PERFORMANCE AND EMISSION CHARACTERISTICS OF VATERIA INDICA OIL AS ALTERNATIVE FUEL FOR PETRODIESEL IN CI ENGINE

PhD Thesis

Submitted in Partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

By

Gangadhara Rao

(ME11P07)

DEPARTMENT OF MECHANICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA

SURATHKAL, MANGALORE - 575025

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May, 2019

DECLARATION

I hereby declare that the Research Thesis titled **"PERFORMANCE AND EMISSION CHARACTERISTICS OF VATERIA INDICA OIL AS ALTERNATIVE FUEL FOR PETRODIESEL IN CI ENGINE"** which is being submitted to the National Institute of Technology Karnataka, Surathkal in partial fulfillment of the requirements for the award of the Degree of Doctor of Philosophy In Mechanical Engineering is a *bonafide report of the research work carried out by me*. The material contained in this Research Thesis has not been submitted to any other Universities or Institutes for the award of any degree.

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NOMENCLATURE

BTE	:	Brake Thermal Efficiency
BSEC	:	Brake Specific Energy Consumption
bTDC	:	Before Top Dead Center
CAD	:	Crank Angle Degrees
FIP	:	Fuel Injection Pressure
IP	:	Injection Pressure
IT	:	Injection Timing
VIME	:	*Vateria Indica* Methyle Ester
FFA	:	Free Fatty Aci ds
EGR	:	Exhaust Gas Recirculation
FAME	:	Fatty Acid Methyle Ester
JOME	:	Jatropha Oil Methyle Ester
KOME	:	Karanja Oil Methyle Ester
RBOME	:	Rice Bran Oil Methyle Ester
WCOME	:	Waste Cooking Oil Methyle Ester
WVO	:	Waste Vegetable Oil
EPA	:	European Panel for Alternative fuel
US	:	Ultra Sound
DICI	:	Direct Injection Compression Ignition
EDS	:	Energy Dispersive Spectroscopy
PFAD	:	Palm Fatty Acid Distillate
CSOME	:	Cotton Seed Oil Methyle Ester
NKOME	:	Neem Kernel Oil Methyle Ester

LHR	:	Low Heat Rejection
WEO	:	Waste Edible Oil
PM	:	Particulate Matter
POME	:	Pongamia Oil Methyle Ester
COME	:	Canola Oil Methyle Ester
CR	:	Compression Ratio
TRRC	:	Toroidal Re-entrant Combustion Chamber
HnOME	:	Honne Oil Methyle Ester
HOME	:	Honge Oil Methyl Ester

ABSTRACT

Vateria Indica Linn seeds contain nearly 19% oil/fat which can be converted into biodiesel by normal method of esterification followed by transesterification generally adopted for high FFA oils. Biodiesel is a promising alternative fuel for CI engines. In the present work, study of the combustion, performance and emission characteristics of a CI engine fuelled with *Vateria Indica* biodiesel blends at 180 bar, 200 bar and 220 bar injection pressures (IP) and injection timings at 19^{o}bTDC, 23^{o}bTDC and 27^{o}bTDC (before TDC) is carried out. Blending is done in volumetric ratios of 10%, 15%, 20%, 25% of biodiesel with diesel which are called as B10, B15, B20, B25. Increasing fuel injection pressure promotes atomization, and full penetration into the combustion chamber leading to better combustion. Blend B25 showed better thermal efficiency of the order of 33.03% and minimum NO_X emission of 1047ppm at 220 bar injection pressure and 75% Load. Advancing the injection is proved to be advantageous because of longer residence time and complete combustion with thermal efficiency of the order of 37%, but it also causes higher NO_X and soot emissions. Blend is restricted to 25% due to low cetane number of biodiesel which causes severe knocking problem at higher blends. Due to high NO_X emission with the blend (B25), NO_X mitigation technique like hot EGR is adopted to the extents of 5% and 10%.Finally, it is concluded that blending up to25% can be adopted with 10% EGR at 220 bar injection pressure with 27^{o}bTDCinjection timing for better performance, combustion and emission characteristics

Chapter 1

INTRODUCTION

1.1 PREAMBLE

Majority of world's energy needs are supplied through Petrochemical sources, coal and natural gasses, hydroelectricity and nuclear energy. All these sources are definite and at the current rate of usage will be consumed shortly. Diesel fuel have an essential function in the industrial economy of a developing country and are used in the different sector such as transport, industries and agriculture etc. Economic survey of India-2011-2012 states that compared to rest of the world, the demand for diesel fuel in India in the years 1994 &1995 was 28.36 million tones and 40.34 million tones respectively. In the year 2000-01 the consumption of diesel was as 43.2% of total consumption of petroleum products. Economic growth leads to commensurate increase in transport. Besides these, the atmospheric pollution due to diesel fuel consumption is also of paramount importance.

Most of vegetable oils are edible in nature & continuous use of them causes shortage of food supply and proves far expensive to be used as fuel for alternative to fossil fuel. Due to this non-edible vegetable oils have been experimented on diesel engine leading to lot of scope in this area.

According to recent survey on the world energy consumption a major portion of the total energy consumed is derived from the combustion of fossil fuels. Because of their inherent physicochemical and combustion properties liquid fuels contribute maximum energy consumption. The world growth of petroleum fuels is shown in Fig 1.1.(UNO Energy action plan report). If the reserves of fossil fuels especially liquid fuels are not utilized economically, they may get exhausted within few decades. Throughout the world attention is focussed to reduce the consumption of liquid petroleum fuels wherever is possible. There are two methods that can be adopted. First is to use the energy consumption devices based on alternative energy source which are either

abundant or are reproducible. The second is to enhance the efficiency of combustion devices. This is usually achieved by understanding the physico chemical processes involved during the combustion.

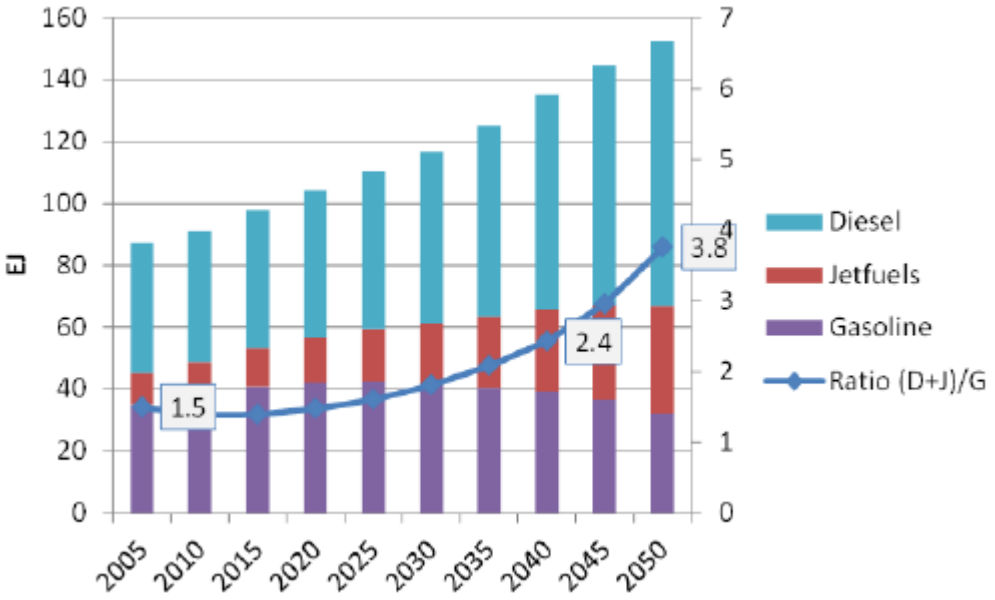

Fig 1.1 Growth of World demand for petroleum derived fuels between 2006-2020

In India, there has been a considerable increase in the number of automobiles in last two decades Currently, the motor vehicle population in India is about 83 million. The transport sector plays a important role in the economic development of any country. But it also brings an unavoidable specter of environmental pollution along with it. This is specially a major problem for a developing country like India.

The hydrocarbon vision- 2025 document projects that in India the present gap between domestic demand and availability of oil from indigenous sources is expected to increase. Since India depends on import of oil, security considerations assume greater significance. Therefore, a sound auto fuel policy to be framed by the government which takes into account all dimensions of the global, regional and domestic fuel supply. India is a diesel based economy. Diesel consumption is around five times the consumption of petrol on account of large scale use of trucks for goods transportation, use of buses, use in agricultural machinery like tractor, water pumps , use of diesel generator sets, industrial use of diesel etc.

Air pollution caused by the combustion of petro diesel is a growing concern. Its increase in its price due to depleting resources is another concern.

According to Mustafa Balat et al (2008) the idea of using vegetable oil as alternative fuel for diesel engines is not a new one. Rudolph Diesel presented his engine using peanut oil as fuel at Paris Exposition of 1900. Use of vegetable oil as fuel was not accepted, as it was more expensive than petroleum fuels. Later various factors as stated earlier, renewed the interests of researchers in using vegetable oil as substitute fuel for diesel engines. Various vegetable oils like Sunflower, Peanut, Soya bean, Rapeseed, Olive, Cottonseed, Jatropha, Pongamia, Rubber seed, Jojoba etc. are tried in recent years as alternative fuels for diesel. Although there has been many problems associated with direct use of vegetable oils they occupy a prominent position in the development of alternative fuels according to Babu A.K et al,(2003) and Wang Y D et al, (2006). According to these authors the problems in using these oils directly in diesel engines are

- Due to high viscosity of vegetable oils injection process becomes poor and atomization becomes poor.
- In efficient mixture preparation of oil with air contributes to incomplete combustion, leading to high smoke emission.
- High flash point results to lower volatility characteristics
- Lube oil gets diluted
- Carbon deposits occur on piston and cylinder walls
- Piston Ring stuck on cylinder wall
- Scuffing of engine liner
- Failure of Injection Nozzle
- Different types and grades of oil perform differently according to local climate conditions
- Both cloud and pour points are significantly higher than that of diesel fuel. These high values may cause problems during cold weather.

These problems are due to large triglyceride molecule and its higher mass which can be solved by chemically modifying vegetable oil (Senthil kumar et al, 2001) Biodiesel thus obtained has characteristics similar to diesel.

Biodiesel has a proven performance for air pollution reduction. Biodiesel is generally produced through the reaction between vegetable oils or animal fat with methanol or ethanol in the presence of catalyst. Glycerol is the by-product of this reaction. Biodiesel is methyl or ethyl ester of prominent fatty acids present in the vegetable oil or animal fat. Biodiesel can be used as direct substitute or extender or as an additive to fossil diesel fuel in compression ignition engine Biodiesel can be used in existing design of diesel with no or little modification. However, the price of biodiesel is presently more as compared to petro diesel. Higher cost of biodiesel is primarily due to the raw material cost.

1.2. VEGETABLE OILS AS FUELS

The vegetable oils, have the chemical structure given in Fig. 1.2 consist of 98% triglycerides and small amounts of mono- and diglycerides (Mustafa balat et al, 2008) Triglycerides are esters of three fatty acids and one glycerol. Triglycerides contain substantial amounts of oxygen in its structure. The fatty acids in vegetable oils vary in their carbon chain length and in the number of double bonds. Different types of vegetable oils have different types of fatty acids. Table 1.1 from A Murugesan et al, 2009 shows the empirical formulae and structure of various fatty acids present in vegetable oils.

The fatty acids in a vegetable oils are in two forms namely free form and as tryglycerides of fatty acids. The major disadvantage of vegetable oils are higher viscosity, along with lower volatility and the reactivity of unsaturated hydrocarbon chains. Vegetable oils have their own advantages viz, they are available everywhere in the world. they are renewable as the vegetables which produce oil seeds can be planted year after year and they are ‘‘greener” to the environment, as they seldom contain sulfur element in them.

Table 1.1: Chemical structure of common fatty acids(Murugesan et al,2009)

Name of Fatty acid	Chemical name of fatty acid	Structure (xx:y)	Formula
Lauric	Dodecanoic	12:0	$C_{12}H_{24}O_2$
Myristic	Tetradecanoic	14:0	$C_{14}H_{28}O_2$
Palmitic	Hexadecanoic	16:0	$C_{16}H_{32}O_2$
Stearic	Octadecanoic	18:0	$C_{18}H_{36}O_2$
Arachidic	Eicosanoic	20:0	$C_{20}H_{40}O_2$
Behenic	Docosanoic	22:0	$C_{22}H_{44}O_2$
Lignoceric	Tetracosanoic	24:0	$C_{24}H_{48}O_2$
Oleic	Cis-9-octadecenoic	18:1	$C_{18}H_{34}O_2$
linoleic	Cis-9,cis-12-Octadecadienoic	18:2	$C_{18}H_{32}O_2$
linolenic	Cis-9,cis-12,cis-15-Octadecatrienoic	18:3	$C_{18}H_{30}O_2$
erucle	Cis-13-Docosenoic	22:1	$C_{32}H_{42}O_2$

1.3 BIODIESEL PRODUCTION

According to Freedman et al, (1986) & Noureddini et al, (1997) biodiesel is produced via the transesterification of the vegetable oil or animal fat feedstock. There are several types of transesterification processes including common batch process, supercritical processes, ultrasonic methods, and even microwave methods., Transesterified biodiesel consists of a mixture of mono-alkyl esters of long chain fatty acids. The most common form of transesterification reaction uses methanol (converted to sodium methoxide) to produce methyl esters (commonly referred to as Fatty Acid Methyl Ester - FAME) or to produce ethyl ester (commonly referred to as Fatty Acid Ethyl Ester - FAEE) by using ethanol. Higher alcohols such as isopropanol and butanol have also been used. Using alcohols of higher molecular weights improves the cold flow properties of the resulting ester, at the cost of a less efficient transesterification reaction.

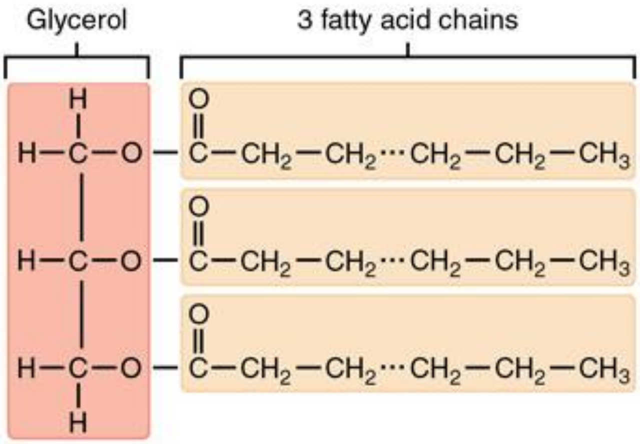

Fig 1.2 Structure of a typical triglyceride molecule

Transesterification is represented as

$R\,COOR^{I} + R^{II}OH \leftrightharpoons R^{I}COOR^{II} + ROH$ ……………………………………(1.1)

Higher alkyl ester + alcohol ⇆ lower alkyl ester + Glycerol

If methanol is used in the process then it is called Methanolysis. Methanolysis of triglycenide is represented as

$CH_2 - COOR^1$ $\qquad$ H_2OH $\qquad$ $R^1\,COOCH_3$

$CH - COOR^2 + 3CH_3OH \leftrightharpoons CHOH + R^2\,COOCH_3$ ………………..(1.2)

$CH_2 - COOR^3$ $\qquad$ CH_2OH $\qquad$ $R^3\,COOCH_3$

Vegetable Oil + Alcohol = Glycerol + methyl ester

The overall transeterification is given by Equation (1.2). However three consecutive and reversible reactions believed to occur. These reactions are represented by Eqn (1.3)

Triglycerides + ROH⇆Diglycerides + R^1COOR

Diglycerides + ROH⇆Monoglycerides + R^2COOR ……………………..(1.3)

Monoglyceries + ROH⇆Glycerol + R^3COOR

Presence of Catalyst (Strong acid or base) Accelerates the conversion (Murugesan, A. et al.,2009)

The base oil is converted to desired ester by lipid transesterification. The free fatty acid in the oil should be either removed or esterifiesd in the presence of acidic catalyst, otherwise it would impair the methanolysis by soap formation. After this processing, the resulting biodiesel unlike straight vegetable oil, has combustion properties very similar to those of petroleum diesel, and can replace it in most current uses.

The methanol used in most biodiesel production processes is originated from fossil fuel inputs. However, methanol is produced by using carbon dioxide or biomass as feedstock, making it free of fossil fuels. Glycerol is the by-product of transesterification process. 100kg of glycerol is produced while 1 tonne of biodiesel is produced Earlier this glycerol had very good market as cleansing agent. This sustained the biodiesel production process. However, with the increase in global biodiesel production globally, the market price for this crude glycerol (containing 20% water and catalyst residues) has crashed. Alternatively research is being conducted globally to use this glycerol as a chemical building block.

The crude glycerol obtained along with biodiesel, has to be purified, typically by performing vacuum distillation. This is rather energy intensive. Then refined glycerol (98%+ purity) can be utilised directly, or converted into other products.

1.4 QUANTITY OF BIODIESEL PRODUCTION

According to Altenesol Energy solutions consultancy report 2007, biodiesel production capacity of the world was growing rapidly, particularly over 40% from 2002-06. For the year 2006, total world biodiesel production was about 5-6 million tonnes, out of which 4.9 million tonnes processed in Europe (of which 2.7 million tonnes was from Germany) and most of the rest processed in USA. In 2008, European production of biodiesel alone had risen to 7.8 million tonnes. To balance the competition from, especially German producers, a duty was added to American imported biodiesel in European union in July 2009. Biodiesel capacity for 2008 in

Europe totalled 16 million tonnes. This can be compared with a total demand for diesel in the US and Europe of approximately 490 million tonnes (147 billion gallons). For 2005/6 the total world production of vegetable oil for all purposes in was about 110 million tonnes, out of which about 34 million tonnes each of soyabeen oil and palm oil.

US biodiesel production in 2011 brought the industry to a new milestone. Targets have been set, under EPA Renewable Fuel Standard for the biodiesel production plants in order to monitor and document production levels in comparison to total demand. Biodiesel production in 2011 reached more than 1 billion gallons according to the year end data released by EPA. This has far exceeded the 800 million gallon target set by the EPA. EPA has projected biodiesel production for 2020 to be nearly 12 billion gallons.

1.5 SOURCES OF BIODIESEL

Various feed stocks for biodiesel production are evaluated by Xiaohu Fan et al, (2009). Biodiesel can be produced from variety of oils. These include:

- Vegetable oils like Jatropha, Pongamia, Simarouba, rapeseed, soyabean, cotton seed, palm oil.
- Waste cooking oil (WCO)
- Animal fats like tallow, lard, chicken fat, and the by-products obtained in the production of Omega-3 fatty acids from fish oil.
- Algae, which can be grown using waste water of sewage without displacing land currently used for food production.
- Oil from halophytes such as Salicorniabigelovii, which are grown in saltwater in coastal areas where conventional crops cannot be grown. It is found that yields are nearly equal to the crops such as soybean grown in fresh water.
- Sewage Sludge.

Many researchers advocate that waste vegetable oil is the best source of oil to produce biodiesel. But the availability is much less than that of petroleum-based fuels. It is

impossible to meet the current rate of consumption. Animal fats are a by-product of meat production and cooking. It is not recommended to raise animals (or catch fish) simply for their fat, use of the by-product adds value to the livestock industry (hogs, cattle, poultry). Nowadays many biodiesel facilities are producing high quality animal-fat based biodiesel.

1.6 USAGE BIODIESEL AS FUEL

Biodiesel can be manufactured from vegetable oils, animal fats, or waste cooking oil. It is a renewable fuel. It burns cleaner with less pollution when compared with petroleum fuel. It is nontoxic and biodegradable.

Pure and unblended form of biodiesel is referred to as B100 or neat biodiesel. Biodiesel is used in compression-ignition engines, which run on petroleum diesel. It's performance in cold weather depends on quantity of biodiesel that is blended with petrodiesel. The smaller the quantity of biodiesel in the blend, it performs better in cold temperatures.

1.7 BENEFITS/ADVANTAGES OF BIODIESEL

Advantages of biodiesel are

- Biodiesel is bio renewable fuel. It can be renewed many times in one generation.
- Biodiesel is nontoxic. It rapidly degrades biologically. The spillages of biodiesel are far less risky than petroleum diesel spillages.
- Biodiesel to diesel cost ratio is around 0.8. Hence biodiesel works out cheaper than petrol.
- Biodiesel has a higher flash point than petroleum diesel, making it safer in handling.
- Modification to fuel injector and combustion chamber are suggested to burn pure biodiesel. Generally Maximum of 20% blending of biodiesel with peroleum diesel is recommended to run in a unmodified diesel engine.
- Biodiesel can be manufactured from recycled vegetable oils and animal fats.

- Biodiesel has a high Cetane number comparable to that for petroleum diesel fuel. The Cetane number is a measure of a fuel's ignition quality. The high Cetane numbers of biodiesel contribute to easy cold starting and low idle noise.
- It reduces the emission of harmful pollutants, mainly particulates, from diesel engines (80% less CO_2 emissions, free from sulphur dioxide). But emissions of nitrogen oxide, the precursor of ozone, are increased from biodiesel
- The use of biodiesel can extend the life of diesel engines because it is more lubricating Furthermore, power output is relatively same as petrodiesel.
- Biodiesel replaces the exhaust odor of petroleum diesel with a more pleasant smell of popcorn or French fries.

In the present work production of biodiesel from *Vateria Indica* oil/fat is explored and its performance and emission characteristics in a single cylinder diesel engine is determined.

1.8 VATERIA INDICA LINN

(Encyclopedia of Life, Gupta et al,(2012).Venkatesh H et al (2010)Vateria indica. tree is also known as the Indian copal tree. Its habitat can be generally found in the evergreen forests of India. These trees are found in the Western Ghats of Karnataka (Dakshin and Uttar Kannada, Chikmagalur, Hassan), Kerala (Cannanore, Calicut, Palghat, Tiruvanantapuram) and Tamil Nadu (Coimbatore, Annamalai,Tinnaveli) of India Generally its maximum height is around 30m. Oil from its seeds is extracted through boiling water floatation method by villagers belonging to the places above mentioned.

Vateria Indica tree is also known as Indian copal tree or dhupa which is shown in Fig 1.3. Evergreen trees, to 30 m high, bark 10-12 mm, greyish, blotched with white and green, smooth; exudation, sticky, resinous; branchlets puberulus. The Bark appears grayish, smooth, blaze cream, Leaves shown in Fig 1.4 simple, alternate; stipule narrow, lateral, deciduous; petiole 25-40 mm, stout, stellate pubescent, swollen tipped; lamina 7-20 x 5-9 cm, oblong, base round, obtuse or cordate, apex acuminate or obtusely acute, margin entire, glabrous, coriaceous, lateral nerves 12-18 pairs,

parallel, prominent, intercostaescalari form, prominent. Flowers shown in Fig 1.5 bisexual, white, 2-3 cm across, fragrant, in terminal panicles, densely stellate puberulus; sepals 5, free, lanceolate, covered with stellate hairs; petals 5, white, obovate, spreading, shortly united at base; stamens many, free; filaments hairy; anthers often slightly hairy at base; connective produced into a filiform appendage; ovary superior, ovoid-oblong, tomentose, 3-celled, 2-ovules in each cell; style filiform, glabrous; stigma small. Fruit a capsule shown in Fig 1.6, 11-15 x 5-6 cm, pale brown, Ovoid or oblong-ovoid, lanceolate, tip acuminate; seed one.". Flowering of the trees starts between January and March. The fruits ripen and fall from May to July(Fig1.7). The yield of fruit is typically around 400 to 500 kg per hectare. A good crop appears every 3 to 5 years with 1 to 2 poor seasons and 1 to 2 average seasons in between (Karmakar Ruma, et al,2011) The resin which is extensively used in Indian medicine is credited with tonic, carminative and expectorant properties. It is also used for treatment of chronic bronchitis, diarrhoea,piles, rheumatism, tubercular glands, boils, throat troubles etc

1.9 KERNEL:

Dhupa kernels shown in Fig1.8 contain 19-23% of pale yellow fat having a tallow-like consistency and turns white on standing. The kernel is 47% by weight of the fruit. The kernel weighs around 55 grams. The kernel is reddish white or green in color. The kernel has a thick brown covering/hull which is hard, brittle, aromatic nature. The moisture content in a fresh kernel is around 41-47%. The kernel can be dried well in sunlight or by steam heating. Drying reduces moisture content to around 6-75%.The dried kernel contains oil/fat around 25%.

Fig1.3 Dhupa(Vateria Indica) Tree

Fig 1.4 *Vateria Indica* leaf

Fig1.5 Dhupa/*Vateria Indica* Flower.

Fig 1.6 Dhupa/*Vateria Indica* capsule

Fig1.7 Dhupa/Vateria Indica seeds

1.10 COLLECTION AND PROCESSING

The seed is collected immediately after the fruit falls down and before the germination in the wet soil and infestation by worms. Collection is done manually and process is around 4-5 weeks. Germ is removed manually and fruits are decorticated by wooden mallets. The kernels are broken into small pieces and sterilized in the process. Kernels are stacked in go down of 4-5 feet layer and agitated, under the sun. The kernel is disintegrated to 6–7 mm size and crushed first through an expeller; oil recovery is around 8-9%.of the seed. But oil recovered is less therefore other methods of oil extraction are presently being explored. In the villages in India aqueous extraction or boiling water floating method is adopted by the people to extract the oil. In this method the seeds are peeled off and kernels are cooked and ground. The dough thus obtained is boiled in water to get oil as supernatant layer.

1.11. OIL AND FAT

Vateria indica oil is known as Piney tallow or Dhupa fat. Dhupa oil contains saturated fatty acids more than 95%. Hence, the oil exists as solid at lower temperature, so the oil is known as fat. In the fat abundance of stearic acid up to 40-45% and Oleic acid up to 25-30% and palmitic acid is present up to 25-30%. Arachadic acid, a saturated

fatty acid, with 20 carbons is present up to 5.0%. The abundance of another fatty acid known as Linoleic acid is merely 0.5%. (Table 1.2)(Sridhar et al,1991)

Fig1.8 Dhupa Kernel

Table 1.2 Fatty acid composition of Vateria Indica Fat

Fatty acid	Percentage
Stearic acid($C_{18:0}$)	43.77
Palmitic acid($C_{16:O}$)	14
Oleic acid	25-30
Arachidic acid	0.4-4.6
Oleic acid	42-48
Linoleic acid	0,2-2.3
Linolenic acid	Up to 0.5%
Myristic acid	Upto 1%

The Dhupa fat is greenish yellow to white, fairly soft with pleasant odour. It can be bleached by exposure to light. The specifications of Dhupa Fat is given in Table 1.3.

