EXPERINENTAL INVESTIGATING OF GDI SPRAY

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Indian Institute of Technology Hyderabad

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Approval Sheet

This thesis entitled Experimental Investigation of GDI Spray by Amit Anurag is approved for the degree of Master of Technology from IIT Hyderabad.

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Dedicated to

The NATION

Abstract

Need of the fuel is growing but its availability is limited. Further, the stringent regulations for emissions from engine has made the world to develop the engines which follows the regulation norms and are more efficient than current one. For the solution of the aforementioned problem, the study of air-fuel mixture is important and this mixture is directly affected by the amount of fuel injected, time of the injection, spray area, spray penetration length etc. The aim of this study is to develop a methodology for the investigation of the spray characteristics of the iso-octane and n-butanol blend (B0, B5, B10 and B20) in a constant volume combustion chamber. Pressure and the temperature of the chamber is raised by the pre combustion of the acetylene and air mixture. After combustion, the combustion product slowly cools down, leaving its heat to the chamber. Once the internal pressure reaches to some predetermine pressure, spray event is initiated. Since butanol is gaining more and more interest for the SI engine fuel, current study will help the engine researcher to understand the in-cylinder phenomenon.

Nomenclature

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Chapter 1

Introduction

Presently, a small climate change plays a crucial role in every aspects of the entire living beings' life. If we do not wake up now, then it would be difficult even for survival of the lives on this beautiful planet. The main threat behind this challenge is the life supporting air which surrounds us, is impure. One of the prominent reasons behind this impurities is the emissions from automotive engines. These emissions include pollutants like nitrogen oxides (NOx) and soot. Also the emission of carbon dioxide (CO_2) is restricted due to its contribution to the greenhouse effect. In everyday life, this means that one has to comply with stringent regulations concerning internal combustion engine emissions.

In order to efficiently use the fossil fuels and reduce the harmful emissions from the engines, thorough investigation of the spray formation process and the introduction of injection system capable of meeting the demand of different engine operating conditions are required. Hence, this study contributes to the characterization of spray and the motivation is based on the growing need for efficient engines while preserving the environment and maintaining the health of all the living beings. Another implication of this study is the current global energy demand and the depletion of the fossil fuels, which makes the efficient use of fuels necessary.

1.1. Current Energy Scenario and Need for Alternative fuel

The crude oil price has been fluctuating in the international market and has significantly increased in the recent past. A Sampled History of Crude Oil Prices (WTI) at The New

York Mercantile Exchange (NYMEX) From 2006 to the Present is shown in Figure 1 below, has reached a level of more than $140 per barrel in year 2008. Such unforeseen escalation of oil price is straining the economies of developing countries as these countries heavily rely on the import of the crude oil. Also, Petro-based oil meets about 95% of the requirement for transportation fuels, and the demand has been rising steadily. Provisional estimates have indicated that crude oil consumption in 2007-08 was about 156 million tons. The domestic crude oil is able to meet only about 23% of the demand, while the rest is met from imported crude. [1]

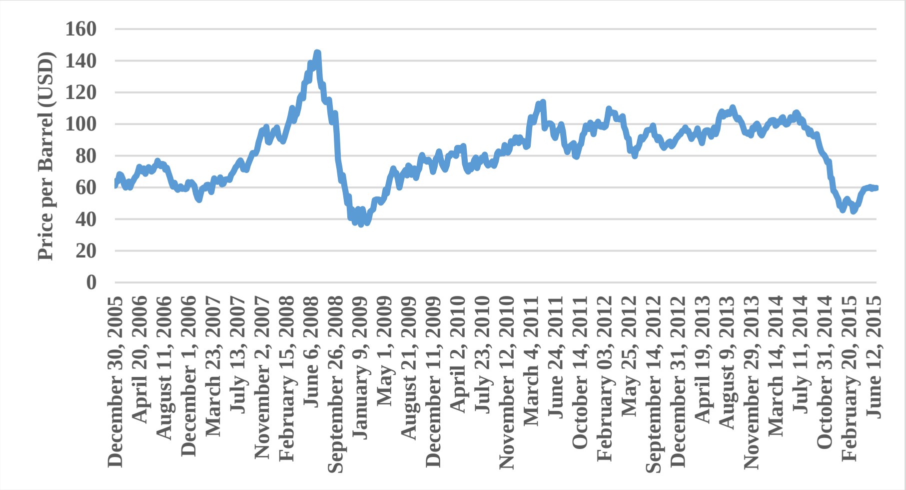


Figure 1 Crude Oil Price History [1]

Hence, India's energy security would remain vulnerable until alternatives to the petro based fuels are not substituted/ supplemented which is based on the indigenously produced renewable feedstock like biofuels. Biofuels are environment friendly and its use would address the global challenge of carbon emission, because carbon dioxide (CO_2)

released during fuel combustion is offset by the CO_2 captured by the plants from which biofuels is produced.

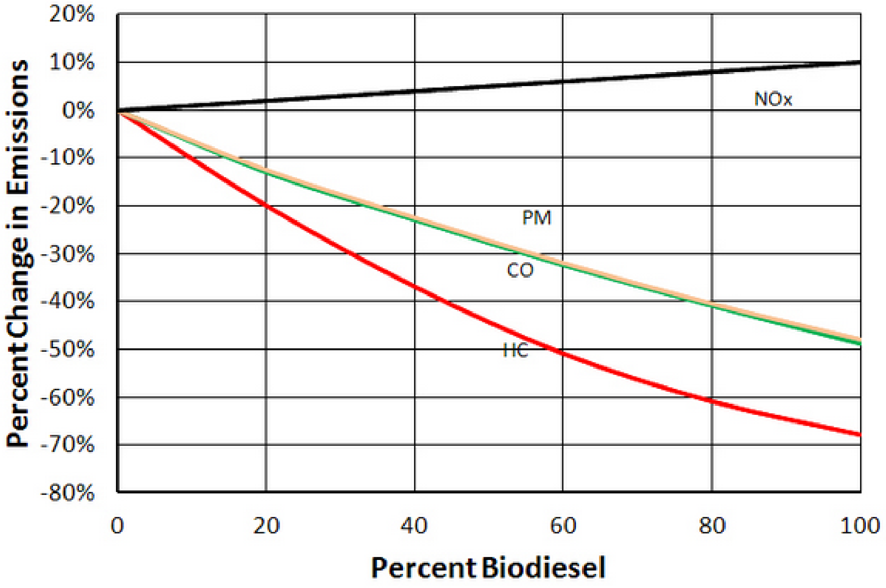


Figure 2 Average Emissions impact of Biodiesel [2]

1.2. Life Cycle Emissions

Life cycle analysis is a technique used to assess the environmental impacts of all stages of a product's life, including raw material extraction, processing, manufacturing, distribution, use, and disposal or recycling. When comparing fuels, a life cycle analysis may focus on particular portions of a fuel's life cycle, such as from extraction-to-use or well-to-wheels, to determine the merits or problems associated with each fuel.

Life cycle analysis completed by the National Renewable Energy Laboratory (USA), and later by Argonne National Laboratory, found that greenhouse gas emissions for 100% biodiesel could be more than 52% lower than those from petroleum diesel. These analyses also showed that biodiesel may reduce petroleum use by more than 88% throughout its life cycle. [3].

1.3. THE VISION AND GOALS of Biofuel Policy of India

The policy aims at bringing use of biofuels which envisions central role of use of biofuels in transportation sector. Also, to ensure that a minimum level of biofuels to be readily available in the market to meet the demand. An indicative target of 20% blending of biofuels, both for bio-diesel and bio-ethanol, by 2017 is proposed. Blending levels prescribed with respect to bio-diesel are intended to be recommendatory in the near term. [4]. The blending level of bio-ethanol has already been made mandatory, which is effective from October, 2008, and will continue to be mandatory leading up to the indicative target.

Year		Reference	CO	HC	HC+NOX	NOX
1991			14.3-27.1	2.0-2.9	-	
1996			8.68-12.4	-	3.00-4.36	
1998			4.34-6.20	-	1.50-2.18	
2000	BS I	Euro 1	2.72-6.90	-	0.97-1.70	
2005	BS II	Euro 2	2.2-5.0	-	0.5-0.7	
2010 (all over India)	BS III	Euro 3	2.3	0.20	-	0.15
2010 (13 metro cities)	BS IV	Euro 4	1.0	0.1	-	0.08

Table 1 Emission norms in India

The above table shows the Indian emission norms for the light duty passenger cars for the petrol engine. In current situation many automobiles on road are following the BS V emission norms and road map for BS VI is ready, which will be implemented in year 2016.

1.4. LITERATURE REVIEW

In year 1876, German inventor Nicolaus Otto gave one of the greatest inventions in the history i.e. "Internal combustion engine." He built the first practical cycle called as Otto cycle. And the efficiency of the cycle is given by

$$\eta = 1 - 1/r^{\gamma-1} \qquad 1.1$$

Where r is the compression ratio and the γ is the specific heat ratio. From the above equation it is clear that efficiency of the Otto cycle is directly proportional to the compression ratio.

1.4.1. Gasoline Direct Injection Engine

Basically, the goal of automotive industries are to develop engines having low specific fuel consumption, high power, low emission, less noise and better driving experience. As these industries are growing and number of cars are increasing day by day, which is evident from the below graph showing number of cars sold from 1990 to 2014 and forecasting for 2015.

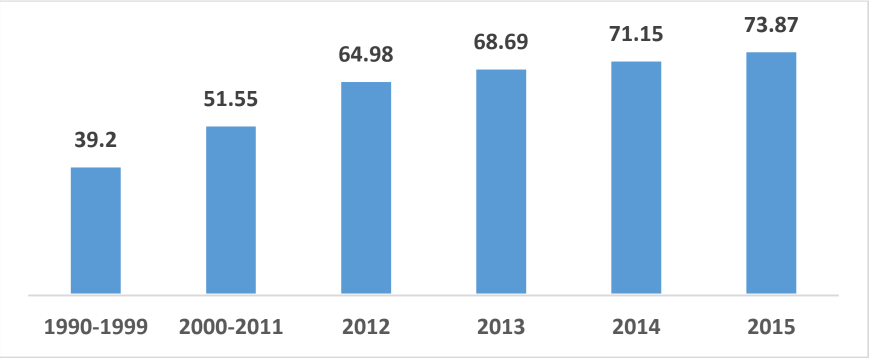


Figure 3 International car sales in millions [5]

The governmental agencies has drawn down the emission limits, which is shown below:

Year		Reference	CO	HC	HC+NOX	NOX
1991			14.3-27.1	2.0-2.9	-	
1996			8.68-12.4	-	3.00-4.36	
1998			4.34-6.20	-	1.50-2.18	
2000	BS I	Euro 1	2.72-6.90	-	0.97-1.70	
2005	BS II	Euro 2	2.2-5.0	-	0.5-0.7	
2010 (all over India)	BS III	Euro 3	2.3	0.20	-	0.15
2010 (13 metro cities)	BS IV	Euro 4	1.0	0.1	-	0.08

Table 2 Emission limits

Furthermore, limited oil available under the earth which implies to the continuous increase in its price has made the automotive industry to develop more efficient engine which fulfill the above mentioned criteria as shown in table 2.

1.4.2. Types of engine system of SI (spark ignition) engine:

1. Carburetor system,

2. Port Fuel Injection system (PFI), and

3. Gasoline Direct Injection system (GDI)

Since the carburetor engine system does not maintain the air-fuel ratio close to stoichiometric at different conditions, which makes such engines to be less efficient and produce more emissions. Therefore, port fuel injection is being used, where inducted air is measured then fuel is injected in the manifold to make air-fuel ratio closer to stoichiometric or the required equivalence ratio.

