Development of Schlieren Visualization System for Study of Flame Characteristics

By

Muhammad Rubaie bin Mohammad Tahir

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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Approved by,

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(Ir. Dr. Shaharin Anwar Sulaiman)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

June 2009

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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MUHAMMAD RUBAIE BIN MOHAMMAD TAHIR

ABSTRACT

The characteristics of flame propagation are one the factors that contribute to efficiency in combustion. Therefore, study on flame characteristics is very important. Schlieren visual imaging system is one of the methods that can be used to study flame propagation due to its capability to capture clear images of the flame. A commercial Schlieren visual system is very costly and usually it is difficult to find a suitable design for specific use in the industry because of limited production in the market. Therefore, development of a suitable and flexible design that can be used for various settings of experiment would be required. The objective of this project is to develop a Schlieren imaging system that can capture flame images. Flame characteristics in real industry are not clearly understood. Thus, this project enables understanding of flame perturbation effect by using Schlieren technique. This project focuses on several parts of study which are critical research on Schlieren techniques, development on Schlieren design and setting, testing on apparatus after fabrication, analysis the flame perturbation image, recommendation on apparatus improvement and and finally conclusion. The methodology of this project includes; literature review, techniques selection, equipment and material selection, design and fabrication, testing, experiment on the apparatus, analysis, improvement and, experiment on flame perturbation characteristics. This project shows that diameter of the lens is the key to enlarge the area of Schlieren image. Further study and research can be done to understand the effect of each component in Schlieren Visualization System to improve the Schlieren image.

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I would like to express my deepest gratitude and thank you to my project supervisor, Ir. Dr. Shaharin Anwar Sulaiman. I am very appreciating for the guidance, ideas, support and patient in advising and assisting the project. The understanding and learning from this project will always guide me in my future career.

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All the kindness and understandable of each individual who directly or indirectly involves in my final year project are remembered all the times.

And most important, I would like to dedicate this dissertation to my father and my mother, Mohammad Tahir Ismail and Faridah Talib, and my fiancée, Sakinah Mohd Halimi for their love and invaluable moral support, which gave me strength to face all the challenges occurred during the preparation of this dissertation.

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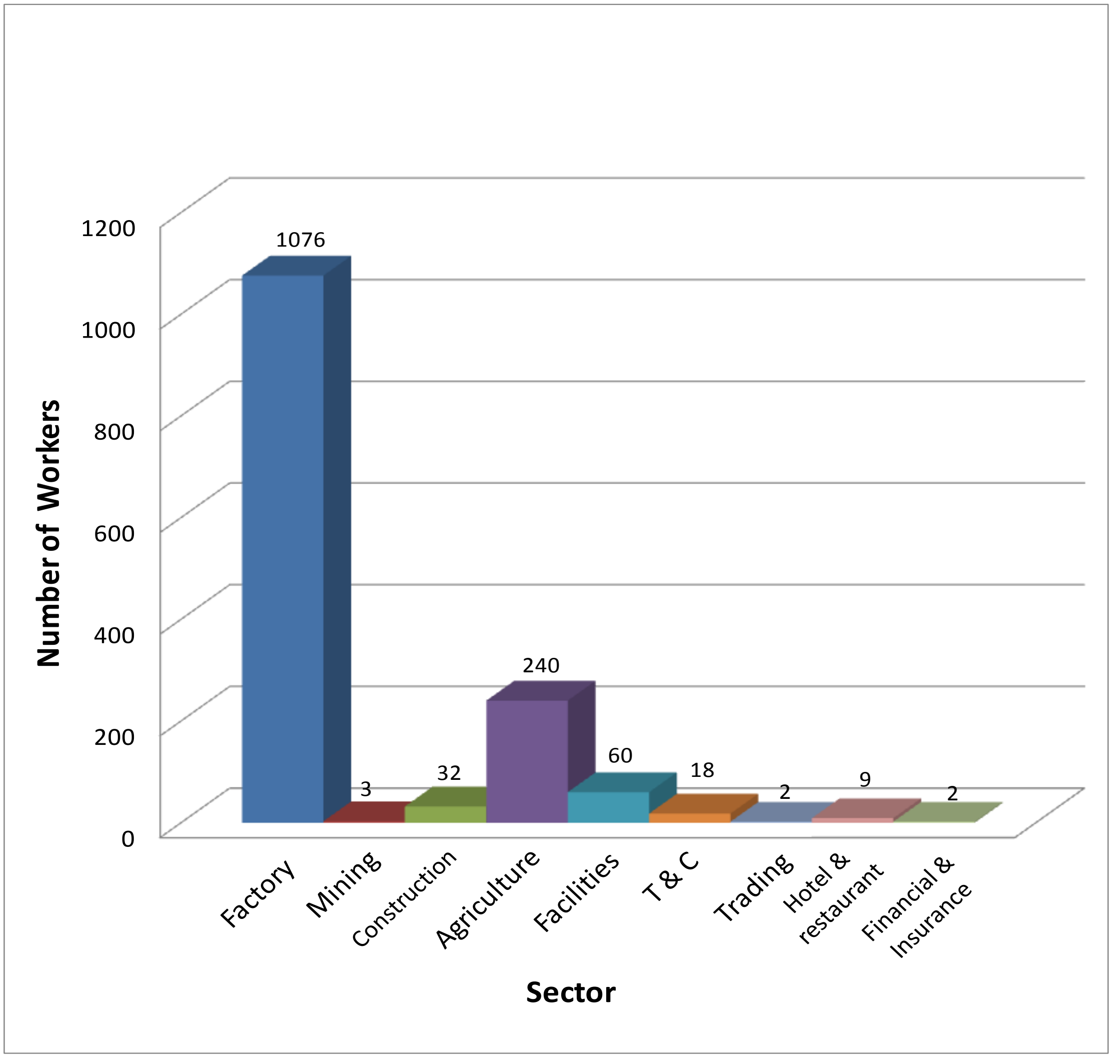
CHAPTER 1
INTRODUCTION

1.1 Project Background

Result and risk assessments are performed to ensure the safety of the design and operation of industrial plants. It is needed to predict explosion that might occur in the industrial plants. Risk assessments are used in design optimization and evaluating cost. The results of this risk assessment were used by management, to quantitatively balance risk and reliability options. The development of predictive techniques is capable to provide realistic estimates of explosion generated. On the other hand, the existence of repeated problem, ahead of a propagating premixed flame can result in increased flame speeds. Therefore, any reliable predictive method must be accounted for all these factors (Fairweather, 1999). The Department of Occupational Safety and Health (Malaysia) presented the statistics of accidents by sectors that occurred until July 2008 as shown in Table 1.1. The Table shows that, the industry inside factory which contain plant industry, manufacturing industry, and other industry sectors have the high number of accident compare to other sectors (DOSH, 2008).

Experimental studies are also required in order to further understand the physical processes that cause the explosion. While experimental and theoretical work on large-scale items of plant, it continues to provide information that is useful in understanding, predicting and mitigating the effect of flame, the complexities associated with the flame process mean that studies in small-scale, simplified geometries are also required to develop basic understanding of the flame perturbation process (Hargrave, 1999). The flame dynamics and structures inside a gas turbine combustor are valuable information in understanding the complex combustion process.



T & C: Transportation and Communication

Figure 1.1: Malaysia Worker Accident by Sector until July 2008 (DOSH, 2008)

1.2 Problem Statement

Study of flame characteristic using existing commercial schlieren system was done at University Technology of Petronas (UTP). However, there have been plenty of limitations in this schlieren system, because it can be operated in the automotive lab only. Furthermore, it is a rigid system and not flexible. Moreover, the captured image is limited to 25mm diameter only. Thus, it is not practical for some of the UTP projects that require schlieren image to be done properly.

1.3 Objective

The objective of this project is to develop a schlieren imaging system for visualization of flame. This is done by using the schlieren system imaging technique, to analyze the flame structure. The benefit of this project is to understand the effect of schlieren system component such as lens type, image system type, pinhole size, and other component on schlieren image capture.

1.4 Scope of Study

The present project involves preliminary research, study on previous design and schlieren apparatus setting. Design selections include cost and simple design but can be broadly used in university laboratories. Most of the equipment and apparatus for this project is already available in the university's laboratories. Consequently, design apparatus; assembly material and equipment, and fabrication are completed within a year. The system is tested with a simple combustion of a candle.

CHAPTER 2
THEORY AND LITERATURE REVIEW

Schlieren is German for ‘striations’. The term was coined by Albert Töpler, who developed the technique in 1906 from a related technique used to identify figuring errors in telescope mirrors. Schlieren photography is a way of visualizing density variations in a gas, and is useful in wind tunnel studies and investigations into heat flow. It employs a shadowgraph principle. A collimated (i.e. parallel) beam of light passes through the test space and is brought to a focus at a knife edge; it then diverges on to a screen or a camera system. Any gas density gradient with a component perpendicular to the knife edge will deviate the light from the region, so that it either clears the edge, giving a bright area on the screen, or is intercepted by it, giving a dark area. The resolution can be improved by a further knife edge at the first focus of the system. Where large spaces are to be imaged, off-axis parabolic mirrors are used rather than lenses to collimate and focus the beam shows in Figure 2.1 (Settles, 2001).

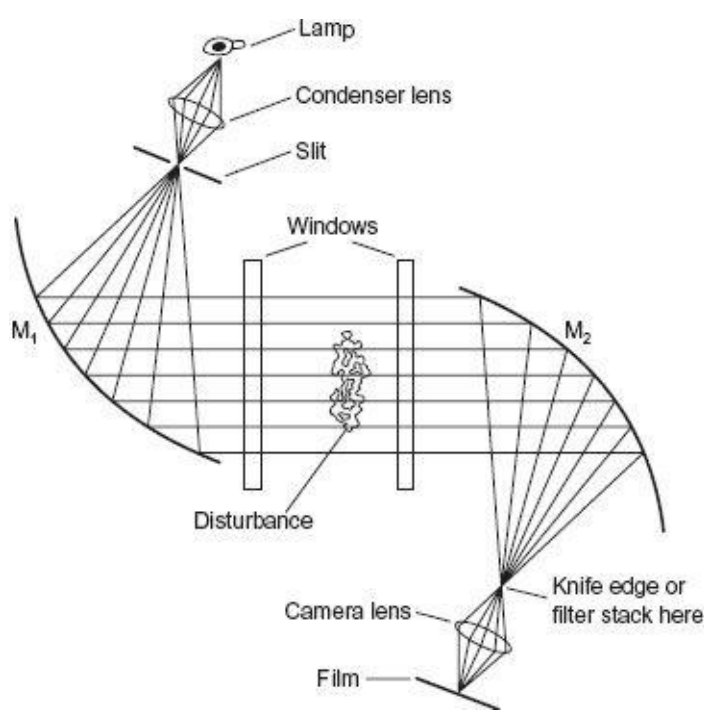


Figure 2.1: Basic schlieren setting (Settles, 2001)

Schlieren photography is sensitive enough to record the pattern of warm air rising from a human hand, but a more sensitive test uses interferometry, in a kind of hybrid of schlieren photography and holography. A laser beam replaces the white light beam, and a beamsplitter and beam combiner form a Mach-Zehnder interferometer set-up shown in Figure 2.2. This shows density differences directly, rather than density gradients.

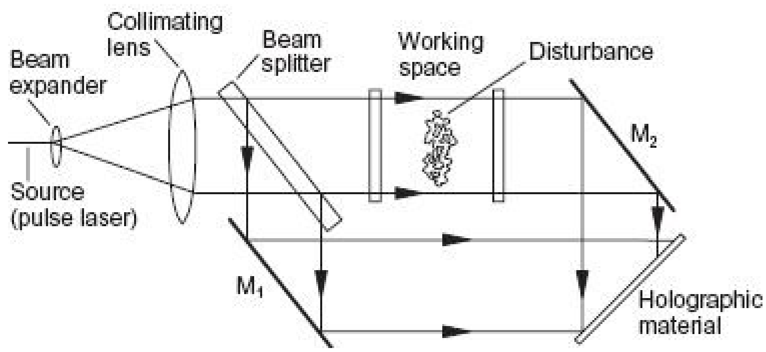


Figure 2.2: A laser beam replace the white light beam in Schlieren (Settles, 2001)

Schlieren is optical inhomogeneities in transparent material not visible to the human eye. Schlieren physics developed out of the need to produce high-quality lenses void of these inhomogeneities. These inhomogeneities are localized differences in optical path length that cause light deviation. This light deviation is converted to shadow in a schlieren system. Schlieren were first observed by Robert Hooke in 1665 using a large convex lens and two candles (Hooke, 1665). One candle served as a light source. The warm air rising from the second candle provided the schlieren. The conventional schlieren system is credited mostly to August Toepler. Toepler's original system was designed to detect schlieren in glass used to make lenses (Toepler, 1864). In the conventional schlieren system, a point source is used to illuminate the test section containing the schlieren. An image of this light is formed using a converging lens (also called a schlieren lens). This image is located at the conjugate distance to the lens according to the thin lens as denoted in Equation 2.1:

$$\frac{1}{f} = \frac{1}{d_0} + \frac{1}{d_i} \qquad (2.1)$$

where f is the focal length of the lens, d_o is the distance from the object to the lens and d_i is the distance from the image of the object to the lens. A knife edge at the point source-image location is positioned as to partially block some light from reaching the viewing screen. The illumination of the image is reduced uniformly. A second lens is used to image the test section to the viewing screen. The viewing screen is located a conjugate distance from the plane of the schlieren (Rienitz, 1975).