Table 1.3 Specification for Dhupa Fat

Character	Range
Refractive index at 60^0C	1.45-1.46
Iodine Value	36-51
Saponification Value	186-193
Unsaponifiable matter	1.0-2.0

1.12 Uses of oil/ fat:

Dhupa of *Vateria Indica* Fat obtained after any method has to be chemically l refined before it is being made edible. It is filled as Cocoa Butter Substitute/ Extender after proper processing, as well as in yarn-sizing and manufacture of candles, soaps and other cosmetics. It is used in confectionary and as an alternative for ghee .

In the present work use of *Vateria Indica* oil/fat as alternate fuel is being explored.

1.13 Organization of the thesis:

The present work is dealt in detail in the thesis and thesis is arranged in an orderly fashion. Chapter 1 introduces the concept of biodiesel to the reader and elaborates on *Vateria Indica Linn* a new source of biodiesel. The literature survey done regarding biodiesel production and performance and emission characteristics of various biodiesel are summarized in chapter 2. Objectives of the research work are listed in chapter 3. The chapter 4 elaborates on experimental set up used and methodology adopted. The chapter 4 also deals with error and uncertainty analysis of the set of readings. The chapter 5 deals with various extraction methods adopted in the present work to extract *Vateria Indica* fat/oil. The chapter 6 describes the extraction protocol of method of synthesis for *Vateria Indica* Methyl Ester (VIME) or *Vateria Indica* biodiesel developed in the present work. Chapter 6 also discusses in detail about the results obtained for performance and emission characteristics of VIME as alternative fuel for petrodiesel in a single cylinder air cooled CI engine. Chapter 7 elaborates on conclusions drawn in the present work. It also discusses future scope of the present work is discussed in chapter 8 and references and appendices are listed at the end.

Chapter 2

LITERATURE REVIEW

Biodiesel is a sulphur free oxygen rich alternate fuel for petro diesel. The available resources of petroleum crude is limited and it is expected to exhaust in near future. The short supply of petro diesel is expected to be met by biodiesel in the future. There are large number of feed stocks available for the production of biodiesels such as Karanja, Jatropha, Waste cooking oil, microalgae etc. There are two main requirements of biodiesel viz biodiesel production and its performance as diesel fuel alternative. A detailed literature survey is conducted regarding to these requirements and presented in the following sections.

2.1 PRODUCTION OF BIODIESEL

The major challenge as regards of biodiesel production is optimum yield of biodiesel from its sources. The factors effecting the biodiesel yield and optimization of yield are two main areas of interest. In this section literature review done regarding the production of biodiesel are presented.

Murugesan A et. al. (2007)reviewed the process of production of biodiesel through transesterification of vegetable oils. The transesterification also called alcoholysis is the process in which alcohol from ester is displaced by another alcohol. According to Olugbenga Olufemi Awolu et al (2013) main parameters that effect the transesterification reaction are molar ratio of vegetable oil to alcohol, catalysts, reaction temperature and time, content of free fatty acids and water in the vegetable oils. Xiaohu Fan et.al (2009) reviewed the biodiesel production. According to the author various sources or feed stocks have been explored for the production of biodiesel. These sources generally are greases, soap stocks, waste cooking oils, microalgae, vegetable oils such as Jatropha, soya been, rinsed, rapeseed, safflower, cotton seed and animal fats.

Canakei M et.al,(2001)If FFA in a grease is 8-12%(wt) it is categorized as yellow grease and if FFA is more than 35%(wt) it is categorized as brown grease. NgO, H. L et.al.(2008) invented a two stepped process to produce bio diesel from yellow grease. Cao, P. G et.al(2008) Developed an efficient method using diarylammonium as catalyst for the production of biodiesel from greases. The biodiesel was produced from yellow and brown grease using a continuous membrane reactor. The biodiesel produced met ASTMD6751 standards.

A study was carried out by Haas M.J et.al, (2000) to explore the idea of biodiesel production from soap stocks. Soap stocks are produced from refining vegetable oils. These are considered as low value feed stocks for production of biodiesel. Soap stocks contain substantial amount of water which gets emulsified with lipids and it becomes difficult to remove it. The FFA and acylglycerols are present in substantial amount in soap stocks which makes the transesterification reaction more complicated. Alkaline catalyst cannot be used directly because of the presence of high FFA content.(Jin Bi et, al, 2008),A simple high efficiency two step method for extraction of biodiesel from soapstock was developed.

According to Zheng S et.al, (2006)Waste cooking oils(WCO) are commonly available at low costs at large food processing and service facilities.(Wang Y et, al,2006)A detailed study has been conducted on the reaction kinetics of acid catalyzed transesterification of waste frying oil.(Chen G et.al,2006) An investigation on a two step acid catalysed process for the synthesis of biodiesel by using waste cooking oil is done.

According to Metting F.B et. al, (1996) & Spolaore, P et.al, (2006) shortfall in biodiesel production can be dramatically changed when microalgae are used to produce it. A well designed system where in there is better access to water, CO_2 and nutrients was used to grow Microalgae. Microalgae is oil rich with 20-50%.of oil. According to Miyamoto K (1997) oil content of some microalgae exceeds 80% by weight of dry biomass. Despite seemingly bright future of using microalgae to produce biodiesel, its commercialization seems years away.(Vasudevan, P. T et. al.2008) The capital cost of photo bioreactors is the biggest hurdle for commercialization of biodiesel production from microalgae.(Song Chunfeng et al,

2016) Approximately 3.61 MJ of energy per litre of biodiesel can be saved if hydrolysis esterification route is followed instead of conventional drying, lipid extraction, esterification and transesterification route is followed for micro algae.

The following authors viz, Kusdiana, et. al, (2001), Gwi-Taec . al, (2004), Harrington K. J et. al, (1985), Ji-Yeon Park et.al, (2008), Keskin, A et. al, (2008), Karen Arujo Borges et. al, (2012), Farah Halek et.al, (2013),& Sen Yang et. al,(2014) done the investigations on producing biodiesel from non edible oil sources like Rapeseed, Safflower, Pongamia, Cotton seed, Rinsed, Karanja, Mahua, Tung oil, Neem oil, Pequi oil ,Castor oil, Swine manure respectively.An investigation by Azad A K et al,(2016) reveals that Beauty Leaf oil and Castor oil are potential alternative fuels for the transportation in Australia. According to Singh R. N,et. al.(2008) & Sirisomboon, P et al (2007) there is growing interest for production of biodiesel from non edible oil sources like Iatropha Curcus Linn fruits. Palm fatty acid distillate (PFAD) is a waste from extraction of palm oil. (Malvade Ameya Vilas et al, 2013) PFAD is used for production of biodiesel. The calorific value of PFAD biodiesel was found to be 38.6MJ/kg while density was 879 kg/m^3, flash point was 147°C, viscosity was 3.96 mm^2/s and cetane number was 49. Scum is an oil-rich waste from the waste water treatment plants with a high-sulphur level. In a work carried out by Huan Ma et al,(2016) a novel process was developed to convert scum to high quality and low sulphur content biodiesel.

A wide range of researches are conducted to find out the effects of catalysts and process parameters like stirring speed, molar ratio, reaction time etc. Process parameter optimization study biodiesel production done by Verma Puneet et al, (2016) reveals optimum values for different parameter. According to this study biodiesel production reaction temperature should be in the range 50-60°C, reactant concentration measured by molar ratio of alcohol to oil should be in the range 6-12:1. With the use of alkaline catalyst having concentration 1% by weight and optimum reaction time for alkali catalysed transesterification is 120 min. The transformation of soybean oil into fatty acid methyl ester (FAME) was studied by Rahimi Masoud et al, (2016), by using different four-way micromixers. For mass transfer intensification Hexane was added to reaction vessel as cosolvent. A theoretical optimization study

using techniques like three-level-five-factorial central composite design using response surface methodology was done to optimize the reaction conditions. The optimum values for reaction temperature, residence time, hexane to methanol volumetric ratio, oil to methanol volumetric ratio and mixer configuration were discussed arrived at for the production of FAME. At this optimum condition, the observed FAME content was found to be 98.8%.

(Sankaranarayanan T M et al ,2011) the samples of A catalyst MoO_3/Al_2O_3 with different MoO_3 loadings (8, 12 and 16 wt%) calcined at different temperatures (800, 950 and 1100 K) is used in the transesterification of sunflower oil with methanol. The influence of various parameters, such as Molybdinum loading, calcination temperature, reaction temperature and molar ratio of reactants (methanol:oil), on the reaction was studied. A fixed-bed continuous transesterification process for the production of biodiesel using $MoO_3–Al_2O_3$ can be adopted.

Refined, bleached and deodorized palm oil (RBD palm oil) was reacted with methanol in the presence of heterogeneous CaO catalyst with and without c-alumina ($c\text{-}Al_2O_3$) as a support and comparative study is done by Uprety Bijaya K.et al,(2016).These results were also compared to the reaction with presence of sodium hydroxide (NaOH), which is a homogenous catalyst. Optimum conditions for parameters such as the concentration of catalyst, the molar ratio of methanol to oil, reaction time and reaction temperature that affect methyl ester and glycerol formation were were determined. By using CaO as catalyst 96.75% and 92.73% of yield of FAME and glycerol content were obtained which are lower in purity compared to that obtained using CaO/Al_2O_3 (97.66% and 96.36% respectively).(Kumar Manish et al, 2016) Freeze dried sewage sludge used as a feasible feed stock for biodiesel production and its yield was enhanced by optimization of the in situ transesterification conditions such as temperature, catalyst and concentration of sludge solids. Optimized conditions reveal that reaction temperature of 45°C and catalyst concentration of 5% and 0.16g/ml sludge solids resulted in a 20.76 ± 0.04% biodiesel yield.

A research work presented by Ortiz-Martínez V M et al,(2016) offers an in-depth study of the transesterification reaction of Karanja oil in supercritical methanol in one-step catalyst-free pro-cess. Triglyceride (TG) conversion and the yield of

biodiesel were analyzed in the temperature and reaction time ranges of 250–350°C (12–43 MPa) and 15–90 min, respectively, at an alcohol-to-oil molar ratio of 43:1. Optimal reactions conditions were found at 300°C and 90 min with almost complete triglyceride conversion.

Kucchwaha et.al.(2006) carried out an investigation in which instead of a mechanical or magnetic stirrer ,a low frequency ultrasound(33 KHz) was applied to transesterify jatropha oil with methanol in the presence of KOH catalyst . The reaction time was found to reduce compared to conventional stirring method. (Shah S et.al, 2007)Lipace (enzyme) catalysed transesterification of Jatropha oil into biodiesel was done in different studies. (Mishra et al,2012)The transesterification of Simaroubaglauca oil by means of methanol in presence of potassium hydroxide catalyst at less than 65^0C was done. The viscosity of biodiesel obtained was found to be nearer to that of the diesel. The important properties of biodiesel such as density, flash point, cloud point, pour point, carbon residue and ash content are found out and compared with that of diesel.(Korkut Ibrahim et al, 2016) Ultrasound (US) assisted transesterification of canola oil in presence of heterogeneous catalyst calcined dolomite and CaO was investigated in comparison to each other. According to the results, US improved the transesterification reaction by reducing necessary time for high biodiesel yield, using calcined dolomite as well CaO as heterogeneous catalyst.

In a study done by Senthil M et al, (2016) two different catalysts viz, KOH and activated red mud (waste from aluminium industry) were used with catalytic cracking for biodiesel productions from Mahua oil. Two different technologies viz, Energy Dispersive Spectroscopy (EDS) and Scanning Electron Microscope (SEM) were used for characterization of cracking by red mud. The cracking process was carried at 300°C for 2 hours and biodiesel thus obtained blended with diesel in various propotions (B25, B50, B75, and B100) and these blends were examined for physical properties. The results showed that the red mud catalyst yielded in a biodiesel having higher calorific value (44.312MJ/kg) compared to KOH as a catalyst.(Torres-Rodríguez Daniela A et al, 2016) Two ceramics, i.e., pristine Na_2ZrO_3 and Cesium modified Cs-Na_2ZrO_3 (ion exchange method) were used as basic heterogeneous catalysts in biodiesel production. Soyabean and Jatropha oils were trandesterified.

Parameters, such as catalyst concentration ,reaction time and temperature molar ratios of oil to methanol and their effect on biodiesel yield were evaluated. Influence of cesium cation was evaluated from the basic transesterification reactivity. Introduction of cesium significantly modified catalytic activity in biodiesel production.

In a study conducted by Mustafa Canakci (2007), the level of the contaminants like free fatty acids and moisture contents in different feed stocks effecting the efficiency of transesterification into biodiesel was determined. free fatty acids varied from 0.7% to 41.8%, and moisture contents varied from 0.01% to 55.38%. These wide ranges indicated that an biodiesel production process from waste grease and animal fats must tolerate a wide range of properties of the feed stock. Kutkura (Meynaspinosa Roxb.) is a plant species in the genus Meyna from the Rubiaceae family. (Kakati J, et al,2016) Free fatty acid (FFA) content in the katkura oil was determined to be 3.1%, which is less than 4%, hence base catalyzed transesterification was used directly for biodiesel production from Kutkura fruit seed oil. Excepting water content, all other properties of Kutkura FAME met the ASTM D6751 and EN14214 standards.

A 50 L stainless steel jacketed reactor pilot plant is built by Silitonga a S et al (2016) to convert crude palm oil and calophyllum inophyllum oil into methyl ester. Palm oil is directly transesterified using base catalysis while calophyllum inophyllum oil is processed using acid-catalysed esterification followed by alkaline-catalysed transesterification. The properties of the palm and Calophyllum inophyllum methyl esters were found to meet American Society for Testing and Materials (ASTM) D6751 and European (EN) 14214 Standards

Summary:

Various biodiesel sources are explored for the production of biodiesel transestrification process. High FFA vegetable oils required acid esterification process before conventional base catalysed transesterification process. The effect of catalysts used for transesterification was studied by different authors. The optimization of biodiesel yield was done by different authors either by design of experiments or solely by experiments. The effects of reaction time, molar concentration of methanol or ethanol and stirrer speed, reaction temperature and catalyst concentration are gauged.

The detailed study or reaction kinetics is carried out by various authors. Few Authors characterized the resulting biodiesel chemically and physically by determining composition and properties of biodiesel so as to establish the obtained biodiesel met the international standards .

2.2 PERFORMANCE AND EMISSION CHARACTERISTICS OF BIODIESEL

2.2.1 Performance and emission characteristics of biodiesel in single cylinder CI engine under standard operating parameters.

In this section detailed review of literature available on performance and emission characteristics of biodiesel in single cylinder CI engine under standard operating injection parameters namely injector opening pressure and injection angle are presented and summarized.

The performance and emission tests are generally conducted with different types of biodiesels. In India non edible oil sources such as Karanja and Jatropha are extensively selected for the engine studies. Waste frying oil is another feedstock for biodiesels generally tested in diesel engines. Palm, Simarouba, Rinsed, Cotton seed, Sunflower, Safflower etc are also considered for biodiesel production and are tested in the CI engines. Recently there is vigourous research work beeing carried out with microalgae for biodiesel production and the resulting biodiesel is tested in diesel engines.

Effect of Karanja biodiesel (Karanja oil methyl ester; KOME) and its blends on engine performance emissions and combustion characteristics in a direct injection compression ignition (DICI) engine with varying engine speed and load has been investigated (DharAtul et al, 2014). Maximum torque attained by 10% and 20% KOME blends were higher than mineral diesel, while higher biodiesel blends produced slightly lower torque. BSFC for lower KOME blends was comparable to mineral diesel however BSFC increased for higher biodiesel blends. This phenomenon was attributed for lower calorific value of blend and reduced mixing due to higher viscosity of the blends forming lager size droplets. CO, HC and smoke emissions of Karanja biodiesel blends were lower than mineral diesel but NOx emissions were slightly higher. Poor mixing and over leaning of mixture at higher

speeds & loads were reasoned for increased CO and HC emissions. Fuel bound oxygen in blends was attributed for higher NO_X emission by the authors. The investigation showed that up to 20% karanja biodiesel blend can be utilized in an unmodified DICI engine. A comparative study of effect of different biodiesel–diesel blends (B5, B10, B15, B20, B25, B50 and B100) with karanja biodiesel on injection, spray, combustion, performance, and emissions of a direct injection diesel engine at constant speed (1500 rpm) was carried out by Lahane Subhash et al, (2015), A notable conclusion emerged from this study is the optimum biodiesel–diesel blend based on no wall impingement and increase in NOx emission in a conventional (unmodified) diesel engine is up to B15.

The experiments were carried out using pure diesel (B0) and pure Jatropha biodiesel (JB100) as fuels in a study by Paul Gaurav et al,(2014). The performance characteristics shows that brake specific fuel consumption (BSFC) increases and brake thermal efficiency decreases with the use of jatropha biodiesel due to predominance of decrease in heating value of biodiesel. NO_X emission was found increase for higher blends due to higher oxygen content.

(Dhar Atul et al,2015) Total particulate emission is a major pollution parameter. karanja biodiesel was blended with diesel and its effect on on total particulate emission at various engine operating conditions was studied using a direct injection compression ignition engine. It was observed that particulate emission increased with increasing engine speed for all test fuels. The particulate emissions was found to be less at smaller concentration of biodiesel in the blends(upto 20%) At higher loads and speeds particulate emission was found increased due to occurrence of larger amount of combustion in diffusion mode. In the experimental work done by, K. Nantha Gopal et al,(2015), Various blends of Pongamia biodesel such as PME 20, PME 40, PME60 and PME 80 are prepared and tested in a compression ignition engine and comparison with diesel operation was done. The performance found to reduce slightly when the engine was fueled with biodiesel. On the other hand, reduction in CO, HC and smoke was observed. Reduction in net heating value of biodiesel blends and increased density and viscosity of these blends found to decrease the performance and improved combustion due to larger oxygen content was the reason for reduction in emissions.

(Monirul I.M et al,2016) Biodiesel blends of three different biodiesels viz, palm, jatropha and calophyllum inophyllum biodiesels (PB10, PB20, JB10, JB20, CIB10,and CIB20) are prepared and their performance and emission characteristics were compared with diesel fuel at a full-load engine speed range of 1000–2400 rpm. Due to lower heating values and increased viscosity blends generally performed poorly compared with diesel. Results indicated that PB20 has better engine performance, and lower emission compared with diesel and biodiesel blends. Thus, PB20 was found suitable for use in diesel engines without the need for any engine modification.

Engine performance tests were carried out by Mohd Hafizil Mat Yasin et al,(2015) on diesel engine with fuels, diesel and B5 (5%palm methyl ester + 95% diesel) blend. Results showed that at all engine speeds, torque and power outputs for B5 fuel were quite similar to neat petroleum diesel fuel. NO_X emission reduced significantly for both fuels but the rest emission contents were decreased with engine speed. Increase in heating value and increase in oxygen content were attributed for increased torque and power output and reduced emissions of CO, HC and increased NO_X emissions respectively. While extracting Palm fatty is a waste from extraction of a by product known as Palm Fatty Acid Distillate (PFAD). This is used for production of biodiesel in a study by Malvade Ameya Vilas et al,(2013). Engine performance like Brake Power of PFAD blends was found nearly equal to that of diesel. Brake Thermal Efficiency higher comparatively for 50% PFAD blends. Specific Fuel consumption for PFAD blends is slightly higher than diesel. Increase in performance was attributed to increased density of the blends at higher blending ratios which resulted in larger quantity of fuel injected for same plunger displacements.

In the experimental investigations by S M Bsasavaraj et al, (2016) with CSOME (cotton seed oil methyl ester) and NKOME (neem kernel oil methyl ester) in a single cylinder, four stroke, direct injection LHR(Low Heat Rejection) engine it was found that, at peak load the brake thermal efficiency was lower by 5.91% and 7.07% and BSFC was higher by 28.57% and 10.71% for CSOME and NKOME in LHR engine respectively when compared with conventional diesel fuel used in normal engine. Higher viscosity and increased density of methyl esters resulted in decreased

atomization and vaporization. This resulted in reduced brake thermal efficiency and poor combustion efficiency. It was also seen that there is an increase in NOx emission in LHR engine along with slight increase in CO, smoke and HC emissions due to aforesaid reasons.

In an experimental investigation done by B. Dinesh et al, (2016) Cymbopogon flexuosus bio fuel was blended with diesel fuel in various proportions on volume basis, namely 10, 20, 30, 40, and 100 percent. The performance, emission and combustion characteristics of the test fuels in a single cylinder diesel engine was determined. higher thermal efficiency and lower hydrocarbon, carbon monoxide, and smoke emission reported for B20. However, NO_X and CO_2 emission was found to be marginally higher for the test fuel considered. Higher thermal efficiency was attributed to higher heating value and reduced emissions of CO and HC are attributed to increased oxygen content.(H. Nidal et al, 2015) Experiments were conducted with almond and palm biodiesel. The blends of these biodiesels on volume basis such as 0%, 10%, 30% and 50% with diesel fuel were prepared and tested. The emission and some performance parameters under various load conditions were analysed. lower brake specific fuel consumption, higher thermal efficiency, and higher exhaust gas temperature reported for almond biodiesel in comparison with palm biodiesel. This was credited to the fact that almond biodiesel having more oxygen content than palm biodiesel. As for as emissions are concerned almond biodiesel gave lower carbon monoxide(CO), oxides of nitrogen (NOx), total particulate and unburned fuel emissions in the exhaust gas. This was also because of higher oxygen in almond biodiesel which results in better combustion.

soybean oil biodiesel and pure diesel were used as fuels in the compression ignition engine (D. H. Qi et al, 2009) and performance, combustion and emission characteristics of the engine were analysed. The Brake Power of the biodiesel was almost equal to that of diesel. Lower heating value of the biodiesel resulted in higher brake specific fuel consumption. The significant reduction in CO, HC, NOx and smoke under constant speed were observed for biodiesel operation at full engine load. Better oxygen availability in biodiesel structure reduces all the emissions because of better combustion. Based on this study, it is inferred that biodiesel can be used as a

substitute for diesel in diesel engine.(Adolfo Senatore et al, 2015)A study examines the characteristics of 2-stroke diesel emissions using a Detroit 6V53 engine, with 100% rapeseed methyl ester (RME) biodiesel (B100) as fuel. CO & PM emissions decrease when the engine is fuelled with pure biodiesel while the NOx emissions donot increase significantly. This is credited to the fact that the biodiesel is additional oxygen rich fuel which leads to complete combustion. The fuel consumption increases about 8 – 10 % in the biodiesel case due to less heating value.

(Raheman H et al, 2007).The performance of biodiesel obtained from mahua oil and its blend with high speed diesel in a Ricardo E6 engine has been carried out. It is observed that reductions in exhaust emissions and brake specific fuel consumption and increase brake power, brake thermal efficiency for the blend of biodiesel ,B20. Thus B20 became a suitable alternative fuel for diesel that could help in controlling air pollution. Fact that biodiesel is an oxygenated fuel resulted in more complete combustion.

A study by Jinlin Xue, (2013) reviews on WEO biodiesels combustion characteristics, engine power, economy, regulated emissions and non-regulated emissions of WEO biodiesels in a diesel engine. The use of WEO biodiesels leads to A slight difference in combustion characteristics such as ignition delay, rate of pressure rise, peak pressure and heat release rate is reported on use of biodiesel. At the same time the substantial reduction in PM, HC and CO emissions along with the imperceptible power loss, the increase in fuel consumption and NOx emission on conventional diesel engines when compared to base line diesel is reported. The fact that biodiesel is a oxygenated fuel and larger bulk of fuel is injected due to increased viscosity are reasoned for foresaid characteristics of WEO biodiesel.

In the experimental study conducted by, Ozer Can, (2014) two different kinds of waste cooking oils was blended in 5% and 10% with No. 2 diesel fuel. The biodiesel/No. 2 diesel fuel blends were tested in a single-cylinder, direct injection, four-stroke, natural aspirated diesel engine under four different engine loads (BMEP 0.48–0.36–0.24–0.12 MPa) and 2200 rpm engine speed. It was found that blending with 5% and 10% biodiesel fuel shown slight increment in break specific fuel consumption(up to 4%) and slight reduction in break thermal efficiency (up to 2.8%).

Reduced delay period resulted in early combustion and elongated combustion duration. This was attributed for above said phenomena. Combustion continuing in expansion phase simply increased the heat release which could not be converted into work. It was also observed that biodiesel additions also increased NOx emissions up to 8.7% and decreased smoke and total hydrocarbon emissions for the all engine loads. Although there were no significant changes in CO emissions at the low and medium engine loads, some reductions were observed at the full engine load. This was attributed to oxygen enrichment in the biodiesel structure. Also, CO_2 emissions were slightly increased for the all engine loads due to complete combustion.

(Nantha Gopal K. et al, 2014) The important experimental findings of the study reveal that the WCO biodiesel has similar characteristics to that of diesel. The brake thermal efficiency, carbon monoxide, unburned hydrocarbon and smoke opacity are observed to be lower in the case of WCO biodiesel blends than diesel. Decreased performance was argued for lower heating value of biodiesel and higher density and viscosities which lead to poor combustion due to reduced atomization and improper evaporation of droplets of the blend. Reduced emissions are reasoned for large oxygen content in biodiesel. Instead specific energy consumption and emissions of oxides of nitrogen of WCO biodiesel blends are found to be more than diesel.

