ABSTRACT

MOTHE, ANIRUDH REDDY. Local Flame Stabilization Mechanisms in Turbulent Non-Premixed Jet Flames in Vitiated Coflow by Particle Image Velocimetry (Under the direction of Dr. Venkateswaran Narayanaswamy.)

Local flame stabilization mechanisms in turbulent non-premixed jet flames in vitiated coflow are studied in the Turbulent Shear Flow Laboratory at North Carolina State University. Flame stabilization mechanisms in turbulent non-premixed methane jet flames in vitiated coflow are investigated experimentally using Particle Image Velocimetry (PIV) and Luminosity. The theory and mathematical background involved in PIV analysis is introduced and the critical steps required in developing an ideal PIV system are discussed in detail. Alumina tracer particles based PIV setup with two-seeder system was developed for flame analysis. The PIV system is validated by the multiple test conditions before proceeding into flame analysis. Classical lifted flames and turbulent non-premixed jet flames in vitiated coflow for Reynolds numbers 6000, 8000 and 12000 are analyzed using PIV and Luminosity. The speed of flame base in vitiated conditions is compared with classical lifted flames. The results showed that flame stabilizes at lower speed and the dependence on laminar flame velocity was seen all throughout the experiments. Lift off height trends of vitiated conditions are analyzed and compared with the classical lifted flames. The Probability Density Functions (PDF) of strain rate and vorticity values are analyzed.
Local Flame Stabilization Mechanisms in Turbulent Non-Premixed Jet Flames in Vitiated Coflow by Particle Image Velocimetry

by
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To my wonderful mom and dad.
BIOGRAPHY

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I would like to thank my inspiring advisor and great labmates for helping me achieve this.
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1 INTRODUCTION

The first set of eyes that evolved were capable of sensing light by recognizing the fluctuations between ambient brightness and darkness through photoreceptor proteins. This simplest ability to distinguish light from darkness gave unicellular organisms a huge survival advantage that propelled them in the direction of evolution of intricate and complex multicellular organisms. In highly evolved species like humans, the capability to distinguish varied intensities of light, developed into an ability to sense motion. Motion perception is one of the most primitive skills human beings use in day-to-day life and this ability improves their interaction with the environment.

The human eye is a high-speed camera that records multiple images of the surroundings continuously. The neural system relates the apparent position of an object in the current image with the same object in the previous image. This change in the stimuli associated with object movement in the continuous series of images is perceived as motion by the human eye. The human eye technique of motion detection under a controlled environment can be extrapolated to visualize the fluid flow of complex systems through particle tracking. This principle of tracking the apparent position of particles over a range of images helps us develop a global picture of the motion of flow in any given system.

The advent of lasers, high-speed cameras, and powerful computers expanded the reach of this particle tracking method to complex flow fields. Now, flow fields can be visualized instantaneously in the tiniest of flow spaces like blood vessels and the largest of wind tunnels.
at supersonic speeds. This particle tracking mechanism is called Particle Image Velocimetry or PIV. [1]

1.1 Turbulent Lifted Flame

Lifted flames have been the core of combustion research for the last five decades. Lifted flame chemistry is an amalgam of important characteristics like turbulence-chemistry interaction, heat transfer, chemical kinetics etc. Lifted flames serve as a point of convergence of chemical, thermal and fluid interactions yet continues to maintain its simplicity. The interest among researchers was always complemented by ample amount of resources due to the vast variety of industrial applications. After all, dependence on chemical energy (fossil fuels) still accounts to 80% of total energy production.

The advancements in understanding lifted turbulent diffusion flames have been extensively reviewed by Pitts [2] and Lyons [3]. Lyons broadly classifies the flame stabilization theories in turbulent diffusion flames as

1. Premixed flame theory
2. Critical scalar dissipation theory
3. Turbulent intensity theory
4. Large eddy theory
5. Edge flame theory

A significant stride in understanding diffusion flames came with the development of premixed flame theory by Vanquickenborne and Van Tiggelen [4]. This model assumes that the flame
stabilizes at a location where the fuel air mixture is completely premixed and stoichiometric. They have shown that blowout occurs downstream of the jet where the premixing is too lean to sustain a flame. The flame is stabilized when the turbulent burning velocity balances the incoming gas velocity. However, probability density analysis showed that the flame base position in the radial direction is intermittent and depends on large-scale turbulent structures.

Laminar Flamelet model of Peters and Williams [5] [6] proposed that the lifted flame stabilizes at a location where the scalar dissipation rate drops below a critical value. The model reasoned out that the flame therefore stabilizes downstream, where scalar dissipation rate is low enough to accommodate the flame. This model ignored the contributions of partial premixing of fuel and oxidizer to flame stabilization.

Edge flame theory introduced the concept of triple flame [7], where a region of rich zone exists on the fuel side, a diffusion flame in middle and a lean zone on the oxidizer side. The flame is stabilized by a partially premixed leading edge countering the incoming gas velocity. This triple flame structure is supported by the PIV and CH- OH PLIF (Planar Laser Induced Fluorescence) imaging by Watson [8].

Kelman [9] used the concept of premixed leading edge and combined it with the notion of local flame extinction by vortex formation. Kelman showed that the strong vortex fields around the flame base deprive the flame base of fuel, resulting in local extinctions. One of the major drawbacks of this theory is its inability to provide time sequences. Further work is needed in this area to confirm this theory.
1.1.1 Turbulent Jet flames in Vitiated coflow

Turbulent diffusion flames have gained significant attention from researchers over the years. Recently, however, there has been a growing interest in turbulent jet flames in vitiated coflow because of its applicability in combustion systems where hot combustion products are recirculated.

The work of Oldenhof [10] gave a glimpse into the contrast between lifted jet flames in vitiated coflow and classical lifted jet flames. The lift off height in a classical flame is stable and uniform, whereas a jet flame in vitiated coflow is unsteady. Figure 1 illustrates the temporal evolution of liftoff height of a jet flame in vitiated coflow in comparison with the uniform profile of a classical lifted jet flame. The sawtooth profile in Figure 1 indicates the unsteadiness of lifted jet flames in vitiated coflow.

![Figure 1](image)

**Figure 1** Evolution of flame base in jet flame in vitiated coflow vs cold coflow [11]

The conditions surrounding flame stabilization in turbulent methane jet flames in vitiated coflow are analyzed in our experiments using Particle Image Velocimetry and Luminosity.
2 PARTICLE IMAGE VELOCIMETRY

Particle image velocimetry (PIV) is a non-intrusive optical method to visualize flow fields. PIV consists of the following major subsystems:

1. Seeder particles
2. Illumination source
3. High speed CCD camera and lenses
4. Image processing unit

In PIV, tracer particles are added to the flow. These tracer particles are illuminated by thin sheets developed from two pulses of the laser. The light scattered from the tracer particles is recorded on different frames of the camera (sometimes on single frame, depending on the camera) as shown in Figure 2. These images are transferred to a computer where statistical methods are employed to calculate the displacement of particles. The time gap between two lasers pulse is used to determine local velocity vectors.

![Figure 2 Laser illumination of seeder particles [12]](image-url)
2.1 Seeder Particles

The seeder particles are chosen such that they align with the flow instantaneously and do not disturb the flow. In order to check the swiftness of particles in reaching the flow velocities, the following approach can be used.