Schlieren flow visualization is based on the deflection of light by a refractive index gradient. The index gradient is directly related to flow density gradient. The deflected light is compared to undeflected light at a viewing screen. The undisturbed light is partially blocked by a knife edge. The light that is deflected toward or away from the knife edge produces a shadow pattern depending upon whether it was previously blocked or unblocked. This shadow pattern is a light-intensity representation of the expansions (low density regions) and compressions (high density regions) which characterize flow (**Karpen**, 2003).

A variety of system techniques can be use to capture flame perturbation. However, schlieren have been choose because it is the most suitable techniques for this project. Schlieren and shadowgraph techniques are quite similar techniques. The different is that schlieren system set up include knide-edge but shadowgraph set-up is without the knife-edge. This chapter is divided into several sections which include various visualization techniques; the basic principle of schlieren system, various techniques of schlieren setting, and various application of schlieren system.

Changes in the index of refraction of air are made visible by schlieren optics, which are extremely sensitive to deviations of any kind that cause the light to travel a different path. In this demonstration, the difference in the index of refraction of room-temperature air and the slightly warmer air that envelopes hand can be seen, for example, by using a video camera and monitor, it shows the warm convection currents rising from hand or, alternatively, cold air sinking from a glass of ice water. Gas can be visibly poured from a bottle into a glass (until overflowing) and subsequently poured out of the glass. Additionally, the bending of light around objects (diffraction by edges) can also be seen with this technique (Harvard Natural Science, 2009).

2.1 Various Flame Visualization Techniques

Several studies and researches have been made on various visualize techniques. However, the best visualize techniques is the schlieren visualization system, which is capable to capture accurate and clear image of flame propagation.

2.1.1 Natural Light

Natural light source can be visualized by using light source from sun, lamp other equipment. This technique is the simplest and easy to set up. However, the natural light technique cannot capture flame perturbation image properly, thus it would not allow proper study of flames (Inman, 2006).

2.1.2 Shadowgraph

Shadowgraph is an optical method that reveals non-uniformities in transparent media such as air, water, or glass. It is related to, but simpler than, the schlieren and schlieren photography methods that perform a similar function. The result of applying the shadowgraph technique is known as a shadowgram. A shadowgram is not a focused image; but rather a mere shadow. In the shadowgram, the differences in light intensity are proportional to the second spatial derivative (Laplacian) of the refractive index field in the transparent medium under study. Once the distance from the transparent disturbance to the cast shadow becomes too large, then the shadow no longer constitutes a useful representation of the disturbance that caused it (Weinberg, 1963). This project needed the technique that can focus on the object (explosion or flame) so the image will be clearer and sharp. In the present project, shadowgraph is not suitable because the image cannot be captured clearly and accurately compare to schlieren. Since many unused light source in the system is not filtered. Therefore, Shadowgraph is not suitable to be used for this project.

2.2 Basic Principle of Schlieren System

Schlieren basically are optical inhomogeneities in transparent material not visible to the human eye. Schlieren physics developed out of the need to produce high-quality lenses void of these inhomogeneities. These inhomogeneities are localized differences in optical path length that cause light deviation. This light deviation is converted to shadow in a schlieren system. Schlieren flow visualization is based on the deflection of light by a refractive index gradient. The index gradient is directly related to flow density gradient. The deflected light is compared to undeflected light at a viewing screen. The undisturbed light is partially blocked by a knife edge. The light that is deflected towards or away from the knife edge produces a shadow pattern depending upon whether it was previously blocked or unblocked. This shadow pattern is a light-intensity representation of the expansions (low density regions) and compressions (high density regions) which characterize flow (Settles, 2001).

The basic optical schlieren system uses light from a single collimated source shining on, or from behind, a target object. Figure 2.3 shows simple schlieren system diagram with a point light source. Variations in refractive index caused by density gradients in the fluid distort the collimated light beam. This distortion creates a spatial variation in the intensity of the light, which can be visualised directly with a shadowgraph system (Heineck, 1996).

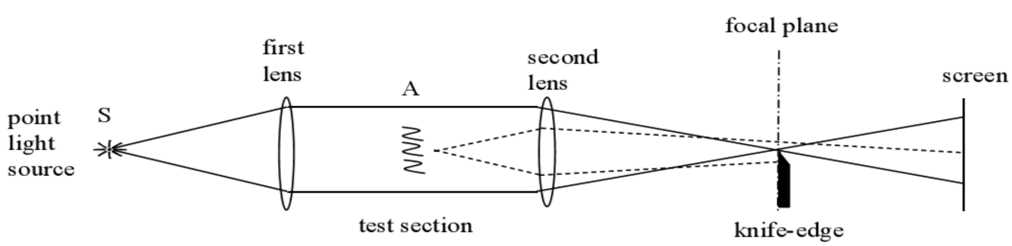


Figure 2.3: Diagram of a simple schlieren system with a point light source (Jeronimo and Haegen, 2002)

In schlieren photography, the collimated light is focused with a lens, and a knife-edge is placed at the focal point, positioned to block about half the light. Figure 2.4 shows typical photographs of flame propagation using schlieren images. In flow of uniform density this will simply make the photograph half as bright. However in flow with density variations the distorted beam focuses imperfectly and parts which have focussed in an area covered by the knife-edge are blocked. The result is a set of lighter and darker patches corresponding to positive and negative fluid density gradients in the direction normal to the knife-edge. When a knife-edge is used, the system is generally referred to as a schlieren system, which measures the first derivative of density in the direction of the knife-edge. If a knife-edge is not used, the system is generally referred to as a shadowgraph system, which measures the second derivative of density (Lackner, 2004).

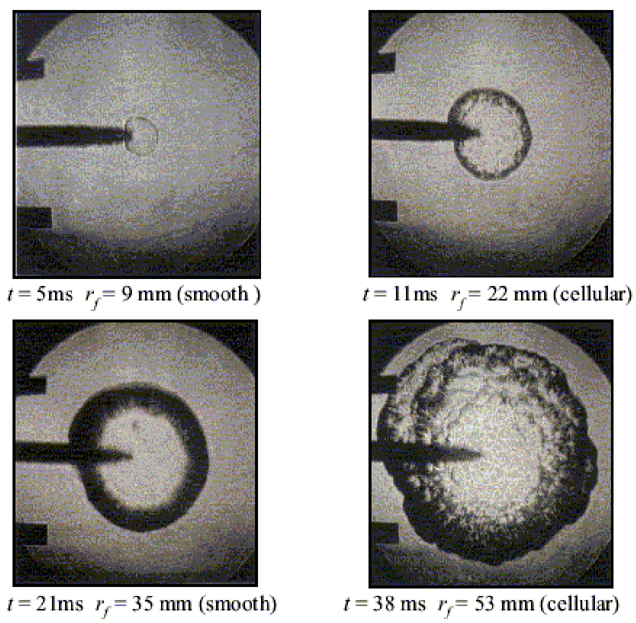


Figure 2.4: Schlieren images of flame propagation (Atzler, 2007)

2.3 Various Techniques of Schlieren System Setting

The setting that being used in this project is using schlieren straight and linear set up. Figure 2.5 shows one of the schlieren equipment settings. This set up was choose because it is suitable to the time given which is a year to complete and can be use easily to capture the flame perturbation. Moreover, the design is simple. The system can be assembled and disassembled easily and portable.

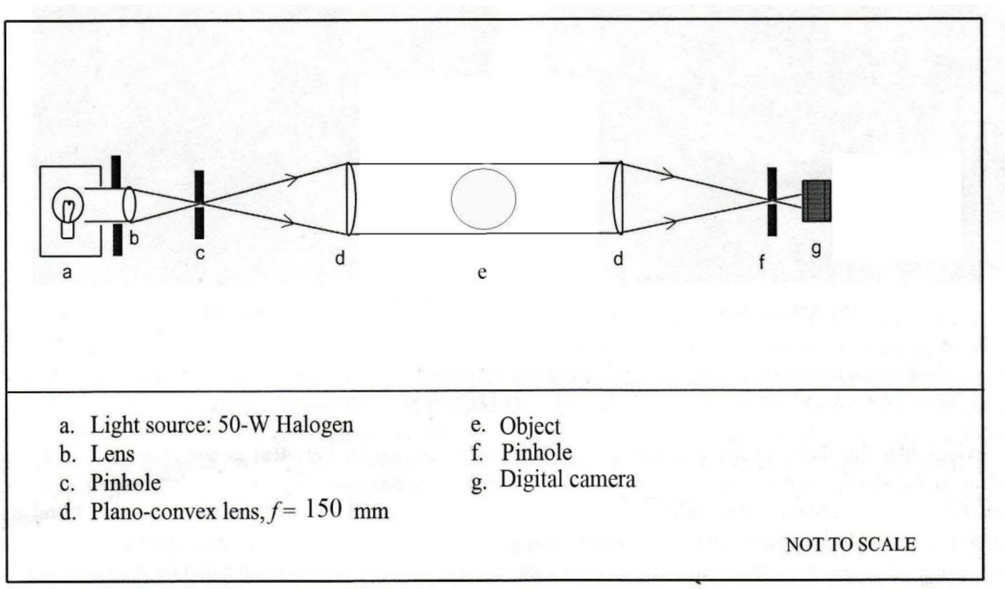


Figure 2.5: Schematic of project schlieren setting (Zawawi, 2008)

2.3.1 Parallel Light Beam Setting

Schlieren images are most often made in a parallel beam of light shows in Figure 2.6, which illustrates a compact setup. A light source is focused on to a slit that is placed off-axis and exactly one focal length from a lens or mirror. This produces a parallel beam of light that illuminates the test specimen. The test field is limited by the size of the major optical elements, so mirror arrangements are more common than refracting systems because large mirrors are easier to find. The collimated light containing the specimen image is focused onto a finely adjustable knife edge by another, similar mirror or lens, where it is partially blocked. Any change of refractive index in a transparent medium cause's part of the light to be refracted in or out of the part of the collimated beam that passes the knife edge, thus appearing brighter or darker than the background in the focused image (Peres, 2007).

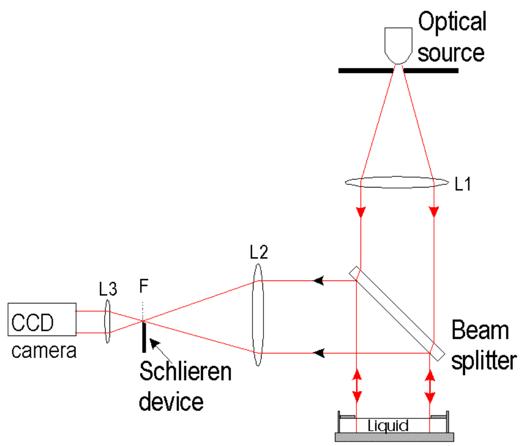


Figure 2.6: Typical Schlieren set-up used for visualizing deviations of an initially parallel light beam (CIMEX Evaporation, 2008)

2.3.2 "Z" Configuration Schlieren

The illustration shows the "z" configuration which minimizes the coma aberration in the focus. Mirrors are most often used because of the absence of chromatic aberration. Figure 2.7 showed the setting of "Z" configuration.

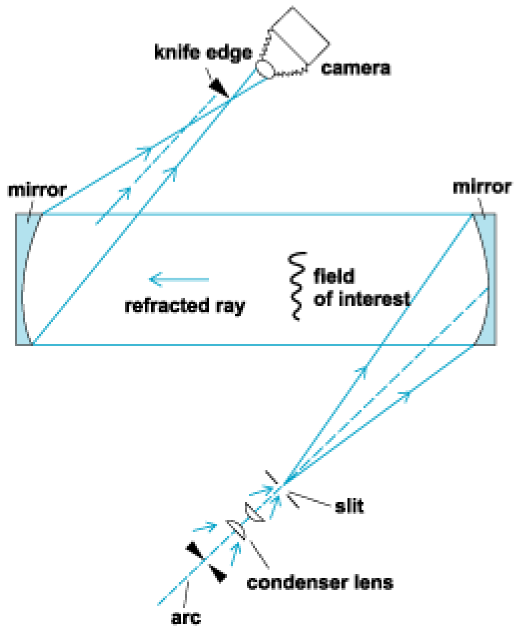


Figure 2.7: Knife-edge method of viewing Schlieren, employing the “z” configuration (Settles, 2001)

Rays of light that are bent by the schlieren in the direction of the knife edge are intercepted and removed from the final image of the region of interest, causing those regions to appear dark. Consequently, the system is most sensitive to the density gradients that are perpendicular to the knife edge. The knife edge is commonly mounted on a rotatable mount so that it can be adjusted during a measurement to optimally observe different gradients in the same field of interest. The intensity in the processed image is proportional to the refractive index gradient. A gradient in the same direction as the knife edge appears dark. Gradients in the opposite direction appear bright. This method, employed with arc light sources, is still one of the simplest ways to view refractive index changes in transparent solids, liquids, and gases. A well-designed schlieren system can easily detect the presence of a refractive index gradient that causes 1 arc-second deviation of a light ray (Settles, 2001).

CHAPTER 3
METHODOLOGY

3.1 Research Methodology

Excellent flow of methodologies is the key in this project. Project methodologies were divided into several main parts which cover study and research, selection process, design and fabricate, experiment, analysis, discussion, and finally improvement. Figure 3.1 shows the flow chart of this project. Table 3.1 shows the suggested milestone on this project for the first semester and second semester of final year project.

