The nature of this temperature distribution shows that central cold air in the air jet is gradually heated towards the IDF downstream. The highest flame temperature is seen in $Z$ between 90-110 mm. It was found that the length of the flame increased with increasing flow of fuel jets. At a constant fuel jet speed the flame length increases but will return again to a certain fuel-air ratio. At $V_f = 0.154$ m/s the highest flame height is 111 mm and at $V_f = 0.330$ m/s the highest flame height is 143 mm.

1. Introduction

Energy is the driving force for various human activities. Energy production in the industrial world is largely sourced from combustion, where combustion is defined as the process of chemical reaction between fuel and oxidizer accompanied by the production of heat energy in the form of light or flame. Fuel is a substance capable of releasing heat when an oxidation reaction occurs, while an oxidizing agent is an element that contains oxygen (eg pure oxygen, air). Processes that may occur during the combustion process include: chemical and physical interaction processes accompanied by the release of heat energy derived from the energies of chemical (exothermic) bonds, heat transfer processes, mass transfer processes, and fluid particle movements. The biggest type of fuel used today comes from the remains of natural fossils with the basic elements of hydrocarbons in the form of: solid as coal, liquid such as gasoline and diesel, and in the form of gases such as methane, propane, butane and others. Various steps to meet energy needs are important topics along with the decreasing number of fossil energy sources. The current energy system is still largely produced from the fuel combustion process in...
steam, gas and steam and gas power plants. Likewise with the transportation system, as well as various processes in the industry that require heat sources from the results of burning fuel in the combustion chamber. The study of combustion greatly affects the increasingly scarce use of fuel. Experimental studies and theoretical studies of combustion have been carried out to better understand the phenomenon of combustion. Simulations with various numerical methods are increasingly being carried out supported by advances in information technology. These steps are basically aimed at obtaining a new method of burning fuel with more savings, cleaner and more stable, so that in the end the fulfillment of the energy needs obtained from the combustion process can be more guaranteed.

Various methods have been examined both in terms of the quantity and quality of the flow of air and fuel mixtures as well as burner equipment engineering. From the aspect of the flow of mixture of air and fuel, one method for obtaining clean combustion is combustion in conditions of mixture with more air value (excess water) that is high or rich in oxygen or poor in fuel. And from the burner equipment engineering aspect, the use of swirler is still an alternative that is often found to improve combustion.

Inverse Diffusion Flame (IDF) is a special type of diffusion flame. This differs from the normal diffusion flame-Normal Diffusion Flame (NDF) is related to the relative position of the fuel outlet and the air outlet / oxidant. At the IDF, a fuel outlet (external) surrounds the air outlet (internal). The low-speed fuel jet drags in because of the high speed of the air and mixes with air. NDF has a wide flammability range. Premixed flame has the characteristics of low soot formation. IDF is a feature of NDF and premixed fire, hence the advantages of both fires in terms of various flame stability, less pollutant emissions and operational safety.

Wu and Essenhigh [1] presented a fire map for IDF using methane. Six different types of fire are proposed for IDF. Mikofski et al. [2] examined the effects of various air flow rates on ethylene and methane IDFs using laser-induced hydroxyl fluorescence and induced laser soot. They observed that fire ethylene has a greater tendency to form soot. Sobiesiak and Wenzell [3] examined the effects of dynamic mixing between natural gas and air in a reverse flame structure. Mikofski et al. [4] examined the relationship between high ethylene flame and methane using luminosity images. They found that the glowing flame height was greater than the height of the reaction zone. Mahesh and Mishra [5] conducted an experimental study on IDF fire structures using LPG behind the burner. They reported variations in fire appearance and centerline temperature distribution at different air-fuel ratios.

Zhen et al. [6] conducted an experiment to study the effect of nozzle length on IDF LPG. The structure of fire and CO concentration are compared in multi jet fuel burners with long and short nozzles. They observed that the potential core and IDF fire base were shorter in the short nozzle compared to the long nozzle case. Mahesh and Mishra [7] conducted a comparative study of IDF LPG behind and coaxial burners. The results show that a compact flame with little luminosity is observed in the backstep burner. Stelzner et al. [8] presented experimental and numerical investigations on the IDF structure of rich methane.

