**Major Project**

**Entitled**

# Experimental Investigation on a Diesel Engine Fuelled with Blends of Acid Oil Biodiesel & Diesel - Performance and Emission Studies

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# CERTIFICATE

This is to certify that the dissertation entitled **“**EXPERIMENTAL INVESTIGATION ON A DIESEL ENGINE FUELLED WITH BLENDS OF ACID OIL BIODIESEL & DIESEL – PERFORMANCE AND EMISSION STUDIES**”** submitted by Mr. PRASHANT VASHISTHA, 10/THR/07 (Roll No. 12299) in partial fulfillment for the award of the Degree of Master of Engineering in Thermal Engineering, is an authentic record of student’s own work carrying by him under my guidance and supervision. It is also certified that this dissertation has not been submitted to any other Institute/University for the award of any Degree or Diploma.

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# ABSTRACT

Energy is the basic input for the socio-economic development of a country. As the demand of energy is increasing day by day, it is essential for every country to opt for other sources of energy which are non-depeleting and biodegradable. Among all the exisiting sources of energy, biofuels seems to be one of the most important energy sources. As diesel engine dominates Indian agricultural Sector, Industry, Transportation Sector etc. it is necessary to identify economical renewable energy sources which can substitute petroleum diesel and hence biodiesel is found to be one of the promising fuels for diesel engine. Biodiesel defined as the mono alkyl esters of long chain fatty acids derived from lipid feedstocks such as vegetable oils or animal fats can be used as a substitute or an additive to diesel fuel. Compared to fossil-based diesel fuel, biodiesel possesses many advantages such as cleaner engine emissions, biodegradable, renewable and superior lubricating property. In spite of the many advantages of biodiesel, it is not yet commercialized all over the world because of the low availability of the good quality oil and their high prices. Therefore, biodiesel should be produced from high FFA oil and other non-edible oils which are available abundantly resulting to their lower cost. In this present study, production of fatty acid methyl ester from acid oil has been carried out which is substantially less expensive than other vegetable oils derived biodiesel. In order to accomplish the objectives of this study, literature review, development of a test rig, performance & emission characteristics tests and determination of Physico-chemical properties are carried out. During the literature review section, it is found that very less work has been done on production of biodiesel from acid oil. Based on the literature review, production of biodiesel from acid oil is carried out using three different catalysts (PTSA, $H_2SO_4$ & MSA) to obtain optimal process for production. A diesel engine test rig was also developed for experimental work in the present project work. Performance and emission test were also carried out when fuelled with petroleum diesel and diesel/biodiesel blends. The engine experimental result shows that the performance of the engine is slightly reduced in terms of brake thermal efficiency (BTE). The BSEC decreases with increase in load and it is found that for B5, B10 and B20, it is slightly higher than diesel. Exhaust emissions including CO & HC were decreased for biodiesel blends as compared to diesel and in case of $CO_2$ & $NO_x$, level of emissions is slightly increased as compared to petroleum diesel.

Approximately 10% increase in NOx emission was observed with 20% biodiesel blend. It is also observed that the emissions decreases for biodiesel-diesel fuel blends. It was also seen that as concentration of biodiesel in biodiesel-diesel blends increases, a downward trend in HC emission is observed. Smoke opacity was also found lower for biodiesel blends in comparison to diesel fuel.

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# NOMENCLATURE

| | |
|---|---|
| % | Percent |
| $\rho$ | Density |
| @ | At the rate |
| < | Lesser than |
| 1M | 1 Mole |
| AN | Acid Number |
| ASME | American Society for Mechanical Engineers |
| ASTM | American Society for Testing and Materials |
| B05 | 5% biodiesel in biodiesel-diesel blend |
| B10 | 10% biodiesel in biodiesel-diesel blend |
| B20 | 20% biodiesel in biodiesel-diesel blend |
| BMEP | Break Mean Effective Pressure |
| BSEC | Brake Specific Energy Consumption |
| BSFC | Brake Specific Fuel Consumption |
| BTDC | Before Top Dead Center |
| BTE | Brake Thermal Efficiency |
| cc | Cubic centimeter |
| CFPP | Cold Filter Plugging Point |
| CI | Compression Ignition |
| $cm^{-1}$ | Per Centimeter |
| CN | Cetane Number |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| Conc. | Concentrated |
| cSt | Centi Stoke |
| CV | Calorific Value |
| DAG | Diacylglycerol |
| FAME | Fatty acid methyl ester |
| FFA | Free Fatty Acid |
| FID | Flame Ionization Detector |

| | |
|---|---|
| g | Gram |
| GDP | gross domestic product |
| $H_2O$ | Water |
| $H_2SO_4$ | Sulphuric acid |
| HAAO | High- acid acid oil |
| HC | Hydrocarbon |
| IC | Internal Combustion |
| IPCC | Intergovernmental Panel on Climate Change |
| kg | Kilogram |
| KOH | Potassium Hydroxide |
| kWh | Kilowatt hour |
| MAG | Monoacylglycerol |
| Min. | Minute |
| ml | Milliliter |
| mm | Millimeter |
| MMT | Metric Million Tonnes |
| MSA | Methane Sulphonic Acid |
| Mt | Million Tonnes |
| Mtoe | Million Tonnes of Oil Equivalent |
| NAOH | Sodium Hydroxide |
| nm | Nanometer |
| Nos. | Numbers |
| $NO_x$ | Oxides of Nitrogen |
| $^oC$ | Degree Celsius |
| PM | particulate matter |
| ppm | Parts per million |
| PTSA | Para Toluene Sulphonic Acid |
| Qty | Quantity |
| rpm | Revolutions Per Minute |
| Rs. | Rupees |
| SDBS | Sodium Dodecyl Benzene Sulfonate |
| $SO_x$ | sulphur oxides |
| SS | Soapstock |

| | |
|---|---|
| TAG | Triacylglycerol |
| TDC | Top Dead Center |
| UBHC | Unburnt Hydrocarbon |
| VOC | Volatile Organic Compounds |
| Vs | Versus |
| WVO | Waste vegetable oils |

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

Energy is one of the most significant inputs for growth of all sectors including agricultural, industrial service and transport sectors. Energy has been at the centre stage of national & global economic development for several decades. The demand for energy, around the world is increasing exponentially, specifically the demand for petroleum-based energy. Petroleum derived fuels, actually, exceeds the demand of any other fuels or energy resources. The world consumption for petroleum and other liquid fuel will grow from 85 million barrels/day in 2006 to 107 million barrels/day in 2030. Under these growth assumptions, approximately half of the world's total resources would be exhausted by 2030. Also, as per many studies, the world oil production would peak sometime between 2007 and 2030 **[1].** Therefore, the future energy availability is a serious global. Another, major global concern is environmental degradation or climate change such as global warming. Global warming is related with the greenhouse gases which are mostly emitted from the combustion of petroleum fuels. In order to control the emissions of greenhouse gases, Kyoto Protocol targets to reduce the greenhouse gas emission by a collective average of 5% below 1990 level of respective countries. The Intergovernmental Panel on Climate Change (IPCC) concludes in the Climate Change 2007 that, because of global warming effect the global surface temperatures are likely to increase by 1.1°C to 6.4°C between 1990 and 2100 **[2].**

## 1.2 Energy Crisis

There is a realization throughout the world that the petroleum resources which are non renewable, are limited and are being consumed at an alarming rate. The growing demand for energy and gradual extinction of fossil fuels has lead to an energy crisis. Most of the power in industries and transportation is derived from oil and coal. Special mention is needed for automobiles where almost all of the fuels for combustion engine today are derived from petroleum, a nonrenewable source of energy, which is nearing its end at an unprecedented pace. The grave name of the energy problem was sharply brought into focus by the oil crisis of 1973. Since then, several price hikes have taken place, upsetting economy of most of the nation. The globe today uses about 147 trillion kWh of energy which is expected to rise in the coming future **[1]**. Figure 1.1 and 1.2 shows the expected rise in the world consumption of energy up to 2030. A major chunk of this rise will be due to the developing countries, which are bound to grow by leaps and bounds.

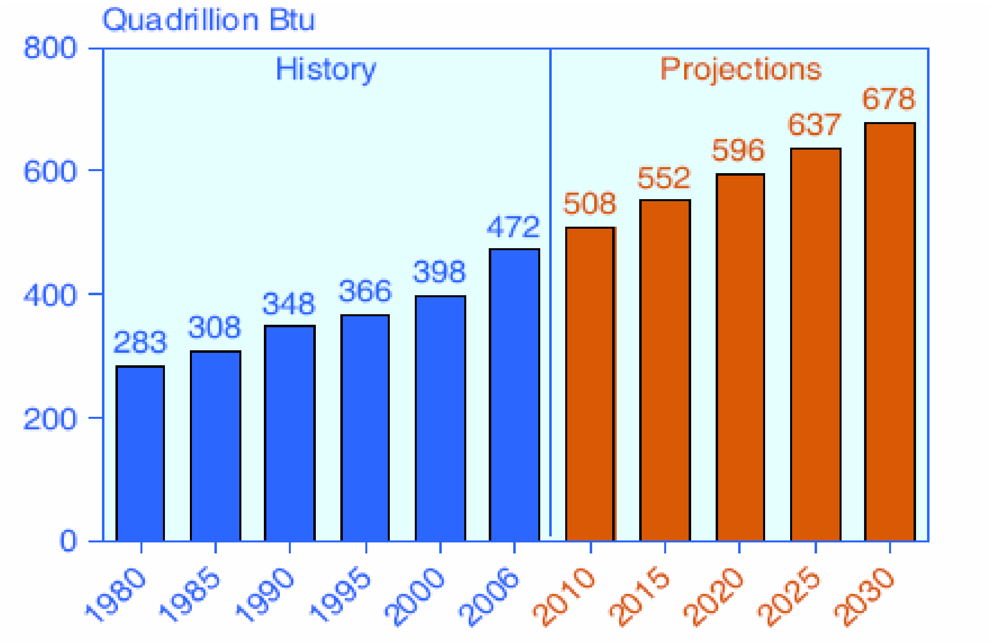

**Figure 1.1: World Marketed Energy Consumption [1]**

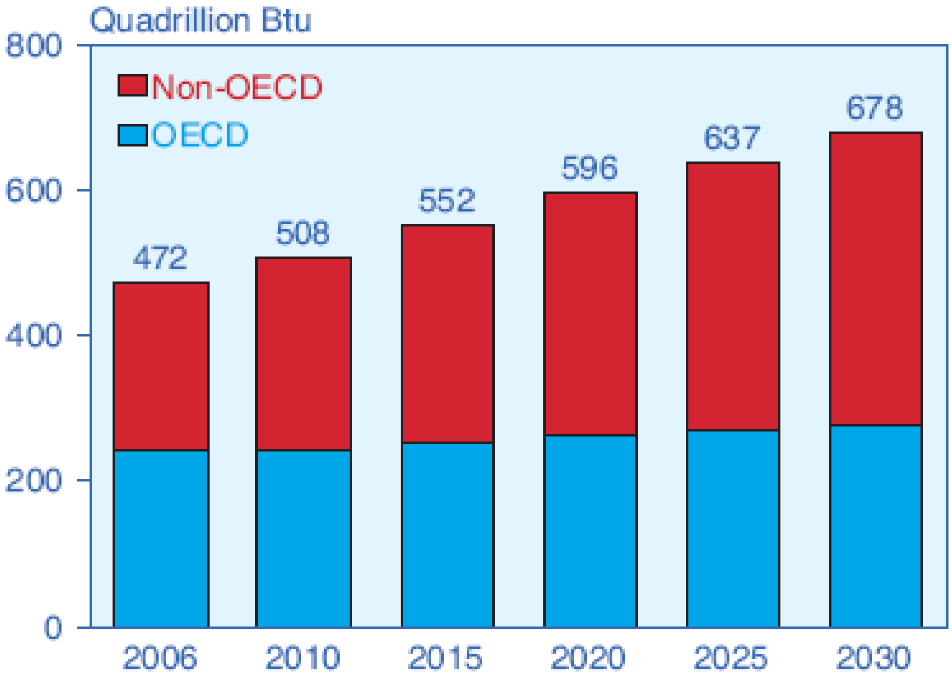

**Figure 1.2: World Marketed Energy Use: OECD vs. Non-OECD [1]**

The developing countries have been achieving spectacular growth rates for some time now, and are expected to grow at similar rate for some more time to come. Figure 1.3 substantiates expectations regarding the rise of energy use, region wise.

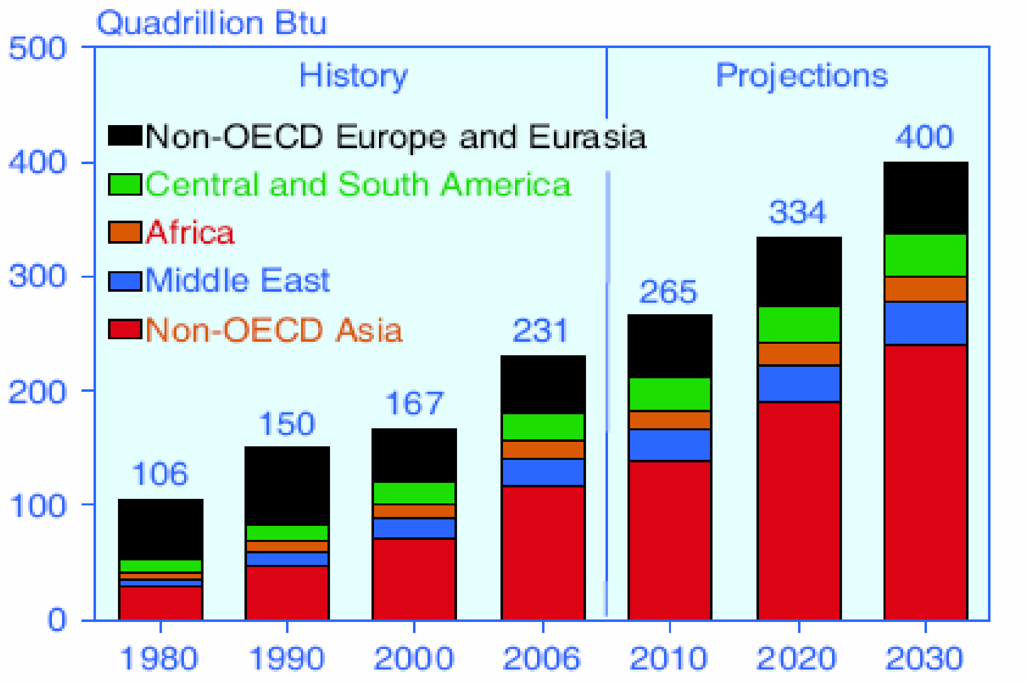

**Figure 1.3: Marketed Energy Use by Region [1]**

Hence, it can be seen that as a "Non-OECD" country, there is a need to develop energy solutions faster in India. Even in the "Non-OECD" countries, regional distribution shows that Asia is poised to grow the fastest in terms of energy use. In Asia, it is well known that the "giant" economies of India and China shall need the lion's share of that to sustain their roaring economies. The tiger and the dragon will soon be the world's top energy consumers. Hence, for India it is needed to develop energy resources fast enough to keep pace with the demand. The country cannot afford to fall back in the global race for progress.