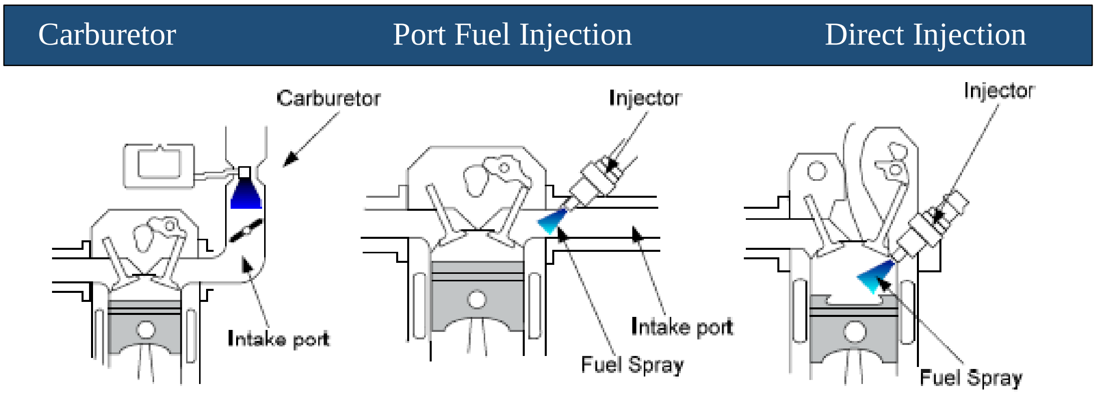
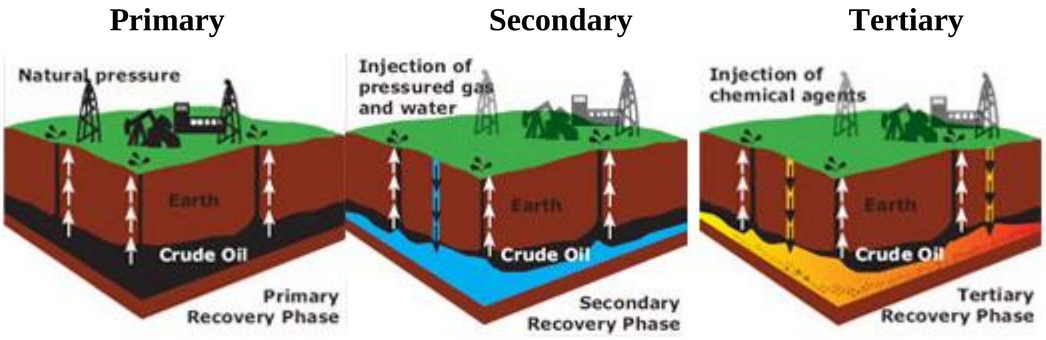

Carburetor | Port Fuel Injection | Direct Injection

Figure 4 Types of SI engine

In the gasoline engine, the air-fuel mixture is prepared in-cylinder and out-cylinder. For port fuel injection (PFI) and carburetor system the mixture is prepared out-cylinder while in gasoline direct injection (GDI) engine, mixture is prepared in-cylinder, as indicated in figure 4. So, in GDI engine during intake stroke, only air is inducted inside the cylinder through intake port and fuel is injected during compression stroke which gives more control over types of mixtures required under various operating conditions.

1.4.3. OIL RECOVERY PROCESS

Addition to it, Improved technology for oil recovery must be implemented (oil recovery is a process by which crude oil is extacted from beneath the surface of earth). There are


Primary **Secondary** **Tertiary**

three phases involved for extracting oil from oil fields. The differences are given in the table 3.

Primary	Secondary	Tertiary
Uses natural pressure to push crude oil to the surface.	Injects pressurized oil and water to push the remaining crude oil and gas left after primary phase.	Injects different materials to flow between oil, gas and rock and recover the crude oil after primary and secondary phase.
Allows 5% to 10% of the oil in the reservoir to be extracted.	Allows additional 25% to 30% of the oil in the reservoir to be extracted.	Allows additional 20% to 30% of the oil in the reservoir to be extracted.

Table 3 Different phase of oil recovery process

Chapter 2

Fundamentals of optical techniques and Liquid spray

2.1.Optical Diagnostic Techniques

Using optical diagnostic technique for spray characterization in a meaningful way is not a straightforward task. Optical technique has many extra edge over other technique as this is a non-intrusive, which is basically means that no physical probe are introduced in the spray zone. Some of the different types of optical technic are as follows:

1. **Schlieren**
2. **Shadowgraph**
3. **Mie scattering**
4. **Focused Shadowgraph**
5. **PDPA (Phase Doppler Particle Analyzer)**

In this thesis we will discuss about the above technique and then it will be discussed, how a modified schlieren system is used and known as focused shadowgraphy to get the spray's vapor penetration length data and mie scattering will also be discussed which gives us information about the liquid penetration length and spray cone angle. In this section, we will discuss about the optics which include optical arrangement, principle of operation. Before further discussion let's first talk about both schlieren, shadowgraph and mie scattering. Schlieren and shadowgraph techniques work on the principle of refraction of light beam in the test section, while mie scattering works on scattering effect of light.

Schlieren image analysis is based on beam deflection (but not displacement) while shadowgraph accounts for beam deflection as well as displacement. [3].

2.1.1 Concept of Schlieren, Shadowgraph and Mie scattering

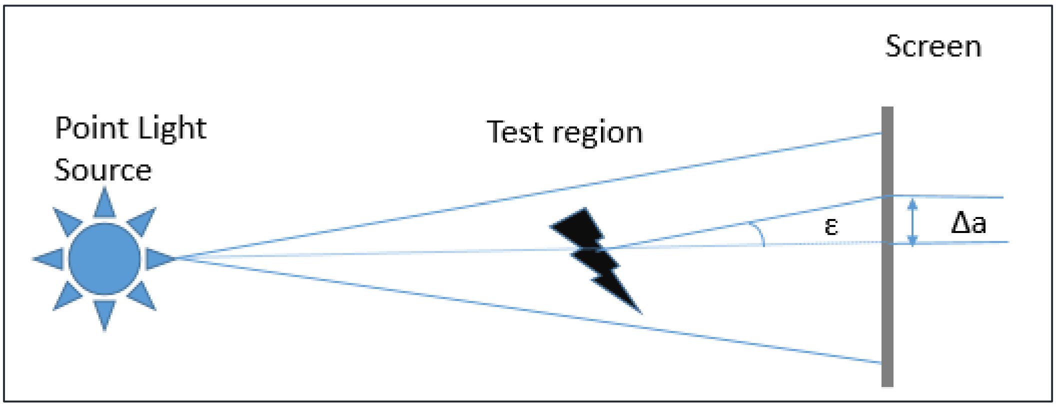


Figure 5 Schematic diagram of Shadowgraph

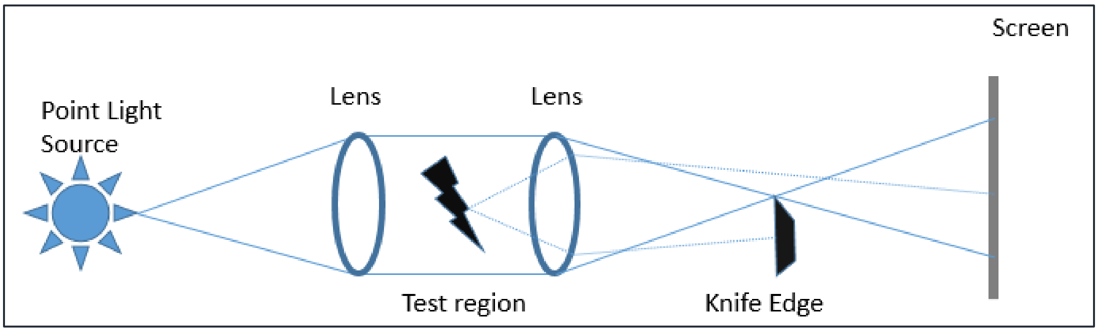


Figure 6 Schematic diagram of Schlieren

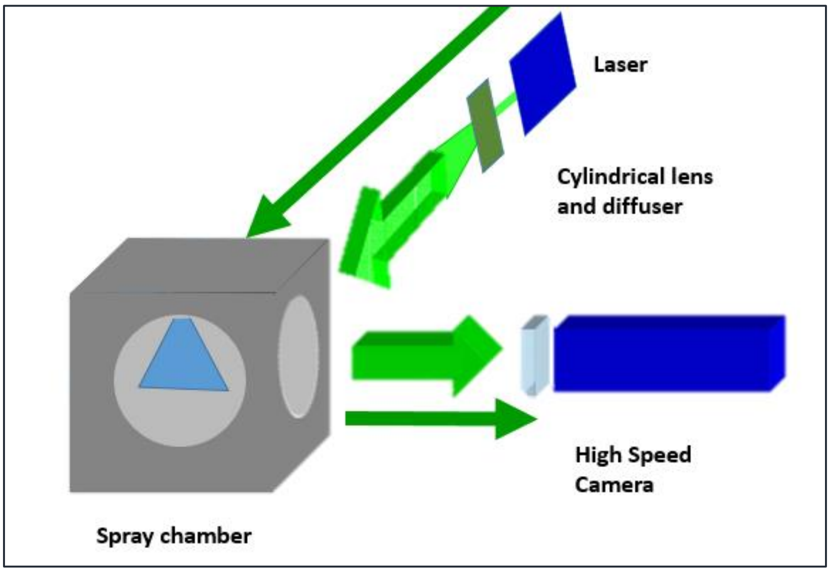


Figure 7 Schematic diagram of Mie scattering

A basic shadowgraph set up is shown in the figure 5. As we know, any light source if falls on the transparent object or on a test region then the light rays are refracted, bent, deflected, scattered from their original path. One such ray is shown in the above figure 5. Having suffered a refraction through angle ϵ, it reaches on the screen displaced from its original path by distance Δa. Now it contributes the extra illumination, where it falls and its previous position suffers an illuminance deficit. By this way basically it generates the contrast differences on the screen. This basic concept is same for schlieren system also whose schematic diagram is shown in figure 6. But the main difference is the use of knife edge which blocks additional refracted light rays resulting into the more contrast of the image. For focused shadowgraph we do not use knife edge in the schlieren setup. In case of mie scattering the light rays fall on the spray then it scatters and the scattered light reaches on the camera.

2.2 FUNDAMENTALS OF LIQUID SPRAY

The presented information in this chapter is mostly based on the books of Stiesch (Modelling Engine Spray and Combustion Process).

2.2.1 Spray Regimes

A typical two-phase flow originated from a pressure atomizer can be divided into different regimes as depicted in figure 8. Directly at the nozzle orifice an intact core of the liquid phase can be identified. It rapidly disintegrates into ligaments (churning flow) and further into droplets, but it still occupies a considerable fraction of the volume. Due to its density, which is significantly greater than the density of the gas phase, the contribution of the liquid phase to the total mass is even greater, this spray region generally referred to as thick or dense spray. Because of the conical spray shape and because of droplet evaporation, the average spacing between droplets expands further downstream of the nozzle, and the void fraction, i.e. the volume fraction occupied by the gas phase, increases and approaches unity. However, due to the liquid to gas density ratio, the mass fraction of the liquid phase may still be noticeable. This intermediate region of the spray is called thin spray. The very thin or dilute spray regime is finally characterized by both volume and mass fractions of the liquid phase that are negligible compared to the ones of the gas phase.

The behavior of various droplets within different regimes of a spray is quite different. Obviously, droplet-droplet interactions such as collision and coalescence can be significant close to the nozzle orifice. Moreover, when the droplet spacing is small the boundary layer around a droplet may be affected by an adjacent droplet. Consequently, it can no longer be assumed that there is an undisturbed gas phase around the droplet in order to calculate the exchange processes between liquid and gas. At the other extreme, in the dilute spray regime the droplet behavior can be calculated based on relations for an isolated droplet with good accuracy. There is still some mass, momentum and energy transfer between the droplets and the gas phase, but the influence that the droplets have on the gas phase is very small. Collisions between droplets are rare and typically neglected in the modeling.