Elbaz and Roberts [9] try to understand the role of entrainment and mixing in IDF methane. Elbaz and Roberts [10] attempted to characterize methane IDF with air and annular fuel jets. They observed that an increase in the air-fuel speed ratio increases the entrainment of the fuel to the air flow; therefore, the air-fuel mixture is increased. Bhatia et al. [11] numerically investigates IDF and NDF. They reported that oxygen enrichment and gravity variation had a significant effect on the NDF flame structure compared to IDF. Barakat et al. [12] presented experimental and theoretical studies of the effects of jet dynamics and geometry parameters of burners on the behavior of IDF fuel LPG. The energy associated with IDF is strongly related to the distribution of temperature and temperature levels. Takagi et al. [13] the temperature characteristics that are numerically examined are derived from preferential diffusion effects on NDFs and IDFs.

Sze et al. [14] presented a detailed study of IDFs in two different burners, one with coaxial settings and the other with circumferentially regulated ports. They observed a higher flame temperature in the harbor arranged in a circular manner because of a more intense air fuel mixture. Dong et al. [15] examined the effect of air port diameters on the characteristics of heat transfer from butane IDF. Zhen et al. [16] reported the effect of equivalence ratios and Reynolds numbers on circulating temperature, fire
appearance and CO₂ emissions. Zhen et al. [17] compared the IDF thermal field with flame and the
flame that was fitted with fire using LPG as fuel.
Kamal [18] compared the characteristics of IDF and NDF soot. Patel et al. [19]; Examining experimentally the appearance of fire and emission characteristics of LPG-fueled IDF with coaxial burners. Long flame, CO and NOx emissions are checked at the equivalent ratio and the angle of the different swirler propellers. IDF with swirl, shows wider, shorter and more stable compared to IDF without swirler. Adequate investment and swirl effects for 30° propeller angles produce an environment that matches low CO and NOx emissions.

Through a literature review, it is known that although a large number of papers are available on IDF, the effect of fuel jet velocity on the distribution of fire, fire stability, equivalence and altitude ratios has not been found. Therefore, our knowledge of the effect of fuel jet velocity on fire characteristics is relatively rare and incomplete. The main purpose of this study was to determine that the effect of LPG fuel jet speed on the characteristics of the flame produced by the IDF burner. Then an experimental test was performed to find out the performance of the IDF burner at the chosen fuel jet speed.

2. Experimental apparatus and procedure

2.1. Experiment Settings

Figure 1 shows the geometry details of the coaxial burner. The burner consists of two coaxial tubes with a inner tube 10 mm in diameter and an outer tube with a diameter of 30 mm. The burner is operated in such a way that the central air jet is surrounded by an annular fuel jet. To investigate the effect of fuel jet velocity on the characteristics of the variable setting flame as shown in table 1.

Figure 2 shows the experimental test setting scheme used in this work. The air is supplied in a coaxial burner from the blower. Valves are used to control air flow. Air flow is measured with a calibrated rotameter (± 2.0% accuracy of full scale) installed in the air duct. Experiments carried out using LPG as fuel. LPG contains 70% C₄H₁₀ (butane), 30% C₃H₈ (propane). The needle valve is used to control the
The flow of fuel. The fuel flow is measured with a calibrated rotameter (± 2.0% accuracy of full scale) mounted on the fuel line. The shape and size of the fire are captured with the help of a high resolution digital camera (24.2 megapixels, ISO 12800 sensitivity) which has video recording capability at 30 fps.

| Research variable | Speed Jet Fuel | Air Speed |
|-------------------|----------------|-----------|
| \( V_f \) (m / s) | 0.154          | 7.431     |
|                   |                | 9.554     |
|                   |                | 11.677    |
|                   |                | 13.800    |
|                   |                | 15.924    |
| \( V_a \) (m / s) | 0.330          | 8.493     |
|                   |                | 11.677    |
|                   |                | 14.862    |
|                   |                | 18.047    |
|                   |                | 21.231    |