## 1.3 Energy Scenario: Indian Context

India had experienced robust growth for the past few years, and after an impressive 9.6 per cent gross domestic product (GDP) growth in 2006-07 the Indian economy is headed towards 8.7 per cent growth in the current fiscal **[3]**. The energy needs of India are also rising to cope up the growth rate. Of the 156.1 million tonnes of crude oil that India consumed in 2007-08, it produced only 34.12 million tonnes

**[4]**. Indian economy is mainly agriculture based and modern agriculture system is heavily dependent upon internal combustion engines for running farm machinery, irrigation pump sets, and other equipments. Indian growth is mainly based on energy, produced by “oil-burning” in IC engines. It is very difficult to find clear blue sky in Indian metropolis. Petroleum fuels are major contributor to ecological imbalance in India. As Indian economy is heavily based upon IC engines, it is not possible in any case to discard them and some other, easily available renewable fuels in India. These renewable fuels must be sought to lease new life to existing engines in order to curb the twin problems of fuel scarcity and air pollution. Various national emission standards have been set by the Government of India through which the fleets are facing greater pressures to switch to cleaner alternative fuels. The alternative fuels are desirable from the fact that they are the only fuels used with recent engine developments, which can meet the stringent EURO-IV emission norms, which are expected to be enforced in India from 2010. India being richer in flora and fauna can look forward to use fuels from bio origin as the suitable alternatives. The prominent bio fuels from Indian perspective are ethanol and biodiesel. India, the world's second most populous nation, has seen its population exploding from 300 million in 1947 to around 1.2 billion today. This rapidly growing population has placed a strain not only on India's infrastructure, but also on its environment. According to the World Health Organization, New Delhi is one of the top ten most polluted cities in the world. Two primary sources of air pollution in India are vehicular emissions and untreated industrial smoke. The number of vehicles has registered a sharp increase more so, during the last decade. In Delhi alone, the vehicle number has crossed about 4.6 million. Today, the vehicular pollution contributes roughly 64 % of total air pollution in Delhi, followed closely by Mumbai at 52% and somewhat controlled figure of 30% for Kolkata. About 50% of the total petroleum products consumed in the country go into the transport sector mainly in the form of high-speed diesel and gasoline **[5]**. India's per capita energy use and carbon emissions, while lower than the world average, result in a substantial percentage of world energy use and carbon emissions, due to the country's large population and heavy reliance on fossil fuels. Increased use of renewable energy is one means of reducing carbon emissions.

## 1.4 Energy Demand and Supply

Energy Security is driven by the demand and supply behaviour. India ranks sixth in the world in terms of energy demand accounting for 3.64% of world commercial energy demand in 2007. Although India ranks fifth in total energy consumption in the world (404.4 mtoe (million tones of oil equivalent), this is only 17.12% of the energy consumed by the largest consumer, i.e. USA (2361.4 mtoe). In per capita terms, its consumption is only about 20% of the global average. Rapid Industrialization and Globalization have pushed the demand of energy to new heights. In the year 2011, India will have a total population of about 1.3 billion people of which 68% will be living in rural areas. Since diesel constitutes 37 % of total petroleum consumption mainly for transportation and other purposes, its demand is integrally related to economic growth and is seen as a growth inducing factor. The stress of the over-burdening population will augment the strain in terms of the volume of fuel required, but the picture of proven oil reserves distribution doesn't reflect the pleasant sight at all. The share with respect to the energy distribution of the remaining oil reserves across the world is shown in figure 1.4.

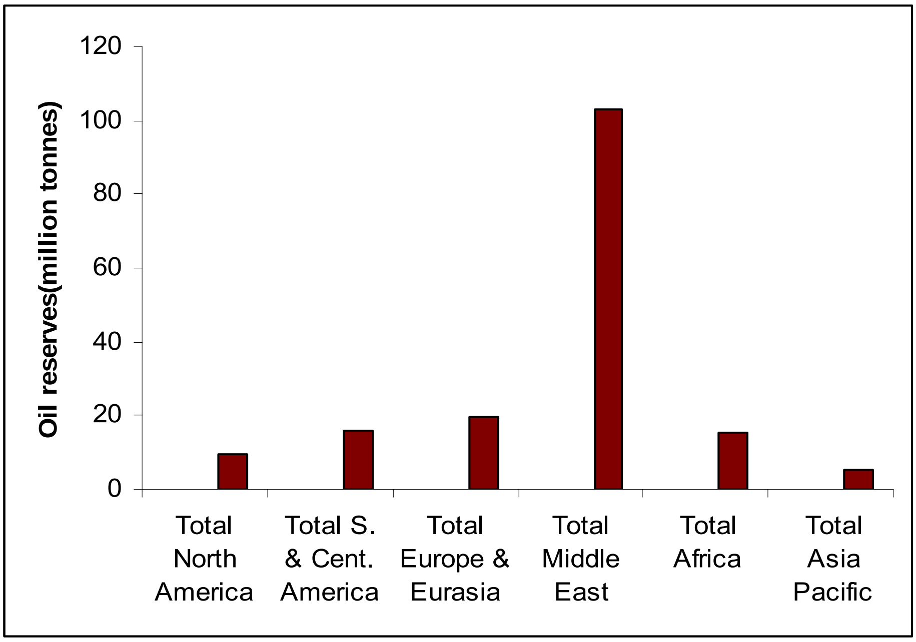

**Figure 1.4: World Oil Reserves, 2008 [6]**

It can be observed, that bulk of the reserves are with Middle East. The condition of the Asia Pacific countries presents a dismal trend, presently, only 3.3%

of the total share is in their buckets. Therefore, it is apparent that the Asian countries have to change their fuel strategy or live with the escalating burdens of oil imports or with joint venture abroad with the hope to meet their requirement. At present, India imports about 77.94 % of its crude oil required. Net import of crude oil has increased from 74.10 MMT in 2000-01 to 121.67 MMT in 2007-08. India paid Rs.2,72,699 crores for importing crude oil in 2007-08. This import comprised about 30 % of the total value of Indian imports in 2007-08 **[4]**. Heavy dependence on import of crude oil is a subject of serious concern. As per The World Energy out Look, India's dependence on oil import would grow to 91.6 % by the year 2020. The trend of import of crude oil in India is shown in table 1.1.

**Table 1.1: Import of Crude Oil in India [4]**

| Year | Crude Oil | |
|---|---|---|
| | Qty MMT | Value (Rs. In Crores) |
| 1996-97 | 33.91 | 18538 |
| 1997-98 | 34.49 | 15897 |
| 1999-99 | 39.81 | 14876 |
| 1999-00 | 57.80 | 30695 |
| 2000-01 | 74.10 | 65932 |
| 2001-02 | 78.70 | 60397 |
| 2002-03 | 85.81 | 62876 |
| 2003-04 | 90.43 | 83528 |
| 2004-05 | 95.86 | 117003 |
| 2005-06 | 99.41 | 171702 |
| 2006-07 | 110.86 | 219991 |
| 2007-08 | 121.67 | 272699 |

As already evident from above discussion that the self reliance of our country is declining and has reached to a very low figure of 21.86% in year 2007-08 as shown in table 1.2. Although, India has invested considerable resources in petroleum sector, the crude oil production has stagnated around 32-33 million metric tonnes per year over the past decade. The majority of India's roughly 5.4 billion barrels in oil reserves are located in the Bombay High, Upper Assam, Cambay, Krishna-Godavari, and Cauvery basins. India's average oil production level for 2007 was 801000 barrels per day **[4]**. But the consumption continues to outstrip production. Over the years, the domestic availability of the crude oil has not kept pace with the demand. Table 1.2 summarizes the trends of demand and supply of crude petroleum in the preceding years.

**Table1.2: Consumption and Domestic Availability of Crude Oil [4]**

| Year | Domestic Production (Mt) | Demand (Mt) | Self Reliance (%) |
|---|---|---|---|
| 1990-91 | 33.02 | 53.72 | 61.4 |
| 1995-96 | 35.17 | 62.51 | 56.2 |
| 2000-01 | 32.43 | 106.523 | 30.4 |
| 2001-02 | 32.03 | 110.738 | 28.92 |
| 2002-03 | 33.04 | 115.031 | 28.72 |
| 2003-04 | 33.38 | 123.815 | 26.96 |
| 2004-05 | 33.98 | 129.84 | 26.17 |
| 2005-06 | 32.19 | 131.6 | 24.4 |
| 2006-07 | 33.99 | 144.85 | 23.46 |
| 2007-08 | 34.12 | 156.1 | 21.86 |

## 1.5 Diesel Engines

Before discussing the combustion characteristics of biodiesel, it would be relevant to discuss the basic concept of compression ignition engine or diesel engine. Compression ignition engine was invented by Rudolf Diesel, which is commonly known as diesel engine today. The engine cycle of the diesel engine is diesel cycle which is a modified Otto cycle and known as constant pressure cycle. The diesel engine relies on a high compression ratio, typically greater than 14:1 to initiate the combustion. This, higher compression ratio is in order to bring the air temperature to a level where auto ignition is promoted when the fuel is injected to the cylinder at the end of the compression stroke. A principal requirement of a fuel for diesel engine is that it must be auto ignited easily **[7]**. Diesel engines are usually classified into two categories; direct and indirect injection. Direct injection means the fuel is directly injected into the combustion chamber. The fuel is injected under high pressure through a nozzle with single or multiple tiny orifices. This results in a fuel spray with very fine droplets thus making it easier for the fuel to evaporate and burn. But, in the indirect injection engines, the fuel is injected into an auxiliary chamber that is adjacent and connected to the main combustion chamber. Most combustion start sooner in this chamber and burning gases exit the chamber with high velocities giving a greater ability for mixing of fuel and air. These types of engines are not very sensitive on the ignition ability of the fuels.

Generally, the combustion process in diesel engines can be divided into four steps

(1) Ignition delay: it is a period between the start of injection and the start of combustion.

(2) Ignition: it is taken place after ignition delay period.

(3) Initial combustion or premixed combustion phase: which occurs after ignition and it consumes about 5% to 10% of injected fuel.

(4) Diffusion controlled or mixing controlled phase of combustion: it occurs after premixed combustion and produce high temperature and pressure in the combustion chamber. It consumes all of the remaining fuel **[8].**

During the ignition delay period many processes occur within the cylinder. Fuel has to be broken down into droplets, heated, vaporized, and mixed with air. Both physical and chemical delays are present and those two delays are not added since they are usually overlapping. Due to the high compression ratio the temperature and pressure of the air at the time of injection are normally well above those required to support chain-reaction in a uniform fuel-air mixture. Under these conditions, ignition of any element of the charge dose not require transfer of energy from another portion but will occur when the local temperature, pressure, and mixing of fuel and air make combustion possible **[9]**. In general, the combustion of the fuel in the compression-ignition engine depend on the local condition in each part of the charge and does not depend on the spread of the flame through the charge like spark ignition engines. However, the local flame may assist the ignition of adjacent sections if the local conditions (e.g., fuel-air ratio) support combustion. Local flames may also reduce the reaction time of adjacent sections by raising their temperature and pressure. The combustion rate or heat release rate is thus a function of the state and distribution of the fuel as well as the pressure and temperature in the combustion chamber, where the latter is initially dictated by the compression ratio **[10]**. Other factors that influence the combustion process are injection timing, turbulence in the combustion chamber, engine revolution along with several other fuel properties such as cetane number, kinematic viscosity, density and distillation temperature. The advantages of diesel engines are that it has greater efficiency, durability and good fuel economy compared to gasoline engines. Therefore, the application range of diesel engines is very wide. Most of the applications of diesel engines are in major transportation sector such as bus, truck, train and ship, and heavy machinery like construction equipments.

## 1.6 Need for Alternate Fuels

To solve dual problems of fossil fuel depletion and environmental degradation, the renewable fuels with lower environmental impact are necessary. Nowadays, many new fuels have been used and biomass derived fuels are among them. Some of the well known biomass derived fuels are ethanol for gasoline engines and bio-diesel for compression ignition engines. Biodiesel is a renewable and environmental friendly alternative fuel for diesel engine which is produced from variety of vegetable oils and animal fats by the trans-esterification process. Transesterification is a chemical reaction in which vegetable oils and animal fats are reacted with alcohol in the presence of a catalyst. The products of reaction are fatty acid alkyl ester and glycerine, and the fatty acid alkyl ester is known as biodiesel. Bio-diesel is an oxygenated fuel containing 10% to 11% oxygen by weight. Also it is a sulphur-free fuel. These lead biodiesel to more complete combustion and less harmful exhaust emissions. However, biodiesel fuel has higher viscosity, density, pour point, flash point and cetane number than diesel fuel. Also the energy content or net calorific value of biodiesel is about 12% lower than that of diesel fuel on a mass basis. Using biodiesel can help in reducing the world’s dependence on fossil fuels and also has significant environmental benefits. Using biodiesel instead of the conventional diesel fuel reduces exhaust emissions such as the overall life circle carbon dioxide ($CO_2$), particulate matter (PM), carbon monoxide (CO), sulphur oxides ($SO_x$), volatile organic compounds (VOCs), and unburned hydrocarbons (UBHC). However, most of the biodiesels give 10% to 15% higher oxides of nitrogen ($NO_x$) when fuelling with 100% biodiesel **[11]**. Depending on the abundantly availability of feedstock in local region, the different feedstocks are tried for the biodiesel production. In the United States, the primary sources for biodiesel production is soy bean oil, while EU nations prefer to utilize rapeseed oil, and in South East Asia regions, palm oil, coconut oil and Jatropha oil are used for biodiesel productions. Growing the production of biodiesel in many countries around the world has been accompanied by the development of standards to ensure high fuel quality. The biodiesel standards are ASTM D6751 in the United States and EN 14214 in EU Nations. The properties of biodiesel are mainly determined by the structure of fatty acids alkyl esters which constitutes it, particularly, the combustion characteristics such as ignition quality, and the fuel properties such as density, viscosity, pour point and oxidation stability of biodiesel are mostly affected by the structure of fatty acids alkyl esters **[12].**

## 1.7 Feedstocks for Biodiesel

A variety of oils can be used to produce biodiesel. These include:

- Virgin oil feedstock e.g. rapeseed and soybean oils are most commonly used in USA and EU.
- Waste vegetable oils (WVO), collected from fast food chain.
- Animal fats including tallow, lard, chicken fat and fish oil.
- Algae- It can be grown using waste materials such as sewage and without displacing land currently used for food production.
- Acid Oil.

As 80% of the price of biodiesel is attributed to feedstock cost, it shall be relevant to explore cheaper feedstocks for biodiesel production economically and acid oil seems to be most promising cheaper feedstock for biodiesel production. Acid Oil is made from soap stock which is a byproduct of edible oil refining process and available in bulk in India.

