# FLAME ANALYSIS SYSTEM FOR METHANE-AMMONIA DIFFUSED GAS USING SCHLIEREN TECHNIQUE

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# Abstract

Optical diagnostics utilizing imaging system have been significant in the experiments of combustion and fluids. Nonetheless, the majority of imaging techniques primarily focus on the analysis of premixed flames. As the interest in alternative fuel systems utilizing diffused gas increases, there is a high demand for the advancement of methods that enable the analysis of diffused flames. The objective of this research is to create a novel Schlieren system by utilizing the Z-type Schlieren technique in experimental settings, building upon the conventional methodology. Additionally, various aspects of fluid mechanics and combustion, including Schlieren imaging, have been explored through the application of multiple optical methods. Schlieren technique is an effective method for combustion diagnostics, based on the fact that light rays are bent whenever they encounter changes in the density of a fluid. Schlieren system is generally used to visualize the flow away from the surface of an object. This research applied the well-known Schlieren setup to analyze methane-ammonia diffused gas from which the hot air around the flames could be visualized. The setup has been designed by using Z-type Schlieren technique to emphasize the three major aspects of light (refraction, coma, and astigmatism). By implementing this system, the diffused flame initialization, formation, lift off and blow out could be projected and analyzed for methane-ammonia diffused flame.

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# Chapter 1: Background

## 1.1 Motivation

Given the vital role combustion plays in modern industry, numerous methods and models have been devised to comprehend the intricate theories and behaviors underlying this complex phenomenon. Combustion, as a rapidly advancing field, encompasses diverse subjects such as ignition, flame dynamics, flame quenching, fuels, and chemical reaction mechanisms. Progress in the science of combustion has significantly contributed to enhancing fuel efficiency, exploring alternative energy sources, advancing power generation and transportation systems, as well as reducing pollutant emissions.

In recent times, optical techniques like Schlieren/Shadowgraph, Radioactive Tracers, PIV, and PLIF have gained widespread usage in visually and numerically analyzing the combustion process. By combining optical visualization, high-speed imaging, and image processing, the understanding of combustion characteristics can be expanded and enhanced [1].

Diffusion flame occurs when fuel vapor and air meet, unlike premixed flame where the fuel and oxidant are already mixed before ignition. The mixing process plays a crucial role in the formation of diffusion flames. To visualize diffusion flames and reveal density variations within them, the Schlieren system is commonly employed due to its capability to detect inhomogeneous density gradients.

For centuries, scientists have relied on the Schlieren method to observe the phenomenon of light refraction when it traverses different substances. While the presence of variations in the refractive index of a material can sometimes be discerned without any equipment, a properly designed optical setup is required to obtain a clear and precise view of these variations. Figure 1.1 illustrates the kind of results that can be obtained using this method. In this particular example, the flame is quite small, and there is no smoke generated. In a regular photograph, only a subtle distortion of the background might hint at the presence of the plume, but the Schlieren photograph provides a much more detailed depiction of its shape and characteristics [2].

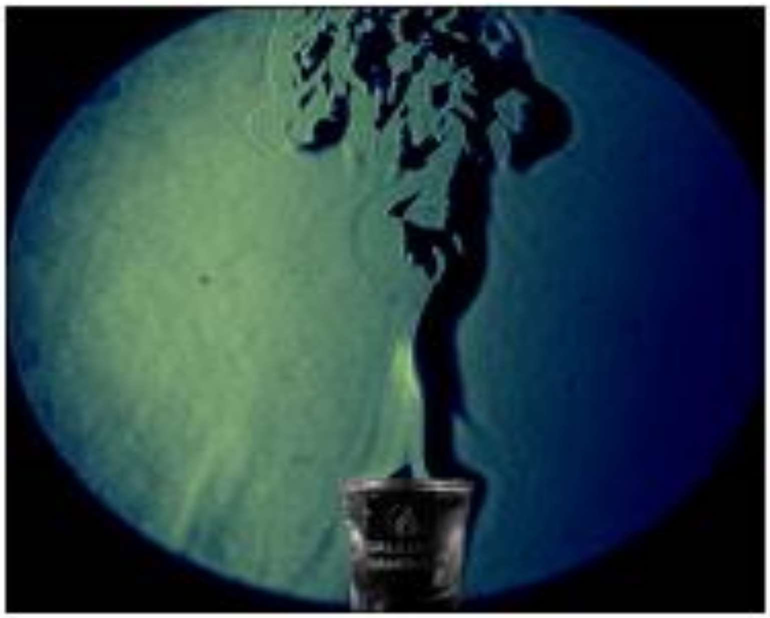

Figure 1.1: A vapor plume rises from burning alcohol. Photograph courtesy of Kasi Metcalfe [2]

## 1.2 Objectives

Based on the motivation discussed in the previous section, the main objectives of the research conducted in this study are listed below:

- To design a customized experimental setup for Schlieren imaging by adapting a conventional z-type Schlieren system.
- To minimize two aspects of light such as coma and astigmatism by employing a precise distance method.
- To determine the optimal position of the knife-edge in order to obtain high quality Schlieren images.
- To apply the newly developed Schlieren technique on a specific test case in order to assess its effectiveness and applicability.

## 1.3 Outline of the Project

Chapter 1 provides an overview of the diffused flame analysis and Schlieren technology as well as identifies the scientific purpose and the project objectives. The literature review is described in Chapter 2. Chapter 3 discusses the methods and design of methane-ammonia schlieren analysis and Chapter 4 covers testing and results of such experimental setup. Finally, Chapter 5 summarizes the project setup and also discusses the feasibility and future work for achieving flame analysis of methane-ammonia diffused flame.

# Chapter 2: Literature Review

## 2.1 Combustion Background

### 2.1.1 Introduction

Combustion is an exothermic chemical reaction characterized by high temperatures, involving the interaction of a fuel (acting as the reductant) and an oxidant (typically atmospheric oxygen). This reaction results in the release of heat and light, giving rise to a flame that flickers. Within the chemical reaction, the atoms are exchanged as molecules collide with each other [2].

$$CH_4\,(g) + 2O_2\,(g) = CO_2\,(g) + 2H_2O\,(g) \qquad (2.1)$$

$$NH_3\,(g) + O_2\,(g) \rightarrow N_2\,(g) + H_2O\,(g) \qquad (2.2)$$

A flame refers to the visible and gaseous component of a fire that arises from a highly exothermic chemical reaction occurring within a narrow region [3].

During a typical chemical reaction, the total quantity of elements such as carbon (C), hydrogen (H), and oxygen (O) remains constant before and after the reaction. However, the molecules involved undergo transformations from compounds like $CH_4$ and $O_2$ to $CO_2$ and H2O. These reactions usually take place within a small portion of the overall volume, known as the reaction zone or flame. Such reactions can produce chemiluminescent intermediates that emit light, contributing to the coloration of flames. Table 2.1 provides several examples of combustion systems, which can be classified based on the method of preparing the fuel/oxidizer mixture: premixed and non-premixed [4]. In any combustion process, the equivalence ratio (φ) is used to define the ratio of fuel to oxidizer. A stoichiometric combustion process occurs when fuel and oxidizer are consumed completely, resulting in $\varphi = 1$. If there is an excess of fuel, the system is considered fuel-rich ($\varphi > 1$), while an excess of oxidizer defines a fuel-lean condition ($\varphi < 1$).

Table 2.1 Basic combustion types and examples

| Fuel/Oxidizer Mixing | Fluid Motion | Examples |
|---|---|---|
| Premixed | Turbulent/Laminar | - Gas turbine (Turbulent)<br>- Bunsen flame (Laminar) |
| Non-premixed | Turbulent/Laminar | - Diesel engine (Turbulent)<br>- Candle (Laminar) |

### 2.1.2 Premixed Flames

A premixed flame occurs when the fuel and oxidizer are blended together before entering the region where the chemical reaction takes place [5]. The combustion process consists of an unburnt region containing reactants and a burnt region consisting of products. The movement of the flame front is a combination of flame propagation and fluid convection. An illustration of this can be observed in a fuel lean scenario of a Bunsen burner, depicted in Figure 2.1. Turbulent flames can occur when there is a higher rate of flame propagation and fluid convection, leading to increased heat and mass transfer. The combustion process in a spark-ignited engine serves as a model for turbulent premixed flames, where the fuel and air are mixed within pipes before entering the combustion chamber [1].

