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Effect of Co-flow Condition on the Performance of Lifted Spray Flame

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ABSTRACT

Combustion is chemical reaction in which fuel is oxidized and large amount of energy is released. When fuel is burnt flame is generated. At low injection pressure, flame remains in contact with the nozzle tip. As the pressure increases flame starts breaking contact with the nozzle tip. At certain high pressure it completely breaks contact with the tip, and flame lifts at a certain height from the tip. The height at which flame is lifted is called Lift off height and the flame is called Lifted flame. As pressure further increases flame gets blown off at particular height, this height is called Blow off height. To obtain flameless combustion mode in a system, the combustion products need to be re-circulated in large quantities to ensure that the flame is blown-off from the primary combustion zone. Flameless combustion mode is preferred in order to minimize NO_x and CO emissions. Therefore, it becomes extremely important to understand the characteristics of lifted flames and their blow-off characteristics of spray flames under different conditions of co-flow velocity, fuel flow rate, preheating, and dilution of co-flow air. Co-flow condition involves the effect of varying co-flow velocity on the lifted spray flame.

In order to understand the flame characteristics we should know the spray characteristics as well. Thus, laser diagnostic methods such as PIV and Shadowgraphy can be used to study the spray characteristics like velocity and droplet diameter distribution.

In the present work, the above mention techniques are studied. Also the effect of various parameters like injection pressure, mass flow rate, and co-flow condition on lift-off height & blow-off conditions is studied with the help of experimentation.

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I. INTRODUCTION

The pollutant emissions from the combustion of the fossil fuels for power generation and propulsion systems have been negatively affecting the environment. Researchers are trying to reduce the emissions of greenhouse gases GHG through continuous improvements in the combustion processes whenever combustion process takes place, unwanted bi-products are also generated. These products include gases like NO_x and CO. Flameless combustion technique is proven as effective method for suppression of thermal NO_x in combustion systems. The burning of liquid fuels in flameless combustion mode becomes much more complex. Hence, the investigations on lifted spray flames are important to understand the flame dynamics.

In the present work, the effect of co-flow conditions and injection pressure on flame lift off height, blow-off, and flame fluctuations will be studied experimentally. Although a large amount of work on the behavior of lifted flames with gaseous fuels has been reported in the literature, very little work has been done for liquid fuels characterizing the flame lift-off and blow-off characteristics with different co-flow conditions. In this topic, how the co-flow of air affects the stability of lifted spray flame and how it is useful for the flame stability as well as for improving combustion is discussed.

Spray combustion is used in most of the industrial applications such as steam generation, industrial furnaces, residential heating, propulsion and power generation. Spray combustion plays a major role of the total energy requirement of the world due to its numerous applications.

The basic process of spray combustion comprise the injection of fuel, breakup of fuel into small droplets called atomization to increase the surface area so that the evaporation and heat transfer is enhanced and then burning.

A. Spray Flame

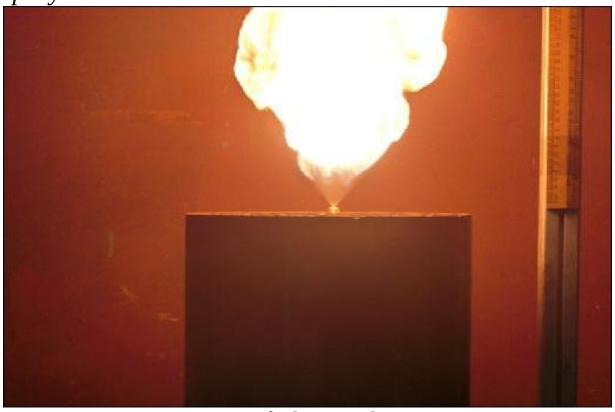

Fig. 1 Lifted Spray Flame

Fig. 1 shows the lifted spray flame for kerosene.
A spray flame is different than the gaseous flame because the composition is not uniform. The droplets in the spray are polydisperse in nature and all droplets are having different velocities. This nature of spray flame affects the propagation and stabilization of flame. The essential stages involved in spray combustion are atomization and burning of liquid fuel. The fuel is transmitted from the fuel storage tank by a fuel handling system such as pumps, filters and then atomized with nozzles in which the fuel is atomized into small droplets. These droplets are usually injected directly into the combustion chamber where they burn. Fig. 1 shows the lifted kerosene spray flame.