By using the analogy of Stoke’s law for spherical objects in low Reynolds system [1]

\[ U_p - U_f = d_p^2 \frac{(\rho_p - \rho_f)}{18u_f} a \]

- \( U_p \) – velocity of particle
- \( U_f \) – velocity of fluid
- \( d_p \) – diameter of particle
- \( \rho_p \) – density of particle
- \( \rho_f \) – density of fluid
- \( \mu_f \) – viscosity of fluid
- \( a \) – acceleration of fluid

\[ U_p(t) = U_f \left[ 1 - \exp\left( -\frac{t}{\tau_s} \right) \right] \]

\[ \tau_s = d_p^2 \frac{\rho_p}{18\mu_f} \]

Relaxation time \( \tau_s \) serves as the simplest tool to calculate the time taken by seeder particles to attain the flow velocity. Using relaxation time \( \tau_s \), the location of the test section is adjusted such that tracer particles have sufficient time to attain flow velocities. This parameter only
works as a preliminary tool; in reality, acceleration of the fluid is not constant and equations are not valid in high Reynolds number systems.

2.2 Illumination Source

In PIV, high-energy laser pulses illuminate the particles. The following features are expected from an ideal laser source:

1. As dual pulses of the laser illuminate particles, a laser system with either high repetition rate or dual pulsing capability is desired.
2. External trigger mechanism with reliable repetition rate.
3. Externally controlled quality switch (Q switch) mechanism with precise pulsing time (order of nanoseconds). The Q-switch control capability helps to maximize the energy of the laser pulses.
4. The two pulses of the dual pulse laser must be identical to each other.
5. The two pulses of the dual pulse laser must be aligned such that they are focused at the same location. If the laser pulses are misaligned, they may illuminate different test locations, causing erroneous results.

2.3 Cameras and Optical setup

The evolution of high-speed cameras has increased the temporal resolution of PIV cameras that enabled acquisition of instantaneous detailed velocity profiles of high-speed flows. In PIV, image acquisition is done by two modes:

1. One illumination per frame approach
2. Multiple illuminations per frame

The second approach does not keep track of pulsing sequence, resulting in directional ambiguity. The first approach has an organized tracking mechanism internal to the system to resolve the directional ambiguity.

The following characteristics are expected from an ideal PIV camera:

1. High acquisition rate triggered by an external source
2. Detailed information about the delays associated with camera response time
3. Internal memory to store large number of images or high data transfer rates
4. Easy to use camera software facilitating wide range of image storage options
5. High temporal resolution, high quantum efficiency with high bit depths is preferred

The cost of CCD cameras varies drastically with camera acquisition rate and frame grabbers used by the camera. Hence, an informed choice must be made depending on accuracies desired from the experiments.

2.3.1 Optical Setup Theory

The lenses and mirrors are exposed to high-energy pulses from lasers; therefore, all the lenses and mirrors must be rated for the specific wavelength of the laser.

Laser light focused by a perfectly aberration free lens does not form a point but instead forms a circular disk and this circular pattern is termed Airy disk.
Figure 3 shows an Airy disk with decreasing intensity (indicated by the varying white shade) with increasing distance from the center. Though the diameter of the Airy disk is very small, it plays a significant role when the imaging involves micrometer-sized seeder particles. Airy disk limits the minimum image diameter that can be measured by the optical system.

The relation between object distance, image distance and focal length is given by

\[
\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}
\]

\(d_o\) - Object distance

\(d_i\) - Image distance

\(f\) - Focal length of lens

Magnification is given by \(M = \frac{d_i}{d_o}\)
The diffraction particle size is given by [13]

\[ d_s = 2.44^* (1 + M) \lambda \frac{f}{D} \]

\( d_s \) - Diffraction particle size

\( \lambda \) - Wavelength of the light

\( D \) - Diameter of the aperture

\( \frac{f}{D} \) ratio is called f-number of the lens denoted by \( f_n \)

The adjusted diameter of particle corrected for diffraction given by [1]

\[ d_c = \sqrt{(d_s)^2 + (Md_p)^2} \]

This equation shows that if the particle size is inconsequential compared to diffraction diameter, then effective diameter depends entirely on diffraction diameter and vice versa.
2.3.2 Depth of field

A converging lens generates a perfect image if the converging rays intersect at a point. If the camera lenses are not tuned precisely then a blurred image is formed, called out-of-focus image. Imperfect adjustment of the camera lens results in converging rays to intersect at numerous points along a small distance surrounding the point of focus. Figure 4 illustrates the contrast between perfect focus imaging and out-of-focus imaging.
The distance between the farthest and nearest point around which recognizable images are formed is called depth of field. Depth of field $\delta z$ is given by the following equation [14]

$$\delta z = 4(f_a)^2 (1 + M^{-2})^2 \lambda$$

The $\delta z$ value should be larger than the thickness of the laser sheet in order to prevent out of focus imaging.

2.4 PIV Image processing

In PIV, statistical analysis is based on correlation methods [15]. Cross-correlation [16] technique is used to relate dual frames recorded in short intervals and auto-correlation [17] method is employed when single exposure of the camera records dual pulses of the laser.

In contrast to particle tracking methods where flow field is established by tracking each particle individually, correlation based PIV works by developing averaging zones of particle displacements. These zones of motion are a small subpart of an image and are referred to as interrogation windows. Figure 5 demonstrates the division of 768 x 768 pixel area into interrogation windows of 128 pixel x 128 pixel window size.
In correlation method the combined intensity field is given by

\[ R(x, t) = I(x, t) \ast I(x + d, t) \]

- \( x \) – displacement coordinate
- \( t \) – time coordinate
- \( I(x, t) \) – intensity field of image
- \( I(x + d, t) \) – intensity field of image after displacement
- \( R(x) \) – Correlation function

In auto-correlation [1],

\[ R(x, t) = R_c(x, t) + R_f(x, t) + R_p(x, t) \]
\( R_c(x,t) \) – convolution of mean intensities
\( R_f(x,t) \) – fluctuating noise component
\( R_p(x,t) \) – self-correlation peak

Figure 6 shows the convolution peak, fluctuating noise peak and self-correlation peak. The self-correlation peak dominates in the auto correlation function as shown in Figure 6.

![Figure 6 Composition of peaks in auto-correlation function [18]](image)

In cross-correlation [1],

\[
R(x, t) = R_c(x, t) + R_f(x, t) + R_d(x, t)
\]

\( R_d(x,t) \) – correlation function developed from identical particles in both the images

Figure 7 shows the convolution peak, fluctuating noise peak and correlation function peak. The self-correlation peak dominates in the auto correlation function as shown in Figure 7.
Figure 7 Composition of peaks in cross-correlation [18]
3 DESIGN OF EXPERIMENT

Figure 8 PIV Layout
3.1 Burner Setup

Turbulent jet in vitiated coflow is generated by the burner setup designed by Ramachandran [11]. Vitiated coflow conditions are generated by stabilizing the flame on copper plate. This setup is modified to create conditions required for our experiment. A ceramic honeycomb shown in Figure 11 is placed above a copper plate to achieve conditioned laminar outflow of exhaust gases. This ceramic honeycomb is of 1-inch thickness and is placed at a distance of 2 inches from the copper plate. Air entrainment from the surroundings is avoided by using a hollow cylindrical open-ended 12-inch quartz chamber. The burner setup with all above-mentioned changes is shown in Figure 9.