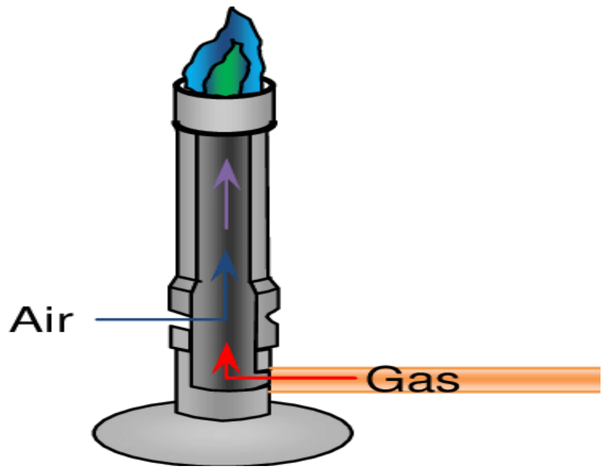


Figure 2.1 A Schematic of a Bunsen burner [6]

### 2.1.3 Diffusion Flames

Diffusion flames occur when fuel and oxidizer come together within a reaction zone through a combination of molecular and turbulent diffusion. The fuel can take the form of a jet of gaseous fuel or a condensed medium like liquid or solid, while the oxidizer can be a flowing stream of gas or the still atmosphere [7]. Diffusion flames involve the simultaneous mixing of fuel and oxidizer and the combustion process. Unlike the propagation of premixed flames, diffusion flames form at the boundary where the fuel and oxidizer (typically air) come into contact. Diffusion flames are often characterized as diffusion-controlled or mixing-controlled, rather than being controlled by the kinetics as observed in premixed flames. In diffusion flames, the fuel equivalence ratio varies from zero on the air side to infinity on the fuel side. Consequently, lean combustion occurs near the air side, rich combustion is present near the fuel side, and stoichiometric combustion occurs in the middle. The flame front, which exhibits the most intense luminosity, corresponds to the highest temperature and is associated with stoichiometric combustion [4]. Figure 2.2 displays the process of laminar diffusion flame in the form of a candle combustion.

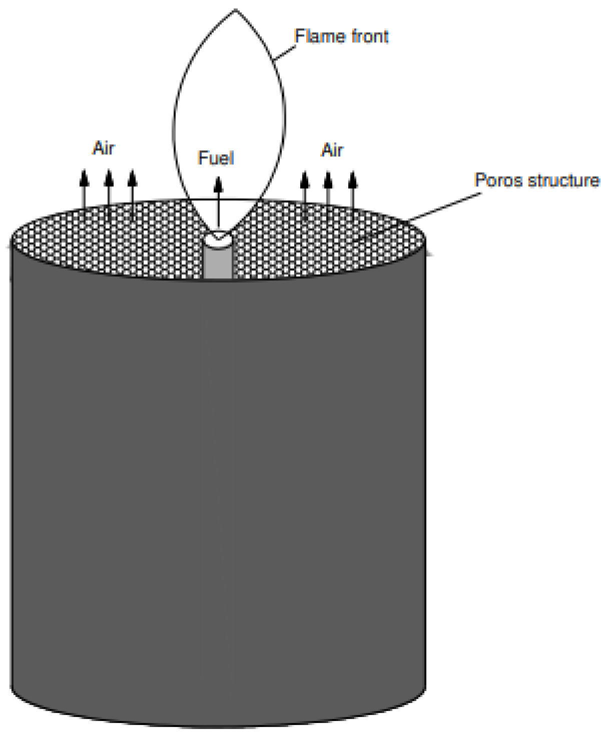


Figure 2.2 Schematic illustration of laminar diffusion flame [4]

The complex physio-chemical processes of diffusion flames are often exemplified by the flame of a candle. The flame surface itself represents the region where fuel vapor and oxygen combine at high temperatures, resulting in the release of heat. The heat emanating from the flame causes the wax at the base of the visible wick to melt. Subsequently, the liquid wax ascends the wick through capillary action, bringing it closer to the hot flame. This proximity leads to the vaporization of the liquid wax. As the wax vapors travel towards the flame surface, they undergo decomposition into smaller hydrocarbons. Simultaneously, oxygen from the surrounding atmosphere moves towards the flame surface through diffusion and convection. The maintenance and location of the flame surface are determined by the delicate balance between these processes.

Under normal gravity conditions, buoyancy-driven convection occurs as a result of the presence of hot, less dense combustion products. This phenomenon leads to several consequences: (a) the buoyancy causes the hot reaction products to be carried away while fresh oxygen is drawn towards the flame zone; (b) solid soot particles form in the region between the flame and the wick, and they are transported upwards, where they are subsequently burned off, resulting in the bright yellow tip of the flame; (c) in order to compensate for the heat loss caused by buoyancy, the flame establishes a close proximity to the wick, anchoring itself there; and (d) the combined effect of these factors causes the flame to assume a teardrop shape.

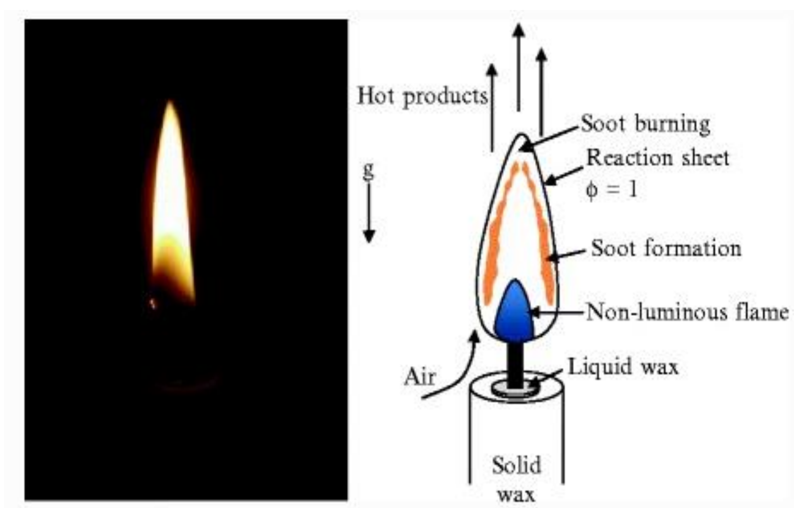


Figure 2.3 Physical processes and the effect of buoyancy on a candle flame [8]

## 2.2 Z-Type Schlieren

The Schlieren technique continues to be a highly effective method for visualizing flows due to its versatility in sensitivity, affordability, and utilization of standard light sources. The origins of the Schlieren system can be traced back to the 17th century when Robert Hook invented the first system. In the 19th century, August Toepler further developed the Schlieren technique as a visualization method [9]. Since its inception, the technique has been widely employed to investigate a diverse range of problems across various research fields, such as combustion [10], aerodynamics [11], fluid mechanics [12], etc.

### 2.2.1 Considering Refraction in Schlieren Technique

Schlieren techniques rely on the principles of light refraction. As depicted in Figure 2.4, when light passes from one medium ($n_1$) to another medium ($n_2$), it undergoes a change in direction if the refractive indices of the two mediums are different.

This phenomenon is governed by Snell's law, which states that the magnitude of the angle change is determined by the difference in refractive indices. The following relationship demonstrates Snell’s law of refraction:

$$n_1 \sin i = n_2 \sin r \tag{2.3}$$

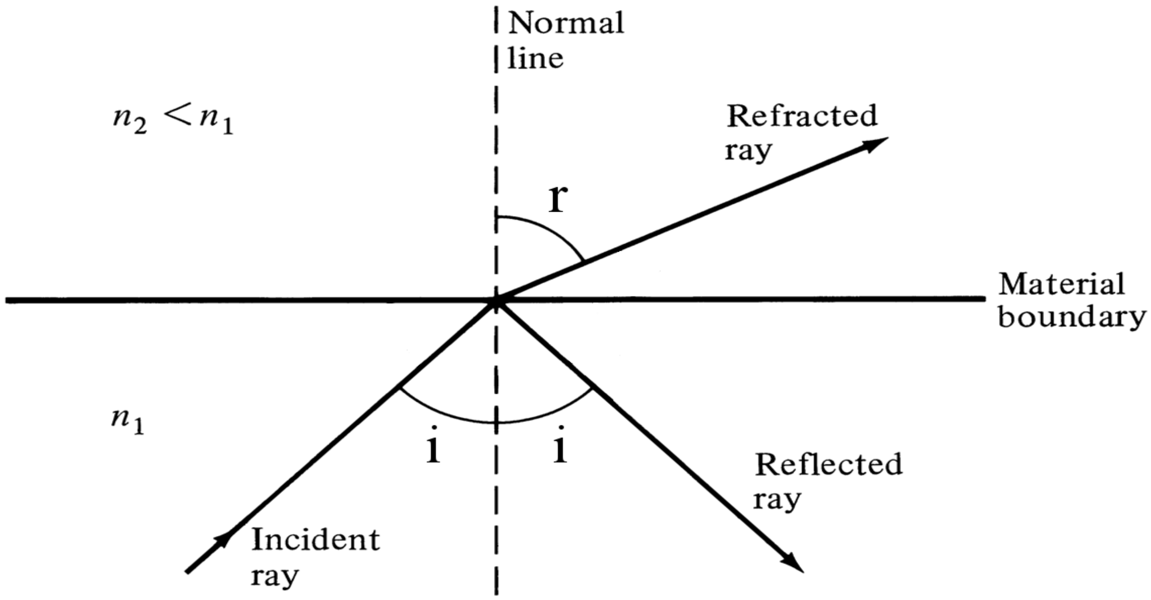


Figure 2.4 Schematic of light refraction theory [13]

