Study of the Effects of Flame Perturbation by High-Speed Schlieren Imaging

by

Ahmad Zamani Masnizam Bin Abdullah Zawawi

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
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Approved by,

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(Ir. Dr. Shaharin Anwar Sulaiman)

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TRONOH, PERAK

January 2008

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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AHMAD ZAMANI MASNIZAM BIN ABDULLAH ZAWAWI

ABSTRACT

The importance of flame triggers study on flame's characteristics. One of the most important characteristics of flame is the flame front, as it determines the interface between the unburned reactant and the burned product. The boundary of a flame usually cannot be seen clearly by naked eyes. The boundary or surface area of a flame could be affected if there is any perturbation. Such characteristics are useful in applications such as boilers, where maximum heat transfer from the flame to the fluid is desired. However, the characteristics of perturbed flame is usually not fully understood, hence further study is required. In order to do that, a reliable imaging system is needed. One of the systems that would be suitable for this purpose is schlieren imaging. With this system, various types of perturbation to the flame can be studied and visualized. Experiments were conducted with and without the schlieren techniques to compare the quality of both results. The results were analyzed and studied for further use in application. The expected results of the images captured by using schlieren technique were of improved quality as compared to those without schlieren, hence providing better understanding of the flame characteristics when being subjected to perturbation. For some reasons, the results were not as expected, due to several factors.

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CHAPTER 1

INTRODUCTION

The application of combustion system in various industrial processes requires understanding of flame structure and properties. In a power plant, the combustor serves as a source of heat to be transferred to the fluid in the tube. In this case, an efficient heat transfer from the flame to the fluid is required to help conserve the energy and to prevent energy waste. In the same application, flame is used in a furnace to crack the gas into its components before further processes such as distillation. In internal combustion engines, the study of flame propagation is crucial to optimize the fuel consumption.

Realizing the importance of flame, studies have been done in order to have better understanding of its characteristics. The scope of studies varies, for example, the study on flame propagation within aerosols by Sulaiman *et al*., (2007). Besides flame propagation, the behaviour of flame when subjected to perturbation is also very important, so that perturbation that can help promote a faster burning rate or optimize heat transfer can be applied.

Flame, when subjected to perturbation, will result in wrinkles and changes of surface area, where in application, the increasing surface area is favoured. By studying the flame perturbation, the characteristics of flame when subjected to disturbances can be recognized. For example, by applying various kinds of perturbation on the flame, desired kind of source of perturbation can be determined. To start of, a reliable imaging system is needed to have good visualizations of the perturbed flame. One of the systems that can be used for imaging and visualization of such phenomena is the schlieren imaging technique.

Many of the previous researches focus on flame propagation and burning rate of both gaseous and aerosol flames. Fewer studies were concentrated on characteristics of flame when subjected to perturbation, hence less knowledge of it had been disseminated.

This project is conducted to study and analyze the characteristics and structure of flame under perturbation. This is done by using the schlieren technique to analyze the structural changes of flame. The scope of the project will include various kinds of perturbation, such as different kind of sizes and shapes.

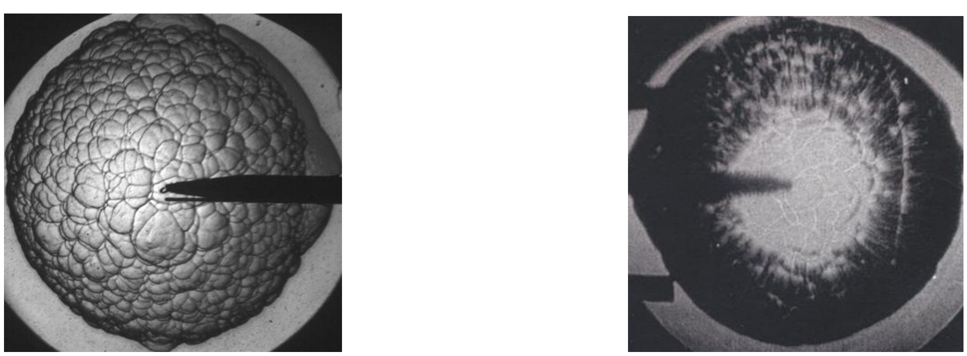
In the present work, candles were chosen as the source of flame, as candles are good examples for the study of natural philosophy due to its physical phenomena (Faraday, 1861).

CHAPTER 2

LITERATURE REVIEW

Studies were conducted through various types of flames to understand their characteristics and to improve their applications. Some of the studies were conducted with imaging technique such as schlieren technique are the studies of aerosol flames with kerosene (Mizutani and Nakajima, 1973), and ethanol (Hayashi and Kumagai, 1974). Through the observation from schlieren cinematography of aerosol flames, it was revealed, that the presence of liquid droplets in the combustion of two-phase fuel mixture could affect the flame instabilities. Such instabilities will promote a faster burning rate as a result of increased surface area of the flame.

