Comparative Study of Spray of Different Liquids

by

Mohd Hafizudin Bin Daud

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

MAY 2011

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Comparative Study of Spray of Different Liquids

by

Mohd Hafizudin Bin Daud

A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

(AP Ir. Dr. Shaharin Anwar Bin Sulaiman)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
MAY 2011

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.

MOHD HAFIZUDIN BIN DAUD

ABSTRACT

Sprays can be defined as a dispersion of droplets with sufficient momentum to penetrate the surrounding medium. Generally a spray is produced by using a nozzle which is normally referred to as an atomizer and the surrounding medium is gaseous. Processes utilizing droplets require enough momentum to transport the droplets to where they are utilized or to provide mixing with the gas. Shape, pattern and some measure of droplet sizes are the primary spray characteristics. The study of sprays of liquid fuels can be hazardous and costly. However, by replacing the liquid fuel with non flammable liquids such as water can reduce these problems. The objective of the project is to find whether water has any similar characteristics with the selected liquid fuel or not. The studies focus on two major components. Firstly, the study focuses on microscopic characteristics such as droplet size and mean velocity. Spray characteristics of different liquids (methanol, diesel and water) are analyzed by Laser Doppler Anemometry (LDA) and Phase Doppler Anemometry (PDA). Laser Doppler Anemometry (LDA) systems are used to measure droplet velocities of fluid sprays. Phase Doppler Anemometry (PDA) systems are used to measure the droplet sizes of fluid sprays. A high speed camera is used in the second part of the research in order to observe the structure of droplets, measure the spray angles at nozzle exit and determine the droplets movement. Spray angle variations are observed under different pressures for each fluid. From analysis of the results, it is found that the water and diesel has similarity in Sauter Mean Diameter. For both horizontal and vertical velocities, water and diesel did not have any similarity in term of spray characteristics.

ACKNOWLEDGEMENT

First of all, the author would like to express utmost gratitude and appreciation to Allah because with His blessings and help, the Final Year Project went very smoothly. Alhamdulillah, all praises to Him that the author have been able to complete this project on time.

This project would not have been possible without the assistance and guidance of certain individuals and organization whose contributions have helped in its completion. First and foremost, the author would like to express his sincere thanks and utmost appreciation to the project supervisor, AP Ir. Dr. Shaharin Anwar Sulaiman for having faith and strong support in guiding the author throughout the whole period of completing the final year project. His kind assistance and guidance from the beginning to the end of this study really help me to undergo my project successfully.

Special express gratitude is also reserved for the Mechanical Engineering Department of Universiti Teknologi PETRONAS for providing excellent support in terms of providing cutting edge knowledge and information not just within the Final Year Project but also the five years spent undergoing every single bit of invaluable knowledge on mechanical engineering.

Apart from that, I would like to thank the technician, Mr. Khairul Anwar Ahmad, for his help and highly cooperation in familiarizing with LDA/PDA equipment. Besides that, special thanks to post graduate students, Mr. Firman and my other friends for helping me with the experiments.

Finally many thanks to the author's family and fellow colleagues for their help and ideas throughout the completion of this study. I hope that the outcome of this report will bring beneficial output to others as well. Thank you very much everyone.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Atomization is defined as the disintegration of a liquid into small drop or droplets. The resultant suspension of fine droplets or solid particles in a surrounding gas is termed spray. Atomization of a liquid into discrete droplets can be brought about a variety of means: aerodynamically, mechanically, ultrasonically or electrostatically. For example, the breakup of a liquid into droplets can be achieved by the impingement with a gas in two fluid atomization and by centrifugal forces in rotary atomization. Atomization processes may also be classified according to the energy used to produce the instability on a liquid. Most practical atomization processes for normal liquid include pressure atomization, two fluid atomization and rotary atomization. Atomization of normal liquids has been long studied in the field spray combustion and spray drying. The widest spread application of the atomization of normal liquid is in spray combustion processes. The liquid involved in spray combustion, spray drying and other normal liquid processes are primarily hydrocarbon oils, emulsions and various non-Newtonian liquids have also been sprayed in some applications. The basic requirement in atomization applications is a narrow droplet size distribution, even a monosize distribution in some spray drying and aerosol spray applications.

Proper application of spray technology offers the potential for significant enhancement of end products and processes in the manufacturing industry. In the internal combustion engines, the efficiency and power output of the engines are highly dependent on the characteristics of the fuel spray injected from the nozzle into the combustion chamber. The process of spraying has two objectives. It divides the liquid fuel into a large number of fine droplets to increase its surface area for rapid heat transfer and combustion, and it distributes the fuel through the combustion chamber for intimate mixing of the fuel and air. Depending upon the injection pressure and viscosity of the liquid fuel, the first portion of fuel coming out from the nozzle usually appears as a cylindrical jet. At a certain distance from the nozzle the jet breaks up into fine droplets to form a conical shaped spray. The distance to which the tip of a fuel spray will penetrate the air in the combustion chamber in a given time depends primarily upon the jet velocity, the combustion chamber air density and the orifice size. An increase in injection pressure increases the spray tip penetration. An increase in combustion chamber air density decreases the penetration.

It is often stated that the primary reason for breaking up liquid into droplets is the advantage gained, for various processes; by resulting increase in the surface area of the liquid. This is certainly the case for many process particularly those where rapid vaporization of the liquid is required. However, in other applications this increase in surface area may be either one of several benefits or an incidental and irrelevant result of the main process. For example, in spray painting the formation of an even surface coating takes advantage of the dispersion of droplets into a nearly homogeneous spatial pattern which is made possible with several types of spraying nozzle. With suitable choices of droplet sizes and momentum, coatings of the required thickness are achieved with minimal splashing and unevenness.

In many industrial applications outside the combustion field, the choice of spraying as opposed to other unit processes is not always an obvious one and it requires careful balancing of the pros and cons. In industrial production processes, sprays are widely used in food processing, pharceutical manufacturing and paper manufacturing. For processes involving vaporization, cooling or cleaning of gases, sprays used in fire suppression, air humidification and gas cleaning and conditioning. Lastly, for agricultural, surface cleaning and treatment, spray painting and coating and printing processes require sprays that have high momentum impact to achieve perfect work or result.

They are issues in the spray polyurethane foam industry on the safety practices, health risks associated with the handling, application and life cycle usage of the spray. The operators of the foam insulation are often in a work-hazard situation that exceeds the current Occupational Safety and Health Administration (OSHA) exposure limits to isocyanate. Therefore it is imperative that the applicators, helpers, and nearby trades be properly educated and protected. Proper Personal Protective Equipment (PPE) is used, including but not limited to, full skin coverage, and full face respirators. Helpers should also be wearing full face respirators.

1.2 Problem Statement

The use of liquid fuels such as methanol and diesel in the study of sprays can be hazardous and costly. Replacing the fuels with non-flammable liquid such as water may be able to minimize the problems related to the fuel sprays. Therefore, a study is needed to see whether the liquid fuel have any similarity with water in terms of spray characteristics to produce important results and data.

1.3 Objective and Scope of Study

The objective of this study is to determine whether the selected liquid fuels can be replaced with water in the study of spray characteristics. In order to achieve the objective, a few tasks and research need to be carried out by studying the characteristics of liquid fuels, the fundamental of sprays and the droplet break up.

The characteristics of sprays are analyzed by using Laser Doppler Anemometry (LDA) for velocity measurements and Phase Doppler Anemometry (PDA) for droplet size measurements. These systems assist to analyze characteristics of fluid sprays in greater detail. High speed camera is used in order to study the structure of the break up zone of sprays. The variables such as radial distance, penetration distance and liquid types are taken into consideration. Recommendations are to be made based on the spray angle, droplets movement and the penetration distance should be more located in order to get the precise result.

CHAPTER 2

LITERATURE REVIEW

2.1 Fundamentals of Sprays

Spray can be derived as a dispersion of droplets with sufficient momentum to penetrate the surrounding medium. Generally spray is produce by using nozzle and is referred to as an atomizer and the surrounding medium is gaseous. Processes utilizing droplets require enough momentum to transport the droplets to where they are utilized or to provide mixing with the gas. Shape, pattern and some measure of droplet sizes are the summarized of the spray characteristics.

Atomization can be divided into two types. The first is primary atomization which is near the nozzle and secondary atomization, which is the break-up of drops further downstream. The main stresses (force per unit area) acting on the liquid during break-up are; inertial, viscous and surface tension. It is difficult to define the spray boundary when the droplet mass flux tends gradually to zero at the edge (Bendig et al, 2002).

2.2 Industrial Applications

In spray painting the formation of an even surface coating takes advantage of the dispersion of droplets into a nearly homogeneous spatial pattern which is made possible with several types of spraying nozzle. With suitable choices of droplet sizes and momentum, coatings of the required thickness are achieved with minimal splashing and unevenness (Nasr, 2002). Recent experimental work on fine water sprays indicates that they may have a wider application in the fields of fire extinction and combustion suppression than previously anticipated.

The means of producing fine sprays are briefly examined and the major results of some case studies are reviewed. It is stated that for various industrial applications, it need different types of sprays in order to achieve complete work (Nolan, 2000).

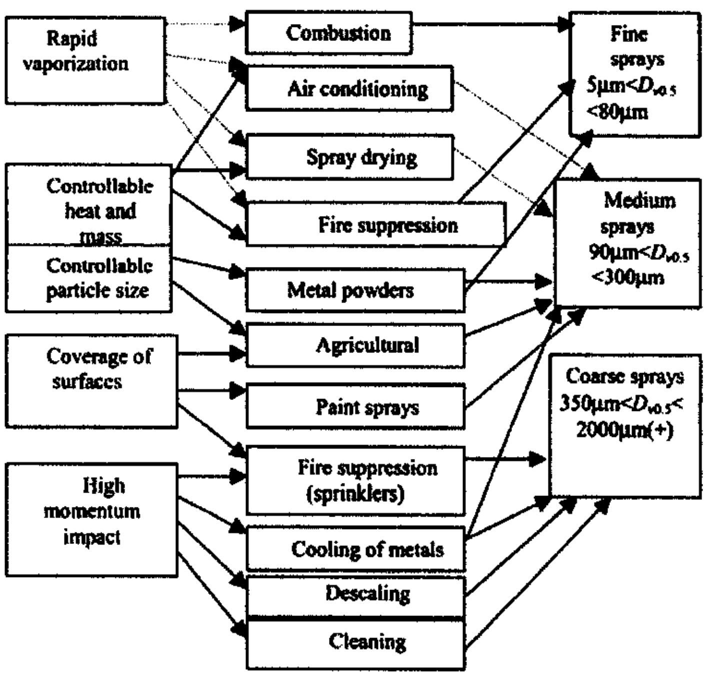


Figure 2.1: Properties of sprays and example of their uses (Nasr et al, 2002)

2.3 Full Cone Spray

Full cone nozzles yield complete spray coverage in a round, oval or square shaped area. Usually the liquid is swirled within the nozzle and mixed with non-spinning liquid that has bypassed an internal vane. Liquid then exits through an orifice, forming a conical pattern. Spray angle and liquid distribution within the cone pattern depend on the vane design and location relative to the exit orifice. The exit orifice design and the relative geometric proportions also affect the spray angle and distribution. Full cone nozzles provide a uniform spray distribution of medium to large size drops resulting from their core design, which features large flow passages. Full cone nozzles are the style most extensively used in industry (Bartell, 1991).

2.4 Droplet Size Terminology

The drop size is normally used for the correlation of the combustion behaviour. Droplet sizes are different for each fluid and even for the same liquid droplets differ in size. Therefore, there is a need for averaging in order to determine a suitable mean size that corresponds to necessary droplet properties (Lefebvre, 1989). Sauter Mean Diameter (SMD) or D_{32} is commonly used, which is given by:

$$\text{SMD}=D_{32}=\frac{\sum_{i=1}^{k} n_i D_i^3}{\sum_{i=1}^{k} n_i D_i^2} \tag{2.1}$$

where n_i is the number of droplets within a range of is centred on diameter D_i and k is the number of ranges.

2.5 Droplet Break up

According to Lane (1949, 1951, 1952), a single drop subjected to a steady stream of air would initially flatten into a disk. At the critical air velocity, it would be blown out into the form of a hollow bag attached to a circular rim. Fine shower droplets are produced from the bursting of this bag. However, the rim (70% of the mass of the original drop) broke up into much larger drops, which is known as the bag break up mode (Figure 2.2). Besides that, he discovered droplets that were subjected to transient gas flows exhibited a different break up mode known as stripping or shear break up. The droplet is deformed in the opposite direction to that of the bag break up and formed a convex surface to the flow. The edges of the saucer shape were drawn out into a thin sheet and then into fine elements. These will turn into droplets.

Hinze (1949) showed that the increase of droplet viscosity could delay the onset of break up. High viscous fluids produced incomplete break up. He proposed the critical Weber number as 13 for shock flows. And for falling droplets, the proposed critical Weber number was approximately 22. He also discovered that the break up process consisted of several stages, including extreme droplet flattening, formation of a torus with an attached hollow bag-shaped film, and bursting of the film.