According to the Gladstone-Dale relation, for specific species, the refractive index n has a linear relationship with density ρ:

$$n - 1 = k\rho \tag{2.4}$$

Therefore, the change in angle caused by refraction is directly related to the disparities in density between the mediums. The refractivity, represented by the term (n-1), of a gas relies on various thermodynamic parameters of the gas, including temperature, pressure, composition, and so on. In many instances, the simple perfect-gas state equation ($P / \rho = RT$) can be utilized.

### 2.2.2 Astigmatism and Coma in a Two-Mirror System

Spherical mirrors exhibit spherical aberration when either the object or the image is positioned at an infinite distance from the mirror. Two significant types of aberrations associated with spherical mirrors are coma and astigmatism. When it comes to refractive or diffractive optical systems, particularly those used for imaging a wide range of wavelengths, coma may vary depending on the wavelength, thereby becoming a form of chromatic aberration [14]. Conversely, astigmatism is a refractive error caused by an asymmetry in the rotational refractive power of the eye [15].

Astigmatism can be eliminated by positioning the second mirror in an orthogonal direction rather than tilting it in the opposite direction to the first mirror. This configuration is illustrated in Figure 2.5 for the lens-based version of the system, where the second lens is displaced orthogonally rather than in the opposite direction to the displacement of the first lens [16].

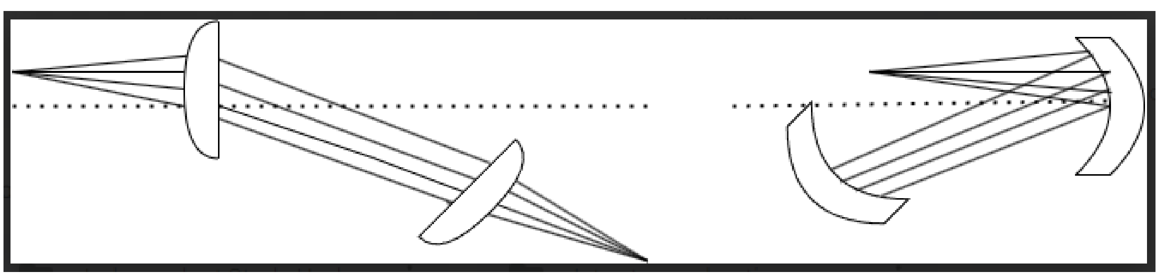

Figure 2.5: Coma corrected system by tilting the mirrors in orthogonal directions [16]

### 2.2.3 Z-Type Schlieren Imaging

Figure 2.6 demonstrates the construction of a basic Schlieren system using two lenses, geometric optics, a knife-edge, and a point light source. The beam emitted from a point source is adjusted using a lens, and another lens then refocuses the beam to form an image of the point source. A knife-edge is positioned at the focal point of the second lens, and from there, the beam continues towards a viewing screen where a real inverted image of the test area is produced. As the knife edge displaces a portion of the background rays, the loss of background intensity is evenly applied to the screen when the test area possesses uniform refractive indexes. However, if the test area contains a higher refractive index, the light will be refracted downwards and obstructed by the knife-edge.

Consequently, the formation of a darker spot on the screen occurs. Conversely, if the light is refracted upwards, a brighter spot is produced. These darker and brighter spots observed on the screen correspond to positive and negative gradients of refractive index in the direction perpendicular to the knife-edge.

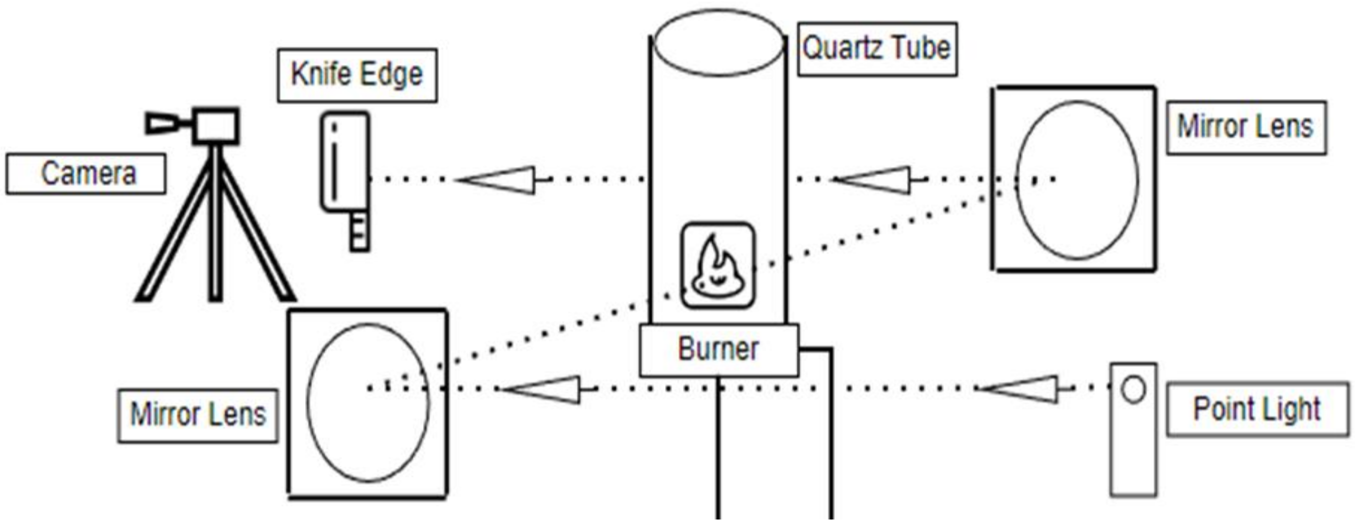


Figure 2.6 Schematic of Z-type Schlieren Setup

The light source is positioned precisely at the focal point of the right-hand mirror, while the knife-edge is placed at the focal point of the left-hand mirror. This arrangement creates a parallel beam between the two mirrors, resulting in a larger test area compared to single mirror systems. As the left-hand mirror converges, the beam becomes focused and partially obstructed before reaching the camera at the end. An example of direct and Schlieren photographs of a burner flame is presented in Figure 2.7. The Schlieren image provides additional information about the imperceptible regions that are absent in the direct image.

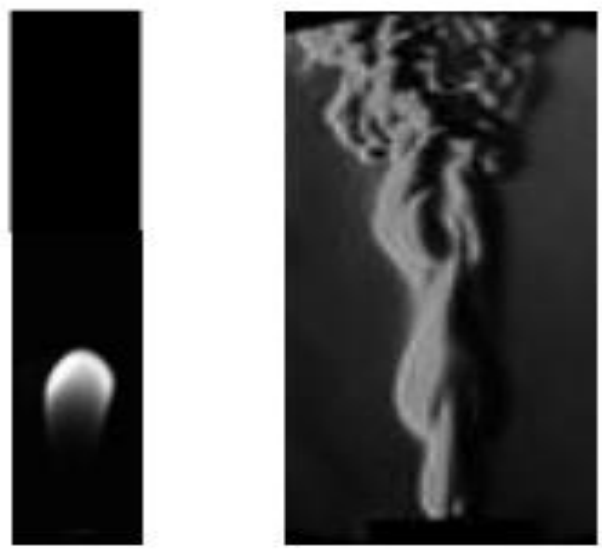

Figure 2.7 Direct and Schlieren imaging of a burner flame [1]

Hariharan and Mishra (2019) conducted a study on a circumferential inverse jet diffusion flame burner to investigate the characteristics of flame height and Schlieren visualization. Their findings revealed that the entrainment zone, characterized by vigorous mixing, is located within the base field. The transition and main field regions exhibit intense combustion, and this information was reported in their study [17]. Figure 2.8 illustrates the Schlieren results obtained for a specific fuel velocity at different air jet velocities.

