CERTIFICATION OF APPROVAL

Fundamental Study of Sprays of Different Fluids

by

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A 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,

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UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

January 2010

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.

ANNAORAZOV REJEP

ABSTRACT

The demand for petroleum based fuel increases because of growing transportation industry. Besides petroleum fuels, there are alternative fuels, such as ethanol, biodiesel, propane and hydrogen. Alternative fuels need to be developed to meet high demands of fuel, to increase the efficiency and to make transportation more environmental friendly. This report is about fundamental study of alcohol sprays. The concept of alcohol sprays is not well understood and research on this topic needs to be done in order to gain more information and to make this information useful. This concept is applied in the combustion chamber. The purpose of this report is to represent an introduction about the project and state the problem along with the objectives and methodology used to solve the problem. The first chapter makes brief introduction to the project. The report continues with the second chapter, which is literature review. Then it is followed by methodology. Conclusion part summarizes the report content. The objective of the present research is to study characteristics of different fluid sprays which are mean velocities and droplet sizes. It also observes the break up structure of different types of different fluid sprays. The study focuses on two points, which are: characteristics of fluids and the observation of the structure of alcohol and measurement of spray angle at nozzle exit. Spray characteristics of four different fluids (methanol, ethanol, diesel and water) are analyzed by Laser Doppler Anemometry (LDA) and Phase Doppler Anemometry (PDA). Laser Doppler Anemometry (LDA) systems were used to measure droplet velocities of fluid sprays. Phase Doppler Anemometry (PDA) systems were used to measure the droplet sizes of fluid sprays. These results were compared with other fluids such as diesel, water and oil. All the results are analyzed to further understand the characteristics of four different fluid sprays. Digital camera was used in order to observe the structure of fluids and to measure the spray angles at nozzle exit. Spray angle variations were observed under different pressures for each fluid.

ACKNOWLEDGEMENT

First and foremost, I would like to praise God the Almighty for His guidance. Although difficulties occurred, His guidance has given me the chance to still accomplish a challenging Final Year Project (FYP) successfully.

My deepest appreciation goes to my supervisor, Ir. Dr. Shaharin Anwar Sulaiman who has given me endless guidance and advice in order to complete the project. He has never failed to give me support and has always been understanding despite all the errors and delays that I have made upon completing the project.

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

I would also like to thank PETRONAS for the sponsorship provided throughout these years.

Last but not least, I would like to thank my parents and family for their continuous love and support.

Thank you.

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ABBREVIATIONS

IC	Internal Combustion
LDA	Laser Doppler Anemometry
PDA	Phase Doppler Anemometry
Re	Reynolds Number
SMD	Sauter Mean Diameter
We	Weber Number

CHAPTER 1

INTRODUCTION

1.1 Background Study

Methanol and Ethanol are primary alcohol fuels. Ethanol is free from water and it is high octane alcohol which is produced by sugar or starch fermentation. Fermentation processes are used to create ethanol from grain or other renewable agricultural products. A yeast enzyme is introduced to change the sugar into ethanol. In the USA, E85 fuel, a blend of 85% ethanol and 15% unleaded gasoline (Bechtold 2002). Methanol is typically made by reforming natural gas, a fossil fuel. Alcohol fuels can be used as an alternative fuel. Alcohol was used for internal combustion engine, which was patented by Nikolaus Otto in 1877 (Philadelphia 1876) before gasoline had been discovered.

Alcohol fuel is completely renewable, because the main resource of alcohol is grain. Single acre of corn can provide as much as 300 gallons of ethanol (Tracie Close 2008). Alcohol also has high oxygen concentration, what makes cleaner-burning energy source for vehicles. Alcohol has no negative effect to environment.

Since E85 fuel uses corn as the most common source, it is considered as a renewable resource. Therefore, many major motor vehicles like Daimler Chrysler and Ford are doing their parts to manufacture flexible fuel vehicles (Bechtold 2002). Flexible-fuel vehicles have been designed to run on any mixture of these two fuels from the same tank. According to Biofuel Energy Corp (2009), “E85” is a standard ethanol motor; the number “85” represents the percentage of ethanol. Small concentration of gasoline is used to overcome cold-start issues and to produce flame.

Flexible-fuel vehicles have about 30 different types that run on E85 ethanol. There are over six million late model FFVs on the road today and many more being made every year. But majority of these vehicles run on gasoline because of small number of E85 ethanol fuel stations (Tracie Close 2008).

Table 1.1 compares the power output and Best Mean Effective Pressure (BMEP) of gasoline and alcohol engines. Alcohol has higher octane number which results in higher compression ratio. The higher latent heat leads to higher charge induction, enabling the alcohol engine to produce approximately 10% higher power output

Table 1.1: Comparison of Key Engine Factor with Ethanol and Gasoline (Govindarajan, 2008)

Parameters	Ethanol (Compression ratio = 11)	Gasoline (Compression ratio = 8.9)
Brake Hose power (1000 RPM) (3000 RPM) (5000 RPM)	 170 220 175	 130 180 150
Mean effective pressure (kg/cm^2) 1000 RPM 2000 RPM 3000 RPM 4000 RPM 5000 RPM	 10 11 11.6 11.3 10.6	 8 9.5 10.8 10.3 9.0
Brake horse power 1000 RPM 3000 RPM 5000 RPM	 50 160 240	 50 150 225

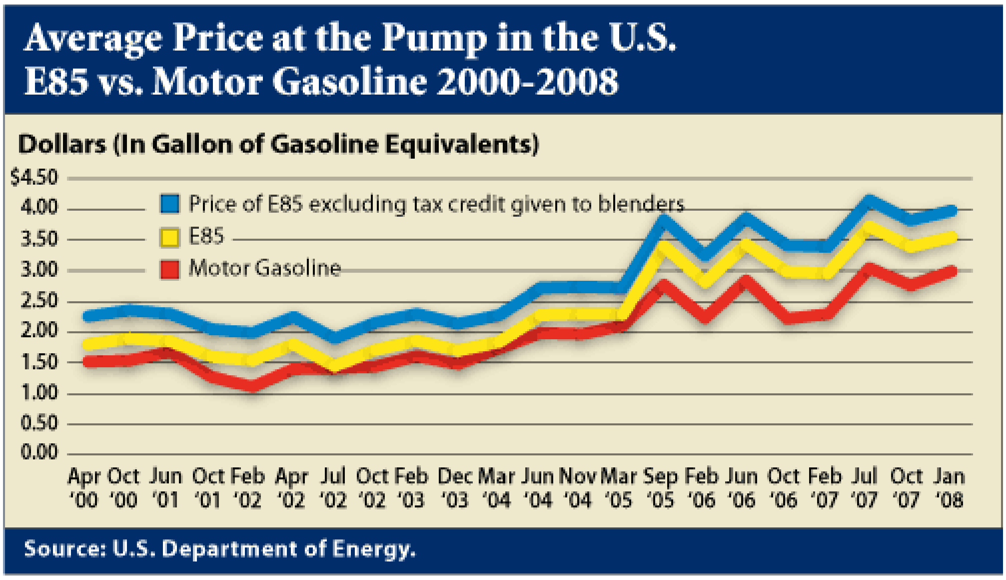

Figure 1.1: E85 versus gasoline price (U.S. Department of Energy, 2008)

The cost of alcohol based fuel has to be considered in order to use it as an alternative fuel. As shown in Figure 1.1, Ethanol fuel costs less per gallon than gasoline. On the other hand, ethanol contains less energy than traditional gasoline. The distance travelled by using gasoline will be more than the distance travelled by using E85.

Alcohol has several advantages over gasoline. It burns much cooler compared to gasoline and has less vibration. Alcohol is less flammable which will reduce the chance of fire in case of accident. It is free from air pollution, has lower evaporative emissions. Alcohol deposits no carbon in the engine which will result the longer life of engine. The characteristics mentioned above are important.

Combustion characteristics of alcohol have to be observed in order to use it as a fuel source. Flame speeds and extended flammability limits are higher in alcohols. Higher pressure can be achieved, because of great number of product moles per mole of burnt fuel. Alcohols are more resistant to engine knock.

1.2 Problem Statement

The characteristics of some fluid sprays are not well understood, although researches on the characteristics have been done. However, there is no specific study conducted on these types of fluids. Previous studies mostly focused on the transition modes of droplet break up only. The spray concept is applied in combustion theory. This project analyzes the characteristics of alcohol, diesel, water sprays to produce important results and data. These data and results are compared to each other. The study also observes the structure of alcohol sprays.

1.3 Objectives

The main objective of this project is to study the characteristics of related liquid (methanol, ethanol, diesel and water) sprays; which are droplet sizes and mean velocities. The results of those liquids are compared to each other.

1.4 Scope of Work

The present work covers the study of characteristics, such as spray velocity, droplet size of sprays and the break up structure of different fluid sprays. Spray characteristics are important in relation with combustion process in engine. The results and data of different fluid sprays are compared to each other and discussed accordingly.

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. Digital camera is used in order to study the structure of the break up zone of sprays. The variables such as pressure spray angle, radial distance, penetration distance and liquid types are taken into consideration.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 Alcohol and Gasoline Fuels

Gasoline is a mixture of hydrocarbon substances and it can occur in different phases. Hydrocarbon fuels are obtained from refined crude oil. Gasoline is a combination of benzene, toluene, octane and other aromatics.

Alcohols have to be manufactured by fermentation or distillation processes in order to use it as a fuel. Alcohol is more expensive than gasoline because of the steps involved in manufacturing. But gasoline prices are increasing significantly which will result in a higher market for alternative fuels.

Alcohol contains oxygen, but gasoline does not. The first practical internal combustion engine was patented by Nikolaus Otto in 1877. The company "Ford" produced vehicles from 1928 to 1931 which was designed to use several kinds of fuels, including alcohol based fuels. By the time petroleum industry gained power and farm-based alcohol producers failed to compete with them.

Alcohol has engine fuel characteristics. High octane rating of alcohols prevents the engine detonation. It also burns cleanly. An engine which uses alcohol runs cooler than gasoline powered engine. This increases engine life and decreases the chance of overheating.

The advantages of alcohols fuels are (Beam & Ganesan, 2004):

a. The sources can be obtained from both manufactured and natural.
b. Its high octane fuel with anti knock index numbers of over 100 allows the engine to run more efficient by using higher compression ratios.
c. The burning process in the chamber produces less overall emissions compared to gasoline.

d. More moles of exhaust gases are formed when alcohols are burned. Thus, it will give higher pressure and more power in the expansion stroke.
e. Alcohol has high latent heat of vaporization, which results in a cooler intake process. This raises the volumetric efficiency of the engine and reduces the required work input in the compression stroke.
f. Alcohol fuels have low sulphur content.

Table 2.1: Sample Anhydrous Ethanol Specification (Govindarajan, 2008)

TEST	***SPECIFICATION***
Description/Appearance	*A clear, mobile, volatile liquid*
Colour	*Colourless*
Odour	*Characteristic and spiritous*
Ignition	*Flammable, burns with a blue smokeless flame*
Solubility	*Must comply with pharmacopoeia*
Clarity	*The solution is clear*
Alcoholmetric test (@ 20 °C)	*Not less than 99.5 v/v*
Acidity or Alkalinity	*Complies with pharmacopoeia*
Reducing Substances	*Complies with pharmacopoeia*
Methanol higher alcohols and esters	*Complies with pharmacopoeia*
Benzene and other UV light absorbing substances	*Not more than 5 ppm*
Heavy Metals	*Complies with pharmacopoeia*
Residue on evaporation	*Complies with pharmacopoeia*
Density @ 20 °C	*788.16 to 791.20 kg/cubic metre*
Aldehydes	*Not more than 10 ppm*

Methanol is the simplest of a long series of organic compounds called alcohols; its molecular formula is CH_3OH (Cetiner Engineering Corporation, 2010). The modern method of preparing methanol is based on the direct combination of carbon monoxide gas and hydrogen in the presence of a catalyst at elevated temperatures and pressures.