In another example, studies were conducted recently on spherically propagating laminar flames of iso-octane-air aerosol mixtures, by using both Schlieren Imaging and natural light imaging (Sulaiman *et al*., 2007). From the observation, it was shown that the schlieren technique produced clearer image of the cells on the flame surface than that with natural light technique. Included inside the study, is the comparison of images produced between using digital camera and drum camera. From Figure 2.1, they concluded that schlieren images are sharper, and the flame structures and cellular can be seen more clearly if the camera being used is a digital camera.



(a) with digital camera

(b) with drum camera

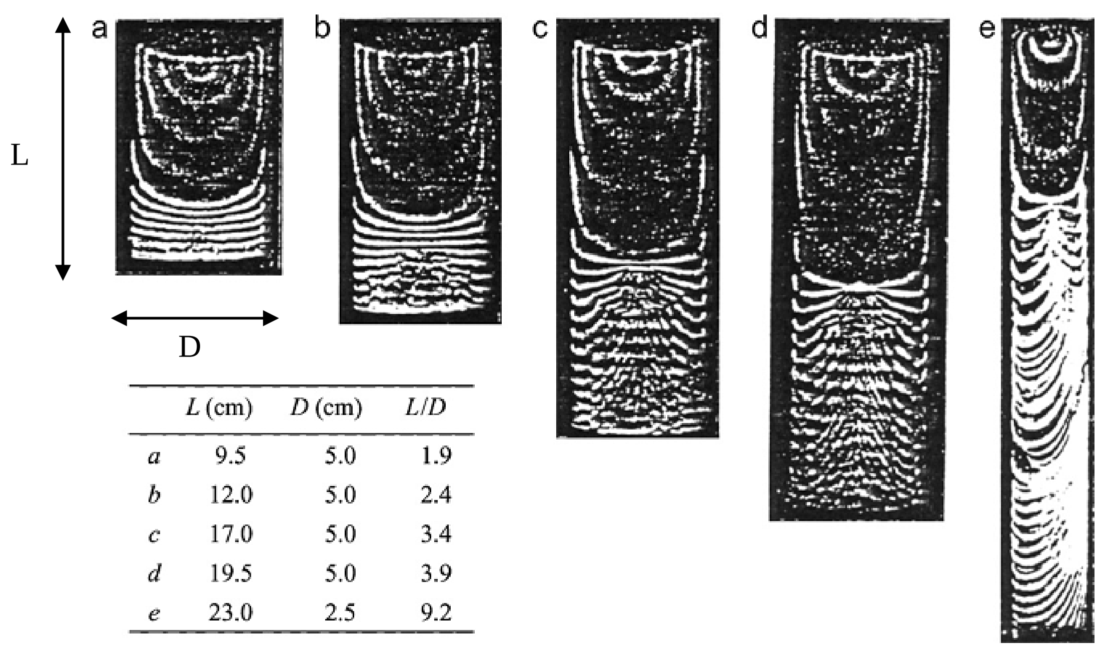
Figure 2.1: Comparison of observed flame structures using two different cameras, for an aerosol iso-octane air flame (Sulaiman et al., 2007).

In an advanced studies on burning rates and instabilities in the combustion of product and vapour mixtures (Sulaiman, 2006), correlation between crtitical Peclet number, Pe_{cl} and Markstein numbers, $Ma_{sr,}$ showed that aerosol mixtures experience earlier instabilities compared to the gaseous flames. The visualization techniques used in this study were the Schlieren Imaging System.

In another research on gases flame (Dobashi, 1996), the effects on gas explosion behavior of gas flow turbulence, combustible gas concentration distribution, and flame front instability, which are the most probable causes that disturb the propagating flame front during gas explosions, were examined. It is shown that the gas flow turbulence increases the flame propagating velocity and this makes the pressure rise rapid. When the gas flow turbulence exists the pressure increase from the initial pressure is observed to be proportional to about the 3.6th power of the time *t* from ignition, whilst if no gas movement exists it is proportional to the 3rd power of *t*. For a non-uniform concentration of a combustible gas, the gas explosion behavior strongly depends on the concentration distribution. The flame front becomes unstable by acceleration of the gas induced by a following pressure wave propagating toward the unburned gas side and generated flame front disturbance grows quickly, causing the flame propagating velocity to increase rapidly. As a result, a fast pressure rise is observed and it is proportional to the 6.4–6.8th power of *t*.

Pu *et al.*(2007) in their studies examines the parameter *maximum effective burning velocity* ($u_{eff,max}$), which describes the reactivity of fuel-air mixtures as a function of the dispersion-induced turbulence intensity. Series of tests were run in both cylindrical and spherical explosion vessels with different sizes. From the tests they concluded that combustion process in closed vessels can be divided into two sub-processes, namely initial adiabatic process and non-adiabatic process. Initial adiabatic process refers to the constant volume combustion inside spherical and cylindrical vessels. For example, for constant volume combustion inside a spherical vessel, flame front propagates in radial directions freely until almost reaching the wall, and the process is considered adiabatic. Once the flame reached the wall, heat loss is no longer negligible, and the flame is distorted.

