Determination of sauter mean diameter of four different fuels and their effects on performance and emission in a CI engine

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By

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CERTIFICATE

This is to certify that the thesis entitled, "**Determination of sauter mean diameter of four different fuels and their effects on performance and emission in a CI engine**" submitted by **Mr. Niraj Toppo** in partial fulfilment of the requirements for the award of Master of Technology in Mechanical Engineering with Thermal Engineering specialization during session 2012-2013 in the Department of Mechanical Engineering, National Institute of Technology, Rourkela.

It is an authentic work carried out by him under my supervision and guidance. To the best of my knowledge, the matter embodied in this thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

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ABSTRACT

Spray characteristics play a vital role on mixture formation of injected fuel with air in a compression ignition (CI) engine. The better mixing rate of fuel with air helps to improve performance and reduce the tailpipe emissions of the CI engine. Spray characteristics are generally influenced by engine's injection characteristics and fuel quality. The physical properties of fuels like viscosity, density, bulk modulus and surface tension affect the droplet size that causes spray formation. In this experimental study, the droplet size in terms of sauter mean diameter (SMD) of different non conventional liquid fuels were studied experimentally and compared the performance and emission parameters with diesel fuel. For this purpose, an experimental setup was developed in a lab scale to capture the droplets of injected fuel at 200 bar injection pressure. The fuel was injected on a magnesium oxide coated plate materials. The droplet size and spray angle were measured with the help of image analyzer. The results showed that as the blending ratio increases, the spray size distribution and mean diameter become large. For all the blended fuel Sauter mean diameter (SMD) is higher than that of diesel.

KEYWORDS- Sauter mean diameter, Image analyzer, Magnesium oxide, blended fuel.

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NOMENCLATURE

Sl. No.	Short form	Full form
1	SMD	Sauter mean diameter
2	CI	Compression ignition
3	TPO	Tyre pyrolysis oil
4	WPO	Wood pyrolysis oil
5	UTO	Used transformer oil
6	JME	Jatropha Methyl Ester
7	JOE	Jatropha Oil Emulsion
8	H_2O	Water
9	CO_2	Carbon dioxide
10	CO	Carbon monoxide
11	NO	Nitric Oxide
12	MgO	Magnesium oxide
13	CR	Compression ratio

CHAPTER 1
INTRODUCTION

1.1 GENERAL

In a compression ignition (CI) engine, the fuel is introduced into a hot air stream and gets ignited and burnt. This is in contrast to the spark-ignition (SI) engine which uses a spark plug to ignite an air-fuel mixture. The CI engines are manufactured in two-stroke and four-stroke versions. Since the 1910s, they have been used in submarines and ships. They were introduced in locomotives, trucks, heavy equipment and electric generating plants later. In early 1930s, the use of CI engines was picked up in a few automobiles. Since 1970, CI engine have been used larger on-road and off-road vehicles. As of 2007, about 50% of all new car sales in Europe are the CI engines. Now a days, the CI engines are more preferred than SI engine because, the former has a higher thermal efficiency and durability than the later. As a result, the diesel fuel consumption increases drastically. The diesel run automotive vehicles and stationary engines emit more pollutants to the environment. The fuel quality plays an important role on the combustion parameters. The fuel quality also predominantly affects the formation of emissions in the CI engines. As there is a heavy demand for CI engine fuel, many researchers and engineers try to explore and utilize variety of alternative fuels. Before, utilizing any alternative liquid fuel in a CI engine, it is necessary to study the fuel properties and the spray formation of fuel.

1.2 ENERGY SCENARIO OF CI ENGINE APPLICATION IN INDIA

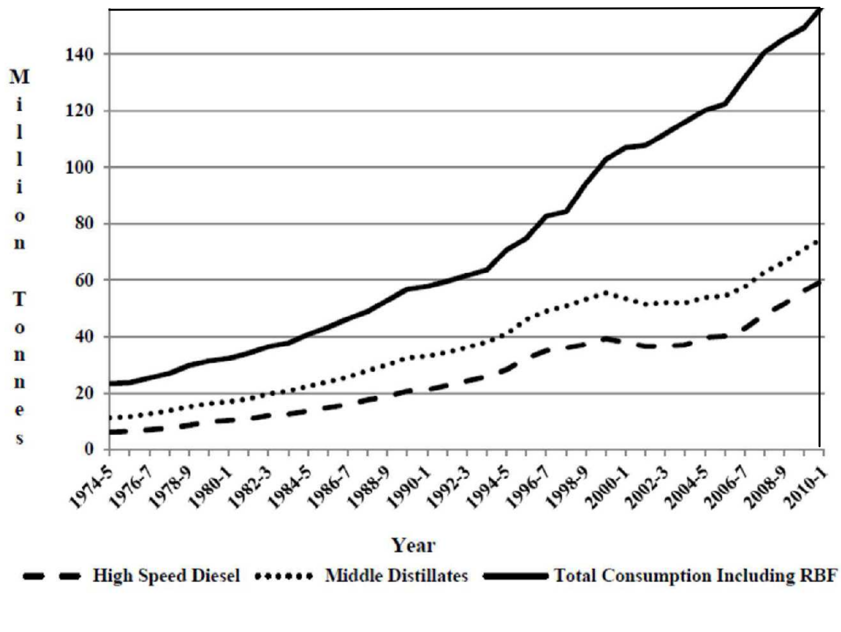


Figure 1.1 Consumption of diesel and petroleum products in India,1974-1975 to 2010-11

Figure 1.1 illustrates the consumption of diesel during the period 1974-2011. It is seen from Fig.1.1 that the consumption has significantly increased from six million tonnes to about 60 million tonnes between the years 1974-1975 and 2010-2011. During that period, the shares of diesel in total consumption of petroleum products has varied from 27 percent in the period 1974-1975 to a high 43 percent in the years 1995-1996 and 1997-1998 respectively.

1.2.1 USES OF DIESEL IN INDIA

Among the existing fuels, diesel presents wide applications in India. Diesel is consumed in the following applications:

1.2.1.1 Transportation

Goods – railways (freight), maritime (carriers, liners), military vehicles, heavy and light commercial vehicles; Passenger – railways, roadways [buses, personal vehicles (cars, utility vehicles)], waterways [motor-boats, steamers, ferries, catamarans, yachts, cruise ships].

1.2.1.2 Power generation

Power plants, industrial captive power, back-up generators (large commercial, residential units). Diesel engines are used in running water-pumps for irrigation is likely accounted under either 'power generation' or more likely 'farm equipment'. Diesel engines are used to power mobile telephone towers which are likely accounted under 'power generation'. Some suggest that roughly one-third of diesel for power generation caters to the need of the telephone towers.

1.2.1.3 Industry

In industry, diesel is generally used as stand by for conveyors, pumps and motors. To meet the emergency power needs, the switch gears involved continuously monitors the electrical current and if the power is interrupted for any reason it automatically loads to the generators. Today, many five star hotels, manufacturing plants, municipal buildings, data centres, tele-communication organizations, hospitals, nursing homes, financial institution, mining companies and financial institution have diesel engine generators as back up.

1.2.1.4 Agriculture

Diesel technology is used for the world's farms and ranches, powering two-thirds of all farm equipment. The typical use of diesel in agriculture: used to pump the water or provide power for growing crops or raising livestock. Agriculture uses diesel engines as the source to power almost $19 billion worth of tractors, combines irrigation pumps and other farm equipment.

1.2.1.5 Military equipment

Diesel engines are used to move weapons systems and to power all kinds of auxiliary mobile and stationary equipment, including generators, compressors, pumps, most of the amphibious force vessel (e.g. vehicle transporting troops equipments, material to mission sites), Auxiliary ships (e.g. combat support vessels), Military sealift command (All oilers and fleet ocean tugs, combats stores etc.), Navy sealift force (e.g. Tanker and Roll-on-Roll off ships), Ice-breakers propelled by diesel-electric systems (e.g. work horse icebreakers), Most armor and self-propelled artillery are diesel powered, with a wide range of uses and functions(e.g. armored personnel carriers, ambulances, mortar carriers, anti-aircraft gun carriers, missile launchers), almost all military equipments and logistics systems (e.g. prime movers, heavy-equipments transporters, special attack vehicles etc.).

Table 1.1 gives the share of diesel consumption in broad areas of economic activity, in India. The contribution of respective activities to GDP is also presented. It is observed that diesel is used as an input in activities that together account for about two-fifths of GDP in India during 2008-9 and 2009-10.

Table 1.1 Sector-wise share of GDP and total diesel consumed (percent)

Sector	Mode	Diesel consumed			GDP	
		2008-9	2009-10	2010-11	2008-9	2009-10
Transportation	Railways	4.2	4.0	4.0	1.0	1.0
	Water	1.4	1.2	0.9	5.6	5.5
	Aviation	Negligible				
	Road	59.6	60.0	60.4		
Industry		10.2	10.7	10.5	15.6 (10.6)	15.9 (10.7)
Power Generation		8.3	8.3	8.2	2.0	2.0
Agriculture		11.9	12.1	12.2	15.7 (13.3)	14.6 (12.3)
Miscellaneous		4.2	3.5	3.6		

1.3 FUELS FOR CI ENGINES

An internal combustion (IC) engine converts the heat energy obtained from the chemical combination of fuel with oxygen, into mechanical energy. Since, the heat energy is derived from the fuel, a fundamental knowledge of the types of fuel and their characteristics is essential in order to understand the combustion phenomenon. The characteristics of the fuel have considerable influence on the design, efficiency, output and particularly, the reliability and durability of the engine. CI engines can be operated on different types of fuels liquid, gaseous and solid fuels. Depending upon the types of fuels to be used the engine has to be designed accordingly. An alternative fuel may be a renewable or non-conventional fuel derived from various organic substances that can substitute or replace conventional fuels for CI engines to a little or a greater proportion. Conventional fuels include fossil fuels (petroleum (oil), coal, propane, and natural gas), Some well-known alternative fuels include biodiesel, alcohol (methanol, ethanol, butanol), chemically stored electricity (batteries and fuel cells), hydrogen, non-fossil methane, non-fossil natural gas, vegetable oil, and other biomass sources.

1.3.1 SOLID FUELS

The solid fuels find less practical applications at present, because of the problems associated with the handling and disposal of ash after combustion. However, in the initial stages of the engine development, solid fuels such as finely powdered coal were attempted. Compared to the gaseous and liquid fuels, the solid fuels are quite difficult to handle, store and feeding are quite cumbersome. Because of the complications in the design of the fuel feed systems, these fuels have become unsuitable in solid forms. Attempts are being made to generate gaseous or liquid fuels from charcoal for the use in CI engine. Examples of solid fuels include coal, charcoal and biomass.

1.3.2 LIQUID FUELS

In most of the modern CI engines, liquid fuels which are the derivatives of liquid petroleum are being used. Liquid fuels are easy to transport, and can be handled with relative ease. Also, they are relatively easy to use for all engineering applications, and home use. Most of the liquid fuels are derived from crude oil; however, fuels such as hydrogen, ethanol, and biodiesel, derived from the biomass and the other feed stocks are also categorized as liquid fuels. Crude oil is formed from the fossilized remains of dead plants and animals by exposure to heat and pressure in the earth's crust. Petroleum products are the main fuels for IC engines as on today. There are varieties of alternative liquid fuels considered presently which are biodiesel, alcohol, vegetable oil etc.

1.3.2.1 BIODIESEL

Biodiesel is a methyl or ethyl ester of fatty acid made from vegetable oils and animal fats. It was discovered even before fossil fuel like gas, coal and oil. It is environmental friendly than other fuel like petrol or diesel. It is a clean fuel and a more economic as it encourages the recycling process and can be manufactured from waste oils. It can be easily pumped and handled. It contains no petroleum and it can be blended with diesel at any level to create biodiesel blends. The use of biodiesel in a CI engine results in reduction of unburned hydrocarbons, carbon monoxide and particulate matter emissions. Biodiesel is a clean fuel, as it contains no sulphur, no aroma but it contains 10% oxygen, which helps it to burn fully. It has been designated as an alternative fuel by the U.S. Department of energy and the Department of Transportation. The raw materials for biodiesel vary for each country. Sunflower, rape seed oil etc., are used as a raw material in Europe, soyabean is used as a raw material in the U.S, palm oil is used in Thailand and, frying oil and animal fats is used in Ireland. Biodiesel can be used in diesel engines as B5, a blend of 5% biodiesel in diesel fuel or B20 or B100. In India, biodiesel is produced from non edible oils obtained from Jatropha cureas, Karanj, Mahua (Madhuca Indica) etc. The by product of biodiesel from the process are the seed oil cake and glycerol, which have good commercial values.

1.3.2.2 ALCOHOLS

Alcohols are used as an alternative fuel, because they can be easily obtained from natural and manufactured sources. Alcohols are of two types, ethanol and methanol which can be produced from sugarcane waste, and many other agricultural products. All starch rich plants like maize, tapioca, and potato can also be used to produce alcohol as well as cellulosic waste materials can also be used.