Understanding of detailed process of spray combustion required the adequate knowledge of burning of individual droplets because spray flame is nothing but the combined burning of individual droplets. It also required the knowledge of droplet size distribution and all processes from conversion of bulk liquid to droplets.

B. Liquid Fuel Nozzle

Design of atomizer or the injection nozzle plays a vital role in the atomization of droplets in order to get the required droplet size and velocity distribution. There are numerous ways to atomize the liquid, based on which, different kind of atomizers are designed according to their application. Atomizer used in this study is the Danfoss Solid Cone Nozzle as shown in fig. 2.

Fig. 2 Danfoss Simplex Nozzle

There are two basic types of simplex nozzles. In one design the spray is comprised of drops that are distributed fairly uniformly throughout its volume. This is generally described as solid cone spray. The other nozzle type produces a hollow cone spray in which most of the drops are concentrated at the outer edge of conical spray pattern. Solid cone type of nozzle is used in gas scrubbing, coke quenching, chemical processing and drenching operations. It consists of one piece cast body with a removable vane type core. This core features a cylindrical core that functions as plain orifice atomizers to provide drops at the centre of the conical spray pattern.

This nozzle has a special orifice outlet configuration to accent the corners of the spray pattern. It is designed to provide the sensibly uniform distribution of drops in a square pattern and is used for gas washing, fire protection, foam breaking, gravel washing and vegetable cleaning. The main drawback of solid cone nozzle is relatively coarse atomization, the drops at the centre of the spray being larger than those near the periphery. Hollow cone nozzles provide better atomization and their liquid distribution is also preferred for many industrial purposes, especially for combustion applications

II. Laser Diagnostic Methods

a Laser Diagnostic Methods are used to study the spray characteristics of liquid fuel. In order to study the flame characteristics we must know the spray characteristics. So to study the spray characteristics we must know the droplet size, droplet velocity etc. For this purpose, we use Laser Diagnostic Methods.

These methods include-

A) Shadowgraphy
B) Particle Image Velocimetry (PIV)

A. Shadowgraphy

Fig. 3 shows the schematic setup used for the shadowgraphy.

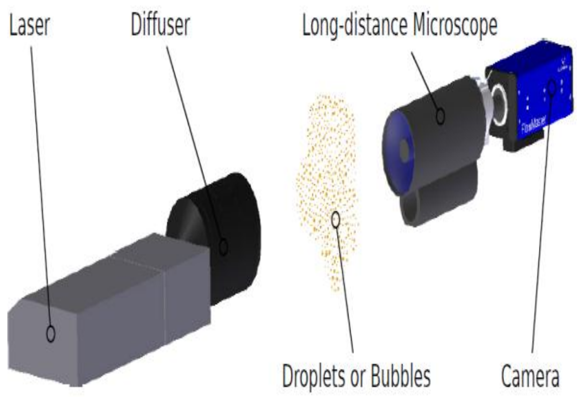

Fig. 3 shadowgraphy

The shadowgraphy technique (backlighting) is used to visualize particles (e.g. droplets from a spray or bubbles in liquid). The technique is based on high resolution imaging with pulsed backlight illumination. The measurement volume is defined by the focal plane and the depth of field of the imaging system. This technique is independent of the shape and material (either transparent or opaque) of the particles and allows to investigate sizes down to 5 µm using an appropriate imaging system and light source. The light source could be a pulsed laser with special illumination optics or a flash lamp. This depends on the size and velocity of the particles. Using a short laser pulse as illumination it is possible to 'freeze' motions of more than 100 m / s. A double-pulse laser combined with a double-frame camera allows investigating size dependent velocities. This technique provides information like size distribution, shape and velocity of particles.

B. Particle Image Velocimetry

Fig. 4 shows the schematic of setup used for the PIV method.

Many technical and scientific developments require a measuring technique that can measure the velocity distribution across an extended area of a flow field. PIV is such a technique. PIV is an optical, non-intrusive method that is related to both flow visualization and optical point techniques has developed over the last 20 years. This technique can provide an accurate quantitative measure of the instantaneous flow velocity field across a planar area of a flow field.