Pure methanol is an important material in chemical synthesis. Its derivatives are used in great quantities for building up a vast number of compounds, among them many important synthetic dyestuffs, resins, drugs, and perfumes. Large quantities are converted to dimethylaniline for dyestuffs and to formaldehyde for synthetic resins. It is also used in automotive antifreezes, in rocket fuels, and as a general solvent. Methanol is also a high-octane, clean-burning fuel that is a potentially important substitute for gasoline in automotive vehicles.

Methanol is a colorless liquid, completely miscible with water and organic solvents and is very hygroscopic. It boils at 64.96° C (148.93° F) and solidifies at -93.9° C (-137° F). It forms explosive mixtures with air and burns with a nonluminous flame. It is a violent poison; drinking mixtures containing methanol has caused many cases of blindness or death. Methanol has a settled odor. Methanol is a potent nerve poison.

Table 2.2: Physical properties of methanol (Cetiner Engineering Corporation,2009)

Melting Point :	-97.7 ^{0}C
Boiling Point :	65 ^{0}C
Relative Density :	0.79
Formula:	CH_3OH
Molecular weight:	32.042 kg/kmol
Heat of Formation :	201.3 MJ/kmol
Gibbs Free Energy :	162.62 MJ/kmol
Freezing point:	-97.7 °C
Boiling point:	64.6 °C (at atmospheric pressure)
Critical temperature :	512.6 K
Critical pressure :	81 bar abs
Critical volume :	0.118 m³/kmol

Table 2.3: Basic data for Ethanol-Water Binary mix (Ackland, 2007)

Value	Units	Ethanol	Water	Reference
Liquid density	g/mL	0.789	1	Perry 3.2
Vapour density @ 90C	g/mL	0.0015	0.001	PV=nRT
Molecular weight	g/mol	46.0634	18.0152	Perry 3.2
Liquid Heat Capacity	J/gK	2.845	4.184	Perry 3-183
Heat of Vapourisation	J/g	855	2260	Perry 3-178
Vapour Pressure @ 90C	torr	1187	525	Perry 13-4
Liquid Viscosity	kg/ms	0.00037	0.00032	Perry 3-252
Vapour Viscosity	kg/ms	108×10^{-7}	125×10^{-7}	Perry 3-311
Surface Tension @ 20C	mN/m	22.39	72.75	Kay & Laby
Vapour Diffusivity ethanol/air	m2/s	102×10^{-7}		Perry 3-319
Liquid Diffusivity ethanol/water	m2/s	128×10^{-11}		Perry 3-319

2.2 Combustion Characteristics of Alcohols

The combustion characteristics of alcohols and hydrocarbons differ from each other. Alcohols have extended flammability limits and higher flame limits. Alcohols also produce higher pressure. They can mix with the water in any proportions because of their polar nature of OH group. Alcohols are less volatile and have high boiling point and high flash point.

In order to start the combustion of alcohol there need to be air. Combustion can be initiated by flame, spark or can be ignited by application of energy by means of heat and pressure. The energy level of the mixture reaches sufficient for ignition. The high latent heat of vaporization of alcohols cools the air entering the combustion chamber of the engine. This results in increase of air density and mass flow, which will lead to increase of volumetric efficiency and reduce compression temperature. As a result this will improve the thermal efficiency by 10%.

Alcohols have high flame speed, which gives earlier energy release in the power stroke and increase power. Alcohol contains oxygen which depresses the heating value of the fuel when compared to hydrocarbon fuels. Cold starting is very difficult with neat alcohols, because they have high heat of vaporization and constant boiling point. This problem can be solved by blending alcohol with gasoline. The boiling point of absolute alcohol is 78.3 ℃ (O'Leary, 2000). Gasoline has high vapour pressure and it is high volatile, so they are used for cold start.

2.3 Characteristics of Diesel

Diesel fuel is a petroleum based fuel similar to gasoline. But there is a difference between them. Gasoline and oxygen mixture is ignited in the engine cylinder by a spark from the spark plug, but diesel fuel is ignited by compression Diesel fuel is heavier than gasoline, it consists of hydrocarbons that range from C10 to C24 (Tallberg, 2003). Diesel is also called as petroleum diesel or fossil diesel and it is produced from the fractional distillation of crude oil between 200 °C (392 °F) and 350 °C (662 °F) at atmospheric pressure (Wikipedia, 2009).

Table 2.4: Typical diesel fuel properties (Northrop Grumman, 2010)

Test	**Minimum**	**Average**	**Maximum**
Gravity, °API	30.9	33.7	38
Flash point, °F	145	168	156
Color, ASTM	0		L2.0
Viscosity, kinematic, cSt at 104° F	2.3	2.76	3.08
Cloud point, °F	-4		26
Pour point, °F	-15		10
Sulfur content, wt%	0.001	0.036	0.041
Aniline point, °F	126		128
Carbon residue on 10%, wt%	0	0.0.55	0.07
Ash, wt%	0	0.001	0.001
Cetane number	40.6	44.1	52
Cetane index	39.1	43	44.5
Aromatics, vol%	19.5	33	39.2
IBP	333	365	351
10% recovered	386	423	453
50% recovered	464	512	530
90% recovered	591	614	616
End Point	643	664	689

2.4 Characteristics of Water

Water is important liquid in life. Water is used by human, animal, plant and it indispensable resource for the economy. Water also plays a fundamental role in the climate regulation cycle. Pure water is colourless and odourless. Chemical formula for the water is H_2O. One atom of oxygen is bound to the two atoms of hydrogen. Positively charged hydrogen atoms attract negatively charged oxygen atom. Water molecules attracts each other, they tend to clump together. Therefore water drops are, in fact, drops. If there were no gravity forces, a drop of water would be in a spherical shape (Wikipedia, 2010). Water has three stages; solid, liquid and gas. Water is universal solvent, because it dissolves more substances than any other liquid. Water has a neutral pH, which means; pure water is neither acidic nor basic. Water changes its pH when substances are dissolved in it. Water conducts heat more easily than any liquid except mercury. That is why large bodies of liquid water like lakes and oceans have essentially a uniform vertical temperature profile. (Pidwirny, 2006).

2.5 Fundamentals of Sprays

A spray is a dispersion of droplets with sufficient momentum to penetrate the surrounding medium. Generally nozzle is used as a spray producing device 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. The characteristics of a spray are summarized by its shape, pattern and some measure of droplet sizes.

There are two types of atomization. The first one is primary atomization, 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)

In jet break up fluid viscosity, surface tension, gas motion and inertia are important factors and need to be considered. It is observed that the surface energy of a uniform circular cylindrical jet is not the minimum attainable for a given jet volume (Azzopardi and Hutchinson, 1983). Rayleigh (1878) in his studies neglected the effects of gravity and ambient gas; he showed that the mechanism of the jet breakup is the hydrodynamic instability caused by the surface tension. Weber and Chandrasekhar discovered that the viscosity has only a stabilizing effect that reduces the breakup rate and increases the drop size.

When jets wave grow on thin sheets produced by some atomizers, they grow and drops precursors. The process starts from sheet to ligament and then finally to drops.

The Weber (*We*) number is a dimensionless value useful for analyzing fluid flows where there is an interface between two different fluids (The Engineering ToolBox 2005). Drops are subjected to aerodynamic forces are unstable if $We > We_{critical}$. According to Lane (1951), $We_{critical}$ is usually taken as 12. This is also called as secondary atomization.

2.6 Droplet Size

The drop size is an important parameter as it is normally used for the correlation of the combustion behaviour. Droplet sizes are different for each fluid. 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:

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

where

n_i = the number of droplets within a range of is centred on diameter D_i

k= the number of ranges.

SMD is an indicator of the degree of atomization produced by injector. Besides that, surface mean diameter or D_{20} is also used to represent an average diameter with a surface area equal to the mean surface area of all droplets. This is given by:

$$D_{20} = \sqrt{\frac{\sum_{i=1}^{k} n_i D_i^2}{\sum n_i}} \tag{2.2}$$

2.7 Droplet Break up

The objective of the liquid atomization is to produce small drops. When energy is imparted to liquid, it will produce smaller drops. These smaller drops will result in larger specific area. The characteristics of droplet break up depend on non dimensional parameters such as Weber (*We*) and Reynolds (*Re*).

According to Lane (1951, 1949, 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 2.1). 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.

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 2.1 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:

- For bag break up type, it 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.

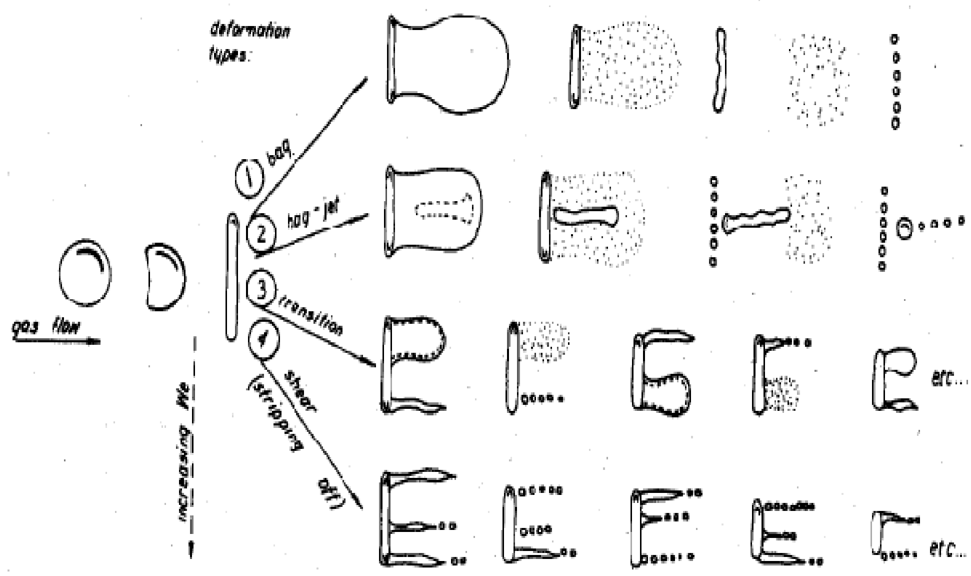

Figure 2.1: Illustration of different possible transition modes of droplet break up (Krzeczkowski, 1980)

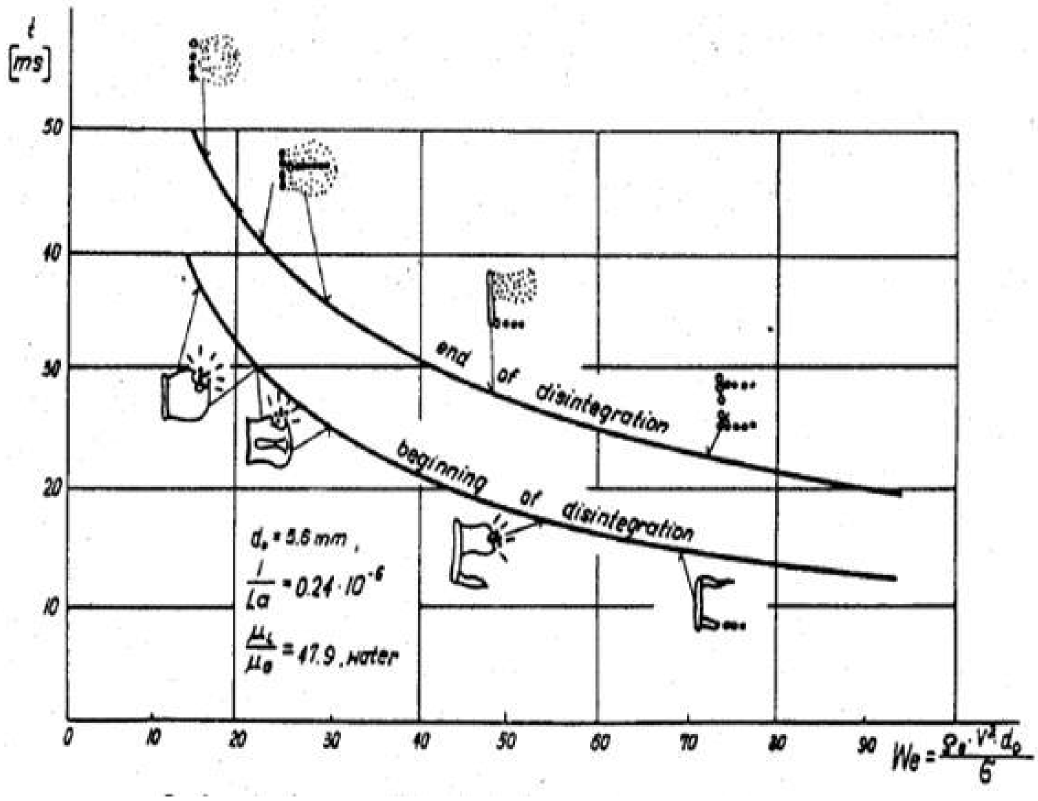

Figure 2.2: Graph of break up duration versus Weber number for water droplets (beginning and the end of disintegration), (Krzeczkowski, 1980)

Based from the findings in the literature review, studies have been done by Krzeczkowski to investigate on the effect of fluid viscosity on the alcohols only. Most of the studies are mostly on water. Although a study on alcohols has been done, it is only focusing on one main variable which is the fluid viscosity. Thus, a break up study in this project will have different variables such as pressure for evaluation.