Similar results were obtained by Pugazhvadivu M et al, (2005) for waste frying oil The engine performance of single cylinder CI engine was improved and the CO and smoke emissions were reduced using preheated waste frying oil because of better mixing due to better evaporation. In the study conducted by, H. Sanli et al,(2015) fuel quality biodiesels produced from waste frying oil using methanol and ethanol were tested as pure and 20% (v/v) blend with petroleum-based diesel fuel (PBDF) in a direct injection (DI) diesel engine running at 600 Nm and three different engine speeds (1100, 1400 and 1700 rpm). The results showed the similar trend..

In a study by C.V. Sudhir et al (2007)**,**the fresh palm oil biodiesel and palm oil based WCO biodiesel were prepared. Engine performance exhaust emissions characteristics were determined for both the biodiesel for the purposes of comparison. Both these biodiesels closely performed. At higher load operation of esters of WCO fueled engine suffers nearly 2% brake thermal efficiency loss because of low heating value.

Interestingly hydrocarbon emissions of WCO biodiesel fuel were observed to be approximately 35% lower than baseline diesel operation because of increased oxygen content. (Anderson Antunes de Paulo et al, 2016). Braziliann commercial diesel (petroleum diesel with 5% biodiesel) and pure waste frying oil-based biodiesel (B100), volumetric blends of WCO namely 20%, 30%, 50%, 75% are tested in a diesel power generator. Best power performances was achieved by B5 and B30, whereas B20 showed the higher thermal efficiency and the lowest fuel consumption as well. When concentrations of methyl esters of waste frying oil is increased from 5% to 100% increased concentrations of CO_2 and NOx and decreasing concentrations of CO, NO2, SO2 and CxHy in the flue gases were observed. Increase in performance and reduction in emission was attributed to the increasing quantity of oxygen in the blends which resulted in better combustion. The engine performance and emission characteristics with waste cooking oil biodiesel were studied and compared with pure diesel fuel by A Yamin Jehad et al,(2013). Improvements in performance in terms of increased torque,power,thermal efficiency and decreased specific fuel consumption is observed. This was attributed for higher oxygen content in the biodiesels structure and better combustion. Compared to biodiesel diesel showed reduced amount CO emission because higher burning temperature.

Two B100 biodiesel samples were prepared by Singh Devendra et al, (2015), by patented routes from the lipids extracted from marine microalgae Chlorella variabilis (BA) cultivated in salt pans and wasteland-compatible Jatropha curcas (BJ). Transient performance and emission characteristics of a heavy duty diesel engine fuelled with these B100 fuels (BJ and BA) were studied over European Transient Cycle. Test results showed that both B100 biodiesels outperformed petro-diesel in terms of particulate matter (PM), carbon monoxide (CO) and hydrocarbon (HC) emissions, with slight penalty on NOx emissions. Biodiesels are oxygenated fuel which resulted in better combustion leading to reduced emissions of PM,CO,HC but increased emission of NO_X. Among the two biodiesels, merits of BA were established over BJ in terms of nitrogen oxides (NOx) emissions and specific fuel consumption. Increased Torque for BA is accredited for higher NO_X.

Recently dual biodiesel blends are increasingly tested for their performance and emission characteristics.(Devan P.K et al,2009) The various blends of paradise oil and eucalyptus oil are prepared on a volume basis and tested in a single cylinder, four-stroke DI diesel engine. The results indicate a 34.5%, 49%, 37% reduction in HC emissions and smoke and CO emissions respectively for the Me50–Eu50 blend when compared with diesel with a 2.7% and 2.4% increase in NOx emission and brake thermal efficiency respectively for the Me50–Eu50 blend at full load. Increased oxygen content in the formulae of dual fuel blend is credited to increase in thermal efficiency and reduction in emissions. In a study by Ankur N et al,(2016) two different kinds of biodiesel namely palm (Elaeisguineensis) and jatropha (Jatropha curcas) mixed together and blended with diesel in different proportions in diesel and tested in a single cylinder DI diesel engine with varying loads after going through physical properties analysis. The results showed that for lower blend of biodiesel D90PB5JB5 (i.e. 90% diesel & 10% biodiesel) with diesel 4.65% average increase in brake power than diesel. There was slight reduction observed in BSFC for lower blends. Higher biodiesel blend D20JB40PB40 (i.e. 20% diesel &40% Jatropha biodiesel and 40% Palm biodiesel) have showed up to 15% average increase in brake thermal efficiency. There were 7.1%, 17.7% and 14.5% average reductions in CO emissions with samples D90JB5PB5, D80JB10PB10 and D70JB15PB15 (biodiesel blends containing 10%, 20% & 30% biodiesel) respectively, when compared to diesel. Lower blends of biodiesel samples D90JB5PB5 and D80JB10PB10 showed 5.3% and 9.2% average increase in NOx emissions respectively, than diesel. Increase in brake thermal efficiency and reduction in emission was attributed to increase in oxygen concentration as blending ratio increased.

In a study by Ramón Piloto Rodríguez et. al(2011),Palm oil and rapeseed oil biodiesel gave shorter ignition delay than fossil diesel fuel. In a study by Mohammed EL-Kasaby & Medhat A, Nemit-allah on jatropha biodiesel blends B0, B10 and B50 the delay period decrease with the increase of both cylinder pressure and temperature for all blends. This may be attributed to the fact that with increasing the pressure the mixture molecules become closer and the probability of increasing the active collisions between these molecules is higher, as a result the chemical reactions will be accelerated to complete the combustion with shorter delay period.

(Hoon Kiat Ng et.al,2013) This computational fluid dynamics (CFD) study is performed to investigate the combustion characteristics and emissions formation processes of biodiesel fuels in a light-duty diesel engine. It is established in this study that an increase in the degree of unsaturation in biodiesel fuels can have detrimental effects on engine-out NO. A numerical study by Claude Valery Ngayihi Abbe et.al,(2015)is applied on neem methyl ester confirms that NO_X emission is higher for biodiesel than the base line diesel. The study done by Upendra Rajak et.al,(2019) involves the numerical simulation of the diesel engine by means of Diesel-RK tool. The NO_X emission formation is occurred within the premixed phase of combustion chamber due to higher flame temperature according to the study.

The work presented by Luka Lešnik et.al,(2014) was carried out experimentally and numerically on a heavy-duty bus diesel engine using mineral diesel fuel, neat biodiesel fuel made from rapeseed oil and their 25% (B25), 50% (B50) and 75% (B75) blends. Lower maximal incylinder temperature also slowed down the emission formations.

The higher content of oxygen in pure biodiesel fuel contributed to a better oxidation process in the combustion chamber and reduced the CO emissions formation rate, while lower in-cylinder temperature reduced thermal NOx formation rate on full engine throttle position.

In a numerical study done by Hui An et.al,(2014)aims to investigate the impacts of biodiesel blend ratio on the emission formation processes of a diesel engine. A tri-component biodiesel mechanism which consisted of methyl decanoate (MD), methyl-9- decenoate (MD9D) and n-heptane, was used to simulate the fuel oxidization and emission formation processes for diesel, biodiesel and their blend fuels. As for NO emission, it is found to be the greatest for diesel fuel, followed by B50 and B100. This is mainly due to the lowered incylinder combustion temperature for B50 and B100, which is the dominating factor determining the formation of thermal NO. The reduced in-cylinder temperature is as expected since the calorific value of biodiesel is lower than that of diesel which will reduce the overall heat release rate.

Summary:

Biodiesel is a bio fuel obtained from different vegetable and animal oils/fats. These biodiesels readily mix with petro diesel. Most of the researchers blended biodiesel with diesel in different proportions and carried out performance, combustion and emission analysis under standard injection parameters. Commonly these blends are named as B05, B10, B15, B20 etc or depending on the source as KOME10,POME10, WCO10 etc. Majority of researchers found that biodiesel improved the performance marginally with imperceptible increase in BSFC or BSEC barring few eg: Nantha Gopal et al,(2015), S M Basavaraj et al,(2016) who observed slight decrease in performance. By using biodiesel it has been the experience of researchers that emission of HC, CO, PM reduced considerably. Majority of researchers found that there is a considerable increase of NO_X emission excepting few to the contrary for eg Dongui.H. Qi et al,(2009). It is also found by many researchers that Ignition delay is reduced for biodiesel blends due to increased cylinder pressure and temperature.

2.2.2 Performance and emission characteristics of biodiesel in single cylinder CI engine under standard Varying injection parameters.

In this section literature review done regarding varying injection parameters like Injection timing and injection pressure in biodiesel application. Interestingly biodiesel/diesel fuels may perform better in altered conditions of injection pressure and injection timings. Hence many researchers are trying to select best operating conditions in view of better performance and emission characteristics.

(Jindal S et al,2011)A biodiesel prepared from jatropha curcus was used in engine used for agriculture purpose, running on pure biodiesel and influence of variation in injection timings were studied. The thermal efficiency was increased by 8 percent when injection timing were retarded by 3 degrees. The main reason attributed to this low ignition delay of the biodiesel which results in early and rapid premixed combustion leading to better thermal efficiency. The effect of varying the injection timing as 18°, 21°, 24°, 27° and 30° CA bTDC on BSEC, Brake Thermal Efficiency, CO, HC and NO emissions were studied by Pandian M et al,(2008).From the experiments it is found that on retarding the injection by 6°CA bTDC from 24° CA

bTDC, the original injection timing, the NOx emission reduced to about 35%. While advancing the injection timing to 6°CA bTDC, the NOx increased by 25%. The BSEC, CO, HC have been found to increase by about 3%,12.65% and 10% respectively on retarding to 18°CA bTDC. When Injection Timing is advanced to 30°CA bTDC these emissions decrease by 6.27%, 32%,and 14.44% respectively. The brake thermal efficiency is reduced by 3.08% on retarding to18°CA bTDC whereas it is improved by 5.09% on advancing the injection timing to 30° CA bTDC.

Improved brake thermal efficiency and reduced CO, HC emissions occur when advancing the injection timings because of improved combustion duration ensuring complete combustion.(CenkSayin et al,2009)The effect of injection timing on the exhaust emissions of a single cylinder, four-stroke, direct injection diesel engine has been experimentally investigated by using methanol-blended diesel fuel from 0%,5% and 15%. The injection timing was varied as 15^0, 20^0 and 25 ^{0}CA BTDC and engine loads 5 Nm, 10 Nm, 15 Nm, 20 Nm at 2200 rpm. When compared the results to those of original injection timing, NO_x and CO_2 emissions decreased, while smoke opacity, UHC and CO emissions increased for the retarded injection timing (15^0CA BTDC). On the other hand, with the advanced injection timing (25^0CA BTDC), smoke opacity, UHC and CO emissions diminished, and NOx and CO_2 emissions enhanced at all test conditions. In terms of BSFC and BTE, retarded and advanced injection timings gave negative results for all fuel blends in all engine loads. Poor performance characteristics on retarding is attributed to high ignition delay and poor combustion at low pressure on advancing the injection.

A study by Ganapathy T et al,(2011) involves Jatropha biodiesel as fuel and the experimental investigation of the influence of injection timing, load torque and engine speed on the performance, combustion and emission characteristics determined. For this purpose, the experiments were conducted using theoretical optimization studies with full factorial design consisting of levels with 27 runs for each fuel, diesel and Jatropha biodiesel. For minimum BSFC, CO, HC and smoke and for maximum BTE, Pmax, and HRRmax injection timing is found to be 340 Crank Angle Degrees. However, minimum NO_X emission yielded an optimum injection timing of 350 CAD. It is found that as injection is advanced due to longer ignition delay of Jatropha

biodiesel better mixing occurs and better combustion proceeds. As a result better BTE and reduced CO and HC emission takes place. Experiments were performed (Jaichandar S et al, 2012) focusing on a blend of 20% Pongamia Oil Methyl Ester (POME) by volume with diesel (B20), in a single cylinder Direct Injection (DI) diesel engine. Two geometries of pistons having Hemispherical and Toroidal Reentrant Combustion Chamber (TRCC) were selected for the study. Along with combustion chamber geometry effect of varying injection timing also studied. The test results disclosed an improvement of 5.64% in brake thermal efficiency, a reduction of 4.6% in brake specific fuel consumption and a 11% increase of oxides of nitrogen (NOx) level for TRCC compared to baseline engine operated with B20 due to better air-fuel mixing and retarded injection timing. It is argued that retarding the injection the delay period reduces due to high pressure and better combustion occurs which results in slight increase in BTE. But authors also argue that on retarding combustion becomes poor and incomplete which leads to increase in CO emissions.

In the experimental investigation done by Suryawanshi J. G.,(2013) neat jatropha oil methyl ester (JME) as well as the blends of varying proportions of jatropha oil methyl ester (JME) are prepared. These were used as fuel along with diesel in a CI engine. Injection timing was set at standard as well retarded. On retarding the injection timing marked improvements in performance and emissions were observed. Since blend had low ignition delay, on retarding vigorous combustion occurred resulting in better combustion.

Corn and soybean methyl esters were blended with diesel at widely recommended ratio of 20% (C20 and S20) and fuelled a diesel engine in a work by Shehata M S et al,(2015). The effect of increasing injection pressure from 180 bar to 200 bar fuel injection pressure (IP) on diesel engine performance using C20 and S20 blends in comparison with that using neat diesel fuel was studied. The major conclusion was that, the increased injection pressure gives better results regarding the engine performance parameters (both BSFC and BTE) in comparison with case of the original injection pressure for all tested fuels, thus the best results are obtained at high injection pressure of 200 bar. It was noticed that with increase in injection pressure

combustion duration was shortened and peak in cylinder pressure and peat heat release rates are improved and thus performance improves.

(Cenk Sayin et al, 2012), The various blends of canola oil methyl ester(COME) with diesel was prepared and was used as a fuel in a single cylinder, four stroke, direct injection, naturally aspirated diesel engine. Effect of varying the injection pressure on it's performance was studied. Four injection pressure were selected namely 18, 20, 22 and 24 Mpa. The tests were conducted at constant engine speed and different loads. A reduction in brake specific fuel consumption and increase in brake thermal efficiency observed at high pressures when compared with the original and lower injection pressures. Increase in injection pressure resulted in increase in Maximum in cylinder gas pressure due to increased amount of combustible mixture. In an experimental investigation by Nantha Gopal et al,(2016) injection pressured varied as 200 bar, 220 bar and 240 bar and neat biodiesel(B100) of calophyllum inophyllum and diesel were selected as fuels for comparison. The parameters like brake thermal efficiency, specific fuel consumption, heat release rate and engine emissions were analysed. The experimental results showed that brake specific fuel consumption of biodiesel has been reduced to a great extent with higher injection pressure. When compared to other injection pressure 220 bar injection pressure showed significant reduction in emissions of unburnt hydrocarbons, carbon monoxide and smoke opacity. Nevertheless NO_X emission is increased with increase in injection pressures and it was higher than diesel. A rise of injection pressure 200 bar to 220 bars showed improvements in performance and emissions. Increase in injection pressure resulted in better atomization and evaporation. A opposite trend was observed when injection pressure is raised from 220 bar to 240 bar. This accredited to poor entrainment of air leading to poor mixing.

(Anbarasu A et al, 2016) In an experimental investigation on the performance and emission characteristics of a CI engine with diesel and blends of canola biodiesel emulsion at 200, 220 and 240 bar. Emulsified fuels showed an improvement in brake thermal efficiency of 28.8% at 240 bar accompanied by the drastic reduction in NO_x at 200 bar. The thermal efficiency increase with injection pressure increase is reasoned for better atomization and better evaporation resulting in better combustion.

But increase of injection pressure resulted in poor HC and CO emissions because of reduced momentum of the droplets leading to poor mixing and inferior combustion. Comparison of performance and emission was done by Jindal S et al,(2011) for different values of CR(Compression Ratio) along with IP(Injection Pressure) to find the optimum combination for operating engine with KME(Karanja Methyl Ester). It is found that the combined increase in CR and IP increases the BTE and reduces BSFC while having lower emissions. This is attributed to better atomization of fuel and better evaporation and mixing. For small-sized direct injection constant speed engines used for agricultural applications (3.5 kW), the optimum combination was found to be CR of 18 with IP of 250 bar

In the study by Kannan G R et al,(2012) a blend of 30% waste cooking palm oil (WCO) methyl ester, 60% diesel and 10% ethanol named as diestrol was selected for engine tests. The effect varying injection pressure and injection timing on the performance, emission and combustion characteristics of a direct injection diesel engine was studied through experimental investigation. At higher injection pressure of 240 bar and injection timing of 25.5° bTDC maximum BTE of 31.3% was observed. Diestrol fuel showed reduction in carbon monoxide(CO), carbon dioxide (CO_2) and smoke emission by 33%, 6.3% and 27.3% respectively in comparison with diesel. Nitric oxide (NO) emission was reduced by 4.3%, while slight increase in the levels of unburnt hydrocarbon (UHC) was observed with diestrol. Diestrol fuel showed higher cylinder gas pressure and heat release rate compared to diesel. A low ignition delay of 12.7° CA was observed with diestrol fuel which was similar to diesel at same operating condition. At higher injection pressure evaporation improved and performance bettered. It was analysed that advancing the injection timing improves the vaporization leading to better mixing thereby enhancing the performance and reducing the emissions.

(Suresh G et al, 2016) Effects of fuel injection timing, fuel injector opening pressure (IOP) and injector nozzle geometry on the performance and combustion of neat canola oil methyl ester (COME) is determined. Fuel injection timing varied as 19^o, 23^o, 27^o before top dead centre(bTDC) and fuel injection pressure varied as 210, 220,230,240 bar. Fuel nozzle injectors with three, four and five holes, each of 0.3mm

size, were selected for the study. The results showed that with retarded injection timing of 19^{o}bTDC, increased injection pressure of 230 bar and a four-hole nozzle injector of 0.3mm size brought about better engine performance with an increased brake thermal efficiency and reduced HC,CO and smoke emission levels. It was reasoned that increased injection pressure and retarded injection timing resulted in better combustion due to increased incylinder pressure and temperature.

Balusamy T et al,(2010) studied the effect of injection timing and injection pressure on diesel single cylinder at constant speed, fuelled with Thevetia Peruviana seed oil methyl ester. Brake thermal efficiency is found to increase and emissions of CO, HC and smoke reduce on advancing the injection timing from the base diesel value and increasing the injector opening pressure. Also, optimum injection time was 27^{o} bTDC and optimum injection pressure were 225 bar respectively. On advancing the injection timing slow burning is offset and increasing the injection pressure increases the atomization, reduces the droplet size and increases the evaporation and mixing according to the authors.

(Wategave S P et al, 2014) Performance and emission studies were done by varying f fuel injection timing (IT), fuel injector opening pressure (IOP) and injector nozzle geometry of COME(cotton seed), HnOME(Honne) and HOME(Honge) in the modified CI engine. It was concluded that improved performance and reduced emissions were observed for a retarded IT of 19^{o}bTDC increased IOP of 230 bar, and four-hole nozzle injector of 0.3mm size. Authors argue that retarding the IT lowers the ignition delay period. Consequently higher heat release rate for the uncontrolled or premixed combustion phase results. Increased IOP improves BTE and reduces emissions because at higher injection pressures due to reduced droplet size, improved spray characteristics and better mixing with air, which result in improved combustion. But gain at high injection pressure is offset at too high IOP of 240 bar which leads to delayed injection.

The results of study Kumar Niraj et al,(2016) demonstrated that higher compression ratio (18:1) and IP (240 bar) along with advance IT (26◦ bTDC) is the best combination for a constant speed engine with brake power of 3.5kW fuelled by 40% biodiesel blend. Advance IT leads to longer ignition delay which increases the

premixed combustion phase duration and achieves better combustion and leads to maximum BTE at that timing. Incresed IOP leads to better atomization and leads to better mixing and combustion according to the authors. This was accredited to improved performance and emission characteristics.

Summary:

It is observed from the literature that there is no agreement on observations regarding injection strategy with biodiesel applications. Most of the researchers concluded that retarding the injection timing increased the thermal efficiency. But few researchers concluded to the contrary that retarding injection timing decreased the thermal efficiency for eg Balusamyet al,(2016) and Kumar Niraj et al (2016). Few researchers inferred that by retarding the injection timing CO, HC and smoke emissions increased for eg Pandian M et al,(2008), CenkSayin et al (2009), Balusamy et al,(2010) and Kumar Niraj et al (2016). Considerable number of researchers felt that CO, HC emissions decreased on retarding the ignition timing for e.g Suresh G et al(2016), Suryavamshi J G (2013),Wategave S P et al,(2016). There is a wide consensus among researchers that NO_X emission increased when injection is advanced. Most of the researchers concluded that increased injection pressure increased the performance and reduced emissions from the single cylinder diesel engine fuelled with blends of biodiesel/diesel.

2.2.3 Performance and emission characteristics of biodiesel in single cylinder CI engine with EGR

In this section detailed literature review on performance and emission characteristics of biodiesel in single cylinder CI engine with EGR is presented. EGR is generally done to reduce NO_X emission. But EGR also reduces thermal efficiency of the CI engine and decreases output. Quantifying the increment in NO_X reduction and efficiency reduction and arriving at optimum EGR volume is an important task.

(Donghui Qi et al,2011)With soybean oil biodiesel experiments showed that, with the increasing of EGR rate, there is slight increase in brake specific fuel combustion (BSFC) and soot emission and nitrogen oxide (NOx) emission was obviously decreased. Under higher EGR rate, the peak pressure was slightly lower, and the peak

heat release rate was almost equal at lower engine load, and was more at higher engine load.

(Suryawanshi G J et al, 2006) Effect of EGR with jatropha methyl ester and it's blends with diesel in a CI engine was studied with combination of 20 % EGR, 4° CA retarded injection timing and 30 MPa fuel injection pressure and compared with standard conditions of No EGR, no injection retard and 20 Mpa injection pressure. Under standard conditions addition of jatropha oil methyl ester (JME) to diesel fuel has significantly reduced HC, CO and smoke emissions but it increases the NO_X emissions marginally. The NO_X emission was drastically decreased with modified conditions. Modified conditions resulted in decreased smoke and unburned hydrocarbon emissions as compared to standard conditions.

An attempt was made by Saravanan S et al,(2014) to reduce NO_X emission of a crude rice bran oil methyl ester (CRBME) blend by retarding fuel injection timing and with exhaust gas recirculation at an increased fuel injection pressure.

(Ozer Can et al, 2016), soybean biodiesel fuel was blended in 20% by volume with diesel fuel and it's performance and emission characteristics at different engine loads (15, 11.25, 7.5 and 3.75 Nm) and 2200 rpm engine speed with different EGR rates (5, 10, 15%) are determined. The results disclosed that the maximum heat release rate and maximum in-cylinder pressure were increased due to the combined effects of biodiesel fuel addition and EGR application. Reasonable increases on the BSFC and reductions on BTE as a maximum 6% and 3% occurred with 15% EGR and 5% EGR, respectively. NOx and smoke emissions were better simultaneously up to 55% and 15% at the high engine load, respectively.

(Rajan K et al, 2009) EGR technique was used to explore it's effect on A twin cylinder four stroke water cooled direct injection (DI) diesel engine with sunflower methyl ester (SFME) biodiesel blends with diesel fuel. The results exhibited that for a 7.5kW power output, B20 SFME with 15% EGR rate produced 25% less NOx emissions compared to diesel fuel.

In an investigation by Kondaiah B et al,(2016), Mahua oil was transesterified to produce Mahua oil methyl ester and the blends of MOME with diesel by volume

namely B0, B25, B50, B75, & B100 are prepared and tested in a single cylinder diesel engine. The engine performance and emission characteristics with and without exhaust gas recirculation (EGR) at different loads were determined. The results show the brake thermal efficiency (BTE) and emissions of B25 is almost closer to diesel. The BTE with EGR is higher than the BTE without EGR for all the blends. The emissions namely smoke, HC, CO, NOx, of engine with EGR are lesser than without EGR for all the blends.

(Vinay K et al, 2015) Neem oil methyl ester (NOME) blends and diesel are used as fuel and an attempt was made explore the effect of EGR. Biodiesel blend of 10% on volume basis is subjected to a study for the effect of 8% EGR and it is found that NOx was reduced by 15% when compared with conventional diesel fuel. It is mainly due to less oxygen available in the recirculated exhaust gases which lowers the flame temperature in the combustion chamber.

Bhaskar et al(2013) studied a diesel engine fueled with fish oil methyl ester(FOME) to find the effect of EGR on the real time control of NO_X and particulate matter emissions. At 20% EGR for B20 of fish oil methyl ester, they were able to present improved reduction in NO_X.

Agarwal D et al,(2006) studied a compression ignition engine fuelled by biodiesel to see how the NO_X emissions can be reduced by EGR. The biodiesel used was rice bran ester and blends with diesel are from B10 to B50. They found lesser NO_X emission and increased HC, CO, and PM emissions using the B20 biodiesel with 15% EGR.

In all the research works mentioned above EGR reduces the NO_X emission and increase CO, HC emissions. Authors concluded that EGR dilutes the burning mixture. Chemical and thermal effects of EGR along with dilution increases the specific heat capacity of the mixture thereby reducing the combustion temperature. As the combustion mixture gets diluted thermal efficiency suffers and emission of CO, HC increases. But emission of NO_X reduces considerably.

(Mohan K. Bobba and Mark P. B. Musculus,2008) The ignition delay is increased with EGR, so that local precombustion mixing is increased, which reduces soot formation

Summary:

Most of the authors aimed at reducing the NO_X emission by intake modification with EGR. According to authors EGR reduces the maximum flame temperature as it dilutes the incoming charge and hence NO_X emission is reduced. Different researchers studied effect of EGR at different levels of 10%, 15%,20% etc. They arrived at optimum EGR level which gives minimum NO_X. According to most of the researchers EGR reduces performance slightly and increases CO, HC, smoke emissions.