The main advantages of alcohol as an alternative fuel are as follows;

- (i) Alcohol can be obtained from a large number of sources either natural or artificial.
- (ii) It emits less emission when compared with gasoline.
- (iii) It is a high octane fuel and has higher flame speed.
- (iv) It has very less sulphur content.
- (v) It gives higher pressure and more power in the expansion stroke.

The disadvantages of alcohols as fuels are as given below;

(i) Alcohol has a low calorific value.

(ii) It has very poor ignition characteristics, because of high octane number.

(iii) Its flame is invisible which is very dangerous during handling of fuel.

(iv) It produces aldheydes after combustion.

(v) Alcohol fuel has low lubricating qualities which creates trouble in injection pump and nozzle.

1.3.2.3 METHANOL

Methanol is the most promising fuel in future which can be obtained from fossil fuel and renewable sources. This includes wood, coal, biomass, petroleum, natural gas etc. Methanol is not good for CI engines, due to its high octane number, but if a small amount of diesel fuel is used for ignition, it can give a good result. Methanol can be obtained from a cheaper source as compared to diesel. Pure methanol and mixture of methanol and gasoline in various proportions have been extensively tested in engines, the most common mixture are M85 (which have 85% methanol and 15% gasoline) and M10 (which have 10% methanol and 90% gasoline).

1.3.2.4 ETHANOL

Ethanol is produced from ethylene or made by fermenting sugar components of the plant materials and it is mostly made from sugar, beats, corn, sugarcane and starch crops. With the advanced technology, cellulosic biomass like trees and grasses are used as feed stocks for production of ethanol. Ethanol can be used as a fuel for the vehicles in the pure form, but it is mainly used as a gasoline additive to increase the octane number and improve the vehicle emissions. Ethanol has been used as an alternative fuel in various countries of the world for many years. It is widely used in USA and in Brazil.

1.3.2.5 VEGETABLE OIL

Vegetable oil can also be used as an alternative liquid fuel for diesel engines, because they are renewable in nature, easily available and can reduce CO_2 emissions. There are many vegetable oils like peanut oil, linseed oil, rapeseed oil which can be used in diesel engines directly or when blended with diesel fuel. The draw backs associated with the use of vegetable oils in CI engines are given below;

(i) The viscosity of vegetable oil is much higher than diesel. It can cause many problems such as fuel handling, atomization and fuel jet penetration.

(ii) Vegetable oil burns slowly. It can give rise to exhaust smoke, fuel impingement on cylinder wall and contamination of lubricating oil.

1.3.3 GASEOUS FUELS

Gaseous fuels are preferred in CI engines and pose no problems as, they mix more homogenously with air and eliminate the distribution and starting problems that are found with liquid fuels. Even though the gaseous fuels are most ideal for CI engines, the problems associated with the storage and handling problems restrict their use in automobiles. Consequently, they are more commonly used in stationery power plants that are located near the source of fuel. Some of the gaseous fuels can be liquefied under pressure for reducing the storage volume. But, this arrangement is very expensive as well as risky. Because of the energy crisis in the recent years, considerable research efforts are being made to improve the design and performance of the engines. Hydrogen fuel is treated as the main alternative gaseous fuel.

1.3.3.1 HYDROGEN

Hydrogen has the potential to solve the environmental problem, air pollution and global warming. Utilization of hydrogen as a fuel for engine is not a new concept. Hydrogen could meet the twin challenges of energy crisis and environmental pollution. Hydrogen can be produced from renewable source. The common pollutants which come out of the exhaust of a gasoline or diesel engine are practically absent in case of hydrogen fueled engine.

The advantages of hydrogen as an alternative fuel are as follow;

(i) There is no carbon in the fuel, so there is no CO or HC in the exhaust of the engine.

(ii) Hydrogen is available in abundance and there are large numbers of different ways of making hydrogen.

(iii) Fuel leakage to the environment is not a problem as it is pollutant free.

(iv) It has high energy content per volume when stored as a liquid.

(v) Hydrogen as an engine fuel is exceptionally clean burning.

1.4 COMBUSTION IN RECIPROCATING ENGINES

In a CI engine, diesel as a fuel is injected at high pressure. During the compression stroke, the air temperature rises to such an extent that when liquid droplets is injected, ignition takes place. One of the major requirement of the CI engine is that ignition should take place very fast. The typical time available for combustion in an engine, for example an engine running with 1500 revolution per minute is 2-4 ms. This requires the droplet size to be very fine. The other requirement for ignition is the environmental conditions, under which it's operates.

1.4.1 DROPLET COMBUSTION [3]

In a CI engine, the air is compressed in the combustion chamber at a high pressure, and the diesel fuel is injected into the combustion chamber in the form of fine spray. In order to know the droplet combustion, it is necessary to determine the burn rate of a liquid droplet, and the thermodynamic and transport properties of the droplet in the combustion chamber.

Burn rate which is a function of diameter is affected by the flow of oxygen past the droplet by free or forced convection. In case of free convection, burn rate is dependent on Grashoff number, and in case of forced convection, it is dependent on Reynolds number.

The differential equation for energy conservation is;

$$\frac{d}{dr}4\pi k r^2\frac{dT}{dr} - \dot{m}\frac{d}{dr}C_pT = 0 \text{ -------- (1.1)}$$

This differential equation is of second order, in which $\frac{d}{dr}4\pi k r^2\frac{dT}{dr}$ represents the conduction heat transfer and the term, $\dot{m}\frac{d}{dr}c_pt$ represents the convection heat transfer.

Now applying the boundary equation;

At $r = r_s$, $T=T_s$

And when $r \to \infty,\ \ T \to T_0$

The equation (1.1) becomes

$$[4\pi r^2 k\frac{dT}{dr}]_{r_s}=\dot{m}L \text{ --------- (1.2)}$$

Where L=latent heat,

In the above equation,

Heat transferred from the outer region to the surface =heat taken away by vaporising liquid.

Again from equation (1.1) and (1.2)

$$\dot{m} = 4\pi r_s(k/c_p)_g\ln(1 + B_v) \text{------- (1.3)}$$

Where, $B_v = C_p(T_0 - T_s)/L$, called the transfer number, which indicates the thermodynamic potential to cause vaporisation. K is the thermal conductivity or transport property and c_p specific heat at constant pressure.

Equation (1.3) indicates the vaporisation rate, which is directly proportional to radius of droplets. The dependence on transfer number is weak as logarithmic term changes little for large variation of B_v. This shows that time for combustion is much smaller than that for vapourisation, which is affected by the transfer number.

1.5 OXIDISER FOR COMBUSTION

Oxidiser is one which accepts electron and fuel is one which can donate its electron. Oxidisers are composed of carbon, hydrogen, nitrogen, oxygen and other CI elements. The various elements which are categorised in terms of donating the electron and receiving the electron are shown by a table called electro negativity table. Table 1.2 gives the Pauling's electro negativity in ascending order.

Table1.2 Electro-negativity of elements

Elements	Electro-negativity	Elements	Electro-negativity
K	0.8	H, P	2.1
Na, Ba	0.9	C, S, I	2.5
Li, Ca	1.0	Br	2.8
Mg,	1.2	N, Cl	3.0
Be, Al	1.5	O	3.5
B	2.0	F	4.0

As we see from Table 1.2, the fluorine has the highest capacity of accepting the electron. The next elements after fluorine are oxygen, chlorine, bromine and iodine. The elements which donate its electron are known as fuel which is carbon, hydrogen, aluminium, magnesium, lithium etc.

1.5.1 AIR AS AN OXIDISER [3]

As fluorine has the highest capacity of accepting the electron, it is very powerful oxidiser, which would react very quickly and form stable products. Therefore, it can't be used as an oxidiser in combustion. The next element after fluorine is oxygen which is most abundantly available and a powerful oxidiser. The power produced by oxygen is very high so it is diluted with inert substance nitrogen to reduce its power.

1.5.2 STOICHIOMETRIC RATIO

Stoichiometric ratio implies the ratio of oxidiser to fuel, which leads to complete product of combustion. The elements which are used as a fuel are carbon and hydrogen and the elements which are used as an oxidiser are oxygen. The stoichiometric reactions are represented as:

$$H_2 + 1/2O_2 \longrightarrow H_2O \quad \text{-------(1.4)}$$

$$H_2 + (1/2)\ O_2 + [79\ /\ (21x2)\ N_2] \longrightarrow H_2O + [79/(21x2)N_2] \quad \text{-------(1.5)}$$

$$CH_4 + (3/2)\ O_2 \longrightarrow CO_2+H_2O \quad \text{-------(1.6)}$$

$$CH_2 + (3/2)\ O_2 + (79/21)\ x\ (3/2)N_2 \longrightarrow CO_2+H_2O + (79/21)x(3/2)N_2 \quad \text{-------(1.7)}$$

In the above equation (1.4), one mole of hydrogen react with half mole of oxygen to give one mole of H_2O or 2 gm of hydrogen reacts with 16 gm of oxygen to give 18 gm of water. The stoichiometric ratio for the above equation is 16/2=8.

In equation (1.5) 1 mole of H_2 react with ½ mole of oxygen and 1.88 mole of N_2 to give 1 mole of water and 1.88 mole of nitrogen. The stoichiometric ratio in this case is 16+[(79/(21x2))x28]/2=34.4.

The stoichiometric ratio in equation (1.6) is 3.4, and in equation (1.7) is 14.7. Thus, we see that in equation (1.7) there is no excess oxygen left with the product being CO_2, H_2O and N_2. The proportion of air to fuel is termed as stiochiometric ratio which is 14.7.

1.6 PRINCIPLE OF FOUR STOKE DIESEL ENGINE

Diesel engines can be of two types based on the number of strokes; (i) two stroke and (ii) four stroke. Four stroke diesel engines are highly preferred than two stroke engines because of the former have the following merits:

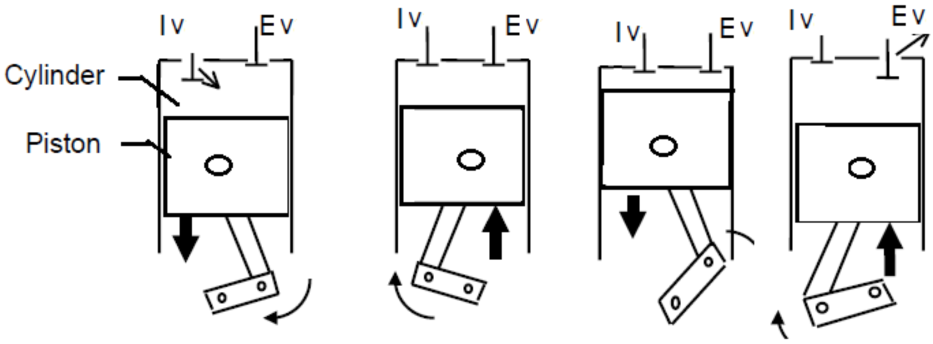
(a) The thermal efficiency of the four stroke diesel engine is greater than two stroke diesel engine.

(b) The overall efficiency of four stroke diesel engines is greater than two stroke diesel engines.

(c) The consumption of lubricating oil is less than that of two strokes.

(d) Four stoke diesel engine have high compression ratio in respect to two stroke diesel engine.

In the CI engine, air alone is inducted during suction stroke. Due to the high compression ratio employed, the temperature at the end of the compression stroke is sufficiently high to self ignite the fuel which is injected into the combustion chamber. A high pressure fuel pump and an injector are provided to inject the fuel into the combustion chamber.
The ideal sequence of operation for the four-stroke CI engine are shown in the Fig 1.2



(a) Suction (b) Compression (c) Expansion (d) Exhaust

Figure.1.2 Cycle of operation of a CI Engine

(i) Suction Stroke: Air alone is inducted during the suction stroke. During this stroke intake valve is open and exhaust valve is closed, Fig 1.2 (a).

(ii) Compression Stroke: Air inducted during the suction stroke is compressed into the clearance volume. Both valves remain closed during this stroke, Fig 1.2 (b).

(iii) Expansion Stroke: Fuel injection starts nearly at the end of compression stroke. Heat is assumed to have been added at constant pressure. After the injection of fuel is completed (i.e. after cut-off) the products of combustion expand. Both the valves remain closed during the expansion stroke, Fig 1.2 (c).

(iv) Exhaust Stroke: The piston travelling from BDC to TDC pushes out the products of combustion. The exhaust valve is open and the intake valve is closed during this stroke, Fig 1.2 (d).

1.7 COMBUSTION IN COMPRESSION-IGNITION ENGINES

In the compression ignition engine, air is compressed into the combustion chamber at a high compression ratio of 16:1 to 20:1 during its compression stroke raising its temperature and pressure to a high value. Fuel which is also highly compressed to a high pressure of 110 to 200 bar by means of a fuel pump is injected through one or more jets into the highly compressed and heated air in the form of liquid jet. Each droplet as it entered into the hot air is quickly surrounded by an envelope of its own vapour Fig 1.3(a), and after that it is flamed at the surface of the envelope.