At Universiti Technologi PETRONAS, Mohd. Shukri (2009) did a research on alcohol sprays. She studied the characteristics of alcohol sprays and observed the structure of sprays. In her experiment she varied the parameters of pressure, penetration distance and radial distance of alcohol sprays. She analyzed the alcohol sprays at 50 kPa, 100 kPa and 150 kPa. She observed that at 100 kPa, downward velocities are much more reliable compared to others. The downward velocities of alcohol sprays did not vary much witch change of radial distance. She observed that at higher pressures lesser droplets can be captured by high speed camera. Spray boundary decreased with increase of pressure

2.8 Laser Doppler Anemometry and Phase Doppler Anemometry

The technology used to measure velocities of flows is known as Laser Doppler Anemometry (LDA). 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.

A 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 (Tampere University of Technology, 2010).

Phase Doppler Anemometry is used to measure droplet size and velocity distribution in a jet. The laser beams from the transmitting optics cross at the focal point of the front lens. The receiving optics (for size measurements) is also looking to the same focal point at certain angle. This angle is very critical since the scattered light intensity and polarization depend strongly on the viewing angle and the refractive indexes of the continuous and dispersed phase. The size measurement is based on the phase difference between the signals received by the two detectors. The placement of the two sensors is illustrated in Figure 2.3 (Tampere University of Technology, 2010).

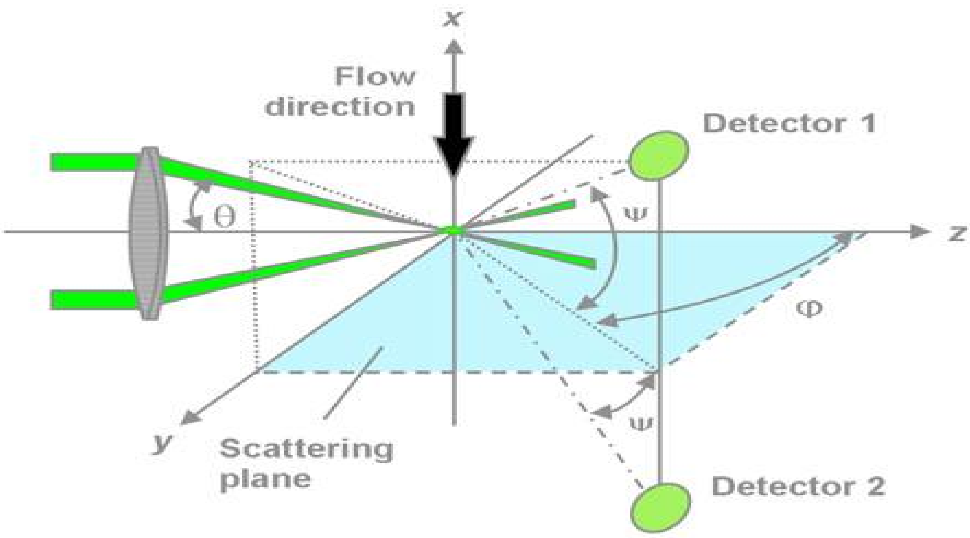

Figure 2.3: Optical setup of a PDA

Figure 2.4 shows the relationship between the droplet size and the phase difference. The curves show non-linearity, which can be explained by the Mie-scattering theory. PDA technique assumes that the particles are spherical, but it can also be used for other particle shapes.

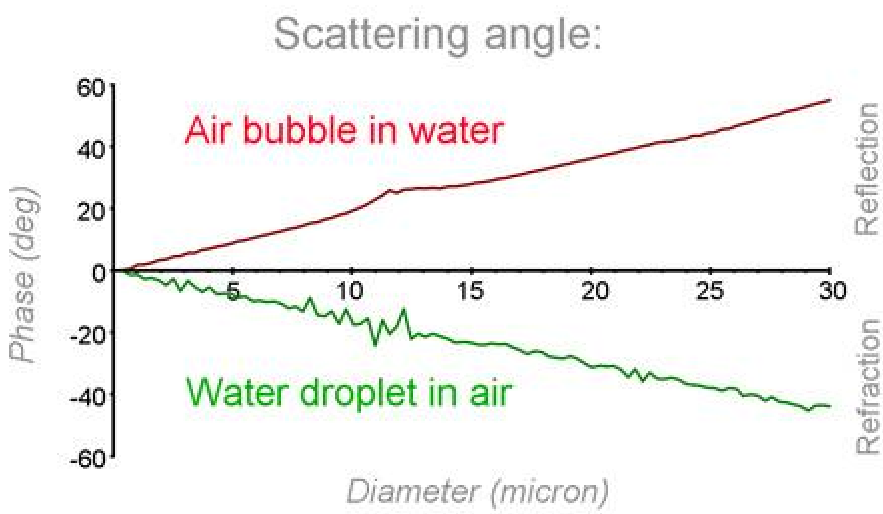

Figure 2.4: Droplet size dependence from the phase difference

CHAPTER 3: METHODOLOGY/ PROJECT WORK

3.1 Research Methodology

This project starts with background research on the topic of Fundamental study of alcohol sprays. Background study plays an important role. Preliminary report has been prepared and highlighted the findings of the research. This is important in determining the experiments to be done during the study of fluid sprays. Progress report was written about the progress of project. Experiments have been planned and scheduled to study and to make comparison between different fluid sprays. The results experiments are discussed and analyzed. Introduction and familiarization to the Laser Doppler Anemometry (LDA) and Phase Doppler Anemometry (PDA) equipment have been done. The discussion about safety issues and experiment procedure has been done with laboratory technician. Any problems that may occur regarding the experiments in the future can be eliminated and discussed in this stage. If there is any problem, steps taken should be revised again.

3.2 Project Scheduling

In the Gantt charts shown in Table 3.1 and 3.2, all the activities are planned thoroughly.

Table 3.1: Gantt chart for Semester I

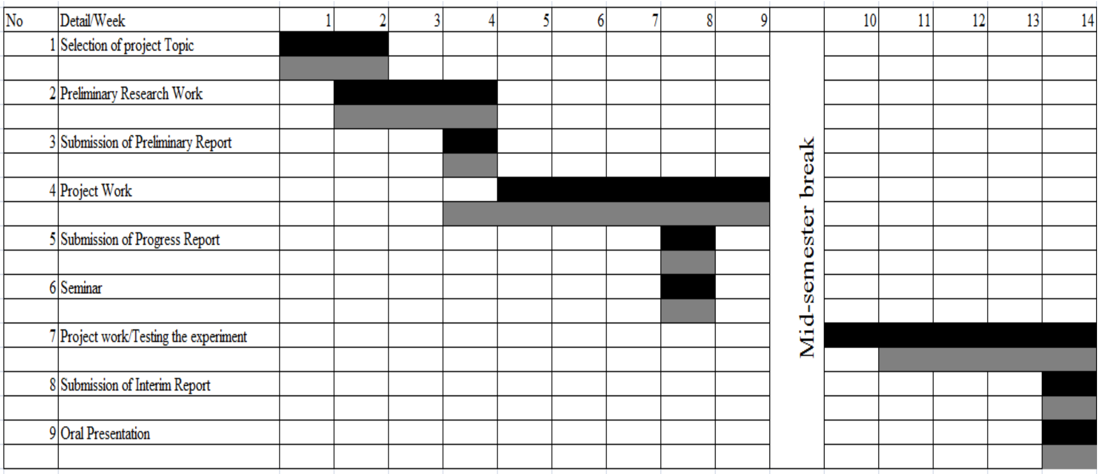

Table 3.2: Gantt chart for Semester II

No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Project work continues								Mid-semester break							
2	Submission of Progress Report 1				*											
3	Project work continues															
4	Submission of Progrss Report 2									*						
5	Seminar									*						
6	Project work continues															
7	Poster exhibition															
8	Submission of Dissertation Final Draft															*
9	Oral Presentation									During study week						
10	Submission of Dissertation Hard bound															

3.3 Tools/ Equipments

For this project, experiments have been planned to study the characteristics of alcohol sprays. To study characteristics of those fluid sprays, Laser Doppler Anemometry (LDA) and Phase Doppler Anemometry (PDA) have been used. LDA has been used to measure mean velocity of the droplets and direction while PDA has been used to measure droplets size. Digital camera was used to take pictures of fluid sprays in order to measure the spray angle. Other tools include spray nozzle and lighting.

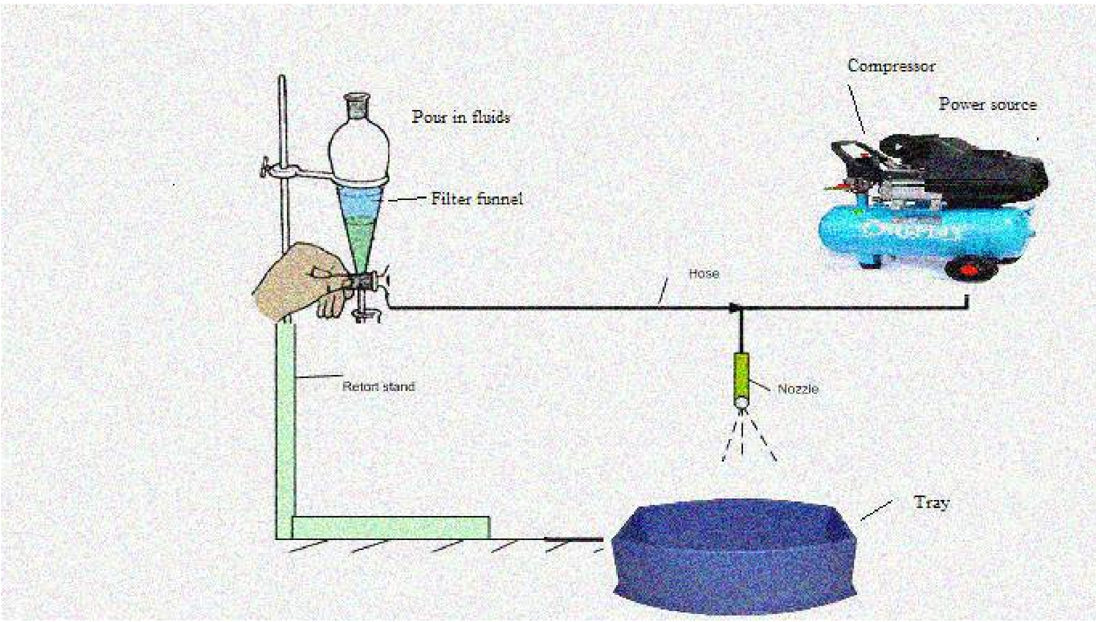

Figure 3.1: Diagram for the experiment

3.3.1 LDA/PDA Systems

So far, the research on this project has been made. The LDA/ PDA system has been used. Spray characteristics are analyzed by using Laser Doppler Anemometry for velocity measurements and Phase Doppler Anemometry for droplet size measurements. These systems assisted to analyze spray characteristics in greater detail. Digital camera has been used to study the structure of the break up zone of sprays and to measure spray angle.