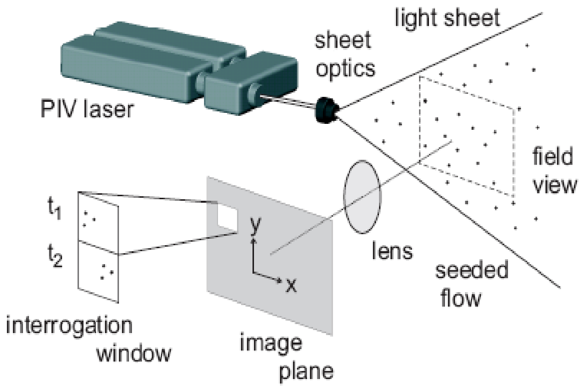

Fig. 4 Particle Image Velocimetry

PIV has become an important tool for quantitative and instantaneous measurement of laboratory flows. The flow is seeded with tiny, neutrally buoyant particles - so called 'tracers' - e.g. oil or water aerosols in air and solid particles in fluids or flames. Using a light sheet, formed by passing a double pulsed laser beam through an optical arrangement including cylindrical lenses, the particles in the flow are illuminated twice with a small time separation between. The displacement of particles in the time between the laser pulses is recorded as either a single image exposed twice or as a pair of two single exposure images. The recorded particle displacement field is measured locally across the whole field of view of the images, scaled by the image magnification and then divided by the known pulse separation to obtain flow velocity at each point. A camera positioned typically perpendicular to the plane of the light sheet is shuttered to capture the light scattered from the particles. Depending on the flow velocity and the factor of magnification of the camera lens the delay of the two pulses have to be chosen such that adequate displacements of the particle images on the CCD are obtained. From the time delay between the two illuminations and the displacement of the tracers velocity vectors can be calculated. For the evaluation of the particle images it is assumed that the tracers follow the flow into the local flow velocity between the two illuminations. The (digital) PIV recording is divided in small subareas so called 'interrogation windows'. Using statistical correlation techniques one local displacement vector is determined for each interrogation window. For this reason the size of this interrogation cell is selected such that all particles within this area have moved homogeneously in the same direction and the same distance. For good results the number of particles within one interrogation cell should be at least ten. The evaluation of the particle images depends on the way these images have been recorded by the used camera. One possibility is to record the scattered light of both illuminations in one frame what is called 'single frame / double exposure'. These pictures can be evaluated by auto- correlation. The other possibility is to record the scattered light from the first illumination in one frame and the scattered light from the second illumination in another frame. This is called 'double frame / double exposure'. These double frame images can be evaluated by cross-correlation.

III.LITERATURE SURVEY

Flameless combustion technique is proven as effective method for suppression of thermal NO_x in combustion systems.To obtain flameless combustion mode in a system, the combustion products need to be re-circulate in large quantities to ensure that the flame is blown-off from the primary combustion zone. Therefore, it becomes extremely important to understand the characteristics of lifted flames and their blow-off characteristics of spray flames [1].

In order to achieve flameless combustion, it is important to study flame characteristics like lift-off height, blow-off height etc. To study these parameters, a pressure-swirl type (solid cone) fuel nozzle is used due to its simplicity of construction, reliability, good quality atomization, and low pumping power requirements.

Characteristics of spray flames have been reported by many researchers. Chiu et al. [2] have observed that when liquid fuel is injected, a when liquid fuel is injected, a dense droplet cloud is formed near the nozzle exit (distance between the droplets is less than the droplet diameter), and the entrainment of surrounding air near the fuel nozzle is very small. As the co-flow velocity is increased, the droplets are moved to the downstream direction, and the distance between neighboring droplets increases, thus making the cloud as less dense and allowing for increased entrainment of air from surroundings [3]. Further downstream, fresh air gets entrained, and some of the droplets are surrounded with excess oxidizer. Due to this, some of the individual droplets at the outer periphery of the spray are surrounded by individual flames [2,3]. In reacting sprays, a flame stabilizes when small droplets are available (to readily provide a mixture of fuel vapor and air) along with large-scale flow structures. This enhances the mixing of the fuel vapor with the entrained air. A similar study on lifted spray flames with and without co-flow is also reported by Marley et al. [4,5]. They have reported that without co-flow, the flame exhibits a double flame structure and flame burns intermittently, and the addition of low-speed co-flow lifts the flame and leads to increased entrainment of air in the spray causing development of single flame structure and continuous smooth burning. The presence of large quantities of oxidizer within the fuel spray creates a unique double reaction zone structure. Therefore it is important to understand flame characteristics in preheat and dilute co-flow conditions.

L Vanquickenborne and A. Van tiggelen performed experimental analysis of Stabilization Mechanism of Lifted Diffusion Flames. They found that, measurements on gas composition, gas flow velocity, intensity and Eulerian scale of turbulence have been made in a free jet of methane emerging from a conventional circular burner into an unconfined atmosphere. Also they found that the base of a lifted diffusion flame occurs in a region where a stoichiometric composition is attained [6].