The length of flame (Ht) is defined as the distance between the burner and the tip of the flame along the vertical center line of the IDF. The tip of the flame means the point where the fire is visible to the naked eye. Ten images were recorded for each IDF configuration. The length of the last flame is considered as the average flame length of ten images under the same conditions. Equivalent ratio, \( \Phi \) is defined as:

\[
\Phi = \frac{AFR_{\text{static}}}{AFR_{\text{act}}} = \frac{(Ma/Mf)_{\text{stoic}}}{(Ma/Mf)_{\text{act}}} \tag{1}
\]

where \((Ma / Mf)_{\text{stoic}}\) is the stoichiometric air-fuel ratio and \((Ma / Mf)_{\text{act}}\) is the actual air-fuel ratio. Variations in flame appearance, flame length, flame distribution and centerline temperature distribution as a function of fuel jet speed, air jet speed, equivalence ratio, are analyzed in the following sections.

2.2. Instrument arrangement and data acquisition

Retrieval of flame temperature data was carried out with 8 R type thermocouples. The diameter of the thermocouple wire was 0.3 mm and the diameter of the ceramic was 4 mm. Thermocouples are mounted vertically on a fire. The temperature is taken simultaneously (8 thermocouples) at each altitude. Data from thermocouple is used as digital data using Analog Digital Converter, using PLC software. Digital
data is transferred to a computer and forms a temperature data table. This data is then processed in MATLAB software for temperature distribution. The measurement mechanism is shown in Figure 3:

![Figure 3. Acquisition Data](image)

### 3. Results and discussions

3.1. Flame appearance and distribution Flame temperature

Wu and Essenhigh [1] identified six types of IDF regimes based on the form of flames. The speed and stoichiometry of air-fuel flow affects the shape and structure of the IDF. The emergence of the IDF reflects the quality of the physical process that is completed during burning. In this study, the flame display of IDF on coaxial burners was investigated for different air flow and fuel conditions. Figure 4 shows the IDF structure. IDF structure has been characterized as a double structure (Zhen et al. [6]). The IDF dual structure consists of a fire base (entrainment zone) at the root of the flame and the next flame torch. The fire neck connects the base of the fire and the flame torch. Fire neck, which is yellow, indicates the presence of soot (soot). The flame torch consists of an inner blue zone and an external luminous zone as shown in Fig. 4

![Figure 4. IDF structure and flame length for $V_f = 0.154$ m / s](image)
Figure 5. IDF structure and flame length for $\phi$; $V_f = 0.154$ m/s

Figure 4. shows variations in fire appearance for increased air jet speeds, $V_a = 7.43$ m/s to 15.92 m/s, with fixed fuel jet speeds ($V_f = 0.154$ m/s). It was seen that the length of the flame continued to increase with the increasing speed of the air jet. An increase in IDF length can be associated with sufficient entrainment of fuel in a central air jet. High-speed air jets are accelerated to react with fuel jets and fuel-rich mixtures form longer IDFs. However, at IDF $V_a = 7.43$ m/s, so weak entrainment results in so very rich and results in soot formation, fires are shorter than higher air $V_a$. 
**Figure 6.** IDF structure and flame length for $V_f = 0.330\ \text{m/s}$

**Figure 7a.** Temperature distribution and equivalence ratio ($\phi$) : $V_f = 0.330\ \text{m/s}$
Likewise, \( V_a = 15.924 \text{ m/s} \), so the high difference between the speed of the air jet and the speed of the fuel jet and the increase in air mass results in the high flame return decreasing. But there is no visible formation of excess soot. As shown in Figure. 4, the length of the blue zone (Hb) has a quadratic trend with \( V_f \). Figure 5. Shows the distribution of flame from the speed of an increasing air jet. The area of fire with high temperature will increase with increasing air jet speed, but will also experience a decrease if in certain compositions jet speed continues to increase.