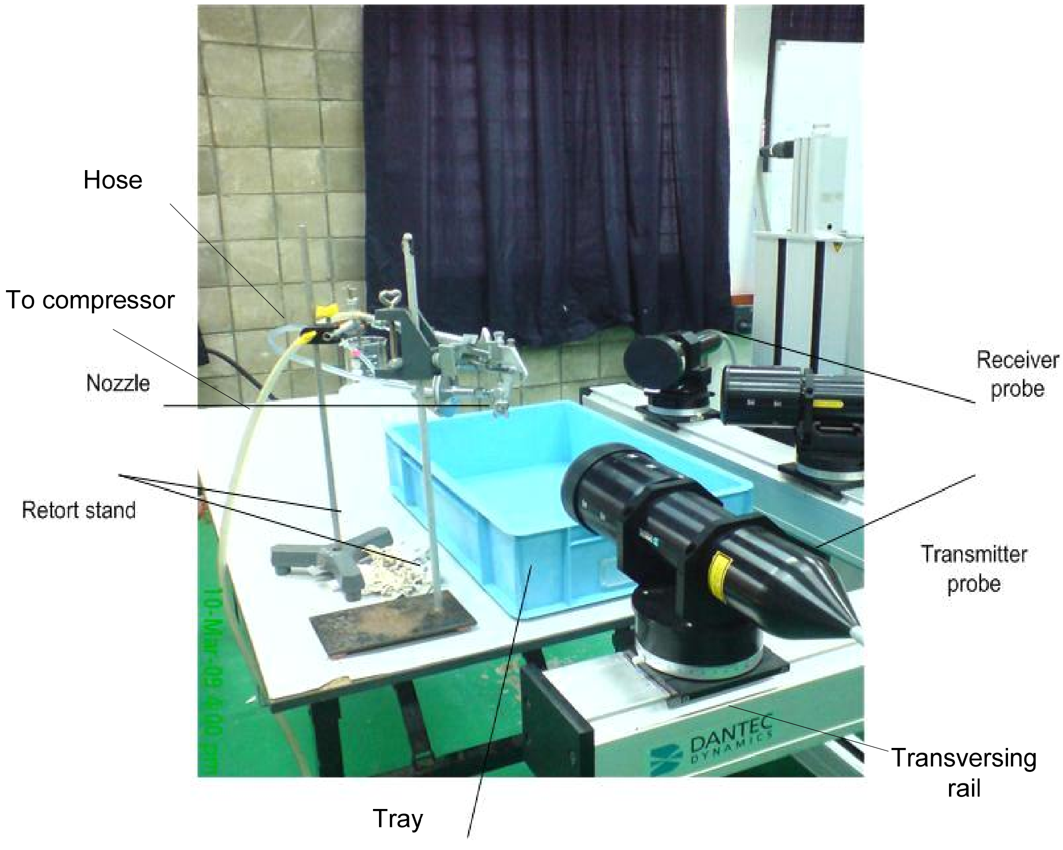

Figure 3.2: Arrangement of LDA/PDA Systems in the lab.

The experiment will vary pressure, location, and liquid types in order to understand alcohols' characteristics. Figure 3.4 is the LDA/PDA Systems diagram.

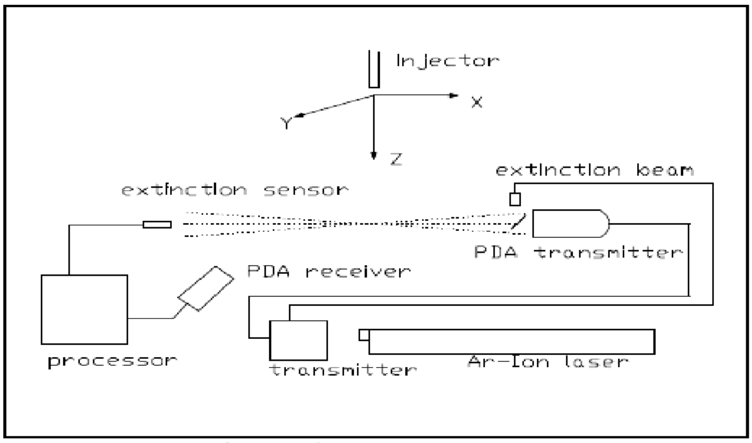

Figure 3.3: Experimental set-up (Palacios et al, 2002)

Based on Figure 3.3, 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 3.4. This is when the diameter and mean velocity of the particle is measured.

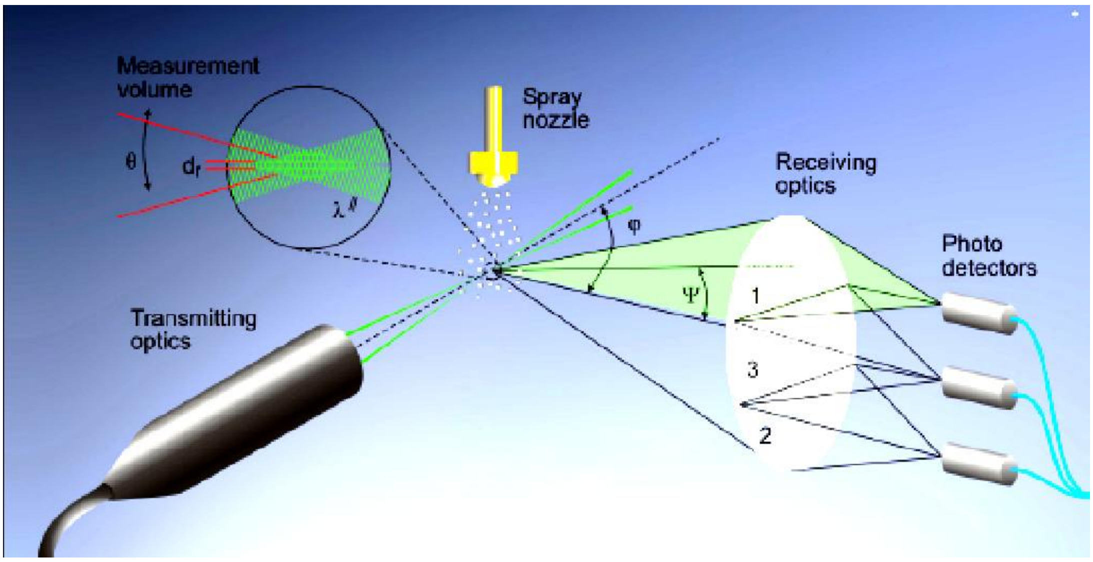

Figure 3.4: Picture showing intersection point for volume measurement

For the experiments, pressure, penetration distance, radial distance and fluid types are varied. The penetration distance and radial distance are varied as shown in Figure 3.5.

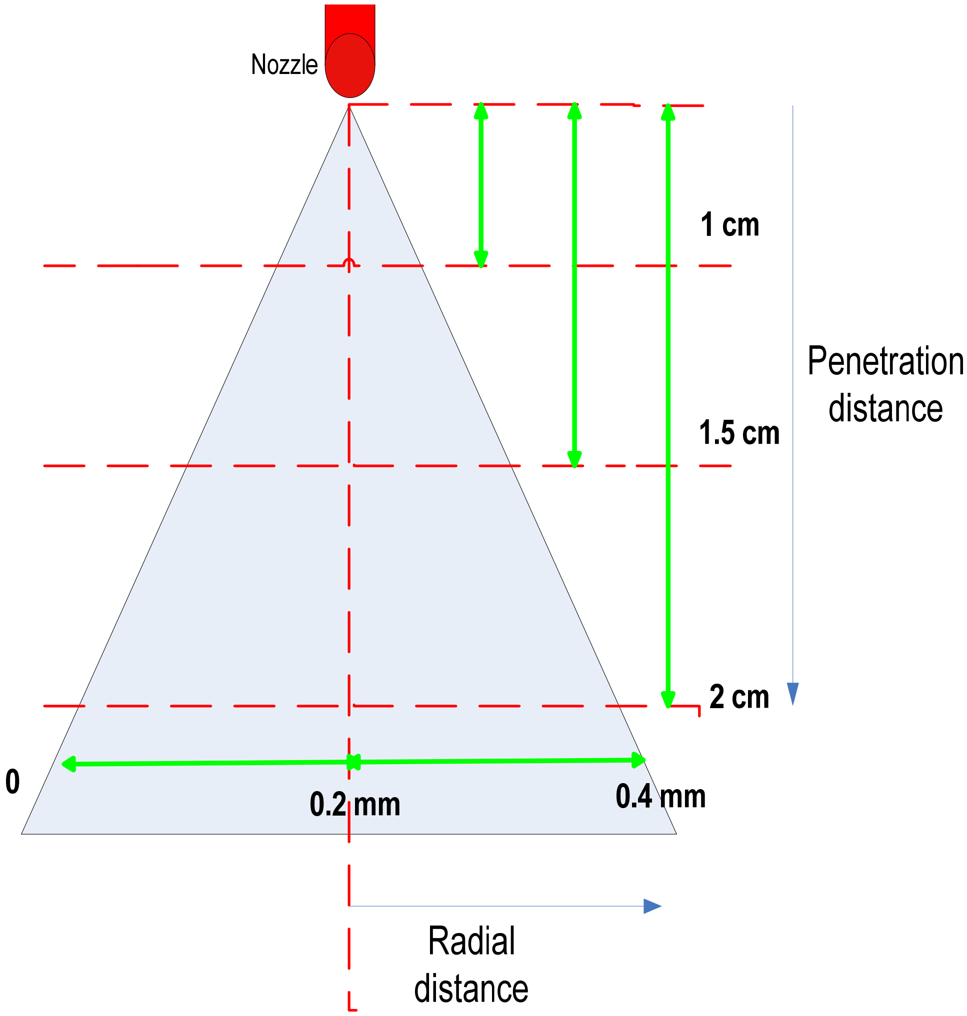

Figure 3.5: Diagram showing penetration distance and radial distance of spray area

Laser Doppler Anemometry (LDA) is a non-intrusive optical technique used to measure velocity and turbulence at specific points in gas or fluid flows. Applications include measurements of free flows around road vehicles, aircraft and ships, and internal flows in pumps, mixers, turbines and engines (Dantec Dynamics).

Principles:

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_{hift}. 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.

Principles:

A. The measurements are performed at the intersection of two laser beams, where there is an interference fringe pattern of alternating light and dark planes.
B. 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
C. Each detector converts the optical signal into a Doppler burst with a frequency linearly proportional to the particle velocity.
D. The processor measures the phase difference between the Doppler signals from different detectors. This is a direct measure of the particle diameter.
E. 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; and

3.3.2 Scale of Industrial Spraying

The development construction and supply of atomizers and their associated spraying equipment tend to form a distinct industry. That is, for example, manufacturers of gas turbines, diesel engines, boilers (all combustion), vehicles (paint spraying), steel, etc. would normally purchase the spraying equipment used in their product (or in plant making their products) from specialist manufacturers. There are perhaps less than one dozen international companies worldwide who each manufacture a wide range of atomizer types for use in a wide range of processes and some of those companies are labeled in Table 4.1. Even so, none of these companies attempts to produce off-the shelf atomizers suitable for every process, although generally atomizers and associated spraying equipment can be designed and constructed to order by such firms. There is a larger number of atomizer and spraying equipment manufacturers who concentrate on only one field, for example agricultural or paint spraying, molten metal atomizers, gas turbine or diesel injectors, etc. again, a selection of these manufacturers is listed in Table 3.3.