## 1.8 Acid oil & its Sources

Acid oil is derived from soap stock where freeze-drying is employed to remove the water after saponification. The resulting dried saponified soap stock (SS) is often subjected to a process termed ‘acidulation’, wherein sulphuric acid and high-pressure steam are employed to acidify heat and mix the SS mass**.** This converts the fatty acids from sodium salts (soaps) to free acids, greatly reducing their emulsifying properties and breaking the heavy emulsion typical of SS. Some hydrolysis of the acylglycerols in the SS also occurs. When steam injection is terminated and the mixture is allowed to settle, it separates into an aqueous and an oil phase. The former contains the sodium sulphate generated by reaction of sodium hydroxide in the saponified SS with the added sulphuric acid. However, as opposed to being produced as a solid in the method described above, this is dissolved in the aqueous solution, which facilitates its disposal. The oil phase, termed ‘acid oil’, is essentially free of water and contains free fatty acids (FFA), acylglycerols, pigments and other lipophilic materials. As acid oil is commercial product, selling for approximately 30-40 % of the cost of refined vegetable oils, the potential suitability of acid oil for biodiesel production was evaluated in the present research work. The acid oil normally contains free fatty acids (59.3%), triacylglycerols (28.0%), diacylglycerols (4.4%) and monacyglycerols, (<1%) by weight. Acid oil can be derived from refining of various edible oils such as soybean, sunflower, safflower, canola, mustard and palm.

## 1.9 Why Acid oil as Feedstock

As already elaborated biodiesel is one of the very promising alternatives for meeting energy security and better environment. Bio-diesel can be made from virgin or used vegetable oils (both edible & non-edible) and animal fats. Since edible oils are in short supply in India, these can not be used for biodiesel production. Besides meeting engine performance and emission characteristics biodiesel will have to compete economically with petroleum-based diesel fuel to survive in the market place. Vegetable oils partially or fully refined and of edible-grade quality, are currently the predominant feedstock’s for biodiesel production. However on commercial scale, the high cost of feedstock precludes mass utilization of biodiesel due to high price. In this context, acid Oil derived from soap stock (SS), a by-product of the refining of vegetable oils, is a potential biodiesel feedstock. It consists of a heavy alkaline aqueous emulsion of lipids, containing about 50% water, with the balance made up of free fatty acids (FFA), phosphoacylglycerols, triacylglycerols, pigments and other minor nonpolar soybean components. SS is generated at a rate of about 6% of the volume of crude oil refined, Its market value is approximately Rs. 11 per kg on a dry weight basis, i.e., about one-fifth the price of crude soybean oil. Some researchers have reported methods for the production of fatty acid esters from SS **[13-15].**

# CHAPTER 2

# LITERATURE SURVEY

## 2.1 Introduction

Vegetable oils were used as fuel for diesel engines to some extent since the invention of the compression ignition engine by Rudolf Diesel in the late 1800`s. During the early stages of the diesel engine, strong interest was shown in the use of vegetable oils as fuel but this interest declined in the late 1950`s after the supply of petroleum products become abundant **[16]**. During the early 1970`s, oil shock, however, caused a renewed interest in vegetable oil fuels. This interest evolved after it became apparent that the world's petroleum reserves were dwindling. At present, in order to replace a part of petroleum based diesel usage, the use of vegetable oils derived biodiesel has been starting in many countries. Vegetable oils are renewable energy source and significant environmental benefit can be derived from the combustion of vegetable oil based biodiesel rather than petroleum based diesel fuels. As vegetable oils contain only trace quantities of sulphur, therefore, the combustion of biodiesel emits 99% less $SO_x$ emission. Since prices of edible oils used for biodiesel production are quite high, efforts have been made to use cheaper feed stocks such as non edible plant oils, waste cooking oil and animal fat so that biodiesel could be produced at affordable price **[17]**. Acid oil seems to be a potential feedstock for biodiesel production. The research work embodied in this thesis aims to prepare biodiesel from high FFA acid oil and to evaluate the performance and exhaust characteristics of a biodiesel/ diesel fuelled CI engine. The available literature on the subject matter of the thesis was thoroughly reviewed and presented in this chapter. A review of current literature shows that among the various alternative fuels which could match the combustion features of diesel oil at a relative low oil price and which can be easily adopted for use in existing engine technologies without any major modification is vegetable oil derived fuel.

## 2.2 Biodiesel Production from high FFA oil

As acid oil has high free fatty acid content, there is a need to neutralize the FFA. There are normally two routes of neutralization of FFA such as saponification of FFA and esterification of FFA using acid catalyst. After neutralization of FFA, the transesterification is carried out to convert triglycerides into mono alkyl esters. It is also seen that the major factors which affect the conversion efficiency of the both esterification and transesterification process are molar ratio of alcohol: oil, amount of catalyst, reaction temperature and reaction duration.

### 2.2.1 Esterification Reaction

Free fatty acids can be esterified by alcohols in the presence of suitable acidic catalyst as shown in figure 2.1

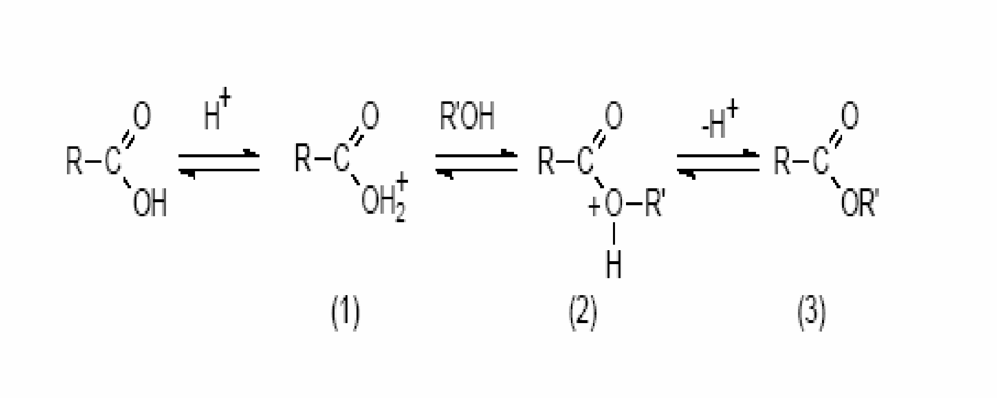

**Figure 2.1: Mechanism of Acid Catalyzed Esterification Process [18]**

Acid catalysed esterification is preferred for oils having high free fatty acid content. The difficulty with alkaline-esterification of these oils is that they contain large amounts of free fatty acids (FFA). These free fatty acids quickly react with the alkaline catalyst to produce soaps that inhibit the separation of the ester and glycerine. A two-step process is developed to convert the high FFA oils to its mono-esters. The first step, acid catalysed esterification reduces the FFA content of the oil to less than 2%. The second step, alkaline catalysed transesterification process converts the products of the first step to its mono-esters and glycerol **[19]**.

In an effort to increase utilization of fats and oils with high concentrations of FFA, acid catalysts were investigated at elevated temperatures to determine their efficacy under various operating conditions. Acid-catalyzed alcoholysis of soybean oil using sulfuric, hydrochloric, formic, acetic, and nitric acids was evaluated at 0.1 and 1 wt% loadings at temperatures of 100 and 120°C in sealed ampoules, but only sulfuric acid was effective **[20]**.

Haas et. al. **[21]** used acid-catalyzed esterification for the synthesis of fatty acid methyl ester (FAME) from acid oil. Soybean acid oil contained 59.3 wt% FFA, 28.0 wt% TAG, 4.4 wt% DAG, and less than 1% MAG. Maximum esterification occurred at 65°C and 26 h reaction at a molar ratio of total fatty acid/methanol/sulfuric acid of 1:15:1.5

Naik et. al. **[22]** adopted the mechanism of a dual process for the production of biodiesel from Karanja oil containing FFA up to 20%. The first step is acid-catalyzed esterification by using 0.5% $H_2SO_4$, alcohol 6:1 molar ratio with respect to the high FFA Karanja oil to produce methyl ester by lowering the acid value, and the next step is alkali-catalyzed transesterification. The yield of biodiesel from high FFA Karanja oil by dual step process has been observed to be 96.6–97%.

### 2.2.2 Transesterification Process

Transesterification process is widely used in the production of biodiesel. In this reaction, fatty acids in vegetable oil are reacted with an alcohol in presence of a catalyst to form fatty acid alkyl ester. Infact, the transesterification can take place with or without a catalyst. Either an acid or alkali catalyst can be used in the transesterification to produce methyl, ethyl or butyl esters of fatty acids. In reaction, the stoichiometric ratio of alcohol to vegetable oil is 3:1 and the products are 3 mol of fatty acid alkyl ester and 1 mol of glycerol. Mostly, the molar ratio of alcohol to vegetable oil is determining the ester conversion rates. It has been reported by that, a molar ratio of 6:1 of alcohol to vegetable oil gives the ester conversion rate over 90%. One of the factor influences on ester conversion rate is the fatty acid composition of vegetable oils. Higher saturated fatty acid compositions in vegetable oils results difficulties in transesterification reaction and produces lower ester conversion rate.

Among the alcohols; methanol, ethanol, propanol and butanol **[23]** are used for transesterification process but methanol and ethanol are preferred because of their lower cost, easy availability and physicochemical advantages. Methanol is further preferred to ethanol as it reacts faster in the medium and can be easily dehydrated as compared to ethanol. In case of methyl esters separation of glycerol is also faster with low stoichiometric ratio.

Freedman et. al. **[24]** studied the variables that affect the yield and purity of esters produced by transesterification process. The water content of all materials, including the catalyst and triglyceride, and the acid value of the triglyceride were required to be very low. Other important factors for transesterification are reaction time and temperature. The reaction temperature depends on the type of alcohol being used and was recommended to be a few degrees below the boiling point of the alcohols used.

Noureddini **[25]** found that increasing the reaction temperature from 30 to 70°C led to significant increases in the reaction rate with temperature up to 50°C, but little increase in reaction rate over 50 °C.

Chen et. al. **[26]** found that acid catalysts are considerably slower than base catalysts. Alkali metal alkoxides are the most effective transesterification catalyst compared to the acidic catalyst. Sodium alkoxides are among the most efficient catalysts used for this purpose, although KOH and NaOH can also be used. Though alkaline metal alkoxides are the most effective, they require absence of water which makes them appropriate for typical industrial processes. Alkaline metal hydroxides (KOH and NaOH) are cheaper than metal alkoxide, but less active. NaOH is cheaper but requires high temperature (70°C) while KOH reacts at room temperature and by-product (potassium sulphate) generated during reaction can be sold as a fertilizer **[27].**

Allen et. al. **[28]** repoeted that reaction times in the range 15-30 minutes were adequate for greater than 98% conversion when canola oil was transesterified with methanol at 60°C.

The optimization of various parameters is necessary for maximizing the biodiesel yield during the transesterification process. Various researchers have made attempts to optimize the process parameters in their studies **[29- 30]**.

### 2.3 Biodiesel as a diesel substitute

Presently, the well known method of biodiesel usage is its blending with conventional diesel fuel. The common ratio is 80% conventional diesel fuel to 20%

biodiesel, which is also known as “B20”. The application of ester of vegetable oils as diesel engine fuels has been studied by several researchers.

Peterson et. al. **[31]** found that the engine performance of a diesel engine fuelled with methyl and ethyl esters of rapeseed oil was comparable to standard diesel fuel with the ester showing slightly lower power output and associated higher brake specific fuel consumption. The methyl ester was reported to produce slightly more power than the ethyl ester.

Shaheed et. al. **[32]** investigated the performance and exhaust emission evaluation of a small diesel engine fuelled with coconut oil methyl esters. They showed coconut oil methyl ester had comparative engine performance to diesel fuel and emission characteristics were equally as good as or better than diesel fuel for most of the exhaust constituents.

Hamasaki et. al. **[33]** investigated the potential suitability of waste vegetable oil methyl ester. They pointed out that the exhaust gas emissions from the waste vegetable oil methyl ester were acceptable and smoke emission was lower than that of the diesel fuel.

Mittelbach et. al. **[34]** found in their tests with methyl esters of frying oil that the level of $NO_x$ was high due to the high combustion temperature. This high temperature was attributed to the high oxygen content of the ester fuel. However, all other emissions, including polycyclic aromatic hydrocarbons (PAH), were low.

Lapuerta et. al. **[35]** collected and analysed the body of work written mainly in scientific journals about diesel engine emissions when using biodiesel fuels as opposed to conventional diesel fuels. Since the basis for comparison is to maintain engine performance, the first section is dedicated to the effect of biodiesel fuel on engine power, fuel consumption and thermal efficiency. The highest consensus lies in an increase in fuel consumption in approximate proportion to the loss of heating value. In the subsequent sections, the engine emissions from biodiesel and diesel fuels are compared, paying special attention to the most concerning emissions: nitric oxides and particulate matter, the latter not only in mass and composition but also in size distributions. In this case the highest consensus was found in the sharp reduction in particulate emissions.

Nabi et al. **[36]** investigated different parameters for the optimization of biodiesel production in the first phase of this study, while in the next phase of the study performance test of a diesel engine with neat diesel fuel and biodiesel mixtures were carried out. Biodiesel was made by the well known transesterification process. Cottonseed oil (CSO) was selected for biodiesel production. The transesterification results showed that with the variation of catalyst, methanol or ethanol, variation of biodiesel production was realized. A maximum of 77% biodiesel was produced with 20% methanol in presence of 0.5% sodium hydroxide. The engine experimental results showed that exhaust emissions including carbon monoxide (CO) particulate matter (PM) and smoke emissions were reduced for all biodiesel mixtures. However, a slight increase in oxides of nitrogen (NOx) emission was experienced for biodiesel mixtures.

Utlu et al. **[37]** examined the usage of methyl ester obtained from waste frying oil. In this study, methyl ester was tested in a turbocharged, four cylinders and direct injection diesel engine. The results were compared with diesel fuel. Engine tests results obtained with the aim of comparison from the measures of torque, power; specific fuel consumptions are nearly the same. In addition, amount of emission such as CO, $CO_2$, $NO_x$, and smoke darkness of waste frying oils are less than diesel fuel.

Godiganur et al. **[38]** used diesel, methyl ester of mahua oil and its blends in a Cummins 6BTA 5.9 G2- 1, 158 HP rated power, turbocharged, DI, water cooled diesel engine at constant speed of 1500 rpm under variable load conditions. The volumetric blending ratios of biodiesel with conventional diesel fuel were set at 0, 20, 40, 60, and 100. Engine performance (brake specific fuel consumption, brake specific energy consumption, thermal efficiency and exhaust gas temperature) and emissions (CO, HC and NOx) were measured to evaluate and compute the behaviour of the diesel engine running on biodiesel. The results indicate that with the increase of biodiesel in the blends CO, HC reduces significantly, fuel consumption and NOx emission of biodiesel increases slightly compared with diesel. Brake specific energy consumption decreases and thermal efficiency of engine slightly increases when operating on 20% biodiesel than that operating on diesel.