2.2.4 Performance and emission characteristics of biodiesel in CRDI engines

Experiments were carried out by Atul Dhar & Avinash Kumar Agarwal (2015) in a single cylinder CRDI research engine in multiple injection mode at 500 and 1000 bar fuel injection pressure (FIP) under varying start of pilot injection (SOPI) and start of main injection (SOMI) timings. Brake specific fuel consumption (BSFC) increased with increasing Karanja biodiesel concentration in test fuels however brake thermal efficiency (BTE) of biodiesel blends was slightly higher than mineral diesel. Lower biodiesel blends showed lower brake specific carbon monoxide (BSCO) and brake specific hydrocarbon (BSHC) emissions than mineral diesel. Brake specific nitrogen oxides (BSNOx) emissions from KOME20 and KOME10 were higher than mineral diesel. Combustion duration of KOME50 was also higher than mineral diesel. In a study by Kamil duda et al,(2018) animal origin biofuels (swine lard and turkey lard had been used as raw material for biofuel production) were tested in a medium-duty, turbocharged, Common Rail, Direct Injection (CRDI) diesel engine. The study confirmed that high quality fuel can obtained from waste fatty material. The mixtures containingup to 75% of bio-component are suitable for modern CRDI combustion engines, though slight deterioration of engine performance parameters can be expected. An experimental study by Parashuram Bedar and G.N. Kumar uses dual cylinder common rail direct injection (CRDI) engine fuelled by Jatropha curcas biodiesel blends produced through Transesterification process. Performance, emissions and combustion properties of an engine at constant speed were measured and analysed. The improvement in brake thermal efficiency (BTE) along with

reduction in carbon monoxide (CO), unburned hydrocarbons (UBHC) and smoke opacity were observed for the B20 biodiesel blend with a marginal increase in oxides of nitrogen (NOx). The experimental investigations on a compression ignition (CI) engine fitted with common rail direct injection (CRDI) facility S.V. Khandal et.al,(2017) is an effort towards the reduction of exhaust emissions without compromising the fuel efficiency. The employment of 15% EGR reduces the NOx emission by 36.9%; but the use of 21% EGR leads to the drastic reduction in NOx by 46.8%, without much compromising the BTE. Also, the engine operation provides the complete freedom from diesel fuel and thereby providing energy security and sustainable source of energy.

Summary:

Experiments were carried out in CRDI engines by fuelling it with biodiesel diesel blends at very high pressures of 500 bar and 1000 bar, Fuels showed good thermal efficiency and better CO/HC emissions. But NO_X emissions seemed to be predominant. Techniques like EGR are attempted and found to be satisfactory in controlling NO_X emissions.

2.3 RESEARCH GAPS

On the basis of the literature work detailed above the following research gaps are identified.

- Conventional aqueous extraction of *Vateria Indica* fat is presently very costly. Alternative extraction methods like solvent extraction are not considered by any researchers.

- Various biodiesel sources are being explored for application in single cylinder diesel engines. But *Vateria Indica* oil/fat is not considered for extraction of biodiesel by any researchers.

- There is no work on performance, combustion and emission characteristics of *Vateria Indica* oil/fat as alternative fuel in single cylinder diesel engines.

Chapter 3

OBJECTIVES

3.1 OBJECTIVES OF THE PRESENT WORK

Vateria Indica Linn is endangered species and red listed by government of India. This species supported the economy of rural India from ages. The tree is used as a timber in house hold application. Its resin found application as medicine in ayurvedic practices. The Vateria Indica seeds were used to obtain a fat called Dhupa fat. Dhupa fat finds application in ointmemts, balms and ayurvedic medicines. The extraction method practiced by villagers for the fat is aqueous extraction or boiling water floating method. This requires large amount of heat. In the past villagers used firewood available in ample quantity to heat the slurry of dough obtained by grinding the kernels of the seed. Recently availability of fire wood has become scares and hence the price of the fat is shooting up. Since aqueous extraction is becoming difficult villagers are losing interest in the extraction and selling the fat. If economical method of extraction is developed, rural India would find the employment in collecting and selling the seeds. If additional application as biodiesel source is developed then large number of trees can be planted and grown which would support the economy of India. In the view of the above facts following research objectives are set for the present research work.

- To economise the extraction of *Vateria Indica* oil. For this purpose various extraction methods are explored and compared.
- To produce biodiesel from *Vateria Indica* seed by trans esterification
- To conduct test for the properties of biodiesel and confirm whether the obtained biodiesel meets the ASTM standards
- To conduct performance, combustion and emission tests in a single cylinder diesel engine with the various blends like B10, B15, B20, B25 of *Vateria Indica* methyl ester and diesel at several **injection pressures of 180 bar, 200 bar, 220**

bar and to select best injection pressure after comparing with base line petrodiesel

- To conduct performance , combustion and emission tests in a single cylinder diesel engine with the various blends like B10, B15, B20, B25 of *Vateria Indica* methyl ester and diesel at best injection pressures and various **injection angles of 19^{o}bTDC, 23^{o}bTDC & 27^{o}bTDC** and to choose the best injection timing after comparing with base line petrodiesel
- To conduct performance , combustion and emission testsin a single cylinder diesel engine with the various blends like B10, B15, B20, B25 of *Vateria Indica* methyl ester and diesel with 5% and 10% EGR(Exhaust Gas Recirculation) at best injection pressure and best injection timing. To arrive at best EGR percentage after comparing with base line petrodiesel.

3.2 SCOPE:

Experimental investigation to be carried out to economise the extraction of *Vateria Indica* fat/oil**.** For these purpose methods like solvent extraction is to be explored. Properties of the fat are to be found out to explore it as alternative fuel in diesel engine is to be carried out. Once the fat becomes economical, extraction of biodiesel from the fat is to be carried out. Once the biodiesel is obtained the composition and properties of biodiesel are to be determined to confirm whether it meets ASTM standards. The obtained biodiesel is to be tested in a single cylinder air cooled Kirlosker diesel engine.

Chapter 4

MATERIALS AND METHODOLOGY

4.1 EXPERIMENTAL SETUP AND METHODOLOGY

The principles, instrumentation and measurement systems used for performance, combustion and emission characteristics of the *Vateria Indica* biodiesel are described in this chapter. The Instruments are carefully selected to fulfil the objectives of the research work. The entire work in the research is divided into three stages. In the first stage engine tests are conducted with diesel and blends of biodiesel with diesel viz, B10, B15, B20, B25 to evaluate engine combustion, performance and emission characteristics to determine the best injection pressure. The injection pressure is varied from 180 bar(standard injection pressure) to 220 bar. Next the fuel injection timing is varied with respect to TDC either by retarding the injection or advancing the injection in terms of crank angle bTDC. After conducting the experiment with various injection angle, injection timing is optimized and the optimum blend was derived. In the next step exhaust gas recirculation is done to reduce the NO_x emission. Best of EGR was found out. The flow rate of exhaust gas is measured through a U-tube manometer connected to orifice plate.

4.2 TEST ENGINE DETAILS

A computerized single cylinder four stroke diesel engine test rig as shown in the Fig 4.1 was selected for conducting the engine tests. Electrical dynamometer, which absorbs power and regulates engine speed is connected to the engine. The test rig has necessary instruments for cylinder pressure, crank angle, air flow, fuel flow, temperature and load measurements. The cylinder pressure is measured using pressure transducer AVL GH140/AH01. Crank angle is measured using AVL 365C Angle encoder. The motherboard of computer has the interfaces for above mentioned instruments through analog to digital convertor (ADC) and PCI-1050. Air flow rate is

measured by orifice meter and fuel flow is measured using digital weight indicator and stop watch. Temperature of engine exhaust is measured using a thermocouple and digital indicator. Load measurements are done by adding wire wound resistances on a rheostat. Fig 4 .1 and 4.2 show the test rig. Specifications of engine and other instruments mounted on the test rig are given detail in appendix 1. The emission characteristics are measured by AVL DI GAS 444(five gas analyser) and AVL 415 SMOKE METER.(Fig 4.3).

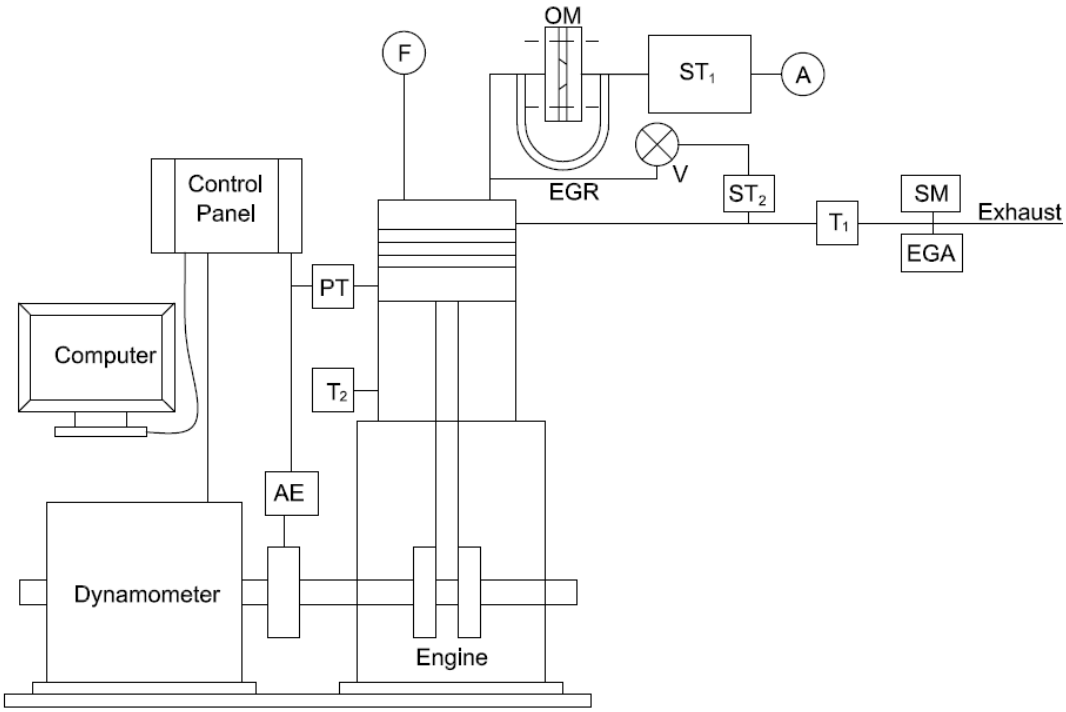

Fig 4.1 Schematic diagram of the experimental Test rig

(A-Air flow, F- Fuel flow, PT- Pressure transducer, SM- Smoke meter, EGA- Exhaust gas analyzer, T_1-Exhaust gas Temperature point,T_2-Engine Temperature point, CM-Calorimeter, ST_1-Surge Tank in intake air line,ST_2-Surge Tank in EGR line OM – Orifice Meter, V- control Valve, EGR- Exhaust Gas Recirculation)

The performance parameters those studied are brake power, Indicated power, Frictional power, BMEP, IMEP, brake thermal efficiency, indicated thermal efficiency, mechanical efficiency, volumetric efficiency, specific fuel consumption,

and air-fuel ratio,(A/F).The detailed specifications of instruments are given in Appendix I.

Fig 4.2 Diesel Engine Test Rig

Fig 4.3 Five Gas analyser and smoke meter.

4.3 MODIFICATION OF THE ENGINE SETUP FOR OPERATION WITH EXHAUST GAS RECIRCULATION

The engine is modified to operate with hot exhaust gas circulation system. After calorimeter exhaust is divided into two passages, one passage carries the exhaust gas to the atmosphere and another is connected to intake manifold. The flow rate of EGR is regulated using the flow control valve in the system. The block diagram of EGR

system is shown in Fig 4.4. The EGR is carried out by considering the mass flow rate of atmospheric air as reference and engine tests are conducted by supplying the mass flow of 5% and 10% EGR concentration.

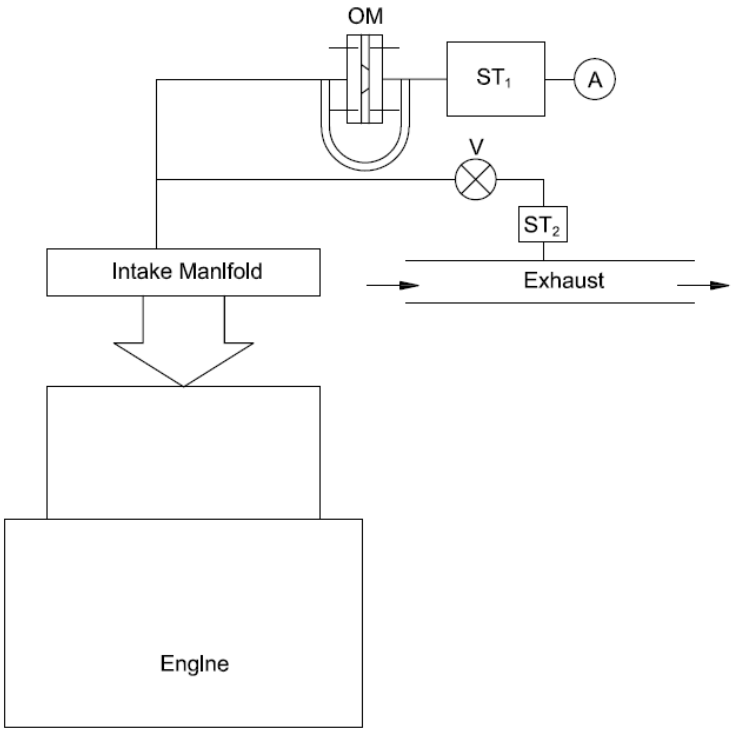

Fig 4.4 Block diagram of exhaust gas recirculation system

(A –Air intake , ST_1-Surge Tank in intake air line,ST_2-Surge Tank in EGR line, OM-Orifice Meter, V-control valve)

4.4 MEASUREMENT SYSTEM

The test bed contains instruments to measure the different parameters during the experiments on the engine. The different measurement systems used for evaluating the engine performance and emission is described in detail this section.

4.4.1 Cylinder pressure measurement

A piezo-elecric pressure transducer AVL GH140/AH01 supplied by AVL engineering company specifications of which are given in Appendix II is used to record the cylinder pressure for a number of consecutive cycles for combustion variability studies. It is assumed that the pressure inside the cylinder is uniform. The transducer

is mounted on the side between the head and cylinder block. The sensor is flush mounted to trace the pressure in the cylinder with one degree, Crank angle resolution. A digital computer operating on Windows XP system that contains a "Dynalog" make data acquisition system acquires In-cylinder pressure Vs crank angle data. The sensor jacket is continuously circulated with cooling water so as to maintain the sensor at a constant temperature so that it does not malfunction. The engine output shaft is fitted with a rotory encoder AVL365 for crank angle signal. Both signals of in-cylinder pressure and crank angle are simultaneously scanned by an engine indicator(electronic unit) and communicated to the computer. The software in the computer draws the In-cylinder pressure Vs crank angle plots along with heat released and cumulative heat release plots.

4.4.2 Exhaust emission measurements

Various exhaust emissions of carbon monoxide (CO, % volume), carbon dioxide (CO_2, %volume), unburnt hydrocarbon (HC, ppm), oxygen(O_2, %volume) and oxides of nitrogen(NO_x, ppm) are measured by an AVL Digas 444 gas analyser. The supplier AVL company calibrated the five gas analyser prior to use and necessary precautions are taken to see its proper working by regular check up of all types of filters and cleanliness of probe. Leakage test and zero adjustments are done regularly. The engine test rig has no catalytic converter and thus the emission readings taken are untreated raw emissions. Appendix III contains specifications of the analyser.

An AVL415 smoke meter is measures the smoke density in the engine exhaust gas. The AVL415 smoke meter reads the soot density(mg/m^3),and Filter smoke number(FSN). The filter paper method is used by AVL415 to determine the soot concentration in the exhaust of diesel and GDI engines. Blackening of filter paper by soot in the sample of engine exhaust is the basis for measurement of Filter Smoke Number(FSN). Intensity of soot on the paper is measured by a photoelectric measuring head and the result is analyzed by a microprocessor. Measured volume exhaust gas can be sampled by the probe manually or automatically makes the measurements of the AVL415 to have excellent repeatability and reproducibility. The Technical specifications of AVL 415 smoke meter is given in Appendix IV.

4.5 CALIBRATION OF THE INSTRUMENTS

Calibration of all measuring equipments is of paramount importance to minimize the experimental errors. Pressure sensors, five gas analyser and dynamometer are calibrated by the suppliers. The temperature sensors are calibrated against standard thermometers. Due care is taken to check the repeatability of readings while conducting the experiments. The engine is allowed to reach steady state operating condition by allowing it to run for sufficient time prior to taking reading at each test point. Average of at least three readings at each test point is taken to minimize the experimental error.

4.6 SCHEME OF ENGINE EXPERIMENTAL STUDIES

The experimental study with regard to the engine has three distinct stages. Fig 4.5 shows the scheme of experiments of the present research work. The first stage of the experiment involves evaluation of steady state engine performance, combustion and emission characteristics with biodiesel-diesel blends of B10, B15, B20, B25. These tests are conducted at standard injection timing of 23°bTDC and fuel injection pressure varied from 180 to 220 bar in steps of 20bar. From these experiments, a best injection pressure is arrived at and used as base line injection pressure for comparison with varying injection timing operations in later stages. The fuel blends are prepared on volume basis just before starting the experiment to ensure that the fuel mixture is homogeneous. The experiments are conducted at constant speed(1500rpm) and varying loads of 25, 50, 75 and 100% of the full load on the engine system

The cylinder pressure crank angle data and heat release rate(HRR) of combustion using a in built program AVL Indimicra software version 6.2. The analysis of obtained data is performed and results are plotted.

In the second stage, fuel injection timing is varied by retarding 4 deg and advancing 4 deg. with respect 23°bTDC. The experiments are performed with diesel-biodiesel blends of B10, B15, B20, B25 at 19°, 23°, 27° bTDC injection timings. The fuel injection timing is varied by varying the stroke length of plunger in the fuel pump

using shims of 2mm thick. The tests are conducted to optimize the injection timing and biodiesel/diesel blend.

In the third stage the engine is tested by with EGR for optimized blend and optimized operating conditions. A measured amount of exhaust gas is recirculated in the engine through intake manifold. Flow rate of the EGR is regulated by using a regulator and the flow rate of exhaust gas is measured by through the orifice meter and U tube water manometer set up. The engine combustion, performance and emissions are studied with 5% and 10% EGR along optimized fuel blend at optimized injection pressure and injection timings. Analysis of the data is performed and required graphs are plotted.

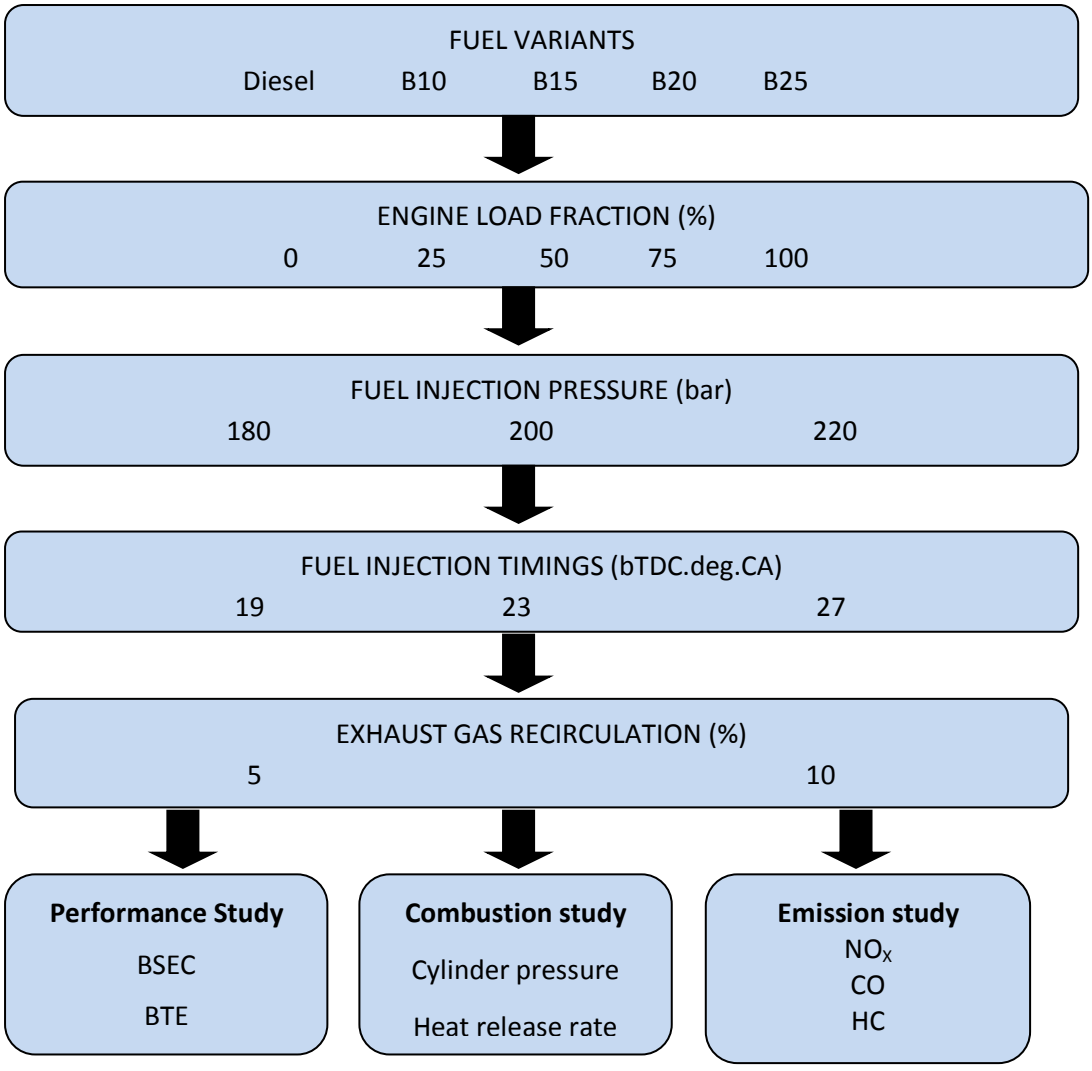

Fig 4.5 Scheme of experiments of the present research work

4.7 *VATERIA INDICA* FUEL BLENDS AND THEIR CHARECTARIZATION

Vateria Indica diesel is blended with neat diesel in various proportion by volume. The blends along with neat diesel are tested in engine test rig and performance, combustion and emission characteristics are determined.

Viscosity of *Vateria Indica* biodiesel is 5.8cst which is little more than that of pure diesel (3.57cst). Blending of this biodiesel with pure diesel in higher proportion is not advisable as mixture would become highly viscous leading to injection problems. *Vateria Indica* biodiesel has little high acid number (0.45) Higher concentration in the blend may lead to reduced engine life and injector life.

Table 4.1 Physical Properties of fuel blends.

Property	**Diesel**	***Vateria Indica* Biodiesel**	**B10**	**B15**	**B20**	**B25**
Flash Point(^{o}C)	74	138	58	62	63	67
Fire Point(^{o}C)	105	180	110	116	120	123
Viscosity(cst) at 40^{o}C	3.57	5.8	3.7	3.9	4.3	4.5
Density(Kg/m^{3}) at 40^{o}C	826	876.2	830.4	832.5	834	836.3
Higher Calorific Value(MJ/kg)	42.35	38	41.8	41.5	41.3	41
Saponification value (mg KOH/g)	-	149.17	8.37	30.80	37.69	76.37
Iodine Value (g I/g)	-	37.82	9.21	20.1	26.39	37.82

The physical properties are determined using the ASTM standards and the values are tabulated in table 4.1.It can be observed that there is significant improvement of flash point, viscosity, density and calorific value when biodiesel is blended with diesel.

4.8 ERROR AND UNCERTAINTY ANALYSIS

Uncertainty analysis of the experimental investigation is an important requirement as it ensures the validity of the measured and reported experimental values. The uncertainty in any measured value is estimated based on the Gaussian distribution method with confidence limits of ±2σ (95.45% of measured data lie within the limits of ±2σ of mean). Thus uncertainty of any measured parameter is given by

$$W_i = \frac{2\sigma}{X} \times 100 \quad \text{---------- 4.1}$$

20 sets of readings speed, load, time for specified amount of air and fuel and emissions of NO_x, HC and CO and CO_2 as well as soot density are taken maintaining the same operating conditions for error analysis. Then the average $\bar{\bar{x}}$ and standard deviation (σ_i) are found out for a particular parameter. The uncertainty values for various parameters are calculated using equation 4.1

For estimating uncertainty in experimental readings Kline and McClintock(1953) method is used.

If an estimated quantity R depends on 'n' independent measured parameters x_1, x_2, x_3,-------x_n. Then R is given by

$$R=R(x_1, x_2, x_3,\text{-------}x_n) \quad \text{……(4.2)}$$

Let w_R be the uncertainty in the result and w_1,w_2, w_3…..w_n be the uncertainties in the independent measured parameters. R is the computed result function of independent measured parameters x_1, x_2, x_3,-------x_n as per the relation $x_1 \pm w_1, x_2 \pm w_2$,.....$x_n \pm w_n$. If the uncertainties in the independent variables are all given with the same odds, then the uncertainty in the result having these odds is given as(Adnan et al, 2012);

$$W_R = \left(\left[\frac{\delta R}{\delta x_1} w_1\right]^2 + \left[\frac{\delta R}{\delta x_2} w_2\right]^2 + \cdots + \left[\frac{\delta R}{\delta x_n} w_n\right]^2\right)^{1/2} \quad \text{……..(4.3)}$$

Using the equation 4.3 for a given operating condition, the uncertainties in the computed quantities such as mass flow rates of air and fuel, brake power, and brake

thermal efficiency are estimated. The percentage uncertainty of various parameters are calculated by using the Kline and McClintock(1953) method as shown in table 4.2

Table 4.2 Uncertainties of various instruments and parameters used in experimentation

Measurement items	Range	Accuracy	Percentage uncertainty
Speed measurement	0-2000rpm	±1rpm	0.62
Load measurement	0-50Kg	±0.1 Kg	0.58
Air flow measurement	200mm of water column	±1mm of water column	1.67
Fuel Flow Measurement	0-50cc	±1 cc	1.1
NO emission	0-5000 ppm	± 1 ppm	1.9
HC emission	0-20000 ppm	±1 ppm	2.5
CO emission	0-10% vol	±0.01 % vol	1.98
Smoke emission	0-100%	±0.1%	0.9

4.9 Measurement technique of EGR

Percentage EGR can be calculated from the following formula

$$EGR(\%) = \frac{M_{EGR}}{M_i} \times 100$$

Sample calculation:

At 25% engine load condition, the intake air during the suction stroke is 60 Kg/hr

The amount of intake air, M_a=60Kg/hr

Amount of fuel consumed, M_f=1Kg/hr

Mass of intake charge, M_i=61Kg/hr

Mass of EGR, M_{EGR}=6.1 Kg/hr

$$EGR(\%) = \frac{6.1}{61} \times 100 = 10\%$$

Orifice meter connected to the intake pipe measures volume flow rate of intake air. The discharge through orifice is given by

$$Q = \frac{C_d a_0 a_1 \sqrt{2gh}}{\sqrt{{a_1}^2 - {a_0}^2}}$$

When No EGR is done Let the Air Flow be Q_0 and for 10% EGR is done it be Q_{10},

Then ,

$$\frac{Q_{10}}{Q_0} = 0.9(approx)$$

i.e

$$\sqrt{\frac{h_{10}}{h_0}} = 0.9$$

i.e,

$$\frac{h_{10}}{h_0} = 0.81$$

For example when EGR is not done for B25 blend at 75% load difference in height of water column in the manometer is 19mm, then for 10% EGR it would be 0.81X19 ie,15.5mm approximately. EGR valve is operated such that new difference in water manometer would be 15.5mm, then it means 10% EGR is done.