Atomizers are manufactured and sold either for new plant and equipment, or as replacement parts, the ratio of the two markets depending greatly on the particular spraying process. There is a tremendous price range depending upon the complexity of the atomizer and the volume of the market. For example, a relatively straightforward two-fluid atomizer designed for a relatively low volume market, such as a specialized spray drying applications, may be several times the cost of a high volume, more complex injector, for the relatively high volume diesel engine market. The catalogues of these various manufacturers are generally valuable sources of information and, increasingly, these catalogues contain useful information an atomizer performance, such as droplet sizes, which are essential when selecting atomizers for particular applications.

There are many materials and methods of manufacture of atomizers, and a selection of these is given in Table 3.4. As well as this selection of relatively mass-produced equipment, there is an increasing interest in the utilization of micro-machining technology. This may be particularly applicable where precise very small orifices and channels are required which may be the case in, for example, medical applications. Finally mention should be made of the scope for using rapid-prototyping techniques when developing atomizers. This is particularly relevant, because atomizer performance cannot generally be predicted with reliability for new designs, so that a rapid build-and-test procedure is of great value (Bendig et al 2002).

Table 3.3: Examples of atomizer and spraying equipment manufacturers (Bending et al 2002).

Company	**Country**	**Applications**
Leecher GmbH	Germany and international	Wide range
Spraying Systems Co.	USA and international	Wide range
Delavan	USA/UK	Gas turbine, Wide range
Bosch GmbH	Germany	Fuel injection
Hamworthy Combustion Engineering Ltd	UK	Combustion
Delphi/Lucas	USA/UK	Fuel injection
DeVilbiss	UK and international	Paint, Medical and others
Lurmark Ltd	UK	Agriculture
Parker Hannifin	USA	Combustion
Niro Atomizer	Denmark	Spray drying
Precision Valve	USA and international	Household aerosols
Schlick GmbH	Germany	Wide range

Table 3.4: Nozzles, materials and production methods (Bending L, Nasr G.G and Yule A.J 2002).

Nozzle	Application	Material	Manufacturing method
Metal nozzle: (All types)	General industry, agriculture	brass, stainless steel, other metals	Machining (drilling, turning, cutting)
Plastic nozzles: (flat jet, full cone, hollow cone, accessories)	Agriculture, surface treatment, general industry	Plastic (PP,POM,PVC,PVDF)	Injection moulding
Ceramic nozzles, small sizes: flat jet, hollow cone	Agriculture, spray drying, general industry	Oxide ceramics, Aluminium oxide, Zircon oxide	Powder injection moulding (PIM, CIM)
Ceramic nozzles, larges sizes: helix hollow cone, full cone	FGD plants, process engineering, chemical industry	Silicon carbide reaction or nitrude bonded	Casting, slip casting
Hard metal nozzles: flat jet, solid jet, hollow cone	Descaling high pressure applications, spray drying	Tungsten carbide	Isostatic pressing, grinding eroding

3.3.3 Spray Nozzle

The project uses high pressure spray nozzle F-75s, which is manufactured by Akoka and the characteristics are listed below:

(a) Operating pressure between 3 to 5 bar
(b) Air inlet is 6.35 mm diameter
(c) Nozzle outlet is 1.3 mm diameter
(d) Full cone spray nozzle

3.4 Experiment to Measure Spray Angle

This experiment uses digital camera in order to capture the picture of spray development. The pictures are then evaluated. The experiment varies pressures (50 kPa, 100 kPa and 150 kPa) and liquid types in order to understand spray characteristics. By taking pictures, the spray angle can be observed. The lights are switched off and the spray background set to dark colour in order to make picture clearer. The pictures were taken several times and the best pictures were selected to measure the spray angles. Figure 3.6 shows sample spray picture from the experiment:

Figure 3.6: Sample water spray picture from the experiment

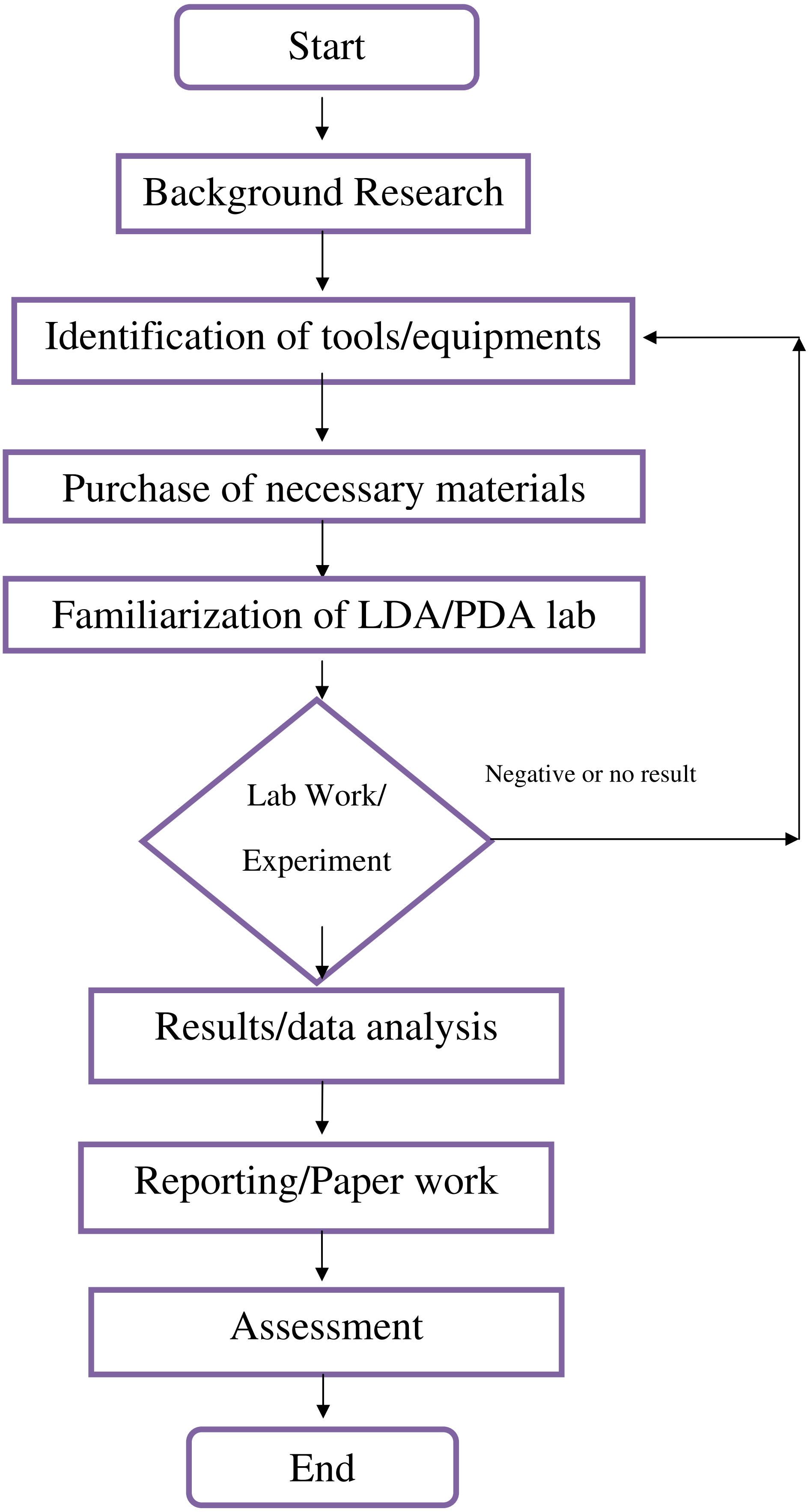

Figure 3.7: Flow of project activities

Table 3.5: Table of experiment plan for LDA/PDA Systems

<table>
<tr><th rowspan="2">Fluids at 0.5 bar</th><th rowspan="2">Measurements</th><th>Trial</th><th colspan="3">Penetration Distance</th><th colspan="3">Radial Distance</th></tr>
<tr><th></th><th>1cm</th><th>1.5 cm</th><th>2cm</th><th>0 mm</th><th>0.2 mm</th><th>0.4 mm</th></tr>
<tr><td rowspan="12">Methanol</td><td rowspan="4">Vertical velocity</td><td>R1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R3</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td rowspan="4">Horizontal velocity</td><td>R1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R3</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Average</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="4">SMD</td><td>R1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R3</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Average</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="12">Ethanol</td><td rowspan="4">Vertical velocity</td><td>R1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R3</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Average</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="4">Horizontal velocity</td><td>R1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td>R3</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Average</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="4">SMD</td><td>R1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R3</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Average</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="12">Diesel</td><td rowspan="4">Vertical velocity</td><td>R1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R3</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Average</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="4">Horizontal velocity</td><td>R1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td>Average</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="4">SMD</td><td>R1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R3</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Average</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="12">Water</td><td rowspan="4">Vertical velocity</td><td>R1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R3</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Average</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="4">Horizontal velocity</td><td>R1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R3</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Average</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="4">SMD</td><td>R1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>R3</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Average</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

CHAPTER 4

RESULT AND DISCUSSION

4.1 Experiment to Determine Characteristics of Fluids

The experiment on water sprays was conducted to determine the characteristics of water sprays only. In this experiment LDA/PDA systems were used. Shown in Figure 4.1 is a set of results of water sprays at 50 kPa, obtained from the LDA/PDA measurements. The results provide information on data count, downward velocity, horizontal velocity, and diameter of droplets. In order to interpret the values, data count was multiplied by 2000. This is done for ease of interpretation. Average value of downward velocity and horizontal velocity were calculated. The SMD values were calculated using Equation (2.1).

Figure 4.1 shows sample graph generated from LDA/PDA measurements. For each experiment, three histograms representing the downward velocity, horizontal velocity and SMD for each fluid at specific penetration distance, radial distance and pressure were presented.

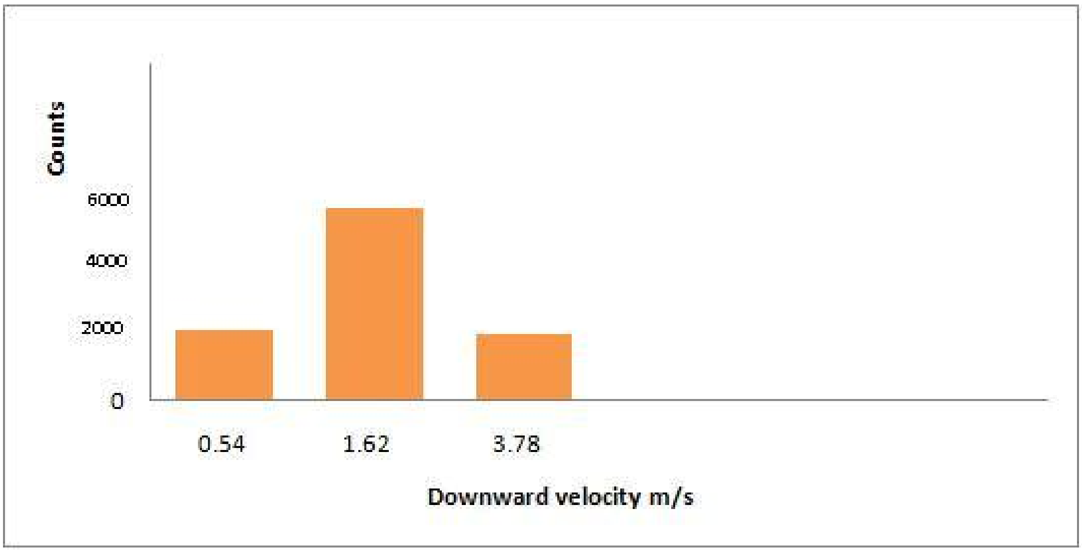

Figure 4.1: Graph of downward velocity generated from LDA/PDA mesaurements for ethanol at 50 kPa.