An experimental study was conducted by G. D. Myers and A. H. Lefebvre on the influence of fuel chemistry on the flame speeds of flowing mixtures of fuel drops in air at atmospheric pressure. They found that, flame speed increases with overall fuel/air ratio in the range studied for all fuels and all test conditions. Also, dependence of flame speed on fuel/air ratio increases with increase in air velocity, SMD and decreases with increase in fuel volatility. Increase in air velocity enhances the burning velocity for any given SMD, fuel/air ratio and fuel type [7].

Stefano Russo and Alessandro Gomez were conducted experiments on laminar spray diffusion flames of ethanol/argon burning in oxygen at pressures of 1 and 3 atm in 2002. Flame characteristics like droplet size and droplet velocity are measured with the help of Phase Doppler Anemometry. They found that, highly diluted spray diffusion flames were successfully stabilized at 1 and 3 atm in a co-flow configuration. Also, if Damkohler Number is less than 1 then complete evaporation of droplet takes place before reaching primary diffusion flame [8].

In year 2004, OH planar laser-induced fluorescence and smoke visualization have been performed by Marley et al in the near field of a turbulent ethanol spray flame to investigate reaction zone structure and the effects of air entrainment on combustion. Results shows, annular air co-flow surrounds an axi-symmetric spray injector utilize a pressure-swirl atomizer to supply a hollow cone fuel spray.

In the absence of a co-flowing air stream, the flame possesses a double reaction zone with an inner structure that burns intermittently with areas of local extinction occurring often at the most upstream locations near the leading edge. Also, the addition of low-speed co-flow increases the liftoff height resulting in higher entrainment rates and enhanced inner zone combustion [5].

Novid Beheshti et al devoted their work for the assessment of a new Eulerian model of two phase turbulent flows which introduced a transport equation for the average area of the liquid–gas interface which was proposed by R. Borghi and co-workers to predict the effects of liquid properties and injection regimes on the atomization quality. It is shown that the model predictions are in good agreement with the observed trends for a wide range of variations of the liquid properties, such as density and surface tension, as well as the injection regimes, defined by the liquid and gas jet exit velocities [9].

In 2007, Kumar et al. proposed a new flame extinction model based on the k/ε turbulence time scale concept. This model is proposed to predict the flame liftoff heights over a wide range of co-flow temperature and O2 mass fraction of the co-flow. They have developed a computational geometry for this model and tested for a variety of conditions: (a) ambient co-flow conditions (1 atm and 300 K) for propane, methane and hydrogen jet flames, (b) highly preheated co-flow, and (c) high temperature and low oxidizer concentration co-flow. They compared the results of computational results and experimental results and they found that predicted flame liftoff heights of jet diffusion and partially premixed flames are in excellent agreement with the experimental data for all the simulated conditions and fuels. Also, it is observed that flame stabilization occurs at a point near the stoichiometric mixture fraction surface, where the local flow velocity is equal to the local flame propagation speed [10].

In 2010, T. Gautam Kalghatgi conducted experiment to predict the lift off height of turbulent jet flames in still air for different gases. The lift-off heights and visible-flame lengths of jet diffusion flames in still air have been determined for gases like hydrogen, propane, methane and ethylene etc. He found that the flame lift-off height varies linearly with the jet exit velocity and is independent of the burner diameter for a given gas [11].

In 2012, Reddy et al. investigated the characteristics of lifted flame for different co-flow conditions. These conditions include a) Normal Co-flow b) Diluted Co-flow c) Preheated Co-flow. He found that the lift-off height is directly proportional to the co-flow velocity. Also he found that lift-off height increases with co-flow dilution. He has also studied the controlling parameters for the lifted spray flame [12]

IV. EXPERIMENTAL DEATILS

A. Equipments Used

Fig. 5 shows the schematic diagram of Lifted Spray Flame Setup as well as different components used.

Experimental setup consist of following equipments; Fuel Tank, Nitrogen Cylinder, Blower, Variac Transformer, Co-flow chamber, velocicalc etc.

Fuel tank is used for storing fuel, either kerosene or diesel etc.