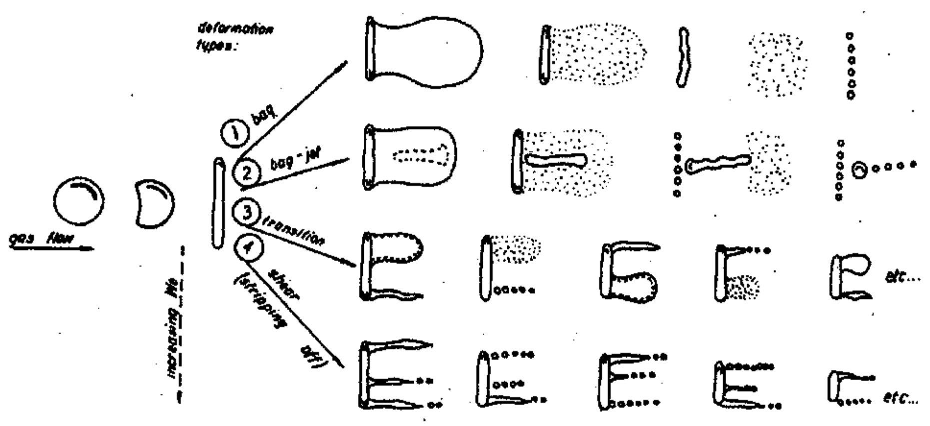


Figure 2.2: Possible transition modes of droplet break up (Krzeczkowski, 1980)

Krzeczkowski (1980) studied break up by using an open-jet horizontal wind tunnel. This was done by releasing droplets at the nozzle exit of the tunnel. He observed the effects of fluid viscosity on the break up modes. Figure 2.2 shows the illustration of different possible transition modes of droplet break up. Based on the experimental data, he suggested four distinct modes of break up:

- Bag break up type is characterized by a hollow bag-shaped film and a ring torus.
- Bag-jet break up is characterized by the additional stamen in the middle of the bag.
- For transition type, it is characterized by an initial bag type break up but transformed into disintegration of the bag film.
- Shear or stripping type is characterized by stripping of the surface layer.

2.6 Factor Affecting Droplet Size

There are factors that affect the droplet sizes which are nozzle type, spraying pressure, flow rate and spray angle. Full cone nozzles have the largest drop size, followed by flat spray nozzles. Hollow cone nozzles produce the smallest drop size. For spraying pressure, droplet size increases with lower spraying pressure and decreases with higher pressure. Flow rate has a direct effect on drop size. An increase in flow rate will increase the pressure drop and decrease the drop size, while a decrease in flow rate will decrease the pressure drop and increase the drop size. In terms of spray angle, it has an inverse effect on drop size. An increase in spray angle will reduce the drop size whereas a reduction in spray angle will increase the drop size (Lefebvre, 1989).

2.7 Weber Number

The main parameter that determines the behavior of a drop when it hits a surface is its Weber number. Also the impact behavior depends upon the surface characteristics which can be divided into cold dry surface, wetted surface and hot surface (Nasr, 2002).

The Weber number of a spherical fluid is defined to be the dimensionless quantity which is given by:

$$We = \frac{\rho\, v\, l}{\sigma} \tag{2.2}$$

where ρ is the density of the fluid, v is the droplet velocity, l is the droplet diameter and σ is the surface tension of the droplet.

For small Weber number, the surface tension of water is strong enough to stop the spreading when water impact into a wall. For larger Weber number, the kinetic energy of the water spreading is greater than the surface tension. Water then groups into fingers along the outer rim of the droplet which have sufficient energy to overcome the surface tension and pinch off into smaller droplets. After the initial spreading or splashing, the surface tension pulls inward creating an upward flow of water known as a Worthington Jet (Comeau et al, 2007).

2.8 Laser Doppler Anemometry and Phase Doppler Anemometry

Laser Doppler Anemometry (LDA) is a technology used to measure velocity of flows. The basic technique of Laser Doppler Anemometry is to take measurement of laser light scattered by particles that pass through series of interference fringes. Velocity of particles is measured by relating the oscillation of scattered laser light with specific frequency. The need for physical contact with the flow is eliminated in LDA, thus producing no disturbances. Relatively high spatial resolution is possible by focusing the two laser beams.

Basically, PDA system has many parts which are laser (typically a continuous wave Ar-iron-laser), fiber optics, frequency shifter, transmitting and receiving optics, signal processor, traversing system and a computer to control the measurement and save data. PDA uses optical detector, which is working in the side-scatter mode for size measurements of particle.

2.9 Eddy Flow

In fluid dynamics, an eddy is the swirling of a fluid and the reverse current created when the fluid flows past an obstacle. The moving fluid creates a space devoid of downstream-flowing fluid on the downstream side of the object. Fluid behind the obstacle flows into the void creating a swirl of fluid on each edge of the obstacle, followed by a short reverse flow of fluid behind the obstacle flowing upstream, toward the back of the obstacle. This phenomenon is most visible behind large emergent rocks in swift-flowing rivers (Wikipedia, 2010).

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

Figure 3.1 shows the process flow for this project. It starts with the literature review. In this stage, the process of finding researches that are related to the project has been made. The researches cover on spray characteristics such as the droplet sizes, droplet velocity, types of droplets break up and types of droplets in different applications. Next, the physical and chemical characteristics of the selected liquid fuel and water are studied. Improvements have been made in terms of the penetration distance and droplet movement in this project. Previous student has made an experiment on the penetration for three sections only. For this time, penetration distance will be divided into five sections to get precise results and each droplets movement for each partial must be identify on different spray angles. Then, familiarization with the LDA/PDA equipments is done before the actual experiments are performed. This is important because during this stage, problems can be detected before starting the actual performance. The discussion about safety issues and experiment procedure has been done with laboratory technician. When all of this is done, the real experiment will be conducted. The experiment involving two types of liquid which are diesel and water. The first experiment is conducted to determine the Sauter Mean Diameter and velocity for each type of liquids at the different pressures. LDA is used to get the diameter and PDA is used to find both vertical and horizontal velocity. Then, the experiment enters into the last step which is using high speed camera. This camera is used to see or study the structure of the break up zone of spray for each liquid at each selected pressures. However, for the fail experiments, they need to be identified the roots for the failure and then to be corrected and repeated. After that, the data will be collected and been analysed. Appendix A shows the Gantt chart for this project. This chart is an ongoing changing process; therefore some data may differ from actual process.

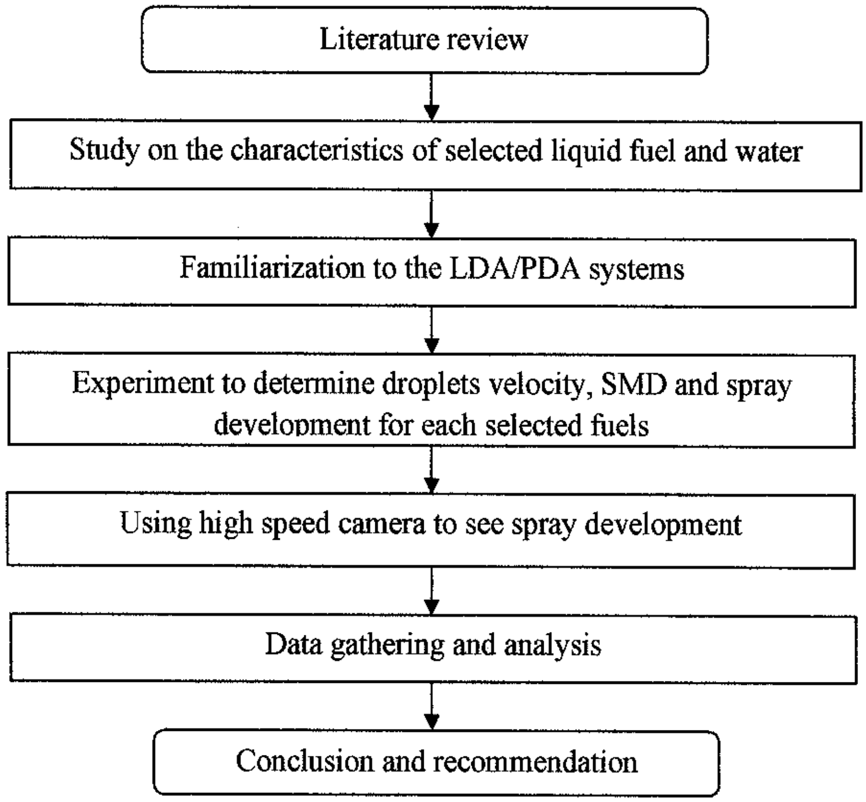


Figure 3.1: Process flow of research

3.2 EQUIPMENT

For this project, experiments have been planned to make comparative study of spray of different liquids. In order to study microscopic characteristics, Laser Doppler Anemometry (LDA) and Phase Doppler Anemometry (PDA) shall be used. LDA is used to measure mean velocity of the droplets and direction while PDA is used to measure droplets size. High speed camera is used to take pictures of droplet break up of selected liquids. Other tools include spray nozzle and pumps.

3.2.1 LDA/PDA Systems

To study the microscopic characteristics of droplets, Laser Doppler Anemometry (LDA) and Phase Doppler Anemometry (PDA) shall be used. LDA is used to measure mean velocity of the droplets and direction while PDA is used to measure droplets size. In LDA, the laser crosses two beams of collimated, monochromatic, and coherent laser light in the flow of the fluid being measured, where these two beams are usually obtained by splitting a single beam. This will result coherency between them. Then the two beams are made to intersect at the focal point of a laser beam. This is where they interfere and then generate straight fringes. The sensor is aligned so that the fringes will be perpendicular to the flow of direction. With the information of fringe spacing, velocity can be obtained.

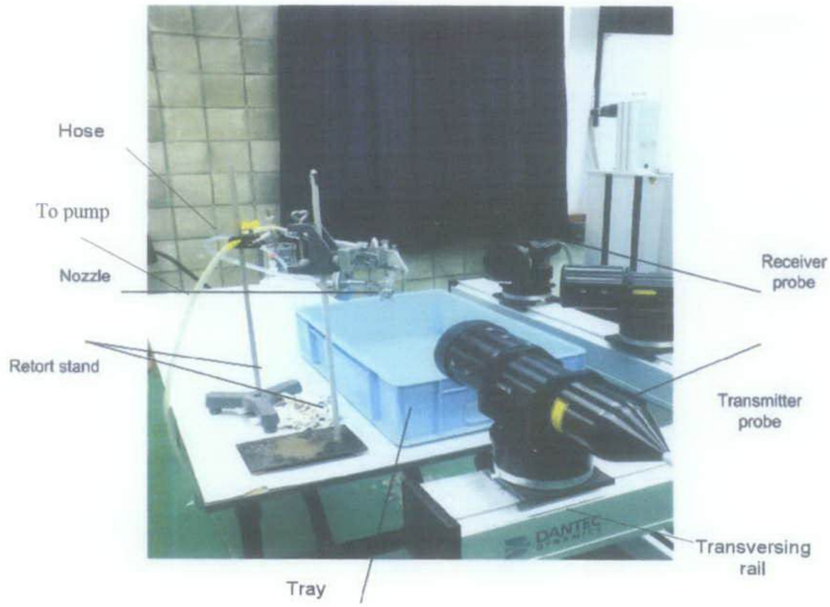


Figure 3.2: Arrangements of the LDA/PDA Systems

Shown in the Figure 3.2 is the arrangement of the LDA/PDA systems. It consists of two transmitter probes. The first probe is to measure the 2D measurement of velocity compound and the second probe is to measure the 3D measurement. For this project, only the probe for 2D measurement is going to be used. The probe has two pairs of laser which are two for vertical and the other two for horizontal. This pairs of lasers will intersect against each other at a certain distance. The probe can be adjusted horizontally by using the transversing rail. The pump will supply pressure to the spray depend on the pressure setting.

The system consists of a transmitter, a receiver, a signal processor and a computer. Laser is split by utilization of Beam Splitter and Frequency Shift Module. These two lasers intersect again at a point, which is called probe volume. When a drop passes through the probe volume, the scattered light forms an interference fringe pattern as in Figure 3.3. This is when the diameter and mean velocity of the particle is measured.