For constant volume combustion inside a cylindrical vessel, with bottom-end ignition, the flame front expands in radial and also axial directions (Pu et al., 2007). As a result, the initially hemispherical flame front evolves into ellipsoidal surface. Heat loss to the wall causes the surface of the flame front to become flattened, then wrinkled. Finally, the unsteady tulip flame dominates the flame propagation’s final stage. Although the entire process involves some heat loss to the wall, it is regarded that the initial phase of constant volume combustion in a cylindrical closed vessels as approximately adiabatic. Ellis (1928) visualized gases flame in mixture of 10 parts CO and 1 part CO_2, propagating in closed cylindrical vessels of aspect ratios (length/diameter) from 1 to 10. From Figure 2.2, estimation of the distance L_{eff} at which the ellipsoidal flame surface becomes flattened, can be done.



	L (cm)	D (cm)	L/D
a	9.5	5.0	1.9
b	12.0	5.0	2.4
c	17.0	5.0	3.4
d	19.5	5.0	3.9
e	23.0	2.5	9.2

Figure 2.2: Tracing of flame front propagating inside a closed tube in mixture of 10 parts CO and 1 part CO_2 (Ellis, 1928).

Some of the studies on flame are conducted by modeling and simulation (Hong *et al*., 2007). In flame modeling, researchers used the Navier-Stokes equations combined with the level set method and jump conditions to model the reaction front. By using the detonation shock dynamics (DSD) framework, researchers showed that computer graphics simulations of flame can obtain features such as flame wrinkling and cellular patterns. Figure 2.3 illustrates cellular patterns of flame produced by DSD equations without the need for vorticity confinement or other turbulence models.

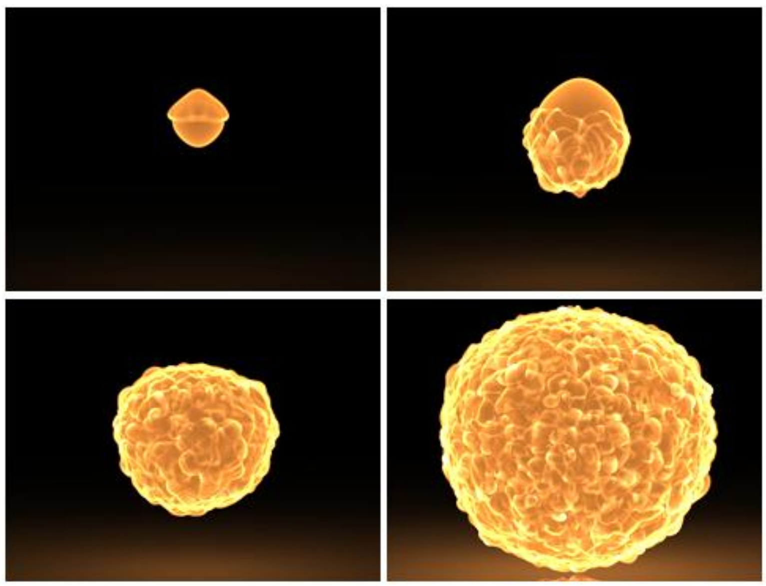


Figure 2.3: Four images from the time evolution of a level set surface using the third order DSD equations, illustrating that cellular patterns are produced by the DSD augmented level equations (Hong et al., 2007).

Faraday (1861), in his experiments exposed clearly the structure and compositions of a candle flame, demonstrating a stream of energy laden vapour feeding into the flame, with analogy of the respiration process in living organisms. His research is further supported by Fife (1988), who concluded that the flame of a candle can be regarded as a dynamic process balancing two flows of energy, i.e. the rate at which energy is dissipated by the flame (through emission of heat and light), and the rate at which energy is released from the wax as the flame consumes its way down the candle.