In the intermediate thin spray regime the liquid phase still accounts for a noticeable mass fraction as noted above. Thus, there is considerable momentum transfer from the droplets to the gas phase, which in turn affects other droplets again. An example are the reduced drag forces on those droplets located in the wake of the spray tip that are decelerated by the gas less rapidly and may therefore overtake the droplets at the former spray tip that have been injected at an earlier timing.

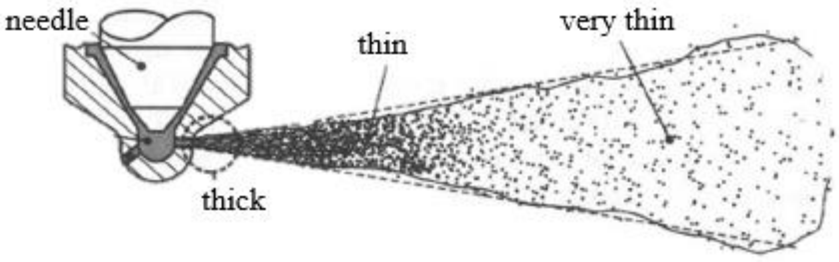


Figure 8 Schematic illustration of different flow regimes

2.2.2 Spray Atomization

In engine fuel injection systems the fuel typically leaves the injector nozzle in a more or less continuous liquid phase that can obviously not be reproduced with the Lagrangian discrete droplet approach. Therefore, additional submodels are necessary in order to describe the breakup processes that lead to the formation of droplets, before the DDM can be applied. This procedure seems reasonable since in high pressure injection systems the disintegration of the continuous liquid phase into small droplets starts very close to the nozzle orifice. Thus, the impact of the intact liquid core on the gas phase is extremely small compared to the influence that the dispersed liquid droplets have on the gas phase in the entire spray.

Two different types of liquid breakup into ligaments and droplets are typically distinguished. The first kind of breakup occurs at or in direct vicinity of the injection nozzle orifice. It is referred to as spray atomization or primary breakup. The primary breakup describes the breakup of the intact liquid phase into first ligaments and droplets. Later on, the relatively large initial droplets can be further distorted and subsequently broken up into smaller secondary droplets. This kind of breakup is termed secondary breakup. Typically, the secondary breakup takes place a little further downstream of the nozzle, i.e. within the thick, thin, and very thin spray regimes indicated in the schematic illustration of figure 8.

2.2.3 Breakup Regimes

The primary breakup of liquid jets at the nozzle exit can be caused by a combination of three mechanisms: turbulence within the liquid phase, implosion of cavitation bubbles and aerodynamic forces acting on the liquid jet.

Due to the pressure drop across the injection nozzle the liquid fuel is accelerated within the small nozzle holes. Thereby a high level of turbulence is generated within the liquid phase that has a destabilizing effect on the jet once it exits the nozzle hole. Additionally, at sharp edges along the flow path inside the nozzle, e.g. at the inlet of the nozzle hole, the streamlines are contracted such that the effective cross-section the flow is reduced and its velocity is accelerated even more. According to Bernoulli's law this causes a reduction in the static pressure, and locally the static pressure may be decreased to a value as low as the vapor pressure of the fuel. The theoretical (linear) pressure distribution inside the nozzle hole is compared to a more realistic distribution along a streamline. The effect is that cavitation bubbles are generated inside the injection nozzle. The cavitation bubbles are swept out of the nozzle into the combustion chamber where they implode and contribute to the disintegration of the spray. The third mechanism is that the relative velocity between the liquid jet and the gas results in aerodynamic forces that act on the liquid surface. Therefore, surface disturbances develop and start to grow that lead to breakup as well.

Chapter 3

Experimental set-up for optical fuel spray diagnostics

The need to develop the experimental setups to perform GDI fuel spray research under engine like conditions has been discussed in the first chapter. In this chapter, experimental setup and procedure will be discussed.

3.1 Description of the constant volume vessel

A picture of constant volume spray chamber is shown below in figure 9. The spray chamber is designed for simulating the spray in an engine. The spray chamber is cubical shaped and the internal volume of the chamber is $1200cm^3$. In order to illuminate the chamber, 4 windows made up of sapphire are mounted on its vertical surface. The sapphire glass windows are circular with a diameter of 60 mm. In order to measure the cylinder pressure, a pressure transducer (BERU Germany, model no.- 0103111104) is installed in the chamber.

Inside the chamber, ambient pressure, and temperature are varied by igniting acetylene gas and air mixture. A spark plug is used to ignite the acetylene-air mixture. During and after the combustion (ignited by spark plug), the combustion products cool over a relatively longer time due to heat transfer to the vessel walls and the pressure slowly decreases, see figure 10. When the desired pressure are reached then the fuel injection system is triggered and fuel injection occurs. The historical data is recorded with high speed data acquisition (HBM Germany) as shown below in figure 10.

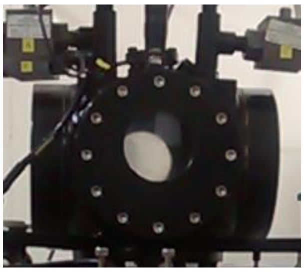


Figure 9 Constant volume spray vessel

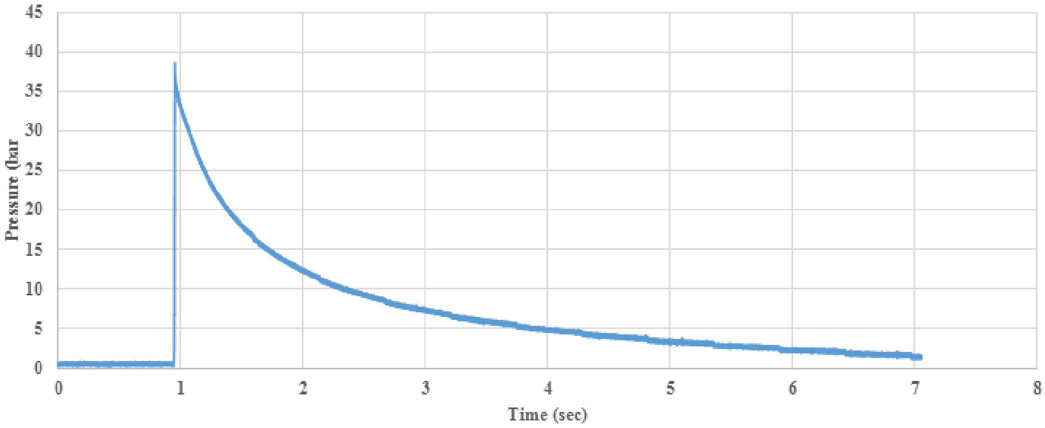


Figure 10 Temporal evolution of pressure inside the vessel

3.2 Experimental Set up

The schematic diagram of experimental setup is shown in figure 11. The whole setup is fixed on the godrej's unitized table. The fuel pump is a separate unit which is placed besides the frame of the experimental setup. Acetylene and air cylinder are placed outside the room.

3.2.1 Focused Shadowgraph – Experimental Setup

A schematic of schlieren (Focused shadowgraph) set up is shown in figure11. If we see closely then we see the setup forms letter z and such type of schlieren arrangement is known as z-type schlieren system. The setup comprises of two parabolic mirror, one plane mirror, one light source, one camera and one knife edge. All the optical components are kept at certain elevation such that optical center line of all the components are at same height. For our study the parabolic mirror used has focal length of 914.4 mm and diameter 152.4 mm. First parabolic mirror is placed at 914.4 mm from light source for collimating the light beam. Second parabolic mirror is placed after the test section in order to decollimate the light beam with a focus at the focal point. Plane mirror is used to reflect the collimated light beam from the first parabolic mirror to the spray chamber. The test section is placed between the plane mirror and second parabolic mirror. Optical components are supported on the adjustable mounts which gives the flexibility to align even smaller misalignment easily.

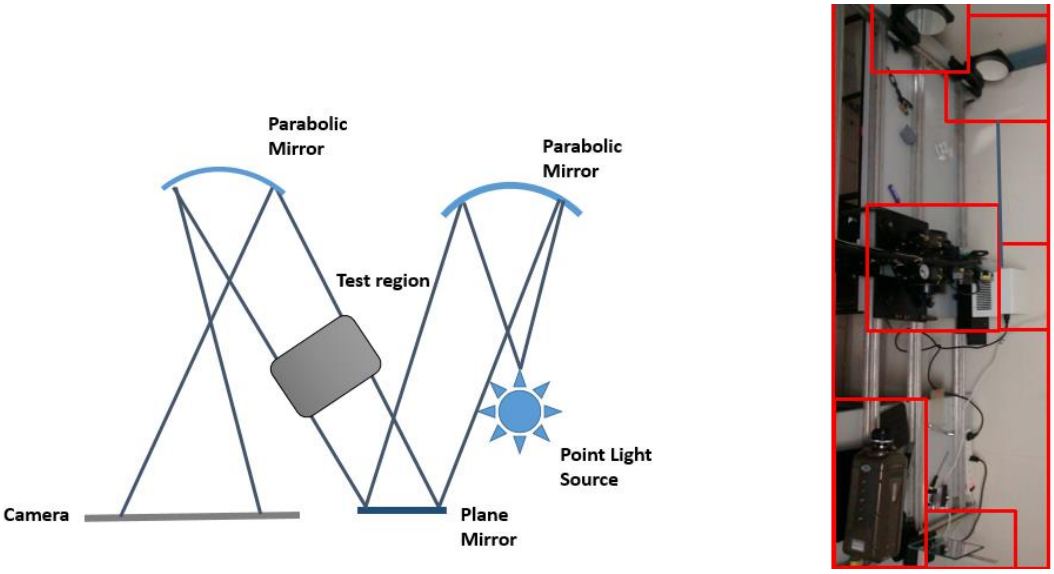


Figure 11 Schematic and experimental setup of focused shadowgraph

3.2.2 Mie Scattering – Experimental Setup

The experimental set up for mie scattering contains laser, cylindrical lens and diffuser, spray chamber setup, and high speed camera as shown in figure 12. Laser used for experiments is a continuous laser. Then cylindrical lens is used for making the laser beam in a conical shape and after that diffuser is used then the light rays basically goes to the spray chamber and strikes on the spray which further scatters and the scattered light reached on the high speed camera.