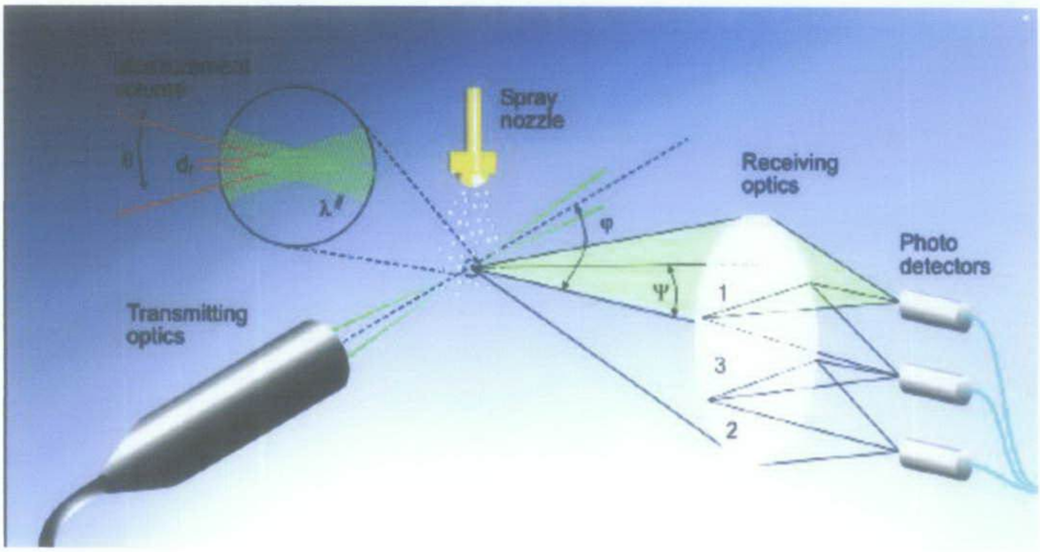


Figure 3.3: Intersection point for volume measurement

PDA is a non-intrusive method in the research of two phase flows. Basically, PDA consists of a laser, fibre optics, frequency shifter, transmitting and receiving optics, signal processor, traversing system and a computer to control the measurement and save the data. In PDA, laser beams from the transmitting optics cross at the focal point of the front lens while the receiving optics looks to the same focal point at certain angle. The size is measured based on phase difference between the signals received by the two detectors.

The basic components are a laser, a beam splitter, transmitting/receiving optics, a photo detector, a signal processor and a data analysis system. A Bragg cell is often used as the beam splitter. It is a glass block with a vibrating piezo crystal attached. The vibration generates acoustical waves acting like an optical grid. The output of the Bragg cell is two beams of equal intensity with frequencies f_0 and s_{shift}. These are focused into optical fibres bringing them to a probe containing transmitting/receiving optics. In the probe, the parallel exit beams from the fibres are focused by a lens into the measurement volume where the beams intersect.

Particle Dynamics Analysis (PDA) is an optical technique to measure the size and velocity of spherical particles simultaneously. These particles can be droplets, bubbles or solid particles as typically occur in sprays, liquid atomisation, bubbly two-phase flows and multiphase flows.

The principles are the measurements are performed at the intersection of two laser beams, where there is an interference fringe pattern of alternating light and dark planes. Particles scatter the light which appears to flash, as the particles pass through the bright planes of the interference pattern. Receiving optics placed at an off-axis location focus scattered light into multiple detectors. Each detector converts the optical signal into a Doppler burst with a frequency linearly proportional to the particle velocity. The processor will measures the phase difference between the Doppler signals from different detectors. This is a direct measure of the particle diameter. Lastly, results are processed by the BSA Flow Software Packages.

The LDA/PDA is manufactured by Dantec Dynamics consists of following components which are:

(a) A 300mW argon-ion laser source, LaserPhysics Reliant 500m;

(b) A laser splitter and manipulator, Dantec 60 × 26;

(c) A signal processor, Dantec 58N80-MultiPDA;

(d) Optical-fiber cables, to convey the beams to the transmitter;

(e) A transmitter with a convergent lens, $f = 600$ mm;

(f) A receiver with a convergent lens, $f = 300$ mm;

(g) A traverse system Dantec 57G15;

3.2.2 High Speed Camera

Figure 3.4: High Speed Camera Phantom v9.1

High speed camera Phantom v9.1 is the most powerful and easiest camera to discover the spray development. Phantom is a totally digital high speed imaging system capable of recording thousand of high resolution images per second. This camera provides with complete creative control over time. With its two main components of the system the Phantom imager with advanced CMOS technology, and the Phantom Camera Control software, they form a system that provides high speed, high resolution image capture in digital cine format, with analytical cine playback, measurements and communications across multiple digital and analog protocols. Below are the specifications of the Phantom v9.1:

a) Full frame 4:3 aspect ratio CMOS sensor composed of 1,632 x 1,200 pixels
b) 14-bit image depth
c) 1,000 frames per second full resolution to 153,846 fps maximum
d) 2400 ISO/ASA monochrome, 600 ISO/ASA colour sensitivity equivalency
e) Continuously Adjustable Resolution in 96 x 8 pixel increments
f) 24 Gigabytes DRAM, 24 Gigabytes non volatile flash memory
g) Extreme dynamic range exposure control

3.2.3 Spray Nozzle

Figure 3.5: Spray nozzle F-75s

The project uses high pressure spray nozzle F-75s, which is manufactured by Akoka. The operating pressure is between 3 to 5 bars. The air inlet is 6.35 mm in diameter and the nozzle outlet diameter is 1.3 mm. It is classified under full cone spray nozzle. The nozzle is connected to the stainless steel centrifugal pump by using a hose.

3.2.4 Spray Rig

Figure 3.6 shows the schematic diagram of spray rig used to supply the pressure to the nozzle. The flow rate of the stainless steel centrifugal pump is 40 LPM and the pump head is 1m. The size of the cylindrical tank is 0.90 m^2 and it is used to supply the liquids to the nozzle. The pump and the tank are connected by a 1.3 m pipe.

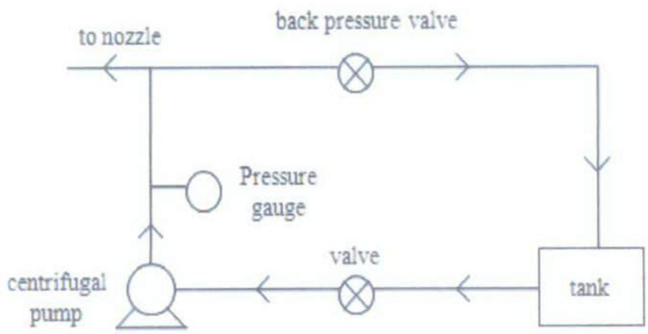


Figure 3.6: Schematic diagram of spray rig

3.3 Distances from nozzle tip

The experiments are conducted at the different distances from the nozzle tip. The function is to find more data on the spray development. The distances are taken from the beginning of the spray's droplet until the end of the spray development. Shown in the

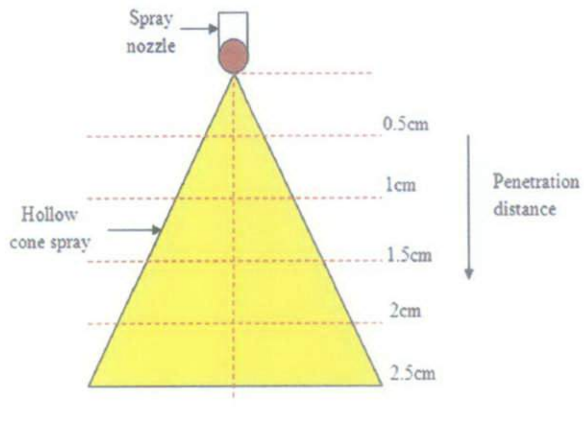
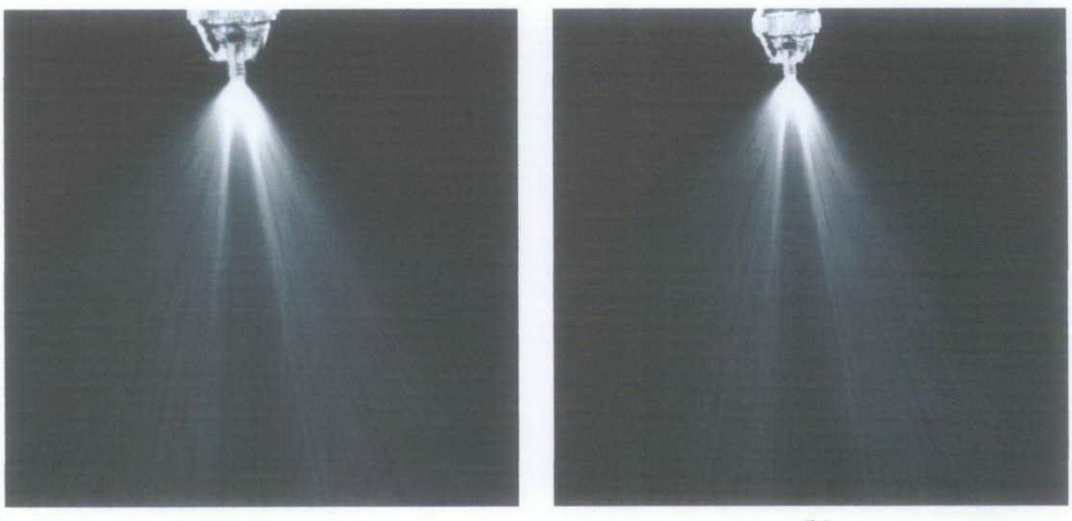


Figure 3.7: Distance from nozzle tip

Figure 3.7 is the distance of spray development from the nozzle tip. From the previous study on the distances, they only take three layers of the penetration distances. In order to find the droplet movement, velocity of droplets and the droplets diameter more detail, the distances are added on to become five layers of penetration distance. First, the reading will be taken at the middle of the spray development. After that, the radial distance data will be taken at an increment of 0.5 cm depending on the width of the spray.

3.4 Measurement Spray Angle

This experiment uses high speed camera in order to capture or see the spray development. The experiment is done by using three varies pressures which is 50 kPa, 100 kPa and 150 kPa and different types of liquid in order to understand spray characteristics. The pictures are taken at the sample rate of 1000 frame per second, and then spray angle can be observed. The additional lights are added in order to make picture clearer. Figure 3.8 shows the typical spray picture of both liquids from the experiment:



(a) (b)

Figure 3.8: Full spray developments at 100 kPa of (a) water (b) diesel

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Comparison of Physical Properties

Before conducting the experiments, the physical properties of water and diesel are compared in order to find any similarity between both liquids. Table 4.1 shows the comparison of physical properties between water and diesel. Both of the liquids are compared in terms of chemical formula, molecular weight, flash point, viscosity, freezing point, boiling temperature and auto ignition temperature. From the table, there is no similarity between water and diesel in the physical properties.

Properties	**Diesel**	**Water**
Chemical formula	C_3 to C_{25}	H_2O
Molecular weight	200	18.015
Flash point, °F	165	-
Viscosity, cP	2.6 - 4.1	1.002
Freezing point, °F	-40 - 30	32
Boiling temperature, °F	370 - 650	212
Auto ignition temperature, °F	600	410

Table 4.1: Physical properties of water and diesel (Northrop Grumman, 2010)

4.2 Characteristics of Water Spray

The experiment on water sprays was conducted to determine the characteristics of water spray only by using the LDA/PDA systems. The results provide information on the data counts, vertical velocity, horizontal velocity and the droplets diameter. The average value of downward velocity and horizontal velocity were calculated. All of the experiments were conducted at three different pressures which are 50 kPa, 100 kPa and 150 kPa. The points of measurement are taken at the middle of the spray development.

4.2.1 Frequency of the droplets

Figure 4.1 shows the spread distribution of the droplet's diameter of water at the vertical distance of 0.5 cm from the nozzle tip and at the pressure of 50 kPa. The data are range from 200 μm to 1000 μm. The droplets are polydisperse spray since it has wide range of large diameter. The SMD at this pressure is 736 μm while the standard deviation is 218 μm. The low standard deviation indicated that the data points tend to be very close to the mean.

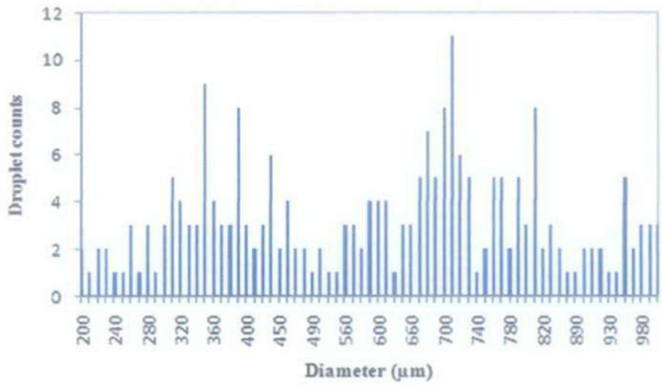


Figure 4.1: Frequency of the droplets

4.2.2 Sauter Mean Diameter of Water

The SMD values were calculated by using Equation (2.1). The sample of calculation is shown in the Appendix B. Shown in the Figure 4.2 is the SMD of water at different pressures and different distances. At 50 kPa, the SMD value is decrease when the distances get larger and the SMD value tend to decrease as the distance from nozzle tip increase. The water spray at 0.5 cm from nozzle tip has the highest SMD value while the water spray at 2.5 cm from the nozzle tip has the lowest SMD value. At 100 kPa, the SMD value is decrease when the distances get larger. The water spray at 0.5 cm from nozzle tip has the highest SMD value while the water spray at 2.5 cm from the nozzle tip has the lowest SMD value. At 150 kPa, there is a large different in the SMD value at each distances compared to the other pressure especially between the 1 cm and 2.5 cm. The water spray at 0.5 cm from nozzle tip has the highest SMD value while the water spray at 2.5 cm from the nozzle tip has the lowest SMD value. For all pressures, it shows the same pattern. The SMD value at 150 kPa has the largest SMD among the other pressures.