From studies by Scott (2003), it is concluded that for big candles, the stored chemical energy is proportional to area of cross section, and the speed at which flame moves down the candle is inversely proportional to the diameter of candle. For smaller candles, the speed of flame is somewhat less than expected, because the flames are not so large. Figure 2.4 illustrates the findings:

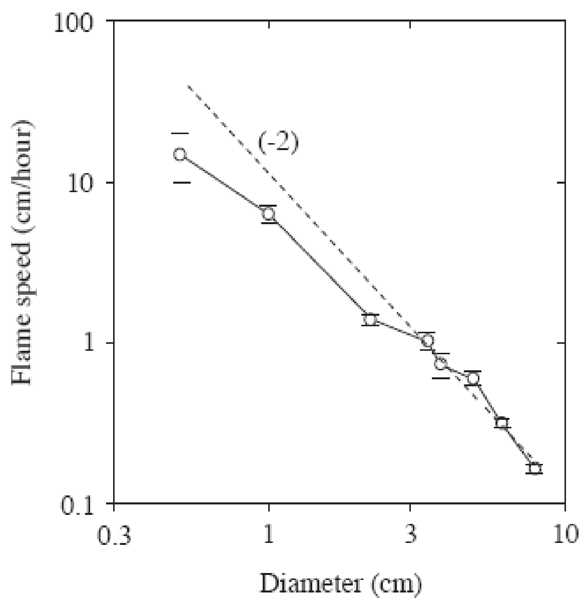


Figure 2.4: Measurements of flame speed (*v*) for candles of different diameters (*d*). The error bars indicate rms deviations of about six individual measurements (Scott, 2003).

CHAPTER 3

METHODOLOGY

This chapter presents an overview of how this project work is carried out. This project is conducted by using the schlieren technique. Schlieren imaging technique is chosen because in previous studies, it produced very sharp and detailed images of flame propagation and flame structures. Subsequent chapters discussed the introduction to schlieren techniques and project work.

3.1 Introduction to Schlieren Technique

In order to conduct this project effectively, it is necessary to understand the fundamentals and the concept behind schlieren imaging technique. Schlieren is a German word, meaning “streaks”. Schlieren imaging technique is sensitive to deviations of any kind that cause changes in index of refraction of air, and therefore cause the light to travel in a different path. Schlieren technique is mean to study the disturbances that alter light propagation through the air, or any other transparent medium.

Schlieren technique works by exploiting the facts that light from a source external to a test object, when made pass through it, will be refracted by any density gradients. After passing through the object, with proper optical arrangements, the refracted and un-refracted light can be separated to yield an image with dark and light areas which correspond to disturbed and undisturbed region of the object. Figure 3.1 illustrates how schlieren concept works (Jeronimo and Haegen, 2002).

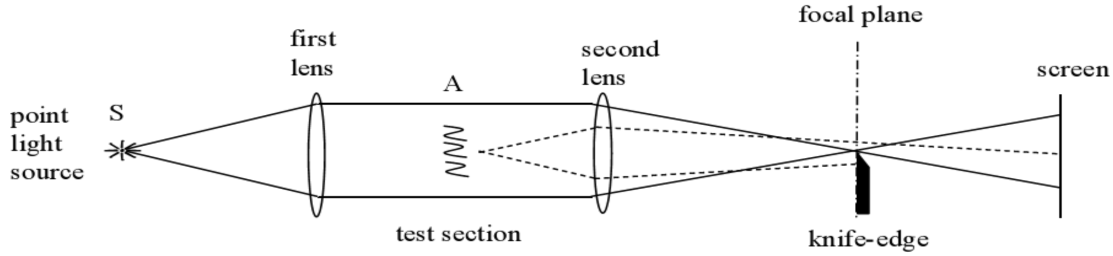


Figure 3.1: Diagram of a simple schlieren system with a point light source (Jeronimo and Haegen, 2002).

A finite schlieren object, put at the test section, refracts many such rays in many directions. All the downward components of these ray deflections are blocked by the knife-edge, painting at least a partial picture of the schlieren object on the screen. In this project, the disturbances will be caused by the flame's boundary layer.

3.2 Project Work

There are many types of schlieren setting, and the one that was used in this project is indicated in Figure 3.2.