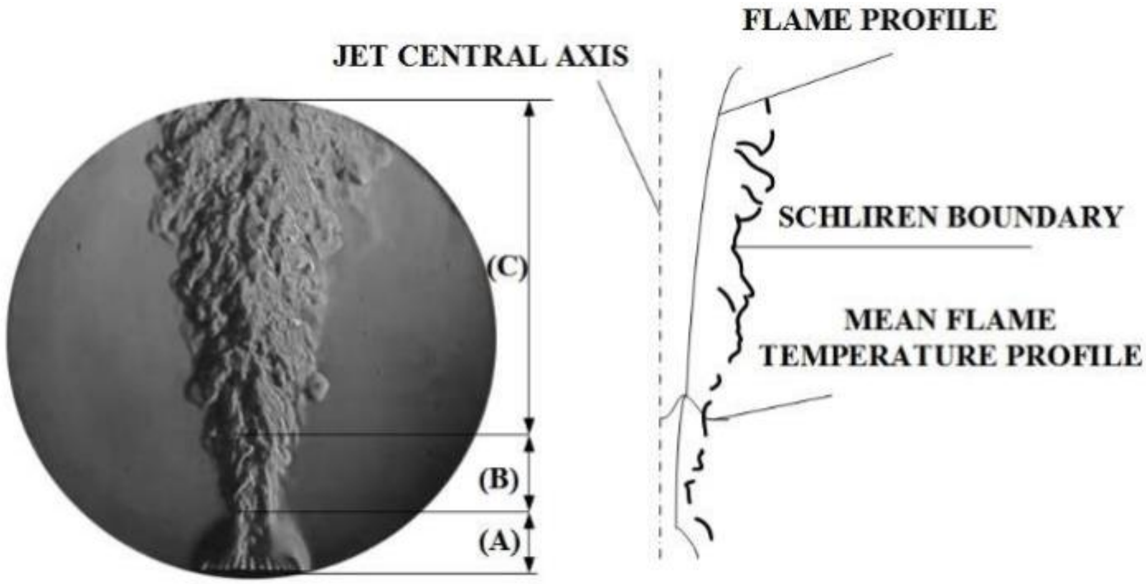


Figure 2.8 Schlieren visualization with a burner topology for fuel velocity 0.88 m/s at different air jet velocities [17]

## 2.3 Gaps in the Existing Literature

Previous research on the Schlieren imaging of diffused combustion has supported the potential use of this method as an effective way for visualizing the density gradient differences. Most of the literature discusses single mirror Schlieren setup, but there is a gap in studies regarding double mirror z-type Schlieren setup. Moreover, the reported z-type Schlieren technique has mostly been studied for mirrors that could be tilted in order to reduce aberrations. Thus, there is a lack of research that studies the method for fixed parabolic mirrors.

The Schlieren technique could be used to visualize density gradient differences by observing the hot plume around the combustion flame for diffused gasses. Even though there have been conducted studies on diffused gas Schlieren imaging, no researchers have designed experimental setup for methane-ammonia-air diffusion flame.

## 2.4 Scope of the Present Study

The aim of this project is to provide an original experimental setup for modeling methane-ammonia-air diffused flame analysis using Z-type Schlieren technique. With this setup, the diffusion flame characteristics such as flame initiation, propagation, and flame length as it transitions from laminar to turbulent could be carefully studied and compared with the other available data.

# Chapter 3: Methods and Design

## 3.1 Schlieren Apparatus

Z-type Schlieren setup was established with Edmund Schlieren Apparatus that includes two parabolic concave identical mirrors with a 6” diameter, one point light source and one parallelepiped knife-edge as shown in Figure 3.1.

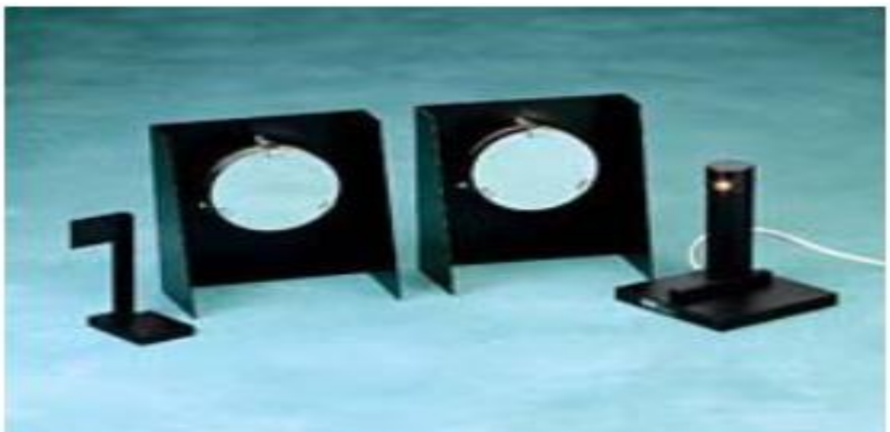

Figure 3.1 Schlieren apparatus: 60” Focal Length, 6” Schlieren System [18]

**Spherical Mirror:**

Two identical aluminized first surface spherical mirrors with 6 inches diameter were used as mirror lenses.

**Point Light Source:**

One light source with a pinhole was used to create a point light source for the Schlieren technology. Sunlite 7C9/CL Incandescent 120V 7W 30Lm Night Light C9 Intermediate E 17 Dimmable bulb was utilized.

**Knife Edge:**

A rectangular-shaped thin plate was used as a knife edge. The dimensions of the plate are one inch length, 0.5 inch width, and 1/16 inches thickness.

## 3.2 Mounting the Apparatus

To mount the apparatus with the correct height and distance, four individual brackets were assembled. T-slotted framing aluminum rails of 16 inches, 12 inches, and 6 inches were used to make the brackets connected by various fasteners (Fig. 3.2, 3.3, 3.4). To hold the apparatus with the brackets, several 3-inch jaw opening spring clamps were used.