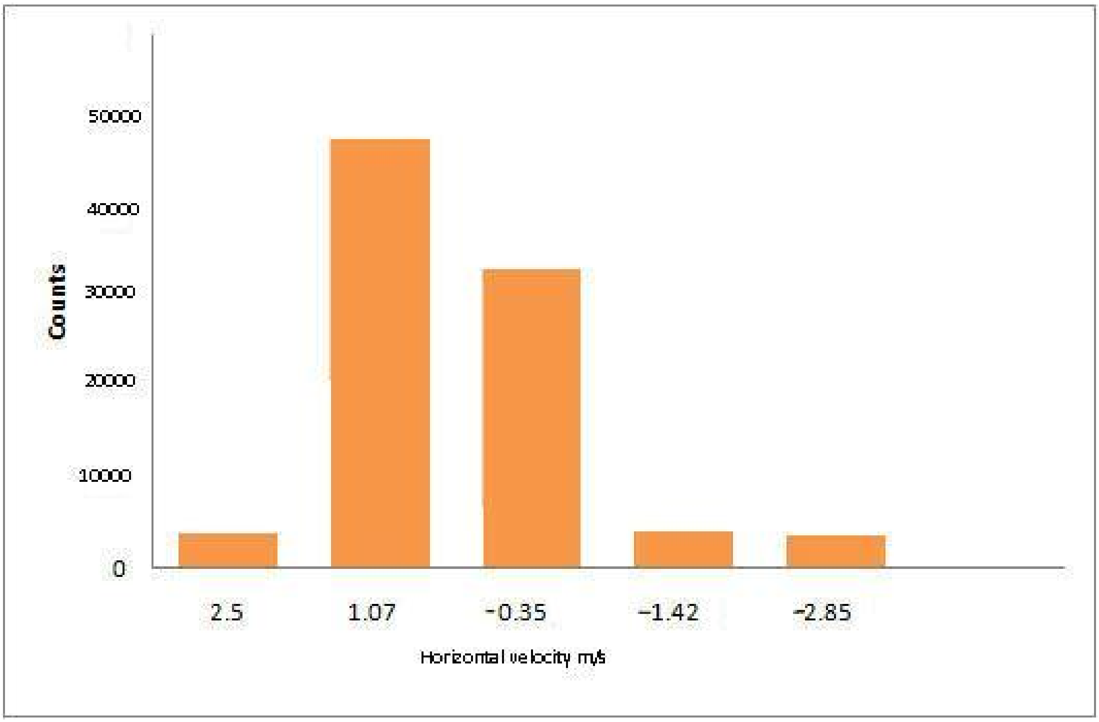

Figure 4.2: Graph horizontal velocity generated from LDA/PDA mesaurements for ethanol at 50 kPa.

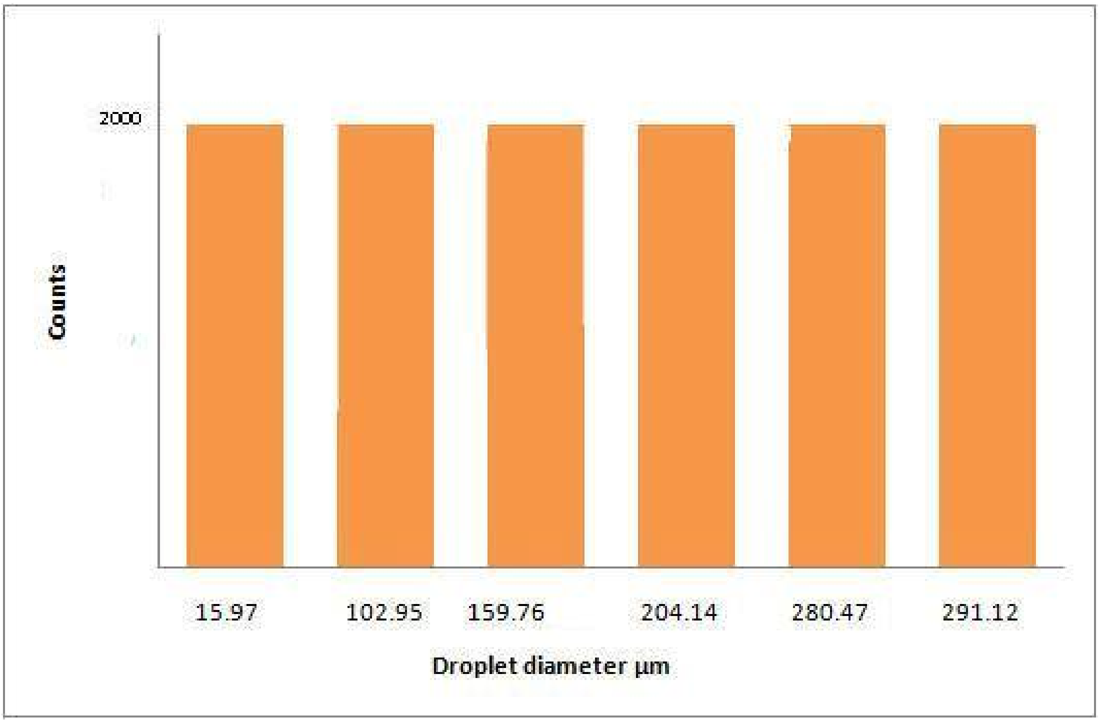

Figure 4.3: Graph of SMD generated from LDA/PDA mesaurements for ethanol at 50 kPa.

Table 4.1: Tabulated data from LDA/PDA system

Fluids at 50 kPa	Measurements	Trial	Penetration Distance			Radial Distance		
			1cm	1.5 cm	2cm	0 mm	0.2 mm	0.4 mm
Methanol	Vertical velocity	R1	1.837	1.2838	1.622	1.6222	2.378	2.583
	Horizontal velocity	R1	0.289	0.212	0.732	0.732	0.192	0.9687
	SMD	R1	250.210	271.410	257.600	257.600	246.260	219.780
Ethanol	Vertical velocity	R1	3.423	1.892	2.703	2.703	3.243	2.703
	Horizontal velocity	R1	-0.345	0.345	-1.103	-1.103	-0.690	0.276
	SMD	R1	238.770	246.270	291.130	291.130	236.100	208.400
Diesel	Vertical velocity	R1	2.892	3.033	3.205	3.205	2.669	3.977
	Horizontal velocity	R1	-0.255	-0.332	-0.221	-0.221	-0.239	-0.570
	SMD	R1	241.680	229.020	231.740	231.740	239.760	264.970
Water	Vertical velocity	R1	4.114	4.156	2.603	2.603	2.353	2.897
	Horizontal velocity	R1	-2.203	-0.341	-0.242	-0.242	-0.109	-0.156
	SMD	R1	213.830	247.870	242.020	242.020	249.810	253.850

Table 4.1 shows the data for all fluids. The experiment was done by using LDA/PDA systems. Penetration distance were varied from the nozzle below in vertical direction as 1 cm, 1.5 cm and 2 cm. Radial distance were varied as 0 cm, 0.2 cm and 0.4 cm.

4.2 Penetration Distance

Referring to Figure 4.2, penetration is varied at location 1 cm, 1.5 cm and 2.0 cm.

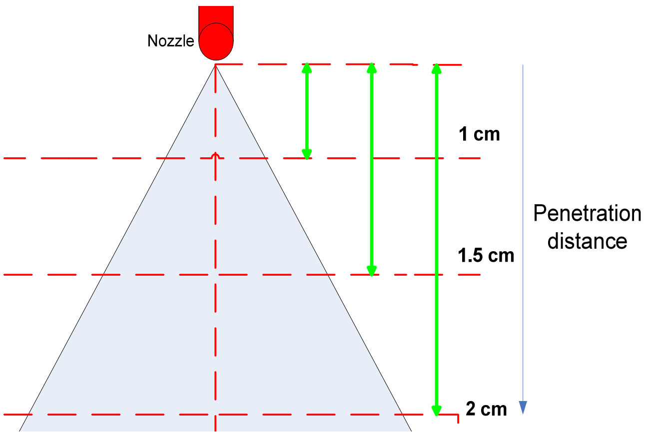

Figure 4.4: Diagram showing penetration distance of spray area at 50 kPa

Figure 4.3 shows the graphical illustration of the data in Table 4.1. Downward velocity measurements were done at various distances for each fluid. The pressure used in this experiment was 50 kPa. As shown in the graph, water sprays has the highest vertical velocity. Ethanol at penetration distance of 1 cm has the second highest vertical velocity. Velocity of diesel increases as the penetration distance increases

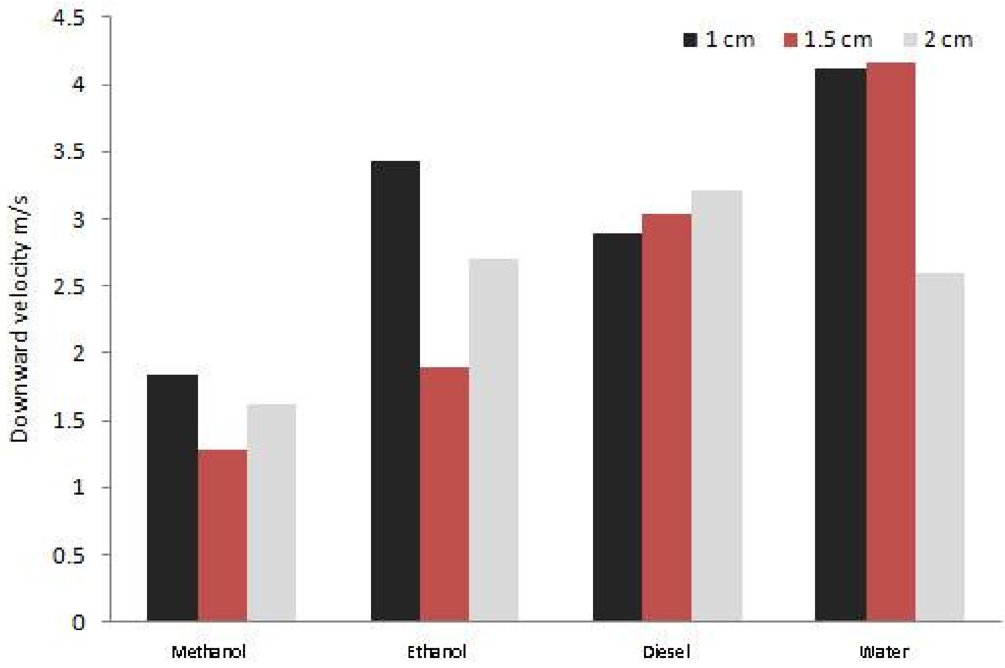

Figure 4.5: Downward velocity versus fluid types at 50 kPa at 1.0 cm, 1.5 cm and 2.0 cm penetration distances

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. As indicated in Figure 4.6, a large standard deviation occurs at pressure 50 kPa. This can be explained by the turbulent flow of the sprays. It is also shown in Figure 4.6 that the pattern for methanol and ethanol are about the same.