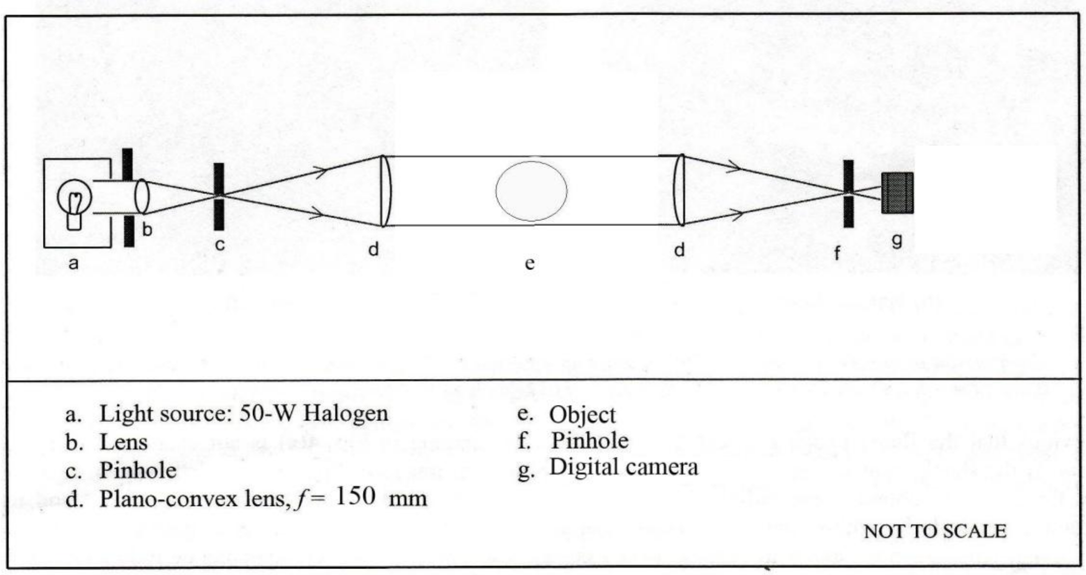


Figure 3.2: Schematic of Schlieren setting.

The schlieren imaging technique consists of a pair of lens, pinhole, and a high speed digital camera. Flames which are exposed to solid objects are recorded by the camera for analysis of the effects of perturbation. The research was expanded further by varying the types of perturbation, such as using different sizes and shapes.

List of items that are involved before the project starts are listed in Table 3.1:

Table 3.1: List of Items.

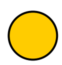
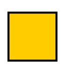
Items	Description
Light Source	- Halogen lamp (50 watt)
Plano Convex Lens	- Material : glass - Diameter : 100mm - Focal length : 150mm
Lens	- Material : glass - Lens Type : Concave - Diameter : 50 mm - Focal length : 150mm
Pinhole	- Metal sheet with 1mm hole at the center
Digital Camera	FujiFilm Finepix F650 : - 6.0 megapixel CCD sensor and an advanced imaging processor - 5.0x optical zoom, 4.4x digital zoom
Candle	- Diameter : 17 mm - Length : 110 mm

After all the equipments and items are ready, the first step was to assemble those items into schlieren setting indicated in Figure 6. After getting the right schlieren setting, several test pictures were taken to grid the area that covered by the camera lens. This grid was useful in the experiment to see the extent of the surface area of the flame.

After that, series of tests were done by taking pictures of the lighted candle (without perturbation) with varying parameters such as the camera's shutter speed and aperture, and also the distances between equipments. The purpose of these tests was to get the right or appropriate schlieren setting, or at least the most suitable one. Although it was time consuming, this was a crucial part of the project, as it gave significant affect to the overall results and observations.

After all the settings were set and the quality of the images of the candle flame observed was quite satisfying, then the project went into the next phase, which was applying perturbation to the flame. Table 3.2 illustrates the items that are used as source of perturbation in the present work:

Table 3.2: List of Source of Perturbation.

Geometry of Items	**Description**
	3mm diameter x 140mm length cylinder rod (copper)
	3mm x 3mm x 120mm length square (copper)
	3mm x 6mm x 120mm length square (copper)

Different types of perturbation were applied to the flame to see the effects of each with respect to the flame structure/geometry. The results observed were recorded and analyzed in the next chapter.

Besides conducting with schlieren setting, the project also was conducted without using the schlieren technique. The purpose of this was to have comparisons of the quality of the images of the flame observed, with or without schlieren, to see which technique produced better images.

There were, however, some problems encountered throughout the project work. For example, in terms of equipment constraint, the railing system used in the experiment was the fixed, non-adjustable railing system. Therefore, the schlieren setting was not flexible as it should be, hence might affect the results.

Plano convex lens that was used in the project was the one that have 150mm focal length. The search for similar lens that have longer focal length had failed, thus only the available lens were used.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results

The results are presented by demonstrating the images captured by chronological order:

i. Experiment I : Without perturbation to the flame.

ii. Experiment II : With perturbations applied to the flame.

iv. Experiment III : Results from extra experiments done.

v. Experiment IV : Experiments repeated without using schlieren.

4.1.1 Without perturbation to the flame

Shown in Figure 4.1 is the image of flame without any perturbation applied to it. On the left hand side is the captured schlieren image, while the image on the right hand side shows the analysis of the schlieren images.