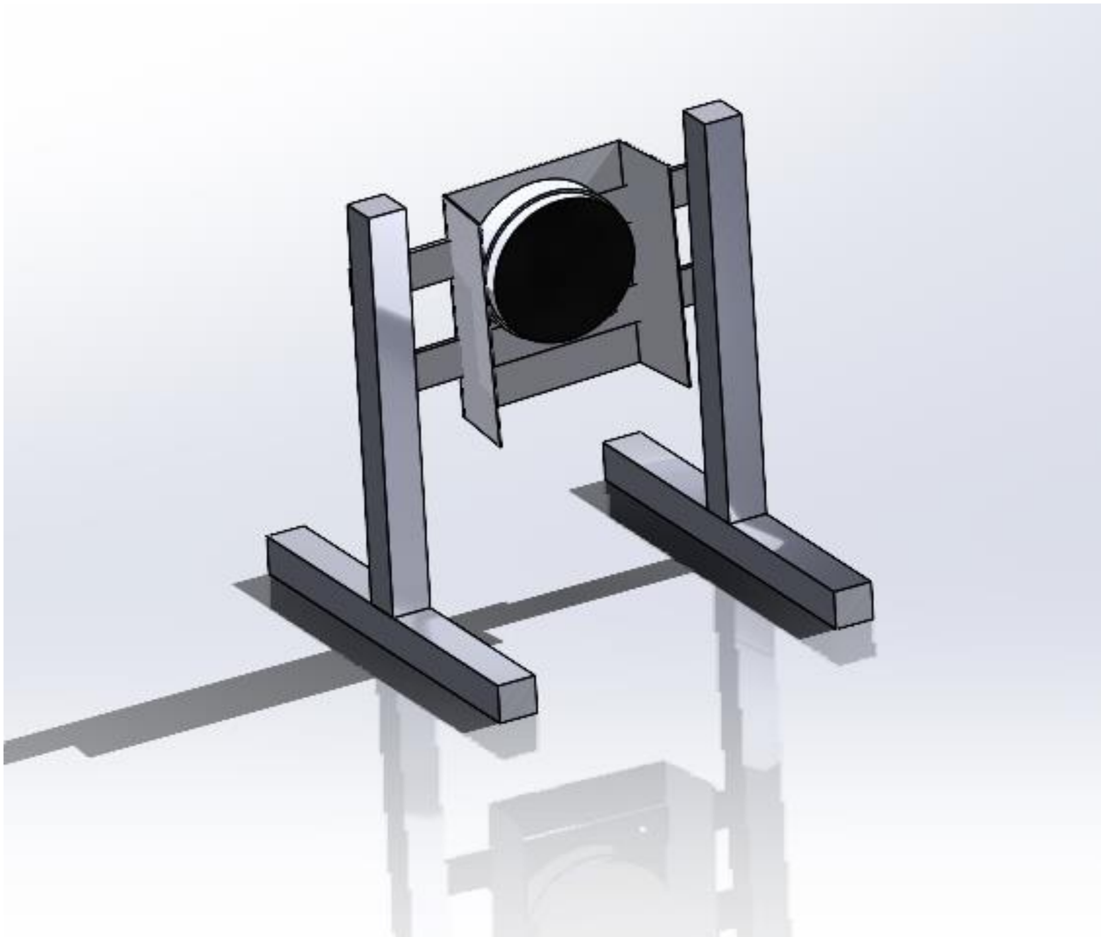

Figure 3.2 Brackets to hold the Mirror Apparatus

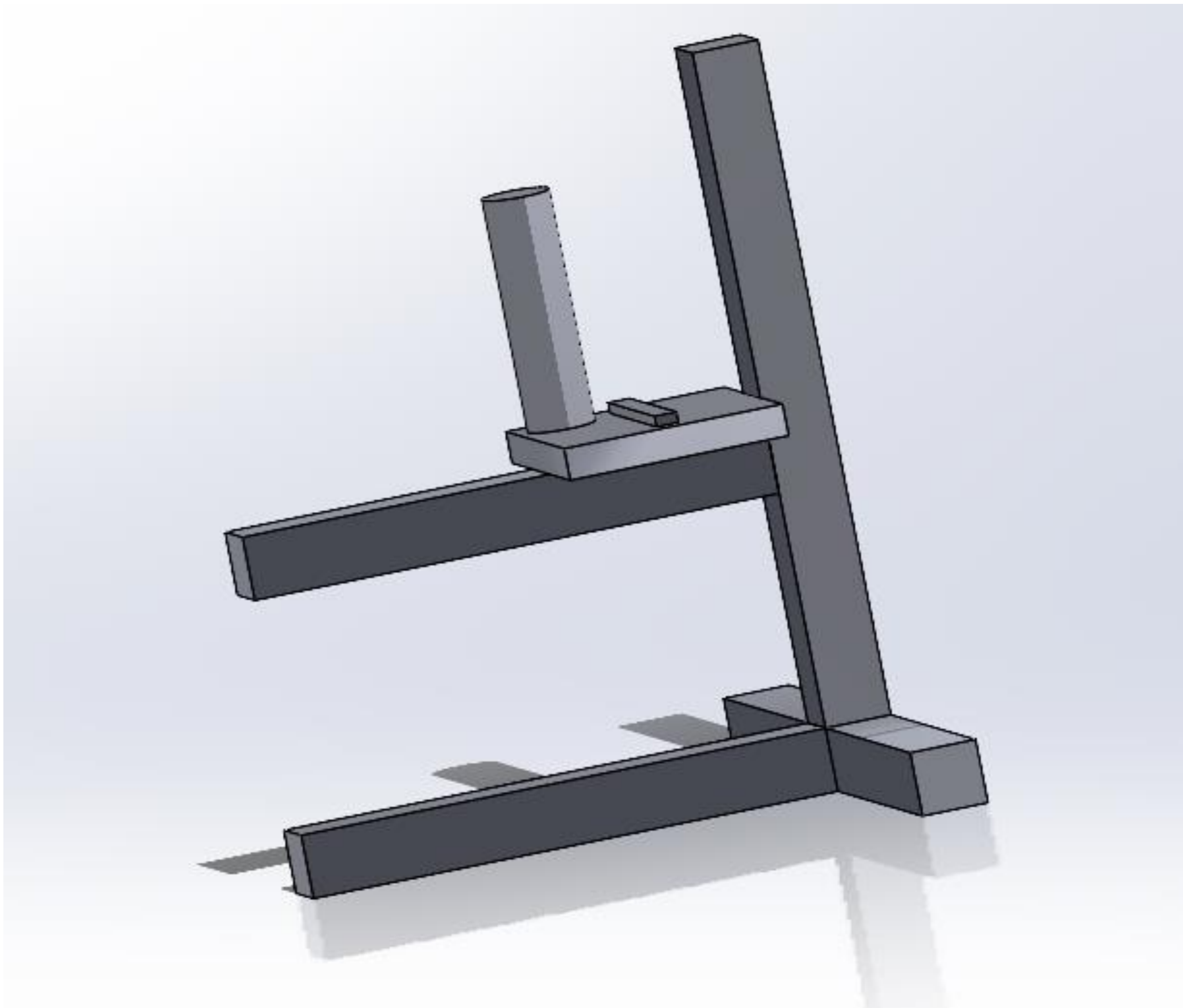

Figure 3.3 Brackets to hold the Point Light Apparatus

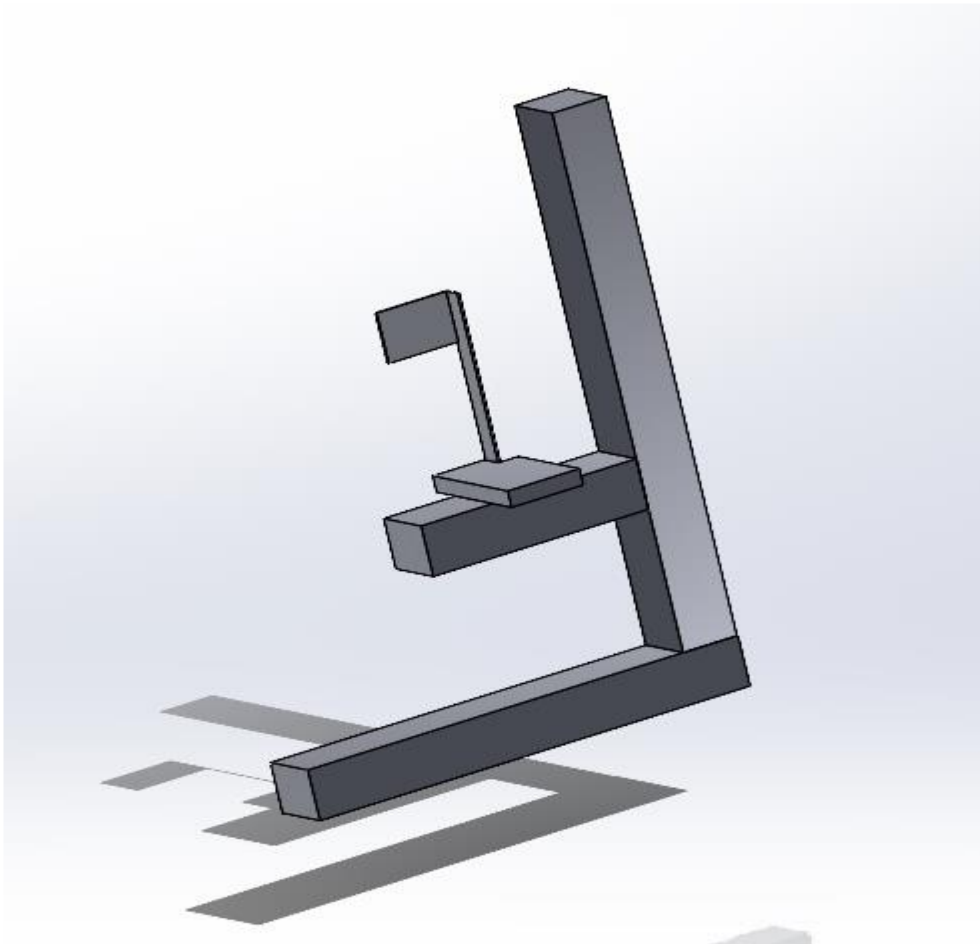

Figure 3.4 Brackets to hold the Knife-Edge Apparatus

### 3.3 Modeling the Flow Straightener

A ceramic honeycomb soldering board structure with 1.6 × 25 mm channels was used to make the flow straightener placed inside the combustor. It was cut by a water-jet cutter into a shape of 2.5 inches outer diameter, 0.5 inches inner diameter, and 1-inch height. The flow straightener was fixed inside the combustor with the help of two 3 inches inner diameters, 3.1875 inches outer diameter, and 0.09375 inches width silicone O-rings. The flow straightener ensured a laminar flow of air. The oxidizer in the combustion process would  pass through two perforated discs and the flow straightener within the combustor and allow for a uniform flow profile. Figure 3.5 shows the final image of the flow straightener after water-jet cutting has been done.