![Figure 9 Burner setup](image-url)
The quartz chamber maintains its structural integrity at very high flame temperatures and at the same time provides excellent optical transmission for laser pulses in PIV. The quartz chamber is painted with high temperature resistant black paint on one-side. This black paint absorbs the laser reflections from the quartz surfaces and provides an ideal background for luminosity and PIV recordings. Figure 10 shows the quartz chamber painted in black paint on one-half.

Figure 10 Quartz chamber with black paint on one side

Figure 11 Ceramic honeycomb
3.2 Seeder System

One of the primary requirements of Particle Image Velocimetry is uniform seeding of the flow region. In order to achieve efficient and homogenous mixing of gases and tracer particles, a two seeder setup is designed. This system adds seeder particles to both the vitiated coflow and the turbulent jet of the burner. Seeder A is connected to the coflow inlet of the burner setup and Seeder B is connected to the center jet tube. The layout of seeder connections is shown in Figure 12.
3.3 Seeding Chamber

A seeding chamber has four major parts as shown in Figure 13. The gas travels through adjustable flow valves and enters the storage chamber through the inlet pipe at the bottom. These gases pick up the seeder particles in the storage chamber and exit through the outlet on top.

Figure 13 Seeding chamber exploded view
A specially designed swirler shown in Figure 14 is used to readily lift seeder particles in the storage chamber. The swirler has four outlets aligned at 90 degrees’ angle to each other. These outlets split the inlet gas into four ports of exit. The gas exits the outlets with the maximum tangential component of velocity. This ensures thorough mixing and lifting of seeder particles.

![Figure 14 Swirler top view (left) and isometric view (right)](image)

The seeder system has a storage chamber of 1 ft height and 3 inches’ inner diameter. The body of the seeding chamber is made of steel to withstand the high-pressure air entering the system. It is designed to handle an internal pressure of 150 psi. A single seeder weighs 21.5 kilograms and this weight by itself is enough to hold the setup from lifting off when high-pressure air enters the seeder. In addition to this, an additional precautionary measure of clamping the seeding chamber in all directions is followed.
3.4 Sheet optics

The beam from the PIV laser has a diameter of 3 mm. This beam is used to make a thin sheet with length ranging from 55 mm to 90 mm. In order to achieve this, an optical setup with two aligning mirrors, one plano-concave, one cylindrical and one plano-convex lens is deployed as shown in Figure 15.

![Optical sheet setup](image)

**Figure 15 Optical sheet setup**

The entire lens and mirror setup used in the sheet formation is rated for 532 nm wavelength. Despite lenses having their peak transmission at 532 nm, there are minor reflections from the lenses. The rogue reflections from this setup are contained from affecting the experiments by entrapping the setup with black cardboards in zones of reflection.
**Working**

A single pulse from the Nd-YAG laser has 25 mJ of energy. Focusing high-energy beam on a point can result in ionization of air; therefore, to avoid ionization, three lenses are used. Three-lens setup makes sure that the light is always focused to form a line instead of a point i.e., beam is either focused in the horizontal direction or vertical direction but not together at the same point. The length of the laser sheet can be adjusted by moving the cylindrical lens; therefore, there is no need to change the lens every time a sheet of new length is required. Figure 16 and Figure 17 illustrates the sheet formation using a concave lens (left), a cylindrical lens (middle) and a convex lens (right) in top and side view.

![Figure 16 Side view of sheet formation](image1)

![Figure 17 Top view of sheet formation](image2)
3.5 Seeder particles

Aluminum oxide (Al$_2$O$_3$) powder is used as the seeding material. It has a mean particle diameter of 5 micrometers. Alumina is non-reactive with the flow and has a high melting point of 2030 °C [19]. As the experiment involves methane combustion, where the flame temperature reaches 2200 K [20], alumina still acts as a good seeding material. The price of alumina is low compared to other seeding materials and it is readily available in the market.

The major problem faced with alumina powder is its tendency to agglomerate. The agglomeration is avoided by following steps:

1. Baking the particles to 250 °C to remove any traces of moisture. The seeder particles are kept as dry as possible by storing them in sealed containers when not in use.
2. The seeding chamber is designed such that there is rigorous agitation by the incoming gases that prevent the seeder particles from agglomerating.
3. All the pipelines are kept small and regular cleaning of the flow lines is ensured

The alumina particles may pose health hazards when large amounts of seeder particles are inhaled, therefore N99 Moldex masks are used throughout the experiments.
3.6 Luminosity Camera

Luminosity images are acquired by a high-speed CCD camera developed by JAI Inc. (Model number: CB-040GE) shown in Figure 18. The camera records images at a maximum of 61 fps. The duration of the camera exposure can be adjusted from 1µs to 16 milliseconds. The camera exposure and acquisition are controlled with the JAI Control Tool software provided with the camera.

![Luminosity camera](image)

**Figure 18 Luminosity camera**

This camera is triggered only through software and cannot be triggered externally with pulse generators. A lens of focal length f=50 cm is attached to the camera. The camera can easily record upwards of 10,000 images consistently without any change in the acquisition rate. This consistency in acquisition offers a great advantage in synchronizing the PIV and luminosity camera.
3.7 Laser and PIV Camera setup

Laser

In the current PIV analysis, PIV Minilite Nd-YAG laser [21] manufactured by the Continuum Lasers Systems is used. The laser offers a repetition rate of 1-15 Hz and pulses two beams each at an energy of 25 mJ at 532 nm wavelength. The laser has a Q switch, which can be triggered externally by a function generator. The beam diameter of the laser is 3 mm and pulse width of the laser pulse is 4-7 ns. In the current analysis, the repetition rate of the laser is set to 200 milliseconds/ 5 Hz.

Accurate information about the laser pulsing timing and the Q switch trigger are obtained from the laser manual. The alignment of two beams is verified by using the iris to check the position of laser impact. If there is any misalignment, the dichroics inside the laser are adjusted until a perfect match between the two laser pulses is achieved. Proper safety precautions should be followed in any operation dealing with the laser system.

The laser system pulses its maximum energy at a certain Q-switch duration specific to each laser. Q-switch time at which energy from the pulse is maximum is identified by plotting Q – switch time with energy meter readings. Initially, a low Q-switch time is selected and then increased in small intervals. The pulse energy recorded by the energy meter shows an increasing trend followed by a decreasing trend as shown in Figure 19 . This graph between Energy Vs Q-switch time delay can be used as a reference for future adjustments.
Laser systems tend to lose their energy over time. If a drop in the beam energy is detected, harmonic plates inside the laser are adjusted until the drop in energy is resolved.
PIV Camera

PIV images are recorded by PCO Pixelfly CCD camera [22] that offers external trigger and dual exposure modes with exposure time ranging from 1 µs to 1 minute. The camera acquisition sequence duration and exposure time can be controlled by the Camware software offered with the camera. The images recorded by the camera have a resolution of 1392 x 1080 pixels and these images are transferred to the RAM of a computer as soon as each image is recorded. The camera is attached to a lens of focal length 105 mm to accurately image the particles. Figure 21 illustrates the dual exposure mode of the PIV camera, where two images A and B are recorded with a short delay between them, followed by storage to the RAM.