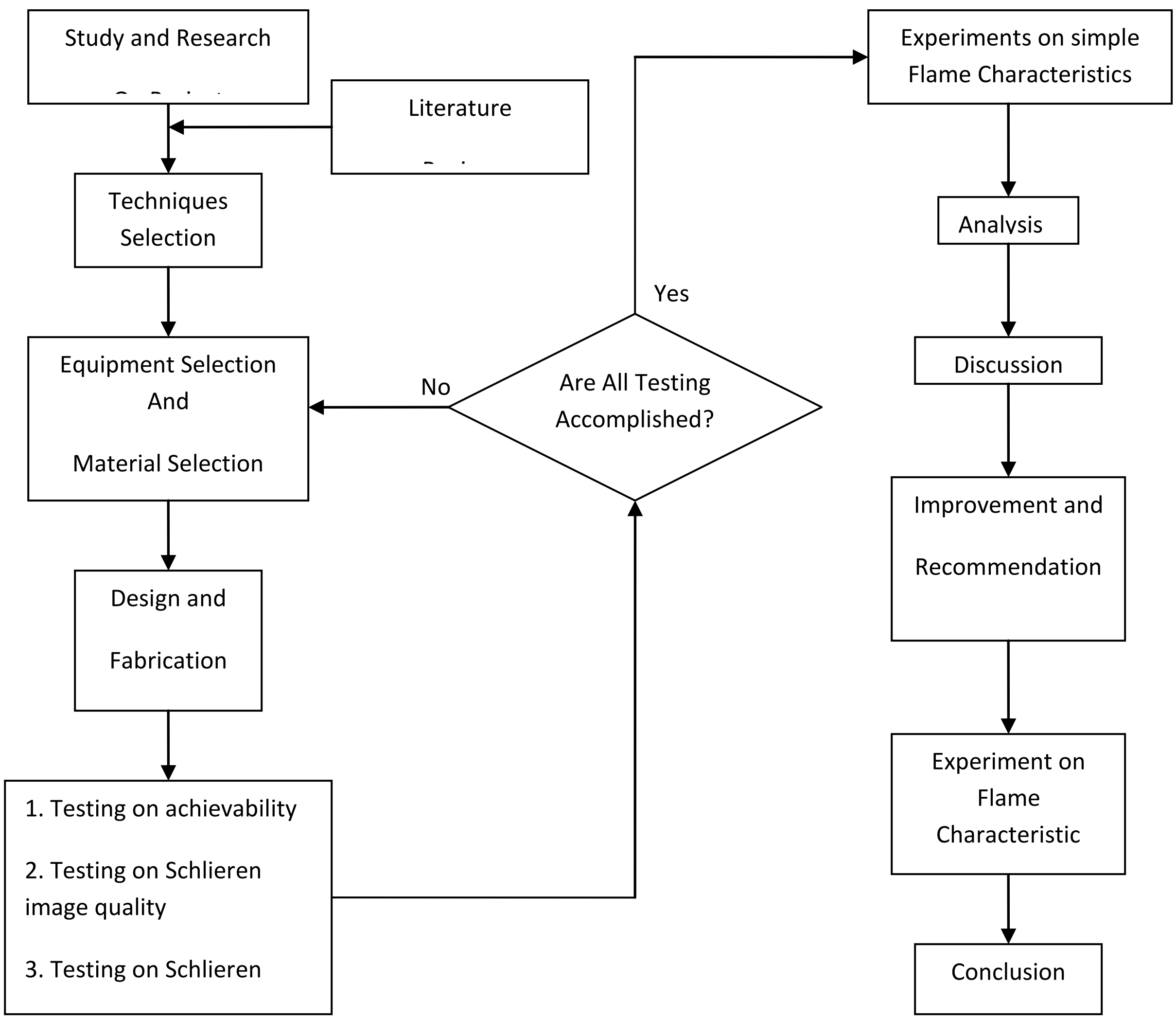


Figure 3.1: Project flow chart

3.1.1 Study and Research

Elements of this project involved in this stage including research and study regarding the overview of the project is to understand the basic concept schlieren system. Many important references were obtained from journal on schlieren system, which describe its concept, setting and discussion on its application.

3.1.2 Techniques Selection

The suitable technique for this project was selected based on the practicality and feasibility for usage of the schlieren system. Various types of experiments needed to be done on selection of schlieren setting by using the selection matrices shows in Table 3.1. From the table, it can be concluded that the highest mark shows the best technique which is most suitable for the project. Separated upstream and downstream schlieren setting have the highest mark, compared to others, based on several aspects and physical characteristic which have been evaluated. Therefore, this schlieren technique was selected for this project.

Table 3.1: The matrices selection process on the Schlieren Techniques Selection

	Practicality in University Experiment	Flexible in Area Captured	Easy to Set Up	Easy to Carry	**Marks**
Schlieren Straight and Linear	2	1	4	5	**12**
Parallel Light Beam Setting	1	2	1	2	**6**
"Z" Configuration	3	3	2	1	**9**
Separated Upstream and Downstream Schlieren	4	5	3	4	**16**

Description for scores : 1 = worst, 2 = bad, 3 = moderate, 4 = better, and 5 = best

3.1.3 Equipment and Material Selection

The tools and equipments were completed and identified based on the design referred. After gathering all the necessary tools, the system was assembled. Available equipment and material selected based on primary source which is university laboratory and other sources. After the most applicable techniques have been selected, the step proceeded on equipment and material selection. This project follows the rational Decision-Making flow (Shigley and Mischke, 2001).

3.1.4 Design and Fabrication

Several designs were proposed, the most comprehensive and efficient design was selected. The design drawings are produced by using AutoCAD software. The design of the prototype's component was subjected to change from time to time for quality and efficiency reasons and at the end, the best design was finalized and fabricated. The fabricated components were then assembled prior to testing for schlieren imaging.

3.1.5 Testing on Apparatus

The next stage was done to see whether the objective has been achieved or not. After the fabrication process finished, experiment to test on achievability and schlieren image were done. However, to make sure the apparatus can be used when conducting the experiment, testing on schlieren vs shadowgraph was done. If the testing fails, process would go back to equipment and material selection.

3.1.6 Analysis and Discussion

The data achieve from the experiments are analyzed and compare with previous experiment done by other researcher, scientist, and engineer from their journals and books. By analyzing the data, and compare from the other sources, it can determine the target and objective of the project is achieved. Thus, discussion on the result was done after the analysis completed the find out any problem or modification on the apparatus to produce a better result.

3.1.7 Experiment on Flame Characteristics

The next step is proceeding with valid experiment of flame characteristics. A few numbers of experiments on flame propagation or perturbation was done in the experiment to collect the accurate data and capture clear image after the modification and improvement on the apparatus. This is to measure the flame characteristics by capture using a camera.

Table 3.2: Project milestone for the first semester of final year project

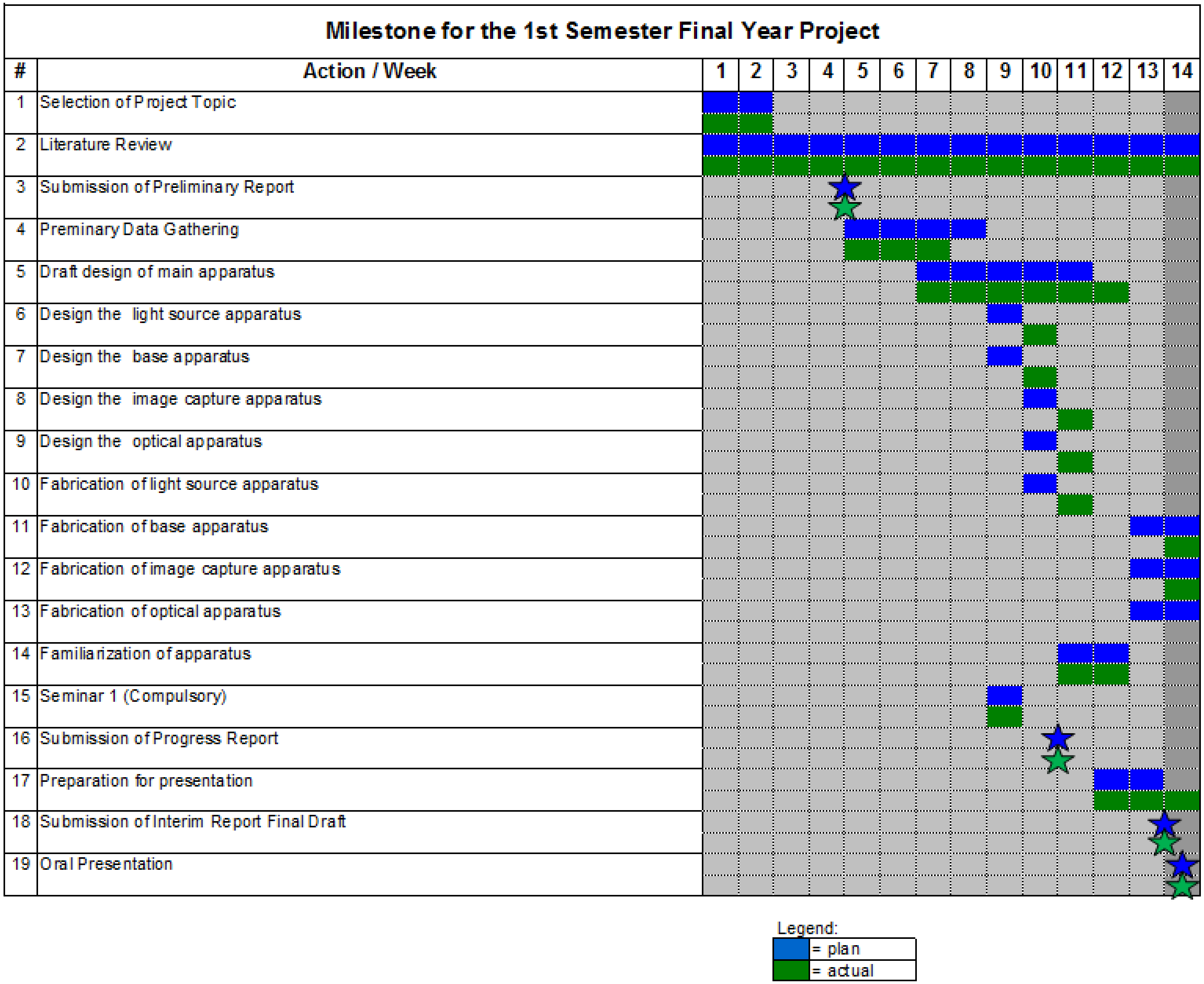


Table 3.3: Project milestone for the second semester of final year project

Milestone for the 2nd Semester Final Year Project															
#	Action / Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Complete fabricate on apparatus prototype (combine all part by part apparatus)														
2	Familiarization on apparatus														
3	Improvement on apparatus														
4	Conduct experiment on flame, bunsen burner , explosion using apparatus														
5	Analysis of laboratory data with results from experiment														
6	Analysis of actual simulation results with the formulated concept.														
7	Analysis of feasibility of the prototype														
8	Preparation for poster, presentation and conclusion														
9	Poster Exhibition														
10	Submission of Dissertation (soft bound)														
11	Oral Presentation														
12	Submission of Project Dissertation (Hard Bound)														

Legend:
= plan
= actual

3.2 Equipment and Components

The schlieren imaging apparatus consisted of a light source, a pair of a convex lens, a pair of normal lens, a pair of pinhole (knife-edge), a high speed camera, several lens holders and the base to support all equipment. Table 3.4 and Figure 3.2 show the list of equipment needed, description and quantity need on this project.

Table 3.4: Summary of equipment

#	Equipment	Description	Quantity
1	Light Source	- HIROX SOLARC Mode LB-24	1
		- ASBN-W High power Tungsten-Halogen Light Source Series	
2	High focal length Plano Convex Lens	- Material : glass	2
		- Lens Type : Plano Convex	
		- Diameter : 50mm	
		- Focal length : 750mm	
3	Double Convex Lens	- Material : glass	1
		- Lens Type : Concave	
		- Diameter : 50 mm	
		- Focal length : 100mm	
4	Pinhole (knife-edge)	- Metal / Semi-Matel sheet with 1mm hole at the center	2
5	Lense Holder	- Adjustable Metal holder	4
6	Digital Camera	- Sony Cybershot DSC-W150	1
		- 8.1 megapixel CCD sensor and an advanced imaging processor	
		- 5.5x optical zoom, 4.6x digital zoom	
7	Candle / Bunsen burner	Candle :	1
		- Diameter : 17 mm	
		- Length : 110 mm	
		Bunsen burner :	
		- standard laboratory specification	

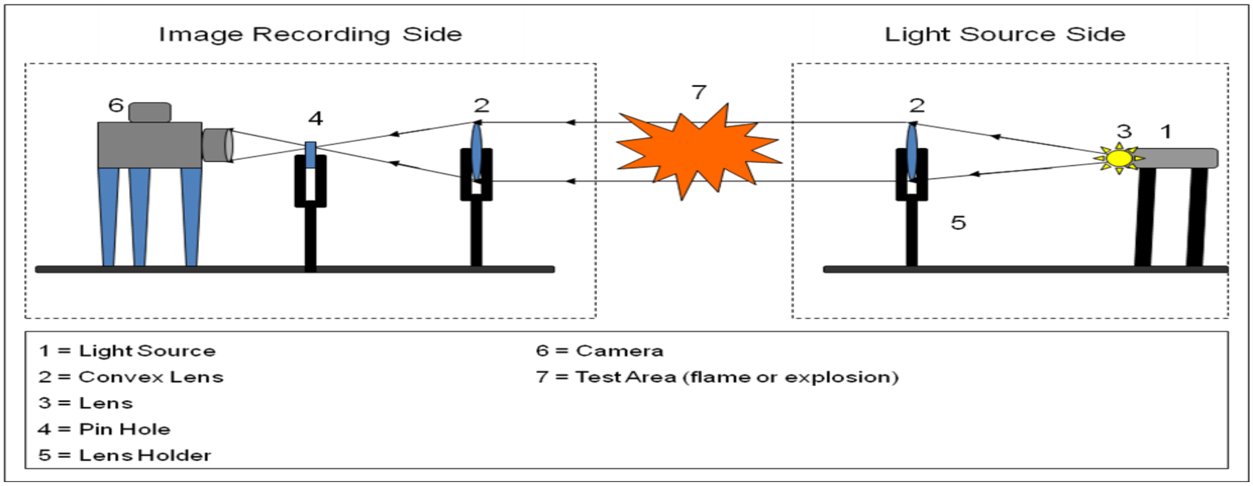


Figure 3.2: Equipment Schematic

3.2.1 Light Source

Figure 3.3: High power Tungsten-Halogen Light Source (Hamamatsu, 2009).