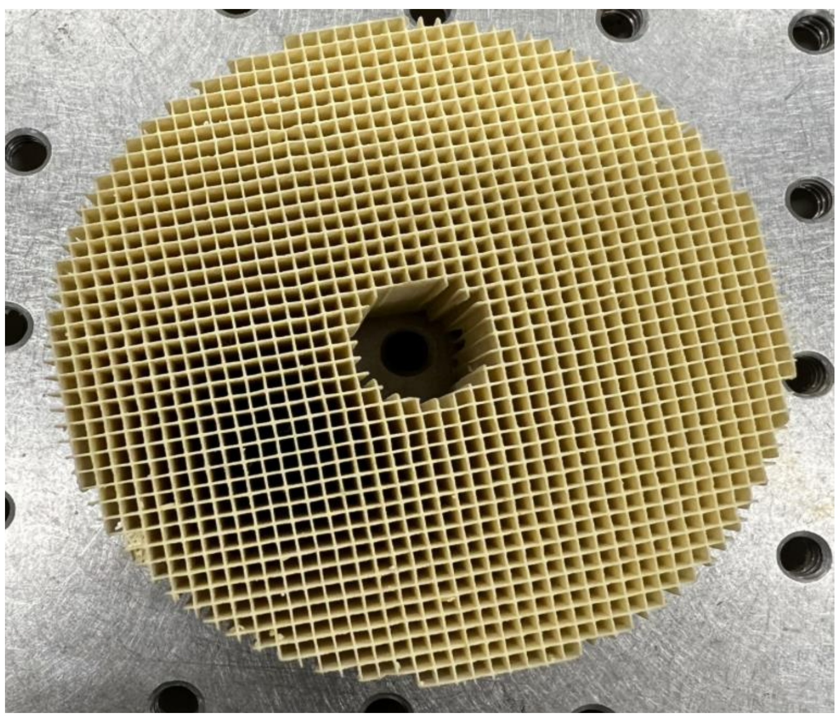

Figure 3.5: Ceramic Flow Straightener after water-jet cutting

A quartz tube was placed to surround the combustion chamber as the temperature gets extremely high in the combustion process. The diameter of the quartz tube is determined by the outer diameter of the combustor. The thickness of the tube is 0.1640 inches which is reasonable considering the intensity of the released heat. The tube is made out of quartz glass to be able to withstand extreme temperatures up to 1150 °C. In figure 3.6, the flow straightener is fixed inside the combustor with quartz tube around it.

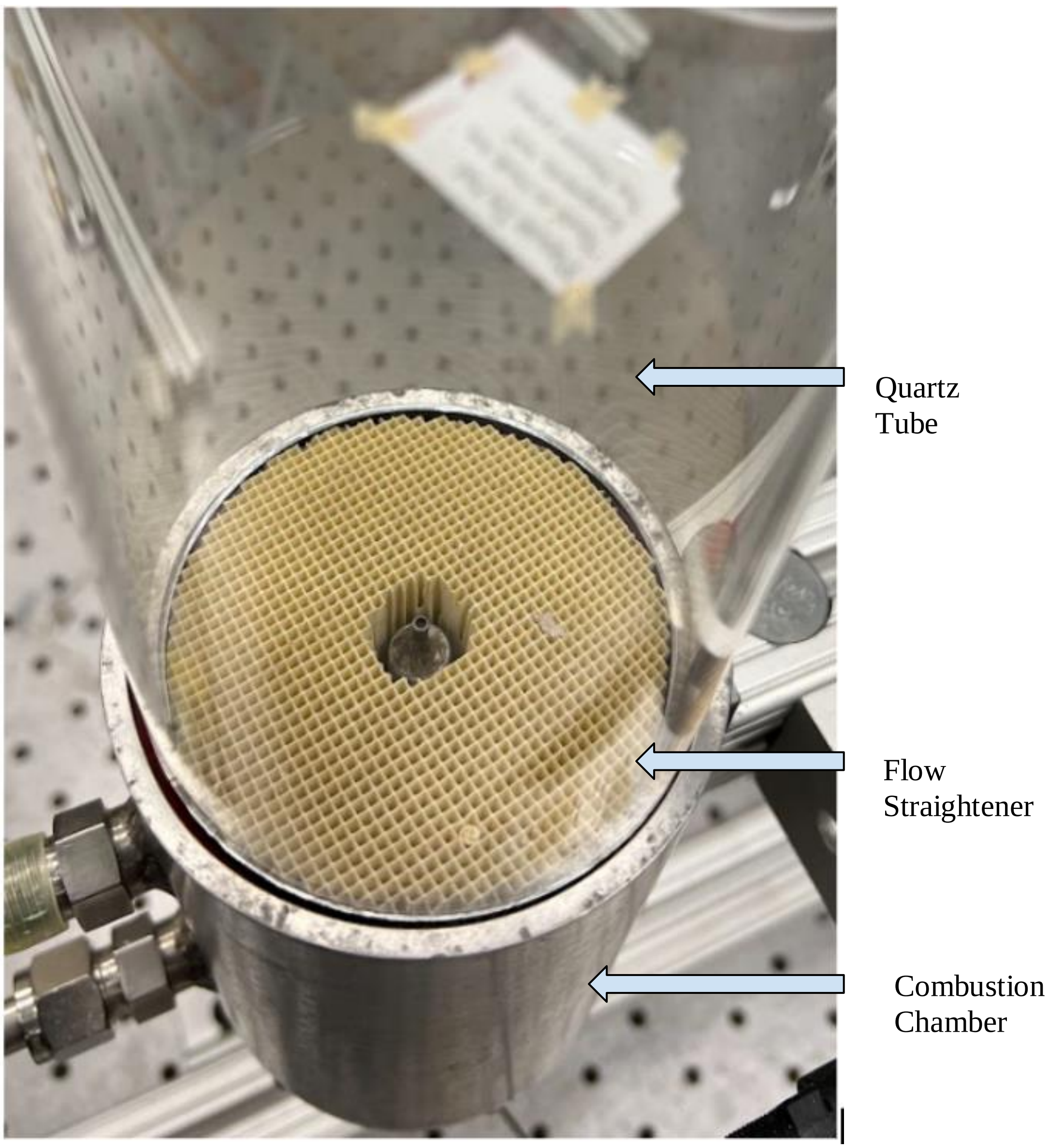


Figure 3.6 Flow Straightener adjusted with O-rings inside the combustor

## 3.4 Fuel and Oxidizer Supply, Pressure Regulator, Mass Flow Meter, and Flow Control Valve

Different types of gas cylinders require different and specific types of pressure regulators for fuel supply, and that is why the pressure regulators used in this research were fitted based on the type of gas cylinder. The oxidizer supply comes from house air which was connected to the burner by a Quincy QR-25. The fuel and oxidizer supplies are fitted with quick-connectors to the mass flow meters. The volumetric flow rate of air would be controlled by adjusting the pressure and measuring the corresponding flow rate using a 0-500 SLPM (standard liters per minute) Cole Parmer mass flow meter. All fuel gas flow rates would be monitored by 0-20 SLPM stainless steel Alicat Scientific mass flow controllers. The gasses would enter a T-joint and then a flow control valve before entering the combustor. The oxidizer would enter the combustor through a different inlet.

## 3.5 Exhaust System

Aluminum duct with 4 inches diameter was used as exhaust hose and placed right over the quartz tube. Galvanized steel exhaust hood was attached to the hose and fixed with the exhaust duct of the fume hood to ensure solid exit of the exhaust gasses created by the combustion process. Figure 3.7 illustrates the exhaust system of the experimental setup.