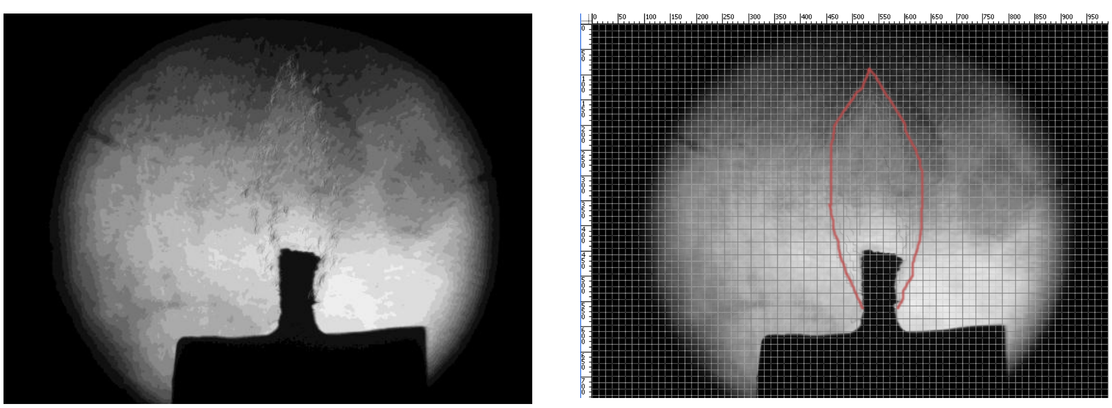


Figure 4.1: Schlieren images of candle flame captured without any perturbations.

The unit used for the grid in the picture on the right hand side is in millimeter. Therefore, each box will have an area of 1mm x 1mm = $1mm^2$. Hence, the area of the flame can be calculated by counting number of boxes that the flame covered. From observation, it yields that the surface area of the flame is $\approx 308mm^2$.

4.1.2 With perturbations applied to the flame

Shown in Figure 4.2 is the image of flame with a 3mm diameter x 140mm length cylinder rod is applied as the source of perturbation.

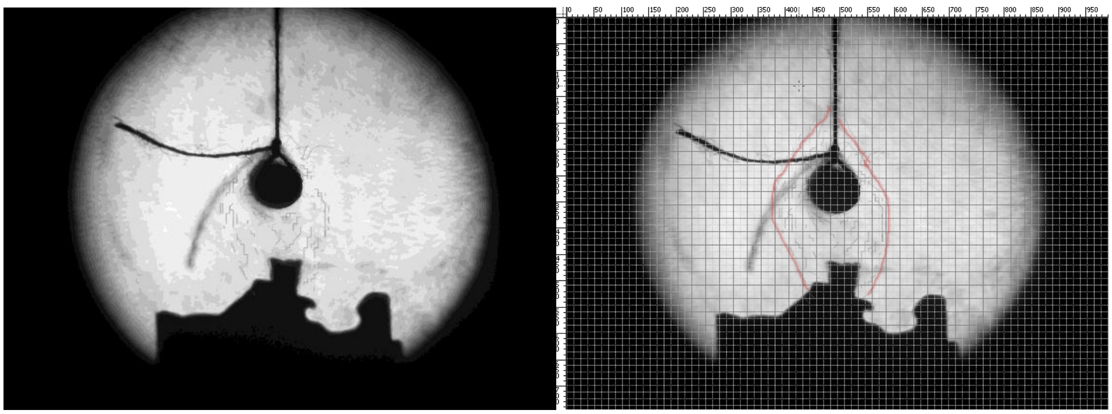


Figure 4.2: Schlieren images of candle flame with 3mm diameter x 140mm length cylinder rod as a source of perturbation.

By applying the same concept, the area of the flame is determined by counting the number of boxes the flame covers when subjected to perturbation. Therefore, from the figure above, the area of the flame is approximately $\approx 260mm^2$.

Shown in Figure 4.3 is the image of flame with a 3mm x 3mm x 120mm length cylinder rod is applied as the source of perturbation.

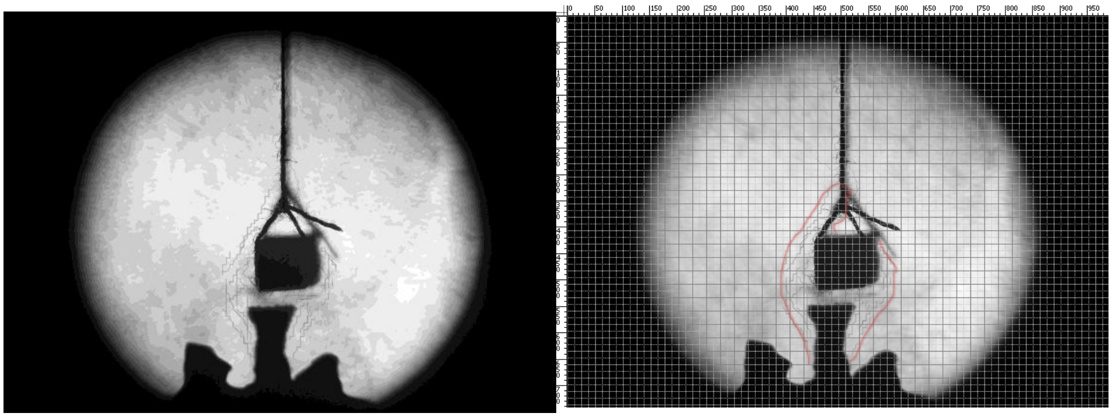


Figure 4.3: Schlieren Images of candle flame with 3mm x 3mm x 120mm length square rod as a source of perturbation.