High power Tungsten-Halogen was selected because it is already built up with the lens inside the light source as shows in Figure 3.3. Therefore it is very practically in doing the experiment. It also provides optimal illumination to monochromators. It offers excellent colour temperature stability. Features adjustable constant current power supply which is can be used in any type of power supply. This light source is more feasible in the project compare the light bulb source which is less safe and less feasible.

3.2.2 Long focal distance Plano Convex Lens

Long focal distance lens of 750mm was chosen for this project primarily because such lens would enable capturing of appropriate field of view of the image. Plano convex lens were selected because it could divert the light to become parallel.

3.2.3 Ordinary Convex Lens

Normal focal length lens of 150mm were selected to convert the normal light source to focus light. The light then goes through the knife edge hole towards the next high focal length lens. The focal length of 150mm is used because it is the most suitable focal length for the experiment.

3.2.4 Pinhole (knife-edge)

A knife edge at the point source-image location was positioned as to partially block some light from reaching the camera when it captures the image. The pinhole diameter is about 1mm at the middle of the metal sheet as shown in Figure 3.4.

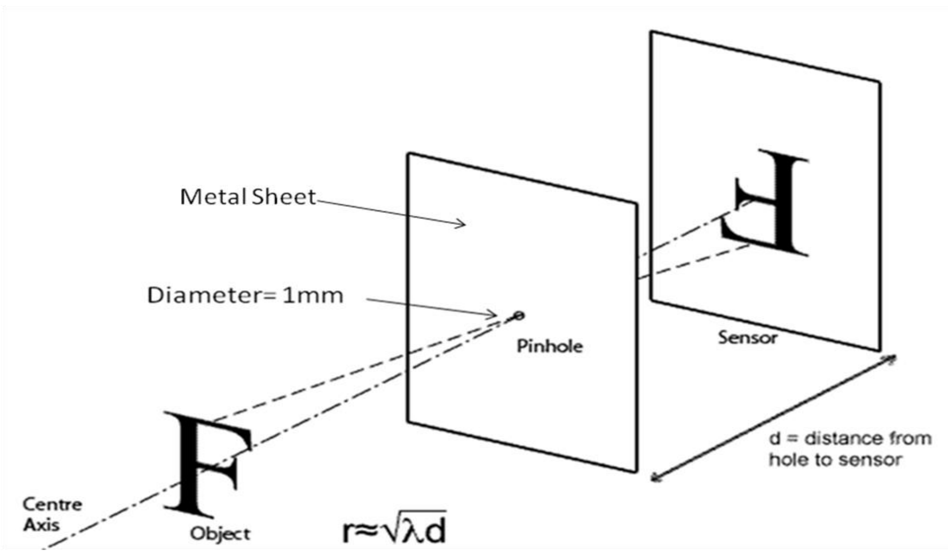


Figure 3.4: Schlieren Pinhole. (Northlight, 2009)

3.2.5 Lens Holder

The lens holder was used to hold the lens. The purpose of a lens holder is to provide stability and keep optical elements firmly in place. The holder had a U-shape. This holder was fabricated by local company in Malaysia, and thus, the cost is lower as compared to the imported ones. The lens holder was also flexible because it could adjust to enable positioning of the lens along the bench. Lens holder holds the lens fittingly to prevent the lens from shifting from is position as shown in Figure 3.5. Lens holder selected because it was the best gadget to grip the lens.

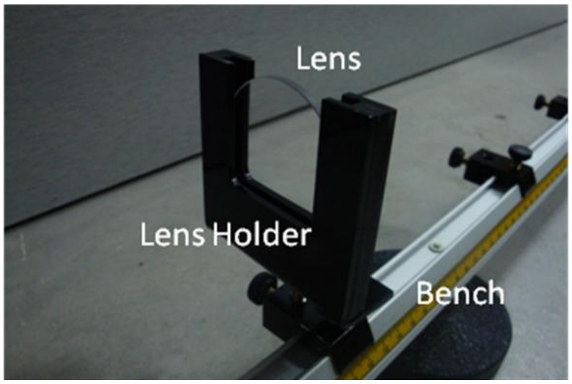


Figure 3.5: Lens Holder

3.2.6 Digital Camera

A camera used to capture the image for this project. Sony digital camera was chosen because of the cost aspect and also reliability to the project result. However, the result might not be as good as the high speed camera but it still able to capture the image clearly and accurately as shown in Figure 3.6. The camera is suitable and reasonable for the project after several factors on material selection being study.

Figure 3.6: Digital Camera Cyber-shot DSC-W150 (Sony, 2008)

3.2.7 Candle

Candle was used as a flame sources because it is easy to obtain and less costly compared other flame source such as vessel explosion, and ignition inside engine. For that reason, candle was use from the beginning of the project. Once the prototype achieved the target by using both of this flame sources, further experiment on bigger flame source such as vessel explosion was done. Hence, candle is vital to save cost and time in the project.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Data Gathering and Analysis

4.1.1 Preliminary Data Gathering and Analysis

A commercial schlieren visualisation system is available at the Automotive Center of Universiti Teknologi Petronas (UTP). Preliminary data gathering using simple flame was made in the laboratory. The purpose of the visit was to understand more on schlieren system and at the same time study the design and setting of the system that was already available. Figure 4.1 shows schlieren visualization setting in UTP Automotive Centre.

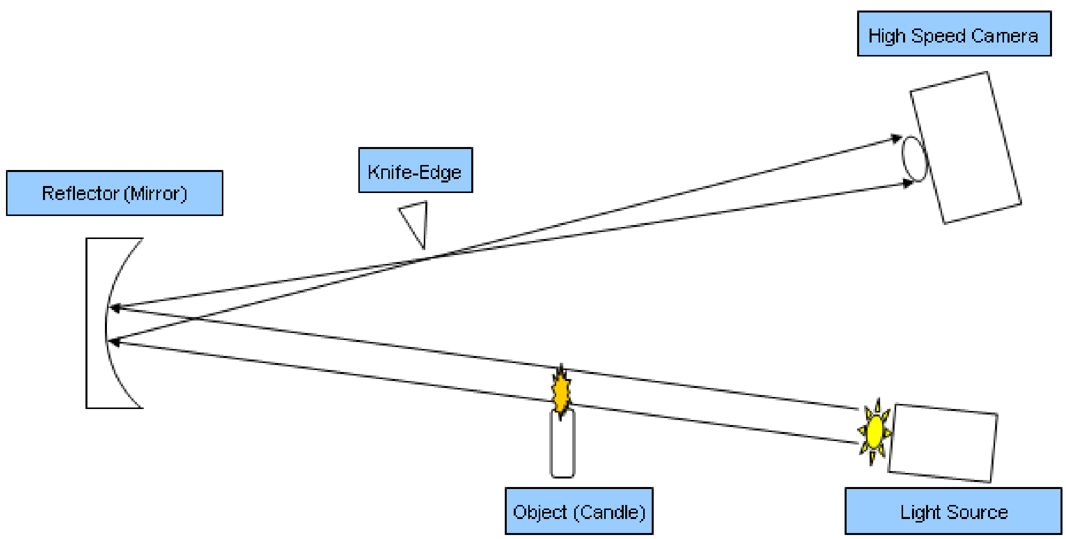


Figure 4.1: Setting of the UTP automotive centre Schlieren Visualization System

The system comprises of a high power tungsten- halogen light use light source, a high speed camera, a reflector (mirror) knife-edge and an object (candle). A high power tungsten-halogen light source was used to give a very strong light source to the light image. The high speed camera could capture 1000 images in a second. This was very helpful to determine the flame characteristics. The function of the reflector mirror was to convert from straight light source to form focusing light that is captured by the camera.

A typical of schlieren image of the flame from this setting is shown in Figure 4.2. The result shows that the schlieren flame image is not very clear since some part of the flame is in white color and some of it in black color. Moreover, because of the other light source such as sunlight from window and also room light disturbed the object and create another light source to the object. The image was clearer after the light source and non-used light source has been control very well. For that reason, the image that was captured by UTP schlieren visualization setting became the standard point for this project. On the other hand, the setting of the schlieren is fairly poor since all equipment is separated from each other.

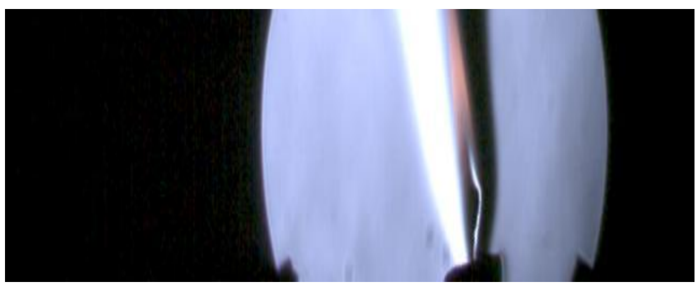


Figure 4.2: Schlieren Candle Flame Image captured using the UTP Automotive Centre's schlieren visualization system

4.2 Schlieren Visualization System

4.2.1 Development of the Draft Design

In mechanical engineering, the development of any product involves some broad steps as mentioned below. Mechanical engineering design is an integral part of this process and shapes the utility of the product developed to a large extent (Kathuria, 2005).

Step 1 - Identify the Idea and Concept

Step 2 – Define the Requirements for realizing the concept

Step 3 – Gather relevant Information on similar products

Step 4 – The Design Phase

Step 5 – Fabrication and installation of prototype

This project works on step one and step two which, identify the idea and concept of this project and define the requirement for realizing the concept needed. Step three focuses on gather relevant information on similar products done by during the site visit at UTP Automotive Centre to gather the data and understand more on the concept and practical of the schlieren device.

This project continues to step four which is the design phase. Half of the work has been done which is draft of the schlieren visualization system. Before the draft design, brainstorming, research and ideas are evaluated, a clear examination of the impact on time and cost goals for the project was done at this stage. Apparatus was divided into two main parts which is image capture part and light source part. The image capture part consist a camera, a tripod stand, a knife-edge, one lens, one lens holder, and one base. Light source part consists of a light source, a stand, one lens, one lens holder, and one base. These two parts was separate to make the device able to capture any object in between them, for example an explosion. The previous design did not separate these two parts therefore the object that can be captured by the device is very limited because only a small object that can be captured. Hence, this project schlieren visualization system is very simple and straightforward to setup. As it is also easy to carry, marketable, and low cost in fabrication by select the simple design but can be used widely in industry.

4.3 Prototype Design

With the help of the AutoCad 2004 software, used to help illustrate the prototype model to make the prototype drawings in accurate and clear design. Several illustrations was made which cover prototype model and all part of components inside the prototype which are lens holder, light source, camera, tripod, knife edge, and bench. The measurement is specified to make the fabrication process become easier and more precise. The unit of the measurement is in millimetre (mm). Below figures show several schematic of schlieren visualization parts by parts in Figures 4.3 to 4.8.

