An Experimental Analysis on Biodiesel Production of Waste Cooking Oil with Hydrodynamic Cavitation and its Performance Testing

A Major Dissertation submitted in partial fulfillment
of the requirements for the award of the degree of

Master of Technology
In
Thermal Engineering

By

DHANANJAY TRIVEDI

Roll No.2K11/THE/08

Session 2011-13

Under the Supervision of
Dr. Amit Pal

Associate Professor

Department of Mechanical Engineering
Delhi Technological University
Bawana Road, Delhi-11004

CANDIDATE’S DECLARATION

I hereby declare that the work which is being presented in this dissertation entitled “**An Experimental Analysis on Biodiesel Production of Waste Cooking Oil with Hydrodynamic Cavitation and its Performance Testing**” in the partial fulfillment of the requirements for the award of the **degree of Master of Engineering with specialization in Thermal Engineering**, submitted to the Department of Mechanical Engineering ,Delhi Technological University, is an authentic record of my own work carried out under the supervision of **Dr. Amit Pal, Associate Professor**, Mechanical Engineering Department, Delhi technological university, Delhi.

The matter embodied in this dissertation has not been submitted by me for the award of any other degree.

DHANANJAY TRIVEDI
2K11/THE/08

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

Dr. Amit Pal
Associate Professor
Department of Mechanical Engineering
Delhi Technological University

ACKNOWLEDGEMENT

I express gratitude and indebtedness to my learned supervisor **Dr. Amit Pal, Associate Professor**, Department of Mechanical Engineering, Delhi technological university, for his invaluable guidance, encouragement and patient review. His continuous inspiration only has made me complete this major dissertation.

I express my sincere thanks to all teachers, classmates and friends for their unconditional support and motivation during this project. It is a great opportunity for me to extend my heartiest felt gratitude to everyone who helped me throughout the course of this dissertation.

I would also like to thank Sh.Vijay, biodiesel research lab and Sh. Lalit Kumar & Sh.Harjeet Singh,I.C. engine lab for extending their cooperation and support for the successful completion of this project.

DHANANJAY TRIVEDI
2K11/THE/08

ABSTRACT

India is fifth largest primary energy consumer and fourth largest petroleum consumer in the world after United States, China and Japan and expected to be third largest energy consumer by 2030. Despite the recent global economic slump, India's economy is expected to continue to grow at 6 to 8 percent per year in the near term.This economic, infrastructural and socio-economic development will accelerate an increase in energy consumption and demand across all major sectors of the India. As India is not self sufficient in the petroleum and has to rely on imports for a considerable amount of its energy use, consequently increasing India's oil import expenditure to over $135 billion in IFY 2011/12. In this context biodiesel is potentially most promising replacement to petroleum-based fuels as it refers to clean burning fuel produced from domestic renewable sources. However, a major restriction in the commercialization of biodiesel production from edible vegetable oils is their high production cost which is due to the demand for human consumption. One alternative to reduce the cost of biodiesel fuel is to use less expensive feed stocks including waste cooking oils and vegetable oils that are non-edible or require low harvesting costs

The present research work is focused on the production of waste cooking oil biodiesel through hydrodynamic cavitation method and comparison of this method with conventional mechanical stirring followed by the performance testing and emission testing of WCO biodiesel blends on an agricultural diesel engine. Results show that high rate of reaction for WCO methyl ester formation through hydrodynamic cavitation method as compared to conventional mechanical stirring method. As per performance testing and emission testing performed in this work, it is evident that waste cooking oil biodiesel blends give better thermal efficiency and have got safer impact on environment as compared to diesel.

.

TABLE OF CONTENTS

CONTENT **Pages**

- Declaration ii
- Certificate ii
- Acknowledgement iii
- Abstract iv
- List of Figures vii
- List of Tables viii
- Nomenclature xi

1. INTRODUCTION

1.1 General 1-2
1.2 What Is Biodiesel? 2
1.3 Historical Background of Vegetable Oils as Diesel Fuels 3
1.4 Biodiesel Production Cycle 3
1.5 Chemistry of Biodiesel: Tranesterification 4-5
1.6 Characteristics of Oils or Fats Affecting Their Suitability for Use as Biodiesel 5-7
1.7 Characteristics of Waste Cooking Oil 8-9
1.8 Current Scenario of Biofuels in India 9-12

2. LITERATURE OVERVIEW

2.1 Biodiesel, Diesel Blends as Potential Fuel Sources 13-22
2.2 Raw Vegetable Oil as Potential Fuel Source 22-25
2.3 Conclusions from Literature Survey 26
2.4 Objective of Present Project Work 26

3. EXPERIMENTAL WORK (Biodiesel Production)

3.1 Materials 27
3.2 Biodiesel Processes 27

3.2.1 Process Flow Chart 27
3.2.2 Process Details 27
3.3 Biodiesel Production Technologies 30
3.3.1 Mechanical Stirring 31
3.3.2 Reagents and Materials Used for Experiment 31
3.3.3 Experiments Performed 31-33
3.3.4 Experimental Results 34-36
3.4 Hydrodynamic Cavitation 37
3.4.1 Experimental Set-up 37-38
3.4.2 Experimental Procedure 38-39
3.4.3 Experimental Results 40-42
3.5 Comparison of Various Techniques 43

4. ENGINE PERFORMANCE STUDIES

4.1 Introduction 44
4.2 Engine Test Setup 45-46
4.3 Eddy Current Dynamometer 46
4.4 Performance Evaluation 47-49
4.5 Preparation of Blends 49-50
4.6 Performance Data 50
4.6.1Diesel 50-51
4.6.2 Biodiesel Blends 51-54

5. RESULT AND DISCUSSION

5.1 Variation of Torque v/s Brake Power 55
5.2 Variation of Specific Fuel Consumption v/s Brake Power 55-56
5.3 Variation of Brake Thermal Efficiency v/s Brake Power 57
5.4 Variation of Opacity v/s Brake Power 58
5.5 Variation of Exhaust Gas Temperature v/s Brake Power 58
5.6 Variation of CO Emission v/s Brake Power 58-59
5.7 Variation of HC Emission v/s Brake Power 60

5.8 Variation of NO_X Emission v/s Brake Power 60-61
5.9 Pressure v/s Crank Angle (ϴ) 61-63

6. CONCLUSION & FUTURE SCOPE 64-65
7. REFERENCES 66-70

LIST OF FIGURES

Figure No. & Name **Page No.**

Figure-1 Biodiesel production cycle 3

Figure-2 India: Import of crude oil and value of petroleum 10

Figure-3 India: Consumption of petroleum products 11

Figure-4 Biodiesel production by different countries. 12

Figure-5 Biodiesel Manufacturing Flow Sheet from Waste Cooking Oil 27

Figure-6 Determination of FFA 28

Figure-7 Alcohol and WCO mixture. 29

Figure-8 Schematic representation of biodiesel reactor 31

Figure-9 Experimental set-up of biodiesel reactor with mechanical stirrer 32

Figure-10 Glycerol separation process 33

Figure-11 Water washing process of biodiesel 33

Figure-12 Time v/s Yield (%) for molar ratio 6:1 36

Figure-13 Time v/s Yield (%) for molar ratio 4.5:1 36

Figure-14 Schematic representation of the experimental set-up 38

Figure-15 Hydrodynamic cavitation reactor experimental set-up 39

Figure-16 Time v/s Yield (%) for molar ratio 6:1 42

Figure-17 Time v/s Yield (%) for molar ratio 4.5:1 42

Figure -18 Comparison of yield for WCO biodiesel at molar ratio 6:1 43

Figure -19 Comparison of yield for WCO biodiesel at molar ratio 4.5:1 43

Figure -20 Experimental engine setup 45

Figure- 21 Line diagram of experimental setup 46

Figure -23 Comparison of torque v/s brake power 55

Figure -24 Comparison of specific fuel consumption v/s brake power 56

Figure -25 Percentage change of sfc of blends with respect to diesel 56

Figure -26 Comparison of brake thermal efficiency v/s brake power 57

Figure -27 Percentage change of bthe of blends with respect to diesel 57

Figure- 28 Comparison of smoke opacity v/s brake power 58

Figure -29 Comparison of exhaust gas temperature v/s brake power 59

Figure -30 Comparison of CO emission v/s brake power 59

Figure -31 Comparison of HC emission v/s brake power 60

Figure -32 Comparison of NO_X emission v/s brake power 61

Figure -33 Comparison of Cylinder pressure Vs Crank angle forWCO-B 20 62

Figure -34 Comparison of Cylinder pressure Vs Crank angle for WCO-B40 62

Figure -35 Comparison of Cylinder pressure Vs Crank angle for WCO-B60 63

LIST OF TABLES

Table No.& Name **Page No.**

Table-1 Summary of proposed bureau of Indian standards for biodiesel 9

Table-2 Comparison of properties of Waste Cooking oil and diesel 9

Table-3 FFA information 29

Table-4 WCO, methanol and catalyst during the experiment 34

Table-5 Time and yield (%) of waste cooking oil for different molar ratio and catalyst percentage 35

Table-6 Oil, alcohol and catalyst during the experimentation 40

Table-7 Time and yield (%) of waste cooking oil for different molar ratio and catalyst percentage 41

Table-8 Specifications of engine test setup 47

Table-9 Description of different blends of biodiesel 50

Table-10 Performance parameters for diesel 50

Table-11 Observation data for diesel 51

Table-12. Performance parameters for WCO-B20 51

Table -13. Observation data for WCO-B20 52

Table -14. Performance parameters for WCO-B40 52

Table -15. Observation data for WCO-B40 53

Table -16. Performance parameters for WCO-B60 53

Table 17. Observation data for WCO-B60 54

NOMENCLATURE

T1, T3	Inlet water temperatures (^{0}c)
T2	Outlet engine jacket water temperature (^{0}c)
T4	Outlet calorimeter temperature(^{0}c)
T5	Exhaust gas temperature before calorimeter (^{0}c)
T6	Exhaust gas temperature after calorimeter (^{0}c)
F1	Fuel flow dp (differential pressure) unit
F2	Air intake dp(differential pressure) unit
PT	Pressure transducer
SM	Smoke meter
bsfc	Brake specific fuel consumption
btheff	Brake thermal efficiency
b.p.	Brake power
VCR	Variable compression Engine

1. Introduction

Rapidly growing population and development activities world over have resulted in heavy demand for new energy resources The current methods to produce, convert and consume energy derived from fossil fuels throughout the world are not sustainable due to limited amounts of fossil fuels and increasing concerns of global warming, there is ever-growing urge to develop fuel substitutes that are renewable and sustainable. Biomass derived fuels such as methane, ethanol, and biodiesel are well-accepted alternatives to diesel fuels as they are economically feasible, renewable, environmental-friendly and can be produced easily in rural areas where there is an acute need for modern forms of energy. [1]

1.1 General

Biodiesel is the name a given to clean burning alternative fuel produced from domestic renewable sources. The main commodity sources for biodiesel in India are edible and non-edible oils obtained from plant species such as, corn oil, peanut oil, olive oil, cotton seed oil, rape seed oil, linseed oil, sunflower oil, coconut oil, palm oil, jatropha seed oil etc. [2]

Edible vegetable oils such as canola, soybean, and corn have been used for biodiesel production and are proven diesel substitutes. However, a major obstacle in the commercialization of biodiesel production from edible vegetable oils is their high production cost which is due to their heavy demand for human consumption. Reducing the cost of the feedstock is necessary for biodiesel’s long-term commercial viability. One way to reduce the cost of this fuel is to use less expensive feed stocks including waste cooking oils and vegetable oils that are non-edible or require low harvesting costs. Waste cooking oil (WCO), which is much less expensive than edible vegetable oil, could be a promising alternative to edible vegetable oil. [3]

Waste cooking oil and fats set forth significant disposal problems in many parts of the world. This environmentally-threatening problem could be turned into both economical and environmental benefit by proper utilization and management of waste cooking oil as a fuel substitute.

Many developed countries have set policies that penalize the disposal of waste cooking oil into waste drainage [4]. The Energy Information Administration (EIA) in the United States (USA) estimated that around 100 million gallons of waste cooking oil is produced per day in USA, where about 9 pounds of waste cooking oil are generated per person per year [5]. The estimated amount of waste cooking oil collected in Europe is about 0.49 - 0.7 million gallons/day [6].

1.2 What Is Biodiesel?

In the most general sense, biodiesel refers to any diesel fuel substitute derived from renewable biomass. More specifically, biodiesel is defined as an oxygenated, sulphur free, biodegradable, non-toxic, and eco-friendly alternative diesel oil. Chemically, it can be defined as a fuel composed of mono-alkyl esters of long chain fatty acids derived from renewable sources, such as vegetable oil, animal fat, and used cooking oil designated as B100, and also it must meet the special requirements such as the ASTM and the European Standards. One popular process for producing biodiesel is Transesterification. [7]

The injection and atomization characteristics of the vegetable oils are significantly different than those of petroleum derived diesel fuels, mainly as the result of their high viscosities. Modern diesel engines have fuel-injection system that is sensitive to viscosity change. One way to avoid these problems is to reduce fuel viscosity of vegetable oil in order to improve its performance. The conversion of vegetable oils into biodiesel is an effective way to overcome all the problems associated with the vegetable oils. Dilution, micro emulsification, pyrolysis, and transesterification are the four techniques applied to solve the problems encountered with the high fuel viscosity.

Transesterification is the most common method and leads conversion of vegetable oils and fats into mono alkyl esters, called biodiesel .The methyl ester produced by transesterification of vegetable oil has a high cetane number, low viscosity and improved heating value compared to those of pure vegetable oil which results in shorter ignition delay and longer combustion duration and hence low particulate emissions.

1.3 Historical Background of Vegetable Oils as Diesel Engine Fuels

The concept of using vegetable oil as a fuel dates back to 1893 when Dr. Rudolf Diesel developed the first diesel engine to run on vegetable oil. However, diesel engines were adapted to burn petroleum distillate, which was cheap and plentiful. In the late 20th century the cost of petroleum distillate rose, and by the late 1970s there was renewed interest in biodiesel. Commercial production of biodiesel in the United States began in the 1990s.Vegetable oils have become more attractive recently because of its environmental benefits and the fact that it is made from renewable resources. Vegetable oils have potential to substitute a fraction of petroleum distillates and petroleum-based petro chemicals in the near future.

1.4 Biodiesel Production Cycle

Figure 1 shows the Biodiesel production Cycle, solar energy and carbon dioxide along with other inputs are used to grow crops that are in turn harvested and processed. As an example, soybeans are crushed to produce oil that is the basic material to be turned into biodiesel. The production process forces the vegetable oil to react with a catalyst to produce fatty acid esters, the chemical name for biodiesel. The fuel is then used in existing vehicles which also produce carbon dioxide.

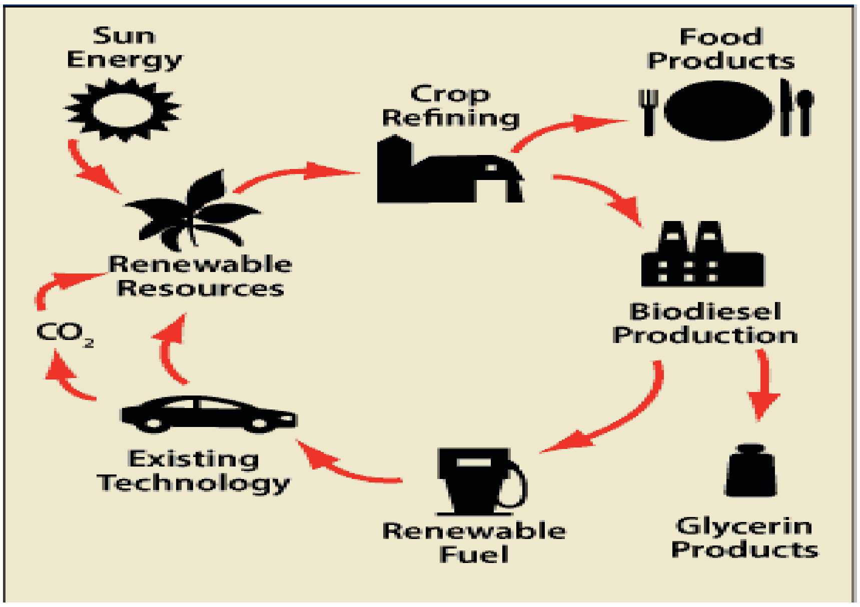
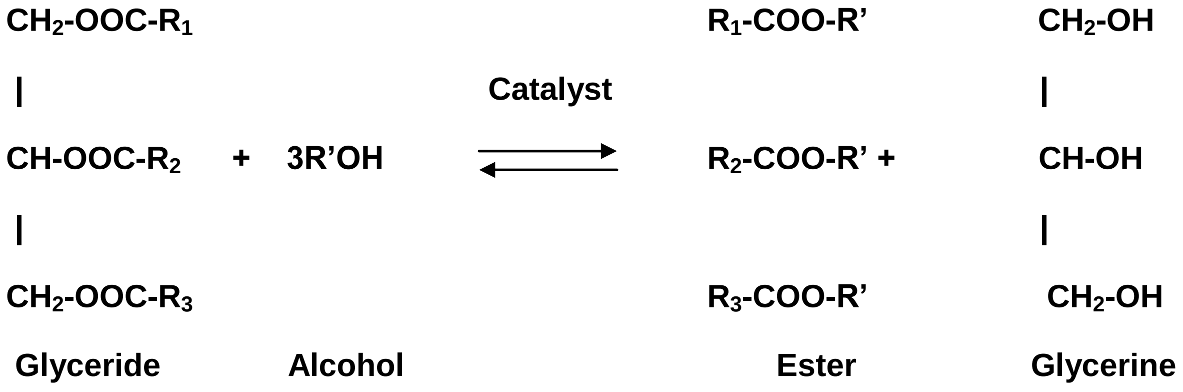


Figure 1. Biodiesel production cycle [7]
[http://www.window.state.tx.us/specialrpt/energy/renewable/biodiesel.php]

1.5 Chemistry of Biodiesel: Tranesterification

Transesterification is the process of separating the fatty acids from glycerol to form fatty acid esters and free glycerol. Fatty acid esters commonly known as biodiesel can be produced in batches or continuously by transesterifying triglycerides such as animal fat or vegetable oil with lower molecular weight alcohols in the presence of a base or an acid catalyst. This reaction occurs stepwise, with monoglycerides and diglycerides as intermediate products. The "R" groups are the fatty acids, which are usually 12 to 22 carbons in length. The large vegetable oil molecule is reduced to about 1/3 of its original size, lowering the viscosity making it similar to diesel fuel. The resulting fuel operates similar to diesel fuel in an engine. [8]



$$\begin{array}{lcccll}
CH_2\text{-}OOC\text{-}R_1 & & & & R_1\text{-}COO\text{-}R' & CH_2\text{-}OH \\
| & & & \text{Catalyst} & & | \\
CH\text{-}OOC\text{-}R_2 & + & 3R'OH & \rightleftharpoons & R_2\text{-}COO\text{-}R' + & CH\text{-}OH \\
| & & & & & | \\
CH_2\text{-}OOC\text{-}R_3 & & & & R_3\text{-}COO\text{-}R' & CH_2\text{-}OH \\
\text{Glyceride} & & \text{Alcohol} & & \text{Ester} & \text{Glycerine}
\end{array}$$

Where, term R’ represents different alkyl groups.

The process of transesterification brings about drastic change in viscosity of vegetable oil. The biodiesel thus produced by this process is totally miscible with mineral diesel in any proportion. Biodiesel viscosity comes very close to that of mineral diesel hence no problems in the existing fuel handling system. Flash point of the biodiesel gets lowered after esterification and the cetane number gets improved. Even lower concentrations of biodiesel act as cetane number improver for biodiesel blend. Calorific value of biodiesel is also found to be very close to mineral diesel

The overall process is normally a sequence of three consecutive steps, which are reversible reactions. In the first step from triglycerides, diglycerides are obtained. From diglyceride, monoglyceride is produced and in the last step from monoglycerides, glycerine is obtained. In all these reactions esters are produced. The stoichiometric relation between alcohol and the oil is 3:1. However, an excess of alcohol is usually more appropriate to improve the reaction towards the desired product.

$$\textbf{Triglycerides + R'OH} \rightleftarrows \textbf{Diglycerides + R'COOR}_1$$

$$\textbf{Diglycerides + R'OH} \rightleftarrows \textbf{Monoglycerides + R'COOR}_2$$

$$\textbf{Monoglycerides + R'OH} \rightleftarrows \textbf{Glycerine + R'COOR}_3$$

The catalyst used for the reaction is mainly of three types which are given below.

<u>Alkali Catalyst</u>

This catalyst can be used with methanol or ethanol as well as any kind of oils, refine, crude or frying. The main alkali catalysts are sodium hydroxide (NaOH) and potassium hydroxide (KOH).