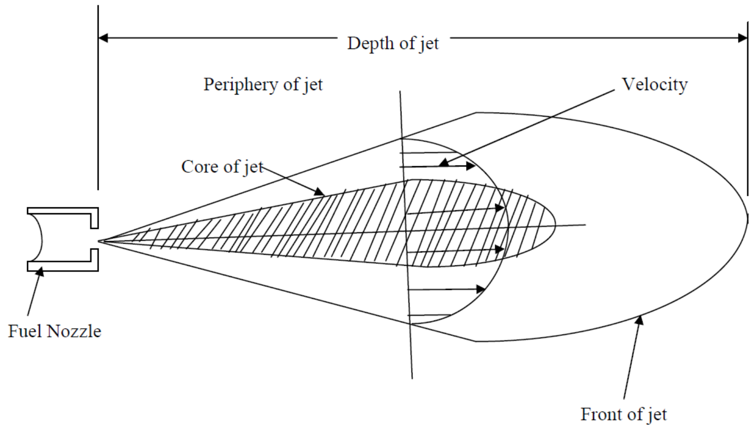


Fig 1.3(a) [Source: Internal combustion engines,V.Ganesan,TMH publishers]

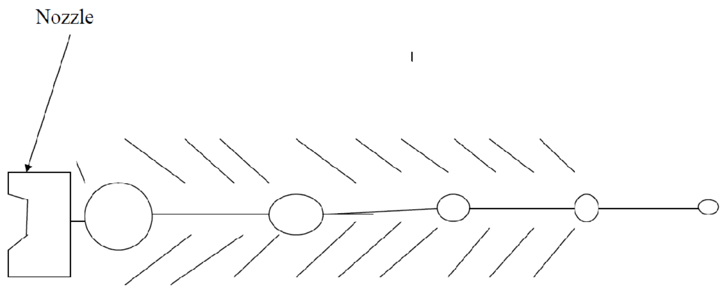


Fig 1.3(b) No Air Swirl

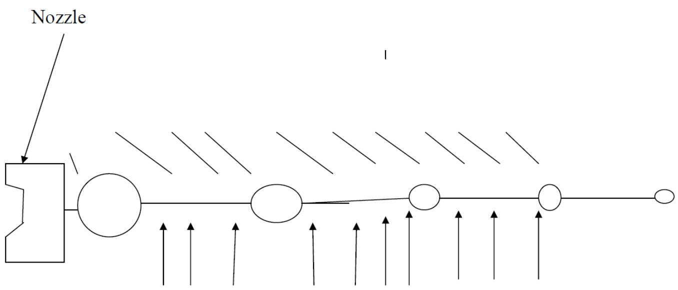


Fig 1.3(c) with air swirl

Figure.1.3 Schematic Representation of a Disintegration of a Fuel Jet [1]

In order to evaporate the liquid the latent heat of vapourization is absorbed from the surrounding air which reduces the temperature of a thin layer of air surrounding the droplet and some time elapse before this the temperature can be raised again by taking heat from the main bulk of air. As soon as this vapour and air comes in contact, it reaches a certain temperature and the local A/F ratio is in the combustion range, ignition takes place. Once ignition has started and a flame is established, the heats required for further evaporation are supplied from that released from combustion.

Thus it is seen that, it takes certain time interval to ignite fuel and air in the combustion chamber called delay period. The duration of delay period depends upon the temperature and the pressure of the fuel. The higher the air temperature, the shorter will be the delay period. The higher pressure also results in the shorter ignition delay because of the increase in the rate of heat transfer. Subsequently the heat is released as a result of a continuous combustion of fuel. This is mainly divided into two phase;

(i) Uncontrolled combustion or premixed combustion.

(ii) Controlled combustion or diffuse combustion.

After this, late burning of fuel occurs where the heat released by the fuel. In the CI engine, the fuel droplet is not injected uniformly in the combustion chamber due to heterogeneous mixture, but it spreads over a definite period of time which is 20-40 degree of the crank travel. The initial fuel droplets meet the air whose temperature is little above their self ignition temperature and are ignited after the ignition delay period. The subsequent fuel droplets find air which is already heated to a much higher temperature by the burning of the initial droplets.

It is not possible to inject the fuel droplet uniformly due to heterogeneous mixture. So under these conditions, if the air in the cylinder is motionless, only a small proportion of the fuel would find sufficient oxygen for burning Fig 1.3(b), and even burning of this fuel would be slow as it is surrounded by its own product of combustion. Therefore, it is essential to impart an orderly and controlled movement to air and fuel so that a continuous supply of fresh air is brought for each burning droplet and the products of combustion are swept away. The effect of this motion of air is called air swirl on the fuel jet as shown in Fig 1.3(c).

1.8 SAUTER MEAN DIAMETER

The Sauter Mean Diameter is the measure of mean droplets diameter, the finer and more homogenous the atomization, the more complete will be physical preparation of the fuel and more easily effective combustion is achieved. The Sauter mean diameter (SMD) is a very common parameter in fluid dynamics used for expressing the fineness of a spray in terms of the surface area of the spray droplets. Studies include the measurement of droplet size using magnesium oxide (Mgo) coating technique and converting into more sophisticated Laser Beam technique. Though Mgo technique is erraneous, it is simple and can be used in any laboratory environment compared to highly sophisticated and very costly Malvern particle analyser which is out of reach of many researches.

1.9 OBJECTIVE OF THE PRESENT STUDY

The objective of the present work is to determine the Sauter mean diameter (SMD) of four different fuels, analyse the images of their sprays and effects of it on performance and emission in a CI engine. The four oils taken for the study are given below;

(i) Diesel oil for reference data.

(ii) A waste oil from industry and its diesel blend.

(iii) A pyrolytic oil from wood and its emulsion with biodiesel.

(iv) A pyrolytic oil from scrap tyres and its biodiesel blend.

CHAPTER 2

LITERATURE REVIEW

Choi and Oh [4] investigated the spray characteristics of diesel and biodiesel blends. Experiments were performed to analyze the effect of blend ratio and injection pressure on the spray behaviour. The spray atomization characteristics were also studied using sauter mean diameter (SMD) of the fuel droplets. It was found that the fuel containing unrefined biodiesel exhibited different spray pattern in comparison with diesel fuel due to the fuel's high viscosity and large surface tension. The results indicated that the increase in the injection pressure caused the SMD to become smaller.

He et al., [5] conducted an experiment to investigate the spray properties, spray tip penetration and cone angle of biodiesel. The experimental setup comprised of an electronic unit-pump (EUP) bench, a constant volume chamber and a high-speed digital camera. The experimental results indicated that the spray tip penetration and cone angles of biodiesel increased with increasing injection durations. Also, with decreasing ambient pressure, the spray tip penetration increased while the cone angle decreased.

Kumar et al., [6] investigated the effect of ambient pressure on spray characteristics such as tip penetration, cone angle and spray area in a constant volume spray chamber of karanja biodiesel (KB100), diesel(KBO) and blends (KB5 and KB20). The results of macro-analysis show that with diesel, B100 gives the highest spray tip penetration, cone angle and spray area followed by KB20, KB5 and diesel respectively because of differences in fuel density.

Reddy [7] studied the droplet size measurement and engine performance using non-edible oils like Mahua, Neem, and Silk worm papae (SWP) oil as substitute fuels. The sauter mean diameter of Mahua, Neem and Silk worm papae oil were measured using magnesium oxide (Mgo) coated technique and converted into equivalent value of Malvern particle laser beam analyzer technique and compared them with diesel. The results concluded that the SMD values of oils were found to be almost same as they were preheated and brought to the viscosity levels equal to that of diesel, largest number of drops fell in the range of 20 to 40 micron at given pressure, and engine run with 100% (pure) Mahua oil, Neem oil and silk worm papae oil can be sprayed without difficulty and no studies also suggested that engine modification is necessary.

Bae and Kang [8] investigated various spray characteristics from different holes of VCO (Valves Covered Orifices) nozzles and its results were compared to standard SAC nozzle. The global characteristics of the spray, including spray angle, spray tip penetration, and spray pattern were measured from the spray images which were frozen by an instantaneous photography with a spark light sources and ICCD.

Choi [9] investigated the spray behaviour and atomization characteristics for the combination of non-esterification biodiesel and fuel additive Water Dipole Power (WDP) and Isopropyl Alcohol (IPA). The process of spray was visualized through the visualization system composed of a halogen lamp and high speed camera, and atomization characteristics were investigated through Laser Diffraction Particle size Analyzer (LDPA). When blending the WDP and IPA with biodiesel, atomization and spray characteristics were improved, and SMD of blended fuel, WDP 25% and biodiesel 75%, was 33.9% reduced at a distance of 6 cm from a nozzle tip under injection pressure 30MPa.

Park et al., [10] focused on the study to investigate the spray characteristics and atomization performance of gasoline fuel (G100), bioethanol fuel (E100), and bioethanol blended gasoline fuel (E85) in a direct injection, gasoline injector in a gasoline engine. The overall spray and atomization characteristics such as an axial spray tip penetration, spray width, and overall SMD were measured experimentally and predicted by using KIVA-3V code. The axial spray tip penetrations of the test fuels were similar, while the spray width and the spray cone angle of E100 were marginally larger than the other fuels. In terms of atomization performance, the E100 fuel among the tested fuels had the largest droplet size because E100 has a high kinematic viscosity and surface tension.

Dong et al., [11] studied the spray characteristics including the spray angle and the spray tip penetration by the comparison of two V-type intersecting hole nozzles with different intersecting angles and a single hole nozzle under variable boundary conditions. The characteristic of fuel droplet diameter was also carried out by using Phase Doppler Anemometry (PDA). Comparing to conventional nozzles, the two V-type intersecting hole nozzles showed a significant improvement of spray spatial distribution with the same exit area and injection pressure level according to the d_{SVER}.

Lin and Lin [12] studied a two-stage transesterification to lower the high viscosity of waste oil. They also utilized an emulsion to reduce the NOx from methyl ester, and used methanol to enhance the stability and to reduce viscosity of emulsified fuel. For this experiment, a constant volume bomb under high temperature, high speed photography were used to analyze spray tip penetration, spray angle, and the sauter mean diameter of fuel droplets, and compared the results with diesel. The experimental results suggested that, the two-stage transesterification can significantly lower the waste oil's viscosity to that which is close to diesel viscosity. At a temperature above 300°C, the waste cooking oil methyl esters had a water content of 20%, spray droplet characteristics were significantly improved, and NOx emission dropped significantly.

Gao et al., [13] studied the spray characteristics of non edible oil using experimental and simulation methods. Parameters such as spray penetration spray cone angle and spray tip speed were measured at different biodiesel ratios in a constant volume vessel with a wide visualization and high back pressure, using a high-speed camera. The experimental results showed that, as the ratio of biodiesel in the blends increased, spray penetration and spray speed increased, but the spray cone angle decreased. The results also showed that the Sauter mean diameters of the blended fuels were greater than that of diesel, and the spray was more concentrated, due to the higher viscosity and surface tension of biodiesel, compared to that of conventional diesel fuel.

Park et al., [14] investigated the emission reduction characteristics of bio-ethanol blended diesel fuel at early injection condition including spray, atomization and evaporation characteristics using a spray visualization system and KIVA-3V code. The results showed that, the droplet size of bio-ethanol blended fuel was smaller than that of diesel, and bio-ethanol blended diesel droplets firstly evaporated by its volatility and the superior atomization characteristics. In early injection condition, the bio-ethanol blend caused an increase in indicated mean effective pressure with an extension of the ignition delay. The HC emission was found to be increased while the CO emission found to be decreased because of the ethanol blend. The geometrical mean diameter and total number density increased as a result of ethanol blending, the particle number in the nuclei mode decreased, and the particle number in the accumulation mode increased in early injection condition.

Choi and Oh [15] performed an experiment to analyze the effects that blending ratio and the injection pressure had on the spray behaviour of blended fuel containing conventional diesel fuel and unrefined biodiesel. The process of spray injection was analyzed through a laser diffraction particle analyzer (LDPA), and spray atomization characteristics were studied using the Sauter mean diameter (SMD) as well as droplet concentrations under various injection conditions. The fuel containing unrefined biodiesel fuel exhibited different spray patterns in comparison to conventional diesel fuel due to the fuel's high viscosity and large surface tension. The results indicate that the increase of injection pressure causes the SMD to become smaller, and an increase in the mixing ratio causes the SMD to become larger.

Payri et al., [16] studied the effect of cavitation on diesel spray behaviour. For this purpose, two bi-orifices nozzle geometries, a cylindrical nozzle and a convergent one, are characterized by means of two fundamental spray parameters: mass flux and momentum flux. Five injection pressures and five discharge pressures have been measured in order to change the cavitation regime inside the nozzle flow. The results showed that in the cylindrical nozzle, cavitation was detected by a collapse on the mass flow rate. The result also imply that the discharge coefficient Cd, will decrease when cavitation number K decreases, and the conical nozzle did not present cavitation effects even in severe pressure conditions.