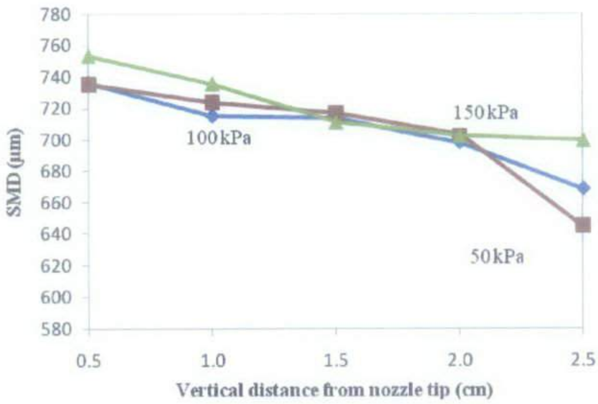


Figure 4.2: SMD of water at different pressures and different distances

4.2.3 Frequency of Vertical Velocity

Figure 4.3 shows the spread distribution of the vertical velocity of water at the vertical distance of 0.5 cm from the nozzle tip and at the pressure of 50 kPa. The highest droplet counts are at the velocity of -4 m/s and the lowest counts are at -1 m/s. Most of the droplets move in the high range of velocity between -4 m/s to -6 m/s. The mean and standard deviation of this vertical velocity is 2.52 m/s and 1.27. The low standard deviation indicated that the data points tend to be very close to the mean.

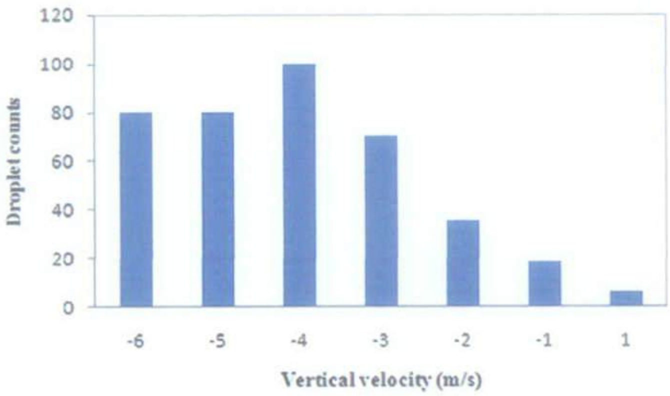


Figure 4.3: Frequency of the vertical velocity

4.2.4 Vertical Velocity of Water

The LDA/PDA data provide the information on the vertical velocity of water. The values are calculated by averaging all of them. The experiments were conducted at three different pressures which are 50 kPa, 100 kPa and 150 kPa.

Shown in the Figure 4.4 is the vertical velocity of water at different pressures and different distances. The data are taken at each of the distance from the nozzle tip. The water spray at 150 kPa has the highest vertical velocity compared to the other velocities. Water at the pressure of 100 kPa has the second highest vertical velocity. The vertical velocity of water decreases as the distance from the nozzle tip increases. This is because the SMD of water become smaller when the distance increases and some of the droplet start to vaporize.

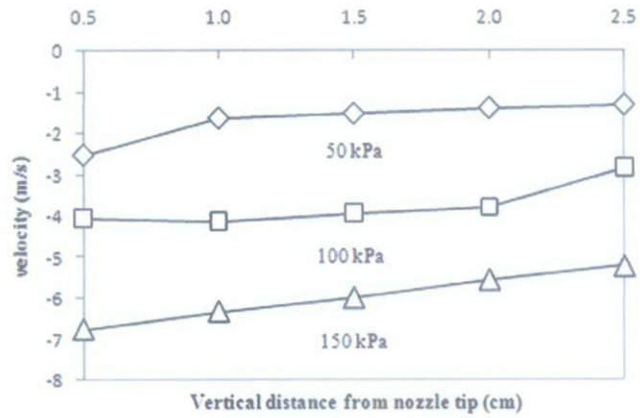


Figure 4.4: Vertical velocity of water at different pressures and different distances

4.2.5 Frequency of Horizontal Velocity

Figure 4.5 shows the spread distribution of the horizontal velocity of water at the vertical distance of 0.5 cm from the nozzle tip and at the pressure of 50 kPa. The data are fluctuating at each velocity and does not show any pattern. Most of the droplet counts are at the middle velocity which is around -4.8 m/s to -5.4 m/s. The lowest data counts are at the -7.4 m/s which are 4 counts out of 17. The mean and standard deviation of this vertical velocity is 1.13 m/s and 4.77. The high standard deviation indicated that the data are spread out over a large range of values.

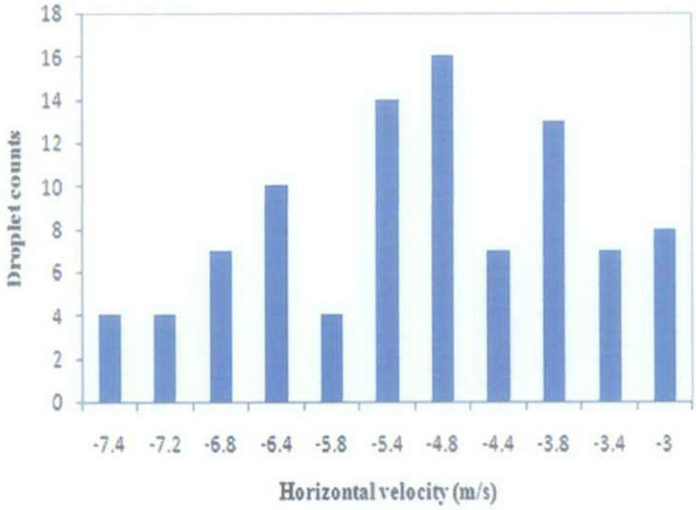


Figure 4.5 Frequency of horizontal velocity

4.2.6 Horizontal Velocity of Water

The LDA/PDA data provide the information on the horizontal velocity of water. The values are calculated by averaging all of them. The experiments were conducted at three different pressures which are 50 kPa, 100 kPa and 150 kPa. Unlike vertical velocity, horizontal velocity possesses both directions. Positive value means that the velocity is moving towards the left while negative velocity is moving towards the right.

Shown in the Figure 4.6 is the horizontal velocity of water at different pressures and different distances. The data are taken at each of the distance from the nozzle tip. The water spray at 150 kPa has the highest horizontal velocity compared to the other velocities. Water at the pressure of 100 kPa has the second highest horizontal velocity. The horizontal velocity of water decreases as the distance from the nozzle tip increases. This is because the SMD of water become smaller when the distance increases and some of the droplet start to vaporize.

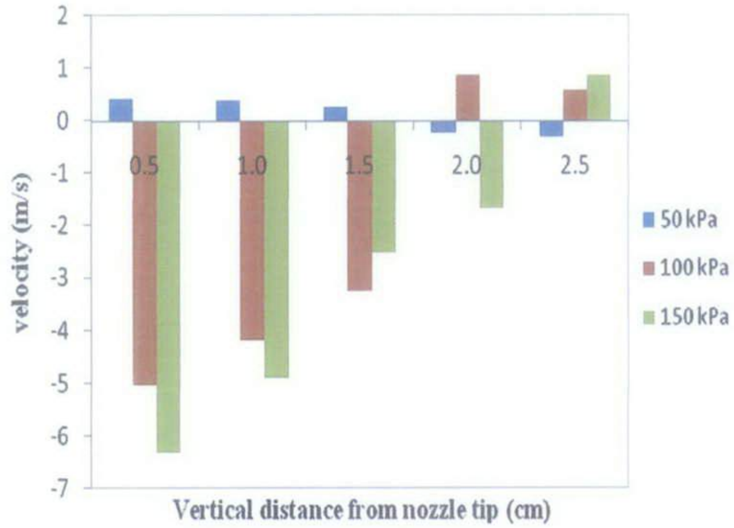


Figure 4.6: Horizontal velocity of water at different pressures and different distances

Table 4.2 shows the data for all pressures and all distances at the middle of the spray development. The experiment was done by using LDA/PDA systems. The distances were varied from the nozzle below in vertical direction as 0.5 cm, 1 cm, 1.5 cm, 2.0 cm and 2.5 cm.

Water	**Pressure**	**Penetration Distance**				
		0.5 cm	1 cm	1.5 cm	2 cm	2.5 cm
average vertical velocity	0.5 bar	-2.52	-1.62	-1.51	-1.38	-1.3
	1 bar	-4.04	-4.13	-3.92	-3.79	-2.83
	1.5 bar	-6.75	-6.31	-5.97	-5.54	-5.21
average horizontal velocity	0.5 bar	0.42	0.4	0.26	-0.23	-0.32
	1 bar	-5.04	-4.2	-3.25	0.86	0.58
	1.5 bar	-6.31	-4.91	-2.51	-1.68	0.87
SMD	0.5 bar	736.27	715.33	714.44	698.41	668.74
	1 bar	735.78	723.79	717.26	703.69	644.69
	1.5 bar	753.46	735.87	711.34	702.59	699.81

Table 4.2: Tabulated data from LDA/PDA systems

4.3 Characteristic of Diesel Spray

The experiment on diesel was conducted to determine the characteristics of diesel spray only by using the LDA/PDA systems. The results provide information on the data counts, vertical velocity, horizontal velocity and the droplets diameter. The average value of downward velocity and horizontal velocity were calculated. The SMD values were calculated by using Equation (2.1). All of the experiments were conducted at three different pressures which are 50 kPa, 100 kPa and 150 kPa. The points of measurement are taken at the middle of the spray development.

4.3.1 Sauter Mean Diameter of Diesel

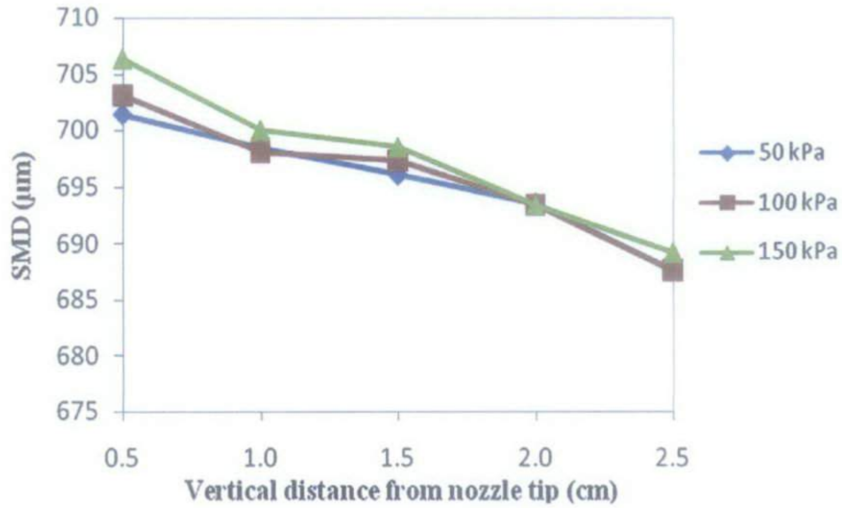


Figure 4.7: SMD of diesel at different pressures and different distances

Shown in the Figure 4.7 is the SMD of diesel at different pressures and different distances. The SMD at the 150 kPa has the largest SMD value at each distance while for 50 kPa, the SMD value has almost smallest value compared to the other pressures. SMD of diesel show the same pattern as the SMD of water as its SMD decreases as the distance from the nozzle tip increases. This is because when the droplets start to vaporize when it is far from the nozzle tip.

4.3.2 Vertical Velocity of Diesel

The LDA/PDA data provide the information on the vertical velocity of diesel. The values are calculated by averaging all of them. The experiments were conducted at three different pressures which are 50 kPa, 100 kPa and 150 kPa.

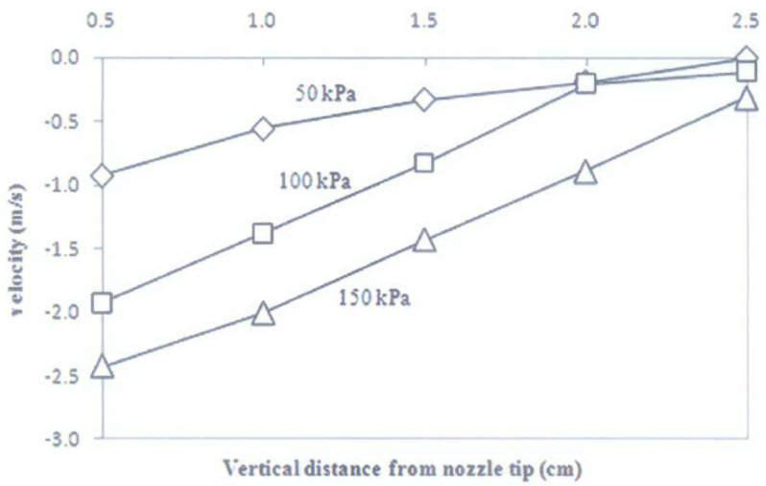


Figure 4.8: Vertical velocity of diesel at different pressures and different distances

Shown in the Figure 4.8 is the vertical velocity of diesel at different pressures and different distances. The data are taken at each of the distance from the nozzle tip. The diesel spray at 150 kPa has the highest vertical velocity compared to the other velocities. Diesel at the pressure of 100 kPa has the second highest vertical velocity. The vertical velocity of diesel decreases as the distance from the nozzle tip increases. This is because the SMD of diesel become smaller when the distance increases and some of the droplet start to vaporize.