<u>Acidic Catalyst</u>

Acid transesterification is a great way to make biodiesel if the sample has relatively high free fatty acid content. The main acidic catalysts are Sulphuric acid (H_2SO_4) and sulfonic acid.

<u>Enzymes-catalyzed</u>

Enzymes-catalyzed procedures use lipase as catalyst, but the lipases are very expensive for industrial scale production and there are three-step process was required to achieve a 95% conversion. Due to this three step process the reaction time is too large.

1.6 Characteristics of Oils or Fats Affecting Their Suitability for Use as Biodiesel

<u>Calorific Value or Heat of Combustion</u>

Heating value or heat of combustion is the amount of heating energy released by the combustion of a unit value of fuels. One of the most important determinants of heating value is moisture content. Air-dried biomass typically has about 15-20%

moisture, whereas the moisture content for oven-dried biomass is negligible. Moisture content in coals varies in the range 2-30%. However, the bulk density of most biomass feed stocks is generally low, even after densification between about 10 and 40% of the bulk density of most fossil fuels. Liquid bio fuels however have bulk densities comparable to those for fossil fuels.

Pour Point

Melt or pour point refers to the temperature at which the oil in solid form starts to melt or pour. In cases where the temperatures fall below the melt point, the entire fuel system including all fuel lines and fuel tank will need to be heated.

Cloud Point

The temperature at which oil starts to solidify is known as the cloud point. While operating an engine at temperatures below oil's cloud point, heating will be necessary in order to avoid waxing of the fuel.

Flash Point

The flash point temperature of a fuel is the minimum temperature at which the fuel will ignite (flash) on application of an ignition source. Flash point varies inversely with the fuel's volatility. The flash point of biodiesel is higher than the petroleum based diesel fuel.

Iodine Value

Iodine Value (IV) is a value of the amount of iodine, measured in grams, absorbed by 100 grams of given oil. Iodine value (or Iodine number) is commonly used as a measure of the chemical stability properties of different biodiesel fuels against such oxidation. The Iodine value is determined by measuring the number of double bonds in the mixture of fatty acid chains in the fuel by introducing iodine into 100 grams of the sample under test and measuring how many grams of that iodine are absorbed Iodine absorption occurs at double bond positions thus a higher IV number indicates a higher quantity of double bonds in the sample, greater potential to polymerize and hence lesser stability.

Viscosity

Viscosity refers to the thickness of the oil, and is determined by measuring the amount of time taken for a given measure of oil to pass through an orifice of a specified size. Viscosity affects injector lubrication and fuel atomization. Fuels with low viscosity may not provide sufficient lubrication for the precision fit of fuel injection pumps, resulting in leakage or increased wear. Fuel atomization is also affected by fuel viscosity. Diesel fuels with high viscosity tend to form larger droplets on injection which can cause poor combustion, increased exhaust smoke and emissions.

Cetane Number

It is a relative measure of the interval between the beginning of injection and auto ignition of the fuel. The higher the cetane number the shorter the delay interval and the greater its combustibility. Fuels with low Cetane Numbers will result in difficult starting, noise and exhaust smoke. In general, diesel engines will operate better on fuels with Cetane Numbers above 50. Cetane tests provide information on the ignition quality of a diesel fuel.

Density

It is the weight per unit volume. Oils that are denser contain more energy. For example, petrol and diesel fuels give comparable energy by weight, but diesel is denser and hence gives more energy per litre.

Ash Percentage

Ash is a measure of the amount of metals contained in the fuel. High concentrations of these materials can cause injector tip plugging, combustion deposits and injection system wear. The ash content is important for the heating value, as heating value decreases with increasing ash content. Ash content for bio-fuels is typically lower than for most coals, and sulphur content is much lower than for many fossil fuels. Unlike coal ash, which may contain toxic metals and other trace contaminants, biomass ash may be used as a soil amendment to help replenish nutrients removed by harvest.

1.7 Characteristics of Waste Cooking Oil

The composition of WCO biodiesel varies somewhat depending on the oil feedstock and the fuel production process. Most vegetable oil feed stocks consist primarily of C16 and C18 fatty acids, but can also include smaller contributions from other C8 to C22 compounds [9]. In addition to differences in cooking oil stocks, variations in frying temperatures and times can affect the composition of the final fuel.

Several studies have identified oleic and linoleic acid as the predominant fatty acid methyl esters present in WCO biodiesel [10, 11]. In a study of used cooking oils, however, Knothe and Steidley [12] observed high variability in WCO fatty acid composition from different restaurants at the same location, which could result in similar variability in the biodiesel.

- **Proximate Analysis**

% fixed carbon: 100-(%ash+%moisture+%volatile

% volatile matter and moisture: 0.078

% ash content: 0.003

% fixed carbon: 99.919

Low moisture and volatile content indicates the used cooking oil doesn’t need pre-treatment to remove the moisture prior processing and high fixed carbon indicates it rich with carbon content. It has high calorific value low heavy metal content and low moisture. With long chain of palmitic acid and oleic acid, it has the potential to be cracked by thermal cracking or catalytic cracking for possible formation of hydrocarbon chain. [13]

Some of the important properties and standards of biodiesel and commercial diesel fuel are given in Table 1 & 2.

Table 1. Summary of proposed bureau of Indian standards for biodiesel [14]

Standard / specification	Unit	Proposed BIS
Density @ 15^oC	g/cm^3	0.87 – 0.90
Viscosity @ 40^oC	mm^2/s	3.5 - 5.0
Flash point	^oC	>=100
Sulphur, max.	%mass	0.035
Water.max	mg/kg	500
Total contamination, max.	mg/kg	20
Cetane no		>=51
Acid no	mg KOH/g	<=0.8
Ester content	%mass	>=96.5
Diglyceride	%mass	<=0.2

Table 2. Comparison of properties of Waste Cooking oil and diesel [14]

Properties	Bio diesel from waste vegetable	Diesel Fuel
Moisture	0.1%	-
Density at 15 ^0C (gm/cc)	0.8966	0.84
Kinematic viscosity at 40^0C (cst)	6.3	4 – 5
Acidity as mg KOH/gm oil	0.12	-
Flash Point	196 ^0C	76 ^0C
Pour point	–11 ^0C	–16 ^0C
Gross calorific value (kcal/kg)	10,425	10,900

1.8 Current Scenario of Biofuels in India

India is the world’s fifth largest primary energy consumer and fourth largest petroleum consumer after United States, China and Japan. Despite the recent global economic slowdown, India’s economy is expected to continue to grow at 6 to 8 percent per year in the near term. With an outlook for moderate to strong economic growth and a rising population, growing infrastructural and socio-economic development will stimulate an increase in energy consumption across all major sectors of the Indian. In Indian fiscal year (IFY) 2009/10, an import of gasoline and petroleum products has outgrown total domestic consumption by more than 14 percent. While India's domestic energy base is substantial, the country continues to rely on imports for a considerable amount of its energy use, consequently escalating India's oil import expenditure to over $135 billion in IFY 2011/12, up 22 percent over the previous year (figure 2)[15]. Petroleum consumption (Figure 3) in India has also grown in tandem to 148 million tons.

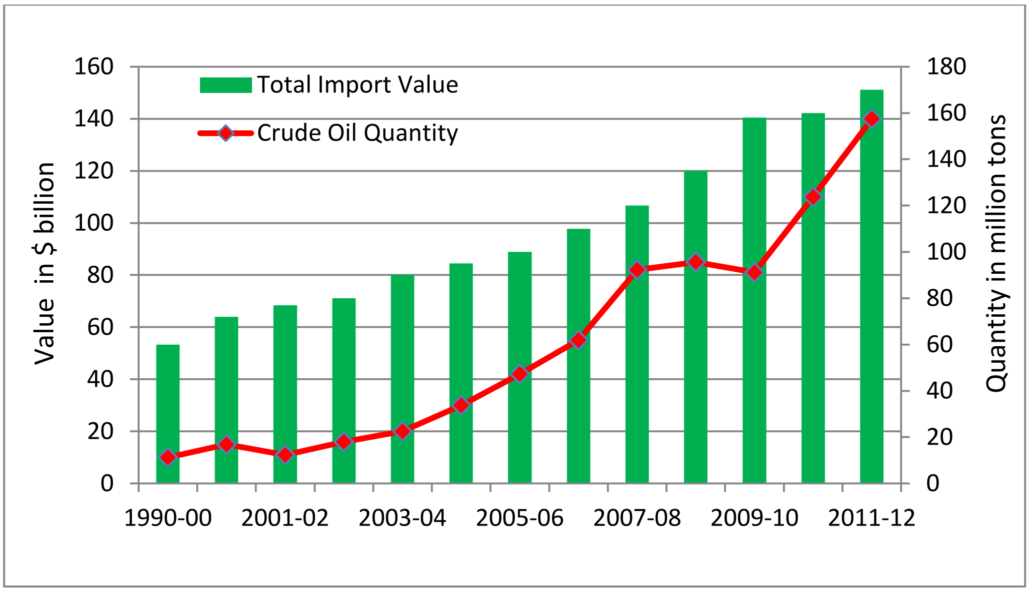


Figure 2. India: Import of crude oil and value of petroleum

(Source: Petroleum Planning and Analysis Cell, GOI)

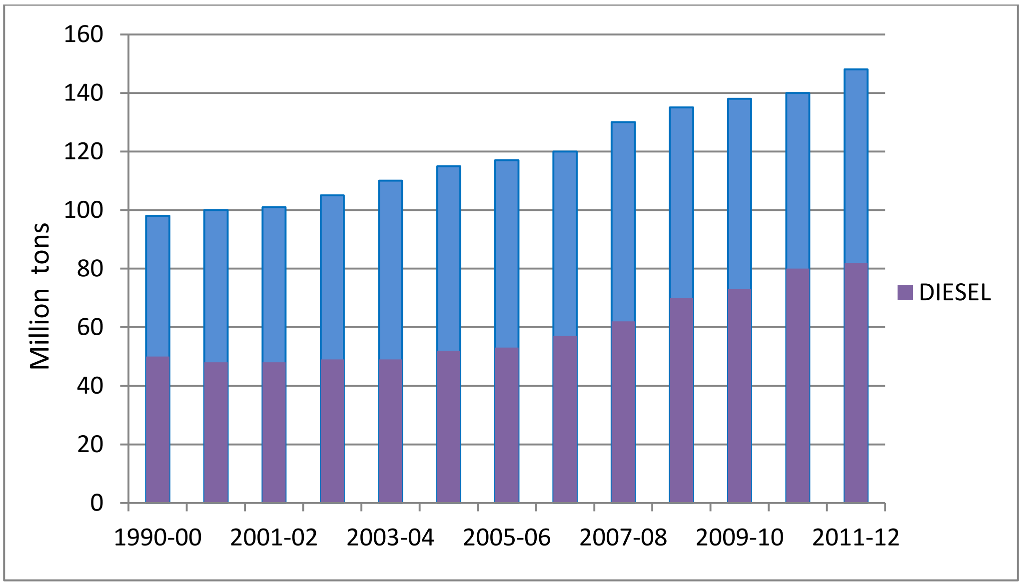


Figure 3.India: Consumption of petroleum products

(Source: Petroleum Planning and Analysis Cell, GOI)

Given that India is the fourth largest global contributor to carbon emissions, the GOI transport policy has targeted EURO-III and IV vehicle emission norms for vehicles, which in turn would require adoption of clean and green fuel. The government is seriously concerned about economic, environmental, energy security while looking to alternate fuels to meet energy demand through safe, clean, and convenient forms of energy at least cost in a technically efficient, economically viable and environmentally sustainable manner. To meet these objectives, the Union Cabinet approved the National Policy on Biofuels on December 24, 2009.

The salient features of the National Policy on Bio-fuels are:

- An indicative target of 20% blending of bio-fuels, both for bio-diesel and bio-ethanol, by 2017 has been proposed.
- Minimum Support Price (MSP) for non-edible oil seeds would be announced with periodic revision to provide fair price to the growers.
- Minimum Purchase Price (MPP) for purchase of bio-ethanol and bio-diesel would be announced with periodic revision.
- Major thrust will be given to research, development and demonstration with focus on plantations, processing and production of bio-fuels.
- Financial incentives, including subsidies and grants, may be considered for second generation bio-fuels. If it becomes necessary, a National Bio-fuel Fund could be considered.
- A National Biofuel Coordination Committee, headed by the Prime Minister, will be set up to provide policy guidance and coordination.
- A Biofuel Steering Committee, chaired by Cabinet Secretary, will be set up to oversee implementation of the Policy.
- Biofuel technologies and projects would be allowed 100-percent foreign equity through an automatic approval route to attract foreign direct investment (FDI), provided the biofuel is for domestic use only, and not for export. Planting of inedible oil bearing plants would not be open to FDI participation

The Indian Railways has started to use the oil (blended with diesel fuel in various ratios) from the Jatropha plant to power its diesel engines with great success. Currently the diesel locomotives that run from Thanjavur to Nagore section and Tiruchirapalli to Lalgudi, Dindigul and Karur sections run on a blend of Jatropha and diesel oil. In one of the biggest initiatives for bio-fuel production in the country, Indian Railways is poised to set up four bio-diesel plants costing about Rs. 120 crore. While two bio-diesel esterification plants are going to be commissioned at Raipur and Chennai during the next two years, the other two units will be set up subsequently. Each plant, estimated to cost around Rs 30 crore, will produce 30 tons bio-diesel per day, which means more than 9,000 tons a year. [16, 17]

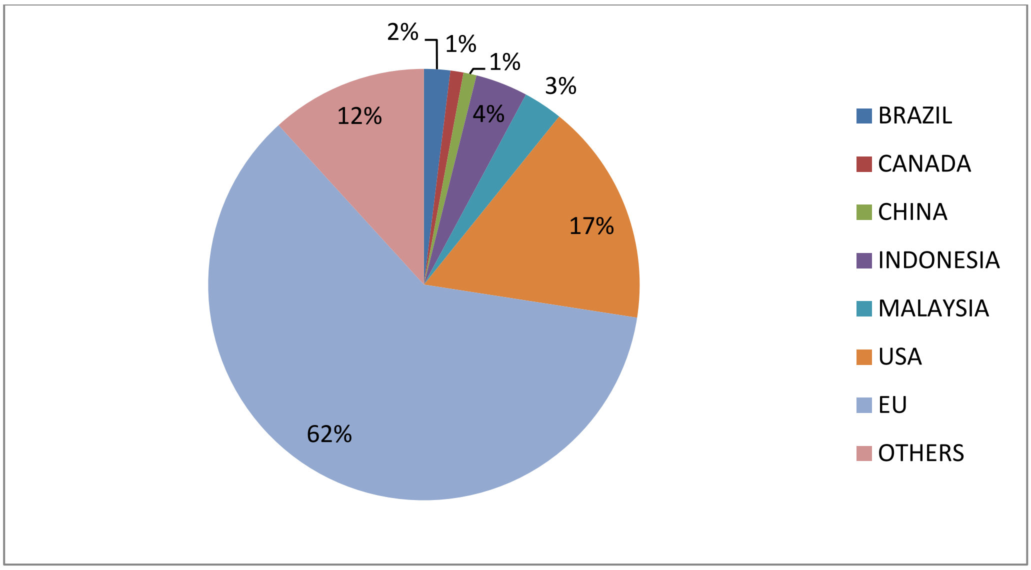


Figure 4. Biodiesel production by different countries [17]

2. Literature Overview

Many studies have been done involving biodiesel from various feed stocks as a primary source of energy. Particularly, during the early 1980's, studies were completed that tested the possibility of using biodiesel as a replacement for diesel fuel. There is no question that biodiesel can be placed in the tank of a diesel vehicle and the engine will continue to run and deliver acceptable performance.

Thus many researchers have been involved in testing programs designed to evaluate performance and emission characteristics. Results of these studies indicated that potential hazards such as stuck piston rings, carbon build-up on injectors, fuel system failure, and lubricating oil contamination existed when unmodified vegetable oils were used as alternative fuels. These effects disappear or reduce with the use of tranesterified vegetable oil that is biodiesel and diesel blends.

This literature review mainly deals with study of performance and emission characteristics of biodiesel from various feed stocks.

2.1 Biodiesel, Diesel Blends as Potential Fuel Sources

Nanthagopal et al. (2009) [18] investigated the performance and emission characteristics of a direct injection diesel engine fuelled by waste cooking oil-diesel emulsion with different water contents are evaluated. The use of waste cooking oil-diesel emulsion lowers the peak temperature, which reduces the formation of NOx. Moreover the phenomenon of micro explosion that results during the combustion of an emulsified fuel finely atomizes the fuel droplets and thus enhances combustion. Experiments show that CO concentration is reduced as the water content is increased and it is seen that 20% water content gives optimum results. Also, there is a significant reduction in NOx emissions. Important conclusions drawn are significant reduction in specific energy consumption (3.31%) with emulsified fuel containing 20% water when compared to diesel, higher smoke intensity by about 13.13% for 20% water content at full load, an increment of about 23.8% at full load in emission of the particulate matter, CO concentration gets reduced as the water concentration is increased, and there is a marginal increment of about 2.78% in brake thermal efficiency for 20% water content when compared to diesel.

Patil et al. (2012) [19] studied the biodiesel production from waste cooking oil using sulphuric acid (Two-step) and microwave- assisted transesterification (One-step) was carried out. A two-step transesterification process was used to produce bio- diesel (alkyl ester) from high free fatty acid (FFA) waste cooking oil. Microwave-assisted catalytic transesterification using BaO and KOH was evaluated for the efficacy of microwave irradiation in biodiesel production from waste cooking oil. On the basis of energy consumptions for waste cooking oil (WCO) transesterification by both conventional heating and microwave-heating methods evaluated in this study, it was estimated that the microwave-heating method consumes less than 10% of the energy to achieve the same yield as the conventional heating method for given experimental conditions. The thermal stability of waste cooking oil and biodiesel was assessed by thermo gravimetric analysis. The analysis of different oil properties, fuel properties and process parametric evaluative studies of waste cook-ing oil are presented in detail. The fuel properties of biodiesel produced were compared with American Society for Testing and Materials (ASTM) standards for biodiesel and regular diesel.

Yoshimoto (1999) [20] investigated the engine performance with a stable emulsified fuel including frying oil, composed of vegetable oils discarded from restaurants and households. It had been further reported that NOx concentration and smoke density were reduced without worsening bsfc with water to fuel volume ratios of 15-30% at a rated power output. Also, emulsified biodiesel with 30% (by volume) showed a significant reduction in NOx while maintaining the minimum bsfc value achieved with gas oil.

Brown (2000) [21] summarized the results of experimental work carried out in the area of diesel emission reductions using advanced catalyst water blend fuel. They reviewed the impact and potential benefits of combining catalyst and water blend diesel to reduce exhaust emissions from engines.

Tests on DI diesel engine with water diesel emulsion by **Subramanian et al. (2001) [22]** indicated a considerable reduction in smoke and NO levels. This was accompanied by an increase in brake thermal efficiency at high out puts. When the oxygen concentration in the intake air was enhanced in steps up to 25% along with the use of water diesel emulsion, the brake thermal efficiency was improved and there was a further reduction in the smoke, HC, and CO levels.

Bertola et al. (2003) [23] found the effect of the introduction of water in the combustion chamber of a DI diesel engine on combustion characteristics and pollutant formation by using water-diesel emulsions with three distinct water amounts (13, 21 and 30%). Analysis of the measured and computed data shows clear and favourable trends. Also, at constant injection pressure, the reduction of NOx and particulate matter was achieved with 30% water emulsion compared to diesel fuel. These reductions were in all cases proportional to the water content in the fuel. This was measured in all engine load conditions.

Kee (2003) [24] summarized the effects of water-emulsified fuel on diesel combustion and emission reduction under various ambient temperatures, equivalence ratios and water addition ratios using a rapid compression machine and a total gas sampling device. It has been indicated that promoted diffusion combustion of emulsified fuels offers shorter combustion duration and an increment in the amount of heat release when compared with those of gas oil. It has been found that this reduction is due to low NOx formation rate.

Senda (2004) [25] investigated the flame structure and combustion characteristics for two waste cooking oils and found that spray tip penetration got in creased and the spray angle was decreased. Particulate matter emissions were lowered with pure biodiesel compared to other fuels in the whole engine operating range.

Rosca (2005) [26] indicated that transesterification process has significantly decreased the viscosity of the methyl ester, which is very close to the one of diesel fuel. The use of methyl ester led to changes in the injection characteristics like increased injection pressure, lower average injection rate, and earlier start of combustion.

Refaat et al. (2008) [27] studied an alternative energy stimulant, ‘‘microwave irradiation’’ for the production of biodiesel. The optimum parametric conditions obtained from the conventional technique were applied using microwave irradiation in order to compare both systems. The results showed that application of radio frequency microwave energy offers a fast, easy route to this valuable biofuel with advantages of enhancing the reaction rate and improving the separation process. The methodology allows for the use of high free fatty acid content feedstock, including used cooking oil. This paper also reported the performance and exhaust emissions from a diesel engine when fuelled with a petroleum diesel fuel and two different biodiesel fuels; one obtained by the conventional technique and the other by microwave irradiation. It was concluded that microwave-enhanced biodiesel is not, at least, inferior to that produced by the conventional technique. Although the results of the power tests of biodiesel are similar to petroleum diesel fuel performance values; a slight increase in sfc (lower than 8 %) was detected with biodiesel.