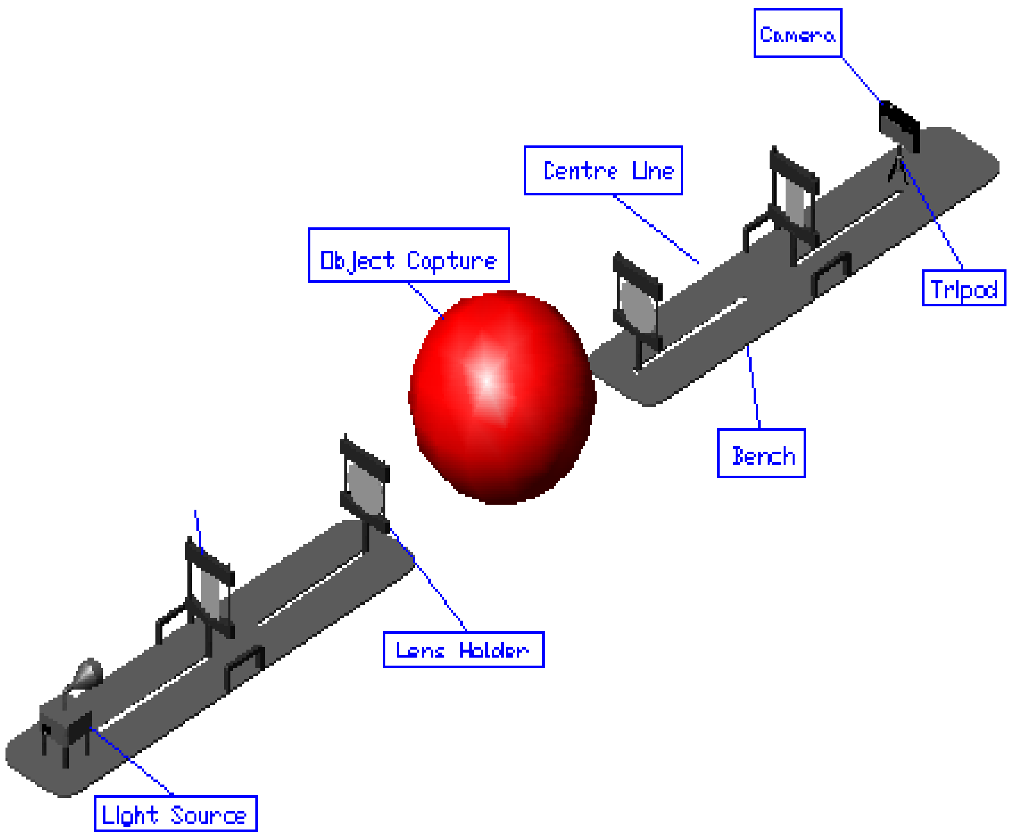
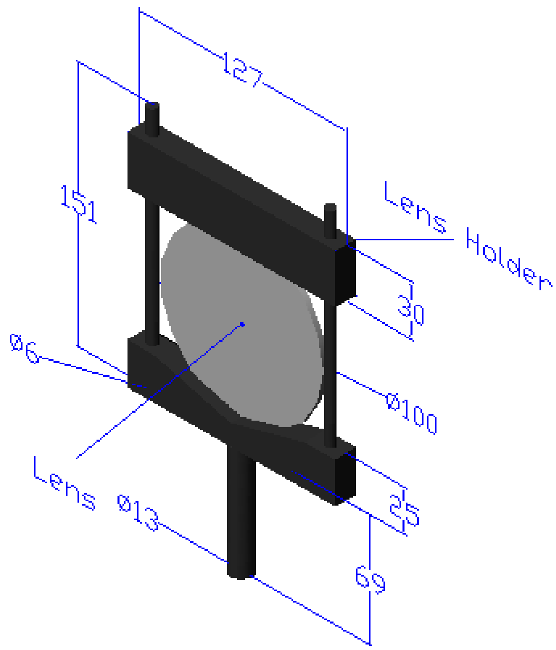
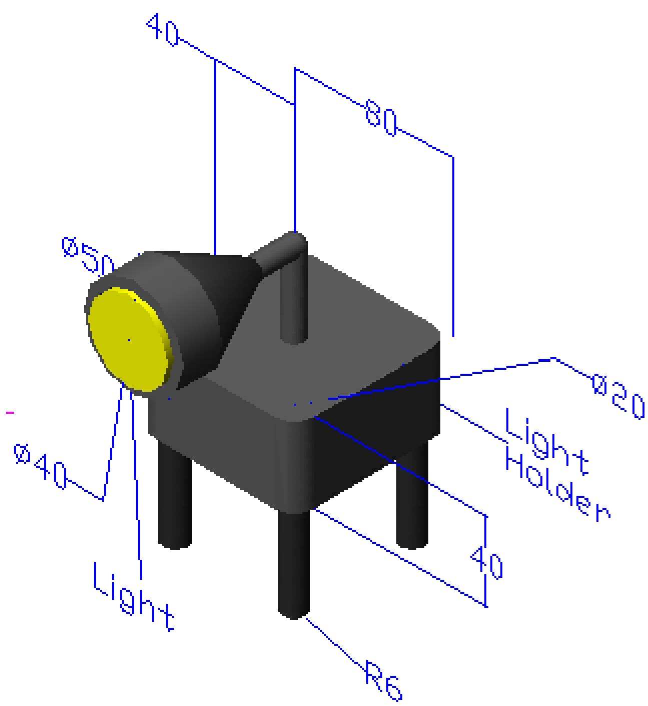


Figure 4.3: Prototype Illustration



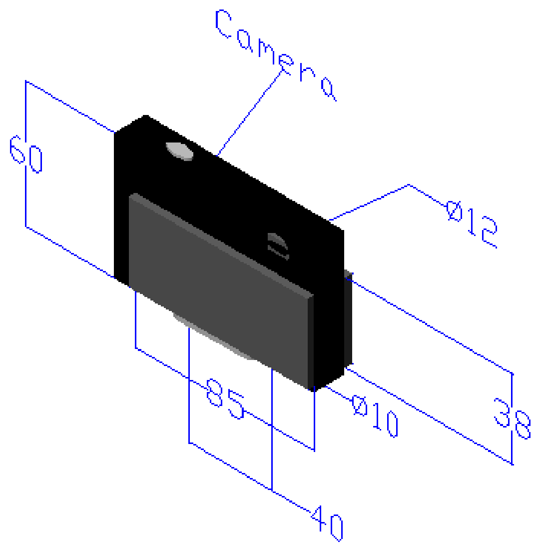
Unit: **mm (milimeter)**

Figure 4.4: Lens Holder



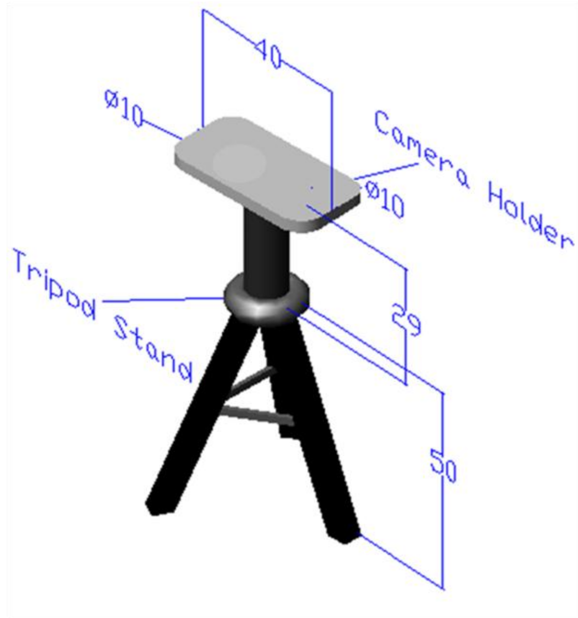
Unit: **mm (milimeter)**

Figure 4.5: Light Source



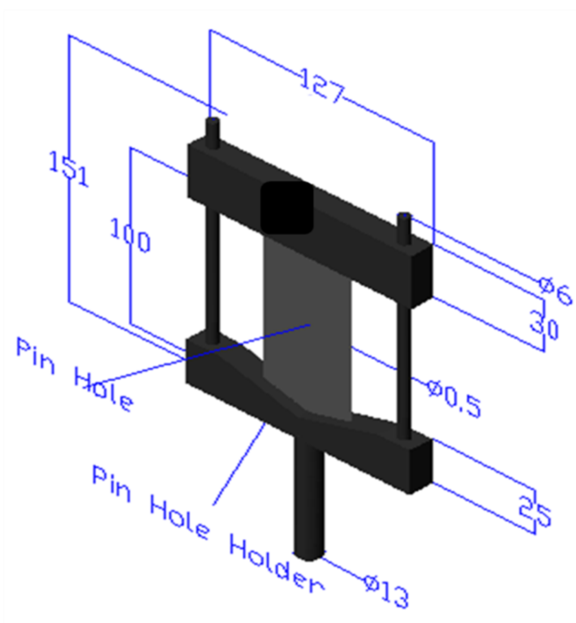
Unit: **mm (milimeter)**

Figure 4.6: Camera



Unit: **mm (milimeter)**

Figure 4.7: Tripod



Unit: **mm (milimeter)**

Figure 4.8: Pin Hole Holder

4.4 System Assembly

The schlieren imaging system, assembles that all components needed to be placed at the exact positions. Figure 4.9 shows the schlieren setting system of the first part and the camera view of the schlieren system. Familiarization with the setting and component parts was done to ensure that the apparatus works properly. Error on the candle light happens on the figure because light from candle travel surround the flame. Therefore, unneeded candle light appeared on the grey block near the experiment apparatus. The setting was divided into several sections which are:

- Upstream (Light Source)
- Downstream (Image Recording)
- Base (Bench, Lens Holder, Pinhole Holder, Lens and Pinhole)
- Object (Flame)

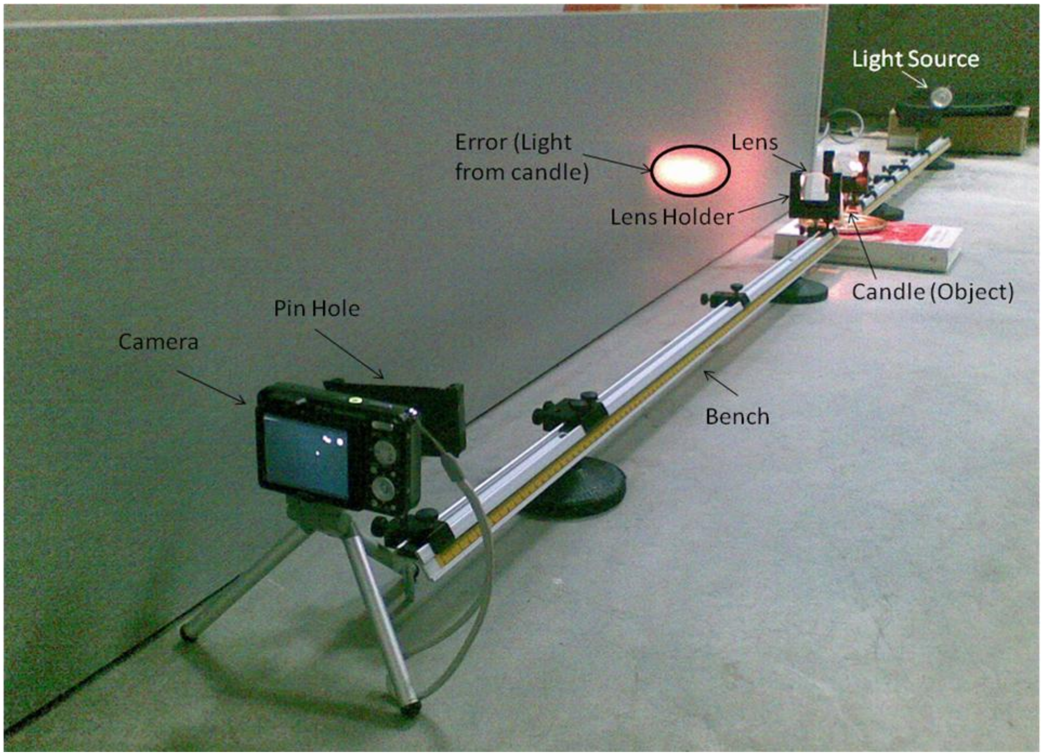


Figure 4.9: Schlieren visualization setting of the first part process.

4.4.1 Upstream

Upstream contain light source that was used to provide light for the system. Shown in Figure 4.10 is the light sourcing that had been used in this project. The "point light source" is a halogen light bulb positioned behind a pinhole. The light bulb should be as close as possible to the pinhole. This is to increase the efficiency of the light.

Figure 4.10: Light source when it is turn off and on

4.4.2 Downstream

This section of the system contains a camera and a tripod to capture the image. It was equipped with a long focal length zoom lens. The length of the zoom lens works best for tight cropping of the image is about 100 to 150 mm.

4.4.3 Base

The base contains bench, lens holder and pinhole holder, lens and pinhole. The bench functions as to hold the lens holder and pinhole holder. The bench is about 100cm long and has a rail to move and adjust for the suitable length for lens holder and pinhole holder. It was made from steel and plastic and supported by two round stands. Figure 4.11 shows the bench and it rail to move the holder any where on the rail. It can slide the holder mount back and forth on the bench rail to get the accurate focus length if focal length of lens changed. Lens holder made from plastic in square shape and steel rod. It has a hole in the middle of it to put the lens inside it. Figure 4.12 shows the lens holder. The pinhole is made from plastic, steel rod, and also a dark black card board. Figure 4.13 shows the pinhole holder for the project. Both holders have a cylinder steel rod to attach the holder to the bench.

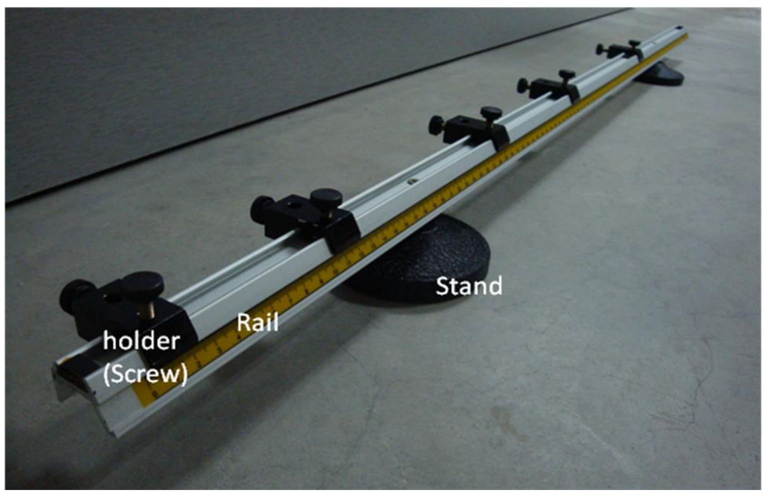


Figure 4.11: Bench that was fabricated for the schlieren visualization system

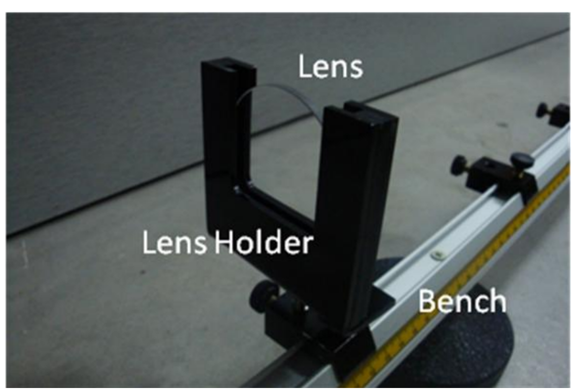


Figure 4.12: Lens holder of schlieren visualization system

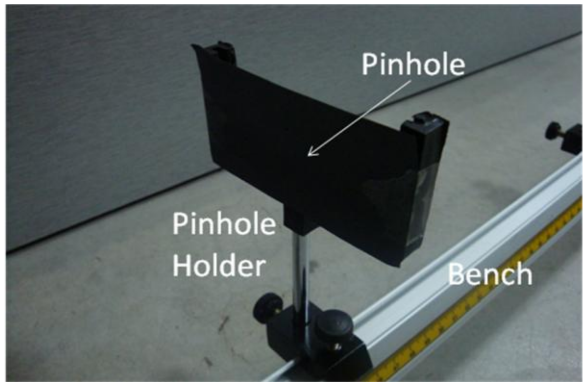


Figure 4.13: Pinhole holder of schlieren visualization system

4.4.4 Experiment Object

A candle was used as an object sample for the first run test. Figure 4.14 shows the type of candle used for the testing. The test needed a very bright candle that produces a clear patterned and must be done in a place free from wind. It is to make sure the result of the experiment is accurate and to decreases other external factors that increase error in the research. Dark area or non-light lab environment is more suitable place to run the experiment because the appearance of other light source can affect the result of the experiment.