4.3.3 Horizontal Velocity of Diesel

Shown in the Figure 4.9 is the horizontal velocity of diesel at different pressures and different distances. The data are taken at each of the distance from the nozzle tip. The diesel spray at 150 kPa has the highest horizontal velocity compared to the other velocities. Diesel at the pressure of 100 kPa has the second highest horizontal velocity. The horizontal velocity of diesel decreases as the distance from the nozzle tip increases. This is because the SMD of diesel become smaller when the distance increases and some of the droplet start to vaporize.

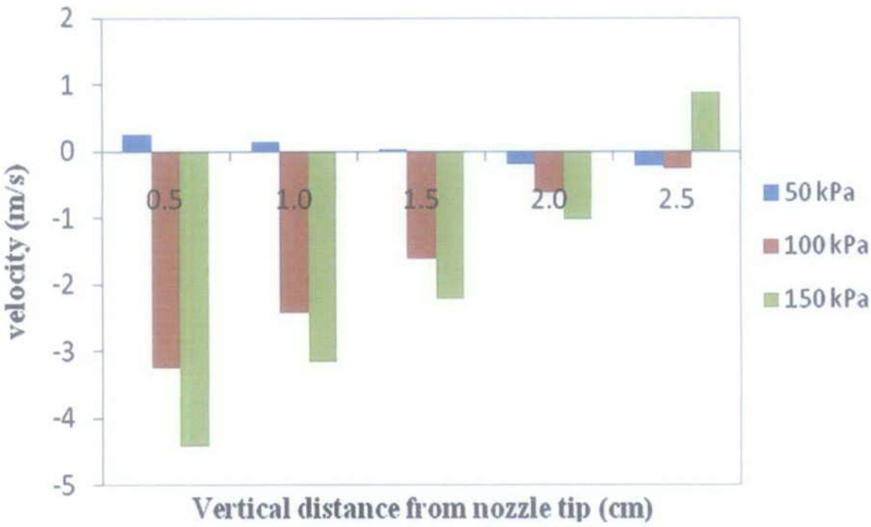


Figure 4.9: Horizontal velocity of diesel at different pressures and different distances

4.4 Comparison of SMD for Water and Diesel

4.4.1 Sauter Mean Diameter at 50 kPa

The purpose of this project is to compare water against diesel in terms of spray characteristics. It will be compared by determining the sauter mean diameter, both vertical and horizontal velocity. Figure 4.10 below shows the comparison of sauter mean diameter between water and diesel at 50 kPa at different distances from the nozzle tip.

Water has the largest SMD value at almost vertical distance from nozzle tip except at 2.5 cm. The largest SMD value is at 0.5 cm distance from nozzle tip which is around 740 μm and the smallest value is around 670 μm. SMD of water decrease as the distance from the nozzle tip increase. For diesel, the SMD are almost constant around

700 μm at each distance. Both of the liquids show the same pattern, as the vertical distance increase, the SMD will decrease.

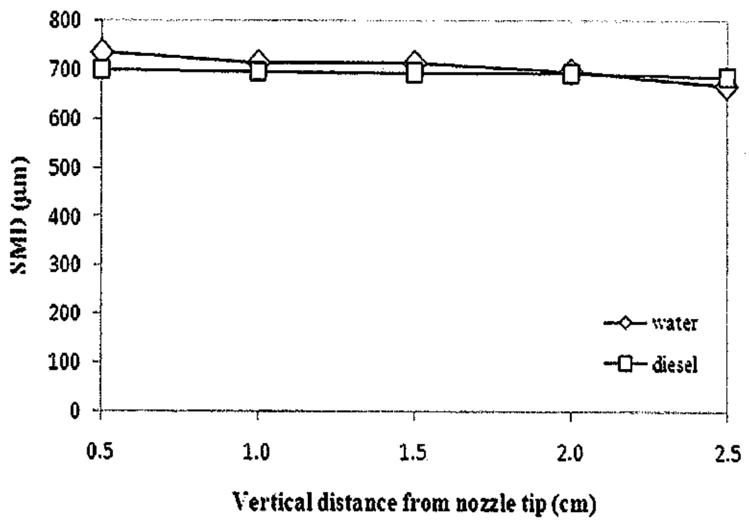


Figure 4.10: Sauter Mean Diameter of water and diesel at 50 kPa

4.4.2 Sauter Mean Diameter at 100 kPa

Figure 4.11 shows the comparison of Sauter Mean Diameter between water and diesel at 100 kPa at different vertical distances from the nozzle tip.

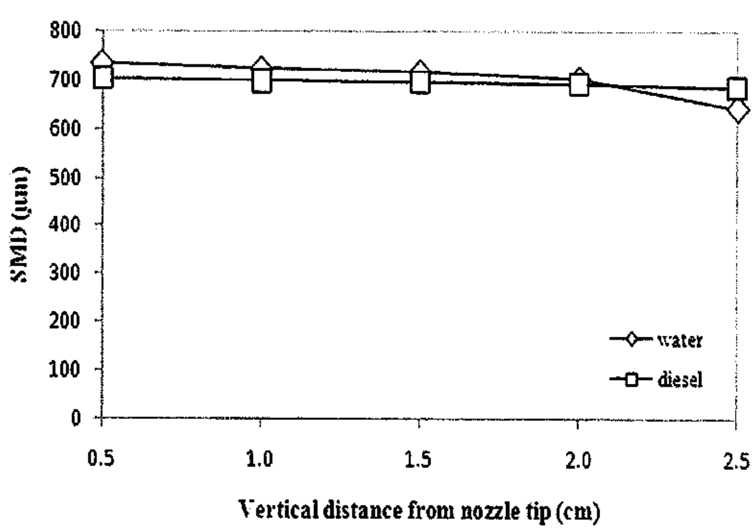


Figure 4.11: Sauter Mean Diameter of water and diesel at 100 kPa

It shows the same pattern as the previous pressure where water has the largest SMD value at almost verticle distance from nozzle tip except at 2.5 cm. The largest SMD value is at 0.5 cm distance from nozzle tip which is around 740 μm and the smallest value is around 650 μm. SMD of water decrease as the distance from the nozzle tip increase. There is a sudden drop about 70 μm at the distance Of 2.5 cm. For diesel, the SMD are almost constant around 700 μm at each distance. The SMD for both liquids show the pattern as the SMD at pressure of 50 kPa. As the vertical distance increase, the SMD will decrease in sizes.

4.4.3 Sauter Mean Diameter at 150 kPa

Shown in the Figure 4.12 is the comparison of Sauter Mean Diameter between water and diesel at 150 kPa at different vertical distances from the nozzle tip. Different against from the previous pressure, water has the largest SMD value at all verticle distance from nozzle tip. SMD of water decrease as the distance from the nozzle tip increase. There is a sudden drop about 60 μm at the distance of 2.5 cm. For diesel, the SMD are almost constant around 700 μm at each distance. At this pressure, the SMD at 2.0 cm are not almost intersect as the previous pressure. The SMD for both liquids show the pattern as the SMD at the previous pressure. As the vertical distance increase, the SMD will decrease in sizes

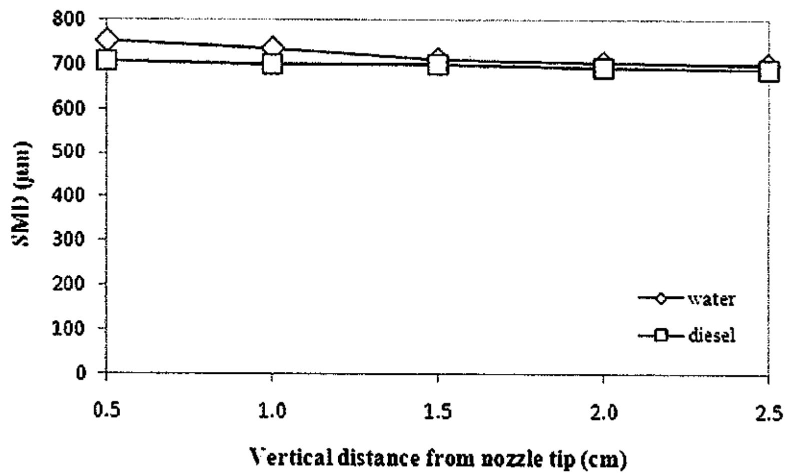


Figure 4.12: Sauter Mean Diameter of water and diesel at 150 kPa

4.5 Comparison of Vertical Velocity

4.5.1 Vertical Velocity at 50 kPa

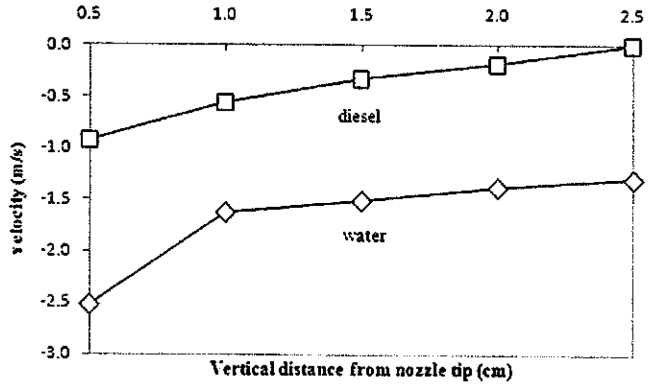


Figure 4.13: Vertical velocity of water and diesel at 50 kPa

Shown in the Figure 4.13 is the vertical velocity of water and diesel at 50 kPa. Water has the highest vertical velocity at each distance against diesel. The highest vertical velocity is at -2.5 m/s of water and the lowest is at 0 m/s of diesel. As the distances from the nozzle tip increase, the velocity of both liquids will decrease.

4.5.2 Vertical Velocity at 100 kPa

Figure 4.14 below shows the vertical velocity of water and diesel at 100 kPa.

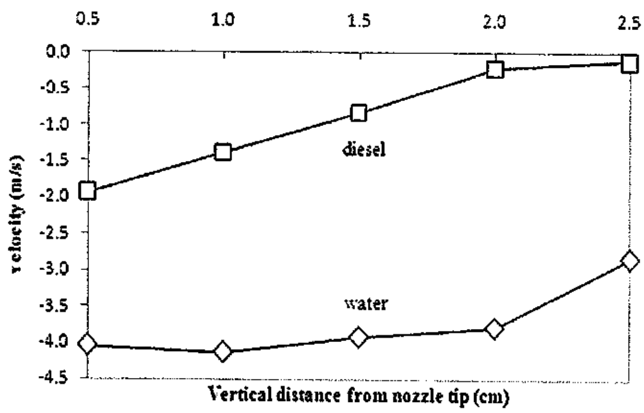


Figure 4.14: Vertical velocity of water and diesel at 100 kPa

Same as the previous pressure, water has the highest vertical velocity at each distance against diesel. The highest vertical velocity is around -4.3 m/s and the lowest is at -0.11 m/s. As the pressure increase, the vertical velocity will increase also.

4.5.3 Vertical Velocity at 150 kPa

Figure 4.15 below shows the vertical velocity of water and diesel at 150 kPa. At this pressure, it shows the pattern as the previous pressure. As the pressure increase, the vertical velocity will increase and as the distance from nozzle tip increase the vertical velocity will decrease. The vertical velocity of water has the highest velocity which is -6.9 m/s.

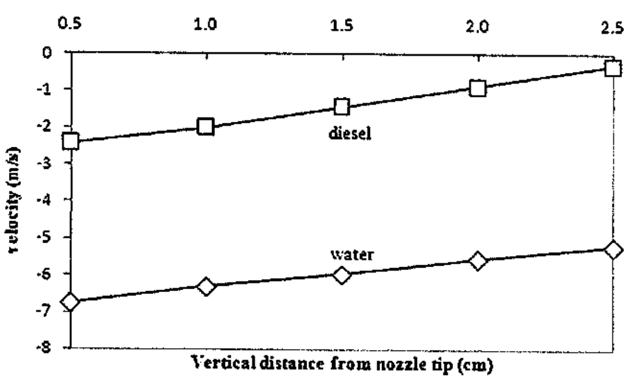


Figure 4.15: Vertical velocity of water and diesel at 150 kPa

4.6 Comparison of Horizontal Velocity

4.6.1 Horizontal Velocity at 50 kPa

Figure 4.16 shows the comparison of horizontal velocity between water and diesel at 50 kPa. Unlike downward velocity, horizontal velocity possesses both directions. Positive value means that the velocity is moving towards the left while negative velocity is moving towards the right. As a result, there is reduction in average horizontal velocity. Water has the highest horizontal velocity at each distance against diesel. As the vertical distance increase, the velocity will decrease. This is because the droplets tend to lost energy and vaporize as the distance increase. In this pressure, the droplets move evenly to both directions.