Baiju et. al. **[39]** investigated the suitability of methyl and ethyl ester from Karanja oil as an alternative diesel fuel. The methyl and ethyl esters of Karanja oil were prepared by transesterification using both methanol and ethanol. The physical and chemical properties of ethyl esters were comparable with that of methyl esters. However, viscosity of ethyl esters was slightly higher than that of methyl esters. Cold flow properties of ethyl esters were better than those of methyl esters. Performance and exhaust emission characteristics of the engine were determined using petrodiesel as the baseline fuel and several blends of diesel and biodiesel as test fuels. Results show that methyl esters produced slightly higher power than ethyl esters. Exhaust emissions of both esters were almost identical. These studies show that both methyl and ethyl esters of Karanja oil can be used as a fuel in compression ignition engine without any engine modification.

### 2.4 Acid oil as biodiesel

As acid oil is a cheap and promising feedstock for biodiesel production, it shall be relevant to refer the work done by previous researchers on biodiesel production from acid oil and its potential suitability as a diesel fuel. In this context, exhaustive review was carried out to refer the work done in this area and is summarized below.

Haas et.al. **[21]** used two approaches for making biodiesel from acid oil as feedstock. In first approach soybean acid oil with FFA content of 59.3% was esterified by acid- catalyzed esterification. Maximum esterification was found to occur at 65°C and 26 h reaction at a molar ratio of total fatty acid/methanol/sulphuric acid of 1:15:1.5. In an alternative approach, the acylglycerol species in soapstock were saponified prior to acidulation. High-acid (HA) acid oil made from this saponified soapstock had an FFA content of 96.2 wt% and no detectable TAG, DAG, or MAG. Optimal esterification conditions for HA acid oil at 65°C were a mole ratio of FFA/methanol/acid of 1:1.8:0.17, and 14 h incubation. Theoretical conversion into biodiesel (FAME) under these conditions was 89%.

Haas et.al. **[40]** reported biodiesel production from a low quality underutilized feedstock i.e. soapstock, by means of simple chemical methods. Multiple approaches were taken in search of a route for the production of fatty acid methyl esters from soybean soapstock. The most effective method involved the complete saponification of the soapstock followed by acidulation. This resulted in acid oil with a free fatty acid (FFA) content greater than 90%. These fatty acids were efficiently converted to methyl esters by acid-catalyzed esterification.

Park et. al. **[41]** investigated biodiesel production from soapstock containing high concentration of fatty acids. Soapstock was converted to high-acid acid oil (HAAO) and then esterified by a solid catalyst, Amberlyst-15. The solid acid catalyst had several advantages for the process such as easy recovery of the catalyst and repeated use. The evaporation process was applied to remove water during esterification reaction of FFA. Water produced during esterification should be removed to reduce the amount of methanol, increase biodiesel purity and reduce the operation time.

Watanabe et. al. **[42]** found enzymatic conversion of acid oil to fatty acid methyl esters (FAME). This was accomplished in two- step conversion system. First step was to hydrolyze the acylglycerols in Acid Oil Supernatant (AOS) by Candida rugosa lipase with water and second step was methyl esterification of FFA to FAME by immobilized Candida Antarctica lipase. The enzymatic process established in this study is advantages in following respects: a) higher degree of esterification, b) utilization of immobilized lipase for longer periods; thus, the production costs are reduced c) the reaction temperature is moderate; thus, the energy for heating can be saved d) a process to remove the acid catalyst is not necessary e) the waste water is neutral in pH and is free from salts.

## 2.5 Statement of the problem

On the strength of the exhaustive review of work done by previous researchers, it is found that less quantum of work has been done on potential suitability of acid oil as feedstock for biodiesel production and no work has been reported on assessing the aptness of acid oil biodiesel in diesel engine. The acid oil can be derived from further processing of soapstock which is a by product of edible oil refining. Hence, for economical production of biodiesel; acid oil, a low quality underutilized feedstock; can be used to produce biodiesel.

In this present research work, efforts have been made on production and subsequent utilization of acid oil biodiesel in the diesel engine. Various catalysts for biodiesel production from acid oil have been used. Engine performance and emissions were measured to evaluate the behaviour of the diesel engine running on different blends of acid oil biodiesel and diesel. Therefore, following mentioned objectives can be formulated for the present research work.

1. Comprehensive literature survey.
2. Column development with different layers.
3. Production of biodiesel from acid oil and its decolourisation.
4. Determination of important Physico-chemical properties of acid oil biodiesel.
5. Development of diesel engine test rig.
6. Conducting exhaustive experiments on the test rig to evaluate performance and emission characteristics of biodiesel-diesel blends and comparison with baseline data of diesel fuel.
7. Analysis of Results

# CHAPTER 3

# SYSTEM DEVELOPMENT AND EXPERIMENTAL PROCEDURE

## 3.1 Introduction

There is no difference of opinion that India is going to face a severe fuel crisis in future because the fuel consumption has increased in all the vital sectors specially transportation and agricultural sector. Diesel engine plays an indispensable role in transportation and agriculture sector and as such diesel consumption will increase multifold in time to come. The diesel engine continues to dominate the agriculture sector in our country in comparison to spark ignition engine and have always been preferred widely because of power developed, specific fuel consumption and durability. A thorough description of combustion mechanism in diesel engine is beyond the scope of this study. However, it would be worthwhile to inform that the fuel is burnt in diesel engine by self ignition at higher temperature and pressure conditions of the order of 600°C and 40 bar, respectively. Diesel as a fuel is injected into the combustion chamber at the end of compression stroke and after certain ignition delay; it burns to give the motive power. In India, almost all irrigation pump sets, tractors, mechanized farm machinery and heavy transportation vehicle are powered by direct injection diesel engines. Keeping the specific features of diesel engine in mind, a typical engine system, which is actually used widely in the Indian agricultural sector, has been selected for the present experimental investigations.

## 3.2 Selection of Test Engine

A kirloskar made, single cylinder, air cooled, direct injection, DAF 8 model diesel engine is selected for the present research work, which is primarily used for agricultural activities and household electricity generation and shown in Plate 3.1.

**Plate 3.1: Test Engine**

It is a single cylinder, naturally aspirated, four stroke, vertical, air-cooled engine. It has a provision of loading electrically since it is coupled with single phase alternator through flexible coupling. The engine can be hand started using decompression lever and is provided with centrifugal speed governor. The cylinder is made of cast iron and fitted with a hardened high-phosphorus cast iron liner. The lubrication system used in this engine is of wet sump type, and oil is delivered to the crankshaft and the big end by means of a pump mounted on the front cover of the engine and driven from the crankshaft. The inlet and exhaust valves are operated by an overhead camshaft driven from the crankshaft through two pairs of bevel gears. The fuel pump is driven from the end of camshaft. The detailed technical specifications of the engine are given in Table 3.1.

**Table 3.1: Specifications of the Diesel Engine**

| **Make** | **Kirloskar** |
|---|---|
| Model | DAF 8 |
| Rated Brake Power (bhp/kW) | 8 / 5.9 |
| Rated Speed (rpm) | 1500 |
| Number of Cylinder | One |
| Bore X Stroke (mm) | 95 x 110 |
| Compression Ratio | 17.5:1 |
| Cooling System | Air Cooled (Radial Cooled) |
| Lubrication System | Forced Feed |
| Cubic Capacity | 0.78 Lit |
| Inlet Valve Open (Degree) | 4.5°BTDC |
| Inlet Valve Closed (Degree) | 35.5°ABDC |
| Exhaust Valve Open (Degree) | 35.5°BBDC |
| Exhaust Valve Closed (Degree) | 4.5° ATDC |
| Fuel Injection Timing (Degree) | 26° BTDC |

## 3.3 Development of an Experimental Test Rig

For conducting the desired set of experiments and measuring required data from the engine, it is essential to get the various instruments mounted at the appropriate location on the experimental setup. Apart from this, a dual fuel system has been developed for diesel and acid oil biodiesel. The photograph of the test rig with instrumentation used is shown in plate 3.2 and overall schematic diagram is shown in figure 3.1.

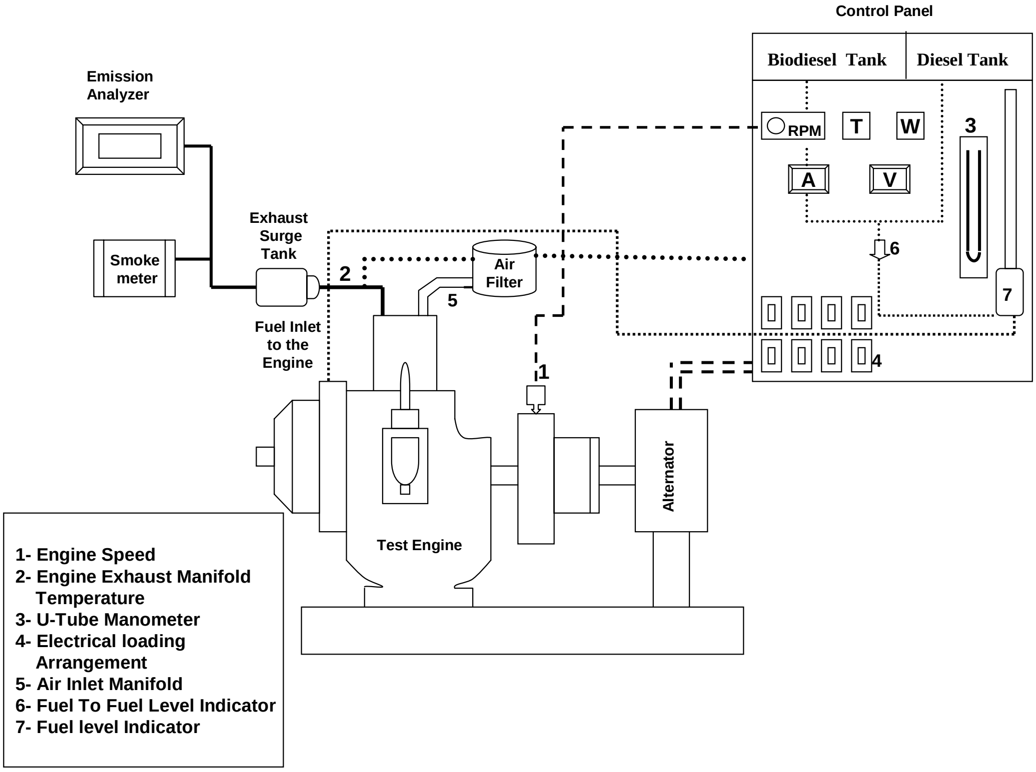

**Figure 3.1: Schematic Diagram of experimental set up**

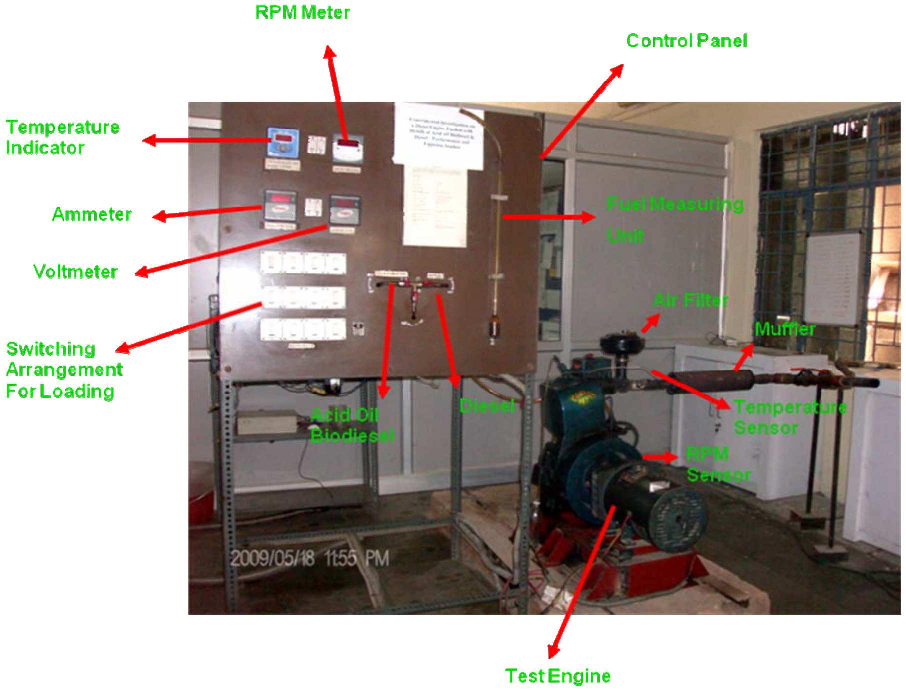

**Plate 3.2: Photograph of the Experimental Set Up**

## 3.4 Installation of the Instrument Control Panel

After finalizing the procedures for data collection, the desired instruments were procured and fitted on a panel. A stand was fabricated and a 1020mm×850mm

Bakelite sheet of 3-mm thickness was mounted on it. Instruments such as voltmeter, ammeter, speed counter, six channels digital temperature display was mounted on the front side of the control panel (Plate 3.3). Electrical load banks, i.e., 12 bulbs each of 500 watts, were mounted on the rear side of the control panel which is shown in Plate 3.4 and their switches provided on the front side of the control panel.

Plate 3.3: Control Panel

Plate 3.4: Load Bank

One burette with stop cocks and two way valves were also mounted on the front side of the panel for fuel flow measurements and selecting between either diesel fuel or biodiesel- diesel blends. The two fuel tanks were mounted on the rear side of the panel at highest position as shown in plate 3.5.

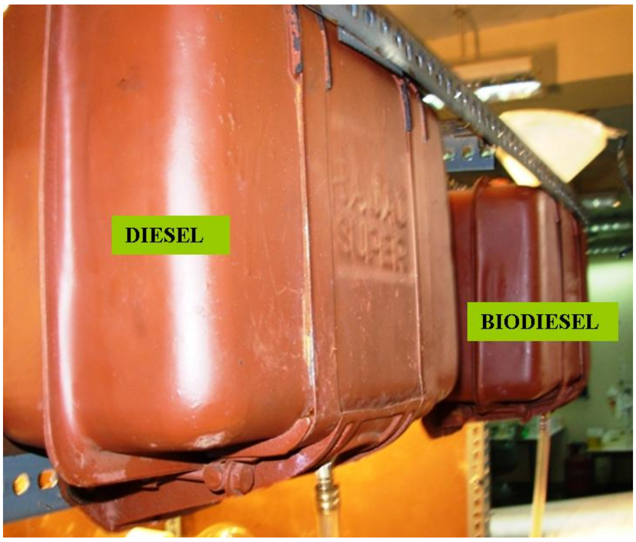

**Plate 3.5: Two Tanks System**

A voltmeter, an ammeter and a wattmeter were connected between alternator and load bank. A nut was welded on the flywheel and the photo reflective sensor was mounted on a bracket attached to engine body. The thermocouples were mounted in the exhaust manifold to measure the exhaust temperature. The AVL 437 smoke meter and AVL Di Gas Analyzer were also kept in proximity for the measurements of various exhaust gas parameters.