Figure 4.14: Candle used for the first testing schlieren process

4.4.5 Parallel Light

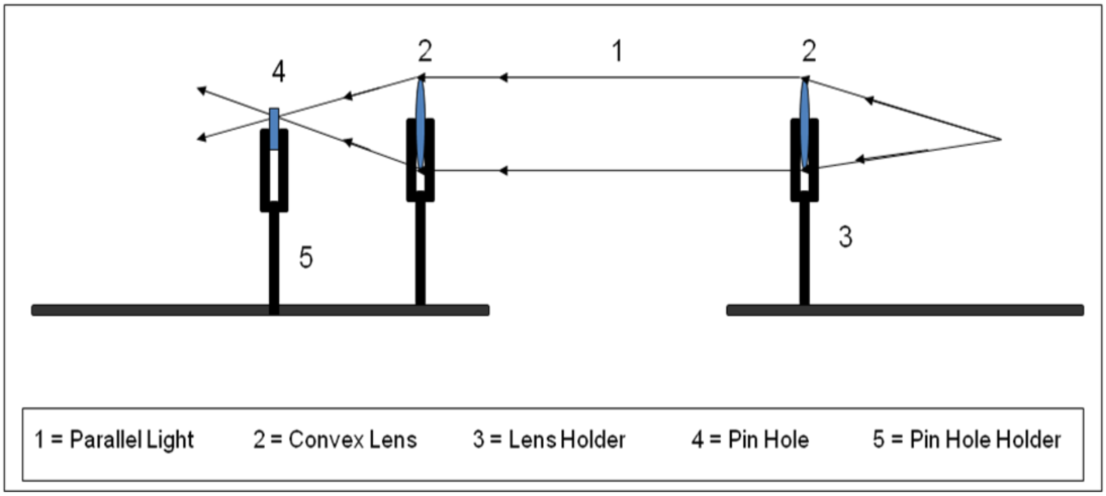


Figure 4.15: Parallel light of the apparatus

Parallel light is one of the components in schlieren visualization system. Parallel light used to capture the image of object in the experiment as shown in Fugire 4.15. Plano convex lens used to convert the focus light into parallel light. The bigger the parallel light, the bigger the area of image of object can be captured. Both plano convex lens must aligned with each other so the parallel light go through the image properly. Parallel light was obtain when focus light from light source travel through pinhole and the plano convex lens.

4.5 System Setting

The apparatus setup must be precisely aligned from one component to other component. This means the light source must placed aligned with respect to the optics bench rail which holds the pinhole, lens and digital camera.

(a) The "point light source" which is a halogen light bulb was position behind a 10mm pinhole. The light bulb was adjusted until the focus point was found at the centre of the pinhole where the pinhole was located (this aligns the filament with the pinhole). The pinhole was mounted on a y-adjustable optics post which was oriented so that the pinhole can be moved on the bench rail horizontally in the direction of the light source as shown in Figure 4.16.

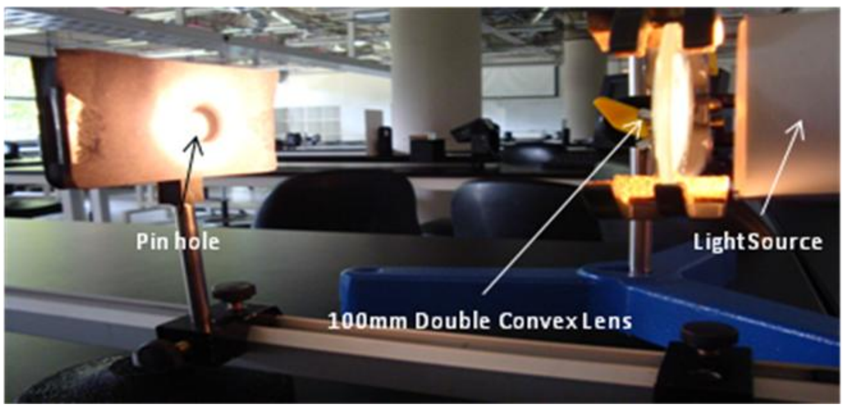


Figure 4.16: Light Source, Double Convex Lens, and Pinhole position

(b) The 750mm focal length plano convex lens was positioned approximately 750mm away from the 100mm focal length double convex lens. While the pinhole was assemble 100mm away from the 100mm focal length as shown in Figure 4.17.

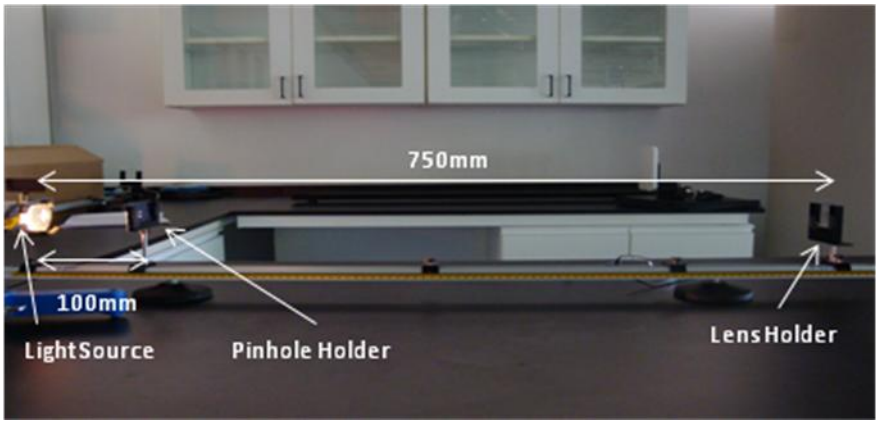


Figure 4.17: Position of 750mm plano convex lens holder in apparatus

(c) Since the distance of digital camera is far, the digital camera used was equipped with a long focal length zoom lens; optical zoom 5x works best to crop the image. Figure 4.18 shows the holder lens that attached on the optics rail and mounted on a y-adjustable optics rail bench. It is oriented so that the lens holder can be moved horizontally in the direction of the light source.

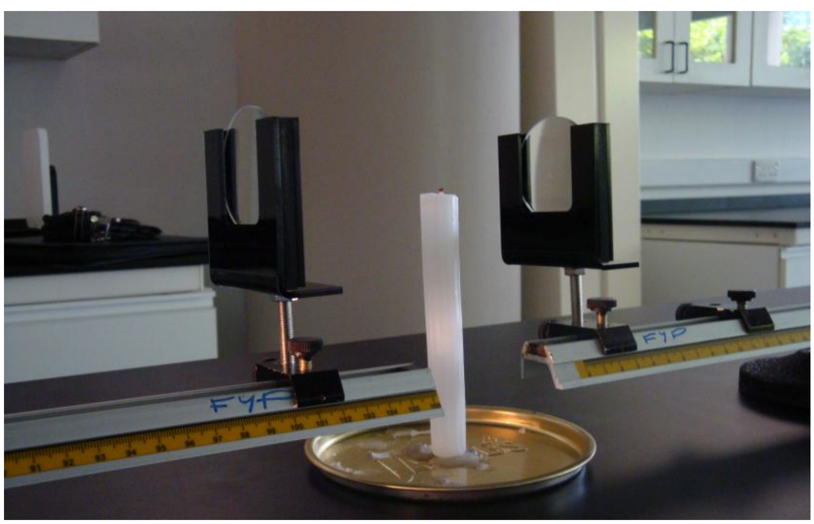


Figure 4.18: Y-direction adjustable lens holder attached with bench

(d) The suitable level (height) of the optics rail was selected on which the point light source, pinhole, and zoom camera is mounted as shown in Figure 4.19. The lens holder that was aligned with the focus point of the source light was used to position both 750mm convex lens.

Figure 4.19: All the component must align with the light source

(e) The lens holders and pinhole holders stand was locked at the suitable position on the rail bench. The lens holder and pinhole holder screws was levelled, and was adjusted to the height of the optics rail so that every focus point hits the lens and pinhole as shown in Figure 4.20.

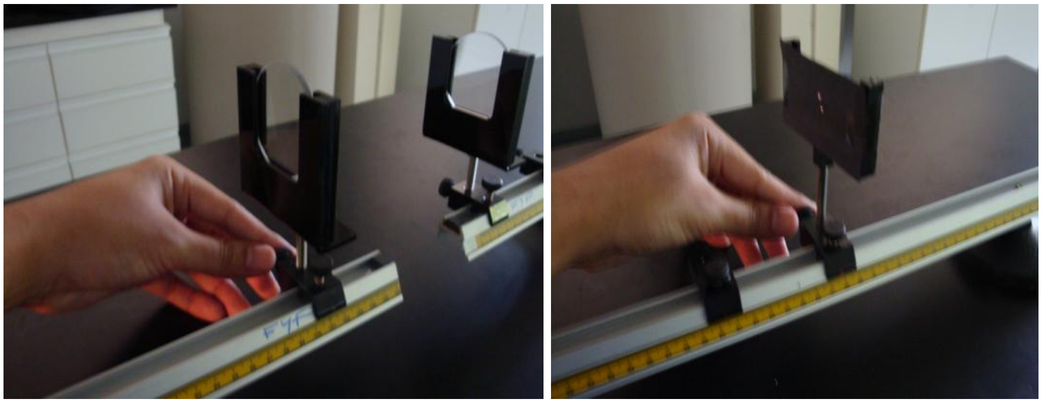


Figure 4.20: Adjust lens holder and pinhole holder position using levelling screw

(f) The camera and tripod was adjusted near to the pinhole, so the image can be captured thru pinhole. Fine-adjust the camera (using the horizontal and vertical adjustment on the tripod) to precisely hit the pinhole with the beam. The digital camera was mount.

(g) The pinhole holders and lens holders was raised and mounted back and forth on the optics rail to coarsely focus the point light source. Fine-tune was done as to adjust the focus light with the longitudinal adjustment screw (on the both lens holders and pinhole holders mount) as shown in Figure 4.21. The camera lens was adjusted to minimum number of exposure and fine-tunes pinhole height. The camera lens was focused on whatever object that is held in between both 750mm convex lens.

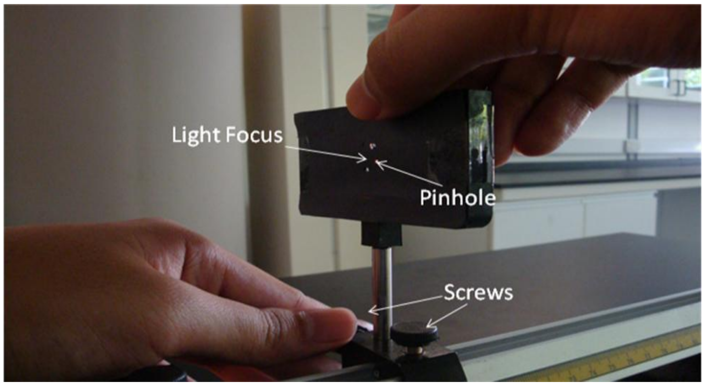


Figure 4.21: Fine tune the pinhole holder align with light source thru the pinhole

(h) After completed and adjusted all the settings, the experiment of the schlieren visualization started with running the experiment to capture the schlieren image. The photo below in Figure 4.22 shows the complete component of the schlieren visualization system. The system contain upstream (light source), downstream (image recording), test area (flame), base (bench, lens holder, lens, pinhole holder, and pinhole), and object (flame).

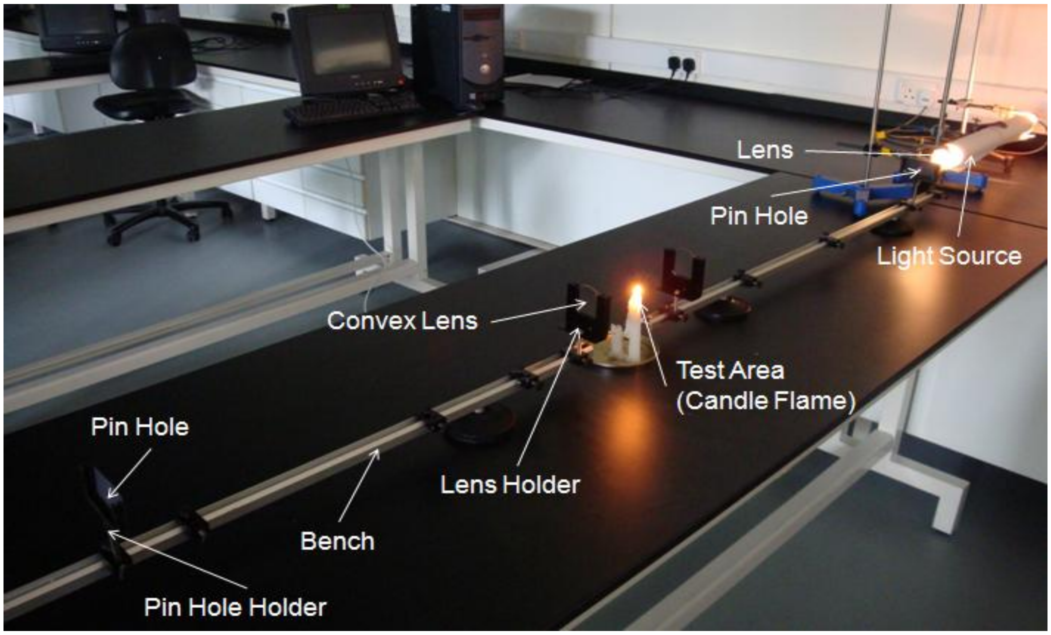


Figure 4.22: Schlieren Visualization System

4.6 Phase I Experiment (Familiarization with Prototype)

After finished with the test to determine the accuracy and efficiency of the apparatus, the experiment was continued by using the digital camera for the first testing of familiarization with the prototype. Only the exposure of the camera was adjusted. However, this limits the visual of the schlieren since aperture of the camera cannot be adjusted because it is fixed on automatic mode, only the exposure can be change for this camera. Figure 4.23 below is the photo of flame with natural light that is capable to only be captured in natural light. In Figure 4.24 shows the image when the light source spotted by light source of light bulb 240 watts.