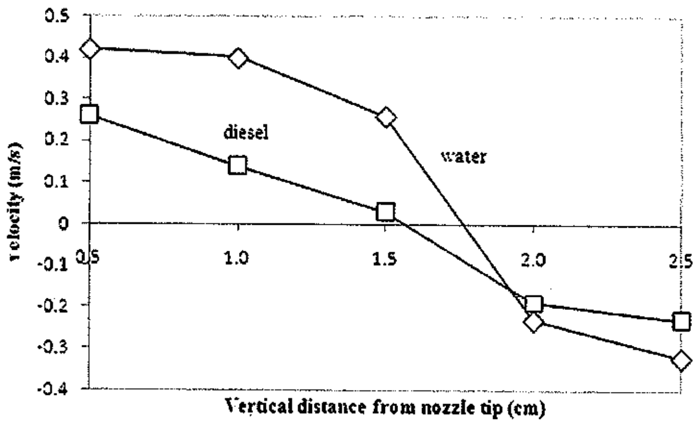


Figure 4.16: Horizontal velocity of water and diesel at 50 kPa

4.6.2 Horizontal Velocity at 100 kPa

Figure 4.17 shows the comparison of horizontal velocity between water and diesel at 100 kPa. The droplets tend to move heavily on the right side as the pressure increase. There is a large increase in the velocity as the pressure change to 100 kPa. The graph shows the same pattern as before where water has the highest velocity against diesel.

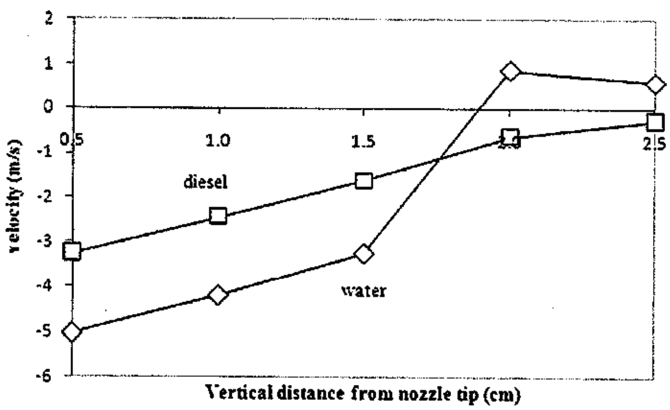


Figure 4.17: Horizontal velocity of water and diesel at 100 kPa

4.6.3 Horizontal Velocity at 150 kPa

Figure 4.18 shows the comparison of horizontal velocity between water and diesel at 150 kPa. The droplets tend to move heavily on the right side as the pressure increase. The velocity increase as the pressure increase and water has the highest horizontal velocity compared to the diesel.

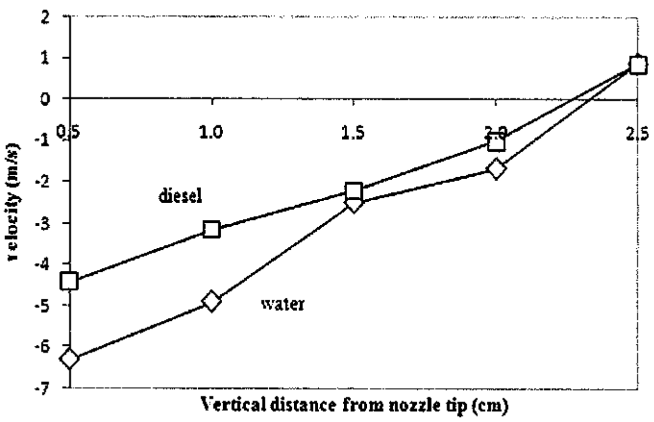


Figure 4.18: Horizontal velocity of water and diesel at 150 kPa

4.7 Radial Distance

The experiment also has been done to determine the Sauter Mean Diameter for radial distance between water and diesel. Figure 4.19 shows the point of measurement of radial distance at each penetration distance. The distance between points to point is 0.5cm. Depends on the width of the spray, the point measurement at the full development spray are more than the pre-swirl spray.

Appendix C shows the tabulated data of radial distance for water and diesel. By assuming that both sides of the spray development are symmetrical, the data are taken at the right side of the spray. There is a large different in SMD value between the middle point measurement and radial distance of both liquids. The SMD at middle spray has bigger size rather than SMD of radial distance. For the SMD of radial distance, the values are approximately same as the distance increased. SMD of water are bigger than diesel at each distance. There is a sudden decrease at 0.5cm and then the data start to increase back until the end of spray width. As the pressure increase, the SMD will decrease as shown in the table.

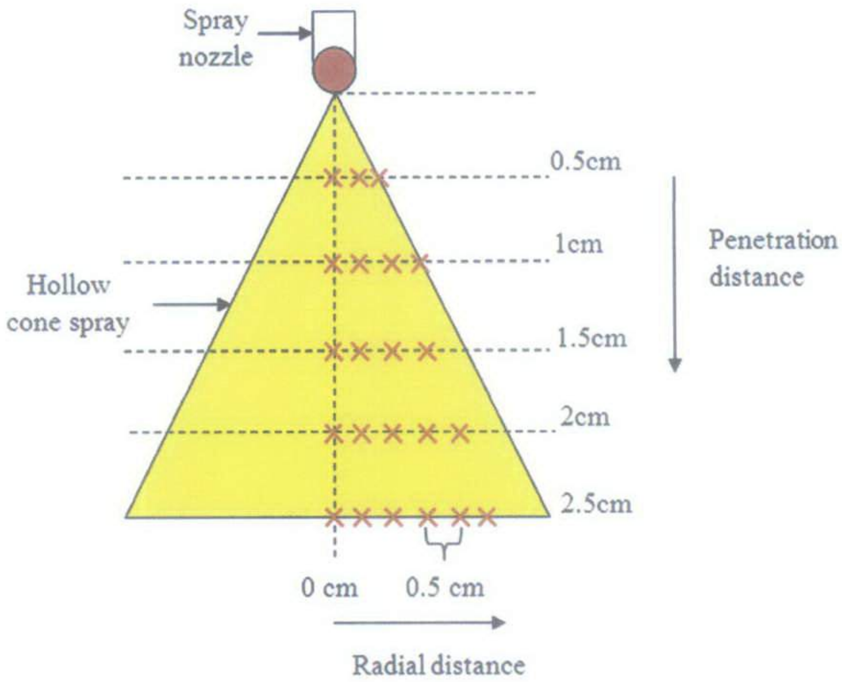


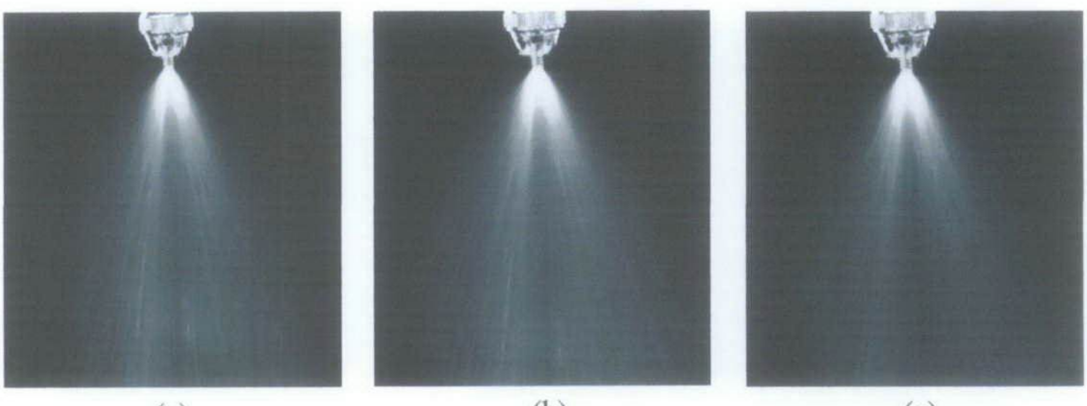
Figure 4.19: Radial distance of spray area

4.8 Spray Angles

This experiment was performed by using high speed camera and some additional light to see the spray development. The camera was set at high exposure and high resolution in order to get clearer picture. It also manages to take around 1000 frames per second under this setting. The pressures are varied at 50 kPa, 100 kPa and 150 kPa. Figure 4.20 shows on how the spray angle was calculated by using Catia V5 software. The picture of the spray is opened in the Catia V5 and a straight line is drawn along the spray width. Then, measuring angle tool is used to determine the spray angle for both liquids.

Figure 4.20: Spray angle measurement method

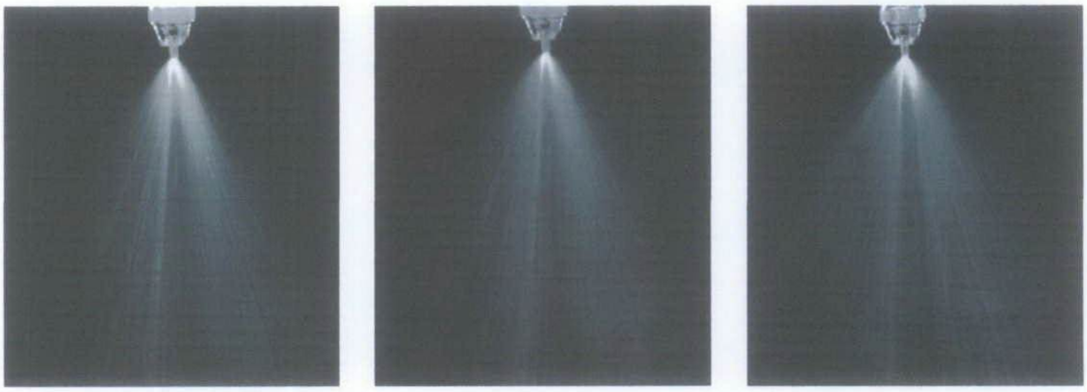
Figure 4.21 show the spray development of water at each selected pressure. As the pressure increase, the spray angle also increases. The spray angle of water at 50 kPa was measured as 50.5°. At 100 kPa, the water spray angle is 53° and at 150 kPa, the spray angle was measured 53.6°.



(a) (b) (c)

Figure 4.21: Water spray at (a) 50 kPa (b) 100 kPa (c) 150 kPa

For diesel fuel, spray structures are shown in Figures 4.22. The spray angle at 50 kPa was measured as 43°. For 100 kPa, the measurement of spray angle was 46°. When the pressure is set to 150 kPa, the spray angle was observed as 47.3°.



(a) (b) (c)

Figure 4.22: Diesel spray (a) 50 kPa (b) 100 kPa (c) 150 kPa

It was observed that the spray angle of water is much higher than the diesel spray. Water has the largest spray angle at 150 kPa which is 53.6^0 while the spray angle of diesel just 49^0 at the same pressure. Water spray show an increment in angle as the pressure increase but the diesel spray did not show big increment as the pressure increase. Below is table 4.3 shows the data of spray angle for both liquids.

Spray	Pressure	Spray angles
Water	50 kPa	51.5°
	100 kPa	53°
	150 kPa	53.6°
Diesel	50 kPa	47.3°
	100 kPa	48.8°
	150 kPa	49°

Table 4.3: Spray angle for water and diesel

4.9 Spray Development

High speed camera is used to see the break up structure of spray development. This experiment was done by capturing the image about 100 frames per seconds. Exposure of the camera was set to high so that the image can be seen clearly. Below is Figure 4.23 shows the typically spray development of water spray at 100 kPa. Spray development for water and diesel are almost same except for the spray angle, Sauter Mean Diameter and velocity. The spray development of diesel spray can be seen in Appendix D.

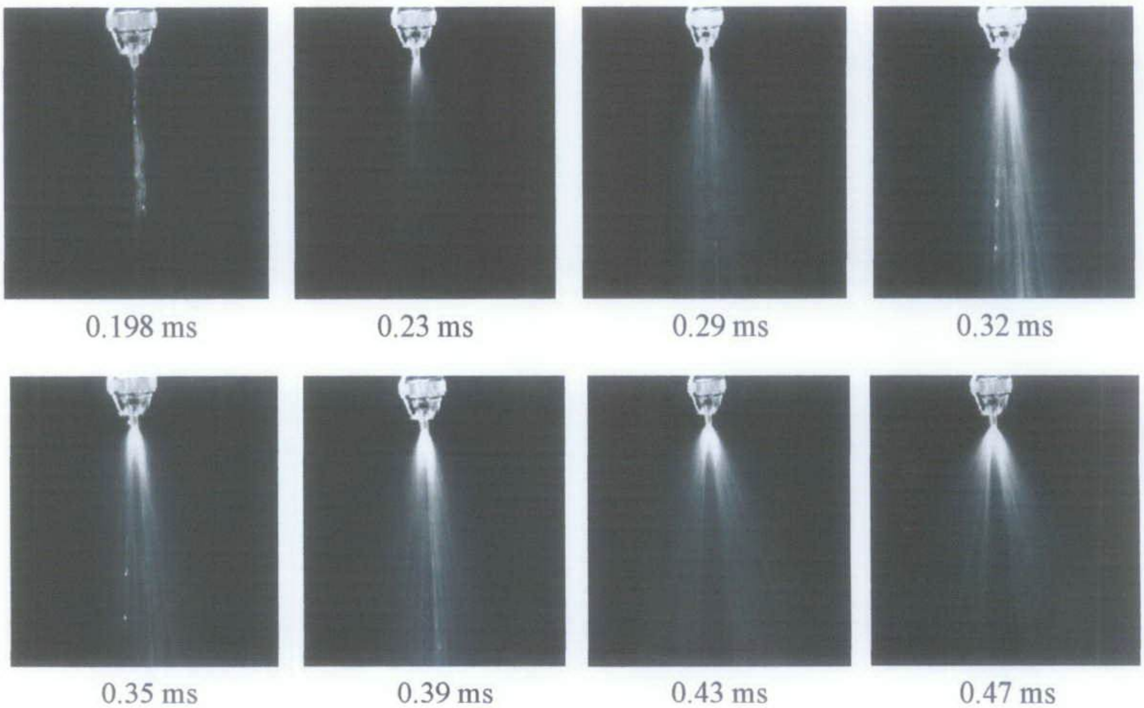


Figure 4.23: Water spray development

The best eight sequences of water spray development are chosen. The water spray start to develop at 0.198 ms with a little of droplets come out. At 0.23 ms, the dispersion of big droplet can be seen with low velocity. At this time, pump tends to stuck because existence of air in the water hose. After a while it becomes normal back.