Thus such a system was chosen to examine the practical utility of acid oil biodiesel in such applications. Besides being a single cylinder system, it was light and easy to maintain. The engine was provided with suitable arrangement, which permitted wide variation of controlling parameters. Due to air cooled engine, absence of radiator, water body and pump made the system more suitable for the tests.

## 3.5 Parameters Selection

The selections of appropriate parameters were essential for engine calculations, and parameters were selected very judiciously. The engine test was done as specified by IS: 10000. The main parameters desired from the engine are listed below.

1. Power produced by the engines
2. Engine speed (Rev/min)
3. Fuel consumption
4. Temperature
5. Smoke & Exhaust Emissions

With a view to calculate the parameters mentioned above, it was essential to pick up the following signals from the test bench.

1. Voltage generated by the alternator
2. Current generated by the alternator
3. RPM of the engine
4. Exhaust gas temperature
5. Fuel consumption rate
6. AVL 437 smoke meter
7. AVL 4000 Light Gas analyzer

Once the parameters were selected, the essential instruments required for sensing these parameters were installed at the appropriate points in the experimental set-up.

### 3.6 Measurement Methods

As already elaborated, the main components of the experimental setup are two fuel tanks (Diesel and blend of acid oil biodiesel with diesel), bypass line, Fuel consumption measuring unit, Electrical loading arrangement, voltmeter, ammeter, RPM meter, temperature indicator and emissions measuring equipments. The engine is started with diesel for at least 10 minutes and once the engine warms up, it is then switched over to blend of acid oil biodiesel and diesel. For switching the engine from diesel to blend, a two way valve is provided on the control panel. Both the fuels from the two tanks can be fed to the engine through this valve separately. The fuel (Diesel or Biodiesel/diesel blend) enters into the engine after passing through the fuel measuring unit with the help of a mechanical fuel pump. The volumetric flow of the fuel can be easily determined with the help of the fuel measuring unit as described below.

#### 3.6.1 Brake Power

The brake power is among the most important parameter in testing the performance of an engine. The power developed by the engine was measured with the help of an electric alternator. The alternator was coupled to the engine with the help of a flexible coupling. The output lead of this mechanically coupled alternator was connected to the control panel along with an ammeter and voltmeter of required range in series and thus by measuring voltage and current, the power developed by the electric generator was known as Brake Power. The lamp load was connected in series with the generator to act as a resistive load bank. Lamp load consisted of 3 rows in parallel with 4 bulbs in series. The rating of incandescent lamps was 250 volts, 500 watts and 300 watts. The dynamometer used in this study was a “Kirloskar” make, 220 volts, 5kVA, single phase alternator. A voltmeter, 0-415 volts AC and an ammeter, 0-30 ampere, were selected for the measurements.

### 3.6.2 Fuel Flow Measuring System

The fuel consumption of an engine is measured by determining the time required for consumption of a given volume of fuel. The mass of fuel consumed can be determined by multiplication of the volumetric fuel consumption to its density. In the present set up volumetric fuel consumption was measured using a glass burette. The time taken by the engine to consume a fixed volume was measured using a stopwatch. The volume divided by the time taken for fuel consumption gives the volumetric flow rate. The test facilities were built up for measuring both diesel and blend consumption rates. For this, two separate tanks, one burette, and a number of valves were provided on the panel as shown in the Plate 3.6.

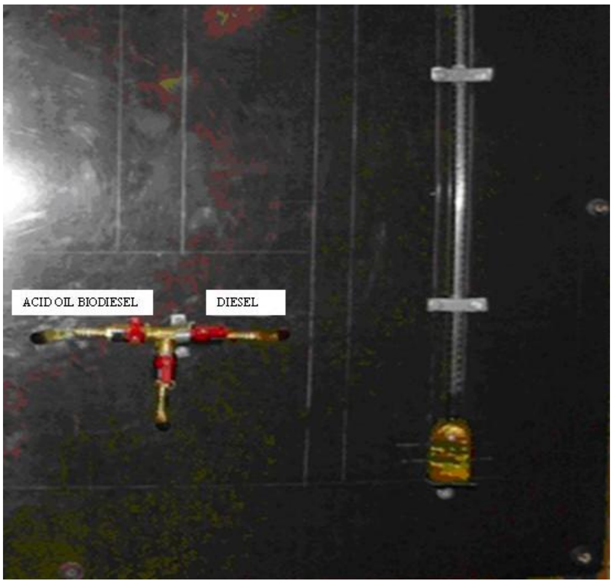

**Plate 3.6: Fuel Flow Measuring System**

This test was carried out only after the preliminary run. After stable operating conditions were experimentally achieved, the engine was subjected to similar loading conditions. Starting from no load, observations were recorded at 20%, 40%, 60%, 80% and 100% of the rated load.

The brake specific fuel consumption was calculated by using the relationship given below:

$$Bsfc = (Vcc \times \ell \times 3600) / (hp \times t)$$

Where,

$Bsfc$ = Brake specific fuel consumption, g/kW-h

$Vcc$ = Volume of fuel consumed, cc

$\ell$ = Density of fuel, g/cc

$hp$ = Brake horsepower, kW

$t$ = Time taken to consume, cc of fuel, sec.

### 3.6.3 Rpm of the Engine

An 'MTC' make digital panel tachometer with proximity/photo reflective sensor was used for measurement of RPM. The instrument is capable of functioning in the range of 1 to 9,999 rpm with a sampling time of 1 second. For measurement, a nut was welded on the flywheel face and sensor was mounted on a bracket near the flywheel in such a way that the distance was less than 5 mm. The display unit is digital and mounted on the panel board. The engine speed measurement arrangement is shown in plate 3.7.

**Plate 3.7: Engine Speed Measurement**

### 3.6.4 Temperature Measurement

Chromel-Alumel K-type thermocouples were connected to a 6 channel digital panel meter to measure temperatures of exhaust gas. The meter was calibrated by a millivolt source up to 800$^o$ C.

### 3.6.5 Exhaust Emission Analysis

The major pollutants appearing in the exhaust of a diesel engine are the oxides of nitrogen. Exhaust emission analysis was done for smoke opacity, UBHC, CO, $CO_2$ and $NO_x$. For measuring the smoke opacity, AVL 437 smoke analyzer was utilized. This instrument provides opacity in percentage. Of the light beam projected across a flowing stream of exhaust gases, a certain portion of light is absorbed or scattered by the suspended soot particles in the exhaust. The remaining portion of the light falls on a photocell, generating a photoelectric current, which is a measure of smoke density. The technical detailed specifications have been given in Appendix I.

For measurement of UBHC, CO, $CO_2$ and NOx, AVL 4000 Light Gas Analyzer was used. The detailed specification of AVL 4000 Light Gas Analyzer has been given in Appendix II. Both the AVL 437 Smoke meter and AVL 4000 Light Gas Analyzer are shown in Plate 3.8.

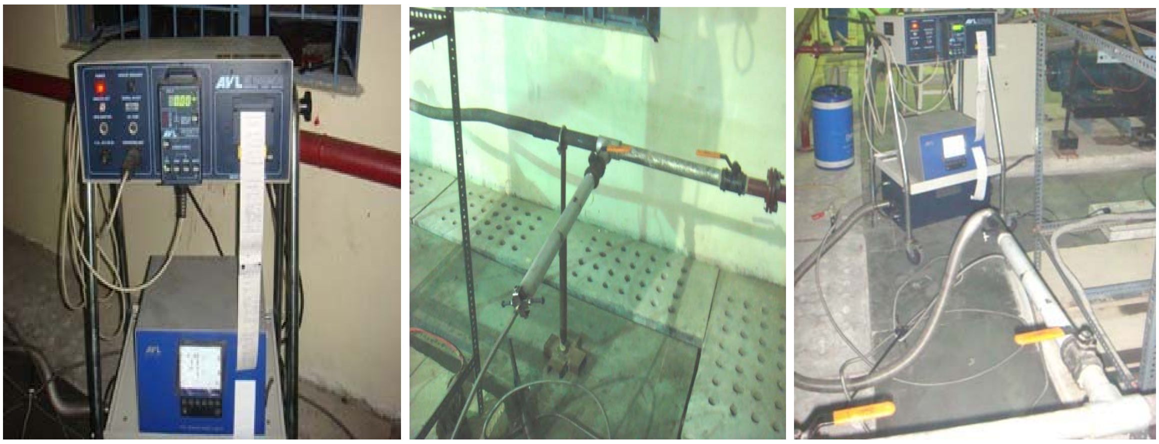

**Plate 3.8: Smoke and Emissions Measuring System**

## 3.7 Experimental Procedures

This elaborates the basic principles and methodologies that have been used during the tests carried out at different aspects of present study. The experimental study has been divided into three parts. First part deals with preparation of biodiesel from acid oil and various process parameters. The second part deals with experimental investigations involving determination of important physico-chemical properties of biodiesel as per suitable ASTM standards. Experimental techniques necessary for performance and emission studies have been discussed in third part.

## 3.8 Acid Oil Biodiesel Production

The primary technological challenge in the use of soap stock derived acid oil as a feedstock for biodiesel production is its high free fatty acid (FFA) content. Acid Oil with FFA content of 59 % was selected as feedstock for biodiesel production. First of all, acid oil was filtered in a special column in which contaminant and moisture present in biodiesel were removed. The esterification of acid oil was done to reduce its FFA content after initial purification. Finally biodiesel was produced by transesterification of esterified acid oil. The stepwise description of biodiesel production process is summarized as follows.

### 3.8.1 Development of Column

A glass column of one metre length and 10 cm diameter was used for removing contaminants and moisture content. Layers of different material were put in the glass column. The layers included glass wool, fuller soil, glass beads and silica gel. After setting these layers, acid oil which is full of contaminants, dust particles etc. is poured into the column and acid oil filters out through different layer which takes 8 or 10 hrs. Silica gel acts as an adsorbent to remove moisture from acid oil. The column used in present investigation is shown in plate 3.9.

Plate 3.9: Development of Column

### 3.8.2 Esterification of Acid Oil

Free fatty acids can be esterified by alcohols in the presence of a suitable acidic catalyst. The esterification process for production of acid oil biodiesel was carried out using methyl alcohol with three different acid catalyst namely Para toluene sulphonic acid (PTSA), concentrated sulphuric acid (Conc. $H_2SO_4$) and methane sulphonic acid (MSA). Acid catalysis was employed because it is able to esterify both free and acyl glycerol- linked fatty acids, although the later react much more slowly than previous one during alkaline transesterification **[24].** The three esterified samples with three different catalysts are shown in plate 3.10.

**Plate.3.10: Three samples using three different catalysts**

Commercial acid oil which was selected as a feedstock for biodiesel production contains free fatty acids (59.3 %), triacylglycerols (28 %), diacylglycerols (4.4%) and monoacylglycerols (1%) by weight. The FFA in acid oil was readily esterified using acid catalysis. It was found that by using concentrated $H_2SO_4$ as a catalyst, time taken for esterification was minimum. It was observed during the experimental investigation that three steps of esterification (carried out at 60°C for 2 hours) were required to bring FFA level of acid oil to ≤0.5% so that subsequent transesterification can be carried out. A complicating factor in the case of soapstock derived acid oil is that, as opposed to virgin fats and oils, it contains a substantial amount of water which is heavily emulsified with the lipid constituents and difficult to remove. Water inhibits acid catalysed esterification reactions. Thus, in designing methods for the production of biodiesel from acid oil, it was necessary to consider both its high water content and the presence of free fatty acids. For engineering simplicity, it was also desired to design a process that would run effectively at ambient temperature and atmospheric pressure. It was also postulated that the accumulation of water released by esterification had prevented complete esterification.

### 3.8.3 Transesterification of Acid Oil

After esterification of acid oil now transesterification has been done to produce biodiesel. Transesterification is also known as alcoholysis. In the transesterification of acid oil, triglycerides react with alcohol is the presence of strong acid or base catalyst, producing a mixture of fatty acid alkyl esters and glycerol. The stoichiometric reaction requires 1 mole of triglyceride and 3 moles of alcohol. A catalyst is used to improve the reaction rate and yield. The transesterification process is shown in figure 3.2.

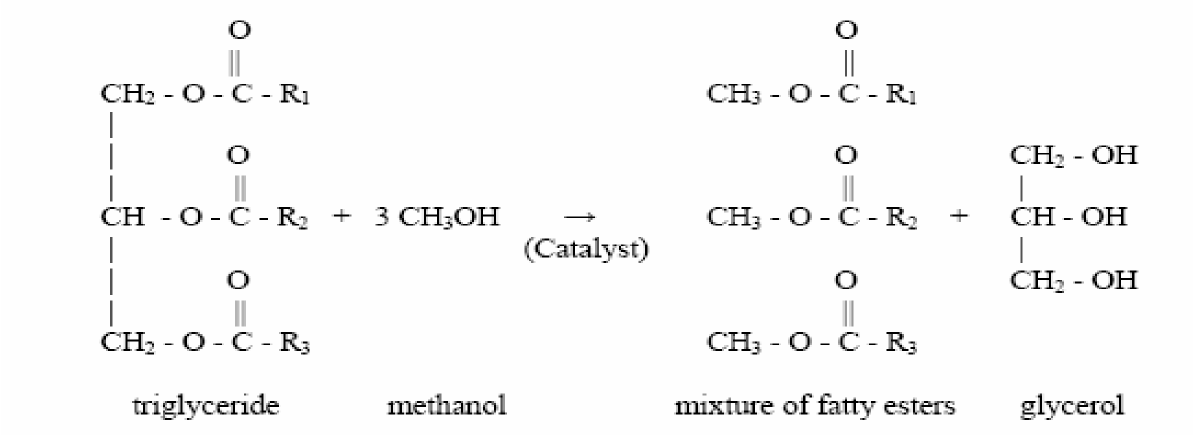

**Fig 3.2: Transesterification Process [16]**

Among the alcohols, methanol and ethanol are used commercially because of their low cost and their physical and chemical advantages. They quickly react with tri-glycerides and NaOH and KOH are easily dissolved in them. Alkalis or acids can catalyze the reaction. Among these, alkali transesterification is fastest and hence it is used commercially. A mixture of acid oil and methanol mixed with potassium hydroxide (used as catalyst) are heated and maintained at 65ºC, while the solution is continuously stirred with the help of magnetic stirrer. Different catalyst concentration (% wt. / wt. of oil) have been used including 1, 1.5 and 2%. Two different molar ratios of alcohol: oil i.e. 3:1 & 6:1 is used. Time taken in transesterification reaction for different cases has been observed. When the reaction is over, product is poured into separating funnel. Two distinct layers are formed, the lower layer is of glycerin and the upper layer is of ester. The glycerol formed is removed by density separation. The process has the effect of increasing the volatility and decreasing the viscosity of the oil, making it similar to the diesel fuel in these characteristics. The upper layer (ester) is separated out and moisture is removed from the ester by heating it above 100ºC.