Chapter 5

EXTRACTION OF *VATERIA INDICA* OIL AND BIODIESEL

In this section of the thesis different methods of extraction of *Vateria Indica* oil/fat is discussed and characterization of different extracts are done and discussed. In the other Half the chapter methods used for extraction of Vateria Indica biodiesel and it's characterization are presented

The available methods for extraction of *Vateria Indica* oil are,

a) Mechanical Extraction
b) Aqueous extraction
c) Solvent Extraction

5.1 MECHANICAL EXTRACTION:

In this method, the cover of *Vateria Indica* seeds are peeled off. The seeds are then broken by mallets and dried in the open sun light and pressed in the Mechanical press. But this method has many disadvantages. The seeds of *Vateria Indica* become suitable for oil extraction during the months of june and july. This is generally rainy season in the coastal belt and Western Ghat regions of Karnataka state of India. Drying the peeled off seeds become difficult during this season because of shortage of sun light. Moreover it is found that the seeds undergo bio decay when dried under sun light. Hence the yield of oil obtained in this method is found to be quite less making the method uneconomical. The method is conventionally not adopted

5.2 AQUEOUS EXTRACTION OR BOILING WATER FLOATATION METHOD OF EXTRACTION OF *VATERIA INDICA* OIL

Aqueous extraction is generally costly method. Using enzyme for Aqueous extraction is beeing explored (Kwaku Tano-Debrah et al,1994) to reduce the cost.

In this Method the cover on the seeds is peeled off manually. The peeled off *Vateria Indica* seeds are broken into small pecies by mallet. These pecies are cooked in water till they become soft. Cooked seeds are then ground in grinder or manually ground (Fig 5.1). The dough thus obtained is made into slurry by adding water. The slurry is boiled for at least an hour. Then oil starts to float as supernatant layour. (Fig5.2) The oil is carefully removed and droped into a container of cold water. After some hours of cooling, oil solidifies in water. It is then removed and convereted into small billets. These billets are found to have long shelf life. The method is very efficient but found to be very costly because of amount of fire wood required. Conventionally yeild is around 15%. There are many disadvantage of aqueous extraction. In this method manual labour required is high and the cost of good quality firewood is more. But however this is conventionally adopted in rural Karnataka. The price of the oil obtained by this method is about 300Rs/Kg. Hence solvent extraction method is tried in the present work and the cost of *Vateria Indica* Oil is reduced to 90Rs/Kg.

Fig 5.1 Dough of ground seed

5. 3 SOLVENT EXTRACTION OF *VATERIA INDICA* OIL

Solvent extraction involves dissolving the oil in a suitable solvent and recovering the oil from the solvent. Solvent extraction of vegetable oils like soya been oil, rice bran

oil, pine seed oil is attempted(Myriam Lorena Melgarejo et al 2012 and Islam M N et al,2015). Solvent extraction method is used for extracting oil from egg yolk(Aleksandra Kovlcuks et al,2014). Different solvents like Hexane, alcohols, terpenes are used (Weibin Kong et al,2015, Ying Li,2014). Conventional Soxhlet extraction is generally done for different oils like yellow horn seed oil, jajoba oil and property analysis is done (Yu-Ji Fu et al,2008, Ferial A Zaher et al,2004). Ultrasound-assisted extraction (UAE) & Solvent extraction (Shadi Samaram et al,2013) for the recovery of oil from papaya seeds are compared. Newer methods like accelerated solvent extraction is attempted to recover oil from Jatropha seeds (Prapisala Thepsithar et al,2013). In many studies, effects of particle size, mass and temperature and duration of maceration on the oil yield are studied(Omeiza James Momoh,2015 and Lawson O S,2010) .

Fig 5.2. Supernatant Layour of oil

Conventional Soxhlet extraction of *Vateria Indica* oil can be carried out using n-Hexane as solvent. But this method is uneconomical as quantity of extract is very limited. Hence in this work a mechanical solvent extraction pilot plant is proposed to extract larger quantity of oil.

5. 3.1 Solvent Extraction pilot Plant

5. 3.1.1 Costruction Details

A solvent extraction pilot plant is proposed and it consist of 6 major components(Fig 5.3&5.4)

1. Cold masciration unit
2. Hopper Unit
3. Connecting hose
4. Evaporator
5. Condensor
6. Heating unit with thermostat

1. Cold Maceration unit:

This is a cylindrical container with appropriate arrangement for pouring powdered seed and n-Hexane. In this unit 1.5Kg of *Vateria Indica* Seed powder with 1.5 Liters of Hexane is accommodated in the trail run. This is a cylinder of 220mm diameter having height of 230mm. A special cylindrical projection vent of 20mm height and 60mm diameter is provided on the top.

2. Hopper unit:

This is a L shaped pipe having two arms which are connected to each other by welding. One arm is having 125mm diameter with length of 275 mm and another arm with same diameter and lentgth of 250mm. In this unit filtered hexane-oil solution travels to the connecting hose.

3. Connecting Hose:

This is a hose pipe of 25mm diameter connecting the Hopper unit with Evaporator unit. Hexane oil solution travels into evaporator through the pipe.

4. Evaporator:

Evaporator unit is cylindrical unit with converging mouth. The dimensions of this unit are given in the fig 5.4. In this unit hexane oil solution is heated and hexane is voporized and oil settles at the bottom.

5. Condensor:

This is a shell and tube type condensor. This consists of a coil of 5mm diameter with coil length of 430mm. The shell is of 60mm diameter and 500mm length. Water circulates in this condensor around the coil in which hexane vopors are cooled. Liquid hexane is collected at the outlet of this condensor.At the outlet a nipple of 5mm dia is provided.

6. Heating Unit:

Heater unit consist of a circular coil of 5mm dia mounted on the circular plate of 230mm diameter. A thermocouple with a thermostat is provided with the heater. Themocouple reads the temperature of the evaporated hexane vapours and thermostat maintains this temperature with the help of digital control circuit. The temperature inside the evaporator can be upto 90^{o}C. All the above parts are made of mild steel of food grade

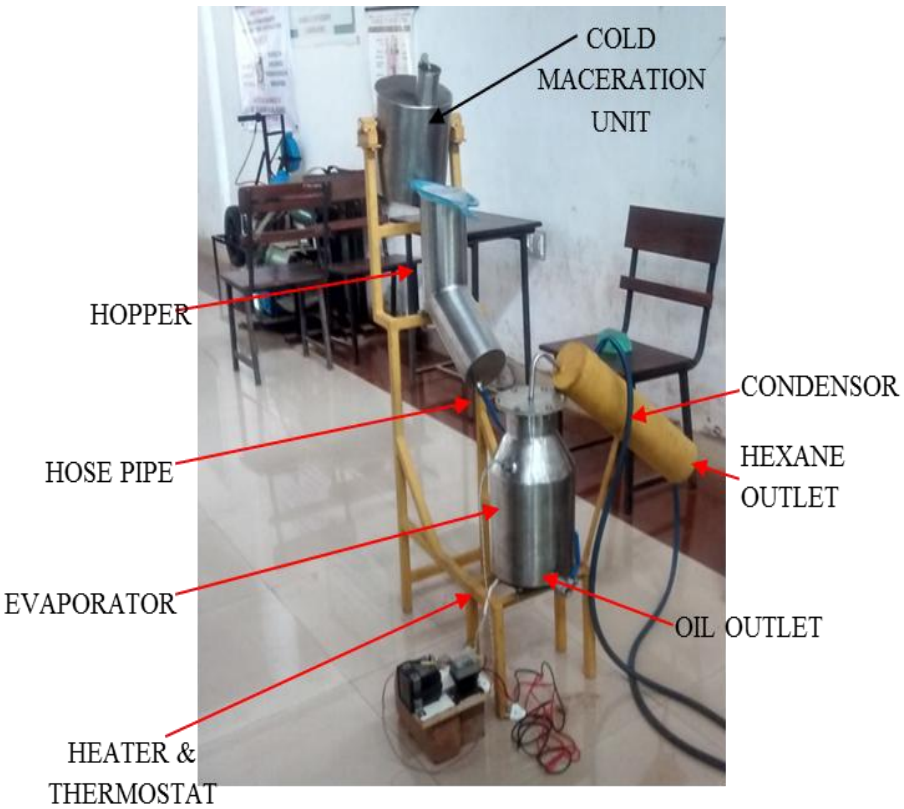

Fig 5.3 Solvent Extraction Pilot Plant

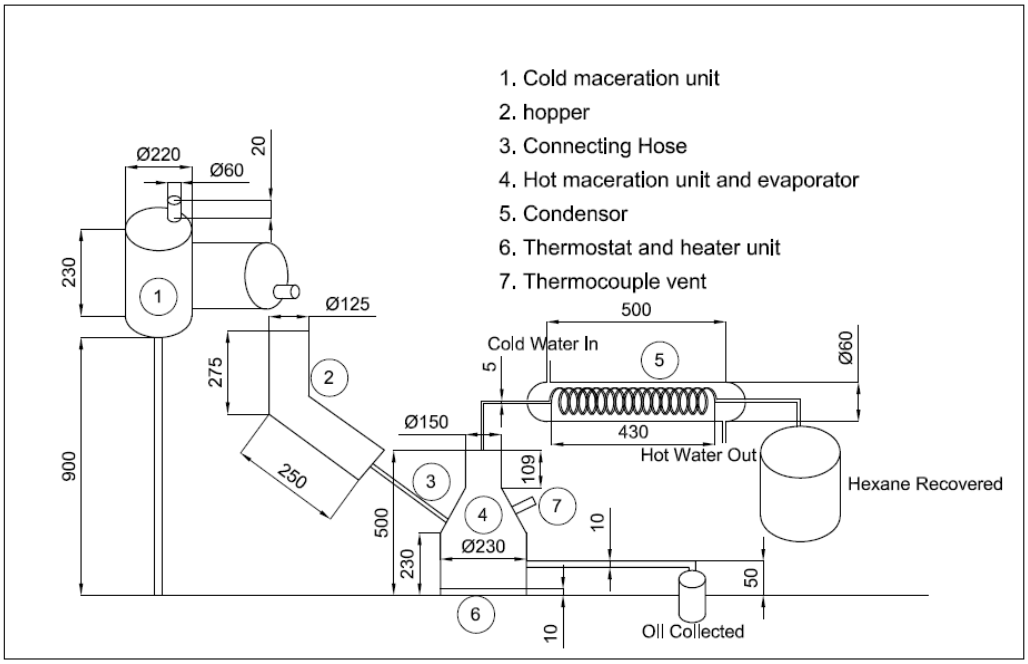

Fig 5.4 Layout of Solvent Extraction Unit

5. 3.1.2 Working of Solvent Extraction Plant

Vateria Indica Seeds are peeled off and powdered in a ordinary mixer. The Powder is dried in a microwave oven. Dried powder is soaked with n-Hexane in cold maceration unit for about 24 hours. n-Hexane is selected on the basis of findings of Bala et al (Manju Bala et al,2011) 1.5Kgs of powder is soaked in 1.5 liters of Hexane. After a day of soaking, powder is filtered out and dissolved oil with hexane is sent into evaporator. Hose is disconnected and hose vent is closed. Heater is put on and a temperature of vapours of hexane are maintained at 90^{o}C with the help of thermostat. Water is circulated into the condenser. After a while of 15 minutes pure hexane is separated and collected in a container. This continued for about 15 minutes. Once Hexane collection stops heater is put off. Hose vent is opened. Thermocouple is removed and vent is kept open. Traces of remaining hexane vapor are allowed to escape through these vents for about half an hour. Oil is collected from bottom of the evaporator through a valve provided for it. This pilot plant capacity is less and larger capacity plant can be built as per requirement.

5. 3.2 Physical and Chemical characterization of *Vateria Indica* Oil

5. 3.2.1 Physical properties

The samples of water extract (aqueous extract) and solvent extracts are shown Fig 5.6 and 5.7. Different Physical Properties of extracts are found and Tabulated (Table 5.1). Density is found by weighing known volume of oil at 45^0C. Specific Gravity is calculated from Density.

Table 5.1 Physical properties of oils

SL.NO	Physical Characteristic	Water Extract	Solvent Extract
1	Specific Gravity	0.884	0.823
2	Density(kg/m^3) at 45^oC	885	824
3	Colour	Reddish Yellow	Greenish Yellow
4	Odor	Odor of the seed	Odor of the seed

Fig 5.5. Water Extract

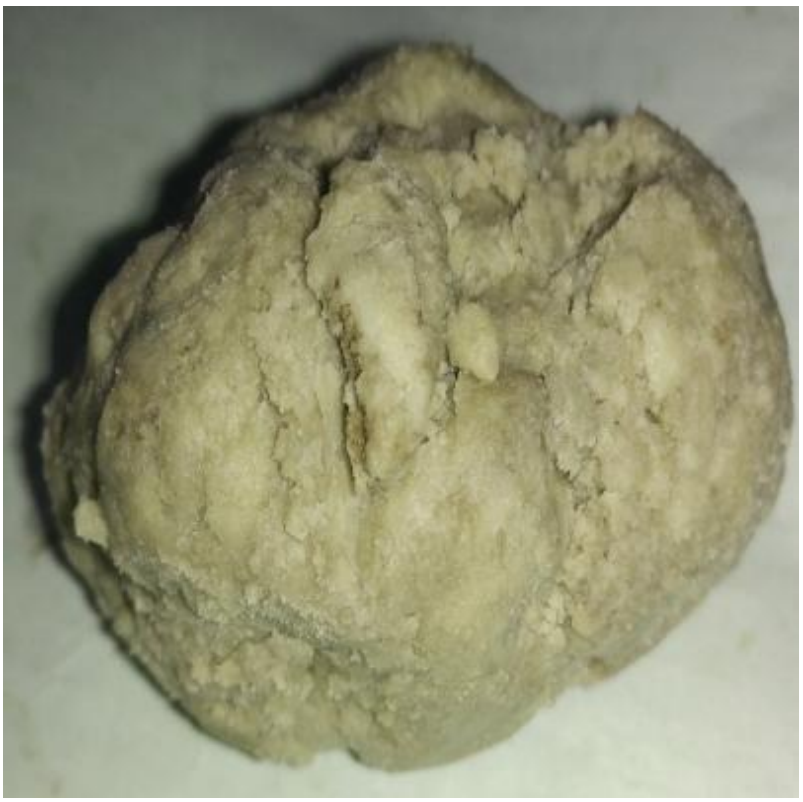

Fig 5.6. Solvent Extract

5. 3.2.2 Chemical properties

Chemical characterization of vegetable oils consists of determining key numbers and finding the constituents of the oil. Biochemical nature of the oil can be studied by determining the key numbers such as Saponification value, Acid value, Iodine value & Peroxide Value.(Islam M N,2015, Okene E.O et al,2014, Dutta Ratna et al,2014, Vanesa Y et al,2011).

5. 3.2.2.1 Acid value (IP 2007)

Acid Value is a number which expresses in milligrams the amount of potassium hydroxide necessary to neutralize the free acids present in 1g of the oil sample.

Method

2g of oil was weighed accurately and transferred into a clean conical flask. To this mixture of equal volumes of alcohol and solvent ether(15ml) were added, mixture was shaken well till the solution becomes clear. The solution is heated for some

time. Then 2-3 drops of phenolphthalein indicator was added and it was titrated against standardized 0.1N KOH solution. End point was found from colourless to pink. Acid value is calculated as

$$Acidvalue = \frac{Burett\ Reading \times ObtainedNormality \times IPFactor}{weightofoil \times actual\ normality} \text{----------(5.1)}$$

For Water extract,

$$Acid\ value = \frac{7.4 \times 0.1 \times 5.61}{2 \times 0.1} = 20.34$$

For solvent Extract,

$$AcidValue = \frac{3.8 \times 0.1 \times 5.61}{2 \times 0.1} = 10.65$$

5.3.2.2.2 Iodine Value (IP 2007)

Iodine Value is defined as the weight of iodine absorbed by 100 parts by weight of fat or oil under certain specified condition.

Method

0.1g of oil was weighed and added to clean conical flask.10ml of CCl_4 and 20ml of iodine monochloride was added to this by using burette. Then iodine flask was shaken well and kept in dark place for 30min. Occasionally it was rotated. To this 15ml of Potassium Iodide solution along with 10ml distilled water was added. Before titrating the flask was shaken properly and titrated against 0.1N $Na_2S_2O_3$ using starch mucilage as indicator towards end point. The blank was also carried out in similar way by omitting the sample. End point was change of colour from blue to green. Iodine value is calculated as

$$IodineValue = \frac{(b-a) \times ObtainedNormality \times 1.269}{Amountofsample \times ActualNormality} \text{ ----------(5.2)}$$

Where a=burette reading with sample

b=burette reading of blank

1.269= conversion factor

For water extract,

$$IodineValue = \frac{(17.8 - 14.6) \times 0.1 \times 1.269}{0.1 \times 0.1} = 40.608$$

For Solvent Extract,

$$IodineValue = \frac{(17.8 - 13.2) \times 0.1 \times 1.269}{0.1 \times 0.1} = 58.374$$

5. 3.2.2.3 Saponification Value(IP 2007)

Saponification value is the number of milligrams of potassium hydroxide required for neutralizing the combined fatty acids and the free fatty acids resulting from the complete hydrolysis (saponification) of 1g of oil.

2.2 grams (water extracted) or 2 grams (Solvent extracted) given fat is weighed accurately and transferred into a clean conical flask. 0.5N alcoholic KOH(potassium hydroxide) was added to the flask. Then reaction mixture was kept in water bath for about ½ h and refluxed using water condenser. The flask was frequently rotated while boiling along with the content. Then the flask was cooled and added with 1ml of freshly prepared phenolphthalein indicator and resulting mixture was titrated against 0.5N HCl. This procedure was repeated by omitting the sample for blank determination. The saponification number was calculated as

$$SaphonificationValue = \frac{28.05(b-a)}{w} \text{ ----------(5.3)}$$

Where Conversion factor=28.05

b=Burette reading for blank

a=Burette reading with sample

w=weight of the sample.

For water extract,

$$Saphonificationvalue = \frac{(26 - 19.8) \times 28.05}{2.2} = 79$$

For Solvent extract,

$$Saphonificationvalue = \frac{(26 - 11.1) \times 28.05}{2} = 208$$

5. 3.2.2.4 Peroxide Value (IP 2007)

Peroxide value is the number of milliequivalents of active oxygen that expresses the amount of peroxide contained in 1000grams of the substance.

Method

About 2g of the oil is weighed and transferred to 250ml glass stoppered conical flask. 30ml of a mixture of 3 volumes of glacial acetic acid and 2 volumes of chloroform are added and swirled till these are dissolved. To this solution 0.5 ml of saturated Potassium Iodide solution is added. This mixture is allowed to stand for 1 minute with occasional shaking. 30 ml of water is added and titrated against 0.01M Sodium thiosulfate until the yellow colour almost disappears. 0.5ml of starch solution is added to the flask and titration is continued shaking vigorously until the blue color just disappears. The procedure is carried for blank also. Peroxide value is calculated as

$$PeroxideValue = \frac{10(b-a)}{w} \text{ ---------- (5.4)}$$

Where

a=Burette reading with sample

b=Burette reading for blank

Dilution factor=10

w=weight of the sample

For water extract,

$$PeroxideValue = \frac{10(0.50 - 0.1)}{2} = 2.00$$

For Solvent Extract,

$$PeroxideValue = \frac{10(0.54 - 0.1)}{2} = 2.2$$

5. 3.2.2.5 Free Fatty Acids (FFA) (ASTM D 664)

Method

About 4grams of NaoH is weighed using a weighing scale & it is then added in to the one liter distilled water flask. The NaoH flakes are broken in to fine pieces by using glass rod until they dissolve fully in the distilled water. Now the N/10NaOH solution is ready to use. Now 25ml of the above N/10 NaoH solution is taken in a clean burette. 50ml of isopropyl alcohol is taken&10ml of raw VI oil is added. The mixture is heated to 60^0c in a conical flask& then allowed to cool. A few drops of Phenolphthalein Indicator is added to the mixture in the conical flask. It is now titrated against N/10 (0.1N) NaoH from the burette until a faint pink colour is obtained. Titration is continued until the pink colour persists for at least one minute. This is the titration end point.

FFA calculation

$$FFA = \frac{28.2 \times Normality of NaOH \times Titre Value}{weight of sample oil} \text{ ----------(5.5)}$$

For water Extract,

$$FFA = \frac{28.2 \times 0.1 \times 29.5}{10} = 8.3 > 4\%$$

For Solvent Extract,

$$FFA = \frac{28.2 \times 0.1 \times 15}{10} = 4.23 > 4\%$$

5.3.2.2.6 Calorific Value (ASTM D5865)

In the current study a bomb calorimeter was used to find HCV of VI oil.

The test involved following parameters.

Mass of the fuel=M=0.5grams

Mass of fuse wire=m_f=30 milligrams

Mass of cotton thread=m_{ct}=30milligrams

Water equivalent of calorimeter=W_s=2330 cal/^oC

Specific heat of water=C_w=4.187KJ/Kg K

Calorific value of fuse wire=C_f=0.335cal/milligram

Calorific value of cotton thread=C_{ct}=4.18cal/milligram

Higher Calorific Value of Water Extract:

$$Higher Calorific Value (HCV)$$

$$= \frac{Heat absorbed by Bomband water - Heat liberated by fusewire - Heat liberated by cotton}{Mass of Fuel Taken} \text{----------(5.6)}$$

$$= \frac{(W_S T) - (E_1 + E_2)}{M}$$

$$= \frac{(2330 \times 1.77 - 0.335 \times 30 - 4.18 \times 30)4.187}{0.5}$$

$= 33{,}346$ kJ/Kg.

Higher Calorific Value Of Solvent Extract:

$$Higher\ Calorific\ Value\ (HCV)$$

$$= \frac{Heat\ absorbed\ by\ Bomband\ water - Heat\ liberated\ by\ fusewire - Heat\ liberated\ by\ cotton}{Mass of Fuel Taken}$$

$$= \frac{(W_S T) - (E_1 + E_2)}{M}$$

$$= \frac{(2330 \times 1.64 - 0.335 \times 30 - 4.18 \times 30)4.187}{0.5}$$

$= 31756$KJ/Kg.

Table 5.2 Different numbers of VI oil

Number	**Water Extract**	**Solvent Extract**
Saponification Value (mg KOH/g)	79	208
Iodine Value(g I/g)	40.608	58.374
Acid Value(mg KOH/g)	20.34	10.65
Peroxide Value(meq O_2/1000g)	2.00	2.2
FFA	8.3%	4.23%
Calorific Value(KJ/Kg)	33,346KJ/Kg	31,756KJ/Kg

5. 3.3 Economy of solvent extraction pilot plant

It is observed that nearly 230ml of oil is obtained for 1.5Kg of powdered seeds and 50ml of hexane is lost in the process. It means that 15% yield oil is obtained. An amount of Rs20000 (298 US $) is made as fixed investment on the plant. 50ml Hexane costs Rs 14 (21 cents). Hence Rs 56 (0.8US$) is the cost of Hexane per liter of oil. If Rs 5 (8 cents) is taken extra for every trial of oil extraction on investment cost, the cost of oil would not exceed Rs 61 (0.9 US$) per litre. One litre of oil can be extracted from 7Kgs of seed. If Rs 4 (6 cents) is taken as cost for labour for collection of seeds, peeling and grinding one Kg of seeds, then Rs28 (48 cents) is required for 1 Kg of oil as labour cost. Total cost of production for extracting 1 Liter of oil would be Rs 89 (1.3 US$). Hence the solvent extraction works out to be best option with regards to biodiesel production. But the oil obtained cannot be used for oral consumption or medicinal purposes due to presence of traces of hexane in the oil. The oil may become suitable for oral consumption after further purification. Even then the cost oil cannot exceed more than Rs 120 (1.8 US$) which is far lesser than present price of aqueous extracted oil which is Rs 300 (4.5US$).

Percentage of oil yield is nearly 15% of the Kernel in case of Solvent extraction whereas it is less than 10% in case of Water extraction. The traditional Aqueous extraction needs more firewood .Hence the cost of oil thus obtained is more. The

solvent extraction pilot plant is found to reduce the cost of VI oil to a greater extent. If larger capacity plant is built with the same concept vapor loss can be reduced and investment cost per liter can be reduced which would reduce the cost of oil or fat further.

5.3.4 Analysis of properties of Solvent and Water Extracts

Density and specific gravity of both the extracts are found to be almost same and are 0.845 and 850 Kg/m^3 respectively (Table 5.1). The density of oil, being directly dependent upon the hydrogen and carbon content, is related to the calorific value of the oil. Therefore, the volume of high dense oil required is less as compared to the volume of lower dense oil to obtain the same amount of heat (Islam M N et al, 2015). Dense nature of both the extracts are almost the same. and their density is slightly more than that of diesel fuel. For other reasons such as more double bonds in triacyl moiety, calorific value is less for both the extracts. The water extract looks reddish yellow in colour and solvent extract resembles greenish yellow in colour (Fig 5.5 & 5.6). Both the extracts smell the smell of seed (Table 5.1).