Payri et al., [17] investigated the influence of orifice geometry on the flow at the nozzle exit and to analyse its effect on the spray in evaporative conditions. The visualization was made in a wide optical access engine for different operating conditions. From the measurements, the dependencies of nozzle geometry, injection conditions and ambient conditions on liquid-phase length were studied and analyzed. A model for liquid-phase fuel penetration in diesel sprays based on the nozzle flow parameters has also been proposed and validated.

Wang et al., [18] studied experimentally and analytically the spray characteristics of biodiesels (from palm and cooked oil) and diesel under ultra-high injection pressures up to 300 MPa. Injection delay, spray penetration, spray angle, spray projected area and spray volume were measured in a spray vessel using a high speed video camera. The study showed that biodiesels gave a longer injection delay and spray tip penetration. The spray angle, projected area and volume of biodiesels were found to be smaller than those of diesel fuel. The estimation on spray droplet size showed that biodiesels generated a larger Sauter mean diameter due to higher viscosity and surface tension.

Kegl and Hribernik [19] paper deals with the study of injection characteristics using different fuels at different fuel temperatures of neat biodiesel from rapeseed oil and, some blends with diesel as well as neat mineral diesel D2. The fuel and fuel temperature influences were investigated experimentally in the mechanically controlled diesel fuel injection system, and the fuel temperature was investigated. On the basis of the measurements of pressure drop through a fuel filter, a minimum fuel temperature for safe engine operation was determined.

Park et al., [20] studied the effects of the energizing duration, ambient gas pressure, fuel temperature, and diesel dimethyl ether (DME) blending ratio on the DME spray characteristics. The DME spray characteristics were analyzed using the spray images obtained from the spray visualization system. The experimental results showed that the DME fuel had a shorter spray tip penetration and a wider spray cone angle compared to those of conventional diesel fuel atomization. The DME spray became blurry at the outer region of the spray, and its evaporation was more active than that of diesel fuel. The droplet sizes of DME were found to be much smaller than those of diesel fuel because of low kinematic viscosity and evaporation of DME.

Kim et al., [21] investigated the experimental and numerical analysis of the macroscopic and microscopic spray characteristics of biodiesel, dimethyl ether (DME), and the biodiesel-ethanol blended fuels in a common-rail injection system. For this, the macroscopic spray characteristics, spray developing process and spray tip penetration of the test fuels were visualized using a laser sheet method. In this work, the effects of different alternative fuels such as biodiesel, dimethyl-ether, and biodiesel-ethanol blended fuel on the spray atomization characteristics were simulated by the KIVA code and the calculated results using the hybrid model combined with the primary and secondary breakup were compared and analyzed with the experimental results in terms of the shape of spray, spray evolution processes, and the SMD distribution.

Subramanian and Lahane [22] studied the injection and spray characteristics of a diesel engine with 7.4 kW rated power output for use of different karanja biodiesel blends (B10 and B20) for the performance improvement and emission reduction. The dynamic injection timing advanced for the biodiesel blends resulting in higher NOx emissions, which increased from 2.94 g/kW-hour with base diesel to 3.40 g/kW-hour with B20. Air entrainment increased for the biodiesel blends, and it enhanced the mixing rate of injected fuel with surrounding hot air. Vaporization time of biodiesel droplets were found to be increased because of larger SMD. However, an increase in over penetration distance, large SMD and high vaporization time for the biodiesel blends would lead to deteriorated performance and emission characteristics of the diesel engines.

Battistoni et al., [23] compared the injection process of two fuels (i) A standard diesel fuel and (ii) A pure biodiesel, methyl ester of soybean oil. Multiphase cavitating flows inside injector nozzles are calculated by means of unsteady CFD simulations using an Eulerian–

Eulerian two-fluid approach and spray evolutions are also evaluated in a Lagrangian framework. Nozzle flow simulations highlighted that the extent of cavitation regions was not much affected by the fuel type, whereas it was strongly dependent on the nozzle shape. Biodiesel provided a marginally higher mass flow in the highly cavitating nozzles. On the contrary, using hole shaped nozzles (to reduce cavitation) diesel provided a similar or marginally higher mass flow.

Lin and Lin [24] investigated the emulsified castor biodiesel (EBD) spray characteristics on DI diesel engine emission and deposit formation. A constant-volume bomb was established to analyze the biodiesel spray characteristics under elevated temperatures. A bio-fuel deposit simulator was developed to solve the EBD deposit problem. The experimental results indicated that the biodiesel generator operated on EBD can improve the fossil diesel emissions. The high NOx emission of CBD was solved by water-biodiesel emulsion method.

Cheng et al., [25] performed an experiment with distilled water as a test liquid to study the spray cooling heat transfer in non-boiling regime. A phase Doppler Anemometry (PDA) was used to study the spray characteristics. The effects of spray flow rate, spray height, and inlet temperature on spray cooling heat transfer were investigated, and the corresponding droplet axial velocity and Sauter mean diameter (SMD) were successfully correlated with mean absolute error of 15%, which were based upon the orifice diameter, the Weber and Reynolds numbers of the orifice flow. The heat transfer in a non-boiling regime was correlated with a mean absolute error of 7%, associated with the working fluid thermo physical properties, the Weber and Reynolds numbers hitting the heating surface, dimensionless heating surface temperature and diameter.

Genbao et al., [26] analysed the droplet size distribution features of the DME/diesel blended fuels and conventional diesel fuel by using a high-resolution digital camera with image processing techniques. Based on the acquired size distribution data, the microscopic spray characteristics including the mean diameter, the characteristic diameter, and the relative span was calculated. According to the experimental results, the finer spray droplets could be observed for the blended fuels compared with the diesel spray, when the mass fraction of DME increases from 10% to 20%, the corresponding droplet size distribution curve moved toward smaller diameters and the number of large droplets reduces, indicating that the spray quality can be improved by DME addition.

Wu et al., [27] investigated a numerical simulation of the combustion characteristics for a closed cycle diesel engine (CCDE) with different intake gas contents under different engine speeds and equivalence ratios. The numerical simulation used KIVA3V-Release2 code as the main program by modifying some subroutines containing different intake gas contents of Oxygen, Argon, and Nitrogen and their thermodynamic properties. The results showed that the pressure will increase earlier, if the percentage of argon was higher when Argon was used to replace Nitrogen, and the ignition delay will be shorter. The higher in-cylinder temperature results from a higher concentration of Argon.

Gogoi and Baruah [28] did an experimental investigation on a small direct injection (DI) diesel engine, fueling the engine with 10% (B10), 20% (B20), 30% (B30) and 40% (B40) blending of Koroch seed oil methyl ester (KSOME) with diesel. The performance and combustion characteristics of the engine at various loads were compared and analyzed. The results showed higher brake specific fuel consumption (BSFC) and lower brake thermal efficiency (BTE) for the KSOME blends. The engine indicated power (IP) was more for the blends up to B30, but found to be reduced for the blend B40 when compared to that of diesel. The KSOME blends exhibited similar combustion trend with diesel. The study revealed the suitability of the KSOME blends up to B30 as a fuel for a diesel engine mainly used in generating sets and the agricultural applications in India without any significant drop in the engine performance.

CHAPTER 3

EXPERIMENTATION

3.1 FUEL PREPARATION FOR THE STUDY

In the present investigation, three types of oils were used to study the droplet size.

(i) Fuel emulsion obtained from biomass (i.e, biodiesel-bio oil emulsion)

(ii) An industrial waste oil and its blend with diesel.

(iii) A non conventional fuel obtained from industrial waste by pyrolysis process blended with diesel.

Biodiesel is defined as mono-alkyl esters of long chain fatty acids which is derived from vegetable oils, animal fats or algae. It is a renewable, cheaper and eco-friendly resources. Biodiesel is produced through transesterification of triglycerides (which are present in vegetable oils and animal fat) with methanol or ethanol or butanol to give methyl or ethyl esters or butyl esters and glycerol as a by product. It is simple to use, biodegradable, nontoxic, and essentially free of sulphur and aromatics. Biodiesel contains no petroleum, and it can be blended with petroleum diesel at any level to create a biodiesel blend. It is much cleaner than fossil-fuel diesel. It can be used in any diesel engine without any modifications in the engine. The availability of biodiesel is limited in many countries which cannot even meet the demand to produce B20, a biodiesel diesel blend where the numeric value 20 refers to percentage of biodiesel. Therefore, the biodiesel can be suitably mixed with another fuel of renewable in nature and checked for its use. In this context, bio-oil obtained from pyrolysis of wood is considered to use with biodiesel.

3.2 USED TRANSFORMER OIL [29]

The oil which is used in the transformers for the cooling purpose is disposed out in the form of waste after its use. After prolonged use, the transformer oil deteoriates and becomes as a waste. However, the waste or used transformer oil (UTO) posses a considerable heating value and some of the properties are similar to that of diesel fuel. After cleaning, it can also be used as an alternate fuel in a CI engine. Transformer oil is an insulating oils which acts as a heat transfer medium so that the operating temperature of a transformer does not exceed the specific acceptable limits.

3.2.1 PYROLYSIS OIL

Pyrolysis oil is obtained by the thermal decomposition of materials in the absence of oxygen or with little presence of oxygen. It basically resembles to tar and contains very high levels of oxygen to be called a hydrocarbon. The pyrolysis oil produced by wood pyrolysis, is referred as bio-oil, is a high viscous, highly acidic and does not ignite easily as it contains a substantial amount of water. Bio-oil usually has a lower calorific value than biodiesel because of high levels of water content and presence of oxygen originating from trees. It generally corrodes the fuel delivery system. If stable emulsion of bio-oil and biodiesel is formed, it may reduce the viscosity to a certain extent.

3.3 WOOD PYROLYSIS OIL

3.3.1 BIODIESEL PREPARATION

In this study, Jatropha methyl ester (JME), a biodiesel was produced by the transesterification process of Jatropha oil. The detailed information related to this process was described by Prakash et al [31].

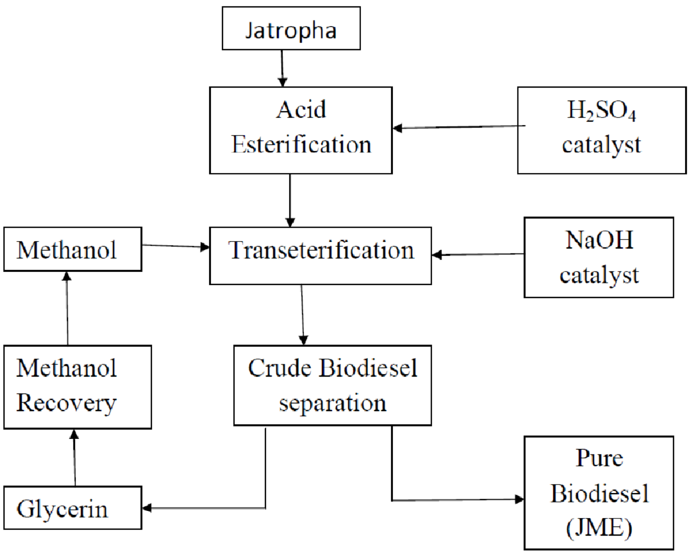


Figure 3.1 Production of JME biodiesel oil

In the transesterification process, vegetable oils and triglyceride is reacted with alcohol in the presence of a strong acid or base, which produces a mixture of fatty acid alkyl esters and glycerol. About 3- 4 gm of sodium hydroxide (NaOH) is dissolved in 100 ml of methanol to prepare methoxide, which is required to initialize the methanol. The mixture is stirred for about 15-20 min in a closed container until the alkali is dissolved completely, and then this mixture is transferred to the reactor containing moisture free Jatropha oil. A continuous stirring of the resulting mixture at the temperature range of 60–65^{o}C is carried out for about an hour, with water. The resulting mixture is taken out and poured into the separating funnel to separate the glycerol and methyl ester of Jatropha oil. Further, water washing is done in order to remove the moisture and impurities from the biodiesel**.** The block diagram of the methyl ester obtained from Jatropha is shown in the Fig. 3.1.