Then, spray continues to develop after getting back the 0.29 ms. Droplet diameters are still bigger in size and it is really hard for LDA/PDA to produce data. At 0.32 ms, the spray tends to spread widely and it showed different pattern compared to the other picture. Maybe due to the condition of the nozzle, sometimes the spray tends to spread widely. At 0.35 ms, water spray started to grow in width and length of the spray. Fine droplets are produced at this stage. At 0.43 ms, it is fully developed of spray cone. The shape of full cone is clearly seen in the picture above. Then at 0.47 ms, the water spray will not develop anymore and after a few second it will enter the collapse stage.

4.10 Drop size Field Plots

Figure 4.24 shows the typical drop size plot for water and diesel at 50 kPa. This plot based on the Sauter Mean Diameter of both liquids at each penetration distance and at each radial distance. This plot is to present the droplet sizes of both liquid so that it can be seen clearly. Based from the figure below, the drop sizes for both liquids are shown to be the same. It is also shown that the sprays are having the same pattern for penetration distance and radial distance. There is a sudden drop in droplet diameter at 0.5 cm of radial distance. Then, the diameter started to grow in diameter back as the radial distance increase.

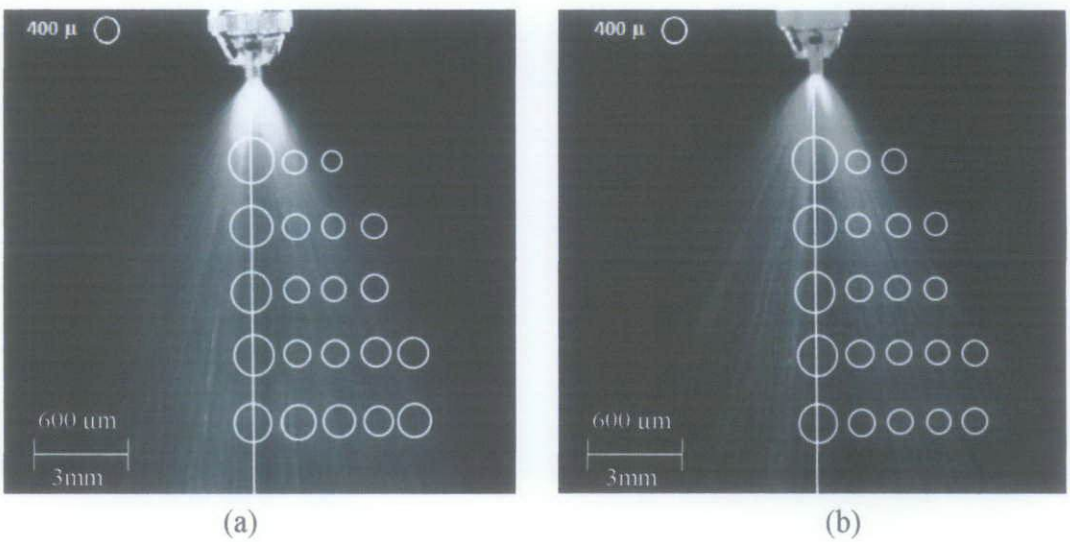


Figure 4.24: Drop size plot at 50 kPa of (a) water (b) diesel

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The objective of this project is to determine whether water has any similarity with diesel in terms of spray characteristics. The experiment on the sprays was conducted to determine the characteristics of the spray only by using the LDA/PDA systems. The results provide information on the data counts, vertical velocity, horizontal velocity and the droplets diameter. High speed camera is used to see the break up structure of the spray development. All of the experiments were conducted at three different pressures which are 50 kPa, 100 kPa and 150 kPa. It also was conducted at different distance from nozzle tip and at different radial distance.

For the Sauter Mean Diameter of both liquids, the points of measurement were taken at the penetration distance and also at radial distance. At penetration distance which is at middle of the spray development, the SMD of both liquids decrease as the penetration distance increase. The SMD tend to increase as the pressure increase. For radial distance, the SMD for both liquids decrease as the pressure increase. The SMD are also smaller than the SMD at the middle of spray development. Overall, the SMD for both liquids show the same pattern and the diameter value also are nearly same.

The vertical velocity for both liquids shows the same pattern. As the pressure increase, the velocity also will increase and as the distance from nozzle tip increase, the velocity will decrease. At 150 kPa, the velocity is the highest while the lowest velocity is at 50 kPa. Same goes to the horizontal velocity, it shows the same pattern as the vertical velocity. Although the pattern is same, the velocity values are not same for both liquids. Velocity of water spray is higher than diesel spray and the different has an average of 4m/s to 5m/s.

For spray angle, there is a clear different between both of the liquids. Water has higher spray angle than diesel at each pressure. In terms of spray characteristic, it can be concluded that water and diesel has similarity in Sauter Mean Diameter only. Therefore, diesel can be replaced with water in terms of Sauter Mean Diameter.

5.2 Recommendations

Some improvement has been made compared to the previous project. The data were taken at many points of the penetration distance and radial distance. In terms of SMD, vertical velocity and horizontal velocity, the data are more accurate and were taken at many points of the spray. High speed camera is used to study the break up structure and also measuring the spray angle.

However, there is still room of improvement for this project .This project is done by using three pressures which are 50 kPa, 100 kPa and 150 kPa. In the next study, maybe higher pressure could be used. The spray characteristics of both liquids at higher pressure can be determined and the results can be compared with the lower pressure. The future research may use other types of nozzle such as hollow cone nozzle. This nozzle produce an especially fine, atomized liquid flow, with spray patterns characterized by a ring-shaped impact area. Lastly, the droplet produce has high coverage area. It tends to spread widely and the equipment to collect the droplet cannot cover the area. So, a system must be created to cover the coverage of spray development so that the droplet will not spread to dangerous equipment such as LDA/PDA system and will harm the user itself.

REFERENCES

Annaorazov Rejep, "Fundamental Study of Sprays of Different Fluid", Final Year Project Dissertation, Department of Mechanical Engineering, Universiti Teknologi PETRONAS, Tronoh, Malaysia, 2010

Ashgriz, N., 2011, *Handbook of Atomization and Sprays,* New York, Springer

Azzopardi, B.J and Hutchinson, P. 1983, *"The disintegration of liquid droplet",* UKEA Report AERE R10929

Bartell, J., Ferrazza, G., Shick R., 1991, *Effects of Spray Nozzle Design and Measurement Techniques on Reported Drop Size Data.* Report Number 95, Washington, USA

Bendig, L., Nasr, G.G., Yule, A.J., 2002, *Industrial sprays and atomization: design, analysis and applications*, London, Springer

Comeau, D., Tourette, K.L., and Pate, J., 2007. *The effect of Weber number and spread factor of a water droplet impinging on a super-hydrophobic substrate.* Report Number 34, Arizona University, Tucson, USA

Hinze, J.O., 1949, "Critical Speeds and Sizes of Liquid Globules," *Applied Scientific Research* **(1):** 273-288

Klein, Smith., *Physical diesel properties,* viewed 4 Sept 2011, <http://www.ozh2o.com/h2phys.html>.

Krzeczkowski, S.A., 1980 "Measurement of Liquid Droplet Disintegration Mechanism," *International Journal Multiphase Flow* **6**: 227-239

Lading, L. and Andersen, K., 1988, "A covariance processor for velocity and size measurement," *Fourth Symposium on Application of Laser Anemometry to Fluid Mechanics* **(1):** 274-290

Lane, W.R., Prewett, W.C., and Edwards, J., 1949. *Some Experiments on the Shatter of Drops by Transient Blast of Air.* Tech. Paper No.115, Serial 15, Porton, England

Lane, W.R., 1951, "Shatter of Drops in Stream of Air," *Ind. Eng. Chem* **43 (4):** 1312-1317.

Lane, W.R. and Dorman, R.G., 1952. *Further Experiments on the Shattering of Drops by a Supersonic Air Blast.* Tech. Paper No., 279, Porton, England

Lee, G.D. 1986. *Comparison of drop size measurement for similar atomizer.* Report Number SWRI-8858R, Southwest Research Institute, San Antonio, USA

Lefebvre, A.H., 1989, *Atomization and Sprays*, Hemisphere, New York,

Liu, H., 2000, *Science and engineering of droplets: fundamentals and applications*, New York, William Andrew

Nolan, P. F., 2000, *Discussions on the use of fine water sprays or mists for fire suppression*, New York, Springer

Northrop Grumman *"Diesel Fuel Properties"*, viewed 22 February 2010,
< http://pps.ms.northropgrumman.com/diesel.htm>

Pidwirny, M. 2006, *Physical Properties of Water*, viewed 21 March 2010,
<http://www.physicalgeography.net/fundamentals/8a.html>

Wigley, G., Goodwin, M., Pitcher, G., Blondel, D., 2004, *Imaging and PDA analysis of a GDI spray in the near nozzle region.* Loughborough University, UK

Wikipedia, 2009, *Eddy Flow*, viewed 6 July 2011,
<http://en.wikipedia.org/wiki/Eddy_ (fluid_dynamics)>

Wikipedia, 2009, *Laser Doppler Anemometry*, viewed 6 July 2011,
<http://en.wikipedia.org/wiki/Laser_Doppler_velocimetry>

APPENDICES

APPENDIX A
GANTT CHARTS

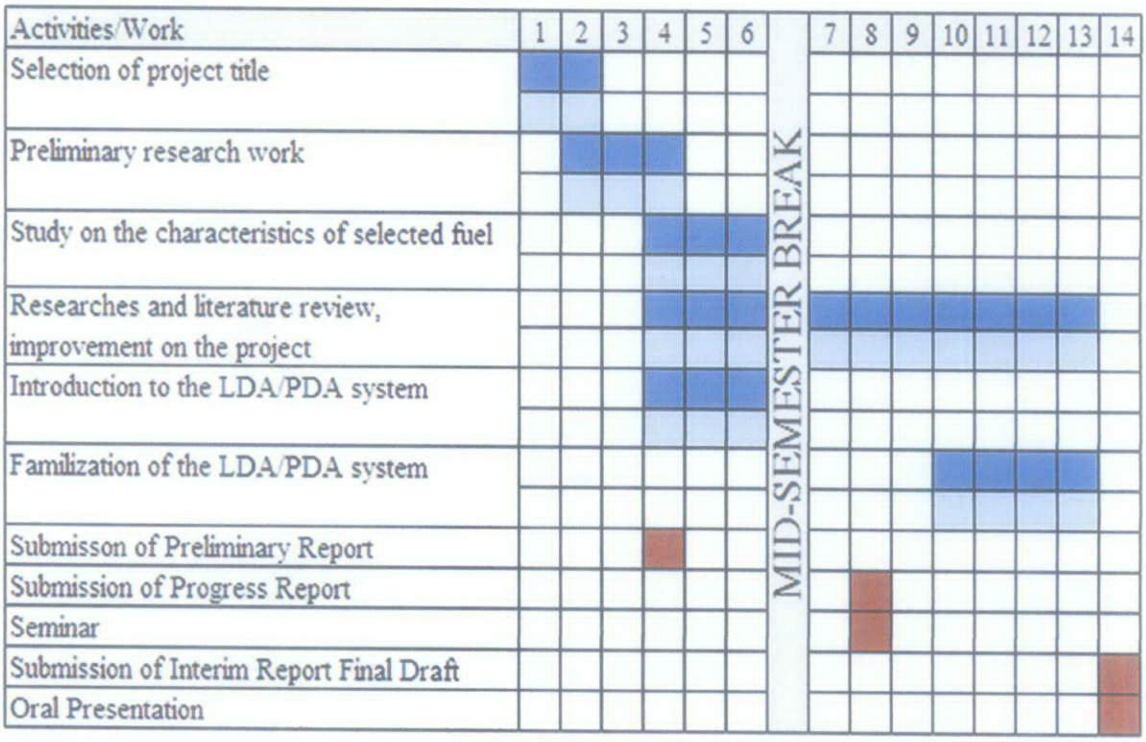


Figure A-1: Gantt chart FYP I (July 2010)