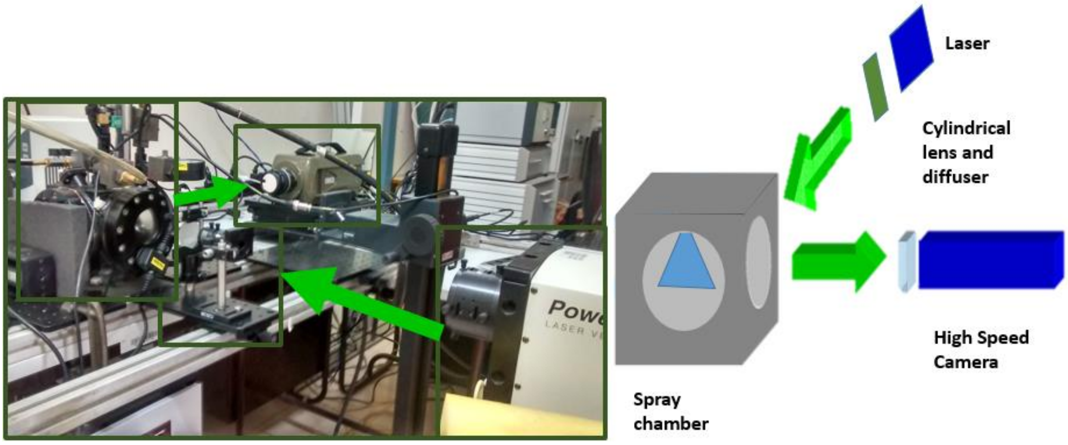


Figure 12 Schematic and experimental setup of mie scattering

3.3 Experimental Procedure and Test Matrix

Before starting the experiment, the constant volume spray chamber was checked for any small leakage by increasing the chamber pressure to 5 bar and left for 30 minutes. The pressure indicator was observed to be stable and ensured there is no small leak at this chamber. We can check only small pressure leakage, as after combustion the pressure usually goes to 30 – 40 bar. If any small leakage happens at this high pressure then it can be observed from the odor of the combustion products which will spread inside the room if there is any leak after combustion. The fuel tank was filled with the test fuel. The constant volume (CV) was pressurized with acetylene and air. In this process, first the chamber is initially filled with a predefined mixture of acetylene and air. This mixture is then ignited with a spark plug that is placed inside the spray chamber. This helps creating a high-temperature and pressure environment. As the products of combustion cool down due to heat transfer to the vessel walls, the pressure and temperature also decreases. When the desired experimental conditions are reached, fuel is injected inside the chamber.

For the current study three different test fuel blends are selected. Pure Iso-octane (B0), 10% (B10), 5% (B5) and 20% (B20) blending of n-butanol by volume with iso-octane has been studied. Physical properties of iso-octane and n-butanol are shown in the table1. In order to study the effect of the pressure, five different pressure conditions were selected (7, 9, 11, 13 and 15 bar).

Properties	Iso-octane	n-butanol
Density (g/ml)	0.691	0.808
Boiling Point (^{0}C)	99	116
Vapor Pressure (bar)	0.14	0.02
Refractive index (20^0 C)	1.391	1.399

Table 4 Properties of fuels

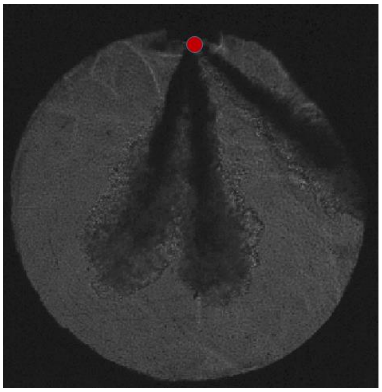
Fuel compositions in % (Iso-octane/n-butanol)	Pressure (bar)
100/0	7, 9, 11, 13, 15
95/5	
90/10	
80/20	

Table 5 Test conditions

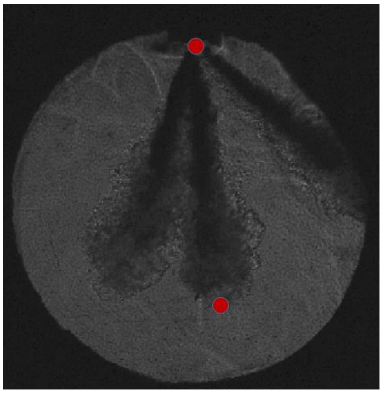
3.4 Image Processing

3.4.1 Calculation of Penetration Length

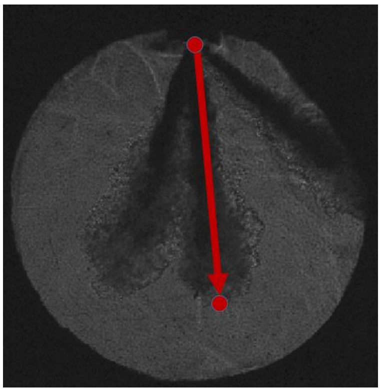
1. First point of injection is selected by manually clicking at the point of injection.



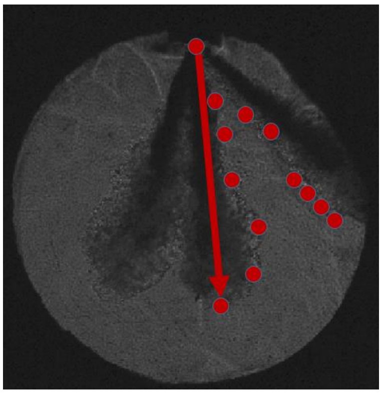
2. Then from a developed spray image, the end point of spray is selected.



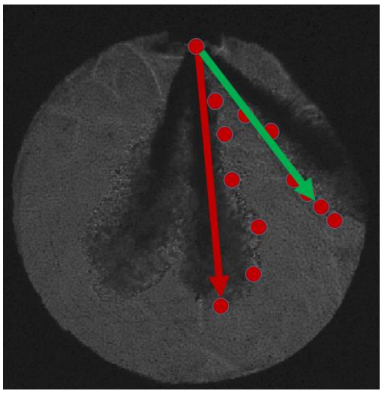
3. Then point of injection and endpoint of spray forms a vector A, whose tail is at point of injection and head at endpoint of spray.



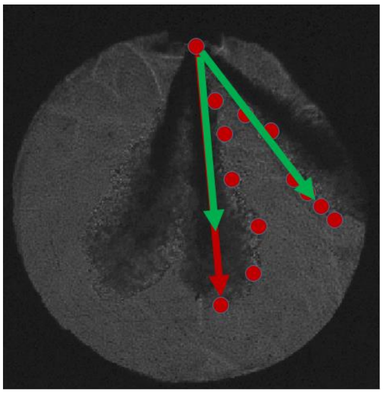
4. All the boundary points which are tracked by the matlab code are selected and only the points which are at the right of the injection points are isolated.



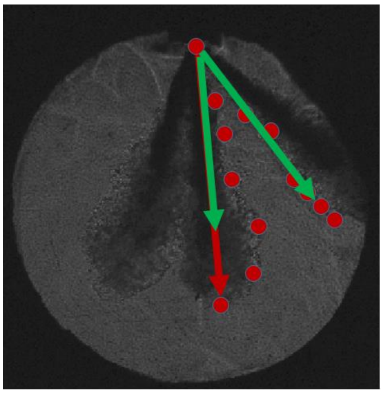
5. All the isolated points forms the Vector B.



6. Then the Vector B is projected on the Vector A.



7. Then maximum of all the projected vector B on Vector A is taken as Penetration Length.



3.3.2 Some Special Functions in Matlab for Image processing

Correction Factor: If an image is a gray scale image and we multiply it by any constant value then the constant value is basically a correction factor which multiplies the all pixel’s gray scale value by the constant value.

Imadjust: It maps the intensity values in grayscales image I to new values in J such that 1% of data is saturated at low and high intensities of I. This increases the contrast of the output image J.

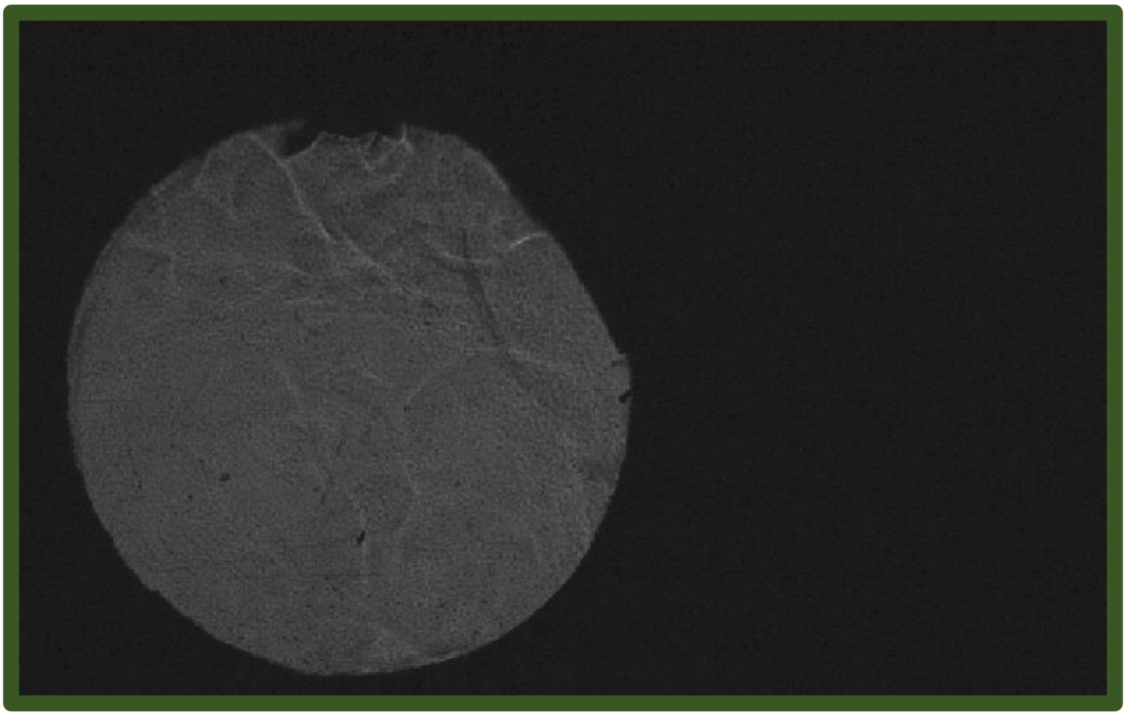
Bwareaopen: It removes from a binary image all connected components (objects) that have fewer than P pixels, producing another binary image, BW2.

Bwtraceboundary: It traces the outline of an object in binary image bw.

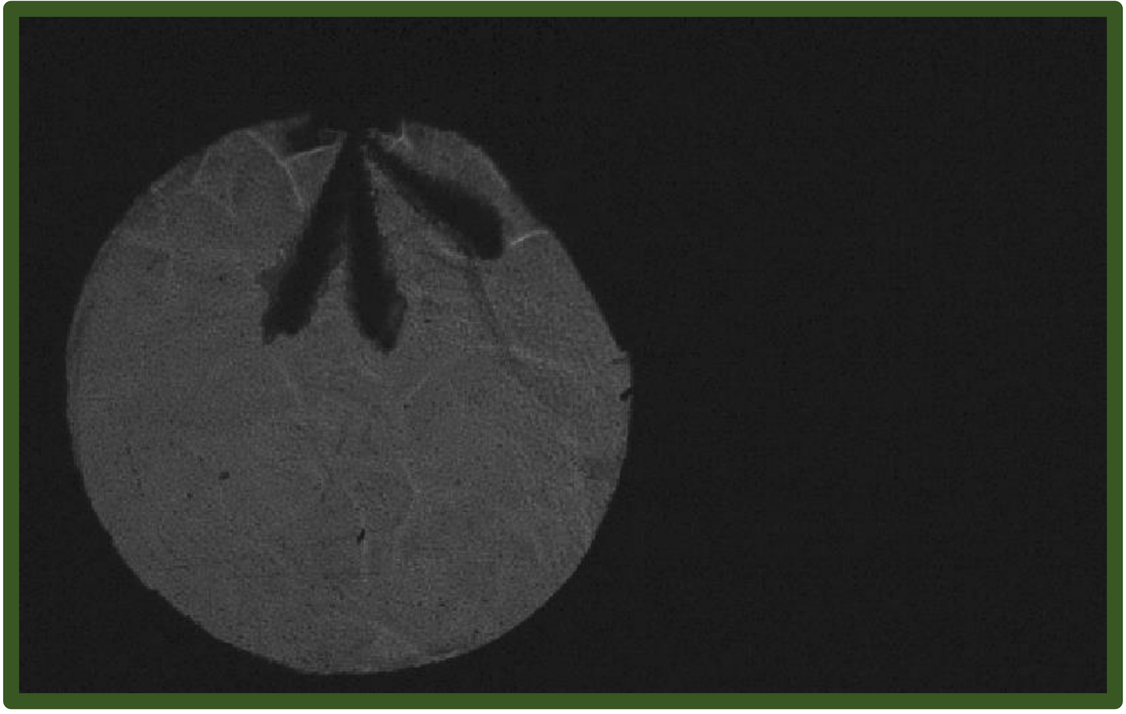
3.3.3 Image Processing Procedure

The image taken by the high speed camera were processed for a quantitative study. In order to represent a spray shape, spray penetration. Three injections were recorded with the identical conditions and processed to evaluate consistency. All scripts were written and run by MATLAB. The following steps have been followed for image diagnosis. The below steps are just an example for the illustration and done for one particular image. But the script written is automated and does the image processing for all spray in a particular experiment.