Karunanithi et al. (2012) [28] attempted to produce biodiesel from waste vegetable oils and the properties of the produced biodiesel have been studied including its emission characteristics. A four stroke, single cylinder is used to study the emission and performance characteristics. The large scale production of Biodiesel and its economic aspects have also been discussed in brief. High temperature of 85 ^{0}C is considered to be the optimum temperature for conversion. Increasing the methanol concentration up to 100 % excess than the stoichiometric proportion yields an optimum conversion. It has been found that the biodiesel yield increases and then reaches the optimum conversion at 5-6% of the weight of the catalyst.

Arslan (2011) [29] investigated the use of waste cooking oil (WCO) methyl ester as an alternative fuel in a four-stroke turbo diesel engine with four cylinders, direct injection and 85 HP. A test was applied in which an engine was fuelled with diesel and three different blends of diesel/biodiesel (B25, B50 and B75) made from WCO. The test engine was run at 18 different speeds with a full load, and the results were analyzed. The biodiesel fuels produced slightly less smoke than the conventional diesel fuel, which could be attributed to better combustion efficiency. The use of biodiesel resulted in lower emissions of total hydrocarbon and CO, and increased emissions of NOx.

This study showed that the exhaust emissions of diesel/biodiesel blends were lower than those of the diesel fuels, which indicates that biodiesel has more favourable effects on air quality.

Khalisanni et al. (2008) [30] determined some properties of used cooking for the production of bio fuel. Preliminary analysis of used cooking oil properties using capillary column shows n-Hexadecanoic acid and Oleic acid as the major compounds present in the used frying oil. The analysis for determination of volatile and moisture content with 3 replicates show an average of 0.02% moisture and volatile content.

Fan et al. (2009) [31] provided a comprehensive review of biodiesel production from lower-cost non-edible oil sources, such as waste cooking oil (WCO), grease, soapstock, *Jatropha* oil, and algae. The engine performances of biodiesel produced from these feed stocks were further evaluated. This review also investigated the various applications for the value-added products from glycerol, the by-product of biodiesel. The emission results indicated that the blends burn more efficiently with less specific fuel consumption, resulting in higher thermal efficiency. Moreover, less carbon monoxide (CO) and unburned hydrocarbons (HC) than diesel fuel were produced for the blends.

Cho et al. (2008) [32] investigated the performance characteristics of preheated waste cooking oil as fuel in diesel engines with minor modification in the engine. Since waste cooking oil is too thick to work in the engine directly so needs to be heated up before using it. To use unmodified oil one needs to modify the existing

Singh et al. (2010) [33] studied hybrid fuels consisting of coconut oil, aqueous ethanol and a surfactant. The engine performance and exhaust emission were investigated and compared with that if diesel. The experimental results show that the efficiency of the hybrid fuels is comparable with to that of diesel. The exhaust emission was lower than those for diesel, except carbon monoxide emissions, which increased. As the percentage of ethanol in the hybrid fuels increases, the CO emission level decreases due to higher air –fuel ratio of the fuel. NO emission Values were 459,454,442 ppm for 87CCO 10E 3B, 70CCO 17E 13B, 54CCO 23E 23B respectively, compared to 852 ppm for diesel at 86% load.

Hence it is concluded that these hybrid fuels can be used as an alternatives fuel in diesel engines without any modifications. Their completely renewable nature ensures that they are environment friendly with regard to their emission characteristic.

Buasri et al. (2008) [34] studied transesterification of waste cooking oil (WCO) containing 5.5 wt% free fatty acid (FFA) was with methanol, ethanol and mixtures of methanol/ ethanol maintaining the oil to alcohol molar ratio of 1:6, 60 °C and initially with KOH as a catalyst. Mixtures of methanol and ethanol were used for transesterification in order to use the better solvent property of ethanol and rapid equilibrium using methanol. Formation of soap by reaction of FFA present in WCO with KOH presented difficulty in the separation of glycerol from biodiesel ester. To untangle this problem, two-step catalyzed process was used for biodiesel synthesis. More than 80% ester was obtained when two-stage method was used compared to 40% ester in single-stage alkaline catalyst. In the case of mixed alcohol, a relatively smaller amount of ethyl esters was formed along with methyl esters. In addition, it was confirmed that the rate depended upon the kind of alcohols, as the number of carbon in alcohol increased, the rate of the ester formation tended to decrease.

Calais et al. (2012) [35] studied the use of waste vegetable and animal oils and fats as unmodified fuels in compression ignition engines. Conversion of waste oils and fats to biodiesel fuel is one possibility but poses some difficulty such that as in the use of toxic or caustic materials and by-product disposal. Conversion to biodiesel may also decrease the economic attractiveness of using waste oils as fuels. One of the authors converted a Mazda 626 to operate on straight vegetable oils and has done over 7500 km. The other author has been using biodiesel in an unmodified Toyota corolla for over 20,000 km. In order to minimize the problem of cold starting the vehicle was first started on diesel and then when the engine has reached normal temperature and oil has been heated, a solenoid valve is operated which switched the fuel system over to the fuel.

Çetinkaya et al. (2007) [36] investigated the engine performance of biodiesel fuel originated from used cooking oil in a Renault automobile and four stroke, four cylinder, and 75 kW Renault Diesel engine in winter conditions for 7500 km road tests in urban and long distance traffic.

The results showed that the torque and brake power output obtained during the used cooking oil originated biodiesel application were 3-5% less than those of diesel fuel. The engine exhaust gas temperature at each engine speed of biodiesel was less than that of diesel fuel. Higher values of exhaust pressures were found for diesel fuel at each engine speed. The injection pressures of both fuels were similar. Based on the experimental results of this study, the authors concluded that used cooking oil originated biodiesel could be recommended as diesel fuel alternative for winter conditions.

Lin et al. (2007) [37] also used WCO to prepare biodiesel and then conducted a study in which the trace formation from the exhaust tail gas of a diesel engine when operated using the different fuel type, including neat biodiesel, biodiesel/diesel blends, and normal diesel fuels, were compared. Among the collected data, they found that B20 and B50 were the optimum fuel blends.

Wang et al. (2006) [38] investigated a two-step catalyzed processes for synthesis of biodiesel by using WCO from Chinese restaurants. In the first step, ferric sulfate-catalyzed methanolysis was carried out, while potassium hydroxide catalysis was used in the second step. The authors made a conclusion that compared with one-step sulfur acid catalysis the two-step catalyzed process provided a more simple and economic method to produce biodiesel from WCO.

Issariyakul et al. (2007) [39] also used the two-step process to transesterify WCO, except that sulphuric acid was selected as acid catalyst and mixtures of methanol and ethanol were used for transesterification in order to use the better solvent property of ethanol and rapid equilibrium using methanol. More than 90% ester was obtained when two-stage method was used compared with ~50% ester in single stage alkaline catalyst.

Chen et al. (2006) [40] used immobilized lipase based on Rhizopusorzyae. Their study was focusing on optimization of several parameters, including the molar ratio of methanol to waste oils, biocatalyst load, and adding method, reaction temperature, and water content. The results indicated that methanol/oil ratio of 4/1, immobilized lipase/oil of 30 wt% and 40 °C were suitable for waste oils under 1 atm. Their reversible inactivation of the lipase was presumed and a stepwise addition of methanol to reduce inactivation of immobilized lipases was proposed. Under the optimum conditions the yield of methyl esters was around 88–90%.

Chatterjee et al. (1999) [41] investigated synthesis of geranyl and citronellyl esters of mixed fatty acids by alcoholysis of coconut oil using Rhizomucor miehei lipase.CNO fatty acids esters of geraniol and citronellol have unique mild flavours that can be used in food materials .both geraniolysis and citronellolysis of CNO produce flavour esters in good yield .depending upon substrate concentration the molar yield is more than 50%. The optimize reaction conditions were: pressure, atmospheric, temperature, 50^0C, incumbation period, 5h, and lipozyme, 10%.

Mei et al. (2008) [42] studied the combustion and heat release of engines using diesel and bio-diesel blends. In this paper, the comparative experiments were carried out with diesel engine using diesel fuel, B20, and B100. The combustion and emissions of engine were analyzed. When the engine uses bio-diesel, the combustion timing occurs in advance, and the ignition delay decreases. At 50% and 100% load at a rated speed, the combustion also happens in advance, the maximal heat release rates are reduced by 11.4% and 25.3%, respectively, and the related point occurs in advance. The specific fuel consumption is raised by about 12% because of the lower calorific value. Total pollution decreases, only NOx emission increases by 5.6%, and CO, HC, and PM emissions are reduced by 41.4%, 38.3% and 38.7%, respectively.

Ozkan et al. (2005) [43] tested waste cooking oil biodiesel fuels in a single-cylinder DI Diesel engine. It was found that Compared diesel fuel, 25% power loss occurred with biodiesel. The performance characteristics of biodiesel were closer to those of diesel fuel. The selling price of waste cooking oil biodiesel fuel is lower than that of diesel fuel as a result of the recycling of raw materials. Based on these results, it may be concluded that the biodiesel fuels can be used as fuel in diesel engines with some modifications. Fuel systems should be optimised for biodiesel fuels, because of the high density and gumming properties. The problems include coking carbon deposites on the injectors to such an extent that fuel atomization does not occur properly , oil ring sticking and thickening and gelling of the lubricating oil as a result of contamination by the vegetable oils.

Pathak et al. (2007) [44] experimented that a multi cylinder naturally aspirated diesel genset (DG) was operated successfully with renewable fuels (bio-diesel of non-edible plant oil such as Jatropha oil, karanja oil, rice bran oil & producer gas) and its performance was verified through extensive, short and long duration trials. Study reveals that mixture of bio-diesel and producer gas offer better break thermal efficiency compared to mixture of fossil-diesel and producer gas. Maximum replacement of biodiesel by producer gas was 86% at 63% engine load with minor losses in engine output compared to fossil-diesel. In general, exhaust gas temperature and specific energy consumption increased with renewable fuel compared to fossil-diesel. It was due to lower calorific value of bio-diesel and producer gas. In compression ignition (CI) engine having 18.4:1 simulated compression ratio, at 84% engine load and with renewable fuel concentration of pollutants like carbon monoxide (CO),hydrocarbon (HC), nitric oxide (NO), nitrogen dioxide (NO_2) were reduced, in general compared to fossil-diesel. However concentration of pollutants were more while compared to fossil-diesel – producer gas mixture.

Sharma et al. (2005) [45] has gone through the various aspects of engine performance using neem-diesel blend (B-20) as fuel were studied through extensive experimentation at different injection pressure. Data thus obtained were analyzed and compared with those of diesel. Significant reduction in emissions was observed as compared to that with diesel. At the same time BTE at higher loads was observed to be slightly low (upto2%) as compared to that with diesel. This effect was more at higher injection pressure. BSFC was slightly higher as compared with diesel and tend to increase with the increase of injection pressure through the load range. Based on these results it was observed that for neem-diesel blend (B-20) optimum injection pressure was 1.57kN/cm^2, as highest BTE and lowest BSFC was observed over the entire load range.

Pereira et al. (2007) [46] described an experimental investigation concerning the electric energy generation using blends of diesel and soybean biodiesel. The soybean biodiesel was produced by a transesterification process of the soybean oil using methanol in the presence of a catalyst (KOH). The properties (density, flash point, viscosity, pour point, cetane index, copper strip corrosion, carbon residue and ash content) of the diesel and soybean biodiesel were determined. The exhaust emissions of gases (CO, CO2, O2, NO, NOx and SO2) were also measured. The results show that for all the mixtures tested, the electric energy generation was assured without problems. The temperatures of the exhaust gases and the emissions of NO and NOx are similar to or less than those of diesel. The results of the tests show the viability of using diesel–soybean biodiesel blends in a stationary engine for the electric energy generation, being an alternative to sustainable development.

2.2 Raw Vegetable Oil as Potential Fuel Source

During World War II, Seddon (1942) experimented with using several different vegetable oils in a Perkins diesel engine. The results of those experiment showed that vegetable oils could be used to power a vehicle under normal operating conditions. However, it was noted that much more work was needed before vegetable oils could be used as a reliable substitute for diesel fuel.

Bruwer et al. (1981) [47] studied the use of sunflower seed oil as a renewable energy source. When operating tractors with 100% sunflower oil instead of diesel fuel, an 8%power loss occurred after 1000 hours of operation. The power loss was corrected by replacing the fuel injectors and injector pump. After 1300 hours of operation, the carbon deposits in the engine were reported to be equivalent to an engine fuelled with 100%diesel except for the injector tips, which exhibited excessive carbon build-up.

Auld et al. (1982) [48] used rapeseed oil to study the effects of using an alternative fuel in diesel engines. An analysis of the rapeseed oil showed a relationship between viscosity and fatty acid chain length. Engine power and torque results using rapeseed oil were similar to that of diesel fuel. Results of the short-term tests indicated further long-term testing was needed to evaluate engine durability when rapeseed oil was used.

Bacon et al. (1981) [49] evaluated the use of several vegetable oils as potential fuel sources. Initial engine performance tests using vegetable oils were found to be acceptable, while noting that the use of these oils caused carbon build up in the combustion chamber. Continuous running of a diesel engine at part-load and mid-speeds was found to cause rapid carbon deposition rates on the injector tips. Short 2-hour tests were used to visually compare the effects of using different vegetable oils in place of diesel fuel. Although short-term engine test results were promising, Bacon recommended long-term engine testing to determine the overall effects of using vegetables oils as a fuel in diesel engines.

Pryde (1982) [50] reviewed the reported successes and shortcomings for alternative fuel research. This article stated that short-term engine tests using vegetable oils as a fuel source was very promising. However, long-term engine test results showed that durability problems were encountered with vegetable oils because of carbon build up and lubricating oil contamination. Thus, it was concluded that vegetable oils must either be chemically altered or blended with diesel fuel to prevent premature engine failure.

Wagner and Peterson (1982) [51] reported mixed results when using rapeseed oil as a substitute fuel. Attempts to heat the oil fuel mixture prior to combustion exhibited no measurable improvement in fuel injection. Severe engine damage was noted during short-term engine testing due to the use of rapeseed oil. A long-term test using a 70%rapeseed, diesel fuel blend was successful for 850 hours with no apparent signs of wear, contamination of lubricating oil, or loss of power.

Sapaun et al. (1996) [52] reported that studies in Malaysia, with palm oils as diesel fuel substitutes, exhibited encouraging results. Performance tests indicated that power outputs were nearly the same for palm oil, blends of palm oil and diesel fuel, and 100% diesel fuel. Short-term tests using palm oil fuels showed no signs of adverse combustion chamber wear, increase in carbon deposits, or lubricating oil contamination.

Ryan et al. (1984) [53] characterized injection and combustion properties of several vegetable oils. The atomization and injection characteristics of vegetable oils were significantly different from that of diesel fuel due to the higher viscosity of the vegetable oils. Engine performance tests showed that power output slightly decreased when using vegetable oil fuel blends. Injector coking and lubricating oil contamination appeared to be a more dominate problem for oil-based fuels having higher viscosities.

McDonnell et al. (2000) [54] studied the use of a semi-refined rapeseed oil as a diesel fuel extender. Test results indicated that the rapeseed oil could serve as a fuel extender at inclusion rates up to 25%. As a result of using rapeseed oil as a fuel, injector life was shortened due to carbon build up. However, no signs of internal engine wear or lubricating oil contamination were reported.

Schoedder (1981) [55] used rapeseed oils as a diesel fuel replacement in Germany with mixed results. Short-term engine tests indicated rapeseed oil had similar energy outputs when compared to diesel fuel. Initial long-term engine tests showed that difficulties arose in engine operation after 100 hours due to deposits on piston rings, valves, and injectors. The investigators indicated that further long-term testing was needed to determine if these difficulties could be adverted.

Tahir et al. (1982) [56] tested sunflower oil as a replacement for diesel fuel in agricultural tractors. Sunflower oil viscosity was 14% higher than diesel fuel at 37°C. Engine performance using the sunflower oil was similar to that of diesel fuel, but with a slight decrease in fuel economy. Oxidation of the sunflower oil left heavy gum and wax deposits on test equipment, which could lead to engine failure.

Yarbrough et al. (1981) [57] experienced similar results when testing six sunflower oils as diesel fuel replacements. Raw sunflower oils were found to be unsuitable fuels, while refined sunflower oil was found to be satisfactory. Degumming and de waxing the vegetable oils were required to prevent engine failure even if the vegetable oils were blended with diesel fuel.

Engler et al. (1983) [58] found that engine performance tests using raw sunflower and cottonseed vegetable oils as alternative fuels gave poor results. Engine performance tests for processed vegetable oils produced results slightly better than similar tests for diesel fuel. However, carbon deposits and lubricating oil contamination problems were noted, indicating that these oils are acceptable only for short-term use as a fuel source.

Goering et al. (1981) [59] studied the characteristic properties of eleven vegetable oils to determine which oils would be best suited for use as an alternative fuel source. Of the eleven oils tested, corn, rapeseed, sesame, cottonseed, and soybean oils had the most favourable fuel properties.

Pryor et al. (1983) [60] conducted short and long-term engine performance tests using 100% soybean oil in a small diesel engine. Short-term test results indicated the soybean performance was equivalent to that of diesel fuel. However, long-term engine testing was aborted due to power loss and carbon build-up on the injectors.

Rao et al. (2008) [61] in his study, used cooking oil was dehydrated and then transesterified using an alkaline catalyst. The combustion, performance and emission characteristics of Used Cooking oil Methyl Ester (UCME) and its blends with diesel oil are analysed in a direct injection C. I. engine. The fuel properties and the combustion characteristics of UCME are found to be similar to those of diesel. A minor decrease in thermal efficiency with significant improvement in reduction of particulates, carbon monoxide and unburnt hydrocarbons is observed compared to diesel. The use of transesterified used cooking oil and its blends as fuel for diesel engines will reduce dependence on fossil fuels and also decrease considerably the environmental pollution.

The performance, emissions and combustion characteristics of a 4.4 kW DI compression ignition engine fuelled with UCME and its blends have been analysed, and compared to the baseline diesel fuel.

The ignition delay of UCME and its blends is found to be lesser as compared to that of diesel. The peak pressure of UCME-diesel is higher than that of diesel. The engine develops maximum rate of pressure rise and maximum heat release rate for diesel compared to UCME and its blends.

2.3 Conclusions from Literature Survey

In this work an extensive literature survey were carried out to know the various aspects of biodiesel research and the following conclusions have been made.

1. Biodiesel from various feed stocks could be potential fuel to be used in compression ignition engines with better thermal efficiency and lower emissions like carbon monoxide and unburned hydrocarbon with slight increase in NO_X emission .however there is still need to find out better and low cost methods for biodiesel production suitable for mass production so that it can be commercialized.

2. Transesterification reaction time is lower with alkali catalyst (KOH) compared to acid catalysts. Proper and environment friendly handling of by products from biodiesel production still need to be studied.

3. Emulsified Biodiesel has lower NO_X emission because of slightly lower temperature inside the cylinder and gases produced.

2.4 Objective of Present Project Work

The objective of the present project work is to produce biodiesel from waste cooking oil through mechanical stirring and hydrodynamic cavitation methods and then compare the yield and eventually carry out its performance testing in compression ignition engine without making any modification in the existing engine to check the performance parameters like torque, brake thermal efficiency and specific fuel consumption and emission characteristics. Performance testing will be performed in 4-stroke, single-cylinder, water cooled C.I. engine which is attached by eddy current dynamometer for loading purpose and computer panel to analyse the performance data.

3. Experimental Work

(Biodiesel Production)

3.1 Materials

WCO containing was collected from hotel Paris Hilton in Saket region of south Delhi. Methanol (CH_3OH) and potassium hydroxide (KOH) were used as reacting agent and catalyst respectively during the transesterification process.