## 3.6 Camera Specifications

A Nikon D5600 camera with Nikon DX AF-S Nikkor 18-105 mm ED lens was used for the experimental setup. The camera features were adjusted to F5.6 aperture, ISO 400, and shutter speed 1/80 with an fps (frame per second) 60. The camera was held by a tripod with the help of a mounter to achieve the expected height. It was positioned right behind the knife-edge to let optimum amount of light to be blocked from entering the camera lens.

## 3.7 Methane-Ammonia Diffused Gas Combustion Process with Z-type Schlieren Setup

In figure 3.7, the schematic of the experimental setup for methane-ammonia combustion system with Z-type Schlieren technique is shown.

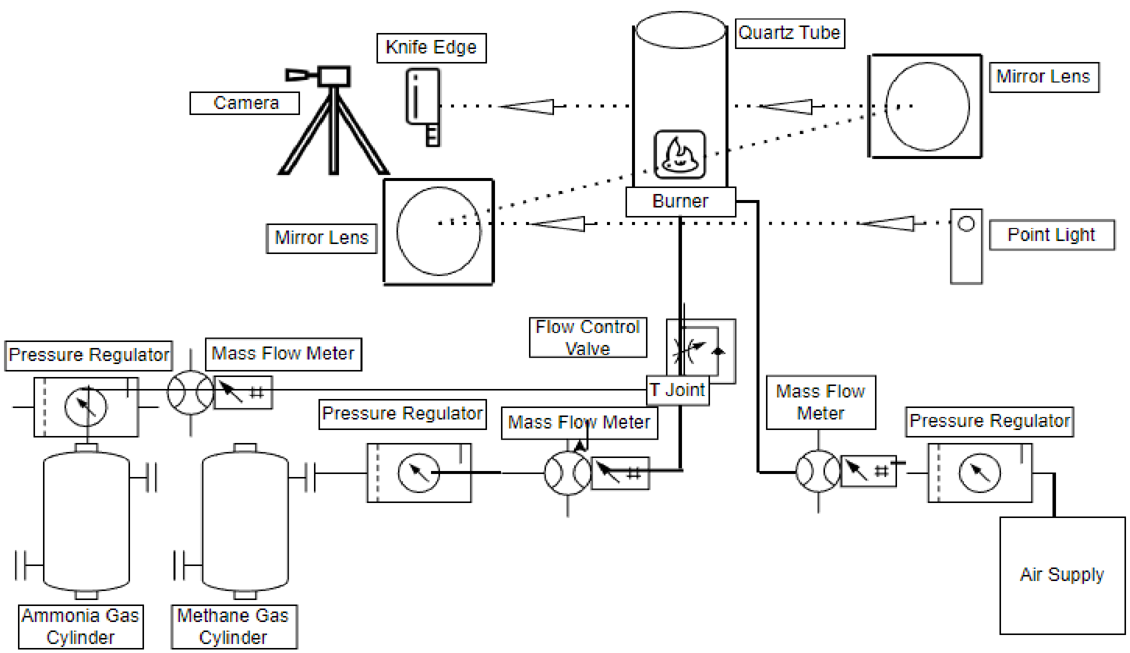


Figure 3.7 Schematic diagram of Methane-Ammonia Diffused Gas Combustion with Z-type Schlieren Setup

# Chapter 4: Testing and Results

Several tests were performed to ensure the safety and performance of the experimental setup, and the outcomes from the testing are discussed in this section.

## 4.1 Leak Proof Testing

AMPROBE GSD600 Gas Leak Detector device (Methane/Propane (ppm)) was used to determine if there was any methane gas leakage in the testing area, and the device showed that there was no such leakage. Figure 4.1 indicates how the device acted in response to the leakage-detecting mode on.

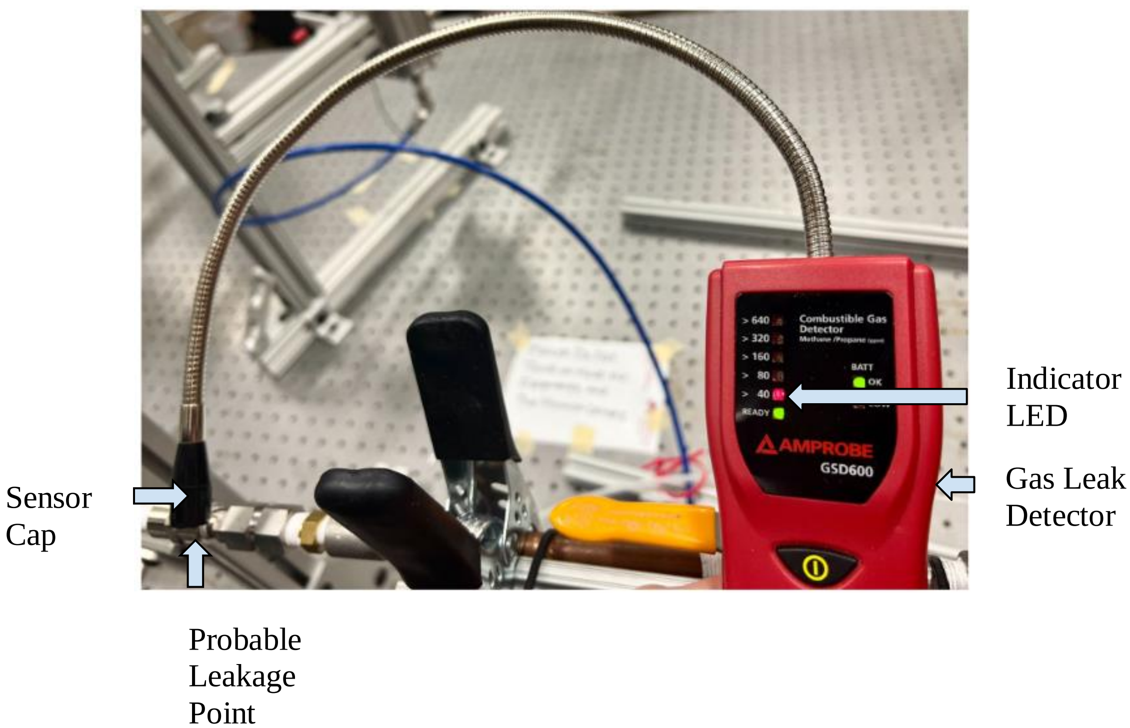


Figure 4.1 Combustible Gas Detector showing leakage proof testing area.

## 4.2 Precision Measurement for Minimum Coma and Astigmatism

The position of the Schlieren equipment on the optical table is the deciding factor for the Schlieren image to be visible. To avoid coma and reduce astigmatism, the equipment should be positioned precisely. The mirrors were positioned diagonally at a 10-degree angle with the vertical axis of the optical table. The distance between the point light source and mirror 1 was 55 inches, and between the knife-edge and mirror 2 it was 60 inches. The combustor was located 30 inches away from mirror 2 and positioned parallel to the mirror faces. Figure 4.2 explains the positioning of the equipment for visualizing Schlieren images.