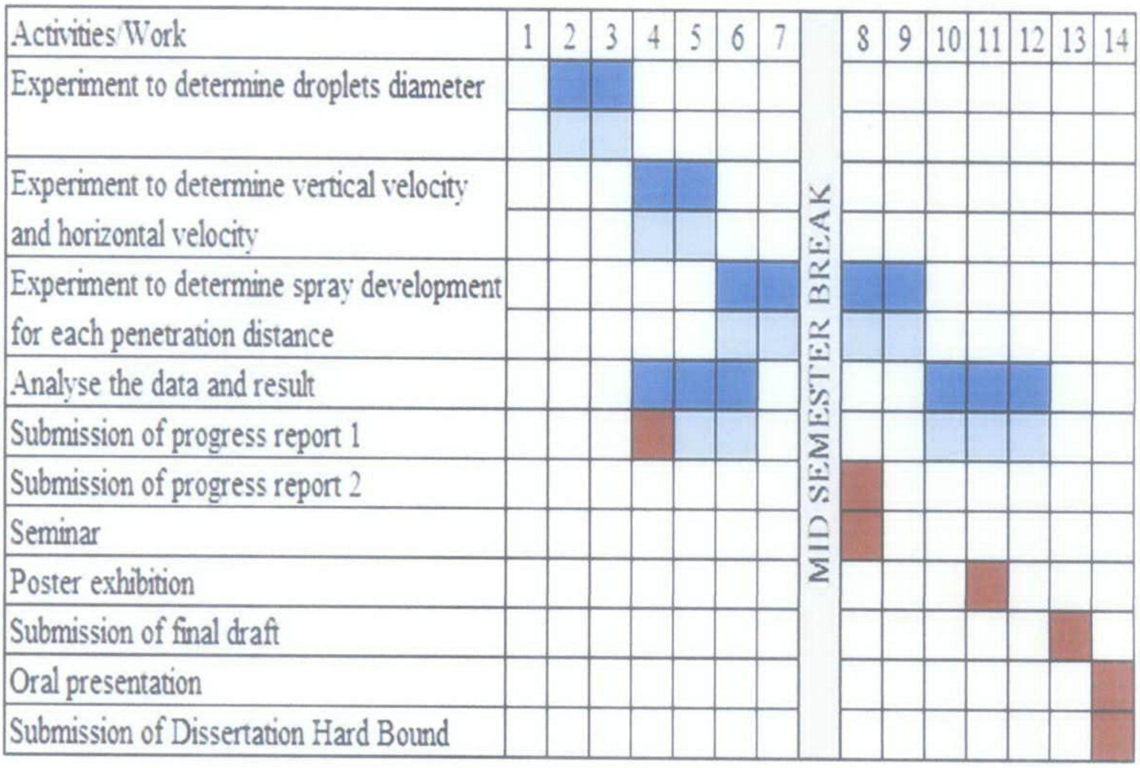


Figure A-2: Gantt chart FYP II (July 2011)

APPENDIX B

CALCULATION OF SMD AND VELOCITY

counts	vertical velocity (m/s)	horizontal velocity (m/s)	diameter (µm)
3	-6	-1.8	20
5	-3	0.8	80
9	-2	1.4	120

Table B-1: Data of LDA/PDA system

Average vertical velocity = $\frac{\Sigma V}{n} = \frac{(-6)(3)+(-3)(5)+(-2)(9)}{17}$

$= 3$ m/s

Average horizontal velocity = $\frac{\Sigma V}{n} = \frac{(-1.8)(3)+(0.8)(5)+(1.4)(9)}{17}$

$= 0.66$ (moving to the left)

$$\text{SMD} = D_{32} = \frac{\sum_{i=1}^{k} n_i D_i^3}{\sum_{i=1}^{k} n_i D_i^2}$$

$$= \frac{(3)(20^3)^{+}(5)(80^3)+(9)(120^3)}{(3)(20^2)^{+}(5)(80^2)+(9)(120^2)}$$

$= 111.40$ µm

APPENDIX C

DATA OF RADIAL DISTANCE

SMD (μm)	Pressure (kPa)	Distance from nozzle tip(cm)	Radial distance				
			0cm	0.5cm	1cm	1.5cm	2cm
Water	50	0.5	736	403	370	0	0
		1.0	715	433	412	429	0
		1.5	714	486	454	493	0
		2.0	698	500	474	489	515
		2.5	668	544	512	503	525
	100	0.5	735	398	410	0	0
		1.0	723	401	424	435	0
		1.5	717	401	401	425	0
		2.0	703	433	412	412	429
		2.5	644	450	433	399	421
	150	0.5	753	368	404	0	0
		1.0	735	387	413	415	0
		1.5	711	393	368	406	0
		2.0	702	414	414	430	490
		2.5	699	403	370	383	456

Table C-1: Radial distance of water

SMD (μm)	Pressure (kPa)	Distance from nozzle tip(cm)	Radial distance				
			0cm	0.5cm	1cm	1.5cm	2cm
Diesel	50	0.5	701	398	323	0	0
		1.0	698	404	380	390	0
		1.5	696	413	401	411	0
		2.0	693	420	419	429	431
		2.5	687	431	424	411	436
	100	0.5	703	363	387	0	0
		1.0	698	379	354	365	0
		1.5	697	381	360	378	0
		2.0	693	394	379	361	380
		2.5	685	401	383	390	413
	150	0.5	706	313	368	0	0
		1.0	700	329	303	318	0
		1.5	698	335	320	330	0
		2.0	693	356	339	350	350
		2.5	689	378	319	360	389

Table C-2: Radial distance of diesel

APPENDIX D

DIESEL SPRAY DEVELOPMENT

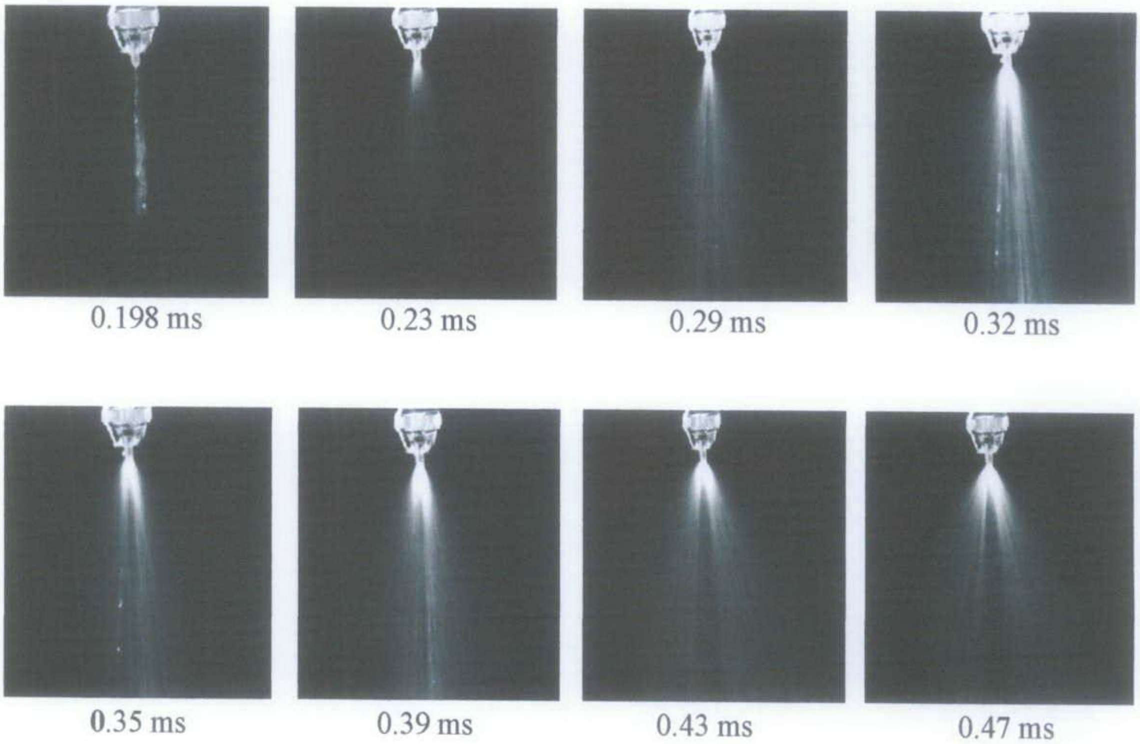


Figure D: Diesel spray development

APPENDIX E

DROP SIZE PLOT

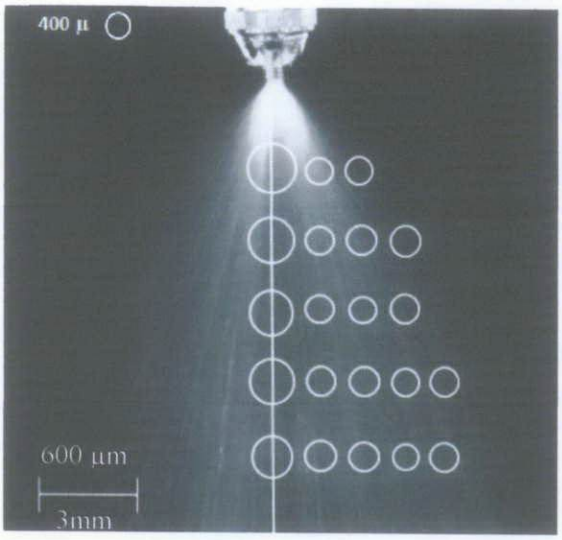


Figure E-1: Drop size plot of water at 100 kPa

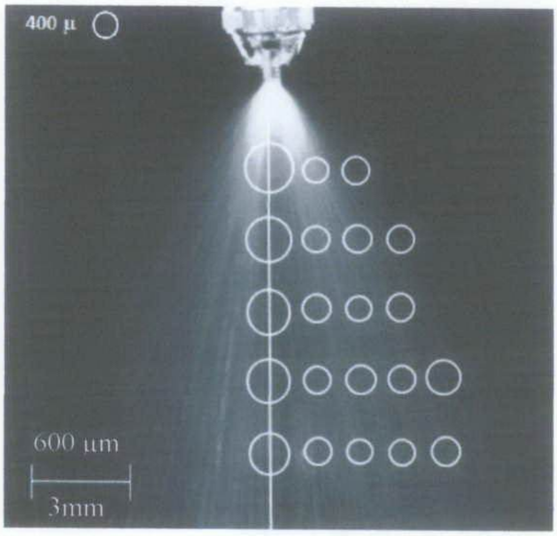


Figure E-2: Drop size plot of water at 150 kPa

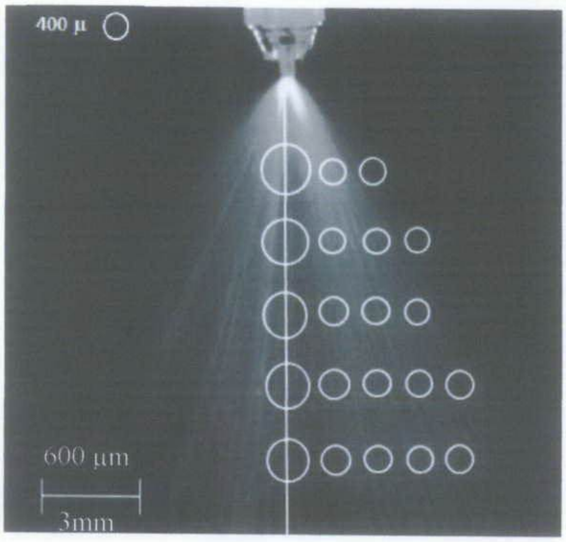


Figure E-4: Drop size plot of diesel at 100 kPa

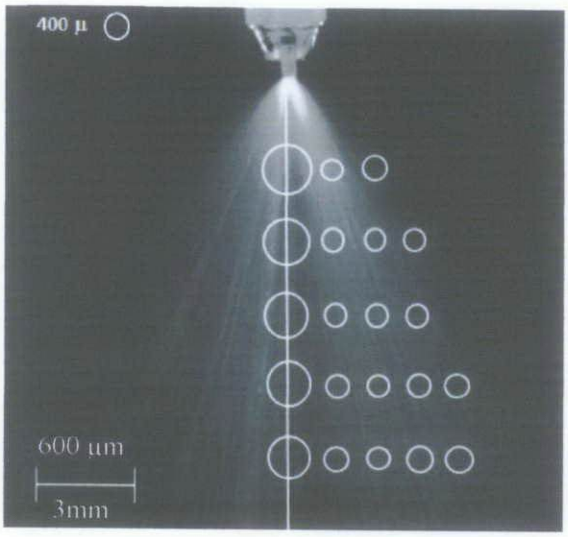


Figure E-3: Drop size plot of diesel at 150 kPa