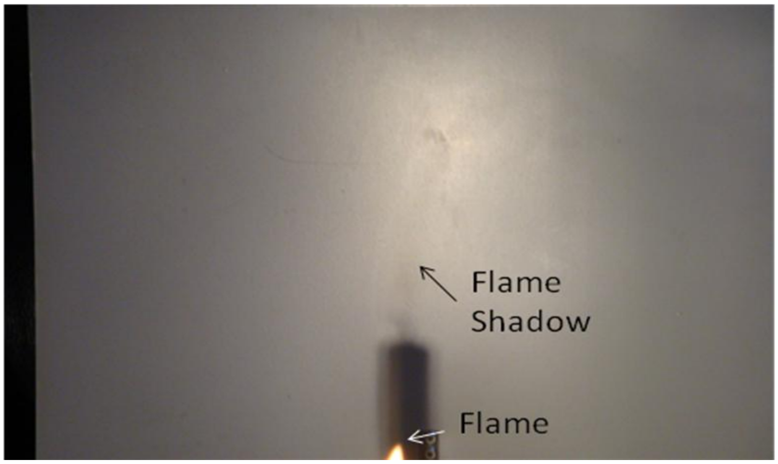


Figure 4.23: Flame image in natural light without spotted by using 240 watts light bulb

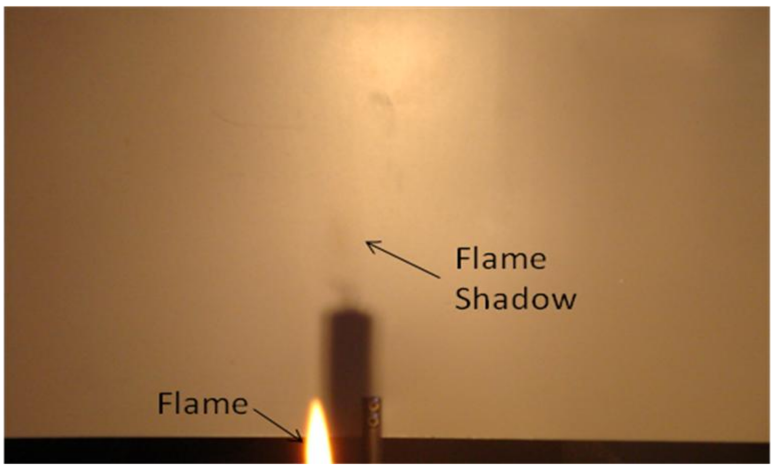


Figure 4.24: Flame image with spotted by 240 watts light bulb

Several setting has been made to get the most suitable schlieren setting for the experiment. However, the camera was incapable to capture the image when there is a light source; since the light is too bright. No flame characteristics can be seen when there is an existing light source. Therefore, the experiment was conducted in a place where there is no light source but the image of the of the flame characteristics seen was not a schlieren image. Figure 4.25 shows the image of flame through pin hole on the testing.

Figure 4.25: Image of candle flame captured by camera through pinhole

4.7 Phase II Experiment (Capture Schlieren Image)

The schlieren visualization image setting was modified to another setting, as shown below in Figure 4.26. This setting was changed in order to get the Schlieren image. A retort stand was utilized to assist the experiment because it can hold the light source. By making the light source stand still, made it easier to be adjusted and moved. Figure 4.27 shows the image of Shadowgraph when the pinhole is taken out of the Schlieren Visualization Image Setting. Shadowgraph was unable to show a clear image of flame characteristics due to many other existing lights that unable to filter since pinhole not has been used in the Schlieren system.

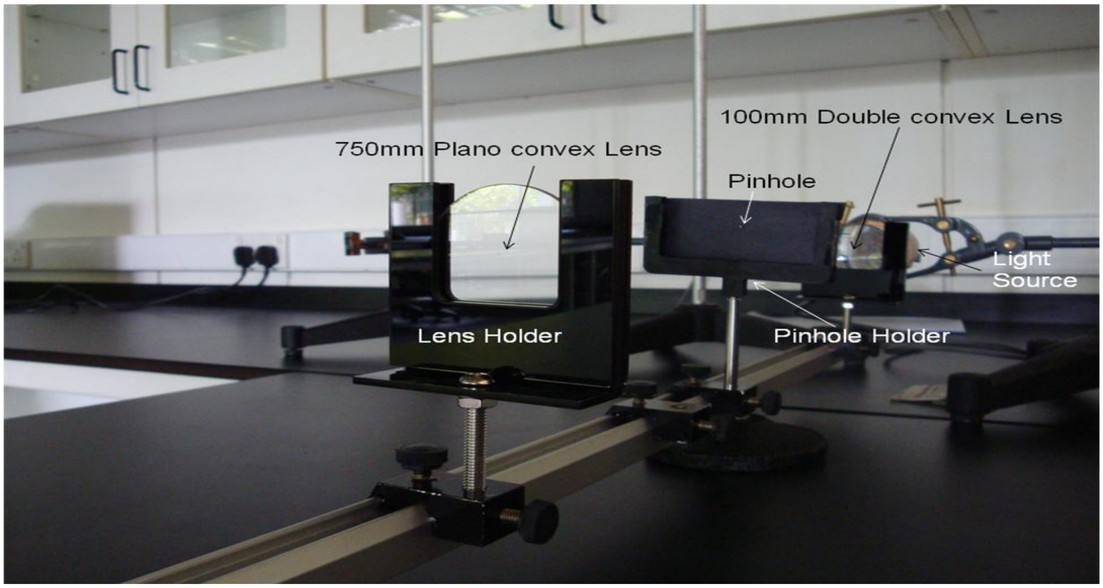
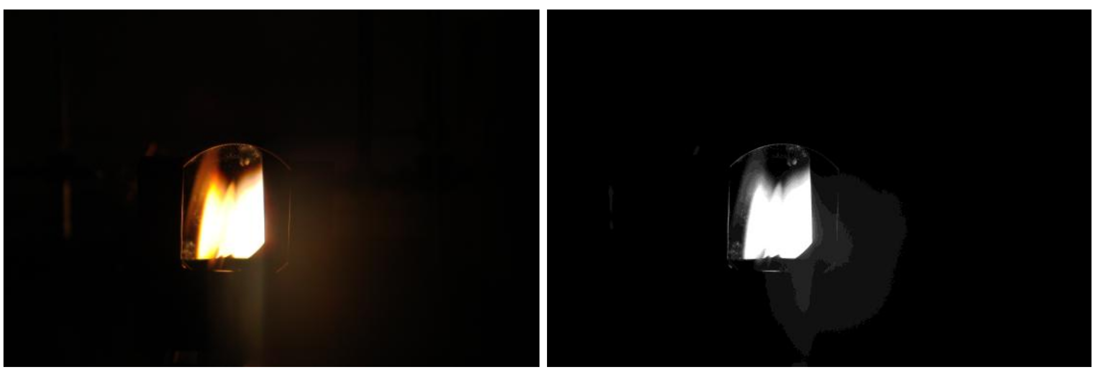


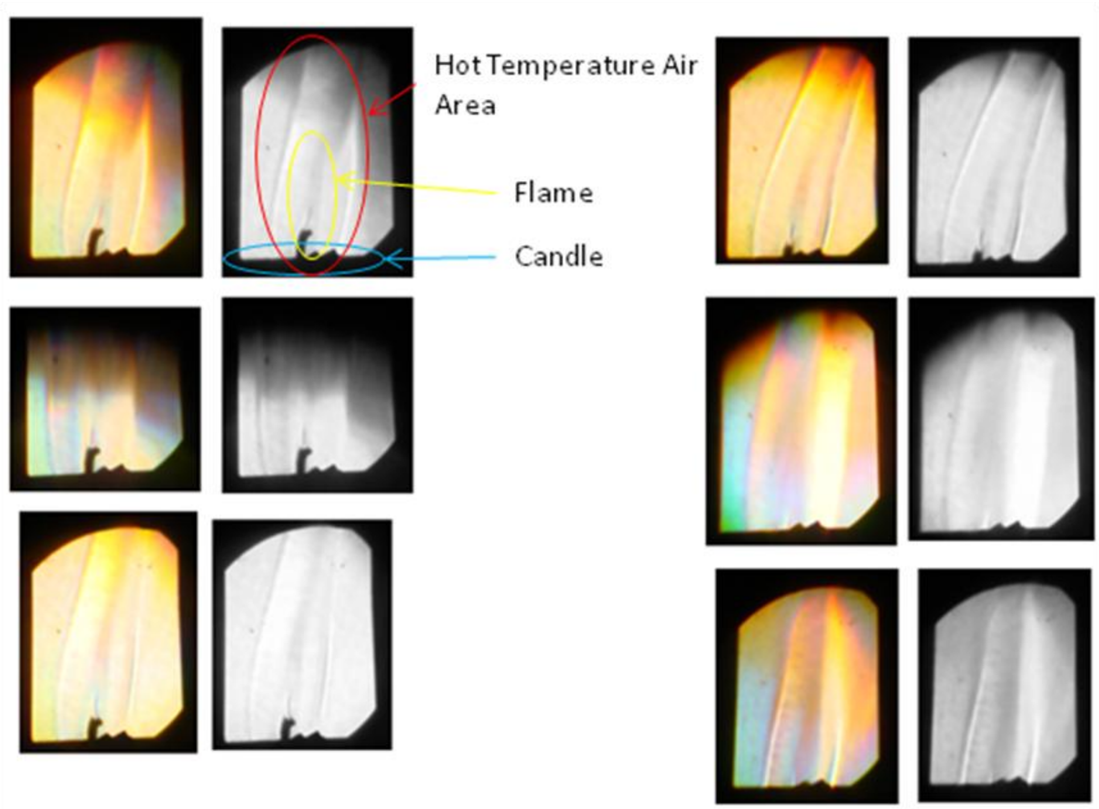
Figure 4.26: Schlieren Visualization Image Setting in Optic Laboratory



Colour Grayscale

Figure 4.27: Flame Shadowgraph image

The first schlieren image captured during the phase II experiment as shown in Figure 4.28 below. Several Schlieren setting was changed as to improve the setting. The light source needed to be moved a bit further from the 100mm double convex lens to obtain the best focus light. The light source was vital in the experiment as it affects the experiment. The light source used in this experiment was Philips 240watt halogen light. The image captured was not differentiated and there is no separation of colour between gradient of flame. Therefore, Schlieren cannot be seen clearly. In addition, to obtain schlieren, a bright, more focus and straight light should be used because of the capability to increase the contrast of Schlieren image colour by gradient. As a result, the image of flame and differentiation between gradient can be seen more clearly. To measure the focal point, a piece of white paper (A4) was used by moving it forward and backward aligns with the bench because, sometimes, the focal length of lens is not really accurate due to the manufacture error. Example of the manufacturer error in this experiment for instance, 100mm focal length lens changes to 110mm focal length lens. Therefore, by using white paper helps to improve the accuracy of focus point of lens. On the other hand, the pinhole and convex lens needed to determine the best position to put the apparatus on the bench. The 750mm convex lens between the flames was adjusted to cover all the flames. However, the images below covered only the body of the flame but miss the flame tip. The reason is because the digital camera has limitation of the visualization since it only can zoom 5x to the image capture, yet the high megapixel which is 8.1 megapixels really improve the experiment. On the other hand, camera with the more functions of manually setting like SLR or high speed camera can improve the image of Schlieren. It is because it can control exposure, aperture, other setting to improve the Schlieren image.



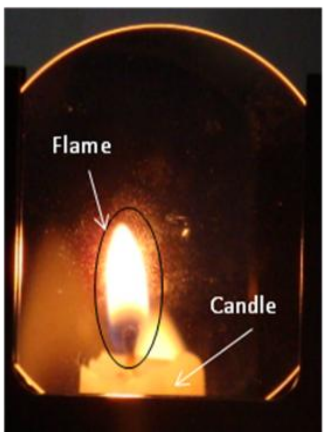
Colour Greyscale Colour Greyscale

Figure 4.28: Several shots of flame schlieren image

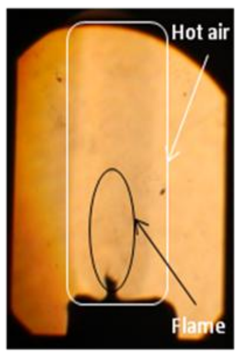
4.8 Phase III Experiment (Study of Schlieren Visualization System)

4.8.1 Differentiate between Natural Light, Shadowgraph, and Schlieren Images

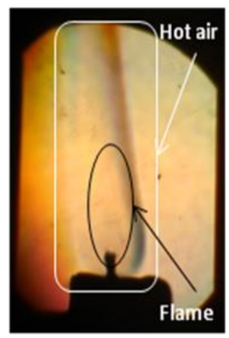
Identical setting and scale of experiments fuctions to capture flame image in natural light, shadowgraph, and Schlieren. The objective of this experiment was to compare the image captured using both settings. The schlieren image shows a clearer image of the flame characteristics. However, the shadowgraph image shows a blur flame characteristics while the natural light image was unable to show any of the flame characteristics. Candle flame images captured with the natural light, shadowgraph and Schlieren is shown in Figure 4.29. This proved that Schlieren captured the flame characteristics better than shadowgraph and natural light. Therefore, Schlieren System is the best system to determine and understand the flame characteristics.