3.3.2 WOOD PYROLYSIS OIL PREPARATION

The schematic diagram of the pyrolysis set up used in this study is shown in Fig.3.2. The production process of WPO is described by Prakash et al. [30]. It is reported that the Pyrolysis oil was extracted by pyrolysis process of waste package wood chips of size 5mm-10mm.The process was carried out in the pyrolysis reactor which has a maximum feed capacity of 1kg of wood chips. The reactor used for pyrolysis oil was cylindrical in shape and has outer diameter 250 mm, inner diameter 200 mm and a height of 250 mm. The reactor was fully covered by glass wool and refractory lining. The pyrolysis reactor was equipped with temperature sensor, temperature control device to set the temperature of operation, energy meter to measure the power required for pyrolysis process and also to estimate the economy for the overall operation. It was also equipped with a condenser flask for condensing the pyrolytic gases into liquid by circulating water around the condenser by the help of a water pump. One end of condenser was connected with the tube from pyrolysis reactor and the other end was connected to a conical flask which was kept for collecting the condensed liquid. The temperature inside the reactor was increased at the rate of 9^{o}C per minute at initial stages and fells to 2^{o}C at next stages. The optimum temperature of operation was in the range of 4^{o}C to 420^{o}C. Therefore, the temperature control device was set to 400^{o}C. The average energy meter reading was 3.9 kWh. The pyrolysis gases coming out from the reactor were of two types, condensable and non-condensable. The moisture present in the wood comes out as water and this generally started at 220^{o}C and continues up to 350^{o}C, then the colour change to dark brown in the liquid. The pyrolysis oil started to come out at 350^{o}C and continues up to 390^{o}C. The typical yield for 500 grams of feed was 150 ml of water and 100 ml of wood pyrolysis oil.

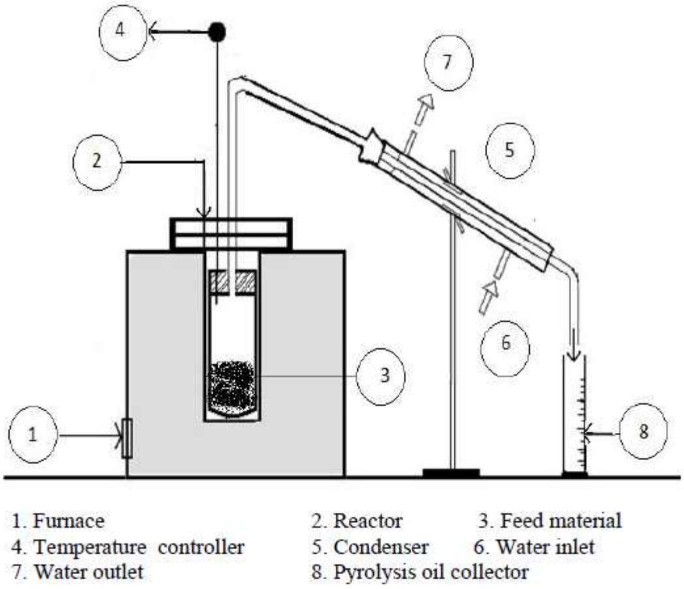


Figure 3.2 Schematic diagram of pyrolysis set up [31]

3.3.3 EMULSIFICATION OF WPO AND BIODIESEL [30]

High viscous fuels can be used as an alternative fuel in diesel engine by adopting different techniques such as blending, preheating, increasing injection pressure and improving ignition quality. But, in the case of WPO, pilot ignition or addition of ignition improver or emulsification with diesel or biodiesel are used. Emulsification is a technique used when a fuel has to be mixed with another fuel which is hydroscopic in nature. The emulsifier provides ability for the water tolerance of alcohol/pyrolysis oil fuel blends. An emulsion was prepared for pyrolysis oil with biodiesel oil using a surfactant ranging from 0.8 to 1.5% by volume. Surfactants are compounds that lower the surface tension of a liquid or interfacial tension between two liquids or that between a liquid and a solid. Surfactant acts as an emulsifier in the emulsification process. The commonly used surfactants for pyrolysis oil with biodiesel emulsions are Tween 80, Tween20, Span20, Span80, Triton x-100 etc. The surfactant Polysorbate-20 commercially known as Tween-20 was used as an emulsifier for the preparation of WPO and diesel emulsion. For the preparation, first the surfactant was added to the diesel and then the pyrolysis oil was also added. The resultant mixtures were shaken well to make emulsions**.** Hence, different emulsions of WPO with biodiesel using Tween20 at varying concentrations have been prepared. Samples of 100ml each are prepared with varying WPO blends i.e. 5%, 10%, 15% and varying surfactants composition i.e. 2% and 4 %.

3.4 BIODIESEL-TPO BLEND

3.4.1 TYRE PYROLYSIS OIL

Tyre pyrolysis oil can be obtained from pyrolysis of automobile waste tyre. Pyrolysis is a thermal degradation of organic matter which is converted into value added products such as oil, gas and char. In this process, waste tyre chips were heated in an oxygen free environment. The volatile vapour evolves during heating, is condensed in a water cooled condenser. Three value added products namely tyre pyrolysis oil (TPO), pyrogas and char are obtained.

3.4.2 PREPARATION OF TYRE PYROLYSIS OIL

For the preparation of TPO, an automobile tyre was cut into a number of pieces. Then the bead, steel wires and fabrics were removed and the thick rubber at the periphery of the tyre was made into small chips. The tyre chips was washed, dried and then fed into a mild steel pyrolysis reactor unit. The pyrolysis reactor which was a fully insulated cylindrical chamber of inner diameter 110 mm, outer diameter 115 mm and a height of 300 mm. Vacuum was created in the pyrolysis reactor which was then externally heated by means of heaters. The process was carried out between 450°C and 650°C in the reactor for about 2 hours and 30 minutes. The product of pyrolysis which was in the form of vapour was sent to a water cooled condenser and then the condensed liquid was collected as a fuel. The non condensable gases were sent out to atmosphere. The TPO collected was crude in nature. The time taken for the pyrolysis process was about 90 minutes. TPO was then filtered by using fabric filter and further filtered by micron filter, which removed impurities, dust, low and high volatile fractions of hydrocarbons. The schematic diagram of the pyrolysis process of waste automobile tyres is as shown in Fig 3.3. The photographic view of the pyrolysis setup is shown in Fig.3.4.

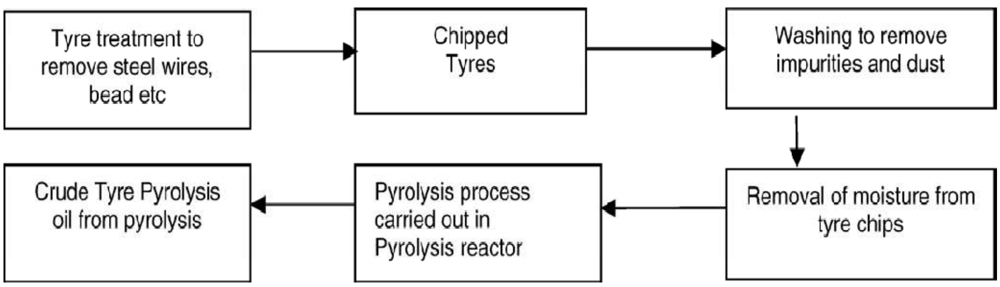


Figure.3.3 Pyrolysis process of waste automobile tyre [30]

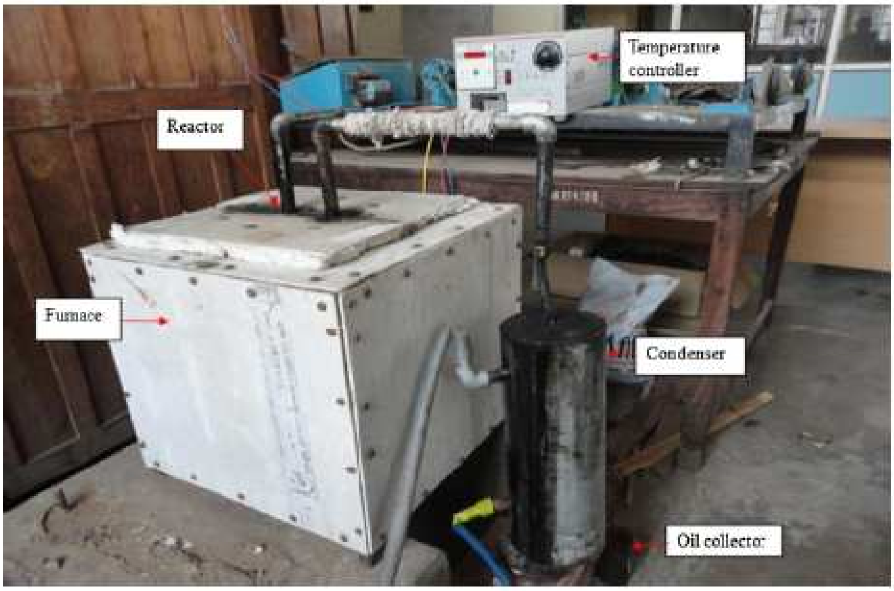


Figure.3.4 Pyrolysis set up

3.5 PROPERTIES OF TEST FUELS

The comparison of fuel properties of different test fuels used in this study is given in Table 3.1.

Table 3.1 Comparision of fuel properties of different test fuels used in this study

Properties	Diesel	UTO	WPO	TPO
Flash point (^oC)	76	150	98	43
Fire point (^oC)	56	176	108	50
Lower calorific value (kJ/kg)	44800	39270	38416	42830
Kinematic viscosity (cSt@27^oC)	2.4	413	4.3	3.2
Carbon residue	0.1	0.020	0.71	2.41

3.6 EXPERIMENTAL STUDY

The experimental programme comprises of three parts. (i) determination of sauter mean diameter (SMD) of UTO, WPO and TPO. (ii) the image analysis of these sprays when used in diesel engine and (iii) effects of these oil on performance and emission of a DI engine.

3.6.1 DROPLET MEASUREMENT

The experimental set up employed to collect the spray is shown Fig. 3.5. The magnesium oxide coated plates were introduced into the fuel spray injected into open atmosphere with the help of nozzle test apparatus. The distance at which MgO coated plate was introduced and fixed at 90 cm from the nozzle tip. The impressions of the droplets created on the coating of the plate were seen through a 10x inverted microscope choosing different regions on the plate. To minimize the error, two samples (1 and 2), were selected from the spray collected on the glass plate. The number of droplets of different sizes were manually counted viewing through microscope and recorded. The injection pressure was fixed at 200 bar and the fuel samples tested were diesel oil, UTO, WPO and TPO and were compared. The crude data was converted into more sophiscated Laser Beam technique Malvern particle analyzer using an empirical equation [4].

3.7 EXPERIMENTAL SET UP FOR SAUTER MEAN DIAMETER

Figure 3.5 shows the experimental set up, to inject the fuel and collect on a MgO plate.

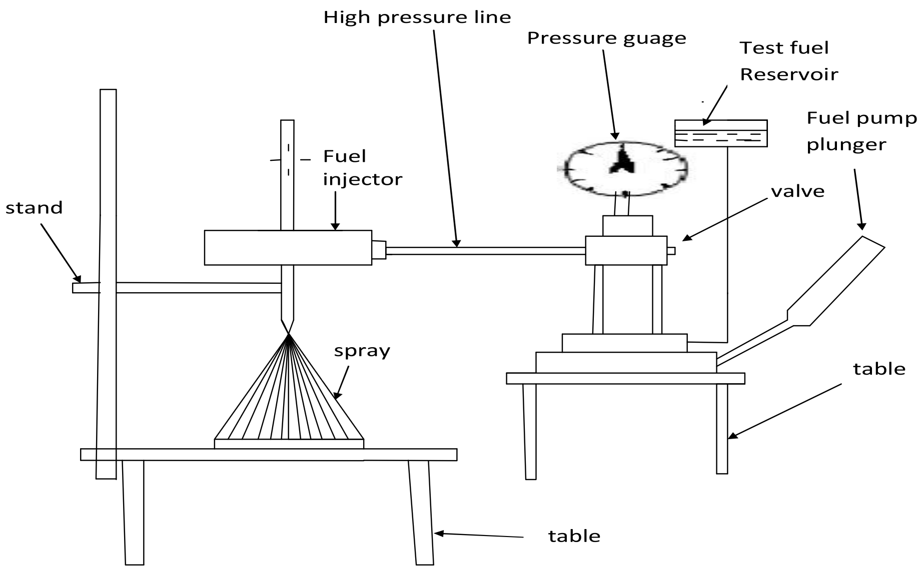


Figure.3.5 Arrangement for experimental set-up

The experimental set up for determining the SMD consists of a fuel tank, fuel pump, fuel pump plunger, valve, pressure-gauge, high pressure line, fuel injector, stand, MgO coated plate and table.

3.7.1 ARRANGEMENT OF NOZZLE AND NOZZLE INJECTOR

A single hole nozzle was used for spraying the tested fuel in the study. The nozzle was connected through a nozzle pipe to reservoir. The nozzle was set at a pressure of 200 bar which was kept at a distance of about 90 cm from the plate so that the fuel sprayed on it can easily impinge on to the MgO coated glass plate.