1. Select Background Image



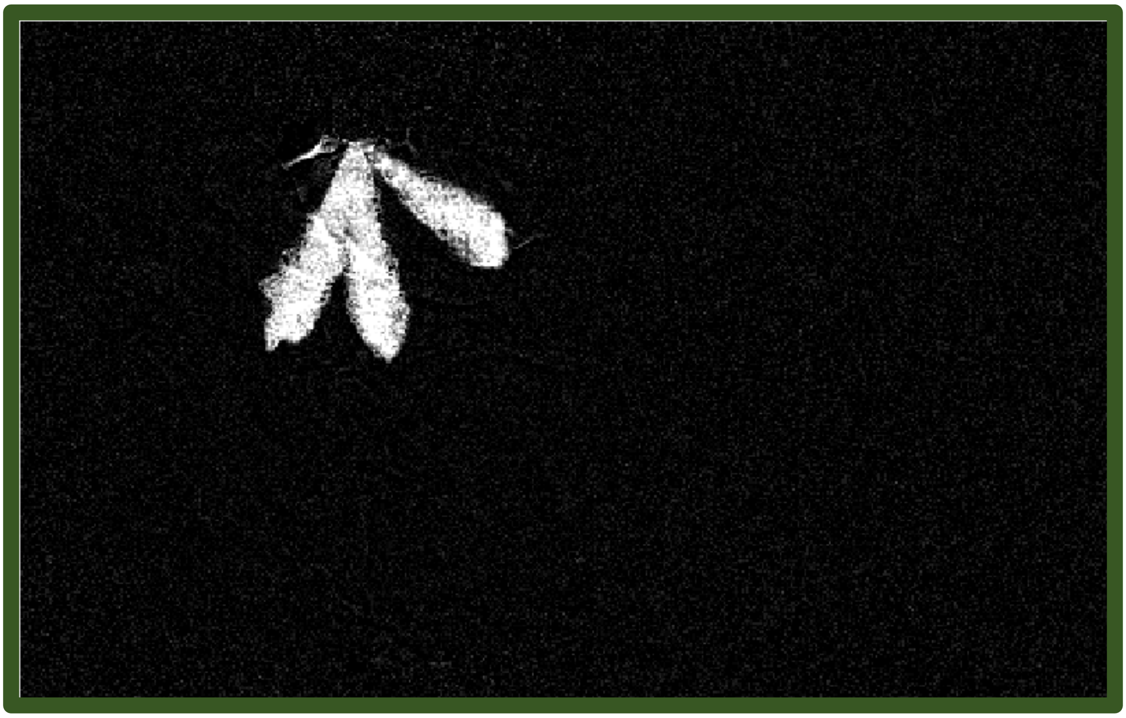
2. Select Spray Image



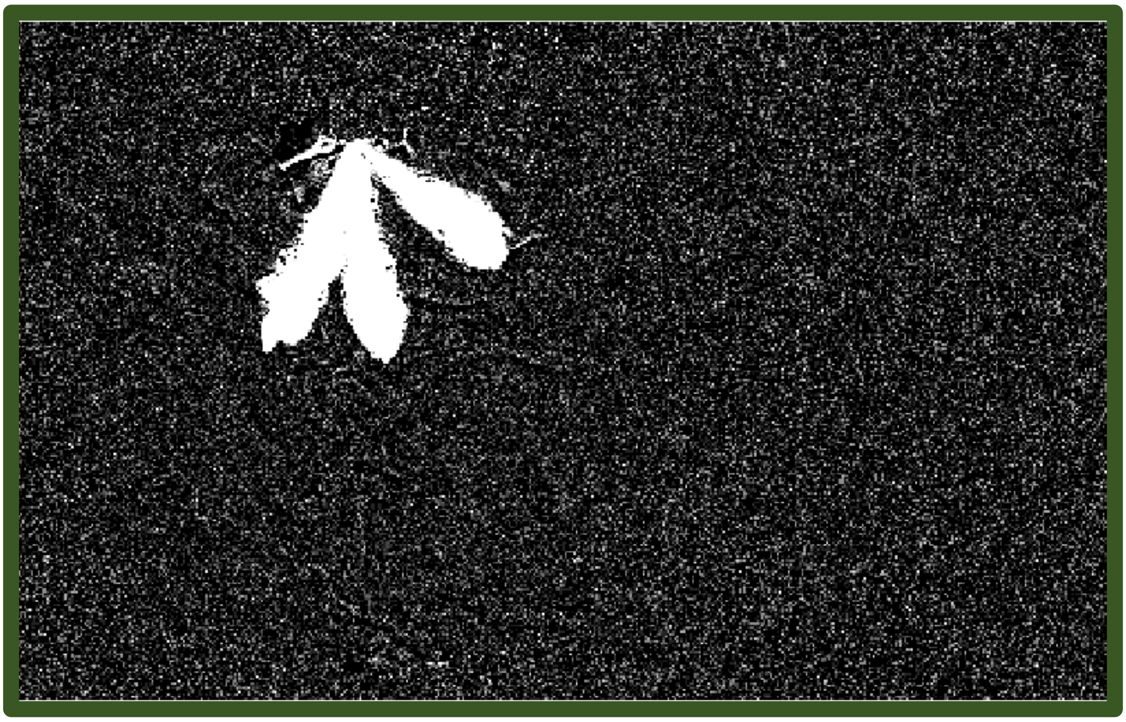
3. Subtraction of Image

4. Subtraction of Image (Correction factor 2)

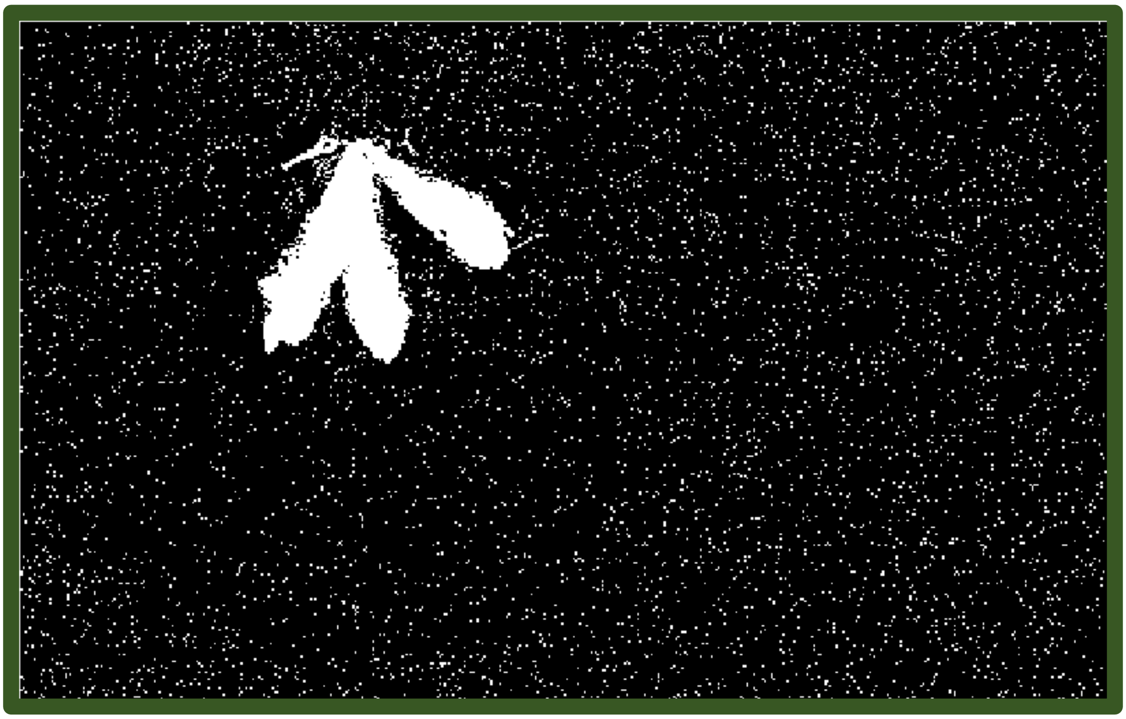
5. Imadjust



6. Imadjust (correction factor 5)



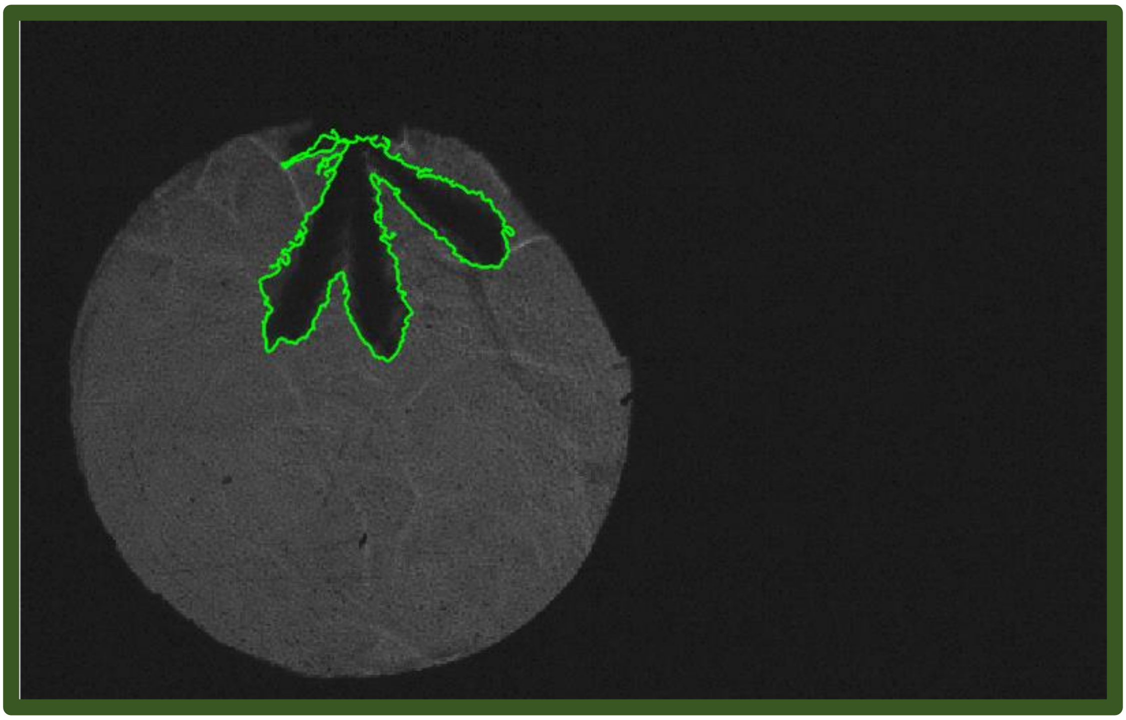
7. Im2bw



8. Bwareaopen (BW,50)

9. Bwtraceboundary

10. Boundary on original image



The following are the algorithms for the image processing

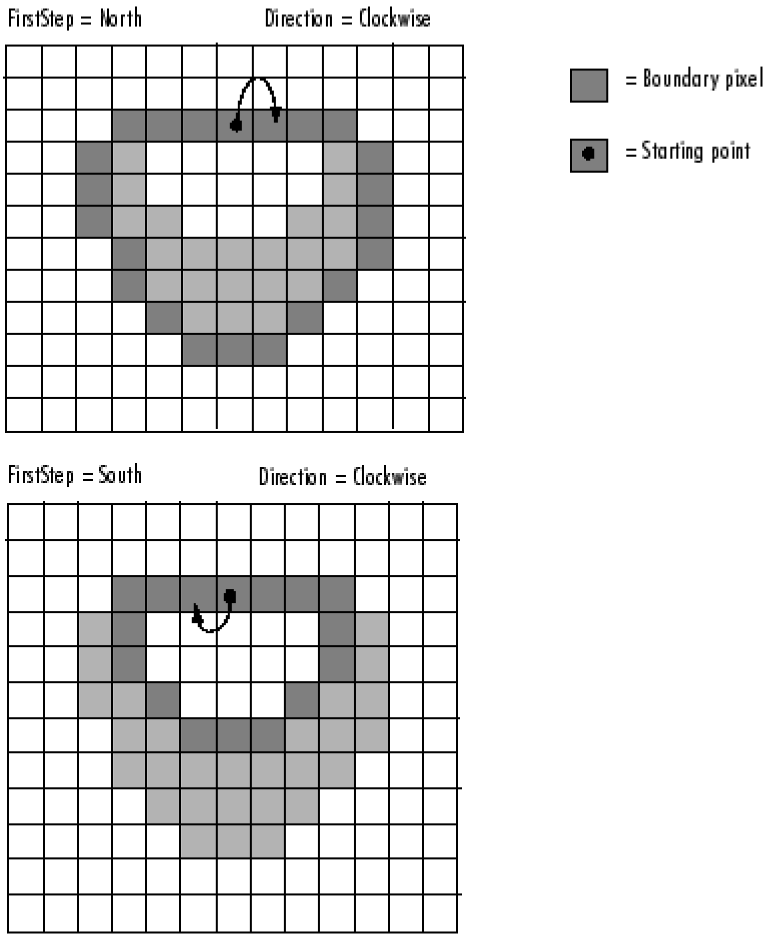
1. Read image and display it.
2. Convert the image to a binary image because bwtraceboundary only work with binary images.
3. Determine the row and column coordinates of a pixel on the border of the object you want to trace. bwboundary uses this point as the starting location for the boundary tracing.
4. Call bwtraceboundary to trace the boundary from the specified point. As required arguments, you must specify a binary image, the row and column coordinates of the starting point, and the direction the first step.
5. Display the original grayscale image and use the coordinates returned by bwtraceboundary to plot the border on the image.

Select First Step and Direction for Tracing

This paragraph shows how the first point is selected and its direction for tracing. For certain objects, you must take care when selecting the border pixel you choose as the starting point and the direction you choose for the first step parameter (north, south, etc.). For example, if an object contains a hole and you select a pixel on a thin part of the object as the starting pixel, you can trace the outside border of the object or the inside border of the hole, depending on the direction you choose for the first step. For filled objects, the direction you select for the first step parameter is not as important.