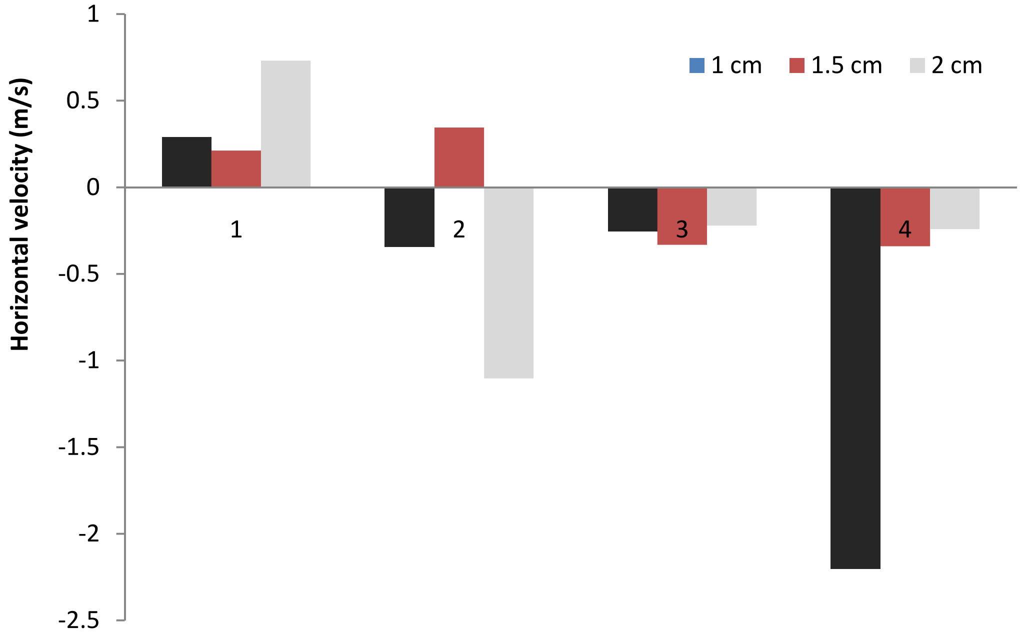

Figure 4.6: Horizontal velocity versus fluid types at 50 kPa at 1.0 cm, 1.5 cm and 2.0 cm penetration distances

In Figure 4.7 the SMD of ethanol increases as the penetration distance increases. Unlike ethanol, SMD of diesel decreases with the increase in penetration distance. Ethanol has the highest SMD compared to other fluids at penetration distance of 2.0 cm. The figure shows that methanol and water have the same pattern. The SMD of methanol is greater at penetration distance 1.5 cm than 1.0 cm. But methanol has lower SMD at 1.5 cm than 1.0 cm. SMD of diesel decreases as the penetration distance increases.

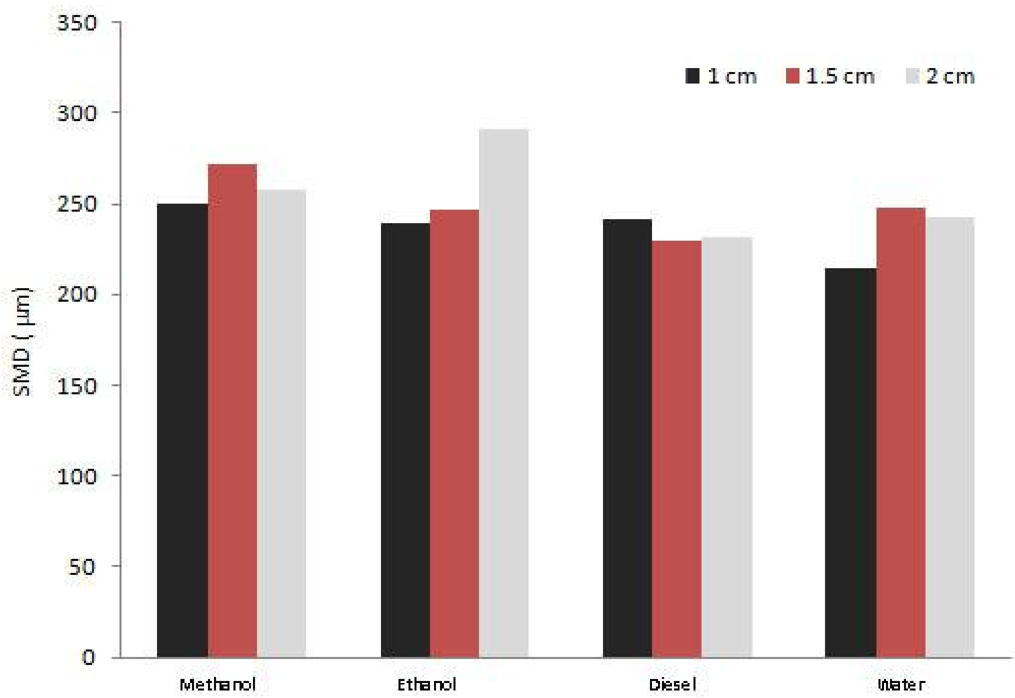

Figure 4.7: SMD versus fluid types at 50 kPa at 1.0 cm, 1.5 cm and 2.0 cm penetration distances

4.3 Radial Distance

For radial distance, three locations have been decided which are at 0 mm, 0.2 mm and 0.4 mm

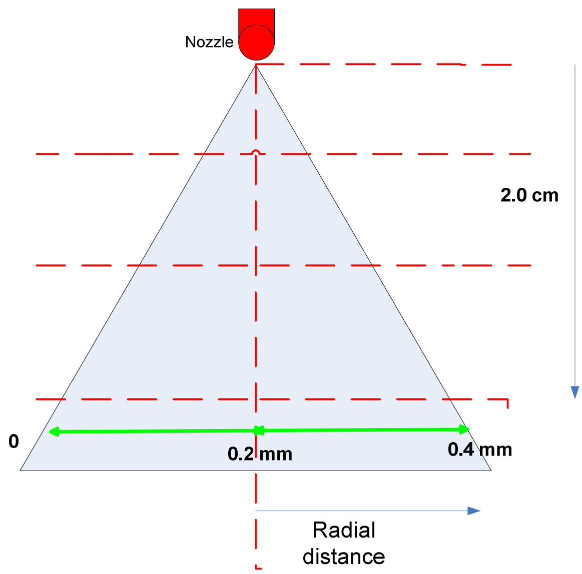

Figure 4.8: Diagram showing radial distance of spray area at pressure 50 kPa

Figure 4.9 shows the graph for downward velocity versus fluid types at various radial distances. The measurements have been taken at 50 kPa. No specific pattern can be observed from the graph below. Diesel spray shows the highest downward velocity at radial distance 0.4 mm. This is the biggest droplet size compared to other fluids. Droplet size of methanol increases as the radial distance increases. Methanol has the lowest vertical velocity among all the fluids. SMD of ethanol varies as the penetration distance changes. It shows highest droplet size at radial distance of 0.2 mm. Water spray has the lower droplet size compared to ethanol and diesel, but it has higher spray droplet size than the spray of methanol.

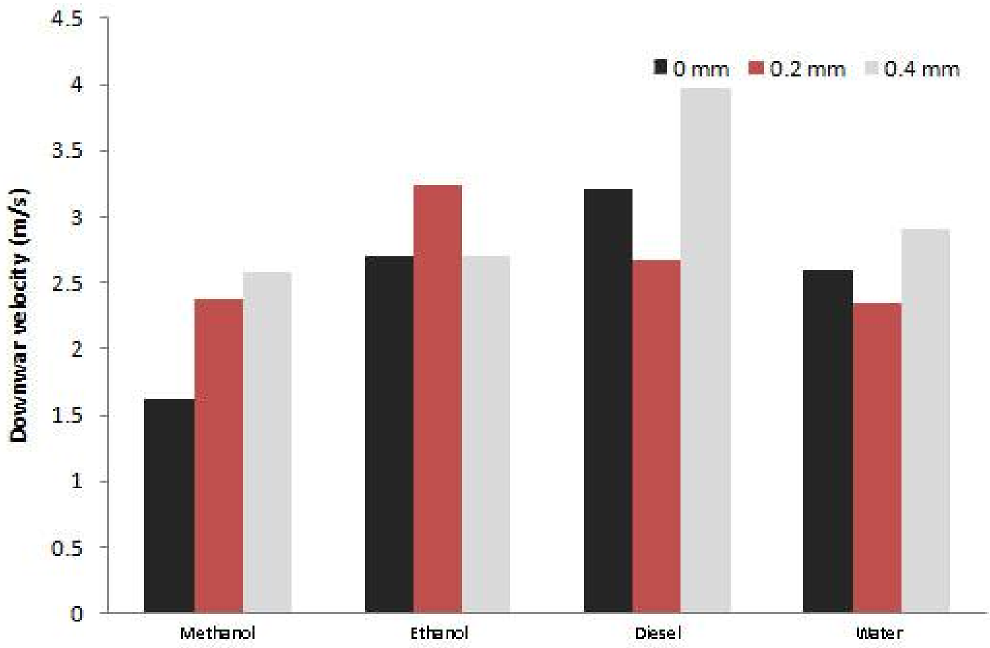

Figure 4.9: Downward velocity versus fluid types at 50 kPa at 0 mm, 0.2 mm and 0.4 mm radial distances

In Figure 4.10, both methanol and ethanol shows higher standard deviation in the values of horizontal velocity. However, methanol has high horizontal velocity at radial distance of 0.4 mm and ethanol has higher horizontal velocity at radial distance of 0 mm. Diesel and water has lowest horizontal velocities compared to methanol and ethanol. It can be due to the different flow patterns of each fluid.

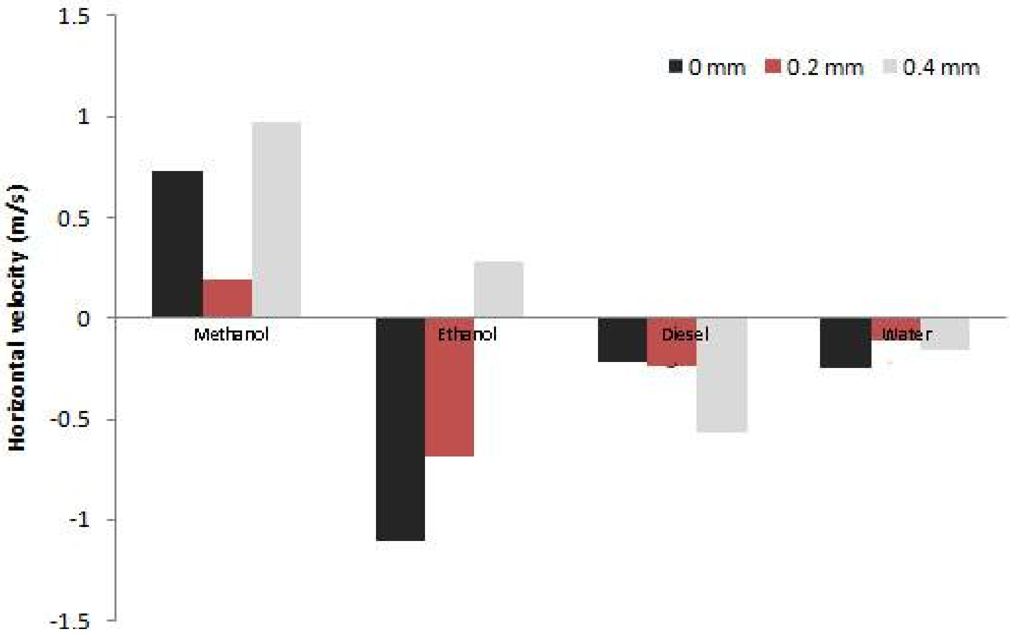

Figure 4.10: Horizontal velocity versus fluid types at 50 kPa at 0 mm, 0.2 mm and 0.4 mm radial distances

Figure 4.11 shows the graph of SMD versus fluid types at radial distances 0 mm, 0.2 mm and 0.4 mm. From the graph, it can be observed that both methanol and ethanol has same pattern for SMD values. Also similar pattern is shared by water and diesel droplet sizes. However, there is no special pattern for generalization. This error could happen due to limited number of experiment trials. The error could happen due to difference in number of counts for each droplet which will result in accuracy of the SMD.