### 3.8.4 Decolorisation of Acid oil Biodiesel

Biodiesel produced from acid oil is dark in color, so there is a need to decolorize it. Fuller soil has been used to decolorize acid oil biodiesel. Acid oil biodiesel and fuller soil is poured into conical flask in the ratio of 1:2 by weight and stirred with magnetic stirrer for an hour at 65 °C temperature. Later, this mixture is poured through a filter paper into a beaker which results in satisfactorily decolourisation of acid oil biodiesel. Stirring of acid oil biodiesel with fuller soil is shown in plate 3.11. In plate 3.12 acid oil biodiesel before and after decolourisation is shown.

**Plate: 3.11. Stirring of acid oil with fuller soil**

**Plate: 3.12.Acid oil Biodiesel**

## 3.9 Acid oil Biodiesel Properties

### 3.9.1 Density

Density is the mass per unit volume. The measurement was made at room temperature. The density was measured with the help of a U-Tube Oscillating True Density meter. The density of acid oil was measured and then compared with that of diesel fuel. The equipment used for density determination is shown in Plate 3.13.

**Plate 3.13: U-Tube Oscillating True Density Meter**

### 3.9.2 Kinematic Viscosity

When a fluid is subjected to external forces, it resists flow due to internal friction. Viscosity is a measure of internal friction. The viscosity of the fuel affects atomization and fuel delivery rates. It is an important property because if it is too low and too high then atomization and mixing of air and fuel in combustion chamber gets affected. Viscosity studies were conducted for different test fuels. Absolute viscosity sometimes called dynamic or simple viscosity is the product of Kinematic viscosity and fluid density. Kinematic viscosity of liquid fuel samples were measured using Kinematic viscometer shown in plate 3.14 at $40^0$ C as per the specification given in ASTM D445. A suitable capillary tube was selected, and then a measured quantity of sample was allowed to flow through the capillary. Efflux time was measured for calculating Kinematic viscosity using the formula given below:

$$v = c^* t \qquad \dots (3.1)$$

Where,

v = Kinematic viscosity, cSt or $mm^2/sec$

c = constant; $mm^2/sec^2$

t = time, second

**Plate 3.14: Kinematic Viscometer**

### 3.9.3 Flash and Fire point

Flash point is the minimum temperature at which the oil vapor, which when mixed with air forms an ignitable mixture and gives a momentary flash on application of a small pilot flame. The flash and fire point of the test fuels were measured as per the standard of ASTM D 93. The sample was heated in a test cup at a slow and constant rate of stirring for proper and uniform heating. A small pilot flame was directed into the cup through the opening provided at the top cover at the regular intervals. The temperature at which these vapor catches flash is observed and called as the flash point of that liquid. Fire point is an extension of flash point in a way that it reflects the condition at which vapor burns continuously for at least for 5 seconds. Fire point is generally higher than the flash point by 5-8$^{o}$ C. A Pensky Martens apparatus used in the study for determination of flash point is shown in Plate 3.15.

**Plate 3.15: Pensky Marten Flash Point Apparatus**

### 3.9.4 Cloud and Pour Point

Cloud and Pour points are important for determining the feasibility of using the fuel in engine at lower ambient temperatures. Fuels with high pour points give flow problems at lower temperature, therefore it cannot be recommended for use in engine at low temperatures. Pour point for fuel oils, lubricating oils and diesel fuels is used as criteria in cold surroundings. The cloud and pour point of the fuel were measured as per the specification given of ASTM D2500 and ASTM D97 respectively. The cloud and pour point apparatus used for determination of these properties is shown in Plate 3.16.

**Plate 3.16: Cloud and Pour Point Apparatus**

The cloud point is the temperature at which a solid material, usually paraffin waxes and similar compounds in the case of petroleum liquid begins to separate when the sample is cooled under carefully controlled conditions. Likewise, the pour point is the lowest temperature at which the liquid will flow in a specific way when cooled under controlled conditions. The cessation of flow results from an increase in viscosity or from the crystallization of wax from the oil. Fuel oils of wax bearing crude oils have much higher pour point then those derived from crude oils of low wax content. A low pour point is a desired property of oil in respect of handling in cold atmosphere.

The pour point is determined by cooling a sample of the oil in a test jar, to a temperature when the jar is displaced from the vertical to the horizontal position, no perceptible movement of the oil will occur within the first 5 second.

### 3.9.5 Calorific Value

The calorific value is defined in terms of the number of heat units liberated when unit mass of fuel is completely burnt in a calorimeter under specified conditions. Higher calorific value of fuel is the total heat liberated in kJ per kg or $m^3$. All fuels containing hydrogen in the available form will combine with oxygen and form steam during the process of combustion. If the products of combustion are cooled to it initial temperature, the steam formed as a result will condense. Thus maximum heat is abstracted. This heat value is called the higher calorific value.

The calorific value of the fuel was determined with the Isothermal Bomb Calorimeter as per the specification given in ASTM D240. The combustion of fuel takes place at constant volume in a totally enclosed vessel in the presence of oxygen. The sample of fuel was ignited electrically. The water equivalent of bomb calorimeter was determined by burning a known quantity of benzoic acid and heat liberated is absorbed by a known mass of water. Then the fuel samples were burnt in bomb calorimeter and the calorific value of all samples were calculated. The Bomb Calorimeter used for determination of Calorific value is shown in Plate 3.17.

**Plate 3.17: Bomb Calorimeter**

The heat of combustion of the fuel samples was calculated with the help of equation given below:

$$\triangle H_s = \frac{W_s \quad T}{M_s} \qquad (3.2)$$

Where,

$H_s$= Heat of combustion of the fuel sample, kJ/kg
$W_s$= Water equivalent of the calorimeter assembly, kJ/$^o$C
$\triangle T$= Rise in temperature,$^o$C
$M_s$= Mass of sample burnt, kg

### 3.9.6 Cold Filter Plugging Point (CFPP)

Cold Filter Plugging Point (CFPP) is defined as the minimum temperature at the fuel filter does not allow the fuel to pass through it. At low operating temperature fuel may thicken and does not flow properly affecting the performance of fuel lines, fuel pumps and injectors. Cold filter plugging point of vegetable oils reflects its cold weather performance. It defines the fuels limit of filterability. The apparatus for CFPP measurement is shown in Plate 3.18.

**Plate 3.18: Cold Filter Plugging Point Apparatus**

### 3.9.7 Gas Chromatograph

During the trans-esterification process, intermediate glycerols, mono- and di-acylglycerols, are formed, small amounts of which can remain in the final biodiesel product. In addition to this partial glycerol, un-reacted tri-acylglycerol as well as un-separated glycerol, free fatty acids, residual alcohol, and catalyst can contaminate the final product. The contaminant can lead to severe operational problems when using biodiesel, including engine deposits, filter clogging, or fuel deterioration. Hence the use of GC has been the most widely used method for the analysis of biodiesel due to its generally higher accuracy in quantifying minor components. However, the accuracy of GC analysis can be influenced by factors such as baseline drift and overlapping signals. The instrument present here is equipped with a FID (flame ionization detector), enabling us to quantify the quantities of various organic compounds present in the sample being tested. Hence, we can find out precisely the percentage of glycerol, alcohols or biodiesel present.

**Plate 3.19: Gas Chromatograph**

## 3.10 Engine testing procedure

The engine was started at no load by pressing the exhaust valve with decompression lever and it was released suddenly when the engine was hand cranked at sufficient speed. The engine was then allowed to run for about 30 minutes till the steady state condition was reached. The engine was gradually loaded keeping the speed with in the permissible range and the observations of different parameters were evaluated. Short term performance tests were carried out on the engine with diesel to generate the base line data and subsequently blends of acid oil biodiesel with diesel was used to evaluate its suitability as a fuel. The performance and emission characteristics of different blends were evaluated and compared with diesel fuel. With the fuel measuring unit and stop watch, the time elapsed for the consumption of 10, 20 and 30cc of fuel was measured and average of them was taken. Fuel Consumption, RPM, exhaust temperature, smoke density, CO, $NO_x$, HC , $CO_2$ and power output were also measured. The engine was always started and stopped with diesel as a fuel. Before turning the engine off, the engine was switched over to diesel so that all the biodiesel –diesel blends in fuel filter and pipe line is consumed.

# CHAPTER 4

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## RESULTS AND DISCUSSIONS

### 4.1 Introduction

This chapter discusses the results of all the tests performed on several aspects with respect to biodiesel production, optimization and utilization. The first part of the chapter shows comparative evaluation of different biodiesel fuel production process and subsequent optimization of the process parameters. The second part deals with the results of various tests conducted for physico-chemical characterization of biodiesel and diesel fuel. The third part discusses the results of engine experiments and combustion analysis.

### 4.2 Process Optimization

As acid oil has high FFA content, the pre-esterification is needed to esterify the free fatty acid (FFA). Three different acid catalysts were selected namely PTSA (Para toluene sulphonic acid), concentrated $H_2SO_4$ and MSA (methane sulphonic acid) for this purpose. It was found that time taken for esterification is minimum by using Conc.$H_2SO_4$ as catalyst. After esterification of acid oil, transesterification was done to produce biodiesel and for transesterification process, 6:1 molar ratio of alcohol: triglyceride was required. It was also found that conversion with Conc.$H_2SO_4$ is 80.27% with MSA is 74.48% and with PTSA is 60.90%. Hence it can be said that results are optimised with Conc.$H_2SO_4$. Biodiesel made from acid oil is dark in color due to dark colour of acid oil therefore fuller soil has been used to decolorize acid oil biodiesel. The ester content with three different catalysts is shown in figure 4.1-4.3.

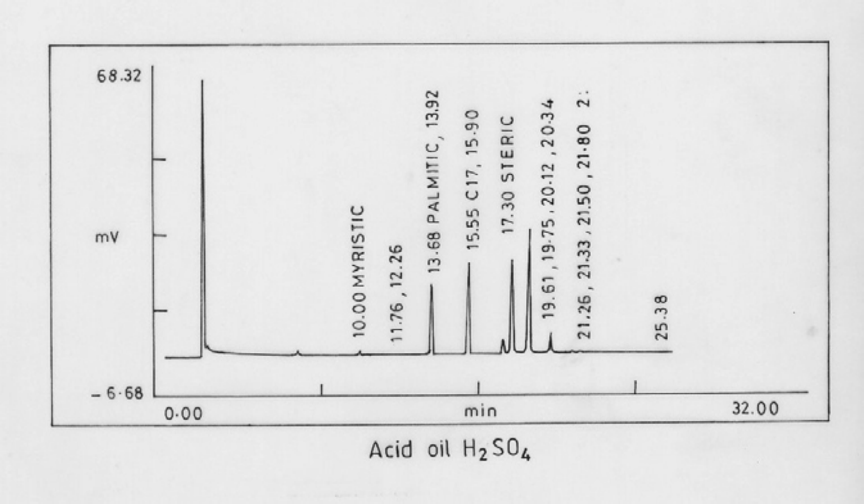

Figure: 4.1. Ester Content using Conc. $H_2SO_4$ as catalyst

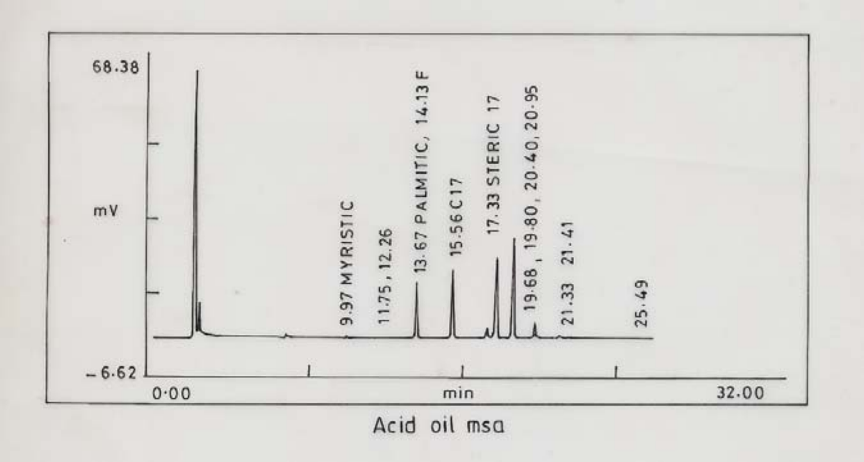

Figure: 4.2. Ester Content using MSA as catalyst

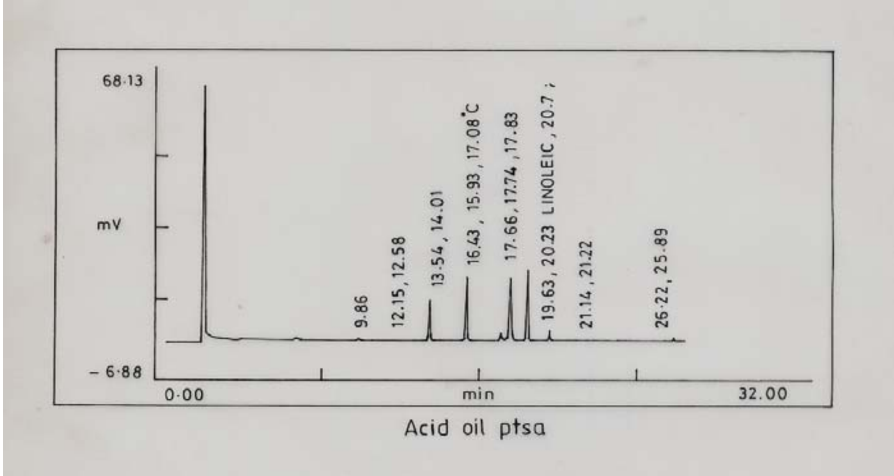

Figure: 4.3. Ester Content using PTSA as catalyst

## 4.3 Evaluation of Physico-Chemical Properties

All the fuels, namely acid oil biodiesel, neat diesel and diesel- acid oil biodiesel blends were analyzed for several physical, chemical properties. Density and viscosity of biodiesel- diesel blends were found to be higher than those of diesel fuel. Blending of biodiesel derived from acid oil in diesel reduces calorific value of the blend due to lower heating value of biodiesel.

**Table 4.1: Measured properties of acid oil biodiesel**

| Property | Value |
|---|---|
| Density@15°C | 0.89444 g/cm$^3$ |
| Viscosity@40°C | 5.953075 cSt |
| Acid No. | 0.50 mg KOH/gm |
| CFPP | -8 °C |
| Cloud Point | -1 °C |
| Pour Point | -9 °C |
| Calorific Value | 37.5 MJ/Kg |

**Table 4.2: Physico-Chemical Properties of fuels used**

| Property | Neat Diesel | B 5 | B 10 | B20 |
|---|---|---|---|---|
| Density at 15°C (g/cm$^3$ ) | 0.83 | 0.833 | 0.836 | 0.843 |
| Kinematic Viscosity at 40°C (cSt) | 2.5 | 2.67 | 2.84 | 3.19 |
| Calorific value (MJ/kg) | 42.2 | 41.9 | 41.7 | 41.3 |

## 4.4 Performance Characteristics

The performance characteristics of the test engine on neat diesel and biodiesel- diesel blends are summarized below.