To illustrate, this figure shows the pixels traced when the starting pixel is on a thin part of the object and the first step is set to north and south. The connectivity os set to 8 (the default).

Impact of First Step and Direction Parameters on Boundary Tracing



Chapter 4

Results and Discussions

Liquid penetration length for different blend (B0, B5, B10, and B20) at different pressure has been studied as shown in figure 13, 14, 15. From the figure it is observed that after 1ms, the liquid penetration length decreases as pressure increases. As described in chapter 1, there are many parameters like aerodynamic drag forces, relative velocity between liquid and gas, the liquid and gas densities and the liquid viscosity and surface tension which affects the evaporation of liquid spray. In addition to this, as the volume is constant from ideal gas law so the pressure would be directly proportional to temperature. Hence, when temperature increases the evaporation of liquid droplets also increases.

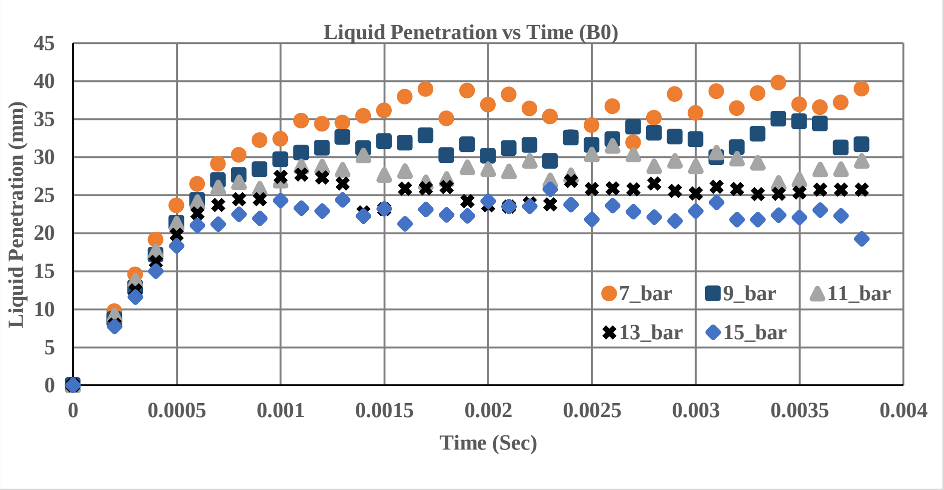


Figure 13

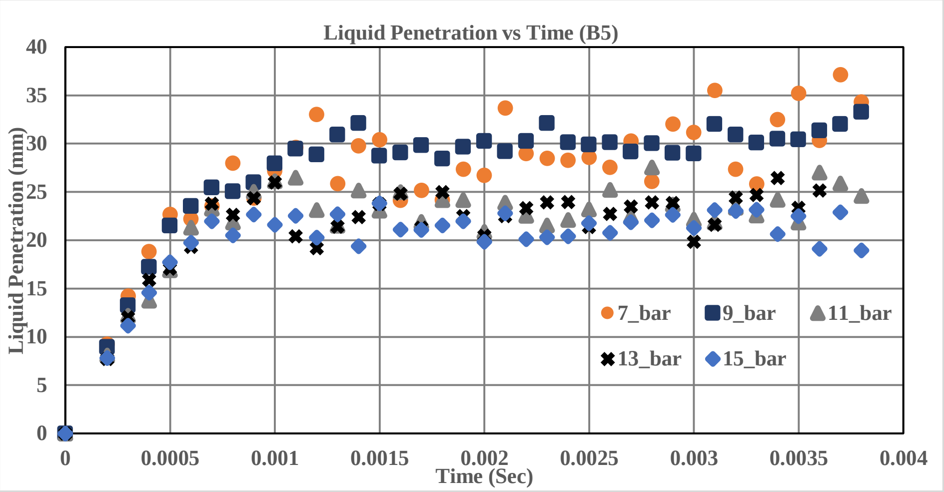


Figure 14

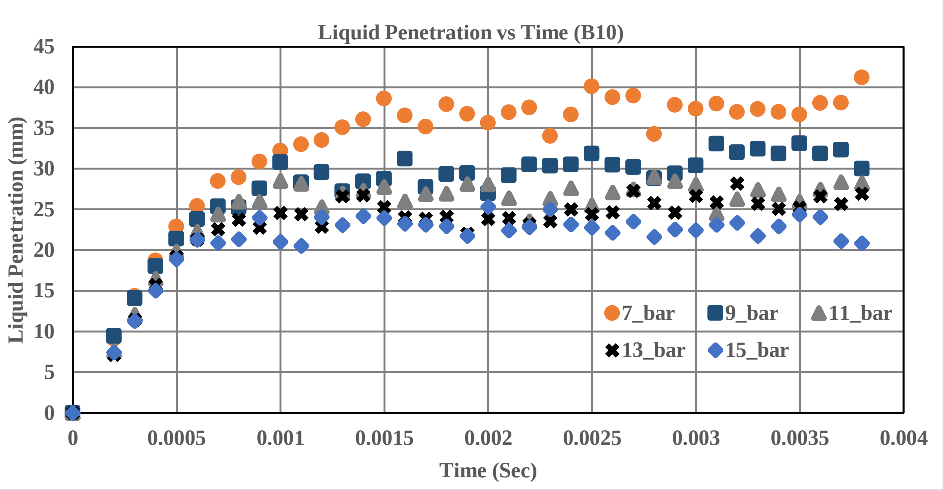


Figure 15

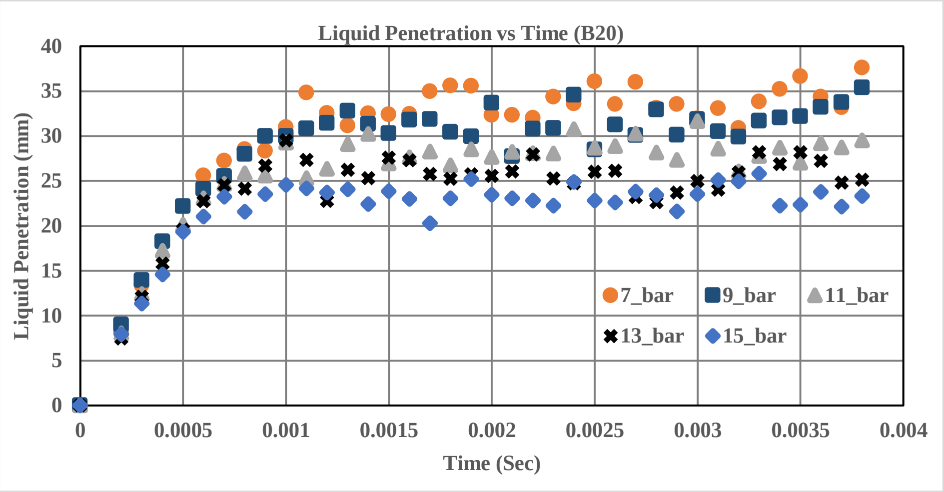


Figure 16

Below figure 17, 18, 19, 20, 21 shows the effect of pressure on vapor penetration length for all blends. It clearly shows that at the ambient temperature and pressure (at room temperature and atmospheric pressure) the vapor penetration length is more than at elevated temperature and pressure. It can be explained as the pressure increases, it does not allow the vapor to travel faster. Hence for ambient condition and at 7 bar the pressure affect is more significant than 7bar and 15bar.