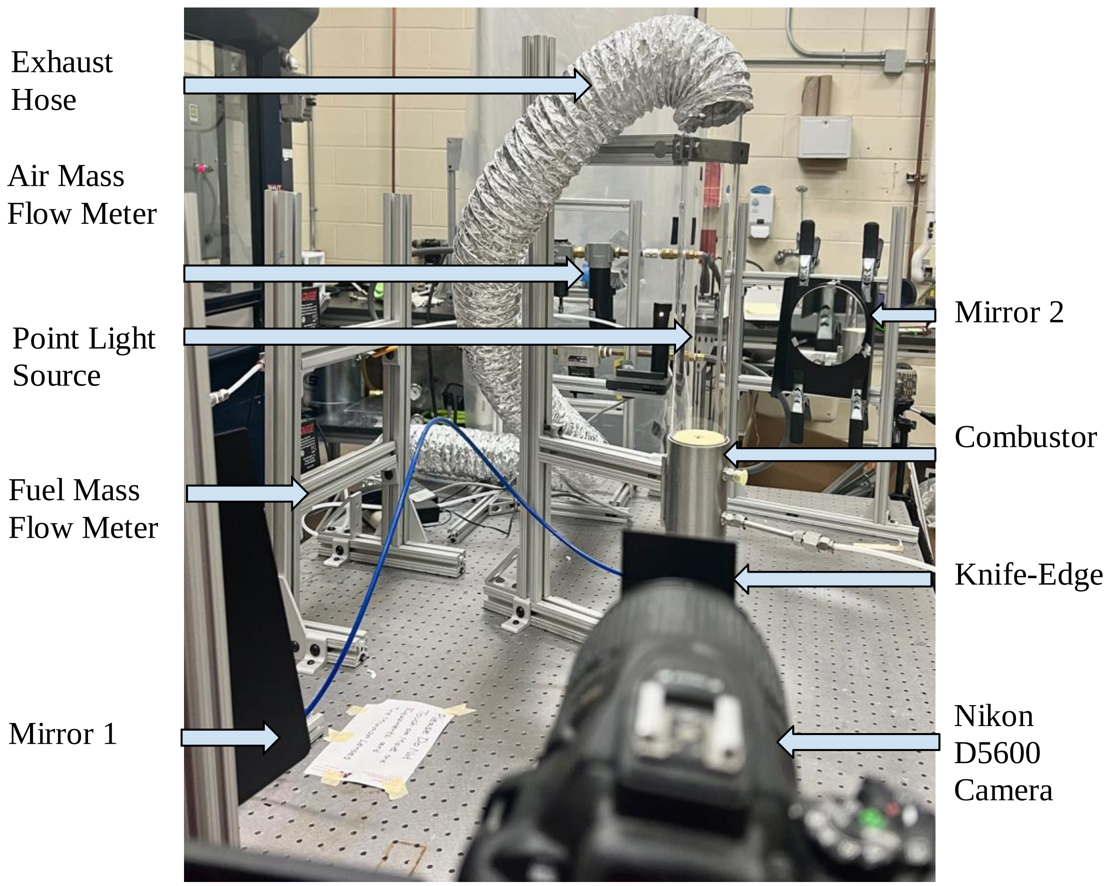


Figure 4.2 Z-Type Schlieren experimental setup at precise distance

## 4.3 Schlieren Images of Candle Flame

Figure 4.6, figure 4.7, and figure 4.8 show the candle flame Schlieren image when the knife-edge is positioned behind the camera in such a way that it blocks 50%, less than 30%, and between 30-50% of light respectively.

Figure 4.3 Candle Schlieren with more than 50% knife-edge

Figure 4.4 Candle Schlieren with less than 30% knife-edge

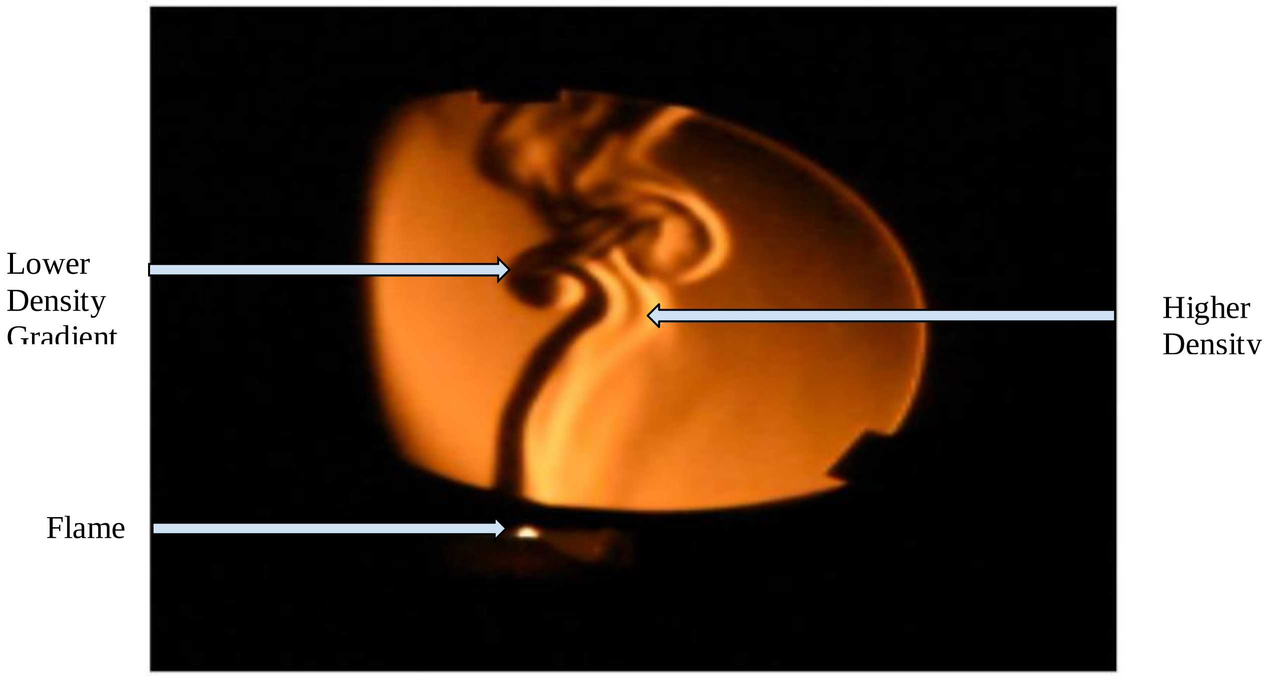


Figure 4.5 Candle Schlieren with optimum % knife-edge

# Chapter 5: Discussion and Conclusion

## 5.1 Discussion

For analyzing diffused gas flame, two-mirror system Z type Schlieren technique is the most effective method. The experimental setup must be accurate to visualize the ideal Schlieren view and apply the images for analyzing flame characteristics.

Instead of tilting parabolic mirrors, applying the precision distance method is a much more practical approach to avoid visual aberrations. When the parabolic mirrors are fixed at their positions, it is difficult to minimize visual aberrations. However, with the help of specifying the distances between the Schlieren apparatus, the visual errors were eliminated.

Flow control valves are crucial for setting up combustion experiments as they ensure flow on or flow off promptly. Adding a final flow control valve before the fuel entrance to the combustor provides control and safety in the experimental setup.

The quartz tube ensures the flame is stable, and the density gradients in the Schlieren images are visually detectable. The quartz tube plays an important role in the setup because there would be a huge airflow in the atmosphere to disturb the flame stability creating a large amount of heat.

The knife-edge position at which it blocks 30-50% of light to enter the camera from mirror 2, gives the best Schlieren view. Hence, the optimum blocking percentage for the knife-edge should be within the 30-50% range.

## 5.2 Conclusion

The successful outcome of this project was applying a practical approach of setting up the Schlieren method for flow visualization for methane-ammonia diffused combustion system.The setup was verified by successful generation of candle Schlieren images.

The major challenges faced in this project were to minimize visual aberrations like coma and astigmatism while keeping the mirrors fixed on their positions. As mirror lenses are sensitive to dirt, bubbles, etc., precautions had to be taken to keep the mirror lenses spot free. Also, ensuring safety for running the experiment with flammable gasses like methane and ammonia was another major concern.

Implementing the experimental setup and the results described in this study on Schlieren imaging, the cold flow pattern of the methane-ammonia fuel jet before ignition can be visualized at different air co-flow velocities [19]. Similarly, Figure 5.1 shows the images from an experiment done by Wang, Zhang, and Zhao (2018). Such analysis could be compared with other flow visualization methods, for instance, holographic interferometry, planar laser-induced fluorescence (PLIF) etc. [20].

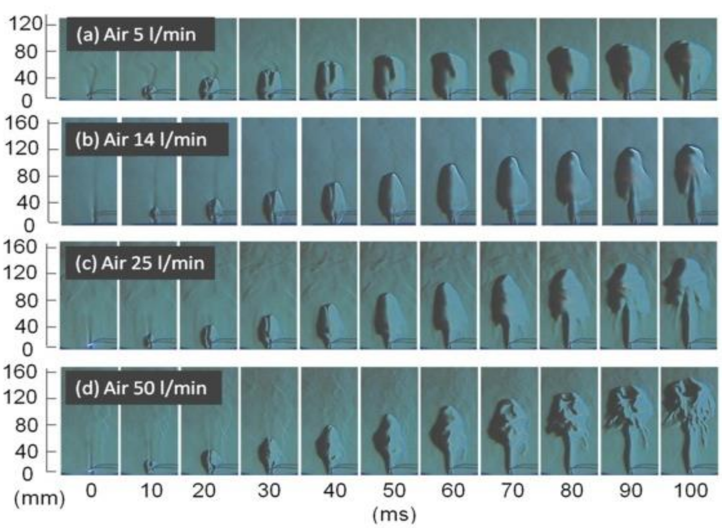


Figure 5.1 Schlieren imaging sequence at different air flow rates

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