### 4.4.1 Brake Thermal Efficiency

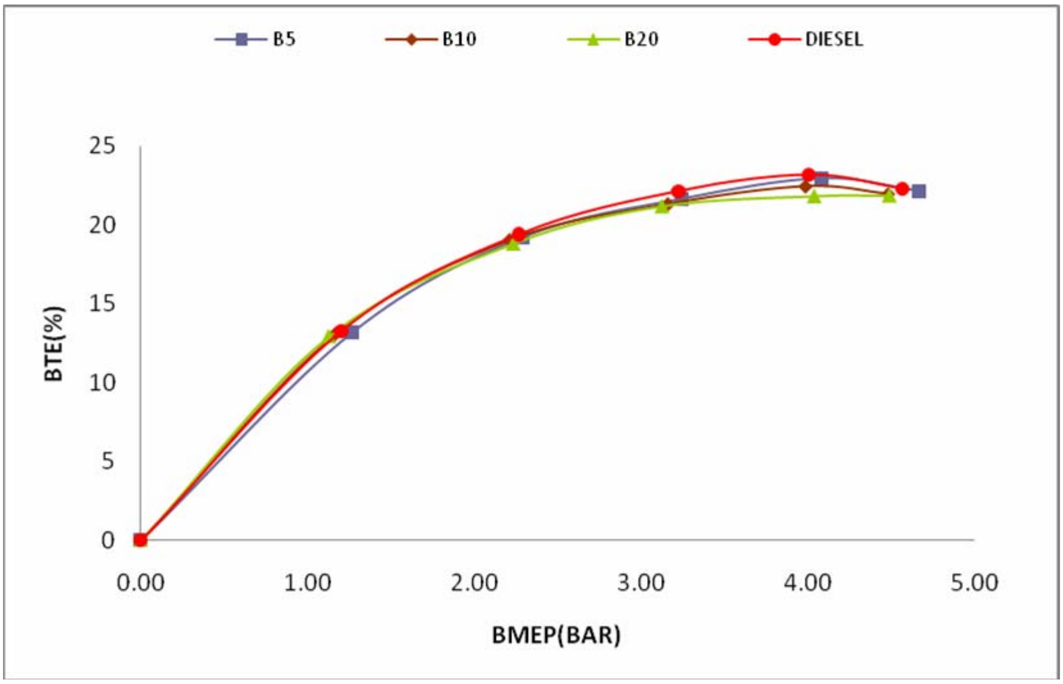

Figure 4.4: BTE VS BMEP

The variation of brake thermal efficiency with respect to bmep for different test fuels is shown in figure 4.4. In all the cases, brake thermal efficiency has the tendency to increase with increase in applied load reaching a maximum somewhere at 80 per cent load and then decreases. The reason for increase in brake thermal efficiency up to a maximum is the reduction in heat loss and increase in power developed with increase in load. This rise is limited by production of undesirable quantity of smoke. The peak brake thermal efficiency in case of diesel, B5, B10 and B20 are 23.19%, 22.93% 22.43% and 21.81% respectively. It can be seen that brake thermal efficiency with biodiesel blend was little lower than neat diesel fuel. The slight reduction of brake thermal efficiency with biodiesel blends was attributed due to following reasons-

1) Higher viscosity and lower volatility results longer ignition delay due to which slow combustion occurs which results in lesser thrust on piston so loss of brake power output and consequently less thermal efficiency.

2) Due to higher density, increase in fuel mass rate is more in comparison to decrease in calorific value hence product of fuel mass rate and calorific value reduces.

### 4.4.2 Brake Specific Energy Consumption

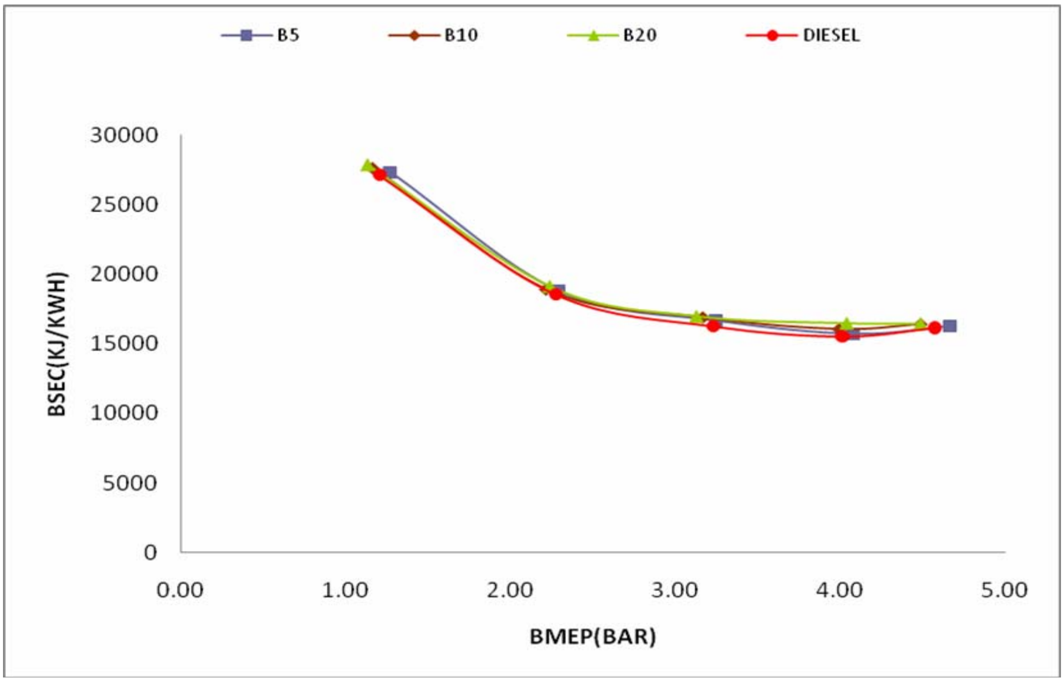

**Figure 4.5: BSEC VS BMEP**

Brake specific energy consumption (BSEC) is an ideal parameter for comparing engine performance of fuels having different calorific values and densities. The variation of BSEC with bmep for different test fuels is shown in figure 4.5. It is observed that for all the fuels, the BSEC decreases with increase in load. This is due to higher percentage increase in brake power with load as compared to increase in the fuel consumption. For B5, B10 and B20, the BSEC is slightly higher than diesel fuel. As brake specific energy consumption is exactly inverse of brake thermal efficiency, it follows opposite trend of efficiency variation. This is due to lower calorific value with increase in biodiesel percentage in the blends [**39**].

### 4.4.3 Exhaust Temperature

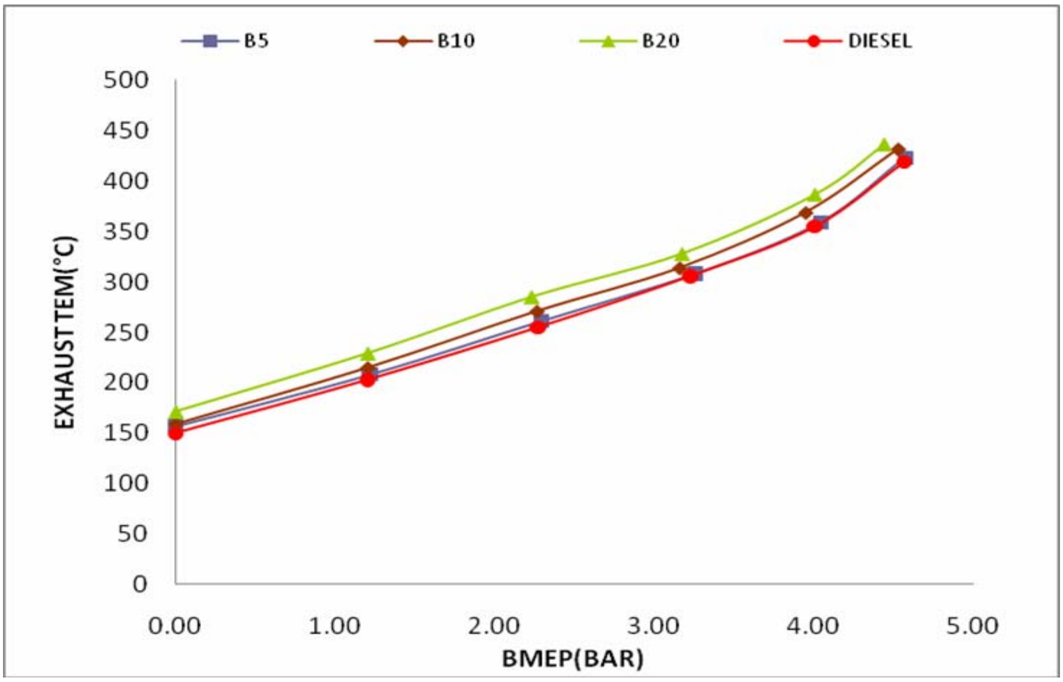

**Fig 4.6: Exhaust Temp. Vs BMEP**

Figure 4.6 shows the variation of exhaust gas temperature with brake mean effective pressure for diesel and biodiesel- diesel blends. The results show that the exhaust gas temperature increases with the increase in load for all the test fuels. The amount of fuel injected increases with the engine load in order to maintain the power output and hence the heat release and the exhaust gas temperature rise with increase in load. Exhaust gas temperature is an indicative of the quality of combustion in the combustion chamber. At all loads, diesel was found to have the lowest temperature and the temperature for the different blends showed the upward trend with increasing concentration of biodiesel in the blends. This trend is due to the reason that biodiesel has higher viscosity than diesel so fuel droplet size in the engine is expected to be larger than the neat diesel. Larger droplets leads to longer ignition delay so more fuel accumulation occurs before combustion which releases higher amount of heat in late combustion phase. As a result of this, the exhaust gas temperature is relatively higher in case of biodiesel- diesel blends.

## 4.5 Emission Characteristics

The emissions characteristics of the test engine on neat diesel and biodiesel-diesel blends are summarized in subsequent section.

### 4.5.1 CO Emissions

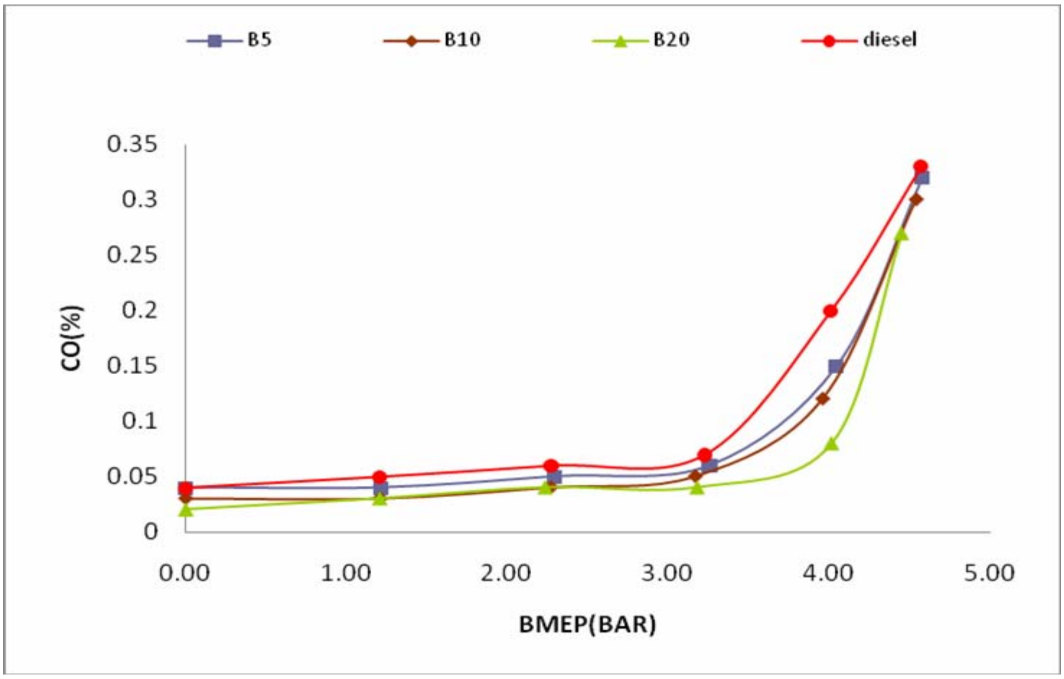

**Figure 4.7: CO Vs BMEP**

Figure 4.7 shows the CO emissions of the diesel fuel and three blends of biodiesel. CO is an intermediate combustion product and is formed mainly due to incomplete combustion of fuel. If combustion is complete, CO is converted to $CO_2$. If the combustion is incomplete due to shortage of air or due to low gas temperature, CO will be formed. A usually high CO emission formed with fuel-rich mixtures, but as combustion is occurred with lean mixture and has an abundant amount of air, CO from combustion is low. Therefore CO increases with load as evident in figure 4.7 because fuel air mixture becomes richer. For biodiesel blends, CO emission was lower than diesel fuel, because biodiesel itself has about 11% inbuilt oxygen content that resulted in complete combustion of the fuel and supplied the necessary oxygen to convert CO to CO2. Compared to neat diesel fuel, 20% biodiesel mixtures reduced CO emissions by 18%.

### 4.5.2 $CO_2$ Emissions

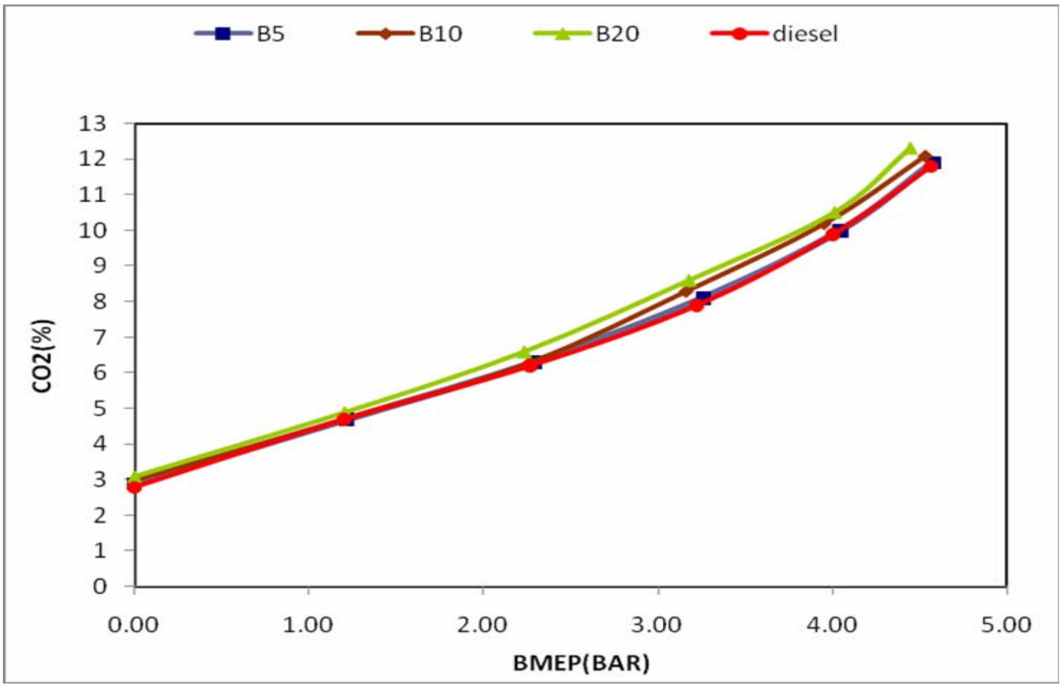

**Figure 4.8: $CO_2$ Vs BMEP**

Figure 4.8 compares the $CO_2$ emissions of various test fuels. The $CO_2$ emission increases with increase in load, as richer air- fuel mixture burns at higher loads. The biodiesel- diesel blends emits more amount of $CO_2$, as compared to neat diesel operation. Due to inbuilt oxygen in biodiesel, more amount of $CO_2$ in exhaust emission is an indication of the complete combustion of fuel. This supports the higher value of exhaust gas temperature. The $CO_2$ emission using neat diesel as fuel is lower because of the incomplete combustion. The combustion of fossil fuels produces carbon dioxide, which are getting accumulated in atmosphere and leads to global warming. The combustion of biodiesel also produces carbon dioxide but as it is a renewable fuel it emits $CO_2$ in same amount as needed by plants during photosynthesis. Hence carbon dioxide levels are kept in balance.