From the figure above, it is estimated that the flame surface area $\approx 180mm^2$.

Shown in Figure 4.4 is the image of flame with a 3mm x 6mm x 120mm length cylinder rod is applied as the source of perturbation.

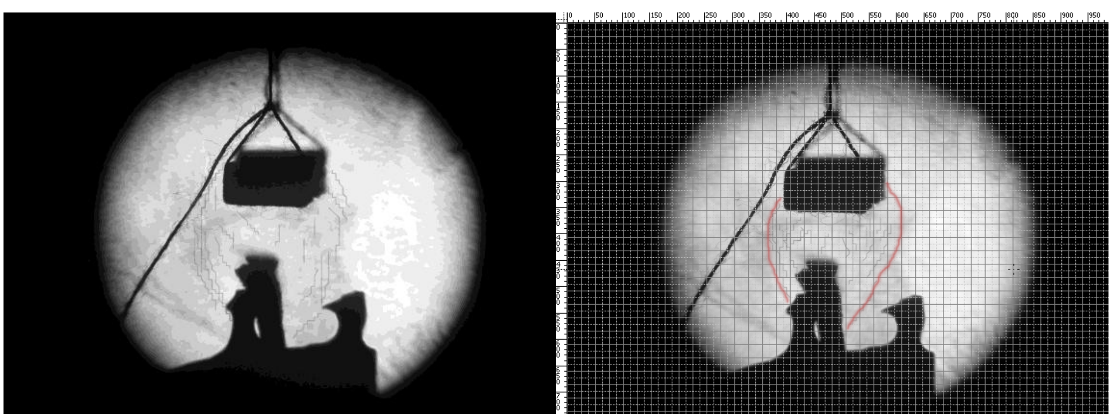


Figure 4.4: Schlieren images of candle flame with 3mm x 6mm x 120mm length square rod as a source of perturbation.

From the figure above, it is estimated that the flame surface area $\approx 204mm^2$.

4.1.3 Results from extra experiments done

Shown in Figure 4.5 is the image of flame by varying the downstream pinhole (pinhole f) by 2mm from focal point.

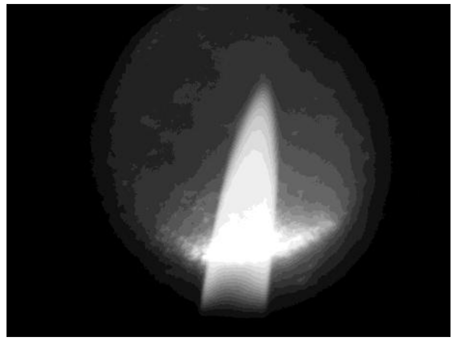


Figure 4.5: Images of candle flame captured with varying the downstream pinhole (pinhole f).

The image shown in Figure 4.5 is different from the previous experiment (Experiment I), indicating that small changes in schlieren setting can cause major changes in images produced.

4.1.4 Experiments repeated without using schlieren

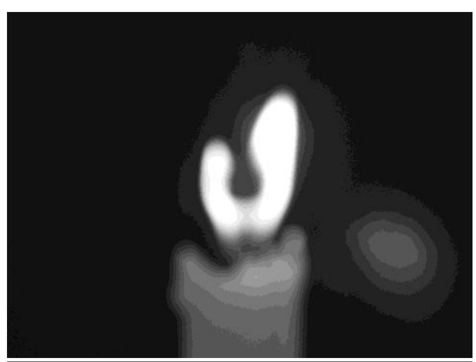


Figure 4.6: Images of candle flame captured without using schlieren technique (source of perturbation - 3mm diameter x 140mm length cylinder rod).

The image shown in Figure 4.6 shows that the flame structure is affected by the presence of perturbation, but the boundary of the flame observed is not clear enough.

4.2 Discussion

Figure 4.7 shows the comparison of the flame surface area for non-perturbed flame and perturbed flame (Experiments I and II).

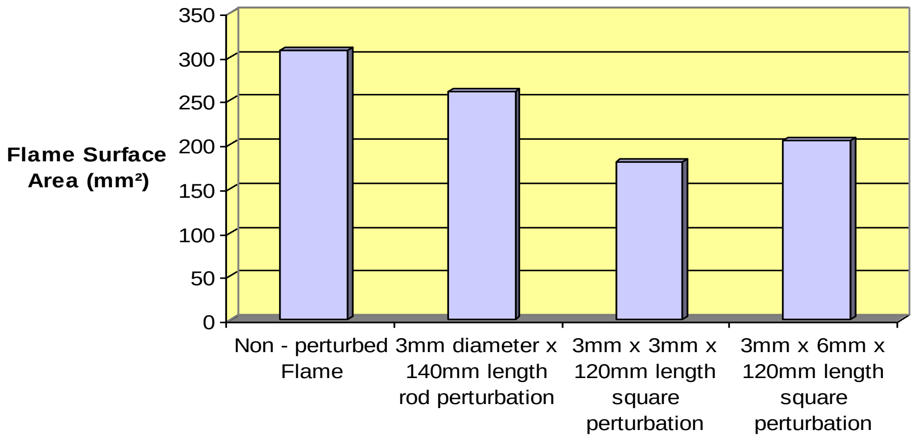


Figure 4.7: Comparison of flame surface area of perturbed and non-perturbed flame.