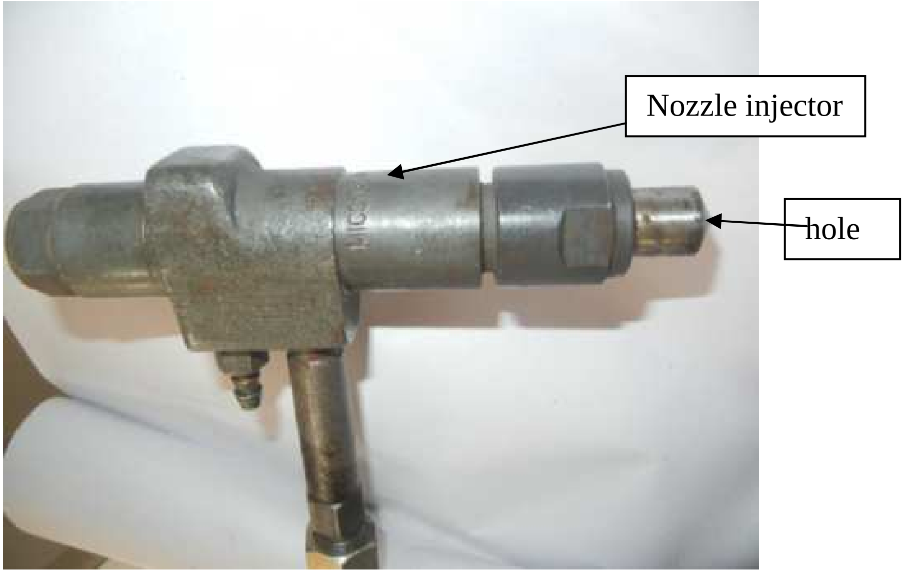


Figure.3.6 Single hole Nozzle

3.7.2 COATING OF PLATES

Figure 3.7 shows the photograph of a MgO coated glass plate. The glass plates were cut into a square shape of size (88 x 88 mm).

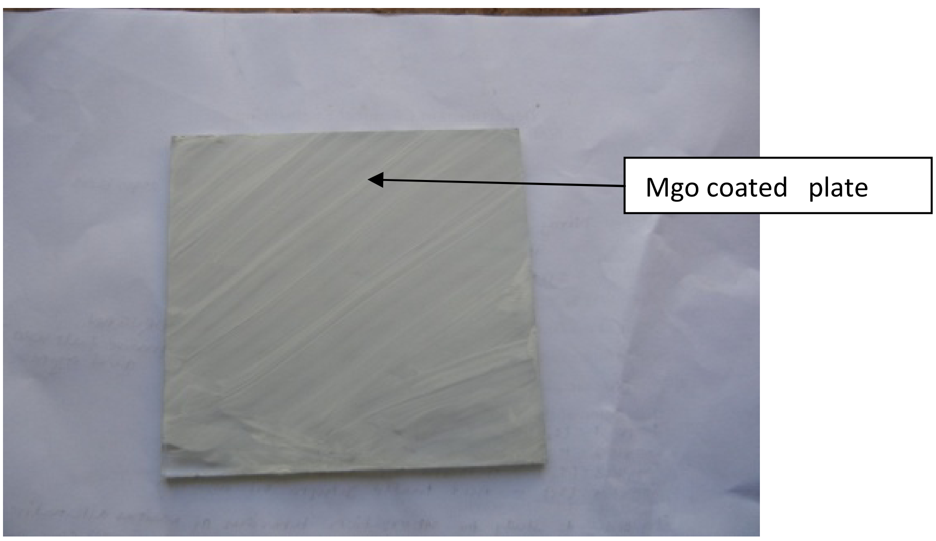


Figure.3.7 MgO coated glass plate

The glass plates were cut into a square shape of size (88 x 88 mm). Magnesium oxides powder was used for coating. Initially, magnesium oxide was mixed with water and a paste was formed. A thin layer of paste was coated on to the glass plate with the help of paint brush so that the light can easily pass through it.

3.7.3 USE OF MICROSCOPE AND SOFTWARE FOR THE STUDY

An inverted microscope was used for the study of droplet size diameter of different fuels. Sprays of different fuels on the glass plates were seen through 10x resolution microscope and snaps were taken through a camera attached with it. The images were saved in the computer.

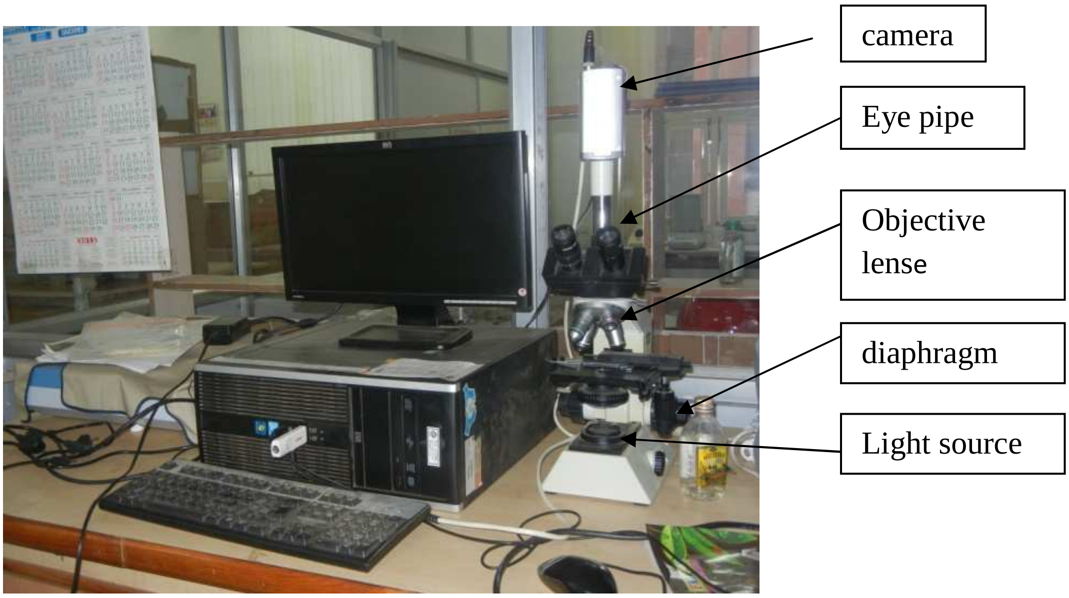


Figure.3.8 An inverted microscope and a computer

Droplets size diameters were measured through NI vision software. To minimize the error two samples (1and 2) were selected from the spray collected on a glass plate and different diameters with different range were manually counted and recorded.

3.8 STEPS INVOLVED IN DROPLET SIZE MEASUREMENT

- Before starting the experiment, the fuel tank was filled with that particular fuel to be tested.
- With the help of plunger, the fuel was injected from the nozzle at a pressure of 190 bar.
- The fuels were sprayed on the magnesium coated glass plate.

- The fuel droplet collected on the glass plate were observed through an inverted 10x microscope.
- Images were taken of different samples at different region.
- Droplets were counted by using NI vision software and compared the droplet diameter of diesel oil with UTO, WPO and TPO.

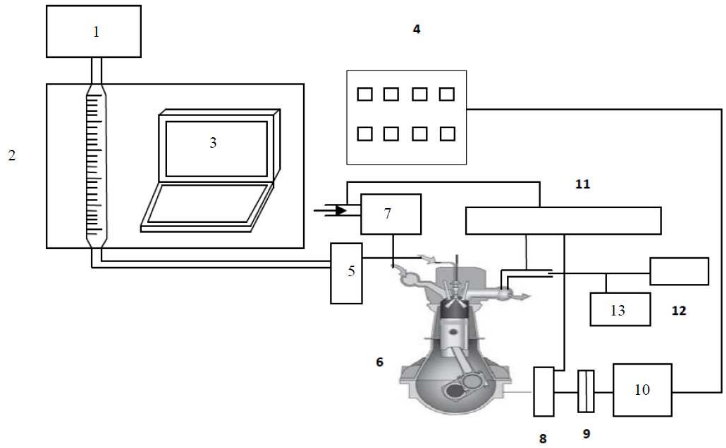
3.9 SPECIFICATION OF DIESEL ENGINE

The test engine used in this investigation was a Kirolaskar TAF-1 single cylinder, four-stroke, air cooled, constant speed direct injection diesel engine. The technical specifications of the engine are given in Table 3.2.

Table 3.2 Technical specification of the engine

Parmeters	**Value**
Bore, mm	87.5
Stroke, mm	110
Rated power,kW@1500rpm	4.4
Compression ratio	17.5
Nozzle opening pressure, bar	200
Injection timing, ^{o}CAbTDC	23

Figure.3.9 illustrates the schematic diagram of the experimental setup to evaluate the performance and emission of a DI diesel engine fuelled with the test fuels. A control panel was fitted with an alternator to provide the load to the engine. Fuel from the fuel tank was admitted to the engine. A burette and a fuel sensor were included in the fuel circuit to measure the fuel consumption and give the input to the computer. In the fuel line a fuel filter and fuel pump were also connected.



1.Fuel tank 2. Burette 3.Computer 4. Load cell 5. Fuel pump
6. Test engine 7. Air tank 8.Fly wheel 9. Flexible coupling
10. Alternator 11. Control unit 12. Sampler

Figure.3.9 Experimental setup [29]

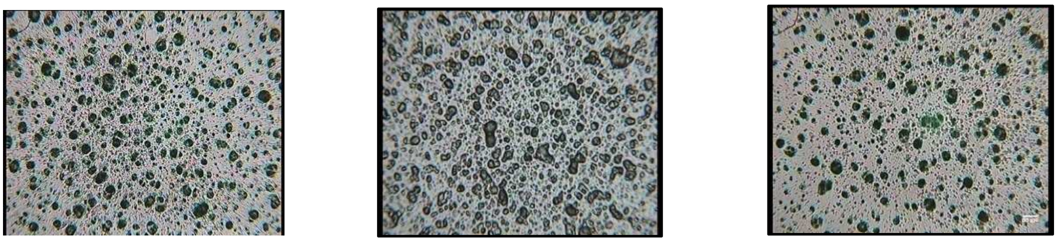
Atmospheric air enters the intake manifold of the engine through an air filter and an air box. An air flow sensor fitted in the air box gave the input for the air consumption to the data acquisition system. All the inputs such as engine brake power, air and fuel consumption, were recorded by the data acquisition system, stored in a computer and displayed in the monitor. A thermocouple in conjunction with a temperature indicator was connected at the exhaust pipe that indicated the exhaust gas temperature. An AVL DiGas444 exhaust gas analyzer was used to measure the engine exhaust gas components in percentage. The technical specification of the AVL DiGas444 analyser is given in Annexure A1. The smoke density of the exhaust was measured with the help of an AVL 437 diesel smoke meter. The technical specification of the AVL 437C diesel smoke meter is given in Annexure A2. All the tests were conducted by starting the engine with diesel only at 0%, 25%, 50%, 75% and 100% loads. After the engine was warmed up, it was switched for the UTO, WPO and TPO operations. At the end of the test, the fuel was switched back to diesel and the engine was kept running for a while, before shut-down to flush UTO, WPO and TPO from the fuel line and the injection system.

CHAPTER 4

RESULT AND DISCUSSION

4.1 DROPLET IMAGES OF DIESEL, UTO AND UTO 40

Figure 4.1 shows the droplet image of diesel, UTO and UTO40 by using MgO coating technique, at an injection pressure of 200 bar and a room temperature of 27^{o}C through a single hole nozzle injector. The glass plate were fixed at 762 mm from the nozzle injector The impression of the droplets created on the glass plate were seen through a 10x microscope choosing different region on the plates. To minimize the error 2 samples were taken.



Diesel UTO UTO40

Figure.4.1 Droplet images of diesel, UTO and UTO40

Table 4.1 gives the number of droplets at different ranges of diameter of diesel UTO and UTO40. Droplets number were counted manually using NI vision software, it is clearly seen that the maximum number of droplets fall within the range of less than 15 microns and minimum in 60-70 microns. The more numbers of droplet of UTO than diesel is due to high viscosity.

Table 4.1 Droplet number of diesel, UTO and UTO40

Injection Pressure =200 bar; No. Of Holes Used= 1 hole

Sl.No	Range of Droplet Diameter	Diesel oil Sample I	Diesel oil Sample II	UTO Sample I	UTO Sample II	UTO40 Sample I	UTO40 Sample II
	Micron	Number	Number	Number	Number	Number	Number
1	>15	1040	1056	1580	1724	1520	1408
2	15-30	164	132	144	116	88	136
3	30-45	72	56	60	52	40	48
4	45-60	24	14	23	21	20	16
5	60-75	15	5	9	6	4	12

4.1.1 DETERMINATION OF SAUTER MEAN DIAMETER

SMD [7] is determined by using the following empirical equation:

$$(SMD)_{Mgo} = \frac{\frac{4\pi}{3}\left[N_1\left({}^{D_1}/_2\right)^3 + N_2\left({}^{D_2}/_2\right)^3 + N_3\left({}^{D_3}/_2\right)^3 + \cdots \ldots\ldots\ldots\ldots\ldots\ldots\ldots.\right]}{4\pi\left[N_1\left({}^{D_1}/_2\right)^2 + N_1\left({}^{D_1}/_2\right)^2 + N_1\left({}^{D_1}/_2\right)^2 + \cdots \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\right]} \ldots\ldots\ldots.(4.1)$$

Where, N_1, N_2, N_3 … … … are the numbers of droplets collected on coated glass plate.