3.2 Biodiesel Production Processes

3.2.1 Process Flow Chart

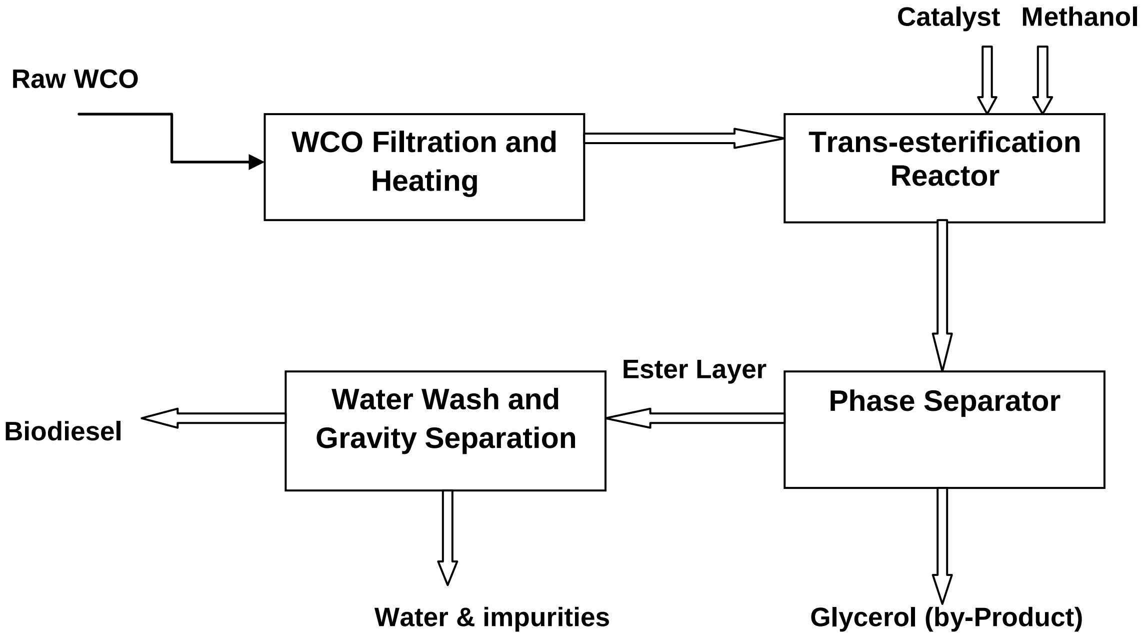


Figure 5. Biodiesel Manufacturing Flow Sheet from Waste Cooking Oil (WCO).

3.2.2 Process Details

3.2.2.1 Filtration and Heating of WCO

Non-oil components of the WCO were removed by separation using filter and moisture was removed by heating the oil upto 120°C and keeping at this temperature for 05 minutes. Heating with electric heater is usually the easiest way to bring the oil up to required temperature.

3.2.2.2 Determination of FFA

In order to determine the percent of FFA in the oil, a process called titration is used. The vegetable oil is first mixed with methanol. Next, a mixture of Sodium Hydroxide (NaOH) and water is added until all of the FFA has been reacted. This is confirmed by checking the pH of the mixture. A pH of about 9 signifies all of the FFA has been reacted.

Figure 6. Alcohol and WCO mixture

One gram of NaOH was dissolved in 1 litre of distilled water (0.1%NaOH) solution. Phenolphthalein solution was used to get the end point. In a smaller beaker, 1ml of WCO oil is dissolved in 10ml of methanol. The mixture was stirred gently until all the oil dissolves in the alcohol and the mixture turns clear. Two to three drops of phenolphthalein solution was added.

Using a burette, 0.1% NaOH solution was added drop by drop to the oil alcohol phenolphthalein solution, stirring all the time, until the solution stays pink. The number of ml of 0.1% NaOH solution gives the amount of NaOH to be used per litre of oil and FFA percentage.

Amount of FFA present in the WCO used in this work is 2.14 wt%.

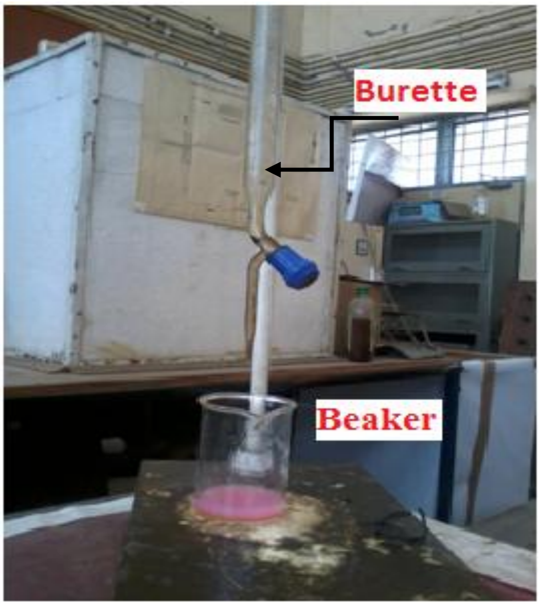


Figure 7. Determination of FFA

Table 3. FFA information

ml titration	%FFA	NaOH (grams) per gallon
0	0	13.25
0.5	0.3578222	15.15
1	0.7156445	17.025
1.5	1.0734667	18.925
2	1.431289	20.825
2.5	1.7891112	22.7
3	2.1469334	24.6
3.5	2.5047557	26.5
4	2.8625779	28.3875
4.5	3.2204002	30.28
5	3.5782224	32.1725

3.2.2.3 Mixing of Methanol and Catalyst

The purpose of mixing methanol and the catalyst (NaOH) is to react the two substances to form Methoxide. The amount of Methanol used should be 20% of the volume of the oil. Methanol and KOH are dangerous chemicals by themselves, with Methoxide even more so. None of these substances should ever touch skin. Vapours should not be inhaled. Gloves and ventilation are required at all times when working with these substances.

3.2.2.4 Transesterification (Biodiesel Reaction)

The methanol in excess is added to the oil in a beaker serving as a batch reactor. The mixture is then agitated for about 60 to 90 minutes and then left overnight for phase separation to take place due to gravity.

3.2.2.5 Draining of Glycerol

After the transesterification reaction, one must wait for the glycerol to settle to the bottom of the container. This happens because Glycerol is heavier then biodiesel. The settling will begin immediately, but the mixture should be left for minimum of eight hours to 12 hours.

3.2.2.6 Washing of Biodiesel

The purpose of washing is to wash out the remnants of the catalyst and other impurities. Generally water washing is preferred in which lukewarm water (about one third of raw biodiesel) is added to raw biodiesel, stirred for a short duration and then impurities are allowed to settle down at bottom with water.

3.3 Biodiesel Production Techniques

This section contains the details of biodiesel production methodologies which are used in the present work like mechanical stirring, hydrodynamic cavitation method and results of these methods are relatively compared.

3.3.1 Mechanical Stirring

In this method, mixing of WCO and methanol is carried out in a tank equipped with a mechanical stirrer as shown in fig 8. An electric motor is used to rotate the shaft around which blades are provided to stir the mixture of immiscible liquids (oil and alcohol are not miscible with each other), as shaft starts rotating a turbulence is created which disrupt the phase boundary between two immiscible liquid and thus resulted in proper mixing. Temperature is measured with the help of a thermometer and kept in the range of the 60-65 °C.

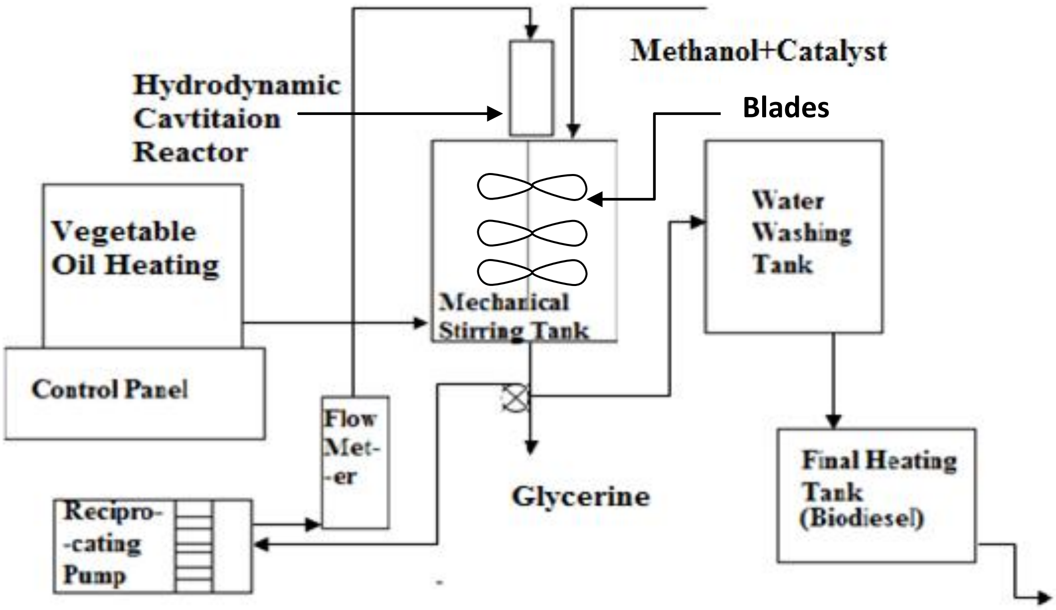


Figure 8.Schematic representation of biodiesel reactor

3.3.2 Reagents and Materials Used for Experiment

1. Waste cooking oil for preparing biodiesel.
2. Methyl alcohol (CH_3OH).
3. Base catalyst (KOH) for accelerating the reaction mixture

3.3.3 Experiments Performed

This experiment has been performed to evaluate performance of mechanical stirring method of biodiesel production in terms of yield (%).

Figure 9. Experimental set-up of biodiesel reactor with mechanical stirrer

Experiment has been performed with the following steps:

1. Waste cooking oil (8 kg) is filtered and then heated to 120^{o}C and kept at this temp for about 05 min to remove impurities and moisture. This reduces the probability of soap formation during the tranesterification reaction. The sample is then cooled to room temperature.
2. Methyl alcohol (CH_3OH) is taken with a molar ratio of (1:4.5 & 1:6) and Catalyst (KOH) is taken as (0.75% and 1% by wt of oil).The mixture of methyl alcohol and KOH is stirred until KOH dissolve in methyl alcohol.
3. Now the WCO and mixture of methanol and catalyst are put together into the tank and mechanical stirring is applied for about 90 min.
4. During the reaction the temperature of mixture is kept in between 60-65 ^{0}C.
5. While reaction taking place five samples are drawn each of 100 gm at a time interval of 30 min, 45 min, 60 min, 75 min and 90 min.

6. Samples are then allowed for phase separation of methyl ester and glycerol in separating flasks as shown in figure 9. Fatty acid has higher specific weight therefore it will settle at bottom. Separation of methyl ester and glycerol will take 8 to 12 hr duration.
7. After complete separation bio-diesel (methyl Ester) is visible in the upper layer and glycerol at the bottom.
8. Bio-diesel is then separated and water washed.
9. To remove impurities and catalyst, water at around 40 ^{0}C is mixed with the methyl ester and left for settling down. Water due to its higher specific gravity collected at bottom. This is shown in figure 11.

Figure 10. Glycerol separation process

Figure 11. Water washing process of biodiesel

3.3.4 Experimental Results

The experiments are performed with alcohol to oil molar ratio as 6:1 and 4.5:1. The amount of oil, alcohol and catalyst taken is shown in Table 4.

Table 4.WCO, methanol and catalyst during the experiment

Molar ratio (methanol/oil)	**Quantity of waste cooking oil (g)**	**Quantity of methanol (g)**	**Catalyst consumed (KOH)**	
			0.75 % (Wt %)	**1.0 % (Wt %)**
6:1	8000	1765	60 g	80 g
4.5:1	8000	1324	60 g	80 g

- <u>For calculation of molar ratio following data are used</u>

  Molecular weight of triglycerides from waste cooking oil = 870

  Molecular weight of methanol = 32

  Hence, 1 gm mole of waste cooking oil = 870 g

  And 1 gm mole of methanol = 32 g

  Catalyst (KOH) = 0.75% and 1% by weight of oil

- <u>Amount of methanol for 8000 g of WCO</u>
- For 1:6 molar ratio = (32 / 870) ×8000 × 6 = 1765.51 g
- 1:4.5 molar ratio = (32 / 870) ×8000 × 4.5 = 1324.13 g

- <u>Sample Calculation for yield</u>
- Quantity of WCO taken = 100 g
- Quantity of biodiesel produced = 90 g (say)
- Yield % = (Quantity of biodiesel produced/Quantity of oil taken)*100

  = (90/100)*100 = 90%

- Experimental Data for Mechanical Stirring Method

Time and yield of biodiesel from waste cooking oil for corresponding molar ratio and catalyst (%) are shown in the table 5.

Table 5.Time and yield (%) of waste cooking oil for different molar ratio and catalyst percentage

Percentage of catalyst	Molar ratio 6:1		Molar ratio 4.5:1	
	Time (min)	Yield %	Time (min)	Yield %
0.75	30	75.25	30	70.85
	45	79.45	45	76.21
	60	86.74	60	84.45
	75	88.90	75	85.12
	90	90.44	90	86.09
1.0	30	80.45	30	73.45
	45	84.45	45	78.89
	60	90.11	60	86.45
	75	91.55	75	87.78
	90	92.48	90	88.47

As shown in figures 12 and 13, biodiesel yield increases as reaction time increases and eventually it becomes constant after 75 min of reaction time. The yield is more for molar ratio 6:1 and 1 % catalyst (max value is 92.48%) as compared to molar ratio 4.5:1 and 0.75% catalyst (max value is 90.44%).

- Yield for 8 Kg of WCO Sample:
  - Molar Ratio 4.5:1 = 85 % for 0.75% catalyst and 88% for 1.0 % catalyst
  - Molar Ratio 6:1 = 89 % for 0.75% catalyst and 91% for 1.0 % catalyst

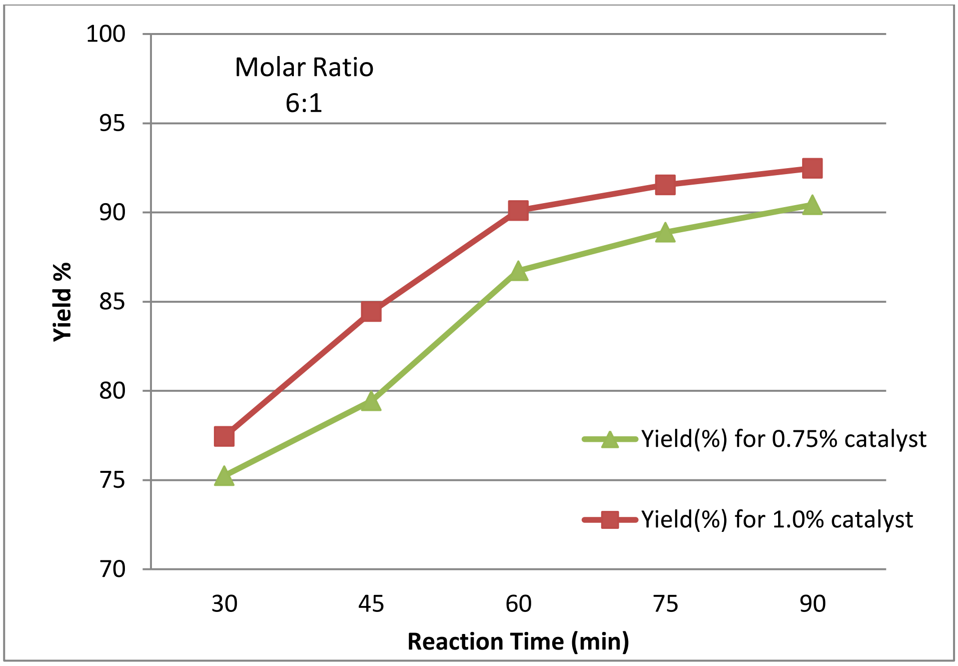


Figure 12. Time v/s Yield (%) for molar ratio 6:1 and different catalyst percentage

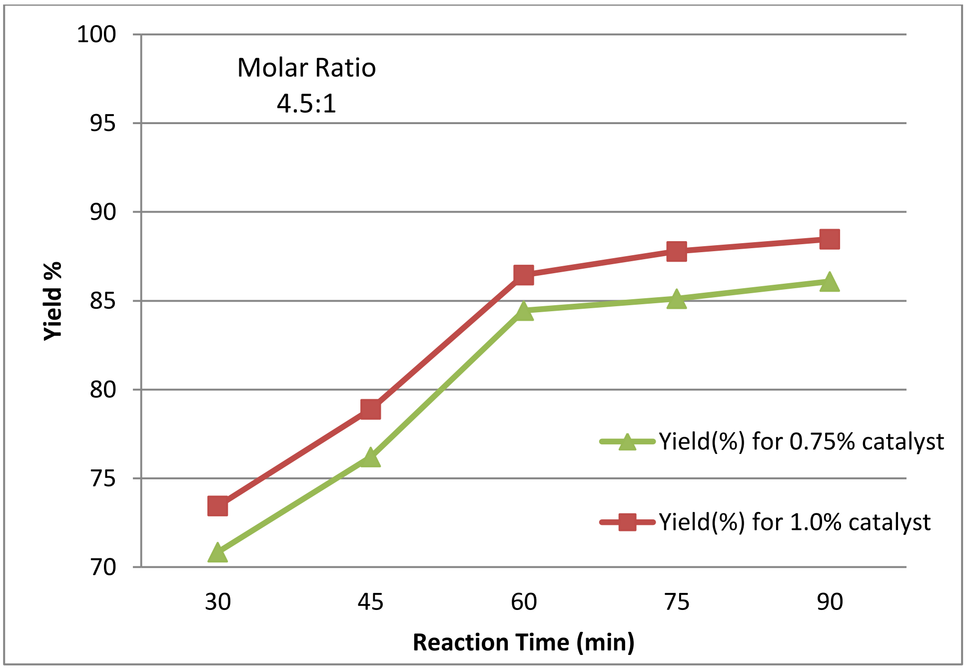


Figure 13.Time v/s Yield (%) for molar ratio 4.5:1 and different catalyst percentage

3.4 Hydrodynamic Cavitation

Like cavitation in turbines and pumps, hydrodynamic cavitation can be generated by the passage of the liquid through a constriction such as throttling valve, venturi orifice plate etc. When the liquid passes through the orifice plates, the velocities at the orifice increase due to the sudden reduction in the area offered for the flow, resulting in a decrease in the pressure. If the velocities are such that their increase is sufficient to allow the local pressure to go below the medium vapour pressure under operating conditions (at constant temperature), vapour bubbles are formed. At the downstream of the orifice, however, due to an increase in the area of cross-section, the velocities decrease giving rise to increasing pressures and pressure fluctuations, because of which bubbles collapse and local cavities (low pressure regions) are formed at a number of locations. Cavities formation at a number of locations in the reactor also depends strongly on the number of holes in the orifice plates. This process generates conditions of very high temperatures and pressures locally. The asymmetric collapse of the cavitation bubbles disrupts the phase boundary and impinging of the liquids create micro jets, leading to intensive emulsification of the system, which result in increase of reaction rate at much faster rate. This process is carried again and again until all the mixture is converted into bio diesel.

3.4.1 Experimental Set-up

The experimental set-up as shown in figure 13 consists of a closed loop fluid circuit comprising a tank with a reciprocating pump, control valve (V_1, V_2 and V_3) and a coupling to accommodate the orifice plate. The photograph of test rig is shown in figure 14. The suction side of the pump is connected to the side of the tank. Discharge from the pump branches into two lines, which help in the control of inlet pressure and inlet flow rate into the main line housing of the orifice with the help of valves V_1 and V_2. The main line consists of a coupling to accommodate the orifice plates (single or multiple holes).

The cavitation conditions are generated just after the orifice plates in the main line and hence the intensity of the cavitation conditions strongly depends on the geometry of the orifice plate. The pressures in the main line before and after the orifice plate are measured with the help of pressure gauges P1 & P2. Tank can also be provided with a cooling jacket to control the temperature of the circulating liquid.

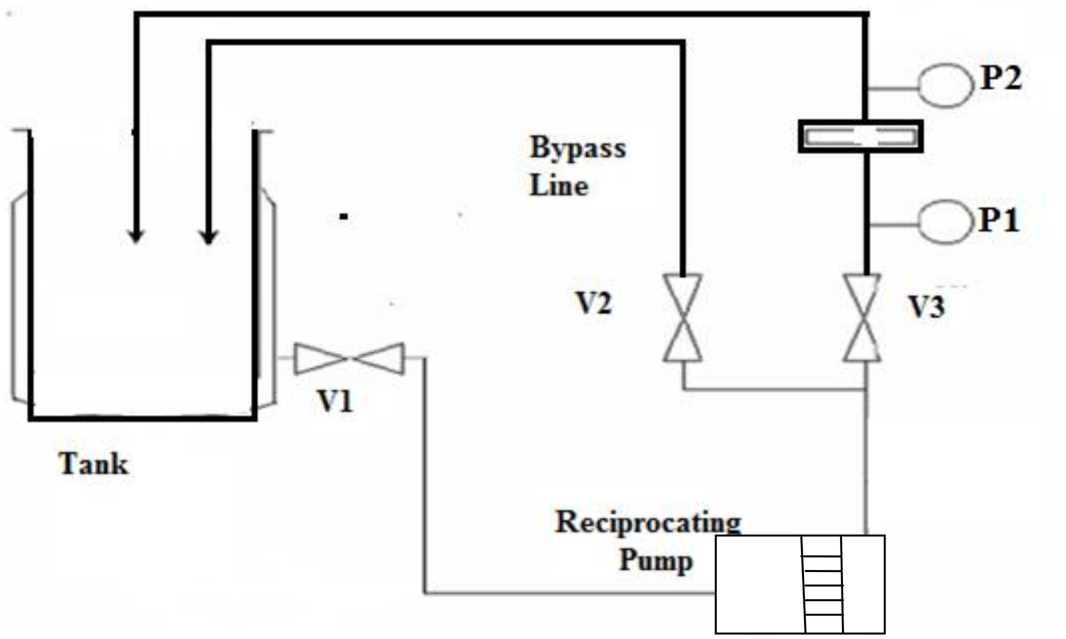


Figure 14.Schematic representation of the hydrodynamic cavitation set-up

3.4.2 Experimental Procedure

This experiment has been performed to evaluate performance of hydrodynamic Cavitation method of biodiesel production in terms of yield (%).