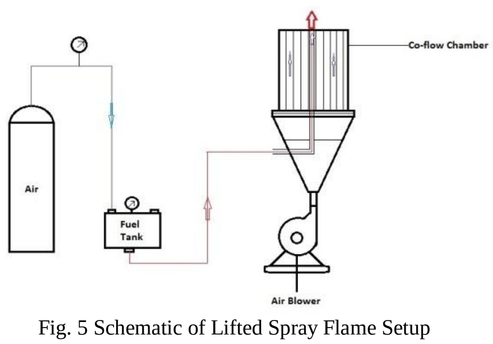

Fig. 5 Schematic of Lifted Spray Flame Setup

Purpose of using nitrogen cylinder is to pressurize the fuel present in the fuel tank with the help of nitrogen gas as it act as inert gas. The pressure range may vary from 5 to 12 bars.

Blower is used to deliver co-flow through co-flow chamber.

Variac Transducer is used to vary the speed of co-flow air from blower as we can control voltage provided to the blower.

Co-flow chamber is used for allowing Co-flow of air to move in direction of flame in vertical upward direction.

Velocicalc is used to measure the velocity of Co-flow of air.

Different Components are shown in images below:

Fig. 6 Nitrogen cylinder connected with the fuel tank

As shown in figure 6, Nitrogen gas from cylinder will come inside fuel tank in order to pressurize the fuel tank.

Fig. 7 Co-flow chamber

Fig. 7 shows the Co-flow chamber for the introduction of Co-flow of air.

B. Methodology

First experiment is carried out for the without Co-flow condition. In this we will not use the co-flow of air. Firstly the scaling is done and fuel in the fuel tank is pressurized with the help of nitrogen cylinder. Then valve of fuel tank is opened so that we get the fuel spray at required pressure through nozzle which is present at the centre of Co-flow chamber. Then spray is ignited so that we get the flame. Simultaneously we take the multiple images of Lifted Spray Flame with the help of high speed camera at certain speed. Then we can get the lift off height of individual image by processing it with the help of Gimp-2 software.

After the readings of without co-flow condition are completed we can repeat the procedure with co-flow conditions in which we will allow co-flow of air at required velocity to travel across periphery of flame. Again after taking multiple images at various velocities we can process images to get the variation in lift off height.

V. RESULT & DISCUSSION

In the above experiment we have calculated lift-off height at pressure of 4, 6, 8 bar for without and with co-flow condition at various velocities of co-flow. These velocities include 0.16 m/s, 0.21 m/s, 0.25 m/s, 0.31 m/s. The results are carried out for the nozzle of mass flow rate 5.84 Kg/hr.

The calculated average values of lift-off height (in mm) at different co-flow velocities are as shown in table below.

TABLE I

LIFT OF HEIGHT AT DIFFERENT PRESSURE AND DIFFERENT VELOCITIES

Pressure	**Co-flow Velocity(m/s)**				
	0	**0.16**	**0.21**	**0.31**	**0.36**
4 Bar	18.432	114.404	184.482	198.209	220.341
6 Bar	27.314	104.724	174.28	222.68	230.543
8 Bar	35.803	79.45	114.98	228.95	238.304

From values given in table 1, we can clearly say that the addition of co-flow results in increased lift-off-height at particular pressure.

Graph drawn below shows the Lift-off height vs Co-flow velocity curve at different pressures. From graph we can say that the trend followed by each pressure line is nearly same.

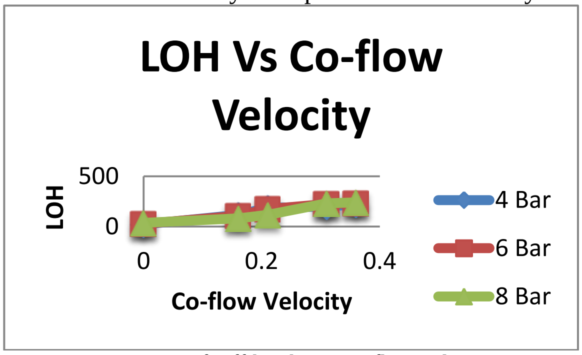

Fig. 6 Lift-off-height Vs Co-flow Velocity

The above mentioned results are for the Kerosene fuel and further work is going on different fuel.

VI.CONCLUSION

From table I, we can say that addition of co-flow results in increased lift-off height of Lifted Spray Flame.

Also, from literature review, we can observe that, without co-flow, the flame exhibits a double flame structure and flame burns intermittently also the addition of low-speed co-flow results in increase of lift off height the flame and leads to increased entrainment of air in the spray. This results in better efficiency of combustion. Also flame tries to get stable in a position where stoichiometry is obtained.

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