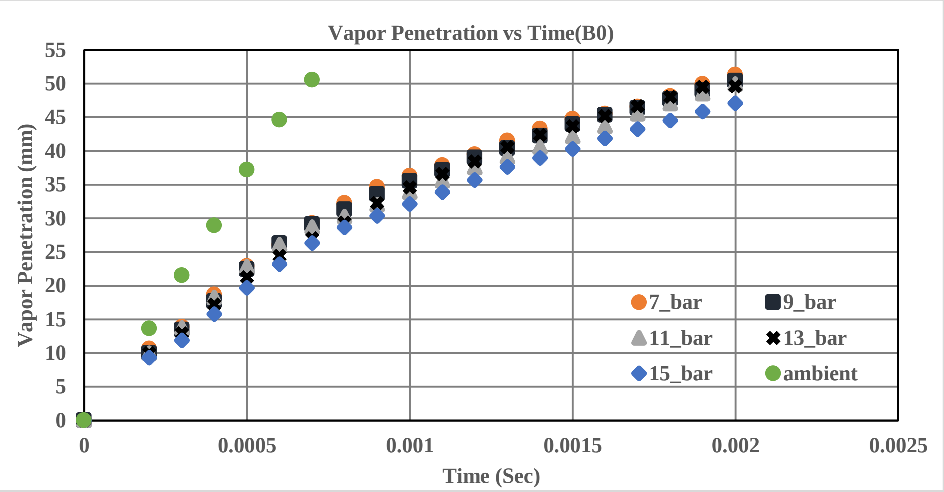


Figure 17

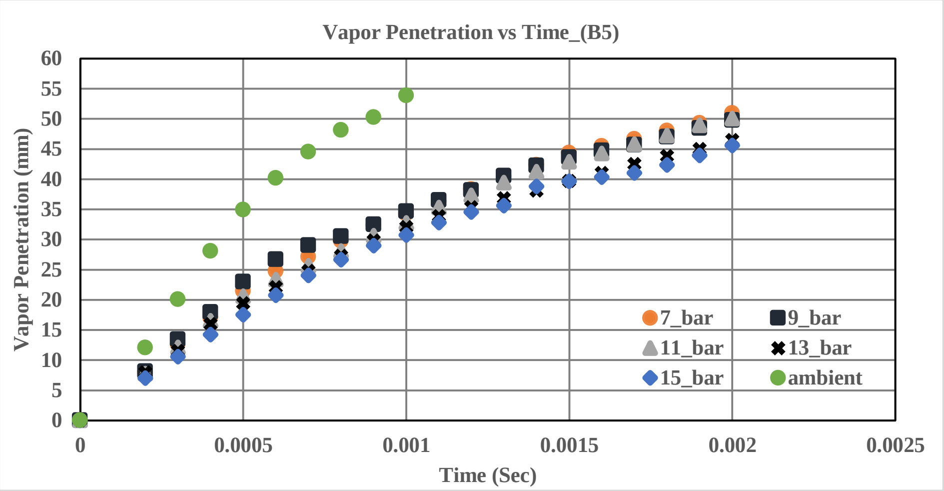


Figure 18

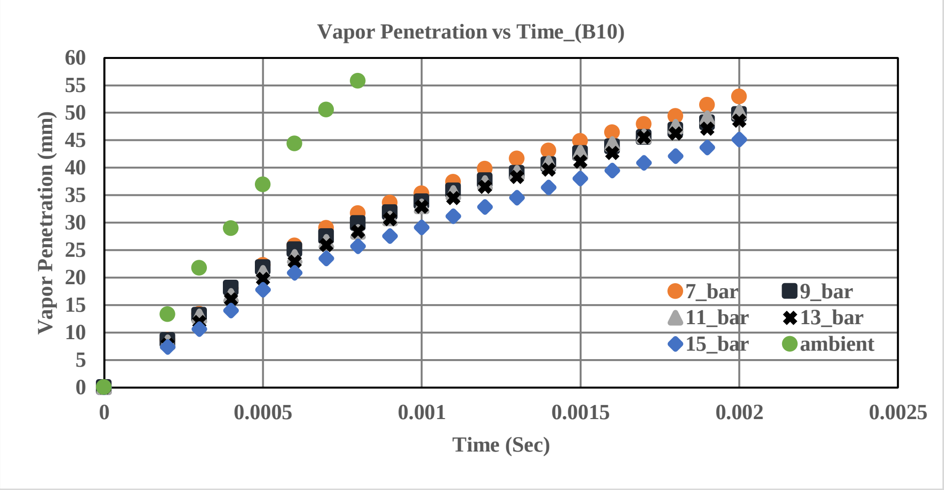


Figure 19

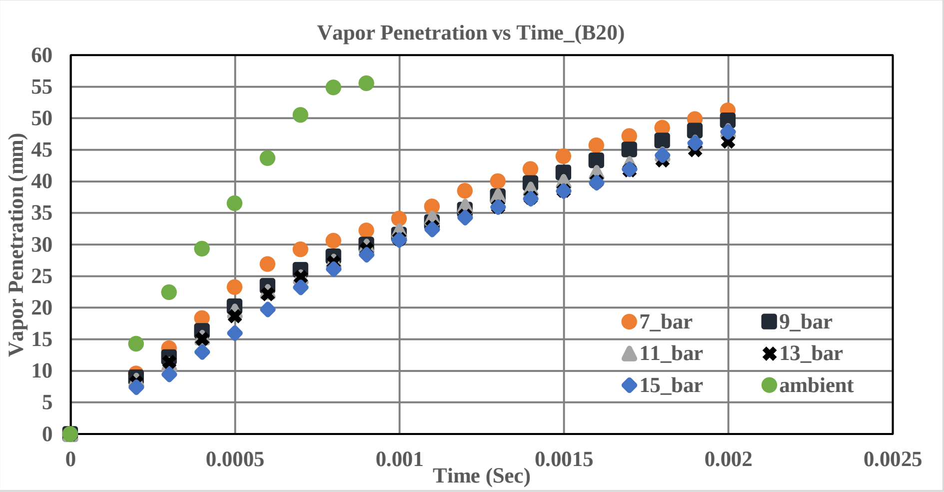


Figure 20

The experiment has been performed three times for each pressure. First the average of three experiment has been found then for the positive error bar, the average pressure is subtracted from the maximum of three pressures and the negative error bar has been defined as minimum of three experiments is subtracted from average pressure. The given figures 21, 22, 23, 24, and 25 show the liquid penetration length vs Time for all blends at different pressure. It clearly shows that penetration length comes under the error bar of others blends, which can be said that the penetration length is same for all the blends.

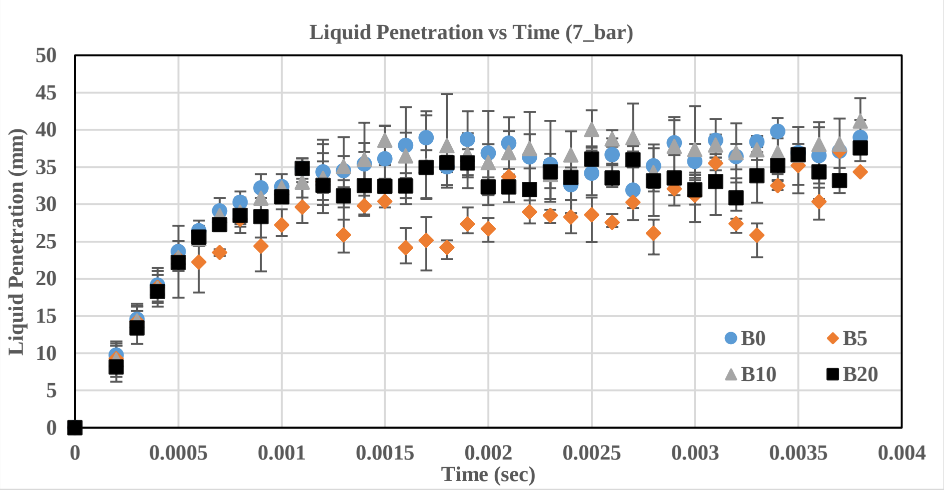


Figure 21

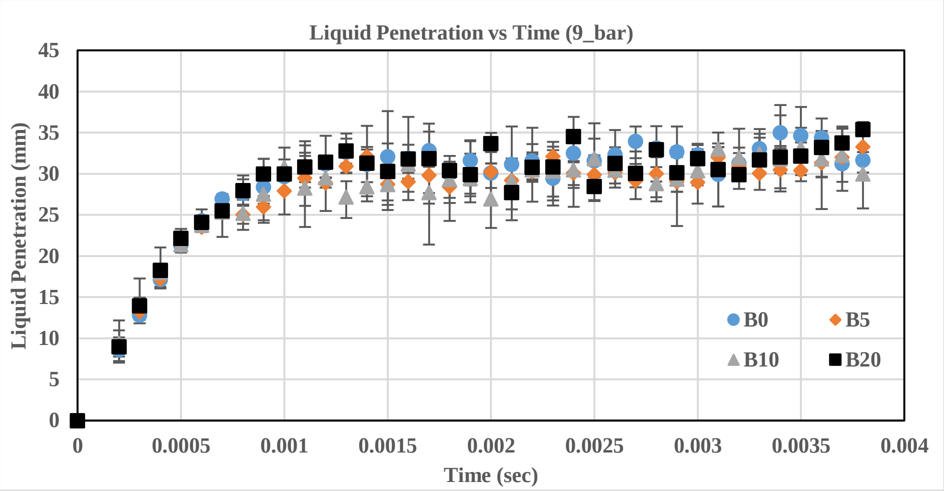


Figure 22

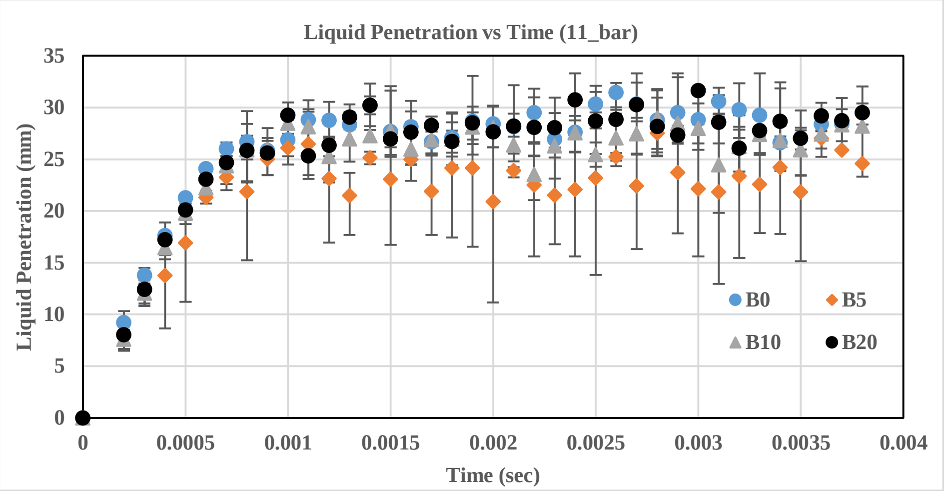


Figure 23

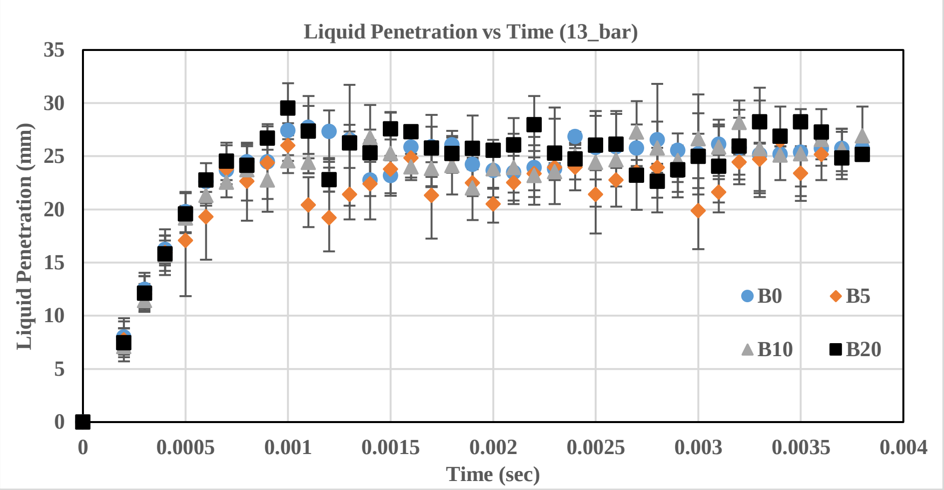


Figure 24

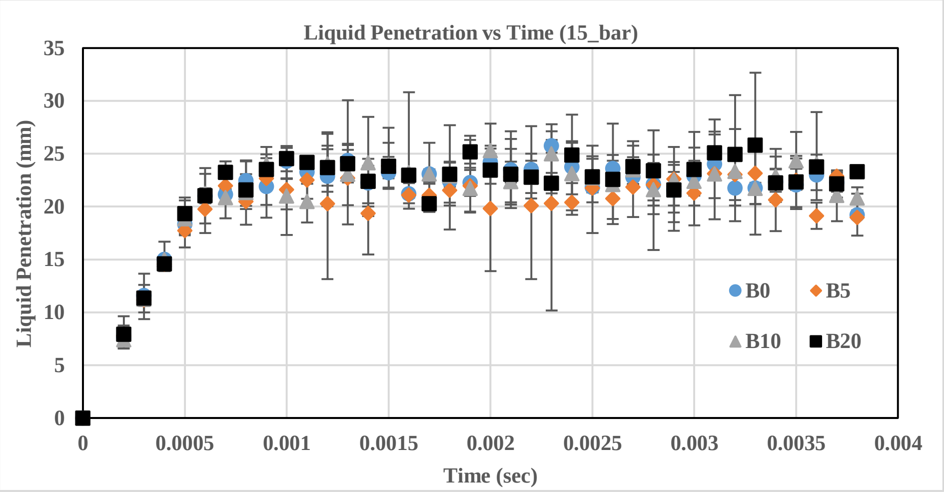


Figure 25

The same is true for the below figure 3.4a, 3.4b, 3.4c, 3.4d, 3.4e, which represents vapor penetration length vs Time. The error bar in the below figure too shows the same vapor penetration length.