Experiment has been performed with the following steps:

1. Waste cooking oil (8 kg) is filtered and then heated to 120^{o}C and kept at this temperature for about 05 min to remove impurities and moisture. This reduces the probability of soap formation during the tranesterification reaction. The sample is then cooled to room temperature.
2. Methyl alcohol (CH3OH) is taken with a molar ratio of (1:4.5 & 1:6) and Catalyst (KOH) is taken as (0.75% and 1% by wt of oil).The mixture of methyl alcohol and KOH is stirred until KOH dissolve in methyl alcohol.

Figure 15.Hydrodynamic cavitation reactor experimental set-up

3. Now the WCO and mixture of methanol and catalyst are put together into the tank and allowed to pass through hydrodynamic cavitation reactor by means of reciprocating pump during the reaction the temperature of mixture is kept between 60-65 ^{0}C.
4. While reaction taking place five samples are drawn each of 100 gm at a time interval of 30 min, 45 min, 60 min, 75 min and 90 min.
5. Samples are then allowed for phase separation of methyl ester and glycerol in separating flasks as shown in figure 9. Fatty acid has higher specific weight therefore it will settle at bottom. Separation of methyl ester and glycerol will take 8 to 12 hr duration.
6. After complete separation bio-diesel (methyl Ester) is visible in the upper layer and glycerol at the bottom.
7. Bio-diesel is then separated and water washed.
8. To remove impurities and catalyst, water at around 40 ^{0}C is mixed with the methyl ester and left for settling down. Water due to its higher specific gravity collected at bottom. This is shown in figure 10.
9. Excess methanol present in biodiesel can be removed by vaporization process.

3.4.3 Experimental Results

The experiment has been performed with alcohol to oil molar ratio as 6:1 & 4.5:1 and catalyst percentage of 0.5% & 1% using waste cooking oil. The amount of oil, alcohol and catalyst taken are shown in Table 6.

Table 6. Oil, alcohol and catalyst during the experimentation

Molar ratio (methanol/oil)	Quantity of waste cooking oil (g)	Quantity of methanol (g)	Catalyst consumed (KOH)	
			0.75% (Wt %)	1.0% (Wt %)
6:1	8000	1765	60 g	80 g
4.5:1	8000	1324	60 g	80 g

- ➢ <u>For calculation of molar ratio following data are used</u>

Molecular weight of triglycerides from waste cooking oil = 870

Molecular weight of methanol = 32

Hence, 1 gm mole of waste cooking oil = 870 g

And 1 gm mole of methanol = 32 g

Catalyst (KOH) = 0.75% and 1% by weight of oil

- ➢ <u>Amount of methanol for 8000 g of WCO</u>
- For 1:6 molar ratio = (32 / 870) ×8000 × 6 = 1765.51 g
- 1:4.5 molar ratio = (32 / 870) ×8000 × 4.5 = 1324.13 g

- ➢ <u>Sample Calculation for yield</u>
- Quantity of WCO taken = 100 g
- Quantity of biodiesel produced = 90 g (say)
- Yield % = (Quantity of biodiesel produced/Quantity of oil taken)*100

= (90/100)*100 = 90%

- Experimental Data for Hydrodynamic Cavitation Method

Time and yield of biodiesel from waste cooking oil for corresponding molar ratio and catalyst (%) are shown in the table 7.

Table 7.Time and yield (%) of waste cooking oil for different molar ratio and catalyst percentage

Percentage of catalyst	Molar ratio 6:1		Molar ratio 4.5:1	
	Time (min)	Yield %	Time (min)	Yield %
0.75	30	82.12	30	81.85
	45	88.12	45	85.21
	60	90.40	60	88.12
	75	94.41	75	92.55
	90	96.01	90	94.09
1.0	30	82.45	30	81.01
	45	89.14	45	86.11
	60	92.11	60	89.45
	75	96.55	75	93.88
	90	98.12	90	95.14

As shown in figures 16 and 17, biodiesel yield increases as reaction time increases and eventually it becomes constant after 75 min of reaction time. The yield is more for molar ratio 6:1 and 1 % catalyst (max value is 98.12%) as compared to molar ratio 4.5:1 and 0.75% catalyst (max value is 95.14%).

- Yield for 8 Kg of WCO Sample:
  - Molar Ratio 4.5:1 = 93% for 0.75% catalyst and 95% for 1.0 % catalyst
  - Molar Ratio 6:1 = 96% for 0.75% catalyst and 98% for 1.0 % catalyst

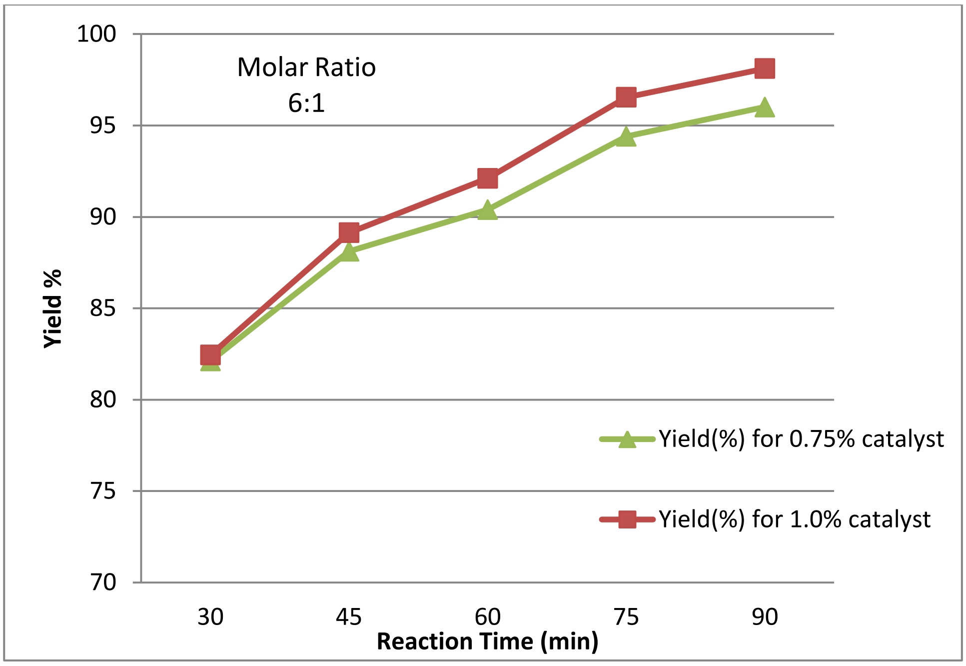


Figure 16.Time v/s Yield (%) for molar ratio 6:1 and different catalyst percentage

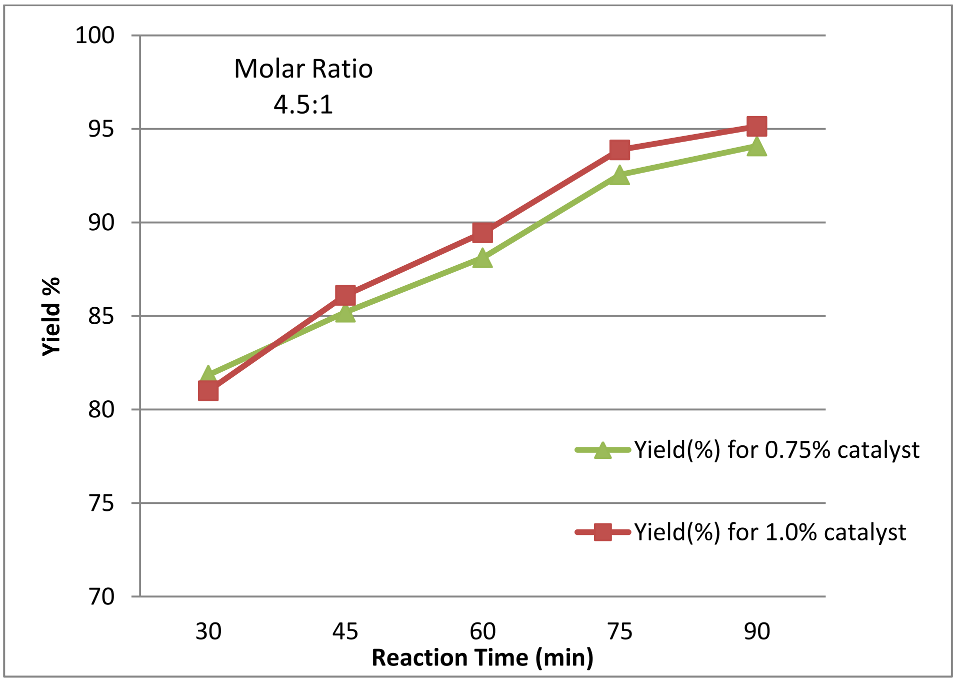


Figure 17.Time v/s Yield (%) for molar ratio 4.5:1 and different catalyst percentage

3.5 Comparison of Various Techniques

Comparison of biodiesel yield from mechanical stirring and hydrodynamic method for molar ratio 6:1 (alcohol and oil) and 4.5:1 for different catalyst (%) is shown in Figure 18 and 19 respectively. It is evident from Figure 18 and 19 that yeild is more in case of hydrodynamic cavitation method and also rate of tranesterification reaction is much faster as compared to mechanical stirring method.

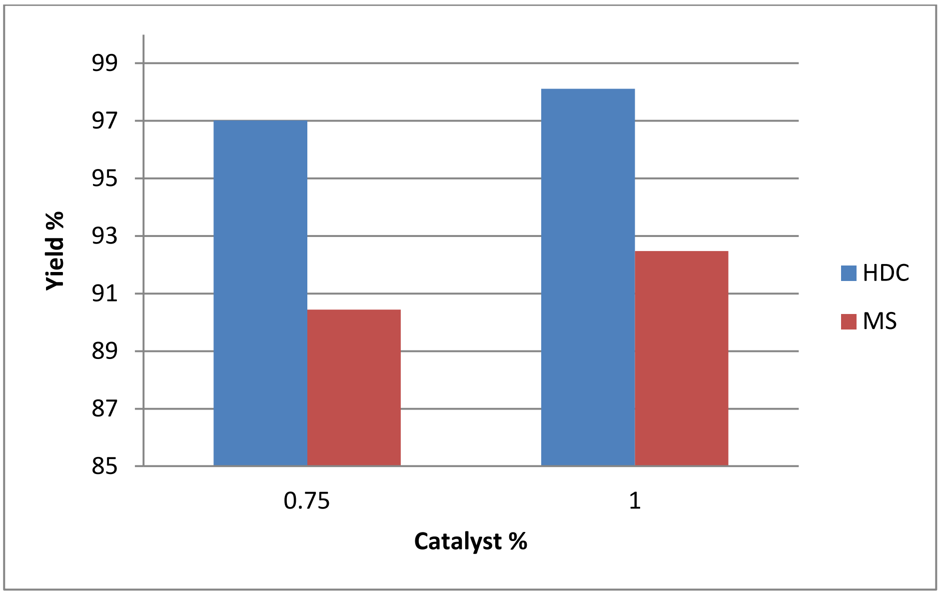


Figure 18.Comparison of yield for WCO biodiesel at molar ratio 6:1

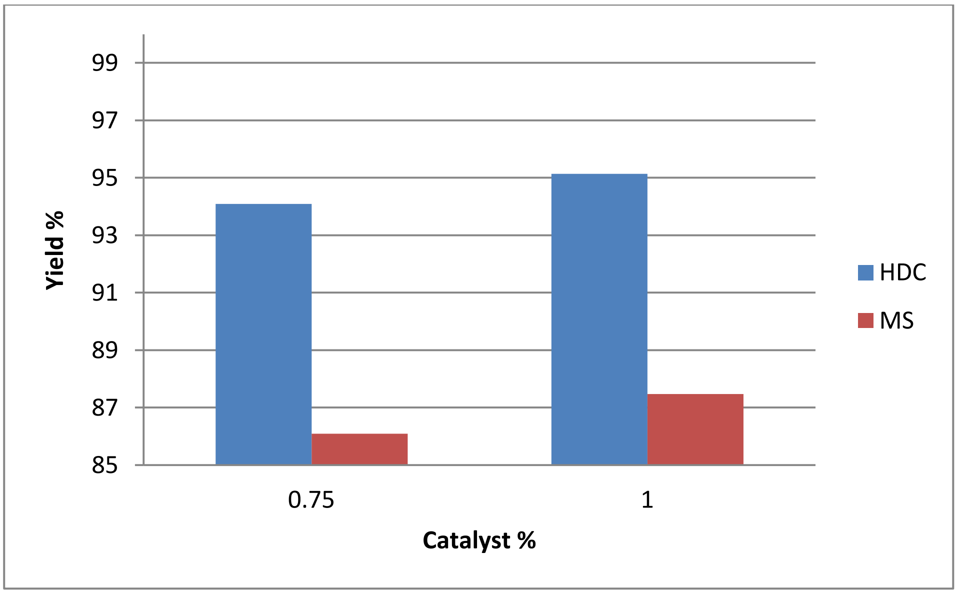


Figure 19.Comparison of yield for WCO biodiesel at molar ratio 4.5:1

4. Engine Performance Studies

4.1 Introduction

The concept of variable compression ratio (VCR) promises improved engine performance, efficiency, and reduced emissions. The higher cylinder pressures and temperatures during the early part of combustion and small residual gas fraction owing to higher compression ratio give faster laminar flame speed. Therefore, the ignition delay period is shorter. As a result, at low loads, the greater the compression ratio, the shorter is the combustion time. The time loss is subsequently reduced. Therefore, it seems reasonable that fuel consumption rate is lower with high compression ratios at part load.

The VCR or, more correctly, variable compression ratio can make a significant contribution to thermo dynamic efficiency. The main feature of the VCR engine is to operate at different compression ratios, depending on the vehicle performance needs. A VCR engine can continuously vary the compression ratio by changing the combustion chamber volume. In a VCR engine, thermodynamic benefits appear throughout the engine map. At low power levels, the VCR engine operates at a higher compression ratio to capture high fuel efficiency benefits, while at high power levels the engine operates at low compression ratio to prevent knock. The optimum compression ratio is determined as a function of one or more vehicle operating parameters such as inlet air temperature, engine coolant temperature, exhaust gas temperature, engine knock, fuel type, octane rating of fuel, etc. In a VCR engine, the operating temperature is more or less maintained at optimum, where combustion efficiency is high. It has been proven that a VCR engine develops much more power for the same engine dimensions, i.e. it is very compact and has a high power-to-weight ratio without any penalty on specific fuel consumption. In other words, reducing the engine capacity at the same power leads to reduction in fuel consumption owing to reduced pumping, friction, and heat losses.

4.2 Engine Test Setup

The setup consists of single cylinder, four stroke, VCR (Variable Compression Ratio) diesel engine connected to eddy current type dynamometer for loading as shown in figure 20. The compression ratio can be changed without stopping the engine and without altering the combustion chamber geometry by specially designed tilting cylinder block arrangement. Setup is provided with necessary instruments for combustion pressure and crank-angle measurements. These signals are interfaced to computer through engine indicator for P−PV diagrams. Provision is also made for interfacing airflow, fuel flow, temperatures and load measurement. The set up has stand-alone panel box consisting of air box, two fuel tanks for duel fuel test, manometer, fuel measuring unit, transmitters for air and fuel flow measurements, process indicator and engine indicator. Rotameters are provided for cooling water and calorimeter water flow measurement. The setup enables study of VCR engine performance for brake power, indicated power, frictional power, bmep, imep, brake thermal efficiency, indicated thermal efficiency, mechanical efficiency, volumetric efficiency, specific fuel consumption, A/F ratio & heat balance. Engine Performance Analysis software package “EnginesoftLV” is provided for performance evaluation.

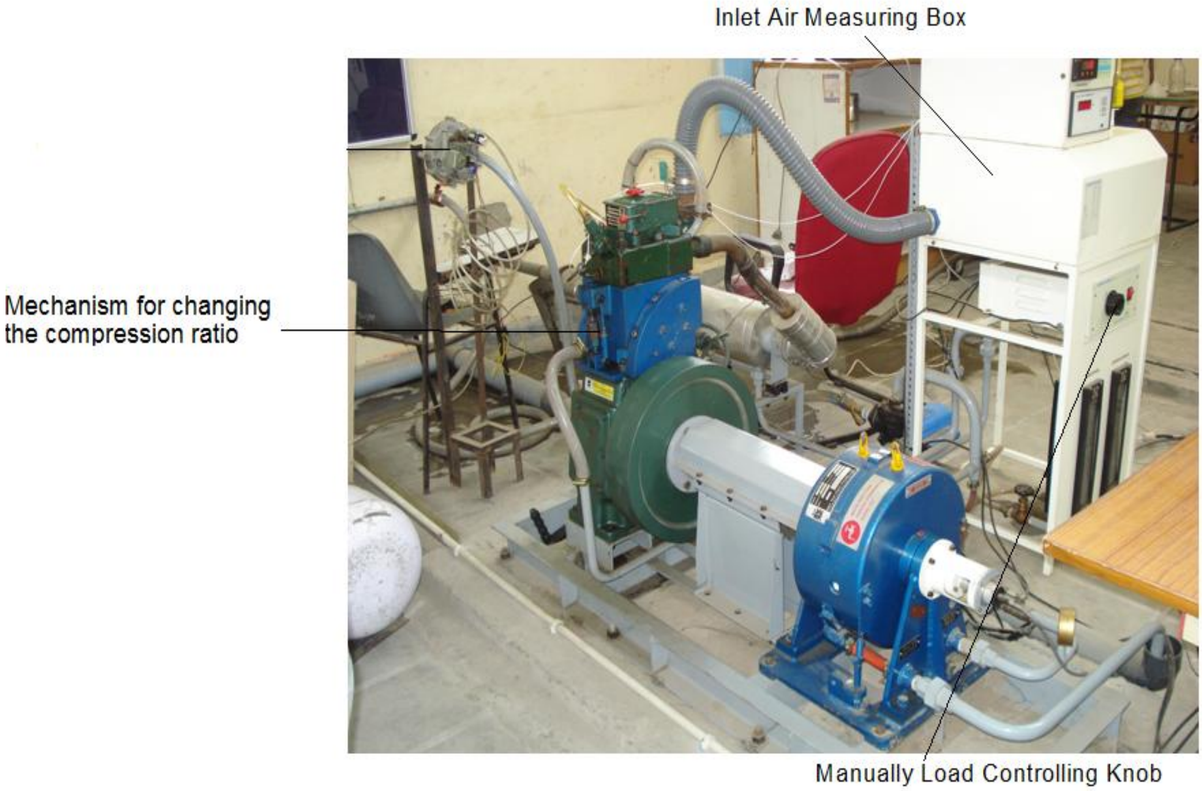


Figure 20. Experimental engine setup

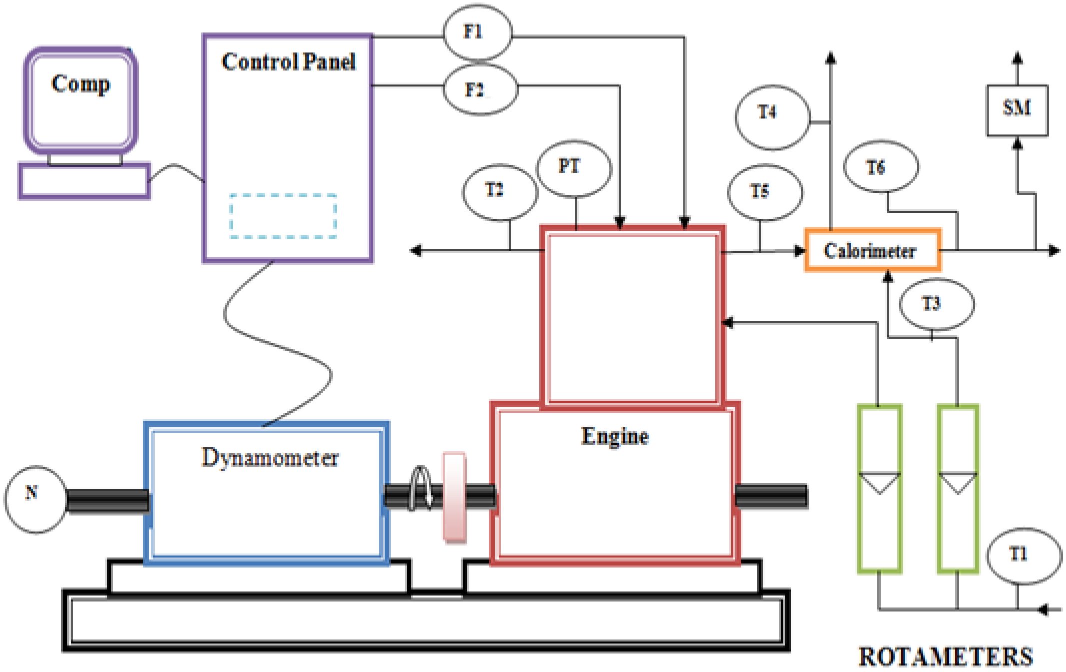


Figure21. Line diagram of experimental setup

F1	Fuel flow unit
F2	Air flow unit
F3	Engine water flow kg/hr
F4	Calorimeter water flow kg/hr
T1, T3	Inlet water temperature ^{0}K
T2	Outlet engine jacket water temperature ^{0}K
T4	Calorimeter water outlet temperature ^{0}K
T5	Exhaust gas to calorimeter inlet temp. ^{0}K
T6	Exhaust gas from calorimeter outlet temp. ^{0}K

4.3 Eddy Current Dynamometer

It consists of a stator on which are fitted a number of electromagnets and a rotor disc and coupled to the output shaft of the engine. When rotor rotates eddy currents are produced in the stator due to magnetic flux set up by the passage of field current in the electromagnets. These eddy currents oppose the rotor motion, thus loading the engine. These eddy currents are dissipated in producing heat so that this type of dynamometer needs cooling arrangement. A moment arm measures the torque. Regulating the current in electromagnets controls the load.