D_1, D_2, D_3 … … …are respective diameters of those droplets.

SMD is further converted into equivalent value of Malvern particle laser beam analyzer by using the following equation:

$$(SMD)_{laser} = 37 - 0.1739\ (SMD)_{MgO} \ldots\ldots\ldots(4.2)$$

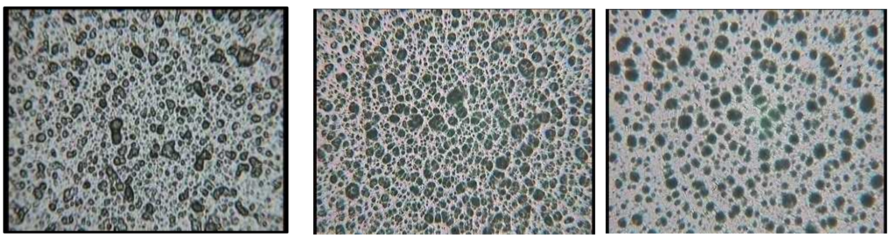
Table 4.2 shows the SMD value of both diesel and UTO in terms of MgO technique and equivalent value of Malvern particle laser beam.

Table 4.2 SMD of the Diesel, UTO and UTO40

Sl No.	Sample oil	Mgo	Laser
1	Diesel(I)	5.74365	35.97105
2	Diesel(II)	6.2093	36.0821
3	UTO(I)	5.0865	36.115
4	UTO(II)	5.281	36.081
5	UTO40(I)	4.792	36.166
6	UTO40(II)	5.37	36.066

4.2 DROPLET IMAGES OF DIESEL, JOE15 AND JME

Figure 4.2 shows the droplet image of diesel, JOE15 and JME by using MgO coating technique, at an injection pressure of 200 bar and a room temperature of 27^{o}C through a single hole nozzle injector.



Diesel JOE 15 JME

Figure 4.2 Droplet images of diesel, JOE15 and JME

Table 4.3 show the number of droplets at different ranges of diameter of diesel, JOE15 and JME. Droplets number were counted manually using NI vision software, it is clearly seen that the maximum number of droplets fall within the range of less than 15 microns and minimum in 60-70 microns.

Table 4.3 Droplet number of Diesel, JME and JOE15

Injection Pressure =200 bar; No. Of Holes Used= 1 hole

Sl.No	Range of Droplet Diameter	Diesel oil Sample I	Diesel oil Sample II	JME Sample I	JME Sample II	JOE15 Sample I	JOE15 Sample II
	Micron	Number	Number	Number	Number	Number	Number
1	>15	1040	1056	484	456	840	888
2	15-30	164	132	120	112	112	100
3	30-45	72	56	68	48	52	48
4	45-60	24	14	14	15	12	13
5	60-75	15	5	4	2	5	4

4.2.1 DETERMINATSION OF SAUTER MEAN DIAMETER

SMD diameter of JME and JOE 15 are calculated from the above stated formulae:

SMD is further converted into equivalent value of Malvern particle laser beam analyzer by using the following equation:

$$(SMD)_{laser} = 37 - 0.1739\ (SMD)_{MgO} \text{..........(4.3)}$$

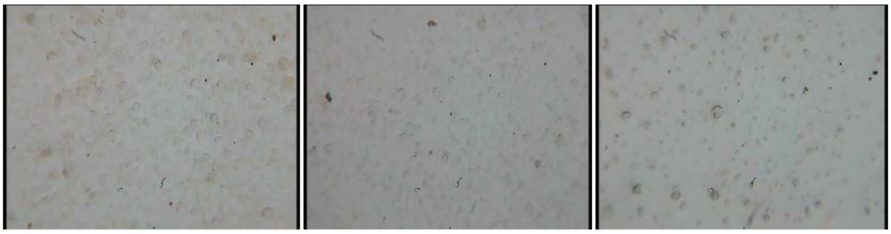
Table 4.4 shows the SMD value of diesel, JME and JOE15 in terms of MgO technique and equivalent value of Malvern particle laser beam.

Table 4.4 SMD of Diesel, JME and JOE15

Si No.	Sample oil	Mgo	Laser
1	Diesel(I)	5.74	35.97
2	Diesel(II)	6.20	35.92
3	JME(I)	5.93	35.96
4	JME(II)	3.97	36.30
5	JOE(I)	5.32	36.07
6	JOE(II)	5.44	36.30

4.3 DROPLET IMAGES OF DIESEL, TPO5, TPO AND TPO15

Figure 4.3 shows the droplet image of TPO5, TPO and TPO15 by using MgO coating technique, at an injection pressure of 200 bar and a room temperature of 27^{o}C through a single hole nozzle injector.



TPO 5 **TPO** **TPO 15**

Figure 4.3 Droplet images of TPO5, TPO and TPO15

Table 4.5 show the number of droplets at different ranges of diameter of TPO5, TPO and TPO15. Droplets number were counted manually using NI vision software, it is clearly seen that the maximum number of droplets fall within the range of less than 15 microns and minimum in 60-70 microns.

Table 4.5 Droplet number of diesel, TPO5, TPO and TPO15

Injection Pressure =200 bar; No. Of Holes Used= 1 hole

Sl.No	Range of Droplet Diameter	TPO 5 Sample I	TPO 5 Sample II	TPO Sample I	TPO Sample II	TPO15 Sample I	TPO15 Sample II
	Micron	Number	Number	Number	Number	Number	Number
1	>15	392	414	432	440	392	402
2	15-30	88	56	97	68	63	59
3	30-45	29	56	38	32	29	36
4	45-60	15	9	11	13	12	9
5	60-75	2	5	2	4	5	7

4.3.1 DETERMINATION OF SAUTER MEAN DIAMETER

Table 4.6 shows the SMD value of diesel, JME and JOE15 in terms of MgO technique and equivalent value of Malvern particle laser beam.

The SMD diameter of TPO5, TPO and TPO 15 are calculated from the above stated formulae.

The SMD is further converted into equivalent value of Malvern particle laser beam analyzer by using the following equation:

$$(SMD)_{laser} = 37 - 0.1739\ (SMD)_{MgO} \ldots\ldots\ldots.(4.4)$$

Table 4.6 SMD of Diesel, TPO5, TPO and TPO15

Si No.	Sample oil	Mgo	Laser
1	Diesel(I)	5.74	35.97
2	Diesel(II)	6.20	35.92
3	TPO5(I)	5.91	35.976
4	TPO5(II)	5.40	36.06
5	TPO(I)	5.32	36.07
6	TPO(II)	5.20	36.09
7	TPO15(I)	5.68	36.01
8	TPO15(II)	4.21	36.26

4.4 COMPARISION OF PERFORMANCE PARAMETERS

4.4.1 BRAKE SPECIFIC ENERGY CONSUMPTION

Figure 4.4 shows the variation of brake specific energy consumption of JOE, JME, ATJOE15, JMETPO20, UTO, UTO40 and diesel at different loads.

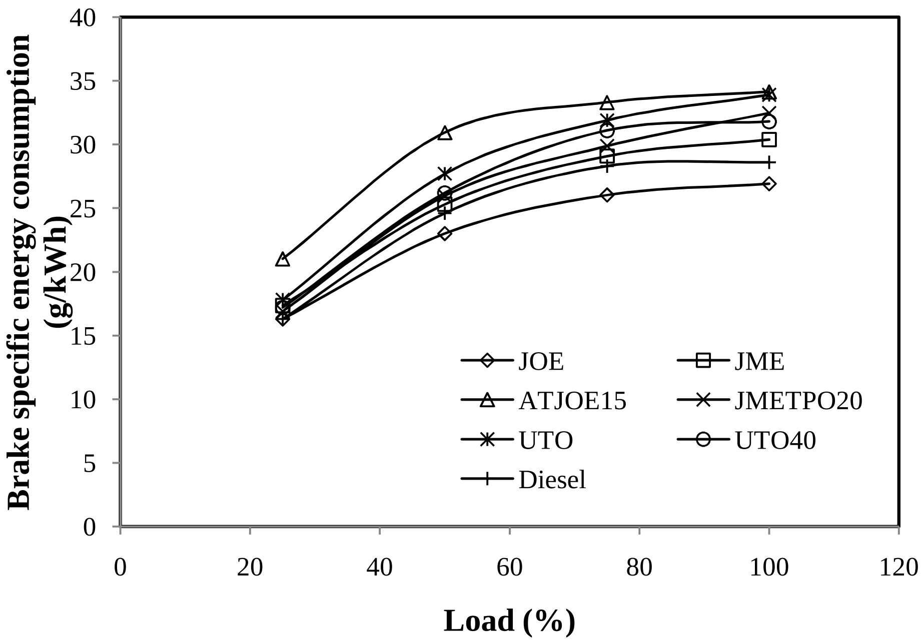


Figure. 4.4 Variation of Brake specific energy consumption with engine load

The brake specific energy consumption is higher for all the fuel as compared to diesel at different loads. It can be observed from the Fig 4.4 that the brake specific energy consumption of JOE, JME, ATJOE15, JMETPO20, UTO, UTO40 and diesel at full loads are 26.91%, 30.38%, 27.98%, 29.87%,33.9%, 31.8% and 28.6% respectively. The BSEC is lower for diesel than all the fuels at full load. This may be due larger value of SMD, the shape of the fuel spray,their atomization characteristics and viscosity of all fuels than diesel.

4.4.2 EXHAUST GAS TEMPERATURE

Figure 4.5 shows the variation of exhaust gas temperature of different fuels at different loads. Exhaust gas temperature is an indication of efficient combustion. Higher values of exhaust gas temperature are indicative of inefficient combustion.

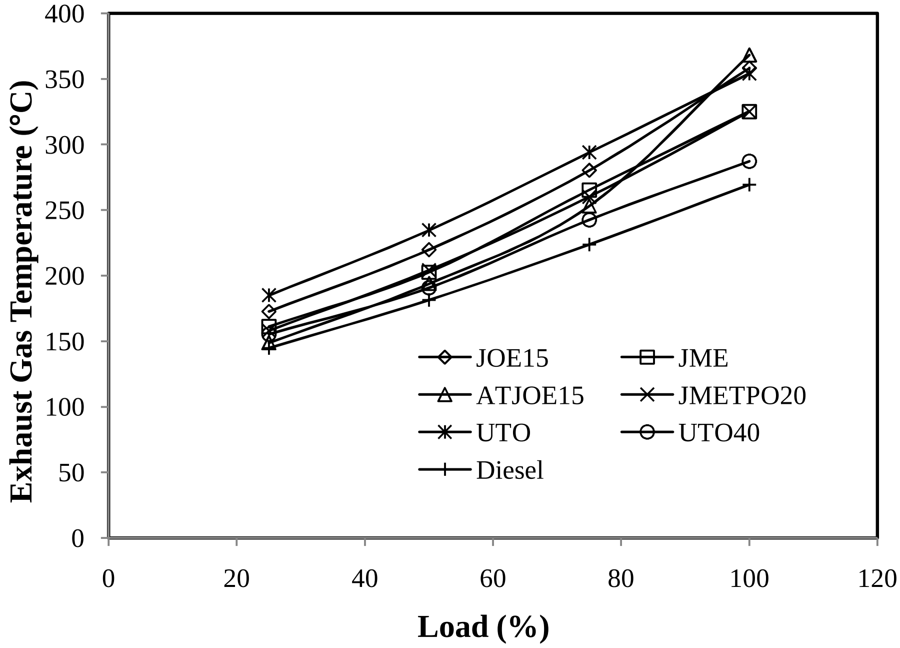


Figure.4.5 Variation of Exhaust gas temperature with engine load

The exhaust gas temperature increases with an increase in the engine load for JOE, JME, ATJOE 15, JMETPO 20, UTO, UTO40 and diesel. The EGT for JOE, JME, ATJOE 15, JMETPO 20, UTO, and UTO40 is higher than that of diesel as a result of higher viscosity, higher SMD and higher density of these fuels. It is observed from the figure that the ATJOE15, JOE15 and UTO shows the highest exhaust gas temperature with respect to JME, JME 20, UTO40 and diesel fuel, at full loads.

4.5 COMPARISION OF EMISSION PARAMETERS

4.5.1 HYDROCARBON EMISSION

Figure 4.6 shows the variation of hydrocarbon emission values of different fuels at different loads. It is observed from Fig.4.6 that unburned hydrocarbon emission decreases for UTO, UTO40, JME, JOE, ATJOE15 and diesel from zero to full load. The HC emission of ATJOE15 and JME is found to be lower than that of diesel fuel, since there is fast breakup of fuel, small number of droplet sizes and higher oxygen content of JME and ATJOE15 leads to complete burning than that of diesel fuel.