![PIV Camera with lens](image)

**Figure 20 PIV camera with lens**

![Camera exposure and recording in dual exposure mode](image)

**Figure 21 Camera exposure and recording in dual exposure mode**
3.7.1 Laser and PIV camera layout

Laser and camera are triggered using a BNC 500 pulse generator with an accuracy of 20 ns. The circuit diagram of the triggering mechanism is shown in Figure 22.

![Laser and PIV camera flow chart](image)

**Figure 22 Laser and PIV camera flow chart**

The camera is triggered in the double exposure mode such that each pulse of the laser is recorded on a different frame of the camera. The timing between the pulses of the laser is adjusted through a pulse generator. The timing diagram of setup is shown in Figure 23.

![Timing Diagram of laser pulses and camera exposure](image)

**Figure 23 Timing Diagram of laser pulses and camera exposure**
3.7.2 Line filter

An ideal PIV camera should only record the illuminated particles. If the intensity of flame is high, then the camera records even the flame signal. The presence of flame may saturate the image resulting in loss of ability to clearly distinguish the seeder particles. This serves as a major hindrance for PIV analysis as information about the particles is lost in the flame signal.

This problem can be overcome by using a line filter. Optical filters are devices that allow a specific band of light to pass through them and reject other bands of light. In this setup, a 532 nm band pass line filter with FWHM of 10 nm made by Andover Corporation was used. The filter is attached to the lens of the camera. This line filter only allows the illuminated laser light to pass through leaving out the flame signal. Thus, the cameras only record the laser light scattered from seeder particles. Figure 24 shows the differences between saturated and non-saturated PIV images recorded with and without line filter respectively.

![Figure 24 PIV image of flame without (left) and with line filter (right)](image-url)
3.8 Key aspects for PIV

3.8.1 Synchronizing Cameras

Luminosity camera can only be triggered by the software provided with it. This poses a difficulty in tracking luminosity images with their respective PIV images.

This problem is addressed by repeating the following steps in each run:

1. View of both PIV camera and luminosity camera are blocked using a black cardboard
2. Laser-PIV camera setup is triggered by the function generator and luminosity camera is triggered by software.
3. The cardboard blocking the view of cameras is removed
4. The first image of the luminosity camera that records a laser pulse is mapped to the first image pair of PIV camera that records that laser pulse
5. Once the above stated first images are identified among the recorded images, then the further mapping is given by the following relation

   Nth-PIV image pair $\rightarrow$ first luminosity image with laser pulse $+12 \times (N-1)$ images

PIV camera records in pairs for every 200 milliseconds. The luminosity camera has an exposure time of 16 milliseconds. Therefore, if the first pair of PIV images with laser pulse is mapped with the corresponding luminosity image, then every next PIV image pair is related to every 12th ($200/16.66$) luminosity image as shown in Figure 25.
3.8.2 Pixel size and Particle size

Particle size, particle density and loss of particles by out of plane displacement significantly affect the accuracy of PIV measurements. If the particles size is very small (less than 1.5 pixels), the pixel displacements tend to be biased in favor of integer displacements. This introduces bias errors in the system. This phenomenon of displacements biased towards integer values is termed peak locking [23]. Numerous advancements like image deformation and window offset are employed in statistical analysis to minimize the effect of bias errors. However, adjusting the effective particle size from 1.5 pixels - 2 pixels yields the best results in PIV with minimum bias error. The probability density function (PDF) histogram of the PIV results act as a good indicator to estimate peak locking effect. The PDF curve for results with less peak locking tends to be uniform compared to the ones with strong peak locking. Figure
26 and Figure 27 respectively demonstrate the PDF curve for 2-3 pixels where peak lock is negligible and the PDF curve for less than 1 pixel where peak locking effect is significant.

Particle density should be uniform in the PIV images acquired. In ideal PIV images, the seeding is perfectly uniform such that no discernable flow fields are visible. However, at least 5 particles per window are expected for accurate PIV calculations. The interrogation window
controls the accuracy of PIV analysis; hence, optimal window size with optimal seeding density should be selected depending on the experiment.

Out of plane motion of particles causes loss of particles from the laser illuminated sheet, resulting in a reduction in the number of particles available for analysis. This problem is significant in highly turbulent flows with sharp velocity gradients in the direction normal to the imaging plane. This out of plane motion can be reduced by adjusting the time gap between two laser pulses such that loss of particles is reduced. However, if the time gap is too small, the accuracy of the system in imaging small displacements is greatly affected. In order to account for out of plane motion, the laser sheet must be thick enough to illuminate the outgoing particles and the depth of field of the camera should be larger than the laser sheet thickness to visualize these outgoing particles.

In our analysis, the camera and lens parameters are adjusted such that particle size remains in the 1.5-2-pixel zone. In the current experimental setup, the PIV camera setup is placed at a distance of 182 cm from the object plane. The camera lens is set to an f-number of 5.6. Table 1 shows the camera parameters used in our PIV camera setup to avoid peak locking effect.
### Table 1 Camera setup parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length - $f$</td>
<td>10.5 cm</td>
</tr>
<tr>
<td>Magnification - $M$</td>
<td>0.061</td>
</tr>
<tr>
<td>F-number - $f_#$</td>
<td>5.6</td>
</tr>
<tr>
<td>Wavelength - $\lambda$</td>
<td>532 nm</td>
</tr>
<tr>
<td>Diffraction diameter - $d_s$</td>
<td>7.71 $\mu m$</td>
</tr>
<tr>
<td>Particle Diameter - $d_p$</td>
<td>5 $\mu m$</td>
</tr>
<tr>
<td>Corrected Diameter - $d_c$</td>
<td>7.72 $\mu m$</td>
</tr>
<tr>
<td>Depth of field - $\delta z$</td>
<td>20 mm</td>
</tr>
</tbody>
</table>

**Time Gap**

Time gap between two laser pulses is another important factor that has a significant effect on the PIV analysis. If the time gap is too small, the lower velocity fields and velocity gradients are not accurately visualized in the analysis. If the time gap is too high, particles are lost due to out of plane motion and due to in-plane motion out of the interrogation window. The following are the allowable limits on particle displacement during $dt$ pulse separation:

\[
0.1 \text{ pixel} < d_s < \frac{\text{Interrogation window size}}{4}
\]

$d_s$ – particle displacement

The pulse separation duration must be chosen such that the above displacement limits are satisfied. Ideally, displacement of 8 pixels gives accurate results for a 64 x 64-pixel window.
3.9 Image Processing

Images recorded by the PIV camera and luminosity camera go through certain image preprocessing steps to transform into a form that can be finally processed by DAVIS software to get the desired flow field vectors.

3.9.1 PIV Image Preprocessing

Images from the PCO pixelfly camera are stored in the computer as 16-bit TIFF images. The following steps are adopted as part of image preprocessing:

1) Background subtraction: PIV images are always associated with background noise signal despite the utmost care taken to prevent any background signal from sneaking into recordings. The major source of background signals is laser reflections on the lens surfaces and reflections from seeder particles coagulated on the quartz tube. Reflections from the lenses can be avoided to an extent by isolating the system with black bodies to absorb the reflected laser light. Reflections from coagulated seeder particles are unpredictable and change with each experiment setting. This random noise is reduced by heating particles, which prevents seeder particles from settling on the quartz surface. The remnants of further noise are removed by averaging background images without seeder particles and subtracting from the actual recordings to acquire true images.