Table 8.Specifications of engine test setup

Product	VCR Engine test setup 1 cylinder, 4 stroke, Diesel
Engine	Make Kirloskar, Type 1 cylinder, 4 stroke Diesel, water cooled, power 3.5 kW at 1500 rpm, stroke 110 mm, bore 87.5 mm. 661 cc, CR 17.5, Modified to VCR engine CR range 12 to 18
Dynamometer	Type eddy current, water cooled
Rota meter	Engine cooling 40-400 LPH; Calorimeter 25-250 LPH
Software	“EnginesoftLV” engine performance analysis software
Smoke meter	Make AVL, for opacity measurement

4.4 Performance Evaluation

A single cylinder Diesel engine is used for the experimental analysis. Fuel was supplied to the engine from an outside tank. All runs started with a 15-min warm-up period prior to data collection. The gap of 5 minutes was provided between the two consecutive runs. The data measured during the tests included, brake power, torque, and fuel consumption, sfc, opacity. During the test brake power was varied by adjusting the brake power knob provided on the control panel of the test rig. The tests were performed with diesel fuel and blends (B-20, B-40 and B-60). The observations were taken at Brake power of 0.5kW, 1kW, 1.5kW, 2kW, 2.5kW, 3kW, 3.5Kw and 4.0kW.

- Formulation used for calculation of various parameters are described below

i. Torque (kg m) =Brake power × Arm length

ii. Brake power (kW) = (2 × π × Speed × Torque × 9.81) / (60 × 1000)

iii. Brake Thermal Efficiency (%) = $\frac{\text{Brake power (kW)}\times 3600 \times 100}{\text{Fuelflowin}\frac{\text{kg}}{\text{hr}}\times \text{calorificvalue (kJ/kg)}}$

iv. Specific fuel consumption (Kg/kWh) = $\frac{\text{Fuelflowin}\frac{\text{kg}}{\text{hr}}}{\text{Brake power (kW)}}$

v. Mechanical Efficiency (%) = $\frac{\text{Brake power (kW)}\times 100}{\text{Indicated power (kW)}}$

vi. Heat balance (kJ/h):

a) Heat supplied by fuel (kJ/h) = fuel flow (kg/h) × Calorific value (kJ/kg)

b) Heat equivalent to useful work (kJ/h) = Break power (kW) × 3600

$$\text{Heat Break power }(\%) = \frac{\text{Heat equivalent to useful work } \times 100}{\text{Heat supplied by fuel}}$$

c) Heat carried in jacket cooling water = $F_3 \times C_{pw} \times (T_2 - T_1)$

$$\text{Heat carried in jacket cooling water }(\%) = \frac{\text{Heat carried in jacket cooling water} \times 100}{\text{Heat supplied by fuel}}$$

d) Heat in Exhaust :

$$Cpex = F4 * Cpw * \frac{(T4 - T3)}{(F1 + F4)\,(T5 - T6)}$$

Where,

$C_{p}ex$ = Specific heat of exhaust gas (kJ/kg ^{0}C).

C_{pw} = Specific heat of water (kJ/kg^{0}C).

F_1 = Fuel consumption (kg/hr).

F_2 = Air consumption (kg/hr).

F_3 = Engine water flow rate (kg/hr).

F_4 = Calorimeter water flow rate (kg/hr).

T_{amb} = ambient temperature (^{0}C).

T_1 = Engine water inlet temperature (^{0}C).

T_2 = Engine water outlet temperature (^{0}C).

T_3 = Calorimeter water inlet temperature (^{0}C).

T_4 = Calorimeter water outlet temperature (^{0}C).

T_5 = Exhaust gas to calorimeter inlet temp(^{0}C).

T_6 = Exhaust gas from calorimeter outlet temp (^{0}C).

Heat in Exhaust (kJ / h) = $(F_1 + F_2) \times C_{pex}(T_3 - T_{amb})$

$$\text{Heat in Exhaust}(\%) = \frac{\text{Heat in Exhaust} \times 100}{\text{Heat supplied by fuel}}$$

e) Heat to Radiation and unaccounted (%)

= Heat Supplied By Fuel (%) - {(Heat in Jacket Cooling Water (%)
+ Heat to Exhaust (%)
+ Heat Equivalent to Useful Work (%)}

4.5 Preparation of Blends

This engine experiment has been performed with different blends of WCO biodiesel and diesel (Diesel, B-20, B-40 and B-60). These blends are prepared in quantity of one liter each by mixing required quantity of WCO biodiesel in diesel. Their description is shown in Table 9.

Calorific value of diesel = 42000 kJ/kg.

Calorific value of WCO biodiesel = 39500 kJ/kg.

Density of diesel = 830 kg/m^3.

Density of WCO biodiesel = 852 kg/m^3.

Table 9. Description of different blends of biodiesel

Type of blend	Amount of biodiesel (ml)	Amount of diesel(ml)	Resultant calorific value (kJ/kg)	Resultant density (kg/m^3)
Diesel	0	1000	42000	830
B-20	200	800	41500	835
B-40	400	600	41000	839
B-60	600	400	40500	843

4.6 Performance Data

Experimental data for performance study are given below:

4.6.1 Diesel

Engine performance parameters obtained from performance testing in single cylinder C. I. engine against different loads for diesel are given below in Table 10.

Table 10. Performance parameters for diesel

Torque (Nm)	BP (kW)	FP (kW)	IP (kW)	BThE (%)	IThE (%)	MechE (%)	Sfc (kg/kWh)	Opacity (%)
3.18	0.54	2.15	2.69	11.85	59.16	20.03	0.72	5.4
6.06	1.01	1.98	2.99	19.01	56.42	33.69	0.45	13.5
9.28	1.52	1.94	3.46	24.62	56.04	43.93	0.35	19.2
12.64	2.06	1.85	3.91	26.4	55.69	52.72	0.32	26.2
15.21	2.47	1.81	4.28	31.67	54.96	57.72	0.27	31.1
18.61	2.98	1.71	4.69	33.86	53.26	63.58	0.25	39.5
22.06	3.52	1.62	5.14	35.87	52.37	68.44	0.24	54.6
25.32	4.01	1.57	5.58	37.12	51.68	71.82	0.23	59.21

Table 11. Observation data for diesel

LOAD (kg)	CR	T1 deg C	T2 deg C	T3 deg C	T4 deg C	T5 deg C	T6 deg C
1.75	18	18.20	25.46	18.20	20.34	145.66	109.87
3.34	18	18.28	25.27	18.28	20.08	168.70	125.15
5.11	18	18.30	25.96	18.30	20.36	184.00	130.04
6.97	18	18.43	28.76	18.43	21.96	215.83	148.33
8.38	18	18.53	32.17	18.53	23.52	244.57	169.53
10.25	18	18.55	33.41	18.55	24.60	263.67	177.24
12.16	18	18.58	36.08	18.58	25.59	285.78	189.60
13.95	18	18.61	37.73	18.61	27.99	312.18	203.26

4.6.2 Biodiesel Blends

Experiments has been performed by taking waste cooking oil biodiesel (WCO-B) blends with diesel in proportion of 20%, 40% and 60% respectively as a diesel engine fuel and following parameters has been obtained**.**

Table 12. Performance parameters for WCO-B20

Torque (Nm)	BP (kW)	FP (kW)	IP (kW)	BThE (%)	IThE (%)	MechE (%)	Sfc (kg/kW h)	Opacity (%)
3.16	0.53	2.26	2.79	11.92	62.40	19.10	0.73	9
6.20	1.03	2.14	3.17	19.57	60.29	32.46	0.45	12.9
9.26	1.53	2.03	3.56	25.19	58.55	43.03	0.35	16.7
12.58	2.05	2.00	4.03	28.95	57.20	50.61	0.30	21.9
15.75	2.55	1.91	4.46	31.91	55.20	57.23	0.27	27.6
18.81	3.01	1.93	4.94	33.68	55.22	61.00	0.26	37.7
21.86	3.48	1.84	5.32	35.09	53.60	65.47	0.25	42.3
25.22	3.98	1.77	5.75	38.41	52.58	69.24	0.24	48.7

Table 13. Observation data for WCO-B20

LOAD (kg)	CR	T1 deg C	T2 deg C	T3 deg C	T4 deg C	T5 deg C	T6 deg C
1.74	18	17.33	23.24	17.33	19.06	145.75	102.4
3.42	18	17.34	23.58	17.34	19.33	162.68	111.45
5.10	18	17.36	23.95	17.36	19.78	181.9	122.83
6.93	18	17.39	24.45	17.39	20.14	205.23	136.9
8.68	18	17.4	24.81	17.4	20.75	228.27	150.84
10.36	18	17.43	25.43	17.43	21.65	255.12	169.89
12.05	18	17.46	25.83	17.46	22.13	280.45	182.52
13.90	18	17.52	26.76	17.52	23.09	308.96	200.7

Table 14. Performance parameters for WCO-B40

Torque (Nm)	BP (kW)	FP (kW)	IP (kW)	BThE (%)	IThE (%)	MechE (%)	Sfc (kg/kWh)	Opacity (%)
3.33	0.56	2.17	2.73	12.92	63.02	20.57	0.68	13.2
6.03	0.99	2.06	3.05	19.35	59.60	32.48	0.46	18.7
8.91	1.49	2.05	3.51	24.54	59.26	41.42	0.36	17.3
12.28	1.99	1.97	3.96	29.31	58.36	50.23	0.30	20.7
15.53	2.51	2.00	4.51	35.21	63.38	55.55	0.28	28.1
18.99	3.03	1.95	4.98	36.21	68.37	60.87	0.27	33.9
22.04	3.51	1.90	5.41	38.74	76.69	65.86	0.24	40.7
25.12	3.97	1.81	5.75	40.33	78.26	70.74	0.25	45.2

Table 15. Observation data for WCO-B40

LOAD (kg)	CR	T1 deg C	T2 deg C	T3 deg C	T4 deg C	T5 deg C	T6 deg C
1.84	18	17.68	23.92	17.68	19.96	149.62	108.59
3.32	18	17.67	24.08	17.67	20.09	162.56	113.09
4.91	18	17.68	24.56	17.68	20.59	182.41	123.60
6.76	18	17.69	25.23	17.69	21.42	203.68	136.72
8.56	18	17.72	25.96	17.72	22.13	226.02	149.31
10.46	18	17.76	26.38	17.76	22.54	251.75	164.58
12.12	18	17.78	27.05	17.78	23.24	276.82	179.45
13.84	18	17.8	27.35	17.8	23.73	303.26	194.12

Table 16. Performance parameters for WCO-B60

Torque (Nm)	BP (kW)	FP (kW)	IP (kW)	BThE (%)	IThE (%)	MechE (%)	Sfc (kg/kWh)	Opacity (%)
3.34	0.56	2.59	3.15	11.50	64.53	17.83	0.78	11.4
6.39	1.07	2.32	3.39	19.60	62.20	31.52	0.46	17.2
8.73	1.43	2.29	3.72	23.11	60.00	38.52	0.39	18.3
11.79	1.92	2.20	4.12	27.23	58.36	46.65	0.33	22.8
15.40	2.49	2.13	4.62	30.72	57.11	51.65	0.29	24.5
18.97	3.04	2.08	5.12	33.02	55.60	59.39	0.27	30.3
21.87	3.48	2.01	5.49	34.37	54.21	63.41	0.26	36.5
25.15	3.98	1.93	5.91	35.74	53.03	67.40	0.25	38

Table 17. Observation data for WCO-B60

LOAD (kg)	CR	T1 deg C	T2 deg C	T3 deg C	T4 deg C	T5 deg C	T6 deg C
1.84	18	17.37	23.18	17.37	18.75	150.03	105
3.52	18	17.37	23.99	17.37	19.21	165.53	112.3
4.81	18	17.38	24.33	17.38	19.58	180.48	121.64
6.50	18	17.39	24.82	17.39	19.94	200.17	132.81
8.48	18	17.4	25.52	17.4	20.42	227.08	150.33
10.46	18	17.42	26.04	17.42	20.9	254.2	166.02
12.05	18	17.44	26.63	17.44	21.32	278.38	180.33
13.86	18	17.44	27.02	17.44	22.39	308.18	197.36

5. Results and Discussions

The experimental investigations are carried out using the diesel and blends on the test engine. The detailed analyses of these results are discussed in this section.

5.1 Variation of Torque v/s Brake Power

Figure 23 shows the variation of torque with brake power for diesel and blends of waste cooking oil and diesel. Variations of torque for different blends and diesel at all values of brake powers are within a very narrow range. The torque developed for diesel (25.32 Nm) is little more than blends (25.22 Nm, 25.12 Nm and 25.15 Nm respectively for WCO-B20, WCO-B40 and WCO-B60) at 4.0 kW.

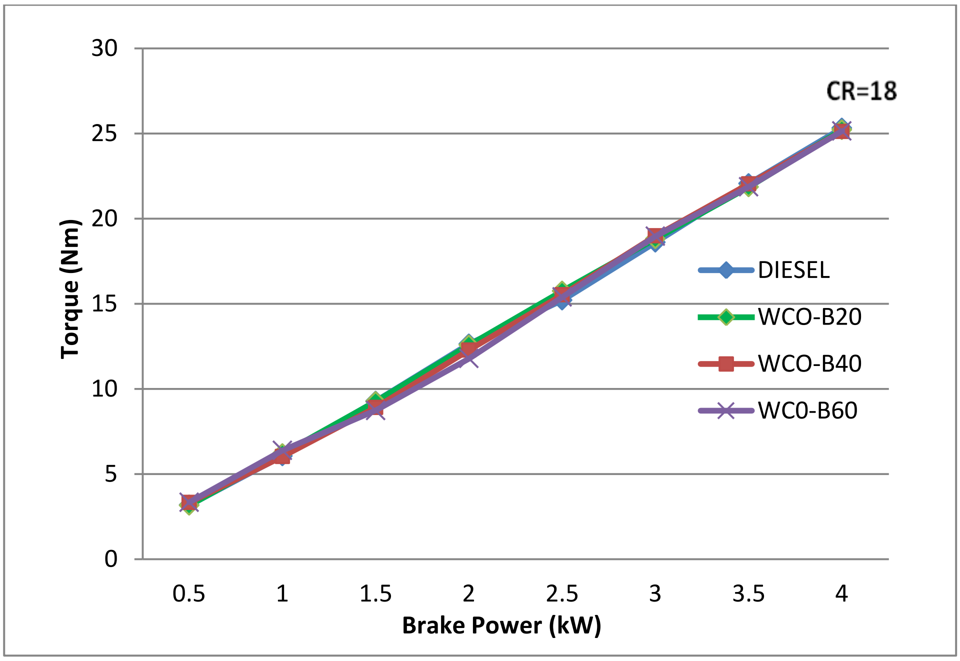


Figure 23. Comparison of torque v/s brake power

5.2 Variation of Specific Fuel Consumption v/s Brake Power

The variation of specific fuel consumption vs. brake power is shown in figure 24 for blends and diesel. For all cases the sfc initially decreases sharply with increase in brake power and afterward remains stable. In case of blends sfc values are higher at the beginning because of higher viscosity. Once the required temperature is attained inside the engine cylinder the values are comparable with diesel but little bit higher specifically for WCO-B20 and WCO-B40 as compared to diesel for a wide range of brake power as shown in figure 25.

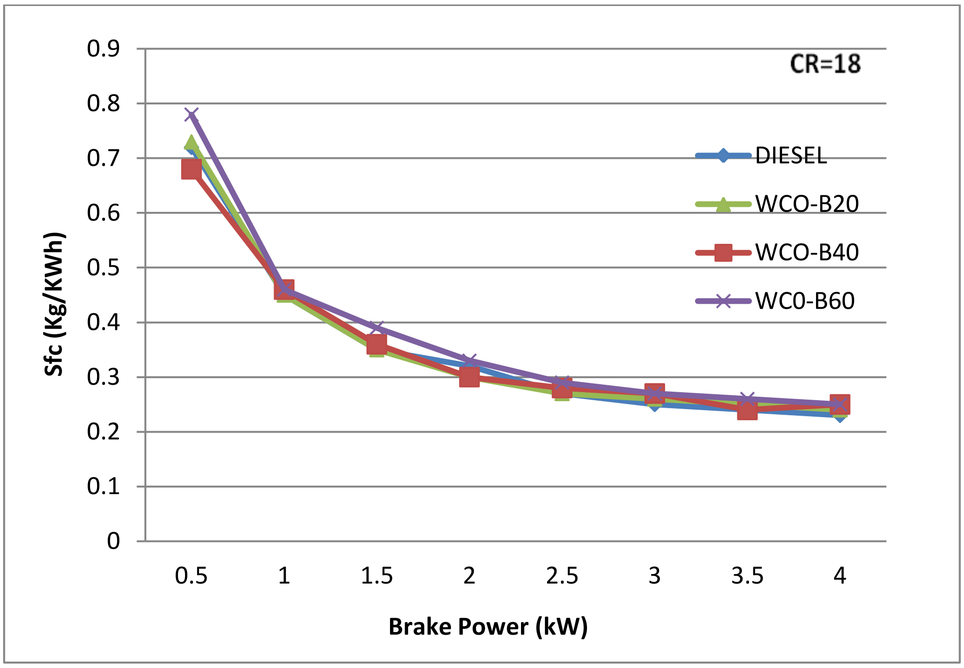


Figure 24. Comparison of specific fuel consumption v/s brake power

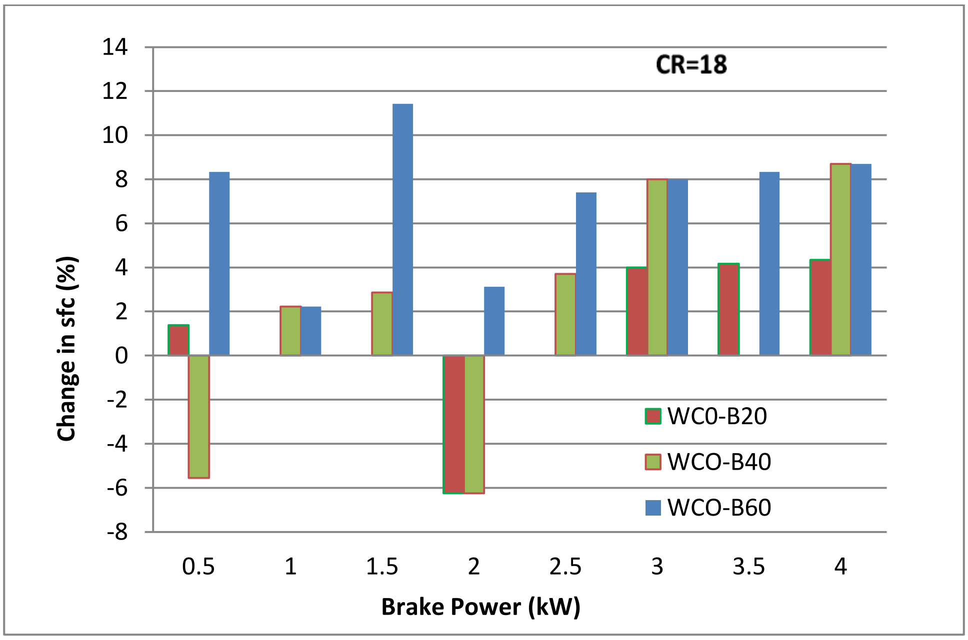


Figure 25. Percentage change of sfc of blends with respect to diesel

5.3 Variation of Brake Thermal Efficiency v/s Brake Power

Figure 26 shows comparison of Brake thermal efficiency v/s brake power for different blends in comparison to diesel. For WCO-B20 AND WCO-B40 blend brake thermal efficiency values are higher as compared to diesel at higher load. This is due to better combustion efficiency of blends caused by presence of extra amount of oxygen. The maximum thermal efficiency achieved by WCO-B40 is around 40.33 % at 4.0 kW.