Saponification values are highly significant in the making of soap (AuwalAliyu et al,2010).The Saponification value of Water Extract is far less than Solvent Extract. Transesterification is regarded as the best technique and the most promising solution to the high viscosity problem. Another attraction of the process is it's low cost and simplicity(Bhuiya M M K et al,2016) Therefore in the view of transesterification, soap formation may be a major hindrance in case of solvent extract. Upgradation of solvent extract is required for eliminating soap formation.

Iodine number is used as a measure of the degree of unsaturation of the fuel. Thermal instability and carbon deposits while burning are due to unsaturation in the fatty acid chain in the fuel.(Dutta Ratna et al,2014) Iodine value of Solvent extract is more that of Water extract. It means that Solvent extract consist of triglycerides that are having more number of double bonds (Amira Jelassi et al, 2014) It mans that even though fatty acid profile indicates the saturation there is unsaturation due to double bonds in Triglyceride moeity. The energy required to break these bonds is more. Hence transesterification of solvent extract require special conditions and up gradation like

acid esterification is required (Table 5.2). At the same time resulting biodiesel may cause carbon deposits.

Elevated acidity makes the production of biodiesel difficult as free fatty acids can impair the transesterification reactions because during basic catalysis they may be saponified (Edmilson Antonio Canesin et al, 2014). The acid value of both the extracts are high. Hence bio diesel production may be impaired.

The acid value of solvent extract is less than the acid value of water extract. The transesterification would result in high acid value biodiesel in case of water extract. (Table4.2). The rancidity incase of water extract is more. The lower fatty acids may be liberated due to hydrolysis in moist conditions. Furthermore these fatty acids may get converted to offensive aldehydes and acids in presence of metallic salts.

Peroxide value (PV) is an important characteristic of the edible oils quality.It is an indicator of the lipid oxidation and deterioration oil properties(Kardash-Strochkova E et al,2001). Large PV values showed the oils to be very unstable to oxidative degradation (Abdulkarim S M et al, 2014). Oxidative degradation leads to increased rancidity during storage(Natalie E et al, 2012).The Peroxide Value of both the solvent extract and water extract are less which indicates the ls(ess rancidity of both the oils and long shelf life for both of them. (Table 5.2)

Free Fatty Acids(FFA) is more than 4% for both the extracts. Therefore acid catalyzed esterification stage is required prior to base esterification (Table 5.2). Both the extracts are having lesser Calorific values compared to other bio oils (Dutta Ratna et al,2014, Oliveira L E, 2013) It is found that Calorific Value of Solvent Extract is slightly less. Hence biodiesel resulting from Solvent extract will have lesser Calorific Value

5. 4 CONCLUSIONS OF OIL EXTRACTION STUDIES

The following conclusions are drawn from oil extraction studies

1. Solvent extraction pilot plant is found to work satisfactorily
2. Solvent extraction is found to be economical in view of both cost and yield.
3. Physical nature of the oil is semisolid fat at room temperature.

4. Solvent extraction suggests the use of the *Vateria Indica* oil as the possible economic feedstock for biodiesel preparation.

5.5 PRODUCTION OF VIME

In this section of the chapter the protocol for the production of Vateria Indica biodiesel is discussed and effects of various factors on the production of the biodiesel are discussed.The chemical and physical characterization of are discussed in detail.

5.5.1 Materials Required for Production of VIME

Vateria Indica fruits were collected from wild region of Hebri of Udupi district, Karnataka state at South West Coast forest. All the chemicals and reagents (methanol, concentrated sulphuric acid, sodium hydroxide, *n*-hexane, anhydrous sodium sulphate) were analytical reagent grade and purchased from Sigma-Aldrich (India). All chemicals and reagents were used as received.

5.5.2 Acid-catalyzed esterification of *Vateria Indica* oil

Further, the extracted oil sample was dried using anhydrous sodium sulphate and directly taken for acid value determination. The acid value of the oil was found to be 10.65, necessitating acid catalyzed esterification before alkali catalyzed transesterification in order to avoid issues such as formation of emulsion during the following base-catalyzed biodiesel synthesis. A 2000 mL three necked round-bottom flask was used as a reactor. Heating of the reactants was done by placing it on a heating mantle whose temperature could be controlled within ±2 ^{o}C. The Reflux condenser is placed in the main neck. One of the side neck was used as a thermo well. Little glycerol is poured into themowell before inserting thermometer for temperature measurement inside the reactor. Magnetic stirrer is used to stir the mixture of reactants. (Bobade SN et al,2012).(Fig 5.7)

Fig 5.7 Acid Esterification and acid Layer separation

Exactly 1000 mL of *Vateria Indica* oil was transferred into a 2000 mL three necked round bottom flask and was heated up to 65^{o}C. Separately, 2.6 mL of concentrated sulphuric acid was added to 150 mL of methanol slowly drop-wise, with stirring and transferred carefully to 2000 mL flask. The reaction mixture was stirred at 750 rpm vigorously at 65^{o}C for 1.5 h continuously. When the reaction completes, the content of the flask was transferred to a dry separating funnel and allowed to settle for about 0.5 h. The lower layer consisting of oil with methyl esters of free fatty acid was separated from the upper acid layer and was taken directly for the next base-catalyzed transesterification step (Fig 5.7)(Olugbenga OA and Stephen KL,2013)

5.5.3 Base-catalyzed transesterification of pre-treated oil

After acid-catalyzed esterification, its acid value reduced to 0.9. The pre-treated oil was transferred to 2000 mL round-bottom flask and the content was heated upto 65^{o}C. Separately, in a 250 mL beaker, 0.2, 0.4, 0.6 and 0.8%of sodium hydroxide solution with balance volume of dry methanol was prepared considering the weight of the oil. The solution was stirred until the sodium hydroxide pellets were completely dissolved to get clear sodium methoxide solution. The prepared solution was heated upto 65^{o}C and slowly transferred into preheated oil. The mixture was stirred at 650 rpm vigorously for 40-90 minutes. The progress of the reaction was monitored by taking small volume of it in a test tube containing little water and observing the glycerine separation. After completion of the reaction, the content of the flask was transferred to a dry separating funnel and allowed to settle glycerol with soap as a bottom layer for about 1 hour. The lower layer was removed and the upper layer of crude biodiesel was purified to take away impurities like dissolved glycerol, soap, etc.(Fig5.8) The upper biodiesel layer was mixed with 100mL of hot distilled water and again it was shaken, finally it was allowed to remain in separating funnel for 1 h. The process of washing with hot water was continued until clear water was seen below the biodiesel in the separating funnel and to achieve the neutral pH in biodiesel. The pH of biodiesel was then checked. The washed biodiesel sample was then heated to about 100^{o}C by placing it on a hot plate for about 30 minutes to remove water and finally it was dried using a drying agent, anhydrous sodium sulphate. The obtained biodiesel is shown in Fig 5.9. The experiments were repeated with fresh batch of oil with varied concentration of catalyst, reaction time, temperature, oil to methanol mole ratio and stirring speed. These batches were performed to optimize the aforesaid parameters in order to obtain the highest yield of biodiesel.

Fig 5.8 Base esterification and Biodiesel separation

Fig 5.9 Vateria Indica Methyle Ester(VIME)

5.6 EFFECT OF VARIOUS FACTORS ON THE BIODIESEL YIELD.

5.6.1 Effect of molar ratio Oil : Methanol

According to kinetics of the reaction stoichiometrically, 3 moles of methanol should react to every one mole of triglyceride which yields 3 moles of its methyl ester and 1 mole of glycerol as per the equilibrium. So, theoretically oil to methanol molar ratio should be 1:03 (by molar masses of oil/methanol). To shift the above trans esterification equilibrium to right, it is necessary to use little excess of methanol.

Normally, higher molar ratio of oil to methanol interferes in the separation of glycerol (Idris AS, 2016) To optimize this parameter, experiments were carried out with 1:04, 1:06, 1:08, 1:10 ratio of oil to methanol (in terms of molecular masses) with different concentration of catalyst loading. All experiments were carried out at constant temperature of 65^{o}C and reaction time 80 min. to calculate the yields. Fig 5.10 shows the variation of VIME yield with molar ratio, oil: methanol. From the results, it is clear that the yield goes on increasing with increase in molar ratio and at 1:06 molar ratio shows the highest yield of 88% with 0.4% (w/w) of catalyst NaOH. Further increase in oil to methanol ratio does not affect the yield of VIME.

5.6.2 Effect of catalyst concentration (weight of NaOH in constant volume of methanol)

The effect of catalyst on yield of VIME was studied with catalyst varying from 0.2% to 0.8% considering the weight of oil. All reactions were carried out at constant temperature of 65 ^{o}C and reaction time 80 min with variation in catalyst concentration in oil. The results are summarized in Fig 5.11 The obtained results indicate that the yield of VIME increases on increase in catalyst concentration and a concentration of 0.4 % (w/w)of NaOH shows highest yield with 1:06 molar ratio of oil to methanol.

5.6.3 Effect of reaction temperature

The reaction temperature is an important parameter that affects the yield of VIME. To optimize the effect of temperature on transesterification reaction, experiments were carried out with variation of temperature from 60 to 70 ^{o}C, a fixed 1:06 molar ratio of oil: methanol, 0.40 % (w/w) of NaOH catalyst and the corresponding yields of VIME were determined. Fig 5.12 shows a graph of yield of VIME verses varied reaction temperatures. It has been noticed that the yield of biodiesel gradually increases with increase in temperature from 50 to 70^{o}C, thereafter it decreases with further increase in temperature. From the graph, it is clear that the highest yield has been obtained at 65^{o}C indicating the optimum temperature of the reaction as 65^{o}C.

5.6.4 Effect of reaction time

Reaction time is one of the important parameters that influences the yield of VIME. Generally, rate of conversion of triglyceride of fatty acids into methyl esters of higher

fatty acids increases with reaction time as the transesterification progresses towards completion. To determine the optimum time, experiments were performed at different time intervals, *viz.*40, 60, 70, 80, 90 minutes. and their corresponding yields were determined. The variation of reaction time with yield of VIME is summarized in Fig 5.13**.** The graph clearly indicates that reaction time increases steadily till 80 minutes and thereafter it remains almost constant indicating completion of the reaction. So, it can be concluded that the optimum value of time of transesterification is 80 minute.

5.6.5 Effect of stirring speed

The *Vateria Indica* oil is immiscible with methanol. Hence, in order to overcome, the mass transfer limit, oil and methanol was brought into contact by continuous agitation. In our experiments, a stirring speed of 650-700 rpm is enough for effective collision of molecules to form the products. Accordingly, all the experiments were conducted at the stirring speed of 650 rpm to obtain good results.

The optimized reaction conditions for maximum yeild are given in the flow chart shown in Fig 5.14.

5.7 PHYSICO-CHEMICAL CHARACTERISTICS OF BIODIESEL (VIME)

Various physico-chemical characteristics, *viz.* density, kinematic viscosity at 40^{o}C,acid value, cloud point, pour point, flash point, fire point, cetane index, calorific value, and copper strip corrosion number of newly synthesized VIME are summarized in Table 5.3. Also, the corresponding values of petro-diesel were listed in the table for comparison

Cetane index of VIME was determined by the method described in ASTMD976. Its kinematic viscosity of VIME was obtained with Cannon-Fenske viscometer tube number 100 (direct type) employing the standard ASTM D445 method. Density of newly synthesized VIME was measured using the method described in ASTM D4052. Flash and fire points of the biodiesel were determined using Pensky-Martin closed cup apparatus, following the procedure as described in ASTM D93. Pour point determination was conducted using pour point analyzer by automatic air pressure method as per the procedure described in ASTM D97. Acid number of VIME was

estimated as per ASTM D974 method. It is expressed in number of mg of KOH per g of fuel sample. Calorific value of VIME was evaluated using a bomb calorimeter as per ASTM D240 procedure. Copper strip corrosion test was conducted for the synthesized VIME following the procedure described in ASTM D130(Mustafa Balat and Havva Balat, 2008, Encinar et al,2002)

Density is one of the important characteristics of a fuel. VIME shows slightly higher value than that of conventional petro-diesel. When compared to the *Vateria Indica* oil, it is much less, but denser than fossil fuel. To overcome this problem for its use as a fuel, VIME can be conveniently blended with petro-diesel to desired percentage (Ertan A & Mustafa C, 2008)

Viscosity is also an important parameter that affects flow in pipeline, atomization and fuel spray rate in injector nozzle. Its value strongly depends on temperature, the higher is the temperature, lower will be the viscosity. Consequently, decreasing temperature causes an increase in viscosity. It can be specified in the form of kinematic viscosity and its value for a biodiesel ranges from 1.9-6.0 mm^2s^{-1}(ASTM D6751). Generally, lower viscosity facilitates handling of fuels at lower temperature. Moreover, most of the engines are designed to use low viscosity engine oils to reduce internal drag. This takes less power from the engine, reduces fuel use, lowers exhaust emissions, and improves engine responsiveness.

The kinematic viscosity of VIME was determined to be $4.5mm^2s^{-1}$, which is higher than that of petro-diesel. The value is slightly greater than that of other biodiesels because of presence of longer chain fatty acid ester and higher extent of saturation, but it is less than the ASTM D6751. Because of presence of electronegative oxygen atom, biodiesel is slightly more polar than petro-diesel, as a result viscosity of biodiesel is higher than that of petro-diesel (Refaat AA,2010)

Acid number of raw *Vateria Indica oil* was found to be 10.6mg KOH/g and it was reduced to 3.9mg KOH/g after pre-treatment with methanol in acid medium and finally the VIME showed the acid value of 0.45 mg KOH/g. This is almost near to the acid value of petro-diesel. The acid value was determined by titrating a known mass of VIME dissolved in ethanol-toluene mixture against standard methanolic KOH solution and using the formula:

Table 5.3 Physico-chemical characteristics of VIME and petro-diesel

Sl. No.	Properties	VIME	Petro-diesel
1	Density	876.2 kg m^{-3}	826.0kg m^{-3}
2	Kinematic Viscosity @ 40^{o}C	4.50mm^2s^{-1}	3.57 mm^2s^{-1}
3	Acid value	0.45mg KOH/g	0.35mg KOH/g
4	Cloud point	21 ^{o}C	-16^{o}C
5	Pour point	10°C	-10 ^{o}C
6	Flash point	138^{o}C	67^{o}C
7	Fire point	180 ^{o}C	-
8.	Cetane index	62	52.2
9.	Calorific value	38MJ/kg	42MJ/kg
10.	Copper strip corrosion no.	2	0

$$\text{Acid Number} = \frac{56.1 \times V_{KOH} \times N_{KOH}}{\text{Weight of VIME}}$$ where V_{KOH} = volume in mL of KOH solution, N_{KOH}= normality of KOH solution (Sonam M et al,2006)

Cloud point refers to the temperature below which biowax in biodiesel or wax in diesel separates and forms a cloudy appearance. Pour point of a fuel is the temperature below which it becomes semi solid and loses its flow characteristics. The pour point becomes important at lower atmospheric temperature especially in cold countries or regions. Generally, presence of solidified waxes thickens the oil and clogs fuel filters and injectors. VIME shows higher cloud point as well as pour point than that of petro-diesel. This problem can be overcome by blending the VIME with petro-diesel in certain ratio (Demirbas A et al,2006)

Flash point of a fuel is the lowest temperature at which vapors of the fuel will ignite, when an ignition source is brought near to it, while fire point of a fuel is the lowest temperature at which the vapors of the fuel will continue to burn for at least 5 seconds after ignition by an open flame. The flash point and fire point of VIME were found to be 138 ^{o}C and 180^{o}C, respectively. These values are higher than that of petro-diesel, which make VIME safer fuel during its storage, handling and transport (Balat M,2005)

Cetane number is an important property that judges the quality of a fuel. It is an inverse function of a fuel's ignition delay, and the time period between the start of injection and the first identifiable pressure increase during combustion of the fuel. Generally, ignition delay for higher cetane fuels will be shorter than lower cetane fuels. (Srivastava A &, Prasad R ,2000)(Gopinath A et al,2010) In most of time, cetane index is used as a substitute for the cetane number of diesel fuel. It is calculated on the basis of fuel's density and distillation range (ASTM D86). Generally, biodiesel shows higher cetane index than fossil fuel, which is mainly attributed to the presence of long carbon chain fatty acid ester (higher oxygen content) and absence of aromatics as well as sulphur compounds. In the present study, cetane index of VIME was found to be 62 which is higher than that of petro-diesel.

An important property of a useful fuel is its calorific value. It is the total quantity of heat liberated when a unit mass or volume of fuel is completely burnt in excess of oxygen. The higher calorific value of VIME was determined to be 38 MJ kg^{-1}, which is slightly higher than that of normal biodiesel. The calorific value directly influences the performance of any fuel in CI engines. The observed high thermal efficiency may be due to presence of increased percentage of saturated fatty acid methyl esters in the fuel. Generally, thermal efficiency and NO_x emission of saturated fatty acid biodiesel is comparatively better than that of high unsaturated fatty acid biodiesels (Gopinath A et al,2010). The unsaturated fatty acid biodiesel leads to longer premixed combustion and high peak pressure in engines. Further, polymerization of unsaturated fatty acid at high temperature is partly responsible for creating various other problems.

Normally, high acid values of any fuel results in corrosion of important internal parts of CI engine. Therefore, anti-corrosion property of biodiesel has an important role on efficiency as well as life-span of engine. The value of copper strip corrosion number of VIME was found to be 2, which is within the limits set by ASTMD6751 (Prakash, R et al, 2013)

It can be concluded that almost all physico-chemical properties of VIME are comparable to that of petro-diesel and they are found to be within the limit set by ASTM D6751, except pour point.