2) Flame signal subtraction [24]: The flame signal is avoided in the recording to a great extent by using a line filter of 532 nm. The leftover flame signal is removed by using sliding average background subtraction. In this method, the local average intensity of
a pixel over a specified length is calculated and subtracted from the original pixel intensity. The flowing approach is used for calculating local average:

\[ S_{\text{avg}} = I(0) \]

\[ S_{\text{avg}}(i) = \frac{(n-1)S_{\text{avg}}(i-1)}{n} + \frac{I(i)}{n} \text{ for } i \geq 1 \]

\( S(i) \) – Average Intensity of the \( i^{th} \) pixel

\( I(i) \) – Average of the \( i^{th} \) pixel

The filter goes through four passes from left to right, right to left, top to bottom and bottom to top to compute average intensity

Left to right

\[ S_{\text{avg}}(x, y) = \frac{(n-1)S_{\text{avg}}(x-1, y)}{n} + \frac{I(x, y)}{n} \]

Right to left

\[ S_{\text{avg}}(x, y) = \frac{(n-1)S_{\text{avg}}(x+1, y)}{n} + \frac{S_{\text{avg}}(x, y)}{n} \]

Top to bottom

\[ S_{\text{avg}}(x, y) = \frac{(n-1)S_{\text{avg}}(x, y-1)}{n} + \frac{S_{\text{avg}}(x, y)}{n} \]

Bottom to top

\[ S_{\text{avg}}(x, y) = \frac{(n-1)S_{\text{avg}}(x, y+1)}{n} + \frac{S_{\text{avg}}(x, y)}{n} \]
3) Normalization: In an ideal situation, both the laser pulses should trigger at the same energy to illuminate comparable number of particles with similar intensities in two pulses of the laser, but laser energy tends to fluctuate from the expected output. The cross correlation method has a default mechanism to normalize intensities before processing but an additional step of imposing certain threshold intensity limits followed by normalization tend to give better results. For example, in a 16-bit image, all the particles in lower intensity zones (order of 100 counts) and in higher intensity zone (above 60000 counts) are eliminated and followed by normalization.

The preprocessed images are processed in DAVIS software using cross-correlation method to get velocity flow field.

**PIV Post-Processing**

The velocity field acquired from the software has outliers associated with it. These outliers tend to introduce errors in the flow field that are not consistent with the true values. The outliers are eliminated by using DAVIS software. In our analysis, median filters are used to remove outliers.

In a median filter [25], values that deviate from average by certain allowable range are removed and replaced with correlation values that fit the window of the median filter calculation. The criteria to avoid vector removal are:

\[
U_{\text{median}} - a \times U_{\text{rms}} < U < U_{\text{median}} + a \times U_{\text{rms}} \\
V_{\text{median}} - a \times V_{\text{rms}} < V < V_{\text{median}} + a \times V_{\text{rms}}
\]
In Figure 28, median filter is applied to a 9 x 9 window and a mid-vector is detected as an anomaly as it is deviating from vectors in its neighborhood.
Luminosity Preprocessing

The quality of images acquired from the luminosity camera strongly depends on the glow from the hot surfaces of the burner setup. The effect of copper and ceramic glow is avoided by trapping them in closed bounds. The remaining signal is removed by using background subtraction. Figure 29 shows the comparison between luminosity image before and after background subtraction.

![Image showing luminosity image before and after background subtraction](image)

**Figure 29** Luminosity image before and after background subtraction
3.10 Validation

PIV Setup was subjected to a series of tests before proceeding with flame analysis to validate its authenticity in accurately predicting the results.

Test 1

In this condition, only cold-coflow is allowed to run through the system while there is no flow in the center jet. The coflow system is provided with series of flow conditioners to generate coflow with only axial component of velocity and negligible radial velocity. The PIV results of this condition are validated by checking for uni-directionality of the velocity field i.e. PIV vector plot should show only the axial velocity component and minimal radial velocity component.

The coflow is provided with pure air at 300 SLPM, which translates to 0.3 m/s of axial velocity in the test section. Table 2 shows the parameters used in the test.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coflow gas</td>
<td>Air</td>
</tr>
<tr>
<td>Coflow flow rate</td>
<td>300 SLPM</td>
</tr>
<tr>
<td>Coflow velocity</td>
<td>0.3 m/s</td>
</tr>
<tr>
<td>Pulse separation</td>
<td>320 µs</td>
</tr>
<tr>
<td>Q-switch delay</td>
<td>150 µs</td>
</tr>
</tbody>
</table>

The test section is a rectangle with 50 cm x 37 cm cross section. Test window is located one jet diameter above the coflow outlet.
Figure 30 shows the radial profile of average radial velocity at 5 diameters from the coflow exit. The radial component of velocity is minimal as shown in Figure 30; this is in conformity with the experiment condition of unidirectional axial velocity.

Figure 30 Radial profile x-directional coflow velocity at x/D=5
Figure 31 shows the average velocity vector plot superimposed on the average axial velocity contour plot of the coflow in the test window. The velocity vectors (red arrows) in Figure 31 illustrate that coflow has only x-direction (axial) component of velocity with minimal r-direction component of velocity. This confirms that PIV results are in accordance with the expected results.
Test 2

The test conditions used in the current analysis replicate the turbulent non-reacting jet flow experiments of Sandia National Laboratories [26]. Though the PIV setup differs from the Sandia propane jet setup in terms of the gases used and test section sizes, our setup conditions are adjusted to develop a system equivalent to that of the Sandia setup. The data from our setup is expected to replicate the trends seen in the Sandia propane jet. The test conditions in comparison to the Sandia setup are shown in Table 3.

<table>
<thead>
<tr>
<th>Test Parameters</th>
<th>PIV Setup</th>
<th>Sandia Jet [27]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Tube inner diameter (D)</td>
<td>0.53 cm</td>
<td>0.52 cm</td>
</tr>
<tr>
<td>Jet Tube outer diameter</td>
<td>1.27 cm</td>
<td>0.90 cm</td>
</tr>
<tr>
<td>Jet Tube length</td>
<td>0.990 m</td>
<td>2 m</td>
</tr>
<tr>
<td>Coflow diameter</td>
<td>15.2 cm</td>
<td>20 cm Square Cross section</td>
</tr>
<tr>
<td>Coflow gas</td>
<td>Air</td>
<td>Air</td>
</tr>
<tr>
<td>Coflow Velocity*</td>
<td>0.45 m/s</td>
<td>9.2 m/s</td>
</tr>
<tr>
<td>Coflow temperature</td>
<td>294 K</td>
<td>294 K</td>
</tr>
<tr>
<td>Jet Gas</td>
<td>Air</td>
<td>Propane</td>
</tr>
<tr>
<td>Jet velocity*</td>
<td>36 m/s</td>
<td>53 m/s</td>
</tr>
<tr>
<td>Jet Reynolds number*</td>
<td>12500</td>
<td>68000</td>
</tr>
<tr>
<td>Jet Temperature</td>
<td>294 K</td>
<td>294 K</td>
</tr>
</tbody>
</table>

* The values are based on the exit velocity from the jet tube before the test section
Figure 32 shows the radial profile of average axial velocity at a distance of 1 jet diameter from the jet exit. The peak velocity at jet exit (43 m/s) shown in Figure 32 is consistent with the fully developed turbulent flow solution [28].