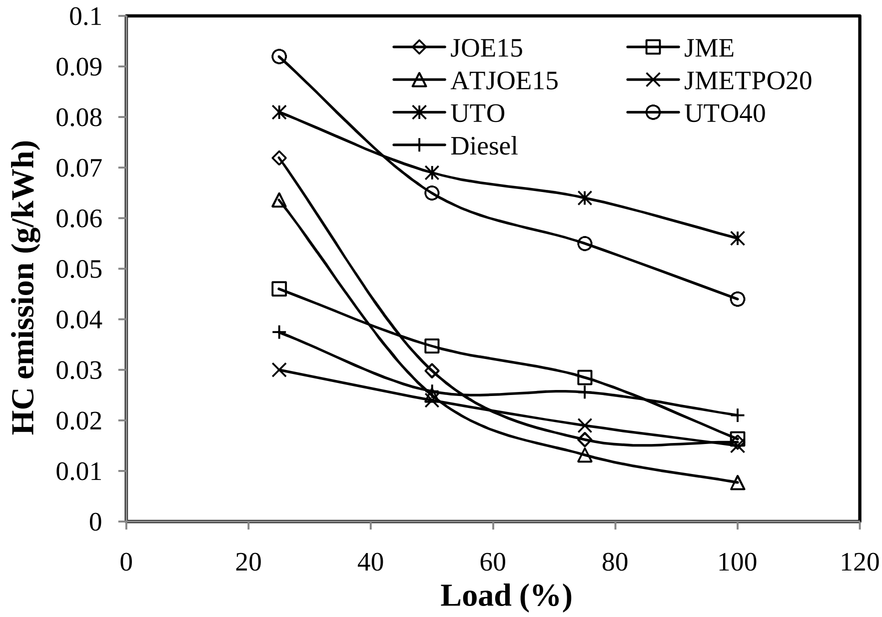


Figure.4.6 Variation of hydro carbon emissions with engine load

4.5.2 CARBON MONOXIDE EMISSION

It can be observed from Fig.4.7 that the CO emission is highest for JMETPO20 compared to all other fuels at full load. The CO emission is an indication for incomplete combustion of fuel air mixture that takes part in the combustion. The CO value is lowest for diesel and higher for all other fuel at full load. The higher CO emission may be due to local rich regions and poor mixture formation in the combustion chamber [34]. Higher SMD values leads to poor air entrainment which leads to poor mixture formation.

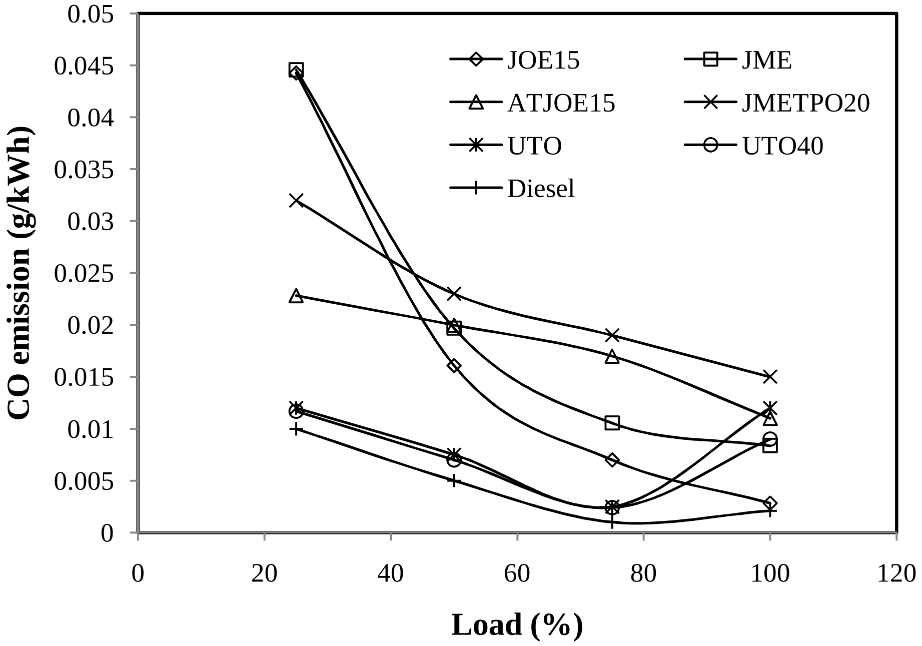


Figure.4.7 Variation of Carbon monoxide emission with engine load

4.5.3 NITRIC OXIDE EMISSION

The variation of NO emission for JOE, JME, ATJOE15, JMETPO20, UTO, UTO40 and diesel at different load are shown in Fig 4.8. It is observed that the NO emission increases with an increase in load for UTO, UTO40, JMETPO20 and diesel. Higher NO emission for UTO and UTO40 may be associated with higher combustion temperature [32]. More fuel is burned inside the engine during high loads, which result in higher temperature. This facilitate the oxidization of nitrogen, which in turn, results in higher NO emissions according to extended zeldovich thermal NO mechanism [33]. In case of UTO and UTO40 the burning continues in the exhaust, due to the heavier molecules present in it, which in turn increases the exhaust gas temperature [37]. This leads to higher NO emission.

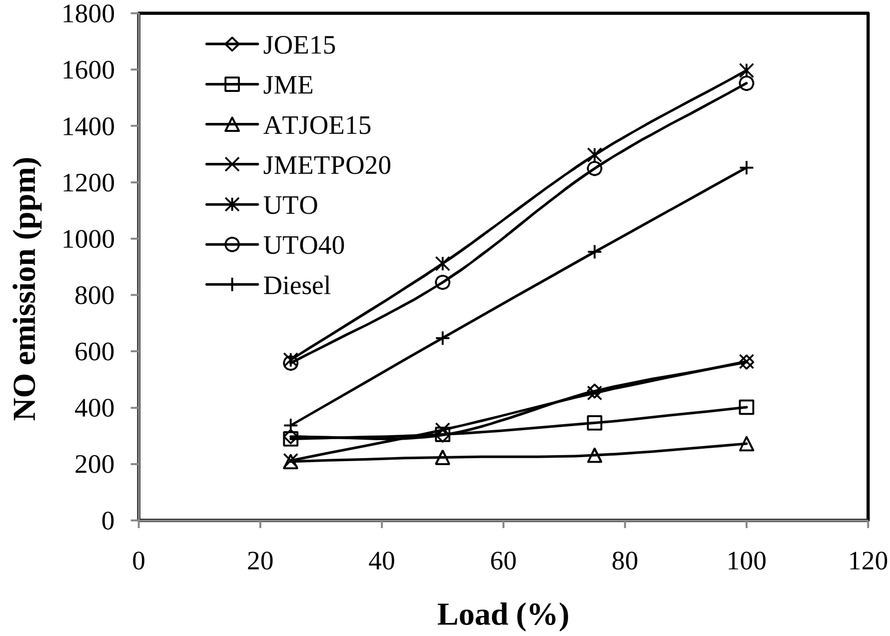


Figure.4.8 Variation of Nitric oxide emission with engine load

It can be observed from Fig.4.8 that the nitric oxide emission of JOE, JME, ATJOE15, JMETPO20, UTO, UTO40 and diesel at full loads are 262, 289, 209, 564, 1597, 1552, 1252 parts per million.

4.5.4 SMOKE

Figure 4.9 portrays the variation of smoke opacity with engine load for the tested fuel.

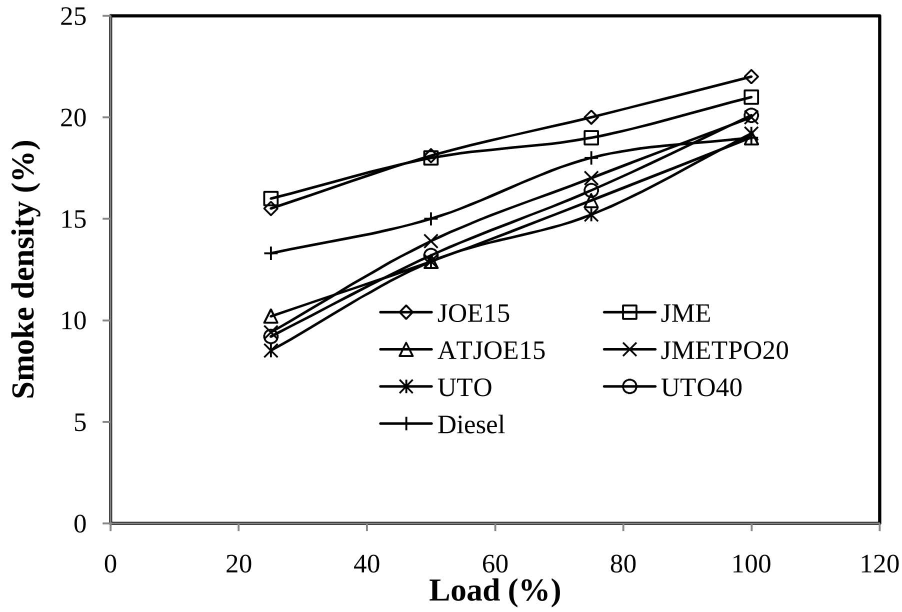


Figure.4.9 Variation of Smoke density with engine load

Smoke is higher when a fuel's ratio of hydrogen to carbon is less than two. It is observed that the smoke density increases at full load. The value of smoke is higher for UTO40, ATJOE15, and JME than diesel than other fuels. This may be due to the effects of enhancement in the spray volume, considerable amount of entrainment in the emulsion spray, and the micro-explosion effect during combustion process [38].

CHAPTER 5

CONCLUSION

Fuel density, viscosity and SMD are the main properties affecting the spray characteristics. Spray characteristics were investigated through a single hole nozzle arrangements. The combustion and emission characteristics of JOE, JME, ATJOE15, JMETPO20, UTO and UTO40 were carried in a single cylinder, four strokes, air-cooled, direct injection diesel engine and compared with those of diesel. The findings from this study are summarized as follows:

- The maximum number of droplet fall within the range of less than 15 micron, and minimum number of droplet fall in the range of 60 to 75 micron of all the tested fuels.
- The sauter mean diameter of JME, ATJOE15, JMETPO20, UTO and UTO40 is higher than diesel.
- As the blending ratio increased, the spray size distribution and the mean diameter became large, and spray size was distributed in a wider range than that of diesel.
- For all blended fuels the sauter mean diameter has considerably increased.
- The brake specific energy consumption is lowest for JOE than all others fuel.
- The exhaust gas temperature of JOE, JME, ATJOE15, JMETPO20, UTO and UTO40 are higher than that of diesel at full load.
- The hydrocarbon emission for JOE, JME, ATJOE15 is lower than that of diesel at full load. However for UTO, UTO40 hydrocarbon emission is higher than diesel.
- Nitric oxide emission for JOE, JME, ATJOE15, JMETPO20 is lower than diesel at full load, however nitric oxide emission for UTO and UTO40 is much higher than others fuel.
- Smoke is lower for ATJOE15, JMETPO20, UTO and UTO40 than diesel at full load.

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ANNEXURE

A1.TECHNICAL SPECIFICATION OF EXHAUST GAS ANALYSER

1. Details of instruments

Si. No.	Instrument	Measurement	Make and model	Measurement technique / method
1	Load cell	Loading device	Indian make	Load cell
2	Burette	Fuel consumption	Indian make	Solenoid type
3	Temperature indicator	Exhaust gas measurement	Indian make	Thermocouple
4	Exhaust gas analyzer	NO	AVL 444 Digas analyzer	Chemiluminescence
		HC		FID
		CO		NDIR
5	Pressure transducer with charge amplifier	Cylinder pressure	Kistler 5395A	Piezoelectric pickup
6	Crank angle encoder	Crank angle	Indian make	Magnetic pick up type

2. Range, Accuracy and Uncertainity

Si. No.	Instrument	Range	Accuracy	Uncertainty
1	Load indicator	250 - 6,000 W	±1 W	0.2
2	Temperature indicator	0 - 900	±1 ^{o}C	0.15
3	Burette	1- 30cc	±0.2 cc	1.5
4	Speed sensor	0 - 10,000 rpm	±10rpm	±1
5	Exhaust gas analyser	NO (0 - 5,000 ppm)	±50ppm	1
		HC (0 - 200,000 ppm)	±10ppm	0.5
		CO (0-10%)	0.03%	1
6	Smoke meter	0-100%	±1 %	1
7	Pressure transducer	0-110bar	±1bar	0.15
8	Crank angle encoder		±1	1

A2.TECHNICAL SPECIFICATION OF DIESEL SMOKE METER

Parameter	OPACITY	ABSORPTION	RPM	Oil Temperature
Measuring range	0-100 %	0-99.99 m^{-1}	400-6000 min^{-1}	0-150°C
Accuracy & Repeatability	± 1 % of full scale	Better than ± 0.1 m^{-1}	± 10	± 3°C
Resolution	0.10%	0.01 m^{-1}	± 1	± 1°C

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