As shown in Figure. 4, when \( V_a \) is small, the length of the blue zone (Hb) increases linearly with an increase in \( V_a \) up to 11.677 \text{ m/s} \). When \( V_a \) increases, the blue zone decreases slightly as shown in Figure 4 (d) - (e). The velocity of the air jet increases from 7.431 \text{ m/s} \) to 15.924 \text{ m/s} \), resulting in a shorter IDF with a thinner flame torch. In addition, the reduction in IDF length was observed with increasing air jet speed. In normal diffusion flames, the fuel is burned with entrained air from the surroundings; therefore, the color is yellow.

At the IDF, the central air jet withstands the fuel jet. The amount of fuel trapped in an air jet controls the extent to which the fuel is burned in pre-mode or diffusion mode. IDF color changes indicate the entrainment effect of the fuel jet. It can be seen that the increase in the speed of the air jet increases the entrainment of the fuel jet, which leads to more fuel being burned in pre-mixed mode. The blue zone represents the initial combustion. At high enough air jet speeds, all fuel is burned in pre-temp mode. Sze et al. [14] have reported the same effect of air jet speed on the length of flame and color of IDFs. This study clearly shows that the appearance of the IDF may depend on the speed of the air jet and the speed of the fuel jet.

The effect of \( \Phi \) on the appearance of the flame, the length of the flame and the non-rotating IDF luminosity can be observed qualitatively through direct visualization of the flame (Fig. 4 and 6). The increase in length and luminosity of non-rotating IDF can be associated with inadequate entrainment of fuel due to increased fuel rate. Because the equality ratio with the air jet speed continues to increase, the fuel momentum also increases. Therefore, a number of fuels do not fall under the entrainment effect of a central air jet. This unburned fuel, burning in diffusion mode on the outside of the flame causes the long flame to elongate with soot formation. The length of the flame is an important characteristic, which helps to qualitatively evaluate the effect of air-fuel mixing. The variation of flame length as a function of \( \Phi \) and velocity is presented in Figure 4,5,6,7 along with the temperature distribution.
3.2. Center line temperature

Figure 8 shows the temperature at the Center line, for each flame observed. It appears that with the increasing speed of the fuel jet the higher the highest average temperature can be achieved at the center line. The highest temperature at the center line is reached at altitudes between 90 mm to 110 mm. For \( V_f = 0.154 \text{ m/s} \) the highest temperature at \( V_a = 15.924 \text{ m/s} \) this is because the equivalence ratio has a value of \( \phi = 1.46 \), so that the fuel mixture - air between stoichiometry and actual is not much different. Likewise with \( V_f = 0.330 \text{ m/s} \) the highest temperature at the center line is at \( V_a = 21.231 \text{ m/s} \) with the equivalence ratio has a value of \( \phi = 1.09 \).

![Figure 8. Center line temperature](image)

4. Summary

An experimental study was conducted to investigate the effects of different fuel jet speeds and air on the appearance of IDFs. The effect of the fuel jet speed on the appearance of the fire was investigated. The effect of the equivalence ratio on the flame length is checked. The main conclusions from this study are summarized below.

1. The length of the IDF flame below the speed of a constant air jet continues to increase with the speed of the air jet. The length of the flame that decreases with the speed of an increased air jet is observed because of better fuel entrainment which increases the mixture of air and fuel. For \( V_f = 0.154 \text{ m/s} \), the highest flame is 111 mm at \( V_a = 11.677 \text{ m/s} \) and \( V_f = 0.330 \text{ m/s} \) at \( V_a = 11.677 \text{ m/s} \) the highest fire height reaches 143 mm.

2. Temperature distribution is seen in more and more high temperature areas as air velocity increases and jet fuel speeds are constant. High temperature areas are in flames with \( V_a = 9.55 \text{ m/s} \); \( \phi = 2.43 \); \( V_f = 0.154 \text{ m/s} \) and \( V_a = 14.862 \text{ m/s} \); \( \phi = 1.56 \); \( V_f = 0.330 \text{ m/s} \). But the increasing speed of air jets in hot areas will also decrease.

3. The highest temperature at the centerline between 90 mm to 110 mm in temperature between 800°C and 1000°C. It can be concluded that the higher the speed of the highest temperature air jet in the line will be higher. This is due to the effective entrainment of the fuel, which leads to a better increase in fuel and air to produce an elongated IDF blue zone.

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