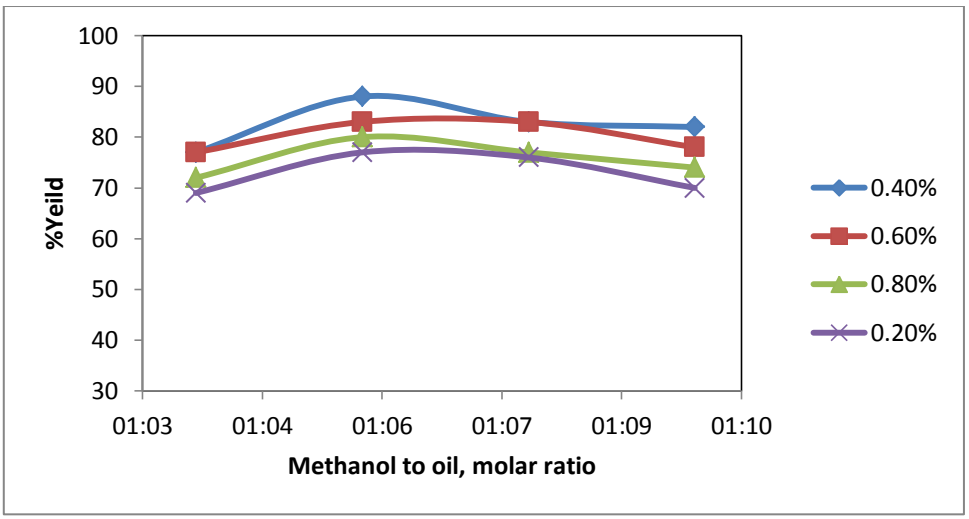

Fig 5.10 Effect of molar ratio of oil to methanol on VIME yield

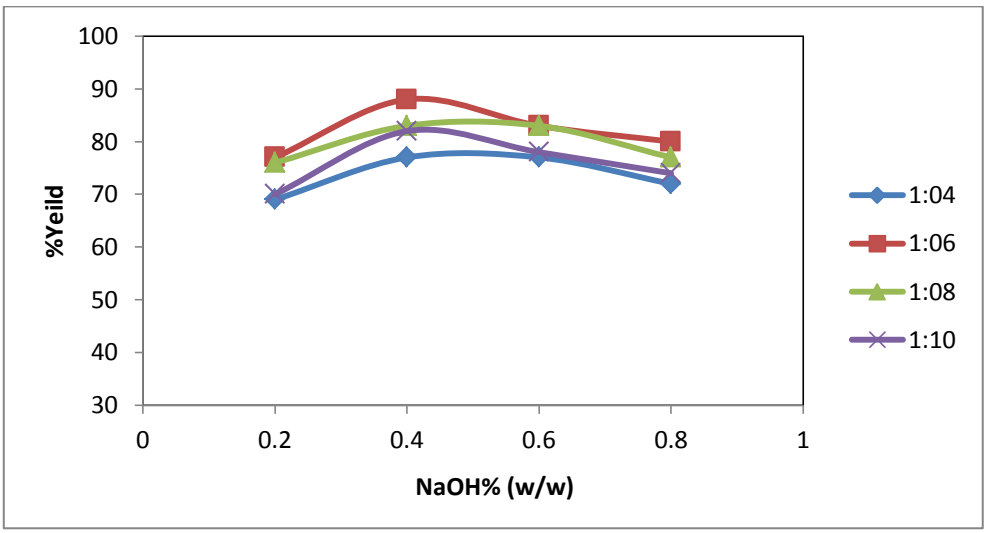

Fig 5.11 Effect of catalyst percentage (w/w) on VIME yield

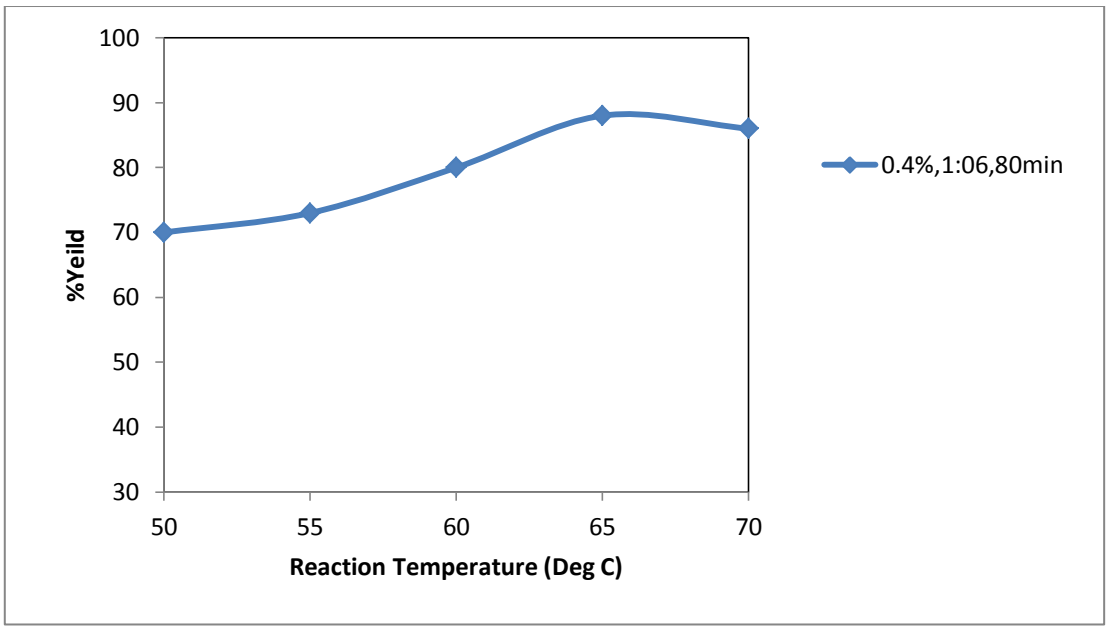

Fig5.12 Effect of reaction temperature on VIME yield

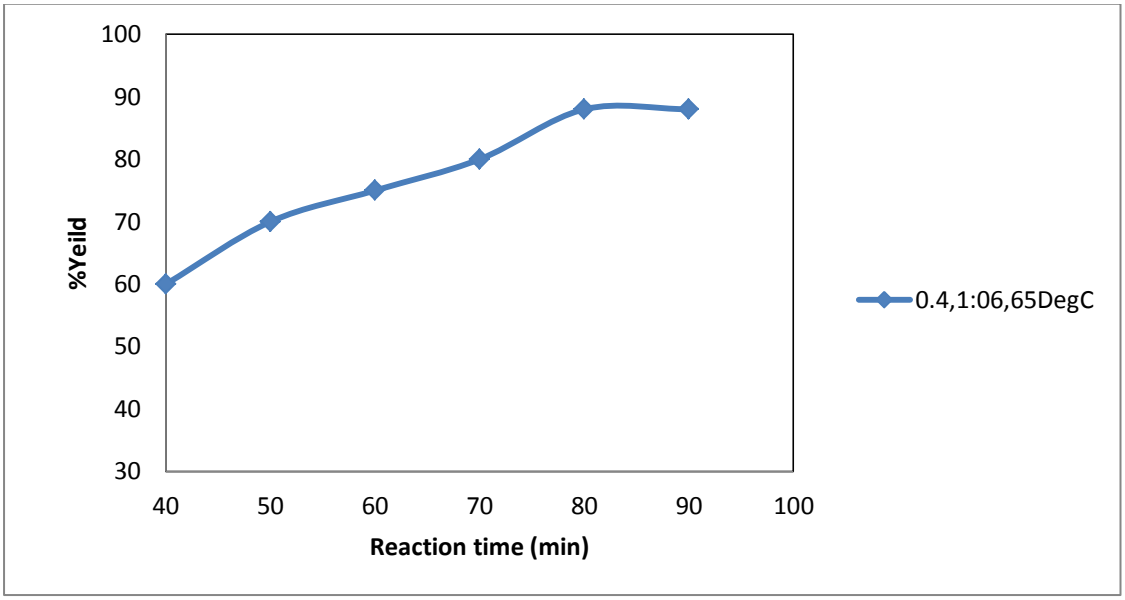

Fig 5.13 Effect of reaction time on VIME yield

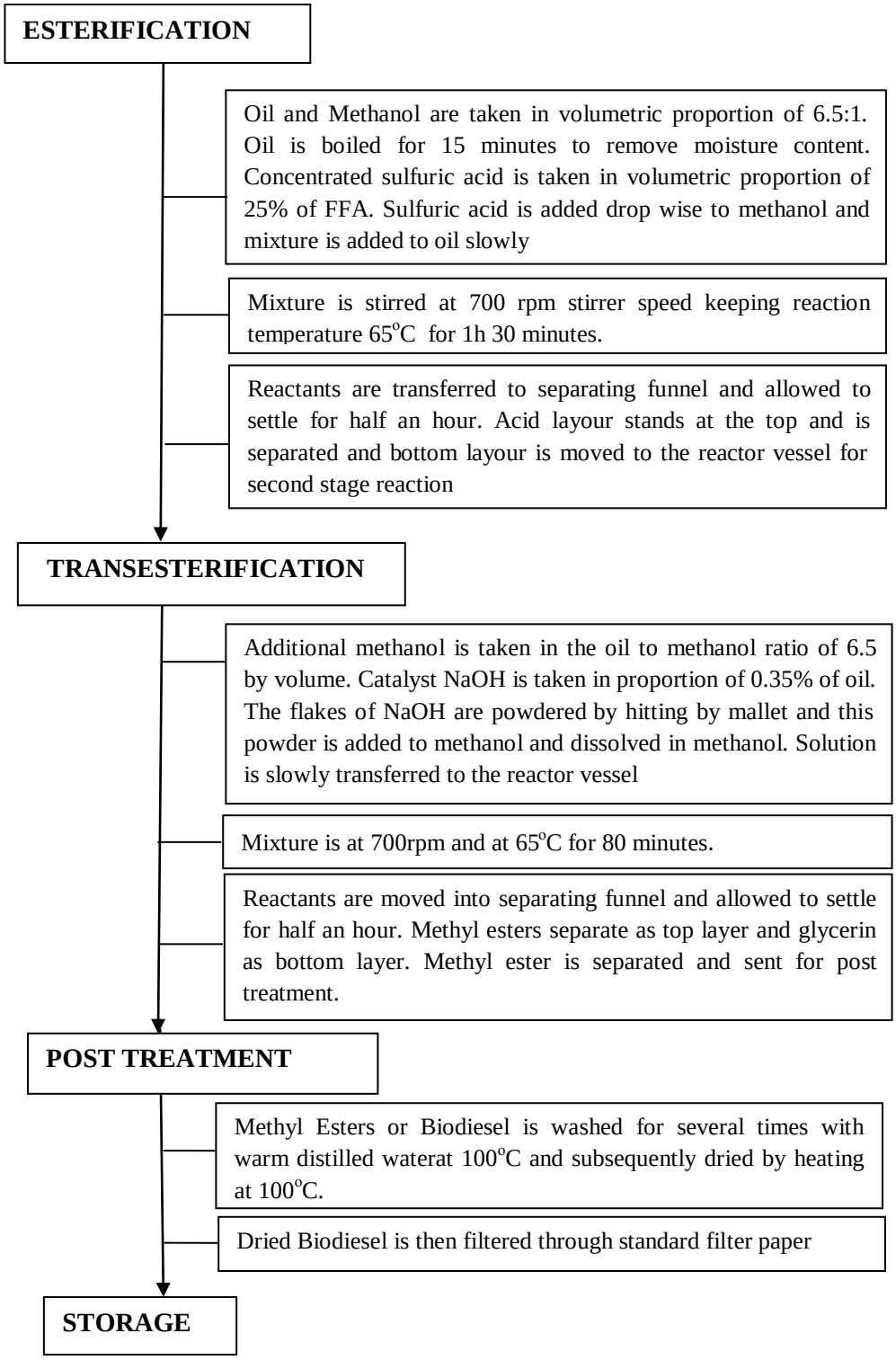

Fig 5.14 Flow chart for extraction of VIME

5.8 CHEMICAL CHARACTERIZATION OF VIME

Fatty acid ester profile was determined by gas chromatography using Thermo Scientific make GCMS, having a flame-ionization detector and a trace GC ultra Zebron ZB 5 ms capillary column of dimension 100 m x 0.25 mm id., 0.25 μm film thickness, split ratio of 1:10, injection temperature of 220^{o}C, flow rate of 1 mL/minute. Initially the oven temperature was 40^{o}C and slowly the temperature was increased to 300^{o}C with 5^{o}C/minute and held for 5 minutes at this temperature. The ratio of the VIME to solvent, *n*-hexane was 1:1000. The total run-time of the test was 30 minutes using helium as carrier gas. Retention times for different constituents were verified against retention times of authentic samples of individual pure fatty acid methyl esters. All relative percentages of abundance thus obtained for each fatty acid methyl ester sample is the average of triplicate runs. Additionally fatty acid ester profile of VIME are determined by FTIR, ^{1}H-NMR and ^{13}C-NMR spectroscopy was performed on a Bruker Alpha FTIR spectrometer, and Bruker (Bilerica, MA) Avance 400 spectrometer operating at 400 MHz with DMSO as a solvent. TMS was used as internal reference and chemical shifts, δ were reported in ppm (Isac G et al,2011 & Anju C et al,2011)

From the past two decades, NMR spectral method is being successfully employed in the study of oil chemistry and it also provides a detailed insights into pathway of the transesterification reaction of an oil. Further, these spectral techniques have been effectively used for quantification of biodiesel obtained from various sources and for confirmation of biodiesel formation (Wyatt VT &Haas, MJ,2009) To identify the different constituents in the test sample, gas chromatography-mass spectrometry (GC-MS) is used which has been regarded as an excellent technique and hence being widely used in oil chemistry to separate and identify individual methyl esters present in biodiesel in order to generate a unique fingerprint for each biodiesel feed stock. It is well-established that the composition of the parent oil with regard to fatty acid profile is found to affect the properties of final esters in biodiesel decisively, evidently saturated feed stocks excel in cetane number and oxidation stability with lower NOx emissions, while exhibit higher kinematic viscosity. In contrast, increasing unsaturation decreases the kinematic viscosity, improves the cold flow properties,

lowers cetane number, and deteriorates the oxidation stability. Interestingly, it is the most unsaturated feed stocks that are susceptible to rejection based on the existing specification limits. To obtain significant correlations between the degree of unsaturation and hence other fuel properties chemical composition data of the sample can be used. This correlation can be explained based on fundamental aspects of fuel chemistry. Consequences of this correlation on real engine operation also can be explained using fundamentals of oil chemistry (Isac G et al,2011). Keeping in view of the above, chemical characterization of VIME was carried out by using FTIR, ^{1}H-NMR and ^{13}C-NMR spectroscopy and GC-MS techniques in order to identify the major ester constituents and their percentage abundance in the sample, as these data play a pivotal role on their physical as well as chemical properties and hence, the quality of biodiesel.

Mid-range (4000-600 cm^{-1}) FTIR spectrum of VIME is shown in Fig 5.15**.** It is evident from the spectrum that appearance of a medium peak at 721 cm^{-1} is due to rocking mode of vibration of CH_2 group in the methyl esters. This peak, which has been overlapped by =C-H group indicates the presence of $-(CH_2)_n-$ linkage in the components. Small but weak peaks in the region of 850-880 cm^{-1} are attributed to =C-H bending mode in the unsaturated esters, characteristic absorption at 1195 cm^{-1} points out the stretching vibration of C-O bond and medium peak in the region of 1435 cm^{-1} shows the stretching of >C=C< group. A sharp but weak peak at 1463 cm^{-1} can be ascribed to bending vibration of C-H bond of the ester methyl group. A characteristic sharp peak at 1742 cm^{-1} appeared in the finger print region, which is the strongest in the entire spectrum is ascribed to >C=O group with the stretching mode of vibration, confirming the presence of ester group in the biodiesel. Further, the peaks at 2852 and 2922 cm^{-1} indicate symmetric and asymmetric stretching vibrations of C-H of alkyl group, respectively. A very small (shoulder) peat at 3000 cm^{-1} is due to stretching vibration of =C-H of alkene group, indicating presence of low percentage of unsaturated fatty acid ester in the biodiesel. Thus, the analysis of FTIR spectrum indicates that VIME contains mainly methyl esters of long chain aliphatic fatty acids (Jefferson SO et al, 2006 & Arun Shankar A,2017)

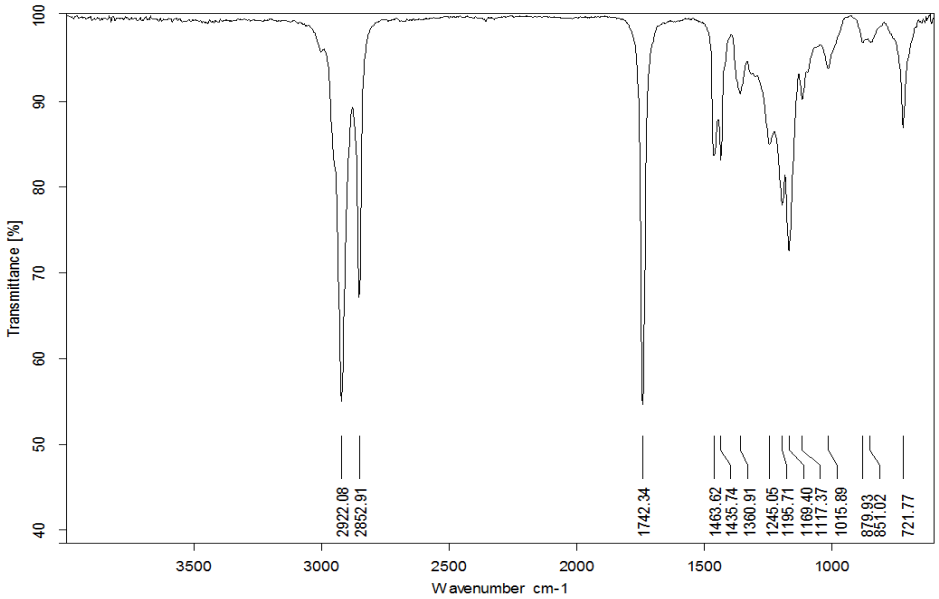

Fig 5.15 FTIR spectrum of VIME

In the present study, 50 µL of biodiesel sample was diluted to 500 µL with dimethyl sulphoxide-d_6 and was used to get one scan for the required ^{1}H-NMR spectrum (Fig 5.16). Essentially, biodiesel is a mixture of methyl esters of different long chain fatty acids like stearic acid, hexadecanoic acid, octadecanoic acid, etc. Therefore, the peaks due to various type of protons, *viz.* methyl (-C***H***$_3$), methylene (-C***H***$_2$-), methyne group (>C***H***-) would appear in the spectrum at different values of chemical shifts, δ in ppm. As the area of peak is proportional to the number of hydrogen atoms of each type in the sample, one can determine the fatty acid composition conveniently. The Fig 5.16 shows the ^{1}HNMR spectrum of pure VIME sample. The spectrum shows a number of clear peaks ranging from δ 0.83 to 5.35 ppm due to the presence of various kinds of protons in the sample. In the spectrum, olefinic protons resonate at δ 5.27-5.35 as multiplet (-C***H***=C***H***-) and the protons due to methoxy group of ester functionality appear at δ 3.56 as a singlet (C***H***$_3$-O-CO-). A set of three signals which appear in the region of δ 2.48-2.49 is due to the absorption by bis-allylic protons of the unsaturated fatty acid chain (-CH=CH-C***H***$_2$-CH=CH-). Further, the α-methylene protons adjacent to ketonic group of ester resonate as triplet in the region of δ 2.24-2.28 as triplet (-C***H***$_2$-CO-OCH$_3$). Appearance of series of peaks as multiplet in the region of δ 1.94-1.99 confirms the presence of α-methylene protons in the structure of

fatty acid ester (-C***H***$_2$-CH=C<). Further, a multiplet at δ 1.47-1.51 shows the presence of backbone β methylene protons to ester group (-C***H***$_2$-CH_2-CO-OCH_3). Furthermore, a sharp peak at δ 1.22 as singlet indicates the presence of methylene group linked to carbon atom of the chain (-(C***H***$_2$)x-). Lastly, a strong peak at δ 0.82-0.86 ppm appears as triplet accounting for terminal methyl group of fatty acid chain end (–CH_2C***H***$_3$) (Monteiro M R.et al, 2009)

The obtained^{13}CNMR spectrum of VIME is shown in Fig 5.17**.** In the spectrum, characteristic peaks were observed at δ 173.22, 129.58, 51.05, 40.12, 39.08, 38.87, 33.20, 31.23, 29.03, 28.95, 28.79, 28.62, 28.53, 28.45, 28.38, 26.50, 24.36, 22.06 and 13.86 ppm. Appearance of a peak at δ 173.22 ppm represents carbon of the ester group (-O-***C***O-) while signals at δ 129.53 ppm signifies the presence of olefinic carbons (-***C***H=***C***H-). A strong peak at δ 51.05 indicates the resonance of methoxy carbon of the ester group (***C***H_3-O-CO-) and signals at δ40.12-38.87 show the presence of carbon of O-CO-***C***H_2- group. Signals at δ 33.20, 31.23 ppm are due to -***C***H_2-CH_2-CH_3 while peaks at 29.03, 28.95, 28.79, 28.62, 28.53, 28.45, 28.38 ppm indicate the presence of all –(***C***H_2)$_x$. Peaks at 26.50, 24.36 ppm are due to –O-CO-CH_2***C***H_2- and a signal due to 13.86 ppm is for -CH_2-***C***H_3. In all, the methylene and methyl carbons of the fatty acid esters appear in the range from δ39.08-13.86 ppm, confirming the assigned structures. Thus, NMR results confirm the data obtained by GC-MS regarding fatty acid profile analysis (Muhammed T et al,2011)

Fig 5.18 shows the GS-MS chromatogram of VIME. The individual peaks shown by the gas chromatogram were compared with standards of MS data base and consequently identified. Relative abundance of four fatty acid esters was calculated from total ion chromatographed by computerized integrator and corresponding relative intensities and results are presented in the Table 5.4. Thus, VIME consists of 1.36% of methyl myristate (methyl tetradecanoate,$C_{15}H_{30}O_2$, RT= 5.51 min), 20.00% of methyl palmitate(C15:0, methylhexadecanoate,$C_{17}H_{34}O_2$, RT= 19.00 min), 33.18% methyl oleate(C18:1, methyl (Z)-9-octadecenoate, $C_{19}H_{36}O_2$, RT= 20.72 min)and 45.45% of methyl stearate (C18:0, methyl octadeconoate, $C_{19}H_{38}O_2$, T_R= 20.95 min). It can be concluded that spectral and GCMS results clearly confirm that the newly synthesized biodiesel contains high percentage of saturated fatty acid ester

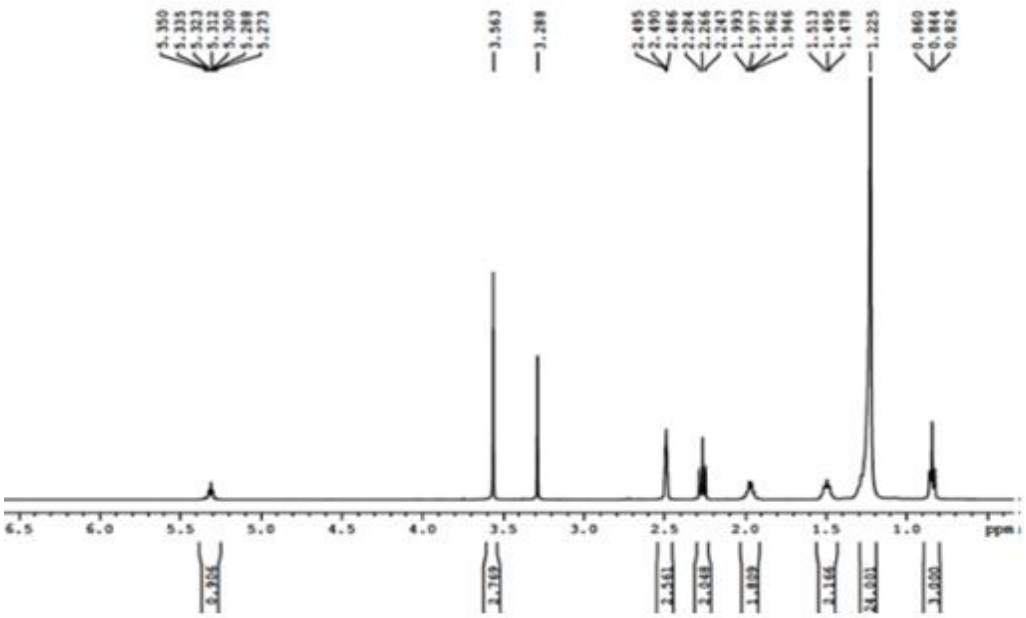

Fig 5.16 [1]HNMR spectrum of *VateriaIndica* Methyl Ester

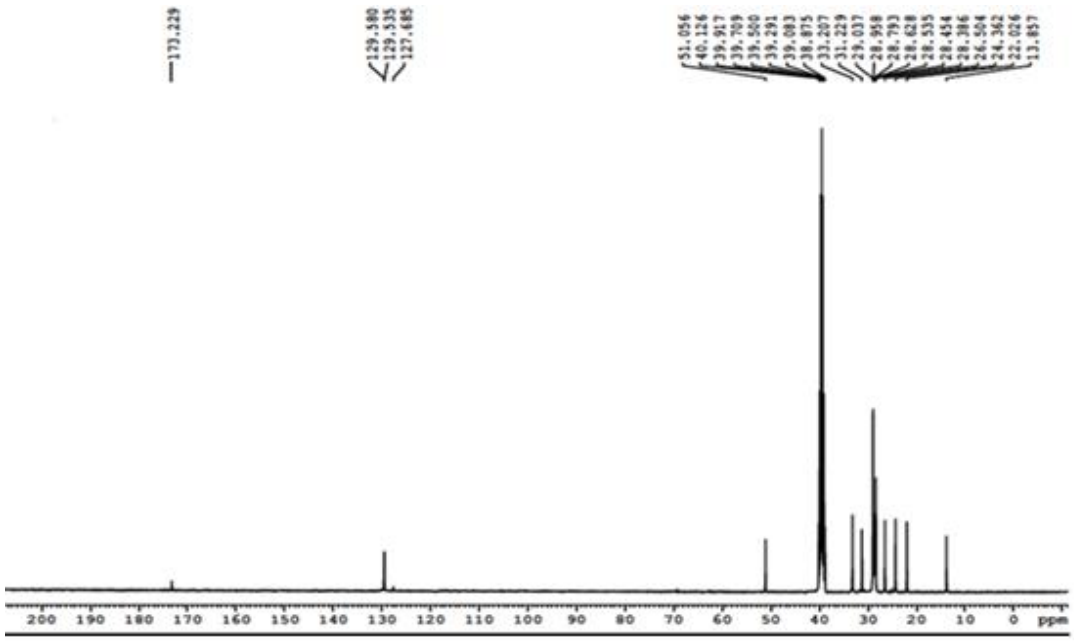

Fig 5.17 [13]C NMR of *VateriaIndica* Methyl Ester

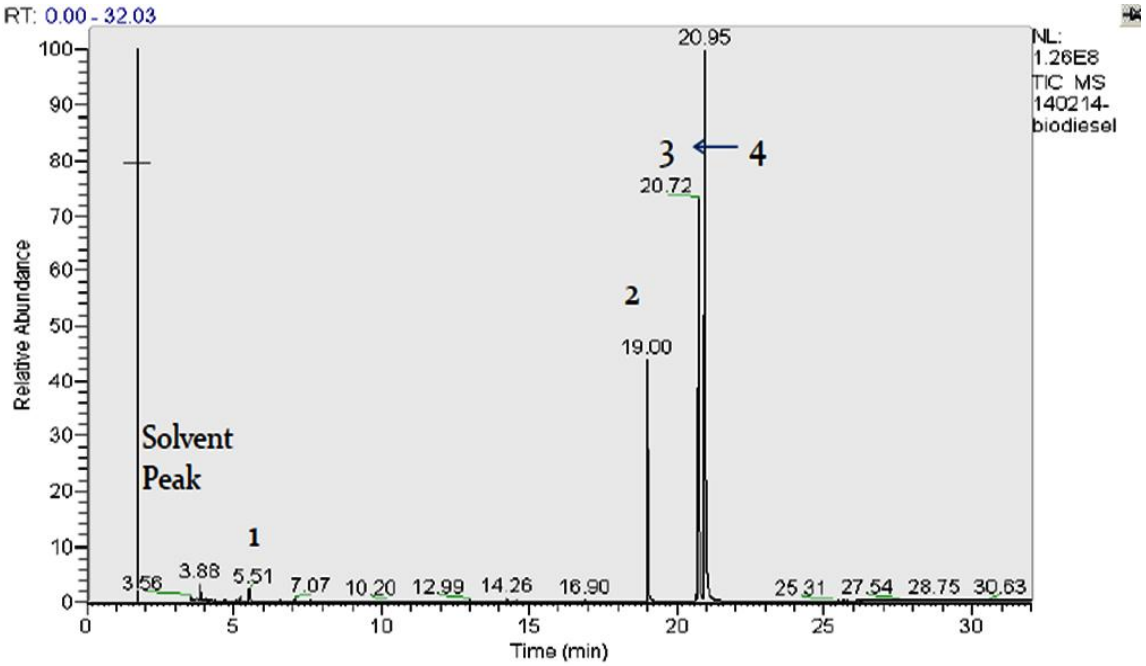

Fig 5.18 GC-MS chormatogram of *Vateria Indica* Methyl Ester

Table 5.4 Fatty acid profile of VIME

Sl. No.	Fatty acid ester	Retention time in min	Relative intensity in parts	% Abundance
1	Methyl myristate, $C_{15}H_{30}O_2$	5.51	3	1.36
2	Methyl palmitate, $C_{17}H_{34}O_2$	19.00	44	20.00
3	Methyl oleate, $C_{19}H_{36}O_2$	20.72	73	33.18
4	Methyl stearate, $C_{19}H_{38}O_2$	20.95	100	45.45

5.9 CONCLUSIONS ON PRODUCTION AND CHARACTERIZATION OF VIME

In the present work, fat/oil from *Vateria Indica* has been explored as a possible feedstock for production of biodiesel and accordingly, the oil extracted from its fresh kernels using a pilot plant, has been converted to biodiesel successfully by normal acid catalysed esterification followed by base catalysed transesterification with methanol. A maximum yield of 88% was obtained when oil: methanol molar ratio of 1:06 was transesterified at 65 ^{0}C, using 0.4% (w/w) of NaOH catalyst. The physico-

chemical properties of the VIME were determined as per the standard protocols and are within the limits set by ASTM standards. Based on the results, it can be inferred that blending biodiesel with petro-diesel in small proportion may reduce the large differences in certain physico-chemical properties between the two feed stocks. Chemical characterization using FTIR, NMR and GC-MS techniques reveal that VIME contains 1.36% methyl myristate, 20% of methyl palmitate, 33.18% of methyl oleate and 45.45% of methyl stearate comprising more % of saturated fatty acid methyl esters. Overall, *Vateria Indica* fat seems to be potential feedstock for biodiesel production in terms of ASTM standards. The production of biodiesel from *Vateria Indica* may provide additional economical value and may help local, regional, national economy of India.

Chapter 6

RESULTS AND DISCUSSION

6.1 ENGINE TESTS

The engine performance, combustion characteristics and emission characteristics with *Vateria Indica* biodiesel-diesel blends under varying injection pressure and injection timing with exhaust gas recirculation are presented in this chapter. The first part of this investigation is studying performance, combustion and emission characteristics of blends B10, B15, B20 & B25 and diesel under varying injection pressures of 180,200,220 bars at standard injection timing of 23^{o}bTDC. In the second part of the investigation performance, combustion, emission studies of blends B10, B15, B20, B25 and diesel are done by advancing and retarding the injection timings viz,19^{o}bTDC, 27^{o}bTDC under best injection pressure. In the next part of the study is the variation of EGR of 5% and 10% is done for best injection pressure and injection timing for optimum blend. Finally best blend with suitable EGR and injection pressure and injection timing are arrived at.

6.2 STUDY OF PERFORMANCE, COMBUSTION, EXHAUST EMISSIONS OF VARIOUS BLENDS AND NEAT DIESEL AT DIFFERENT INJECTION PRESSURE

It is observed that viscosity of biodiesels generally higher than conventional diesel. Due to this at lower injection pressure sauter mean diameter of fuel droplets will be high and hence evaporation rate is low. To decrease the sauter mean diameter(SMD) of biodiesel blends are injected at higher pressure. In this study three injection pressures viz 180 bar,200 bar,220 bar are attempted.

6.2.1 Injection pressure at 180 bar

This section gives the results of the experiments conducted with diesel and various biodiesel-diesel blends of B10, B15, B20, B25 with varying loads of 25, 50, 75 &

100%. Since the electrical dynamometer is used instead of % loads corresponding Brake Powers (kW) of 0kW, 1.125kW, 2.2 kW, 3.285kW and 4.3 kW used for reference. The performance, combustion and emission characteristics are investigated at injection pressure of 180 bars and fuel injection timing is kept at 23°bTDC. The results are presented and discussed with graphs.

6.2.1.1 Cylinder Pressure and Heat release rate

The comparison of the variation of cylinder gas pressure vs. crank angle for the test fuels at 75% load condition is shown in Fig 6.1 & 6.2. There is no trend could be observed in cylinder gas pressure due to pressure perturbations. Pressure perterbations could be due to knocking tendancy particularly in blends. The peek pressure observed for all the fuels in the region between 64 bar to 65 bar.