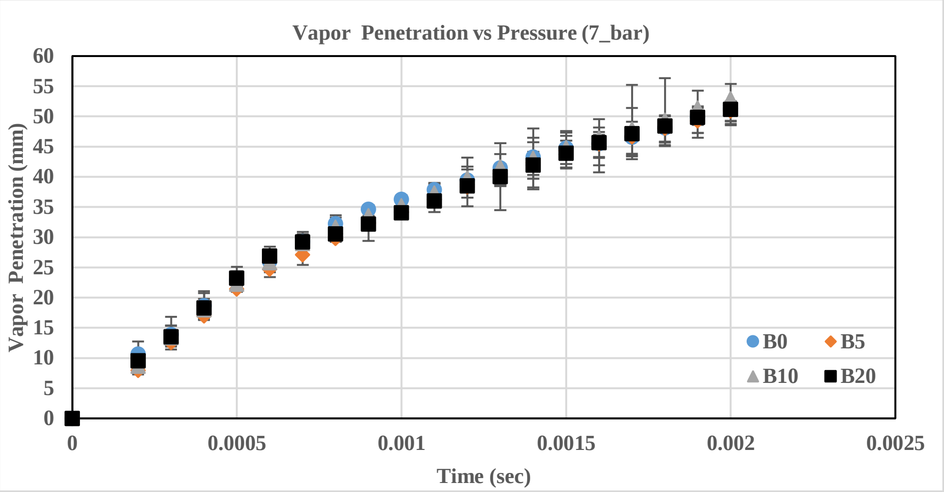


Figure 26

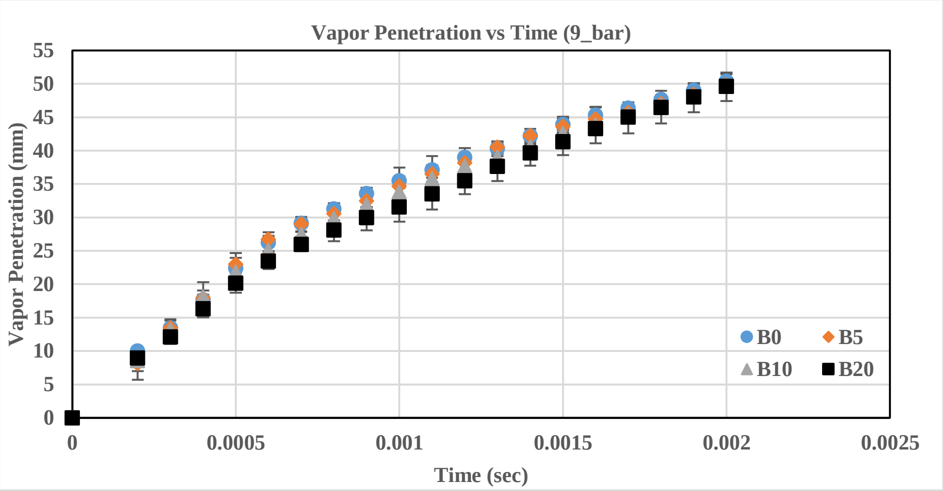


Figure 27

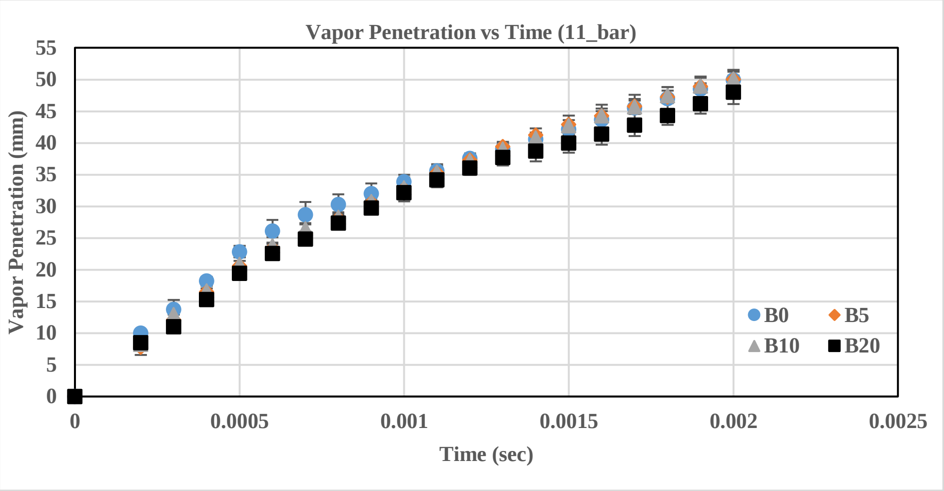


Figure 28

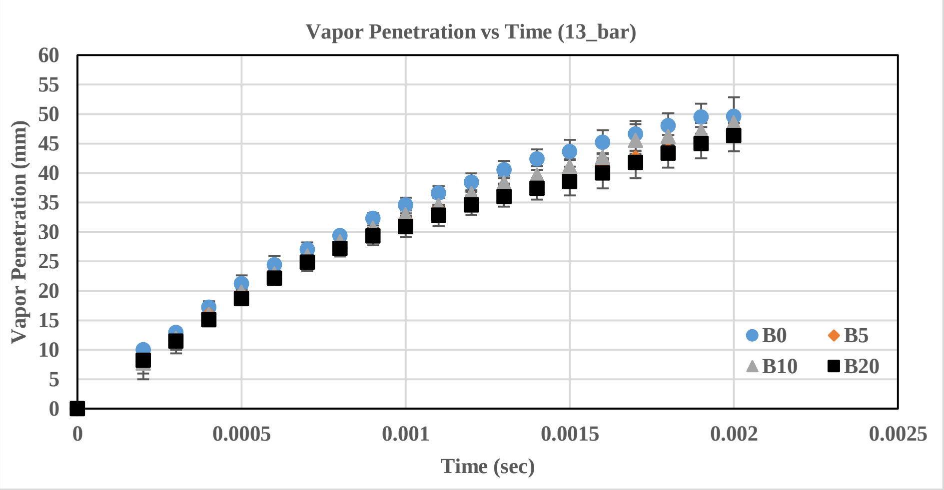


Figure 29

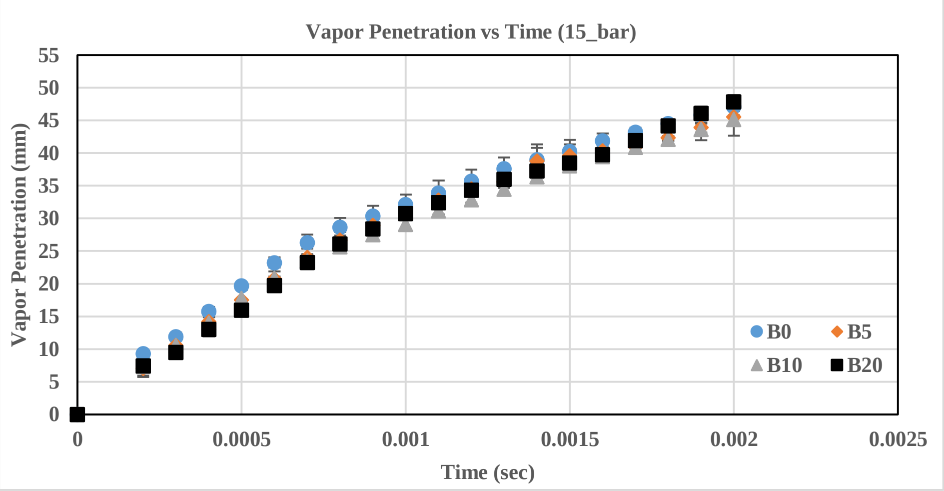


Figure 30

The below figure 31 in which error bar is basically six times standard deviation. The standard deviation of liquid penetration length has been calculated from 1ms to 3.8ms. Then average of penetration length is basically the average of penetration length from 1ms to 3.8ms. Then the graph shows basically$\bar{X} \pm 6\sigma$. Here it is observed that the liquid penetration length is same for all blends at a particular pressure and when pressure increases penetration length decreases.

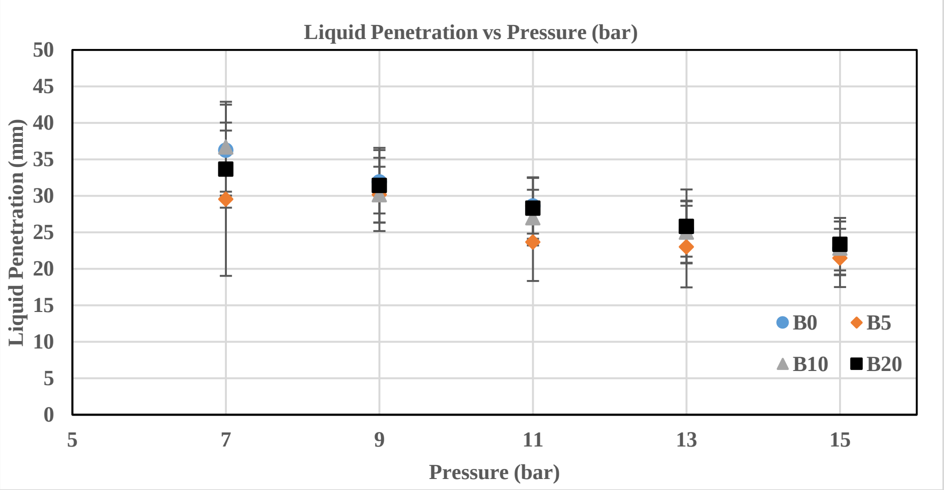


Figure 31

Conclusions

- ✓ Image processing technique has been developed for tracking Liquid and Vapor penetration Length
- ✓ Liquid and Vapor penetration lengths are strongly influenced by chamber pressure.
- ✓ Composition is not affecting the penetration lengths.
- ✓ Difference in vapor pressure seems to be small at the current blend percentages. Further analysis of change in vapor pressure of iso-octane/n-butanol mixture with respect to composition needs to be done.

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[1] http://www.fedprimerate.com/crude-oil-price-history.htm

[2] EPA (US Environmental Protection Agency), a comprehensive analysis of biodiesel impacts on exhaust emissions. EPA420-P-02-001 October 2002; 1-14.

[3] http://www.afdc.energy.gov/vehicles/diesels_emissions.html

[4] National policy on biofuels, ministry of new and renewable energy, government of India.

[5] http://www.statista.com/statistics/200002/international-car-sales-since-1990/