### 4.5.3 $NO_X$ Emissions

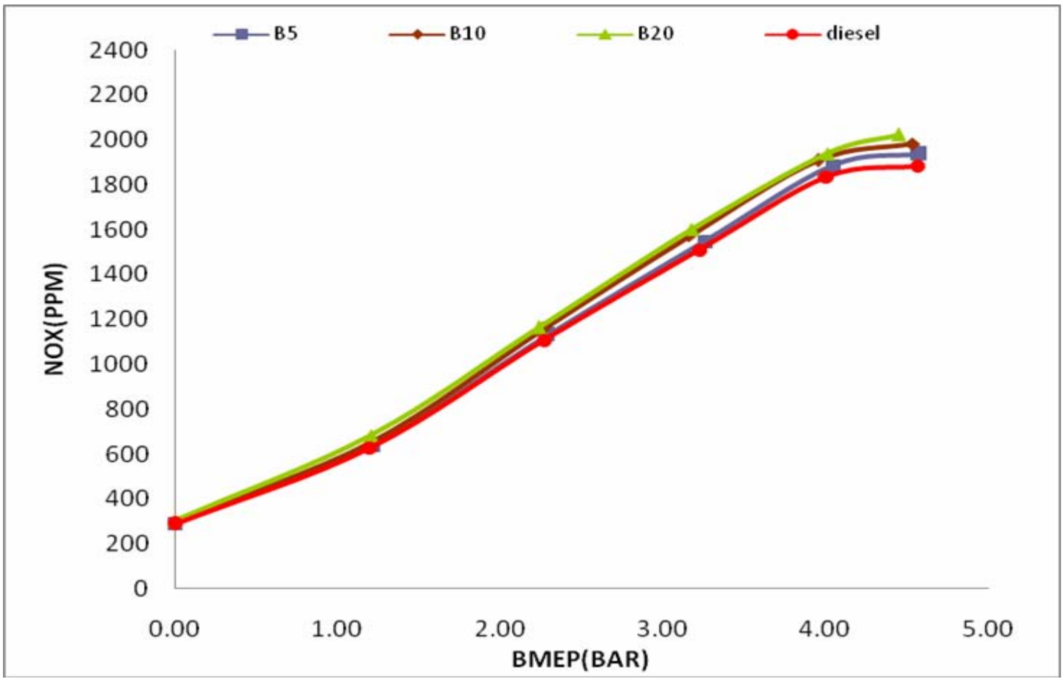

**Figure 4.9: $NO_x$ Vs BMEP**

The variation of $NO_x$ emission for different fuels is indicated in figure 4.9. Naturally $NO_x$ emission increases with the increase in load. It is well known that nitrogen is an inert gas, but it remains inert up to a certain temperature (1100 °C) and above this level, it does not remain inert and participate in chemical reaction. At the end of combustion, gas temperature inside cylinder arises around 1500 °C. At this temperature, oxidation of nitrogen takes places in presence of oxygen inside the cylinder. So with increasing load more fuel burns which lead to higher combustion temperature thus higher $NO_x$ formation takes place. $NO_x$ level was higher for biodiesel blends than diesel fuel at the same load. This can be explained due to the presence of extra oxygen in the molecules of biodiesel blends. This additional oxygen was responsible for higher $NO_x$ emission. Around 10% increase in $NO_x$ emission was observed with 20% biodiesel blends. Reduction of $NO_x$ on biodiesel may is possible with the proper adjustment of injection timing and introducing exhaust gas recirculation (EGR) system.

### 4.5.4 HC Emissions

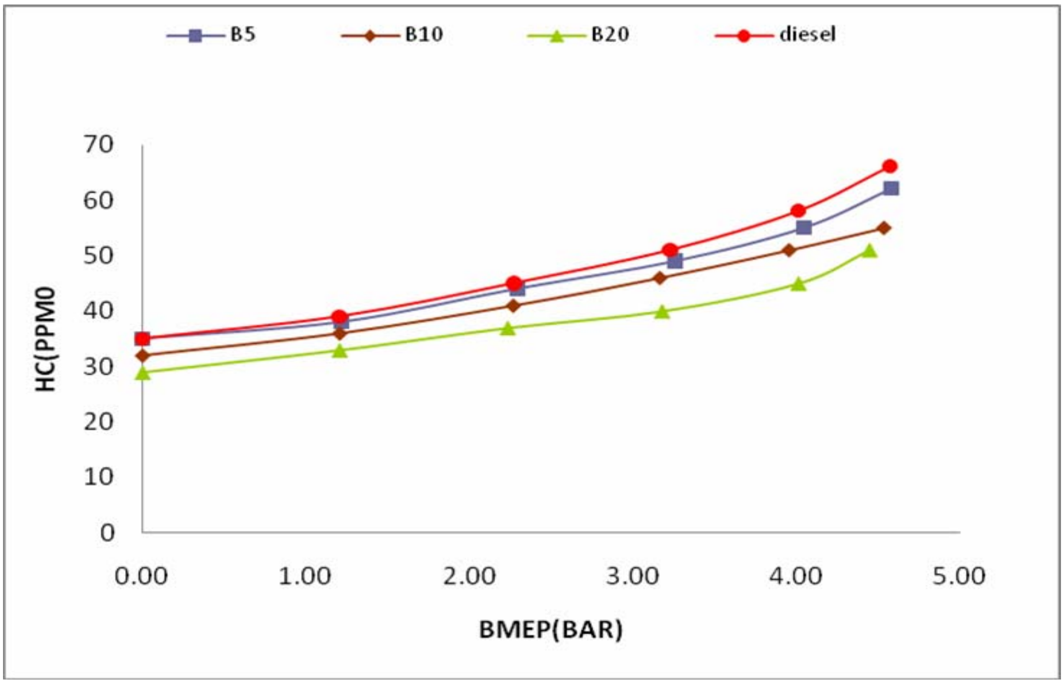

**Figure 4.10: HC Vs BMEP**

Figure 4.10 depicts the variation of HC emissions for different fuels with load. It can be seen that hydrocarbon emissions tend to increase for all fuels with increasing load. This is because of less oxygen available for the reaction when more fuel is injected into the engine cylinder at high engine load which makes the fuel mixture to become very rich at certain points in combustion chamber. As a result, proper combustion does not take place at those points and fuel goes off in the exhaust as hydrocarbons. It can also be seen that with increasing amount of biodiesel in blends, HC emissions tend to decrease and are lower compared to diesel fuel. This is due to inbuilt oxygen content in biodiesel which is responsible for more complete combustion.

### 4.5.5 Smoke Opacity

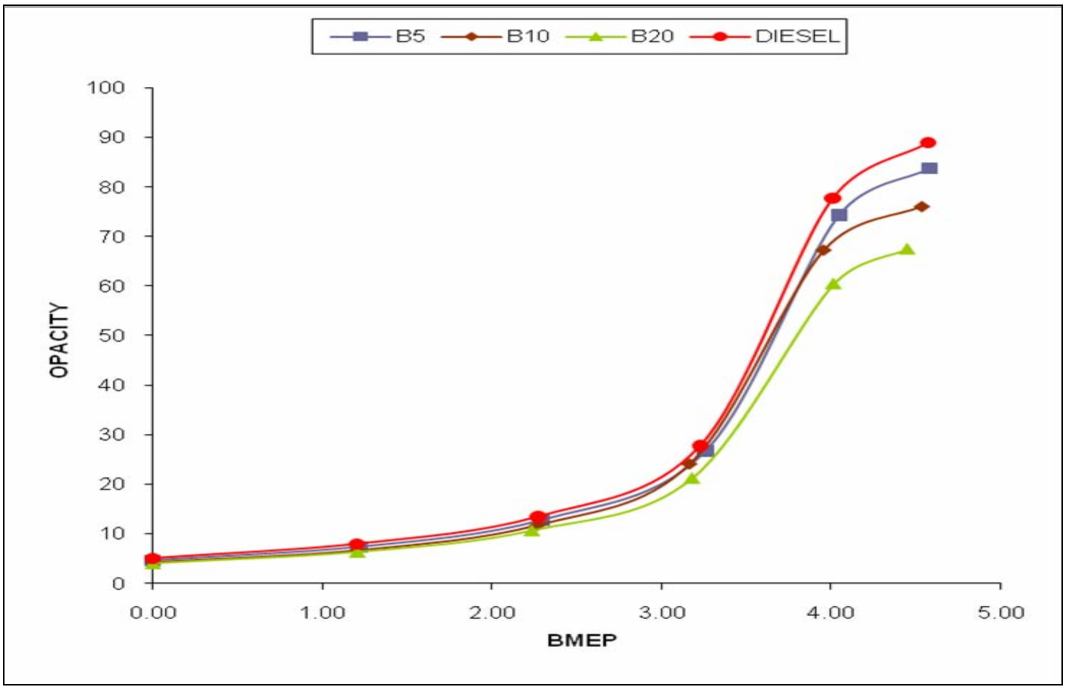

**Figure 4.11: Opacity Vs BMEP**

The variation of smoke opacity with BMEP for diesel fuel and biodiesel blends is shown in figure 4.11. It can be seen that smoke is high mainly at high power outputs for all the fuels. High loads imply that more fuel is injected into the combustion chamber and hence incomplete combustion of fuel is enhanced. Reduction of smoke emissions for different biodiesel based fuels in comparison to diesel fuel has been achieved for all load conditions. The smoke is produced mainly in the diffusive combustion phase, the addition of oxygenated fuel such as biodiesel leads to an improvement in diffusive combustion. Because of the heterogeneous nature of diesel combustion, fuel-air ratios, which affect smoke formation, tend to vary within the cylinder of a diesel engine. Smoke formation occurs primarily in the fuel-rich zone of the cylinder, at high temperatures and pressures. If the fuel used is partially oxygenated, locally over-rich regions can be reduced and primary smoke formation can be limited.

# CHAPTER 5

# CONCLUSION

The acid oil was taken as a feedstock in the present research work mainly to evaluate the potential suitability of acid oil for conversion into biodiesel and subsequent engine application. As acid oil, produced from soapstock, biodiesel production from acid oil is a attractive option as the price of acid oil is much lower than other feedstock.

During the conversion of acid oil into biodiesel, it was found that esterification of free fatty acid is essential and for this concentrated $H_2SO_4$ was found to be most efficient catalyst amongst concentrated $H_2SO_4$, PTSA and MSA. As biodiesel derived from acid oil is dark in colour, it was decolourized using fuller soil.

From the series of exhaustive experiments, the following conclusions can be derived.

1. The brake thermal efficiency with biodiesel blend was little lower than that of diesel. The slight reduction of brake thermal efficiency with increase of biodiesel content in blends can be attributed to lower heating value, high viscosity.
2. The BSEC decreases with increase in load. For B5, B10 and B20 the BSEC is slightly higher than neat diesel.
3. The exhaust gas temperature increases with the increase in load for all the test fuels. At all loads, diesel was found to have the lowest temperature and the temperature for the different blends showed the upward trend with increasing concentration of biodiesel in the blends.
4. CO emission is found to increase with increase in load for all test fuels. For biodiesel blends, CO emission was lower than diesel fuel as B 20 reduced CO emissions by 18%.
5. The biodiesel- diesel blends emits more amount of $CO_2$, as compared to neat diesel operation.
6. The $NO_x$ level was higher for biodiesel blends than conventional diesel fuel. Approximately 10% increase in NOx emission was observed with 20% biodiesel blend.

**7.** It is observed that HC emissions tend to decrease for biodiesel based fuels. It was also seen that as concentration of biodiesel in biodiesel- diesel blends increases, a downward trend in HC emission is observed.

**8.** Smoke opacity was found lower for biodiesel blends in comparison to diesel fuel.

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## APPENDIX – I

## TECHNICAL SPECIFICATION OF AVL Di-GAS ANALYZER

| | | |
|---|---|---|
| Measurement principle | CO, HC, $CO_2$ | Infrared measurement |
| Measurement principle | $O_2$ | Electrochemical |
| | NO (option) | measurement |
| Operating temperature | +5 ……. +45º C | Keeping measurement accuracy |
| | +1 ……. +50ºC | Ready for measurement |
| | +5 ……. +35º C | with integral NO sensor |
| | | (Peaks of: +40ºC) |
| Storage temperature | -20 ….. +60º C | |
| | -20 ….. +50º C | With integrated $O_2$ sensor |
| | -10 ….. +45º C | With integrated NO sensor |
| | 0 ….. +50º C | With water in filter and / or |
| | | Pump |
| Air humidity | 90% max., non-condensing | |
| Power drawn | 150 VA | |
| Dimensions | 432 x 230 x 470 mm (w x h x l) | |
| Weight | 16 Kg | |

## APPENDIX –II

## TECHNICAL SPECIFICATION OF AVL 437 SMOKE METER

| | | |
|---|---|---|
| Accuracy and Reproducibility | : | ± 1% full scale reading. |
| Measuring range | : | 0 - 100% capacity in %<br>$0 - \infty$ absorption $m^{-1}$. |
| Measurement chamber | : | effective length 0.430 m ± 0.005 m |
| Heating Time | : | 220 V …… approx. 20 min |
| Light source | : | Halogen bulb 12 V / 5W |
| Colour temperature | : | 3000 K ± 150 K |
| Detector | : | Selenium photocell dia. 45 mm<br>Max. Sensitivity in light,<br>In Frequency range: 550 to 570 nm. Below 430 nm and above 680 nm sensitivity is less than 4% related to the maximum sensitivity. |
| Maximum Smoke Temperature at entrance | : | 250ºC |