From the observation, it is shown that the presence of perturbation will cause the candle flame to have changes in surface area. But because of the poor quality of the schlieran images produced, it was almost not possible to determine which kind of perturbation will yield the most increment in the surface area of the flame. Only an estimation of the surface area of the flame can be derived from the observation of the current project work. This is most probably due to equipment constraints.

Nevertheless, in terms of heat transferred to the materials (source of perturbation), the direct contact of the flame with the surface area of the materials will cause more efficient heat transfer, it is assumed that the greater the surface area of the materials, the greater will be the rate of heat transfer. This is provided that the flame itself is big enough to reach the optimum surface area contact with the materials.

Based on the observation, it is noted that by using the schlieren technique, the images produced will be different from those captured without using the technique. But the changes are for better or worse, due to several reasons. If the equipments were not set in the proper schlieren setting, it is possible that quality of the images produced will be lower than usual. This indicates that it is very important to have the equipments to be assembled in the right schlieren manner.

Results from Experiment III shows the difference of the images of flame (without perturbation) when there was slight changes in the distance of the downstream pinhole (pinhole f) from the plano-convex lens, compared to Experiment I. These observations tell that any small changes in the setting will result in different kind of images, hence the quality of the images will be questionable. Experiment III that had been conducted had proved the claim.

Another factor that will affect the quality of the images produced is the capability of the equipments themselves, especially the digital camera used. It is crucial to get the suitable camera (preferably high speed) in order to produce good images. The usage of lens also can affect the results. With availability of only plano-convex lenses that have 150mm focal point, it is difficult to get the full image of schlieren object to be captured inside the camera.

Last, but not least, item that have significant impact on the results is the candle itself. During the burning of the candle, there are some noticeable changes in the length of the wick of the candle. These changes might affect the overall flame surface area as the project is being carried out, hence producing flame with larger surface area as time goes by, compared to the starting of the project.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

This project is crucial in order to have better understanding of the effects of flame perturbation. The results obtained from this project can be used in application and/or for further studies and research later on.

Due to some reasons, the results that are observed from this project are not as good as expected. While this can be caused by several factors, but the factors that gave most effects are the equipments that are used in this project. With limited availability and capability, this equipment constraint is the major contribution of the error that might have occurred. Therefore, it is recommended that the project is further continued, but with more accurate and reliable equipments. These will include the adjustable railing system, good digital camera, as well as long focal point plano-convex lenses.

Since candles' flames are prone to changes in their flame geometry/structure, it is recommended that, if a more accurate results in terms of changes in surface area of the flame when subjected to perturbation, a more fixed flame source is used. One good example is the Bunsen burner. Bunsen burner's flames are more stable and will generate more accurate and consistent results.

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APPENDICES

Appendix 1: Schlieren setting used in project work to conduct experiment on flame perturbation.

No.	Detail/ Week	1	2	3	4	5	6	7	Mid sem	8	9	10	11	12	13	14
1	Selection of Project Topic & Topic Approval															
2	Preliminary Research Work															
	- Introduction to Schlieren Technique - Finding the simplest schlieren setting - Identify items to be used throughout the project															
3	Submission of Preliminary Report															
4	Project Work															
	- Finding equipments/items identified before - Do experiments once necessary items are available/purchased															
5	Continue Research Work															
	- Studying previous research on flame															
6	Submission of Progress Report															
7	Seminar															
8	Submission of Interim Report Final Draft															
9	Oral Presentation															

Milestone
Process

Appendix 2: Project Flow of First Semester of 2-Semester Final Year Project.

No.	Detail/ Week	1	2	3	4	5	6	7	Mid sem	8	9	10	11	12	13	14
1	Continue with current project work															
	- using current equipments - try to improve results obtained															
2	Literature / research															
3	Submission of Progress Report 1															
4	Upgrade / improve / continue project work															
	- using new available equipments - try to improve results - searching for alternative equipments/ items that may help improve result															
5	Submission of Progress Report 2															
6	Seminar															
7	Project work continue															
	- improve results - continue searching for alternative equipments/items															
8	Poster Exhibition															
9	Submission of Dissertation (soft bound)															
10	Oral Presentation															
11	Submission of Project Dissertation (Hard Bound)															

Milestone
Process

Appendix 3: Project Flow of Second Semester of 2-Semester Final Year Project.