Our PIV setup could not reach coflow velocities as in the Sandia setup; therefore, in order to accommodate this discrepancy, normalized plots are used for test scenario validation. In Figure 33 and Figure 34, the normalized radial profiles of x-direction and r-direction components of velocity of our PIV setup are compared with the results of the Sandia jet at a distance of 5 diameters from center jet i.e. x/D=5.
Figure 33 Radial profile of $x$-directional velocity of PIV setup (solid line) and Sandia Jet (dotted) at $x/D=5$

Figure 34 Radial profile of $r$-direction velocity of PIV setup (solid line) and Sandia Jet (dashed) at $x/D=5$
4 RESULTS AND DISCUSSION

In our analysis, the flow field surrounding the flame base in vitiated coflow is studied for three different Reynolds numbers $Re=6000$, $Re=8000$ and $Re=12000$. The flow field data acquired from the vitiated coflow case is compared with similar data acquired from the classical lifted flames.

Figure 35 shows the lift off height plot for three different Reynolds numbers calculated from 100 instantaneous luminosity images in vitiated coflow. From Figure 35, it can be inferred that these specific Reynolds numbers offered significantly different flame lift off heights. This provided a chance to look into the velocity field at the flame base at varied distances from the jet tip.

![Figure 35 Flame lift of height for Re=12000(red), Re=8000(green) and Re=6000(blue) in vitiated coflow](image)
All the test parameters used in the experiment are shown in Table 4. The equivalence ratio of the coflow is maintained at 0.625 throughout the vitiated coflow experiments. This equivalence ratio produced cases where auto ignition occurred for all the three Reynolds numbers. The temperature above the jet exit is maintained well above the auto ignition temperature of methane (810 K) by the vitiated coflow. The plot of radial temperature profile at one diameter above the jet exit is shown in Figure 36. In Figure 36, the drop in temperature at the center jet is attributed to heat dissipation to the jet tube and heat loss to the air flowing at Re=8000 in the center jet.

<table>
<thead>
<tr>
<th>Test Parameters</th>
<th>Vitiated Coflow</th>
<th>Classical Lifted Flames</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coflow Air flow rate</td>
<td>259 SLPM</td>
<td>283 SLPM</td>
</tr>
<tr>
<td>Coflow Methane flow rate</td>
<td>23.8 SLPM</td>
<td>0</td>
</tr>
<tr>
<td>Equivalence Ratio of Coflow</td>
<td>0.625</td>
<td>0</td>
</tr>
<tr>
<td>Coflow velocity</td>
<td>0.25 m/s</td>
<td>0.25 m/s</td>
</tr>
<tr>
<td>Methane jet flow rate</td>
<td>50 SLPM, 66 SLPM,</td>
<td>50 SLPM and 100 SLPM</td>
</tr>
<tr>
<td></td>
<td>and 100 SLPM</td>
<td></td>
</tr>
<tr>
<td>Reynolds numbers</td>
<td>6000, 8000 and 12000</td>
<td>6000 and 12000</td>
</tr>
</tbody>
</table>
Flame edges are acquired from the luminosity images using Matlab’s Sobel filter and mapped with the respective PIV images. Figure 37 shows the flame edge extraction from the luminosity image using Sobel filter. The instantaneous flame edge extracted from luminosity images are superimposed on the respective PIV images to visualize flow field at the flame base. Figure 38 and Figure 39 shows superimposed images of instantaneous flame edge and corresponding PIV velocity vectors and axial velocity contour plot.

Figure 39 suggests that velocity gradients and vorticity fields exist at the zone of fluid-flame interaction. This behavior motivated us to look into the velocity field surrounding the lifted flame for different Reynolds numbers.
Figure 37 Flame edge extraction from luminosity image

Figure 38 Vector profile surrounding the flame base (black line)
Figure 39 Enlarged Vector profile surrounding flame base (black)
**Probability Density Function**

All further analysis centers around developing probability density plots for the data collected from the experiments. The PDF is calculated using the following sequence of steps:

1. Matlab Distribution Fitting toolbox is used for PDF calculations. 1000 data sets are processed for each density plot to ensure accuracy. A large number of data sets minimizes the effect of random noise associated with the results.

2. The first step in developing the PDF is deciding the bin width. Matlab offers Freedman-Diaconis Rule for bin width determination by default, but this width is modified using the custom bin width option. If the bin width is too small, it creates high noise levels, and if it is too big, approximated results are acquired. The bin width is set such that the noise level is low and accuracy is not compromised. A compromise is achieved by using Freedman-Diaconis rule to get an estimated bin size, followed by changing values in the estimated bin size neighborhood to acquire precise results.

3. Once the PDF is calculated, an Empirical Cumulative Distribution Function (ECDF) is developed by plotting mid points of each bin on the x-axis and the corresponding bin height on the y-axis.

All throughout this report ECDF and PDF are used interchangeably. The plots have different bin size depending on the data range. For example, velocity with data ranging from 5-50 m/s has a bin size of 0.5 m/s and the strain rate with data ranging from 100-10000 1/s has a bin size of 500 1/s.
4.1 Axial Velocity

4.1.1 Vitiated coflow

The axial component of velocity at the flame base for the vitiated coflow case is calculated for Re=6000, Re=8000 and Re=12000. Figure 40 shows the probability density function of this data. The mean jet exit velocity at the jet base is 27 m/s, 36 m/s and 54 m/s for Re=6000, Re=8000 and Re=12000 respectively. Figure 40 illustrates that the maximum probable velocity at the tip of the flame base is well below the mean jet exit velocity.

Figure 40 PDF of Axial velocity at flame base for Re=6000, 8000 and 12000 in vitiated coflow
The PDF of axial velocity shown in Figure 40 hints at the following possible scenarios:

i) The flame base prefers lower velocity zones over high velocity zones.

ii) The jet center line is associated with high velocities; implying that flame base gravitates to move away from the jet centerline and closer to low velocity zones.

In order to check the validity of the second scenario, the most probable location of the flame base in the test section in the radial and axial direction is identified by developing a PDF of the radial and axial location of flame base.

![PDF of Radial location of flame base in vitiated coflow](image)
Figure 41 and Figure 42 show PDF of radial and axial location of flame base for three different Reynolds numbers in vitiated coflow condition. From the PDFs in Figure 41 and Figure 42, the most probable location of flame base is tabulated as displayed in Table 5

<table>
<thead>
<tr>
<th>Reynolds Number</th>
<th>Axial distance x/D</th>
<th>Radial location r/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>6000</td>
<td>42.75</td>
<td>-4.5</td>
</tr>
<tr>
<td>8000</td>
<td>35.75</td>
<td>-3.25</td>
</tr>
<tr>
<td>12000</td>
<td>29.75</td>
<td>-3.75</td>
</tr>
</tbody>
</table>
Table 5 shows that the radial flame base location ranges between 3-5 diameters. This shows that the flame base prefers a location away from the jet centerline. Therefore, the second scenario that the flame base exists in a zone away from high velocity jet centerline where velocity is low is valid.

### 4.1.2 Classical lifted flames

PDFs similar to Figure 41 and Figure 42 discussed previously are developed for classical lifted flames for Reynolds numbers Re=6000 and Re=12000. Figure 43 shows the PDF of radial and axial location of the flame base in classical lifted flames for Re=6000 and Re=12000.