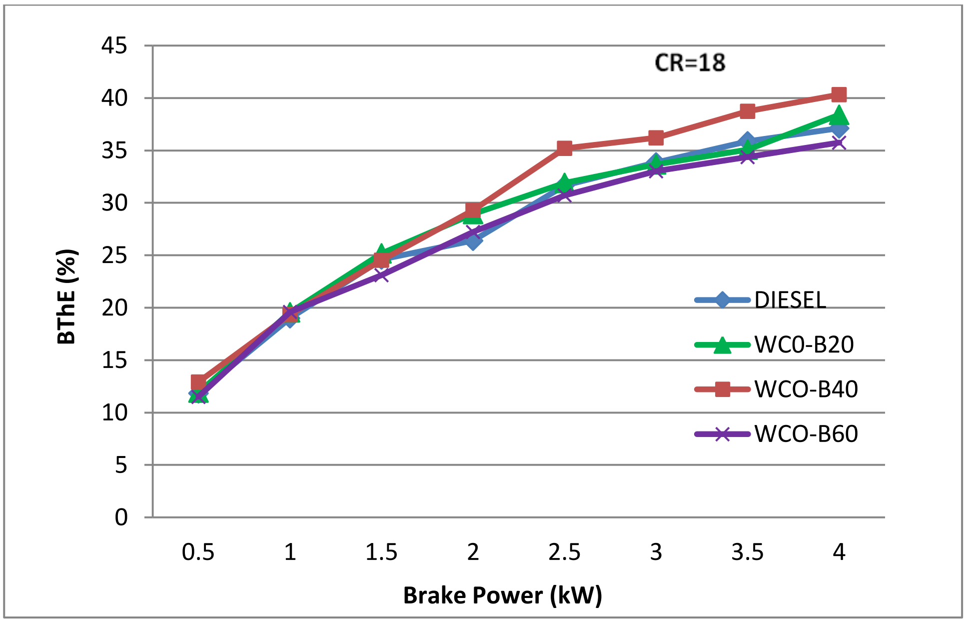


Figure 26. Comparison of brake thermal efficiency v/s brake power

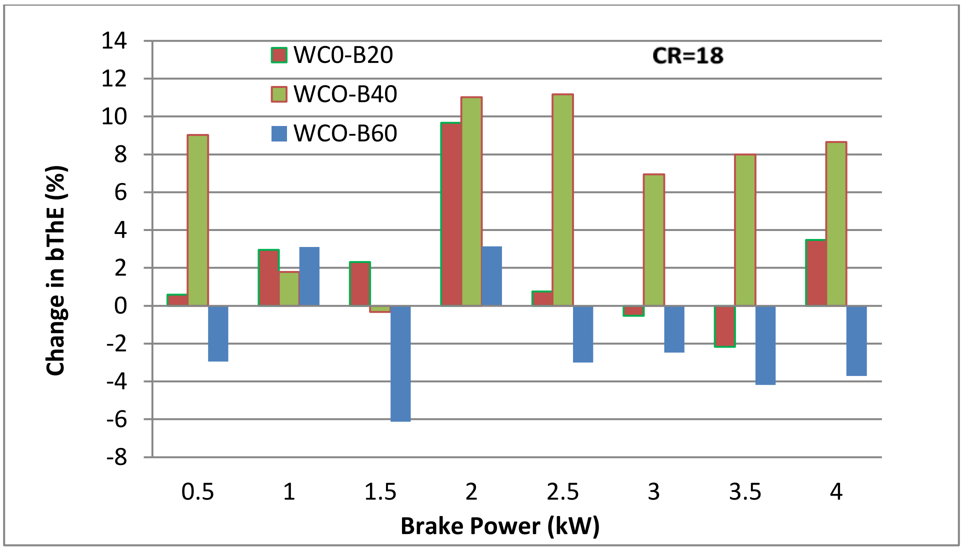


Figure 27. Percentage change of bthE of blends with respect to diesel

5.4 Variation of Smoke Opacity v/s Brake Power

To understand the pollution aspect of WCO and diesel blends the variation of opacity v/s brake power are shown in Figure 28 for blends in comparison to diesel. The opacity value for diesel is higher as compared to all type of blends for wide range of Brake power. At all brake power condition the opacity of all blends has less value than diesel except lower bp values (0.5 kW and 1kW). Maximum value of opacity has obtained at 59.21 at 4.0 kW brake power for diesel and for blends 45.7 at 4.0 kW for B-20.

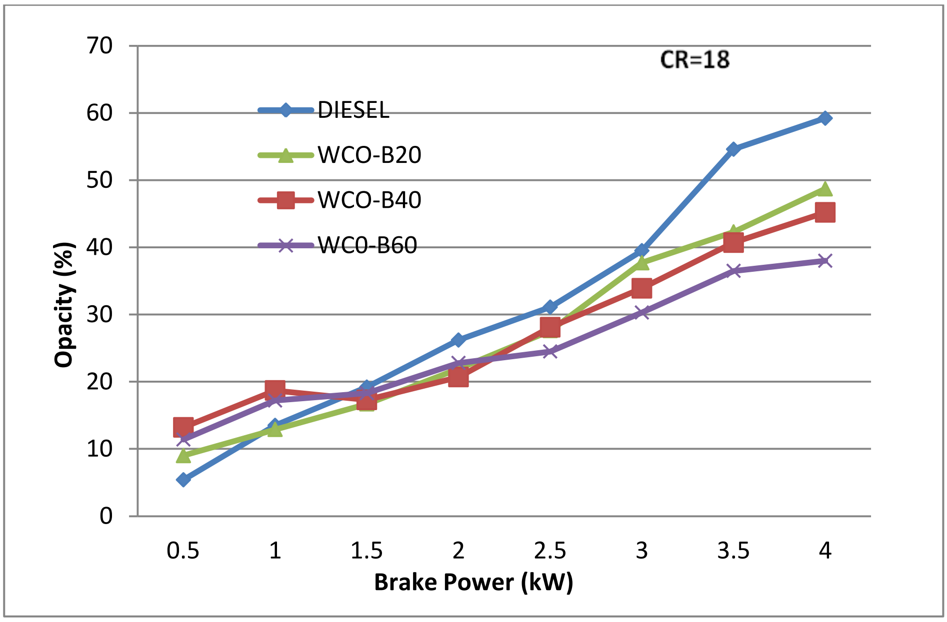


Figure 28. Comparison of smoke opacity v/s brake power

5.5 Variation of Exhaust Gas Temperature v/s Brake Power

Exhaust Temperature of the blends such as WCO-B20, WCO-B40 and WCO-B60 at various brake powers compared to diesel are shown in the Figure 29. The Ex. Temperature values are higher for blends because of better combustion efficiency. This high temperature is also indication of more NOx emission in case of blends.

5.6 Variation of CO Emission v/s Brake Power

The characteristics of CO emission are shown in figure 30, for each fuel, there is a decrease of CO emission on increase of the engine load or brake power. The peak concentrations at the 0.5 kW brake power are 0.05%, 0.04%, 0.035% and 0.034%, respectively, for diesel, WCO-B20, WCO-B40 and WCO-B60. Then higher combustion temperature at higher engine load contributes to the general decreasing trend. With the addition of biodiesel, CO emission also decreases. The reason lies in the fact that the oxygen contained in the biodiesel fuel enhances complete combustion in the cylinder and reduces CO emission.

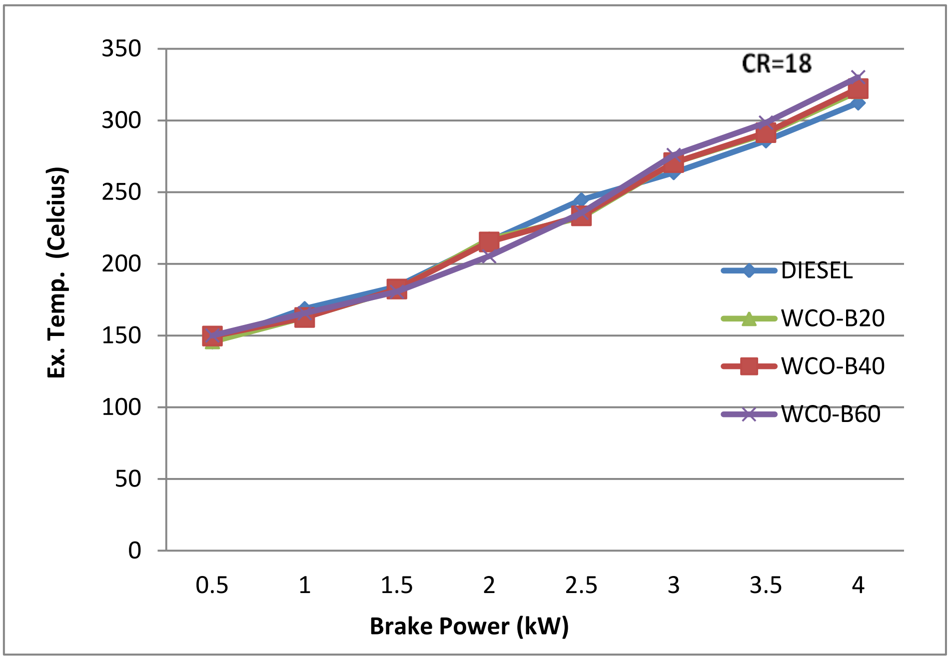


Figure 29. Comparison of exhaust gas temperature v/s brake power

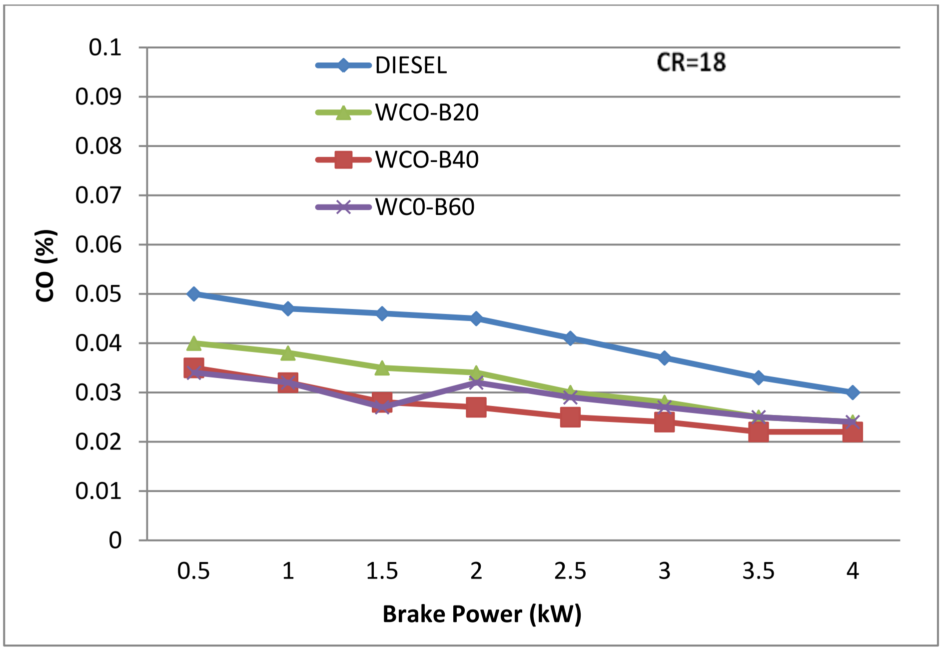


Figure 30. Comparison of CO emission v/s brake power

5.7 Variation of HC Emission v/s Brake Power

As shown in figure 31 for Diesel, the HC emission decreases with increase of brake power due to the increase in combustion temperature associated with higher engine load. For biodiesel blended fuel, the HC emission is lower than that of diesel and decreases with increase of biodiesel in the fuel. However, the lower volatility of biodiesel compared with diesel contributes to the larger difference in HC emission at low engine loads. The maximum concentrations of HC are 38 ppm, 28ppm, 26 ppm and 25 ppm, respectively, for diesel, WCO-B20, WCO-B40 and WCO-B60.

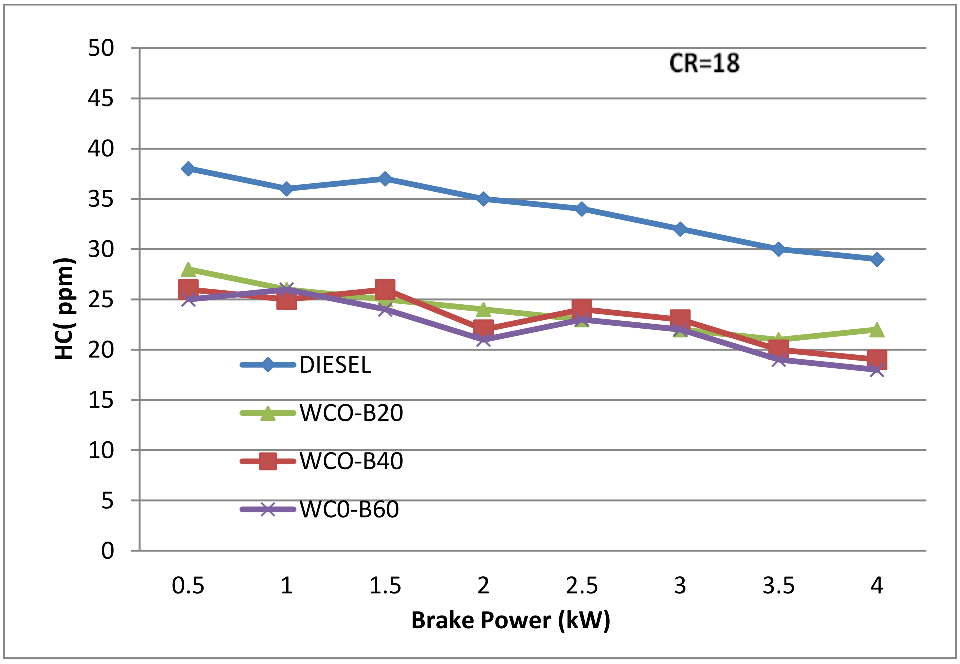


Figure 31. Comparison of HC emission v/s brake power

5.8 Variation of NO_X Emission v/s Brake Power

As shown in figure 32, NOx concentration increases with increase of bp for all the fuels. Compared with diesel, NOx emission of the biodiesel blended fuel increases slightly at all tested engine loads and the increase is more obvious at higher engine loads. WCO-B60 blend has shown lower values compared to other blends, this could be because of lower calorific value which resulted in low amount of heat release and hence less temperature. The peak concentrations at 4 kW bp are 1216 ppm, 1345, 1388 ppm and 1300 ppm respectively, for diesel, WCO-B20, WCO-B40 and WCO-B60.

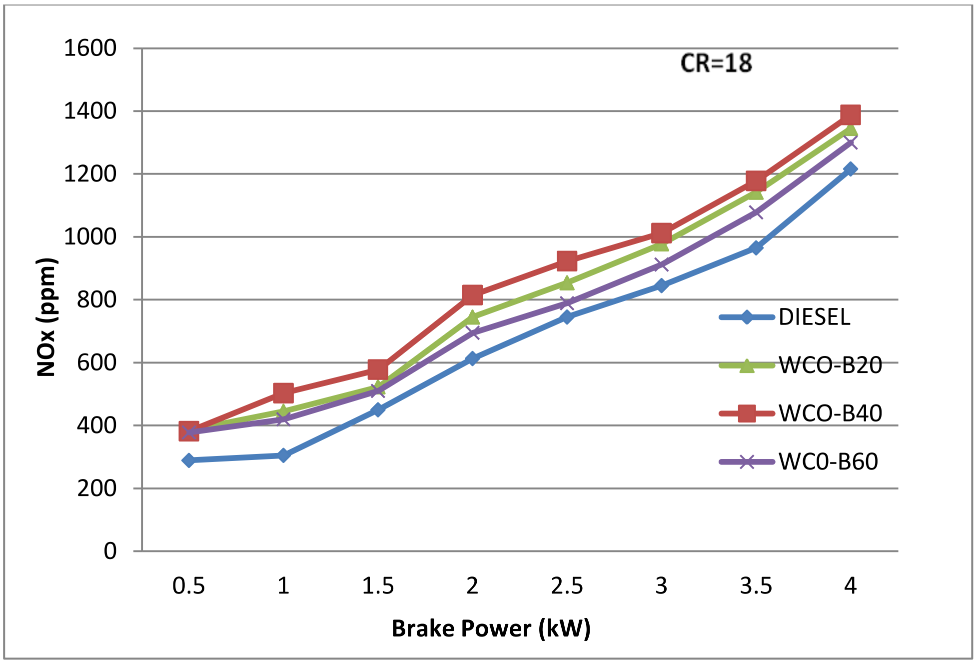


Figure 32. Comparison of NO_X emission v/s brake power

5.9 Pressure v/s Crank Angle (ϴ)

P-ϴ diagrams of WCO-B20, WCO-B40 ,WCO-B60 blends with diesel are shown in figures 33,34 and 35 .Figures show that P-ϴ curve of blends are almost resemble to the P-ϴ curve of diesel. At various crank angles, pressure observed for WCO-B20, WCO- B40, WCO-B60 and diesel are 66.71369 bar at 366^0 , 67.17946 bar at 367^0, 70.83749 bar 369^0 and 67.9974 bar at 368^0 . Blends follow the similar pattern of pressure rise to that of diesel at all brake power conditions. Because of higher ignition delay the rate of rise of pressure is more in case of diesel as compared to blends .This higher rate of rise pressure is main culprit of knocking in compression engines.