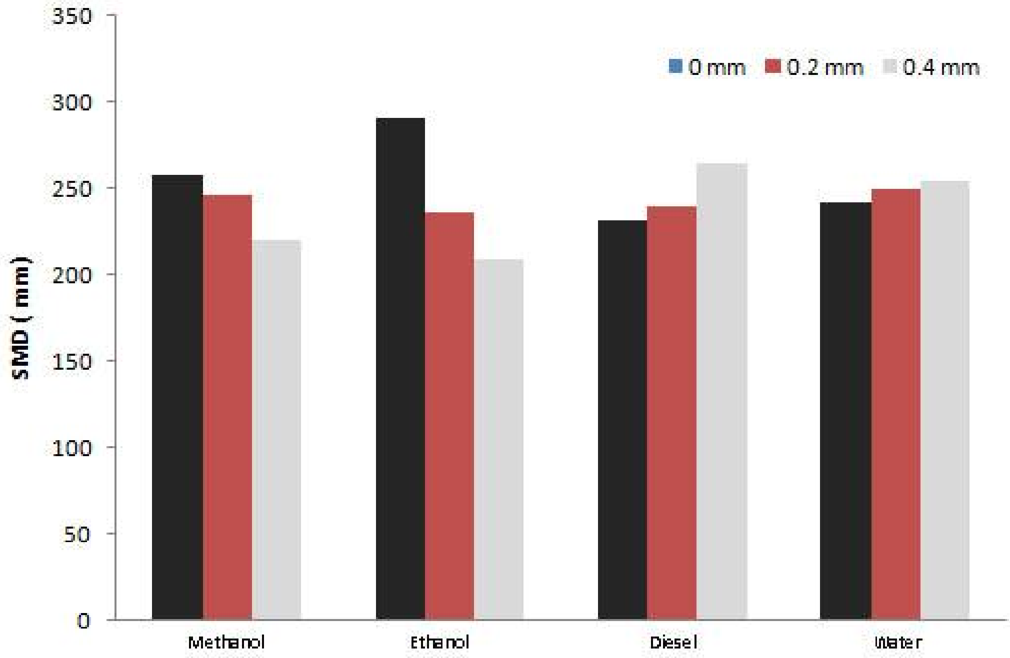

Figure 4.11**:** SMD versus fluid types at 50 kPa at 0 mm, 0.2 mm and 0.4 mm radial distances

4.4 Spray Angles

This experiment was performed by using digital camera. The pictures of sprays were taken in a dark room. The digital camera's place set to static location in order to set the same distance for all liquid sprays. The pressure is varied as 50 kPa, 100 kPa and 150 kPa for each liquid.

4.4.1 Methanol

Figure 4.12: Spray structure of methanol at 50 kPa

Figure 4.13: Spray structure of methanol at 100 kPa

Figure 4.14: Spray structure of methanol at 150 kPa

It is observed that from the Figures 4.12, 4.13 and 4.14 that the spray angles of methanol increase as the pressure increases. The spray angle of methanol at 50 kPa was measured as 23.8°. For pressures 100 kPa and 150 kPa, the spray angles are 25.7° and 31.5° consecutively.

4.4.3 Ethanol

Figure 4.15: Spray structure of ethanol at 50 kPa

Figure 4.16: Spray structure of ethanol at 100 kPa

Figure 4.17: Spray structure of ethanol at 150 kPa

In figures above spray angles and structure of sprays of ethanol can be seen clearly. Spray angles were measured for each pressure. At 50 kPa, the spray angle is 27.8^{o}, the spray angle of ethanol at 100 kPa was measured as 31.1^{o} and for 150 kPa, the spray angle is 31.7^{o}. Spray angle varied bigger when the pressure was set from 50 kPa to 100 kPa, but it slightly increases when the pressure reaches to 150 kPa. It can be observed that both methanol and ethanol spray angles increase with the increase in pressure.

4.4.4 Diesel

Figure 4.18: Spray structure of diesel at 50 kPa

Figure 4.19: Spray structure of diesel at 100 kPa

Figure 4.20**:** Spray structure of diesel at 150 kPa

For diesel fuel, spray structures are shown in figures above. As it can be from the pictures, the spray angle of diesel is not so clear. This might be due to high evaporation of diesel fuel. The spray angle at 50 kPa was measured as 23.3$^{o.}$ For 100 kPa, the measurement of spray angle was approximately 23.7^{o}. When the pressure is set to 150 kPa, the spray angle was observed as 22.8^{o}. Diesel spray angles are different than the previous fluids, which are methanol and ethanol. There is no big difference between spray angles for diesel fuel as we change the pressure.

4.4.5 Water

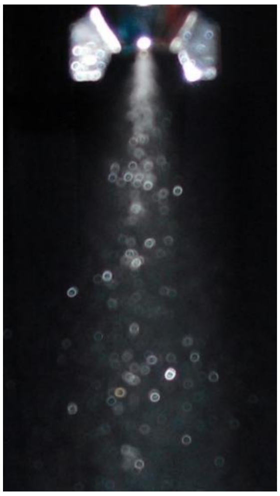

Figure 4.21: Spray structure of water at 50 kPa

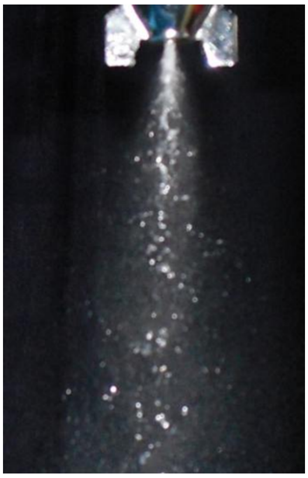

Figure 4.22: Spray structure of water at 100 kPa

Figure 4.23: Spray structure of water at 150 kPa

As it can be seen from the figures above, the spray angles of water increase directly with the increase in pressure. The spray angle of water at 50 kPa was measured as 27.1^{o}. At 100 kPa, the water spray angle is 29.2^{o} and at 150 kPa, the spray angle was measured 30.2^{o}.

Spray angle was calculated by drawing a line along the spray pattern. Two lines were drawn and the angle between those lines was measured as spray angle. Spray angle calculation by using picture softwares are shown in Figure 4.24. A summary of the spray angles for different fluids and pressures is shown in Table 4.2

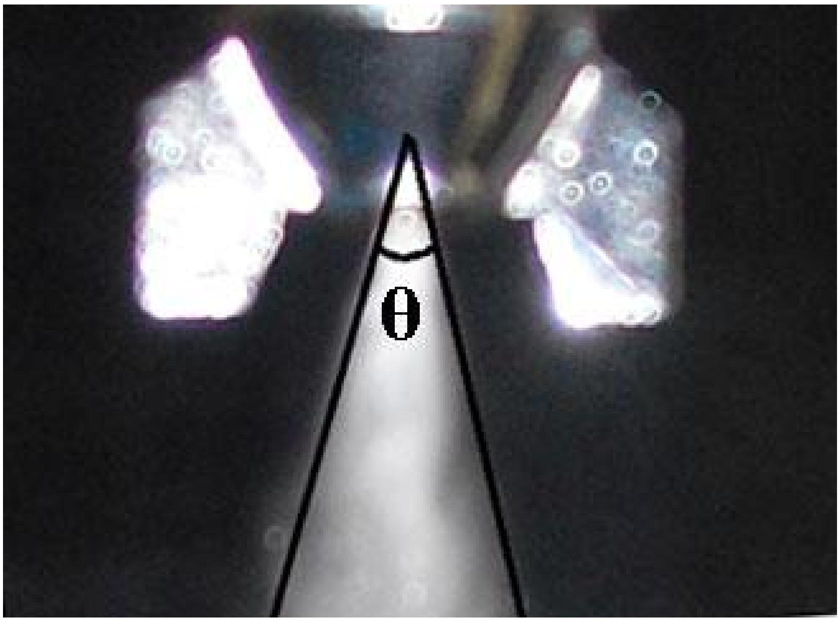

Figure 4.24**:** Spray angle measurement method

Table 4.2: Table of spray angles

Fuid type	Pressure	Spray angles
Methanol	50 kpa	23.8°
	100 kPa	25.7°
	150 kpa	31.5°
Ethanol	50 kpa	27.8°
	100 kPa	31.1°
	150 kpa	31.7°
Diesel	50 kpa	23.3°
	100 kPa	23.7°
	150 kpa	22.8°
Water	50 kpa	27.1°
	100 kPa	29.2°
	150 kpa	30.2°

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This project has two main objectives, which are; to study the characteristics of alcohol and break up structure of alcohol sprays. The other fluid spray types were compared to each other. The LDA and PDA experiments have been done in order to get data and results of sprays. Digital camera has been used to measure the spray angles of fluids at the nozzle exit.

Pressure was varied as 50 kPa, 100 kPa and 150 kPa for each fluid. However difficulties were faced in taking measurements at higher pressures. The values for horizontal velocity, downward velocity and SMD were taken easily at 50 kPa.

Water had the highest vertical velocity. Ethanol at penetration distance of 1 cm had the second highest vertical velocity. Velocity of diesel increased as the penetration distance increases. The pattern for horizontal velocity of methanol and ethanol are same. Large standard deviation occurs at pressure 50 kPa for water sprays.

The measurements were taken at 50 kPa. Diesel sprays had the highest downward velocities at radial distance 0.4 mm. Downward velocity of methanol increased as the radial distance increased. Methanol had the lowest vertical velocity among all other fluids. Downward velocity of ethanol varied as the penetration distances changed. Both methanol and ethanol showed higher standard deviation in the values of horizontal velocities. Methanol and ethanol had same pattern for SMD values. Also similar pattern was shared by water and diesel droplet sizes.

5.2 Recommendations

The experiment on water was done as a trial. The problem faced in the experiment was failure of compressor to keep the pressure stable. This problem was discussed with lab technician and supervisor. The compressor was changed and the problem was resolved successfully. Another problem was the failure of the software to read the results at pressures higher than 100 kPa. This problem was discussed and the necessary actions were taken.

However more detailed study could be done, such as taking more measurements of fluids. Alcohols evaporate very quickly, so this experiment had limited number of trials. And also penetration distances and radial distances could be varied for many distances in order to get good picture of spray characteristics of involved fluids.

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APPENDICES

APPENDIX A-1: SAMPLE CALCULATIONS OF SMD AND VELOCITY

Table A1: Table of information of results generated from LDA/PDA

Vertical velocity(m/s)	Counts	Horizontal velocity	Counts	Diameter μ m	Counts
-16.5	4000	-3.5	4000	95	2000
		-2.5	2000		
		-0.75	4000		

Average vertical velocity= -16 m/s (shows downward velocity)

Average Horizontal velocity= $\frac{\Sigma V}{n}$

$$= \frac{(-3.5)(4000) + (-2.5)(2000) + (-0.75)(4000)}{(4000 + 2000 + 4000)}$$

$= -2.2$ m/s (moving to the right)

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

$$= \frac{(2000)(95)^3}{(2000)(95)^2}$$

$= 95 \mu m$

Table A2: Properties of water

Property	Value
Molar mass	18.015
Molar Volume	55.5 moles/liter
Boiling Point (BP)	100°C at 1 atm
Freezing point (FP)	0°C at 1 atm
Triple point	273.16 K at 4.6 torr
Surface Tension	73 dynes/cm at 20°C
Vapor pressure	0.0212 atm at 20°C
Heat of vaporization	40.63 kJ/mol
Heat of Fusion	6.013 kJ/mol
Heat Capacity (cp)	4.22 kJ/kg.K
Dielectric Constant	78.54 at 25°C
Viscosity	1.002 centipoise at 20°C
Density	1 g/cc
Density maxima	4°C
Specific heat	4180 J kg-1 K-1 (T=293…373 K)
Heat conductivity	0.60 W m-1 K-1 (T=293 K)
Melting heat	3.34 x 105 J/kg
Evaporation heat	22.6 x 105 J/kg
Critical Temperature	647 K
Critical pressure	22.1 x 106 Pa
Speed of sound	1480 m/s (T=293 K)
Relative permittivity	80 (T=298 K)