![PDF of Radial (left) and Axial (right) location of flame base in classical lifted flames](image)

**Figure 43 PDF of Radial (left) and Axial (right) location of flame base in classical lifted flames**

<table>
<thead>
<tr>
<th>Reynolds Number</th>
<th>Axial distance x/D</th>
<th>Radial location r/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>6000</td>
<td>17.62</td>
<td>2.62</td>
</tr>
<tr>
<td>12000</td>
<td>20.75</td>
<td>-1.87</td>
</tr>
</tbody>
</table>

**Table 6 Maximum probable Radial and Axial location of flame base for classical lifted flames**
From the PDFs in Figure 43, the maximum possible location of the flame base is tabulated as displayed in Table 6. Table 6 shows that the radial flame base location ranges between 1.5-3 diameters. It can be inferred that flame base prefers a location away from jet centerline. This observation in classical lifted flames is similar to the observation in vitiated coflow case shown in Section 4.1.1.

### 4.2 Conditional and Unconditional Axial Velocity

**Conditional velocity**: The velocity at the flame base is termed as conditional velocity. PDF of conditional velocity gives insight into the most preferred flame base velocity.

**Unconditional velocity**: The velocity calculated at maximum probable flame location irrespective of the presence of flame is termed Unconditional velocity. For example, in Table 5 for Re=12000, the maximum probable position of flame base is identified as x=29.75D and r=3.75D. At this location, velocity is calculated for all the images irrespective of flame presence. This is called unconditional velocity for Re=12000. The PDF of unconditional velocity gives insight into the most probable speed at the flame base when the flame is absent.

#### 4.2.1 Vitiated coflow

The PDF of unconditional axial velocity in vitiated coflow is compared against the PDF of conditional velocity in vitiated coflow for Re=6000, Re=8000 and Re=12000. Figure 44 illustrates the comparison between PDFs of conditional and unconditional axial velocities for three Reynolds numbers Re=6000, Re=8000 and Re=12000.
From the PDFs in Figure 44, the most probable conditional and unconditional axial velocities are tabulated as displayed in Table 7. Table 7 shows that the most probable unconditional axial velocity is higher than the most probable conditional velocity. This behavior is consistently repeated for all the three Reynolds numbers. The unconditional velocity values are over predicted because of the flame base oscillation above and below the maximum probable flame.

<table>
<thead>
<tr>
<th>Reynolds number</th>
<th>Conditional, m/s</th>
<th>Unconditional, m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak 1</td>
<td>Peak 2</td>
</tr>
<tr>
<td>6000</td>
<td>0.25</td>
<td>-0.25</td>
</tr>
<tr>
<td>8000</td>
<td>0.25</td>
<td>-0.25</td>
</tr>
<tr>
<td>12000</td>
<td>0.25</td>
<td>-0.25</td>
</tr>
</tbody>
</table>
location, which results in few recordings from burnt gases and the others from unburnt gases. The burnt gas velocity is higher than the unburnt gas velocity because of the volume expansion of gas at the flame base. These higher velocity recordings contribute to over predicting the unconditional velocity.

### 4.2.2 Classical lifted flames

PDFs similar to Figure 44 (discussed in Section 4.2.1) are developed for classical lifted flames for Reynolds numbers Re=6000 and Re=12000. Figure 45 shows the comparison between PDFs of conditional and unconditional axial velocities in classical lifted flames for Reynolds numbers Re=6000, and Re=12000.

![Figure 45 Conditional and Unconditional axial velocity PDF at Re=6000 (left) and Re=12000 (right) in classical lifted flames](image)

---

Figure 45 Conditional and Unconditional axial velocity PDF at Re=6000 (left) and Re=12000 (right) in classical lifted flames
Table 8 Maximum probable conditional and unconditional axial velocity in classical lifted flames

<table>
<thead>
<tr>
<th>Reynolds number</th>
<th>Conditional, m/s</th>
<th>Unconditional, m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>6000</td>
<td>0.25</td>
<td>0.75</td>
</tr>
<tr>
<td>12000</td>
<td>0.25</td>
<td>2.75</td>
</tr>
</tbody>
</table>

From the PDFs in Figure 45, the maximum possible conditional and unconditional axial velocities are tabulated in Table 8. Table 8 shows that the most probable unconditional axial velocity is higher than the most probable conditional velocity for all the Reynolds numbers. This observation in classical lifted flames is similar to the observation in vitiated coflow discussed in section 4.2.1.

4.3 Summary

Table 9 Summary of all cases in vitiated coflow and classical lifted flames

<table>
<thead>
<tr>
<th></th>
<th>Vitiated coflow</th>
<th>Classic lifted flames</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds number</td>
<td>6000 8000 12000</td>
<td>6000 12000</td>
</tr>
<tr>
<td>Coflow velocity, m/s</td>
<td>0.25 0.25 0.25</td>
<td>0.25 0.25</td>
</tr>
<tr>
<td>Jet velocity, m/s</td>
<td>27 36 54</td>
<td>27 54</td>
</tr>
<tr>
<td>Axial distance, x/D</td>
<td>42.8 35.8 29.8</td>
<td>17.625 20.75</td>
</tr>
<tr>
<td>Radial distance, r/D</td>
<td>4.5 3.25 3.75</td>
<td>2.625 1.875</td>
</tr>
<tr>
<td>Mean Conditional velocity, m/s*</td>
<td>0.99 1.16 0.85</td>
<td>0.92 0.9</td>
</tr>
<tr>
<td>Mean Unconditional velocity, m/s*</td>
<td>1.625 1.375 1.625</td>
<td>0.96 1.8</td>
</tr>
<tr>
<td>Images per case</td>
<td>1000 1200 1200</td>
<td>1000 1000</td>
</tr>
</tbody>
</table>
*Mean velocities listed in the table above are calculated using the following sequence of steps:

1. The maximum probable data point in the PDF is identified. An area of 70% surrounding this maximum probable data point is calculated as shown in Figure 46.

2. The weighted average of all data points that are present in this 70% area is calculated to give mean velocity.

This method helps to rule out the effect of extreme values on the mean velocity.

Figure 46 70% Area around the maximum probable location
Table 10 Summary of classical lifted flames cases by L. Muniz and M.G. Mungal [29]

<table>
<thead>
<tr>
<th></th>
<th>Classical lifted flames</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re</td>
<td>3900 3800 4000 10500</td>
</tr>
<tr>
<td>Coflow velocity, m/s</td>
<td>0.58 0.43 0.27 0.28</td>
</tr>
<tr>
<td>Jet velocity, m/s</td>
<td>14 14 14 38</td>
</tr>
<tr>
<td>Axial distance, x/D</td>
<td>21.6 17.8 14 31</td>
</tr>
<tr>
<td>Radial distance, r/D</td>
<td>3.2 3 2.6 5.5</td>
</tr>
<tr>
<td>Mean Conditional velocity, m/s</td>
<td>0.9 0.9 0.8 0.8</td>
</tr>
<tr>
<td>Mean Unconditional velocity, m/s</td>
<td>1.4 1.6 1.0 1.1</td>
</tr>
<tr>
<td>Images per case</td>
<td>66 41 44 52</td>
</tr>
</tbody>
</table>

All the cases discussed in the previous sections are summarized in Table 9. A summary of the experiments by L. Muniz and M.G. Mungal [29] on classical lifted flames is shown in Table 10 for comparison.