Natural Light



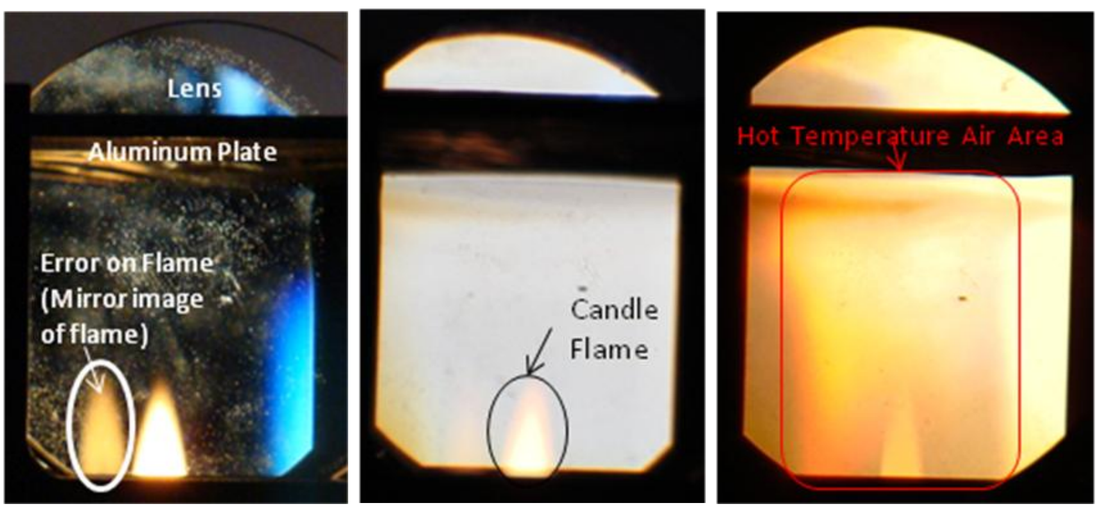
Shadowgraph



Schlieren

Figure 4.29: Flame Candle image captured using Natural Light, Shadowgraph and schlieren in identical system setup

4.8.2 Effect of the Flame Characteristic on Aluminium

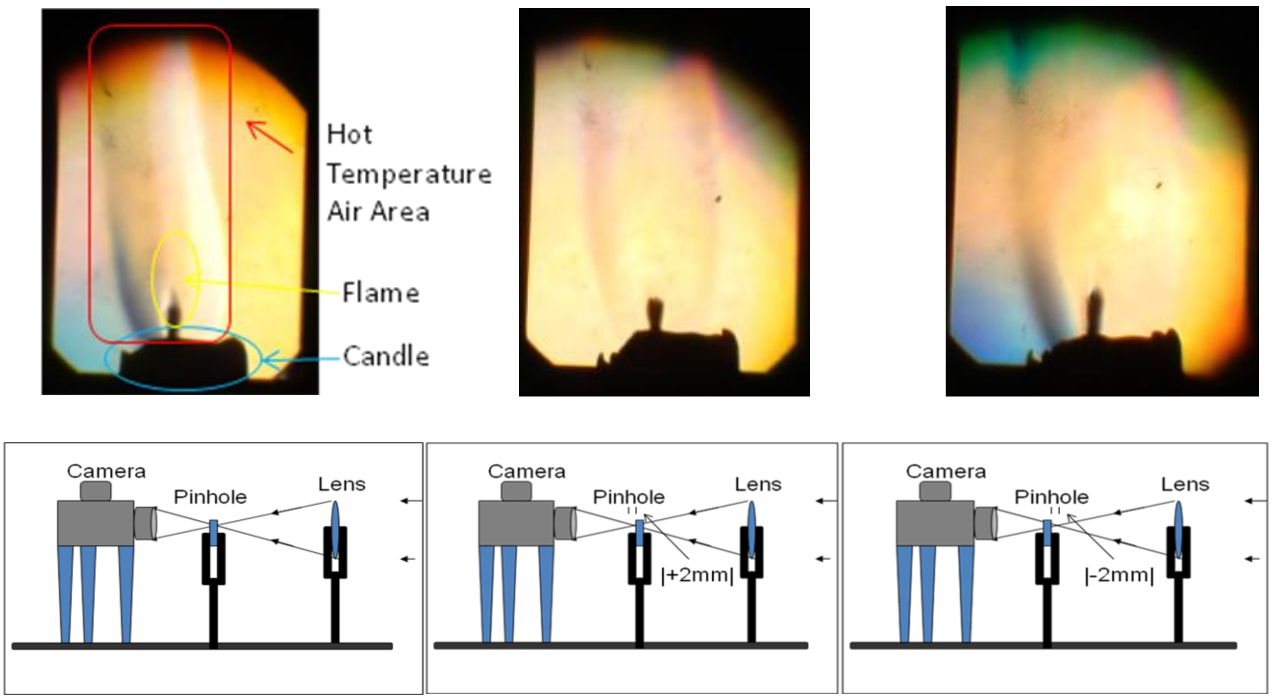


Natural Light **Shadowgraph** **Schlieren**

Figure 4.30: Flame Characteristics image captured using Natural Light, Shadowgraph and Schlieren when it covered by aluminium plate

The objective of the experiment is to study the effect of flame characteristics when it had been disturbed by steel object (aluminum) at the hot air temperature gradient. As shown in Figure 4.30 above, the Schlieren image illustrate the hot temperature air flow gradient which was diverted to the left and right of the plate because not all hot air gradient able to penetrate the aluminum steel plate. Some of the hot air gradient affects the aluminum by burning particular part of the aluminum as shown in natural light image. Based on this experiment, schlieren clearly shows the best the flame characteristics as compared to other system visualization.

4.8.3 Effect of Pinhole Position



(a) Middle of Focus Point (b) Front Focus Point (c) Behind Focus Point

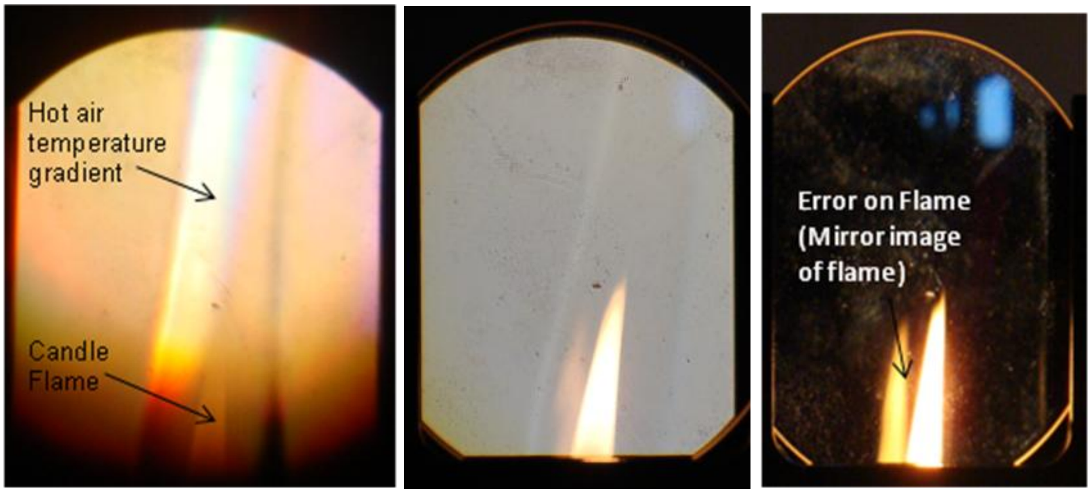
Figure 4.31: Pinhole at (a) middle, (b) front, and (c) behind the focus point.

The pinhole position was experimented in numbers of places either front, middle (center focus point), and behind focus point. The distance for middle pinhole offset by approximately 0mm to focal lens point. The distance for front and behind pinhole offset by about -2mm from focal lens point and +2mm from focal lens point. The main goal of the experiment was to evaluate the quality of the schlieren image when the pinhole position changed as illustrate in Figure 4.31. The images show that middle pinhole is the best position to obtain schlieren image, because different position of pinhole will filter different amount of light source as shown in the experiment. If the light source filtered is too high, schlieren image does not enough light to create a high-quality schlieren image.

On the other hand, if light source filtered is too low, the Schlieren image cannot be seen clearly since many other extra light disturb the schlieren image when capturing the image. There, the pinhole must filter the light at the middle focus point to receive the finest schlieren image.

4.9 Phase IV Experiment (Improvement on Schlieren Image)

Referring to the previous experiment in phase III which already captured the image of three types of visualization system which is Schlieren, Shadowgraph and natural light. Unfortunately, the image is not very clear and some improvement needed to make the image clearly. Thus, phase IV experiment target was to improve the image of Schlieren since several experiments have been done previously to understand on Schlieren visulization system. Figure 4.32 capture the image of better Schlieren by using try an-error method the get the best image. The Schlieren image in the figure not only explains the characteristics of flame but also captured the candle flame itself. The image can be easily observed the candle flame and also the hot air temperature gradient. This will enhance the reader to understand better and differentiate which is the candle flame and which is the hot air temperature gradient. Identical setting also done to Shadowgraph and natural light just to compare and prove again the Schlieren is the best in capturing the flame characteristics.



Schlieren **Shadowgraph** **Natural Light**

Figure 4.32: Clearer Schlieren image that contain Candle flame and hot air temperature gradient.

The photographs in Figure 4.33 are typical schlieren images captured using the system developed in this project. The images can be compared with the existing UTP automotive Schlieren system images shown in Figure 4.34. Small shape of orange color shown in the Figure 4.33 at the center of the hot air temperature gradient is the candle flame. The darkest area on the left side and the white area on the right side of the hot air temperature gradient represent the boundary of hot temperature gradient. It occurs because of the error in light source, double image that over lap each other created the darkest area of the gradient. This is because of the light source and it is difficult to avoid since it also occur in the UTP existing automotive lab Schlieren System as shown in Figure 4.34. Further study needed to be done on the light source effect of the Schlieren to improve the Schliren. However, this project proves and shows better image compared with existing Schlieren system in UTP. The images is clearer and the test areas that can be captured the object also enlarge. Both Schlieren systems imaging below are using the similar size of candle but this project captured larger area of the flame characteristics.

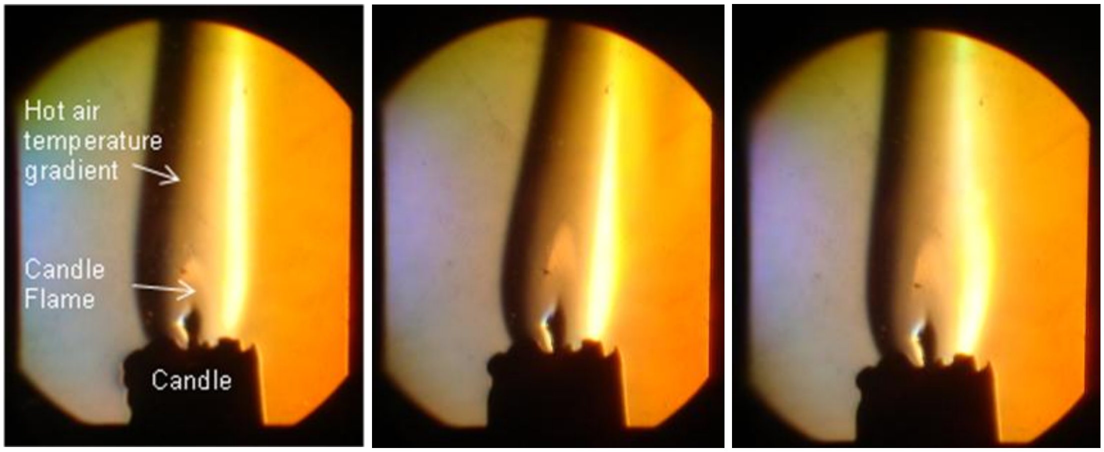


Figure 4.33: Several images of Schlieren by using Schlieren Visualization System

Figure 4.34: Several images of schlieren by using UTP Automotive Center schlieren system.

CONCLUSION

This project is important in order to have better understanding of schlieren visualization system. The outcome achieved from this project can be used for further study and research later on.

The results that are observed that are observed from this project are as good as existing schlieren system in university’s laboratories. Several improvements on apparatus components that include add on adjustable railing system and long focal point plano-convex lenses enhance the quality image of the schlieren. Even the objective of the project achieved, further continued on the project is recommended because other components such as camera with a low exposure and high aperture and better light source will improve the Schlieren image quality. While to improve on the schlieren image area capture, larger diameter lenses are required to obtain bigger area image of schlieren.

Candle flame is prone to changes in their flame geometry/structure. Therefore, it is recommended to use fixed flame source so the result in terms of changes in flame characteristic will be more accurate. Bunsun burner’s flames are more stable since it will generate more clear, accurate, and consistent result.

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