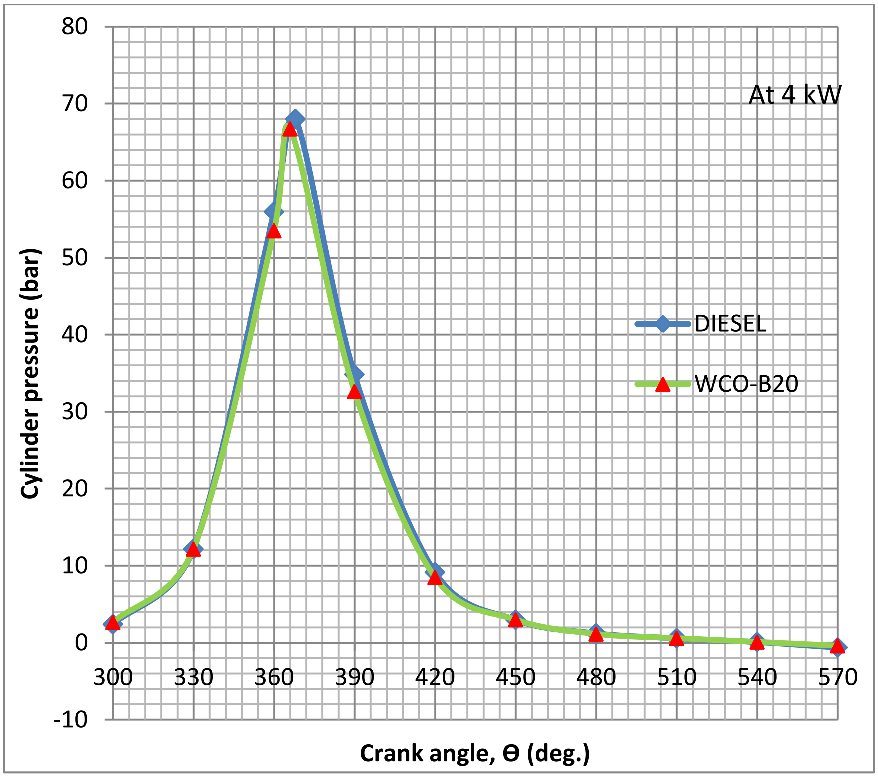


Figure 33. Comparison of Cylinder pressure Vs Crank angle for 20% biodiesel blend

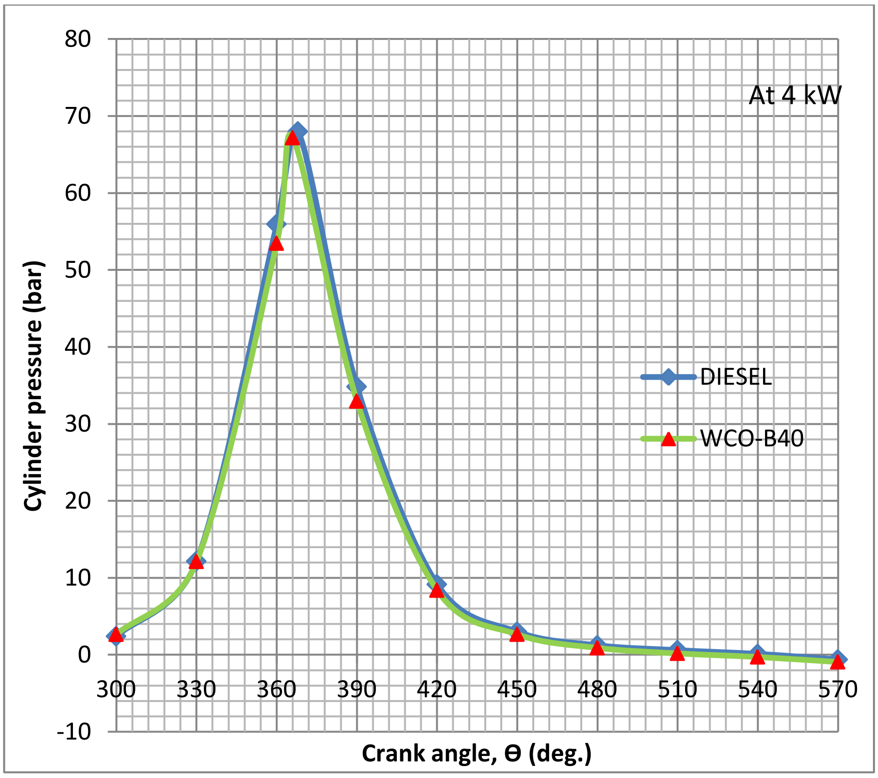


Figure 34. Comparison of Cylinder pressure Vs Crank angle for 40% biodiesel blend

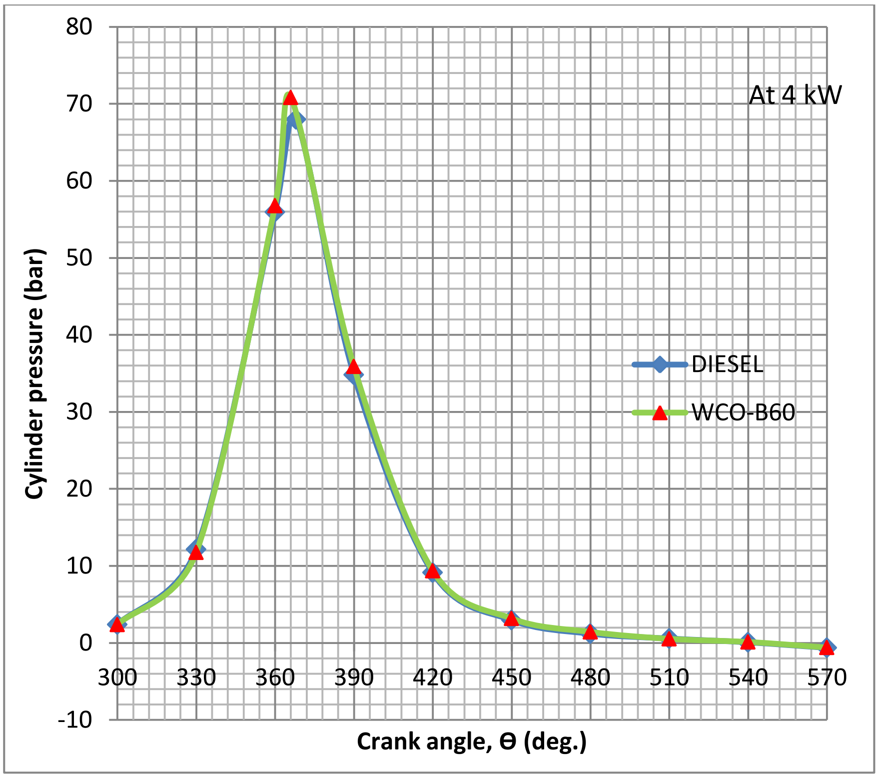


Figure 35. Comparison of Cylinder pressure Vs Crank angle for 60% biodiesel blend

6. Conclusion and Future Scope

The production and performance testing of biodiesel from low-cost waste cooking oil have been investigated. The experimental study performed in this work has demonstrated that the hydrodynamic cavitation method is more efficient than the conventional mechanical stirring method with better yield in less reaction time**.** Waste cooking oil can be a good source of biodiesel production especially in Indian condition where large amount of waste oil is produced and then dumped either into land or river causing environmental pollution. As per performance testing and emission testing performed in this work it can be seen that waste cooking oil biodiesel blends give better thermal efficiency and have got safer impact on environment as compared to diesel fuel.

Following conclusions have been made from the production experiment:

1. High rate of reaction for methyl ester formation through hydrodynamic cavitation method as compared to conventional mechanical stirring method.
2. Higher biodiesel yield is obtained using molar ratio 6:1 as compare to molar ratio 4.5:1.
3. Yield is maximum (98.12% & 92.12%) for 1% catalyst by weight of oil.
4. Yield obtained in hydrodynamic cavitation technique is 98.12 % and for mechanical stirring is 92.48% at 1% catalyst and 6:1 molar ratio.

Following conclusions have been made from the performance and emission experiments:

1. The sfc is slightly higher (average percentage variation is in the range of 4 to 8% higher) than that of diesel for WCO-B20, WCO-B40 and WCO-B60 blends. As compared to WCO-B20 the sfc values are higher for WCO-B40 and WCO-B60

3. The exhaust emissions (CO, HC) from blends are lower than diesel fuel except slight increase in NO_X .Average percentage variation of NOx for blends is in the range of 30 to 50% higher as compared to diesel. However, for WCO-B60 the NOx

values are lower as compared to WCO-B20 and WCO-B40.The reason lies in the fact that calorific value for WCO-B60 is lower which results in less temperature.

4. At all brake power conditions the opacity of all blends has less value (percentage variation is in the range of 10 to 25% lower) than diesel except lower bp values (0.5kW and 1kW). Maximum value of opacity has obtained at 59.21 at 4.0 KW Brake power for diesel and for blends 45.7 at 4.0 kW for B-20.
5. At various crank angles, pressure observed for WCO-B20, WCO- B40, WCO-B60 and diesel are 66.71369 bar at 366^0, 67.17946 bar at 367^0, 70.83749 bar 369^0 and 67.9974 bar at 368^0.

➢ Future scope

This thesis stresses the use of hydrodynamic cavitation method for biodiesel production from waste cooking oil on laboratory scale, however further prototypes need to be developed for the large scale biodiesel production through hydrodynamic cavitation method. The set up can be made capable of withstanding higher pressure conditions for better mixing and rate of conversion. Heterogeneous catalysts can also be employed in order to solve the issues related to by product disposal. The biodiesel can also be tested in variable speed vehicle engines with double fuel filters and some basic engine modifications like higher injection pressure and variable valve timing for long term uses.

References

[1] Freedman B., Butterfield R. O. and Pryde E.H., 1986, Tranesterification Kinetics of Soyabean Oil, Journal of The American Oil Chemists Society, Vol.63, No.10, 1375-1380.

[2] Lang X., Dalai A.K., Bakhashi N.N. and Reaney M.J., 2002, Preparation and Characterisation of Biodiesel from Various Bio-Oils, Bio resources Technology, Vol.80, No.1, 53-62.

[3] Canakci M. And Gerpen J. Van, 2003, A Pilot Plant to Produce Biodiesel from High Free Fatty Feed stocks, Journal of The American Society of Agricultural and Biological Engineers, Vol.46, No.4, 945-954.

[4] Kulkarni M.G. and Dalai A.K., 2006, Waste Cooking Oil-An Economical Source for Biodiesel: A Review, Industrial and Engineering Chemistry Research, Vol.45, No.9, 2901-2913.

[5] Radih A., Biodiesel Performance, Costs, and Use, 2006, Us Energy Information Administration, Http://Www.Eia.Doe.Gov/Oiaf/Analysispaper/Biodiesel/Idexhtml.

[6] Supple B., Holward-Hildige R., Gonzalez E. and Leashy J.J., 2002, The Effect of Stream Treating Waste Cooking Oil on The Yield Of Methyl Ester, Journal of The American Oil Chemists Society, Vol.79, No.2, 175-178.

[7] ElSolh Nada E.M., 2011, The Manufacture of Biodiesel from the Used Vegetable Oil-A thesis, Renewable Energy and Energy Efficiency for the Middle East North Africa Region- Cooperation between Kassel and Cairo Universities.

[8] Meher L.C., Sagar D.V. and Naik S.N., (2006), Technical Aspects of Biodiesel Production by Transesterification-A Review. Renewable & Sustainable Energy Reviews, Vol. 10, 248-268.

[9] Graboski M.S.And L.Mccormick R., 1998, “Combustion Of Fat And Vegetable Oil Derived Fuels in Diesel Engines,” Progress in Energy and Combustion Science, Vol. 24, No. 2, 125–164.

[10] Isariyakul T.,Kulkarni M.G.,Dalai A.K. and N. N. Bakhshi, 2007, Production of Biodiesel from Waste Fryer Grease Using Mixed Methanol/Ethanol System, Fuel Processing Technology, Vol. 88,No. 5, 429–436.

[11] Mittelbach M., And Gangl S., 2001,Long Storage Stability of Biodiesel Made from Rapeseed and Used Frying Oil, Journal of The American Oil Chemists’ Society, Vol. 78, No. 6,573–577.

[12] Knothe G. And Steidley K.R.,2009, A Comparison of Used Cooking Oils: A Very Heterogeneous Feedstock for Biodiesel," Bio resource Technology, Vol. 100, No. 23, ,5796–5801.

[13] Khalisanni K., Khalizani K.,Rohani M.S.and Khalid P.O.,2008, Analysis of WasteCooking Oil as Raw Material for Biofuel Production, Global Journal of Environmental Research ,Vol.2(2), 81-83.

[14] Singh S.P. and Singh Dipti, 2010, Biodiesel Production through the Use of Different Sources and Characterization of Oils and Their Esters as the Substitute of Diesel: A Review, Renewable and Sustainable Energy Reviews, Vol.14, 200–216

[15] Aradhey A., India Biofuels Annual 2012, Global Agricultural Information Network.

[16] National Policy on Biofuels, Government of India, Ministry of New and Renewable Energy, (2009).

[17] Patni Neha, 2011,Feedstocks, Production and Benefits of Using Biodiesel; Priceedings of International Conference on Renewable Energy.

[18] Nanthagopal Kasianantham and Subbarao Rayapati,2009,Experimental Investigation and Performance Evaluation of Di Diesel Engine Fuelled by Waste Oil Diesel Mixture in Emulsion With Water, Thermal Science,Vol.13(3),83-89.

[19] Patil Prafulla D., Gude Veera Gnaneswar, Reddy Harvind K., Muppaneni Tapaswy and Deng Shuguang , 2012, Biodiesel Production from Waste Cooking Oil Using Sulfuric Acid and Microwave Irradiation Processes, Journal of Environmental Protection, Vol.3, 107-113.

[20] Yoshimoto Y., 1999, Reduction of Nox, Smoke and bsfc in A Diesel Engine Fuelled by Biodiesel Emulsion With Used Frying Oil, SAE Paper No. 1999- 01-3598.

[21] Brown K.F., 2000, Opportunities for Diesel Emission Reduction Using Advanced Catalysts and Water Blend Fuel, SAE Paper No.2000-01-0182.

[22] Subramanian K.A. And Ramesh A., 2001, Experimemtal Investigation on The Use of Eater Diesel Emulsion With Oxygen Enriched Air in A Di Diesel Engine, SAE Paper No.2001-01-0205.

[23] Bertola A.,Boulouchos K. and Li R.,2003, Influence of Water Diesel Fuel Emulsions on Combustion and Exhaust Emission of Heavy Duty Di Diesel Engine Equipped With Common Rail Injection System ,SAE Paper No. 2003-01-3146.

[24] Kee S., 2003, Experimental Study on Combustion Characteristics and EmissionReduction of Emulsified Fuels in Diesel Combustion Using A Rapid Compression Machine, SAE Paper No. 2003-01-1792.

[25] Senda J., 2004, Flame Structure and Combustion Characteristics in Diesel Combustion Fuelled With Biodiesel, SAE Paper No.2004-01-0084.

[26] Rosca R., 2005, Fuel and Injection Characteristics for A Biodiesel Type Fuel from Waste Cooking Oil, SAE Paper 2005-01-3674.

[27]. Refaat A.A., Sheltawy S.T. And Sadek K.U., 2008, Optimum Reaction Time, Performance and Exhaust Emissions of Biodiesel Produced by Microwave Irradiation, Int. J. Environ. Sci. Tech., Vol.5 (3), 315-322

[28] Karunanithi B.K.,Bogeshwaran K. And Tripuraneni Manasa, 2012, Bio Diesel from Waste Vegetable Oil,International Journal of Modern Engineering Research ,Vol.2(5),3857-3860

[29] Arslan Ridvan ,2011,Emission Characteristics of A Diesel Engine Using Waste Cooking Oil as Biodiesel Fuel, African Journal of Biotechnology Vol.10(19),3790-9794.

[30] Khalisanni K.,Khalizani K.,Rohani M.S. And Khalid P.O.,2008,Analysis of Waste Cooking Oil as A Raw Material for Biofuels Production ,Global Journal of Environment Research ,Vol.2(2),81-83.

[31] Fan Xiaohu and Burton Rachel, 2009, Recent Development of Biodiesel Feedstocks and the Applications of Glycerol: A Review, the Open Fuels & Energy Science Journal, Vol.2 (2)100-109.

[32] Cho Haeng Muk , Maji S. and Pathak B.D.,2008, Waste Cooking Oil as Fuel in Diesel Engines, SAE Paper No.2008-28-0013

[33] Singh Pranil J., Khurma Jagjit and Singh Anirudh, 2010, Preparation, Characterisation, Engine Performance and Emission Characteristics of Coconut Oil Based Hybrid Fuels, Renewable Energy, Vol.35, 2065-2070.

[34] Buasri Achanai,Chaiyut Nattawut and Phongprasit Kowit,2008, Production of Biodiesel from Waste Cooking Oil Using Mixed Alcohol System. Kmitl Science Journal, Vol. 8, No. 2, 59-63.

[35] Calais Phillip and Clark A.R., Waste Vegetable Oil as A Diesel Replacement Fuel, Annual Meeting at Western Australian Renewable Fuels Association.

[36] Çetinkaya M., Ulusoy Y., Tekìn Y. and Karaosmanoglu F.,2005, Engine and Winter Road Test Performances of Used Cooking Oil Originated Biodiesel, Energy Convers. Manage, Vol.46, 1279-1291.

[37] Liny .F. Wu Y.P.G.and Chang C.T., 2007, Combustion Characteristics of Waste-Oil Produced Biodiesel/Diesel Fuel Blends. Fuel, Vol. 86, 1772-1780.

[38] Wang Y., Ou S.Y., Liu P.Z., Xue F. and Tang S. Comparison of Two Different Processes to Synthesize Biodiesel By Waste Cooking Oil. J. Mol. Catal. A-Chem., Vol.252, 107-112.

[39] Issariyakul T.,Kulkarni M.G. Dalai A.K. and Bakhshi N.N. ,2007,Production of Biodiesel from Waste Fryer Grease Using Mixed Methanol/Ethanol System. Fuel Process Technology, Vol.88, 429-436.

[40] Chen G.,Ying M. and Li W.Z.,2006, Enzymatic Conversion of Waste Cooking Oils Into Alternative Fuel-Biodiesel. Appl. Biochem., Biotech. 129-132, 911-921.

[41] De B.K. Chatterjee T. and Bhattacharyya D.K.,1999,Synthesis of Geranyl and Citronellyl Esters of Coconut Oil Fatty Acids Through Alcoholysis by Rhizomucor Miehei Lipase Catalysis ,Jaocs,Paper No. J9068, 76, 1501-1504.

[42] Mei D., Yuan Y., Wang Z. and Zhang T., 2008, Combustion and Emissions of the Diesel Engine Using Bio-Diesel. Fuel Front. Mech. Eng. Vol.3 (2), 189–192.

[43] Ozkan M., Ergenc A.T.and Deniz O.,2005, Experimental Performance Analysis of Biodiesel, Traditional Diesel And Biodiesel With Glycerine, Turkish J. Eng. Env. Sci., Vol.29, 89 -94.

[44] Pathak B.S., Singh R.N. and Singh S.P., 2007,Performance of Renewable Fuel Based C I Engine, Agricultural Engineering International, The CIGR E journal, Manuscript EE 0014 (9).

[45] Sharma D, Soni S.L., Pathak S.C., and Gupta R.,2005, Performance and Emission Characteristics of Direct Injection Diesel Engine using Neem-Diesel Blends,The Journal of Institution of Engineers (India) Vol.86, 77-83.

[46] Pereira R.G., Oliveira C.D., Oliveira J.L., Oliveira P.C.P., Fellows C.E. and Piamba O.E.,2007, Exhaust Emissions and Electric Energy Generation in A Stationary Engine Using Blends of Diesel and Soybean Biodiesel, Renewable Energy, Vol.32(14) 2453-2460.

[47] Bruwer J. J., Boshoff B.D., Hugo F.J.C., Du Plessis L.M.,Fuls J., Hawkins C., Vanderwalt A.N. and Engelbert A., 1981, The Utilization of Sunflower Seed Oil As Renewable Fuel Diesel Engines, SAE Publication Vol. 2, 4-81.

[48] Auld D. L., Betti B.L.S and Peterson C.L.,1982, Production and Fuel Characteristics of Vegetable Oilseed Crops in The Pacific Northwest Vegetable Oil Fuels, Agronomy Journal, Vol. 74(2),335-339

[49] Bacon D. M., Brear F., Moncrieff I.D. and Walker K.L., 1981, The Use Of Vegetable Oils In Straight and Modified Form As Diesel Engine Fuels, Beyond The Energy Crisis -- Opportunity and Challenge, Third International Conference On Energy Use Management. Vol.3, 1525-1533.

[50] Pryde E. H., 1982, Vegetable Oil Fuel Standards, The International Conference on Plant and Vegetable Oils Fuels(USA), CONF-820860, 101-105.

[51] Wagner G. L. and Peterson C.L., 1982, Performance of Winter Rape (Brassica Napus) Based Fuel Mixtures In Diesel Engines. The International Conference on Plant and Vegetable Oils Fuels, ISBN: 0916150461, 329-336.

[52] Sapaun S. M., Masjuki H.H. and Azlan A., 1996. The Use of Palm Oil as Diesel Fuel Substitute, Journal of Power and Energy (Part A), 210, 47-53.

[53] Ryan T. W., Dodge L.G. and Callahan T.J., 1984. The Effects of Vegetable Oil Properties on Injection and Combustion in Two Different Diesel Engines. J. Am. Oil Chem. Soc., Vol.61 (10), 1610-1619.

[54] Mcdonnel K. P., Ward S.M., Mc Nully P.B. and Howard R., 2000.Results Of Engine and Vehicle Testing of Semi-Refined Rapeseed Oil. SAE,Vol. 43(6), 1309-1316.

[55] Schoedder C., 1981, Rapeseed Oil as an Alternative Fuel for Agriculture, Beyond the Energy Crisis -- Opportunity And Challenge Third International Conference on Energy Use Management, Vol.3, 1815-1822.

[56] Tahir A. R., Lapp H.M. and Buchanan L.C., 1982. Sunflower Oil as a Fuel For Compression Ignition Engines, The International conference on Plant and Vegetable Oils Fuels, American Society of Agricultural Engineers, Record No.19842420207,82-91

[57] Yarbrough C. M., Lepori W.A., and Engler C.R., 1981, Compression Ignition Performance Using Sunflower Seed Oil. Sae Paper Number 81-3576.

[58] Engler C. R., Johnson L.A., Lepori W.A. and Yarbough C.M., 1983. Effects of Processing and Chemical Characteristics of Plant Oils on Performance of an Indirect injection Diesel Engine. J. Am. Oil Chem. Soc., Vol. 60(8), 1592-1596.

[59] Goering C. E., Schwab A.W., Daugherty M.J., Pryde E.H. and Heakin A.J., 1981. Fuel Properties of Eleven Vegetable Oils, ASAE Paper No. 81-3579.

[60] Pryor R. W., Hanna M.A., Schinstock J.L. and Bashford L.L .,1983, Soybean Oil Fuel in a Small Diesel Engine. ASAE Paper, Vol.26 (2), 333-337.

[61] Rao G.L.N., Sampath S. and Rajagopal K.,2008, Experimental Studies on The Combustion and Emission Characteristics of A Diesel Engine Fuelled With Used Cooking Oil Methyl Ester Its Diesel Blends, International Journal Of Applied Science, Engineering And Technology ,Vol.4(2),64-70.