4.3.1 Observations

The follows observations can be made from Table 9 and Table 10:

1. In classical lifted flames, our data is in accordance with data from L. Muniz and M.G. Mungal [29]
2. Lower speed is observed in the conditional case compared to the unconditional case for both vitiated coflow cases and classical lifted flames
3. Laminar flame speed of methane at stoichiometric ratio is $S_L=0.4$ m/s. The mean conditional velocity for all three Reynolds numbers in vitiated coflow case never exceeded $3*S_L$
4. The mean conditional velocity in classical lifted flames never exceeded $3*S_L$, which is consistent with observations from L. Muniz and M.G. Mungal [29]
5. The most probable conditional velocity at the flame base for vitiated coflow never exceeded $S_L$.

6. The most probable conditional velocity at flame base for classical lifted flames never exceeded $1.5 \, S_L$, which is consistent with observations from L. Muniz and M.G. Mungal [29].

### 4.4 Radial fluctuations or Meandering

In the PDF plots shown in Figure 44 and Figure 45, occasionally, high velocity values that exceeded mean velocity values by a large margin were observed. This behavior is attributed to the meandering nature of the jet. Turbulent jet exhibited radial meandering, causing the high-speed jet fluid to move closer to the jet edge resulting in high velocity.

![Figure 47 Scatter plot of flame base location for Re=12000](image)
Figure 47 shows the scatter plot of flame base location for 200 data points at Re=12000. From Figure 47, it can be observed that the flame base fluctuates radially around the center jet. These radial fluctuations cause occasional high velocities at the flame base. This meandering nature of the jet is one more reason to neglect high velocity values in the mean velocity calculations.

4.5 Lift-off Height

The lift-off height in vitiated coflow case consistently decreased with increase in Reynolds number as shown in Figure 48. Figure 48 illustrates change in lift-off height with increasing Reynolds number in vitiated coflow conditions.

![Figure 48 Lift-off height as a function of Reynolds number in vitiated coflow](image)
Figure 49 illustrates change in lift-off height with increasing Reynolds number in classical lifted flames. Figure 49 shows that lift-off height increases till Re=8000, followed by slight decrease at Re=12000.

![Graph showing lift-off height as a function of Reynolds number in classical lifted flames](image)

**Figure 49** Lift-off height as a function of Reynolds number in classical lifted flames

### 4.6 RMS lift-off height fluctuations

Root Mean Square (RMS) lift-off height fluctuation increased with increasing Reynolds number in vitiated coflow cases. Similar behavior was observed in classical lifted flames. Figure 50 shows a plot between RMS lift-off height fluctuations and Reynolds number for both vitiated coflow cases and classical lifted flames. Figure 50 illustrates that RMS lift-off fluctuations increased with increase in Reynolds number for both vitiated coflow conditions and classical lifted flames.
Figure 50 RMS lift-off height fluctuations as a function of Reynolds number in vitiated coflow (left) and classical lifted flames (right)
4.7 Absolute strain rate $|E_{xx} - E_{yy}|$-Vitiated coflow

To further the understanding of flame base stabilization, a PDF analysis similar to that of axial velocity discussed in Section 4.2.1 was done on the absolute strain rate. The PDF of the absolute strain rate calculated at the flame base for three different Reynolds numbers in vitiated coflow is shown in Figure 51. Figure 51 shows that the maximum probable strain rate is approximately the same for all three Reynolds numbers.

Figure 51 PDF of Absolute strain rate at flame base for Re=6000, 8000 and 12000
Figure 52 illustrates the comparison between PDFs of conditional and unconditional absolute strain rates for three Reynolds numbers, Re=6000, Re=8000, Re=12000. The PDF of conditional strain rate peaked at slightly lower values than unconditional strain rate as illustrated in Figure 52. Though the drop in strain rate is very small at the flame base, it is consistently repeated in all the three readings.
4.8 Vorticity-Vitiated coflow

The PDF plot in Figure 44 for Re=12000 case exhibited the presence of a second PDF peak at negative velocity values. A trailing vortex field shown in Figure 53 is detected at the flame base in the PIV recordings. The negative velocity fields could be attributed to the presence of vorticity fields resulting in the occurrence of flow reversal. The superimposed vortex field images from PIV and the flame edge images shown in Figure 53 illustrates the presence of vortex zones near the flame edge.

Figure 53 Vorticity field surrounding flame base (shown as black edge)
5 CONCLUSIONS

The flame stabilization mechanisms in turbulent non-premixed methane jet flames in vitiated coflow are investigated experimentally using Particle Image Velocimetry and Luminosity. Previous theories and research about the stabilization mechanisms in turbulent lifted diffusion flames are presented and the short-comings of these theories are briefly discussed. The theory and mathematical background involved in PIV analysis is introduced. The critical steps required in developing an ideal PIV system are discussed in detail. Alumina tracer particles based PIV setup with two-seeder system was developed for flame analysis. The PIV system is validated by multiple test conditions before proceeding to flame analysis.

As a part of flame analysis, turbulent non-premixed flames at Re=6000, Re=8000 and Re=12000 in vitiated coflow at an equivalence ratio of 0.625 are investigated. These cases are compared with turbulent lifted diffusion flames for Re=6000 and Re =12000. The following conclusions are made from the experiments:

i) The flame base preferred low velocity zone over high velocity zone.

ii) The flame base was radially located at 3-5 diameters from center jet in vitiated coflow case and 1-3 diameters from center jet in classical lifted flames.

iii) The mean conditional velocity in vitiated coflow cases and classical lifted flame cases never exceeded 3* $S_L$.

iv) The most probable conditional velocity at the flame base for vitiated coflow cases and classical lifted flames never exceeded 1.5 $S_L$. 

v) All the observations in the classical lifted flames are consistent with the work of other researchers.

vi) The turbulent jet exhibited radial meandering. This meandering resulted in occasional high velocities at the flame base.

vii) A decrease in flame lift-off height with increasing Reynolds number was consistently observed throughout the experiments in vitiated coflow cases. In classical lifted flames, the flame lift-off height increased with Reynolds number till Re=8000, followed by a decrease in lift-off height for Re=12000.

viii) The RMS lift-off height increased with increasing Reynolds number for both vitiated coflow cases and classical lifted flames.

ix) Vorticity fields are observed at the flame base in vitiated coflow cases. The negative velocities at the flame base are attributed to these vorticity fields.

5.1 Future work

The flame analysis can be made much more reliable and certain, if the PIV data is complemented with CH-OH PLIF experiments. The predictions made from the PIV data about partial premixing can be accurately verified if simultaneous PLIF and PIV imaging is done.

The current work is completely centered around the equivalence ratio of 0.625. The same analysis could be extended to a multitude of equivalence ratios and their effects on the flame stabilization can be studied. The role of vortices in flame stabilization could be explored further. This again needs PLIF imaging to develop accurate conclusions about the role of vortices in flame extinction and stabilization.
The role of turbulent flame speed in stabilizing the flame has not been addressed. There is ambiguity among the researchers about the role of turbulent flame speed in flame stabilization. This area could be explored further to develop conclusive predictions regarding turbulent flame speed.
6 REFERENCES