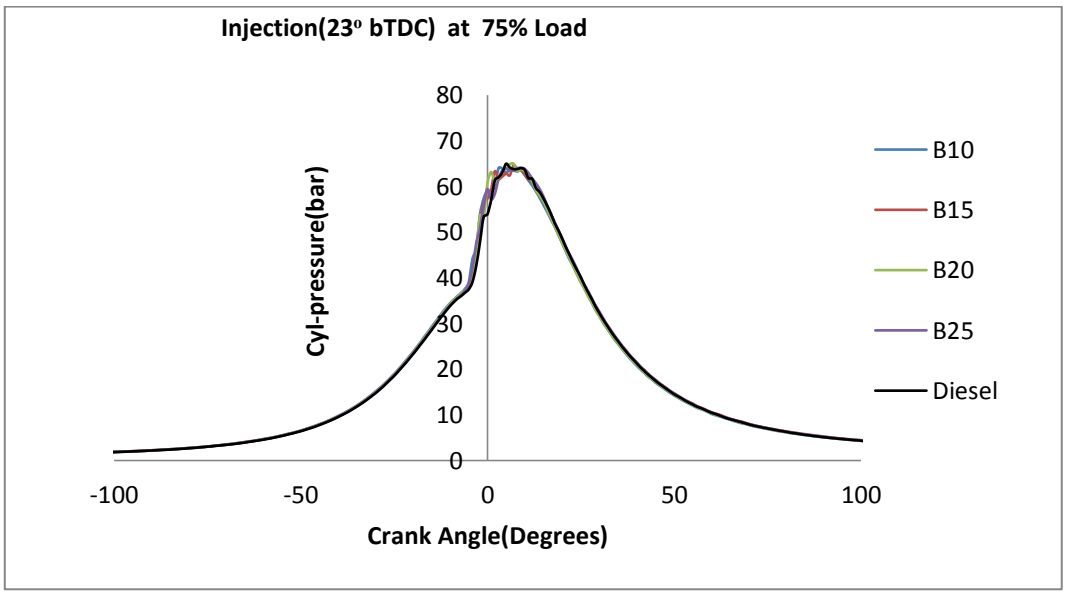

Fig 6.1 Variation of cylinder pressure with crank angle for 180 bar injection pressure

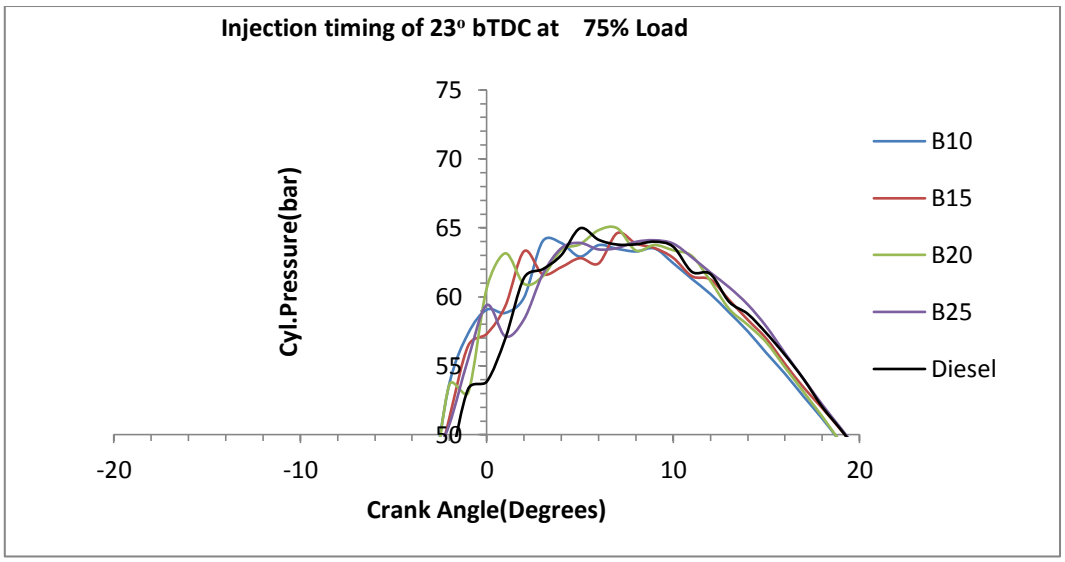

Fig 6.2 Enlarged peak of 6.1

Fig 6.3 shows the heat release rate for all the tested fuels. At the beginning of the curve negative heat release rate is observed because of the vapours of the fuel gets accumulated near the injector during the ignition delay period absorbing heat of vaporization and once the combustion is started heat release rate becomes positive. Diesel fuel does not contain oxygen in its chemical structure hence it requires certain time to initiate combustion process. So higher negative heat release rate was observed for diesel as compared to blends. For all the blends heat release rate is found to be better compared to neat diesel because of more oxygen available in fuel blends and 60% of the combustion is found to occur between 10^{o}bTDC and 20^{o}aTDC for all blends. maximum heat release is found to occur for B25 compared to other blends and diesel fuel. Fig 6.4 shows variation of cumulative heat release rate with crank angle degrees. It can be observed that cumulative heat release rapidly increases in the early part of the combustion and flattens after wards. As the combustion proceeds the heat release becomes better for blends B15 and B25 oxygen in the structure of these blends may be released after a initial heating. For blend B10 combustion seems to take more time and it remains more incomplete as rate of increase of cumulative heat release is less in early as well as late parts of combustion. B20 blend performs poor compared to B15 and B25 as far as heat release is concerned. It may be because for this blend late combustion is found to occur. From the Fig 6.5 and Table 6.1 it is

obvious that exhaust gas temperature for B25 blend is less at 75% load and it is increasing for higher loads. Least energy loss in exhaust gasses is going to occur in B25 because of better combustion.

6.2.1.2 Brake specific energy consumption(BSEC)

Fig 6.6 shows the variation of BSEC for the various fuel blends at different load conditions. For all blends, specific energy consumption decreases upto part load and becomes almost constant there on. BSEC at 75% load for diesel is 15043.87 kJ/kW-hr whereas it is 14268.22kJ/kW-hr, 13584.9 kJ/kW-hr, 13220.71kJ/kW-hr, 12837.54 kJ/kW-hr respectively for B10, B15, B20, B25. The BSEC decreases by 5.2%, 9.7%, 12.1%, 14.7% respectively for B10, B15, B20, B25 blends. Since heat release is better for the blends there is considerable reduction in BSEC compared to diesel even though the calorific values are less for blends. The similar result is obtained by Ali M.A et al (2016) when waste cooking oil biodiesel is used in an experiment. In the present work even though the cumulative heat release is more for B15 & B25 and BSEC is less for these blends. This may be due to additional oxygen available in these blend may improve the combustion efficiency.

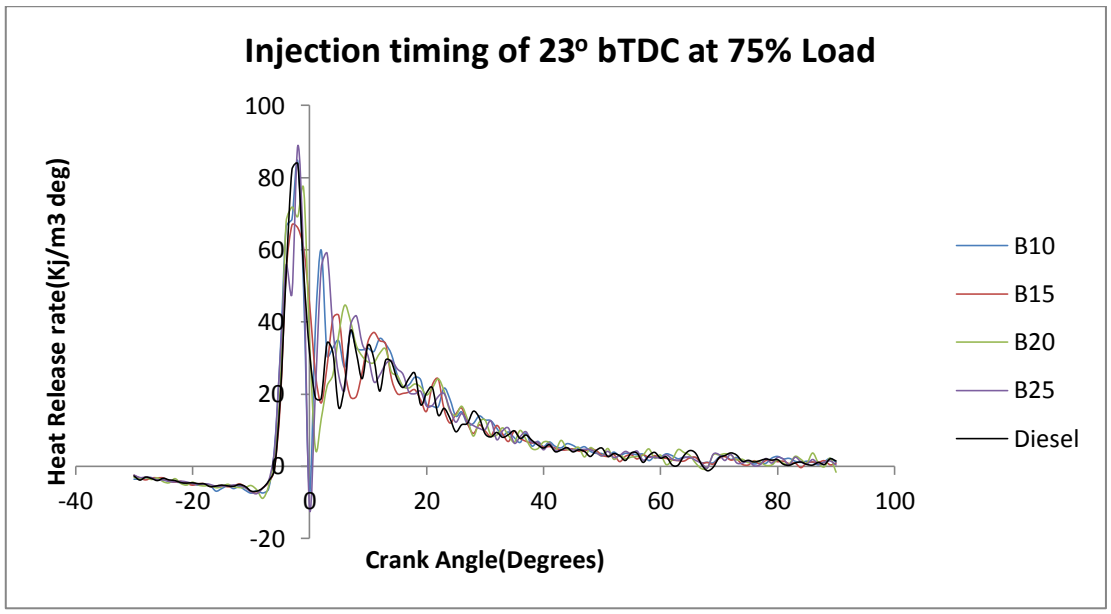

Fig 6.3 variation of heat release rate with crank angle degrees at 180 bar injection pressure

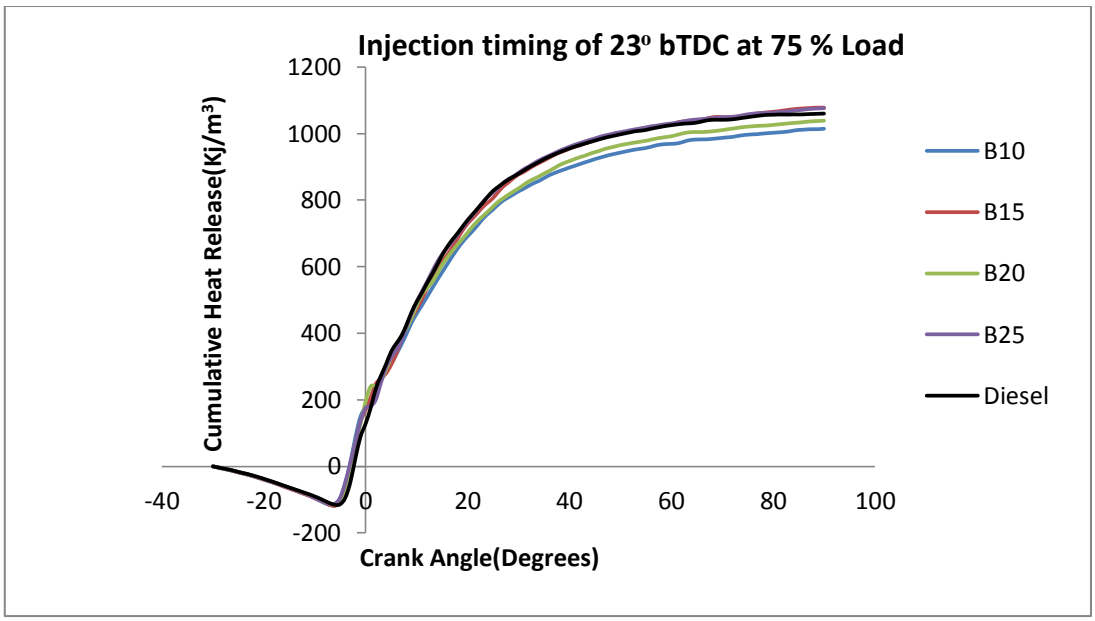

Fig 6.4 Variation of cumulative heat release with crank angle at 180 bar injection pressure

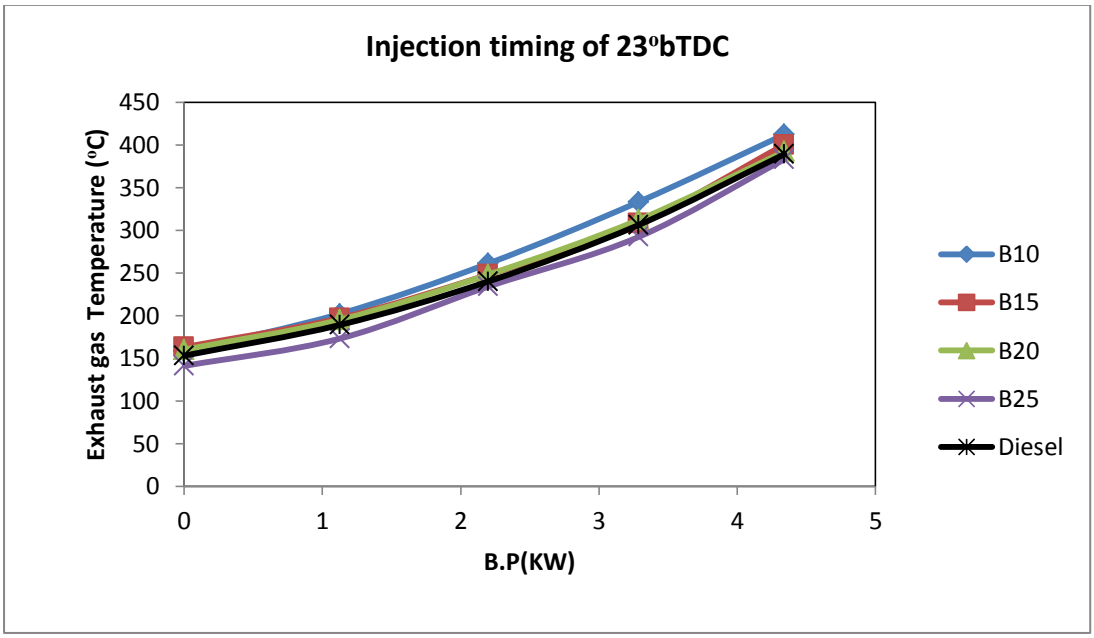

Fig 6.5 Variation of exhaust gas temperature with Brake power for 180 bar injection pressure

Table 6.1 Variation of exhaust gas temperature for different test fuels at 75% load.

Fuel	B10	B15	B20	B25	Diesel
Temperature of the Exhaust(^{o}C)	412	308	312	292	306

6.2.1.3 Brake thermal Efficiency

The Fig 6.7 shows the variation of brake thermal efficiency with varying engine loads. The BTE generally increases with engine load for all the fuels, but it is observed to be maximum for 75% load. Even though cumulative heat release is better for B10, B20 blends compared with B25, BTE is more for blend B25. This may be due to two reasons. One is late combustion occurring for B10 & B20 and another is oxygen quantity is more in B25. But B15 is found to perform poor because heat release is less throughout the stroke for this blend. But B15 found to perform better than B10. This may be because whatever the heat released is transferred to the piston during power stroke. In a study (Mosarof M H et al,2015) it was found that compared with diesel, palm oil blends have less brake thermal efficiency because of lower calorific values at 40%, 60%,and 100% load.

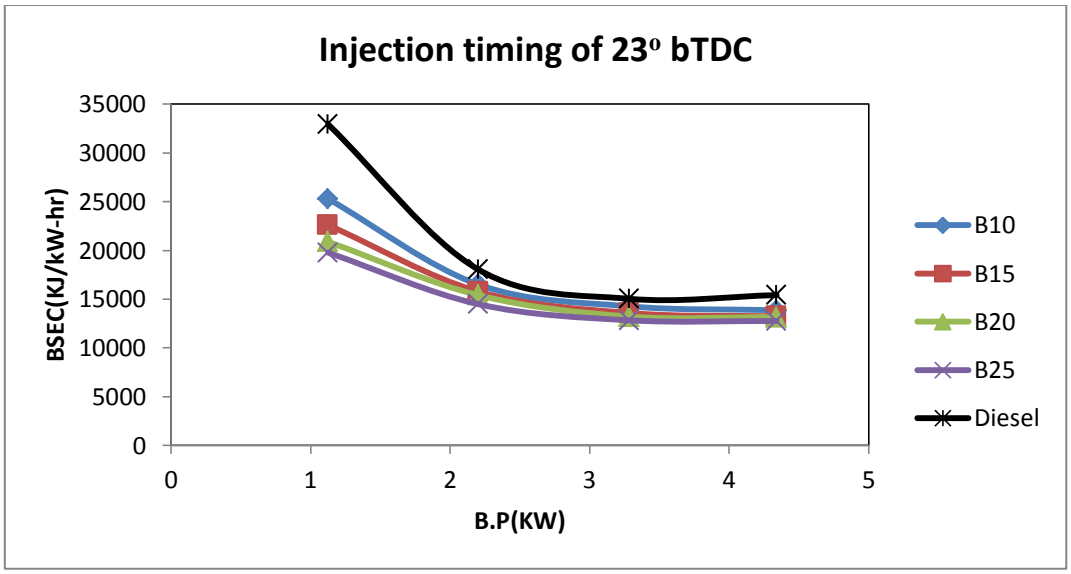

Fig 6.6 Variation of BSEC for the fuel blends at 180 bar injection pressure.

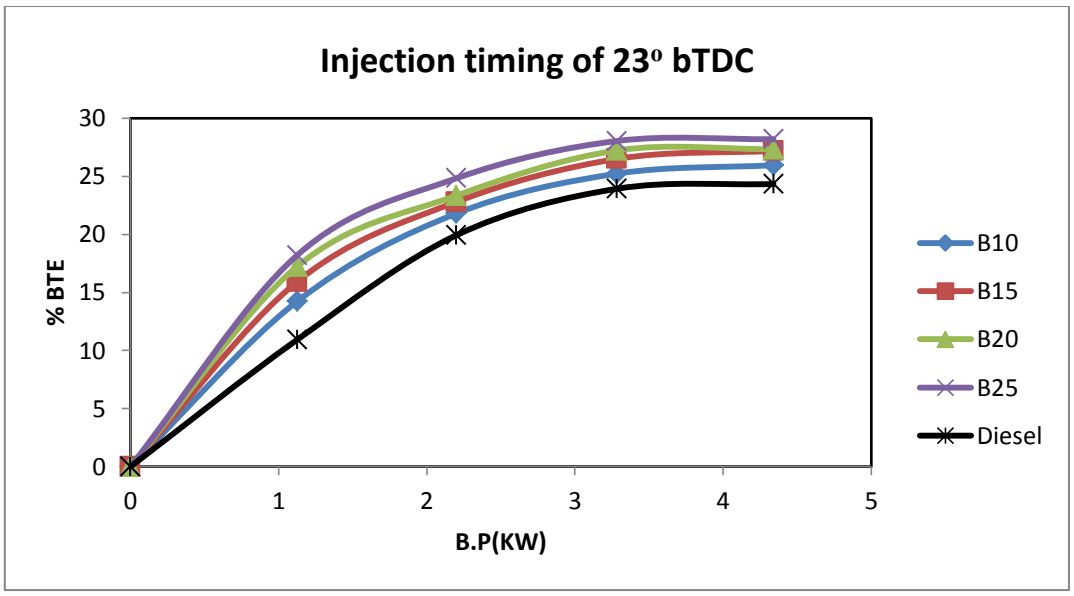

Fig 6.7 Variation of brake thermal for fuel blends at 180 bar injection pressure.

In this study it is found that even though calorific value of *Vateria Indica* biodiesel is less than that of diesel BTE is more for blends when compared with diesel. This may be due to increased oxygen quantity in blends and reduced ignition delay. The blends are found to perform better as the quantity of biodiesel increases. Similar result is obtained by Obed M Ali et al(Obed M Ali et al, 2016) for palm biodiesel. But M. Gumus et al(M. Gumus et al,2010) observed reverse phenomena for apricot seed biodiesel.

6.2.1.4 NO_X emission

Fig 6.8 shows the variation of NO_X emission for various fuel blends at different load condition. NO_X emission is found to increase with load for blends as well as diesel because increased temperature inside the combustion chamber. NO_X emission for diesel at 75% load is 1000 ppm whereas it is 1010ppm, 1080ppm, 1120ppm, 1180ppm for blends B10,B15, B20,B25 respectively. NO_X emission is observed to increase by 1.0% ,8%,12%, 18% for B10, B15, B20, B25 blends respectively compared to diesel. NO_X is formed due to reaction between N_2 and O_2 at high temperature in the combustion chamber. The formation of NO_X depends on in-cylinder temperatures, oxygen concentrations in the reactants and residence time for the reaction to take place. In addition at high combustion temperatures , N_2 and O_2 in

the combustion chamber disassociate into their atomic states and participate in a series of reactions. When compared to diesel *Vateria Indica* biodiesel blends have more oxygen in them. Hence NO_X emission is considerably more for all the blends The same trend was observed with almond biodiesel blends when compared with diesel (Nidal H et al,2015). This may be due to better combustion due high oxygen content in the blends. NO_X emission is more when blending ratio is more. Harveer S. Pali et al(Harveer S. Pali et al, 2015) observed same phenomena ie as biodiesel concentration increased NO_X emission increased for Sal oil biodiesel.

6.2.1.5 CO emission

It is observed from Fig 6.9 that CO emission increases as the engine load increased due rich mixture requirements during high load conditions. Compared to diesel all biodiesel blends have lesser CO emissions. Blend B25 has minimum CO emissions. It is observed that at 75% load blends B10, B15, B20, B25 blends have 16.7%, 33.3%, 50%, 66.7% less CO emission respectively compared with diesel. Since blends are high oxygen content fuels combustion is more complete and hence lesser concentrations of CO are observed. CO emission becomes lesser when biodiesel concentrations increase. This is similar to results obtained by Anderson Antunes de Paulo et al(Anderson Antunes de Paulo et al,2016) Higher concentrations of oxygen in higher blend lead to better combustion and hence lesser CO emissions. This phenomena is observed when citrus sinensis biodiesel when blended with diesel(Gokhan Tuccar et al,2014). When the load increases, CO emission increases due to lack of oxygen in local region and lower excessive air coefficient(Ma Zhihao et al,2011).

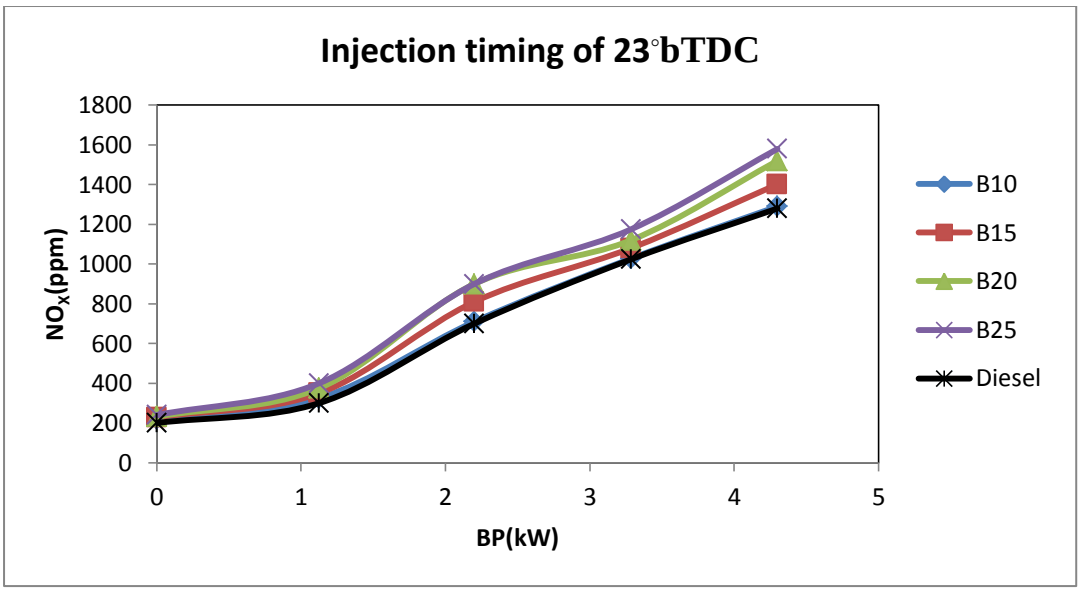

Fig 6.8 Variation of NO_X emission for fuel blends at 180 bar injection pressure.

6.2.1.6 HC emission

The variation of HC emission at different loads for different blends is shown in Fig 6.10 Hydrocarbon emission increases as the engine load is increased and maximum HC emission is observed for 100% Load. It can be observed that as biodiesel concentration in the blends increase HC emission decreases. The reason why HC emission decreases is additional oxygen availability in their structure which would aid the combustion rate to increase and complete combustion occurs. A decrease of HC emission 5.26%, 10.5%, 10.5%, 15.7% is occurring for blends of B10, B15, B20, B25 respectively when compared with diesel at 75% load. The higher cetane index of biodiesel results in decreased delay period for higher blends and hence better combustion is occurring and reduced HC emissions. In a similar study done on camelina biodiesel emission of HC for blend B7 was found to be 37.5% lower and HC emission for B100 fuel was found to be 68.8% lower compared to that of diesel fuel(A. Engin Ozcelik,2015)

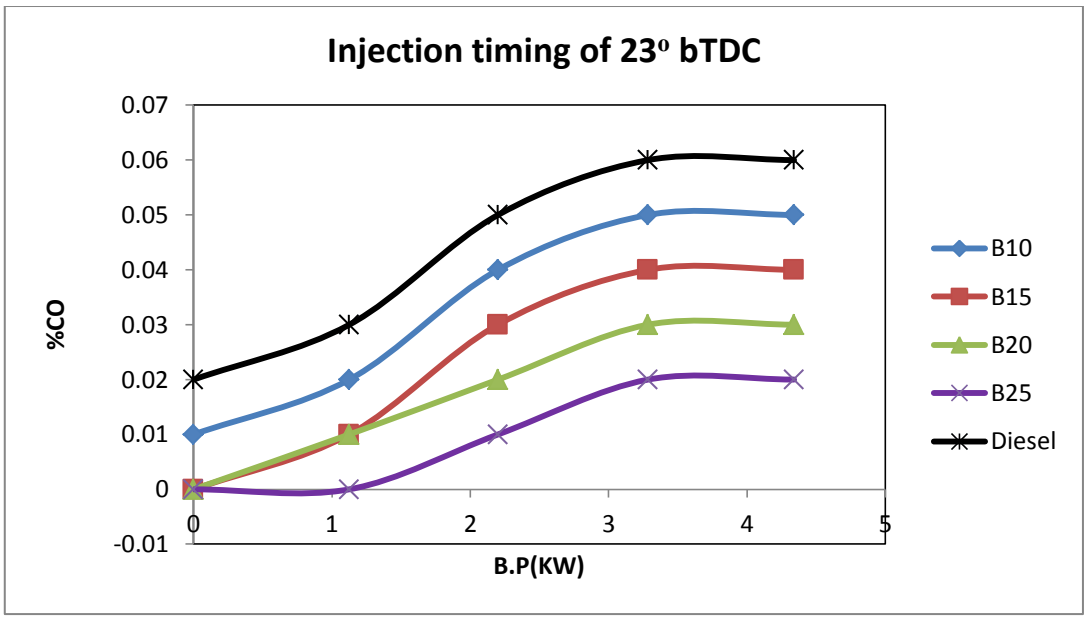

Fig 6.9 Variation of CO emission for fuel blends at 180 bar injection pressure.

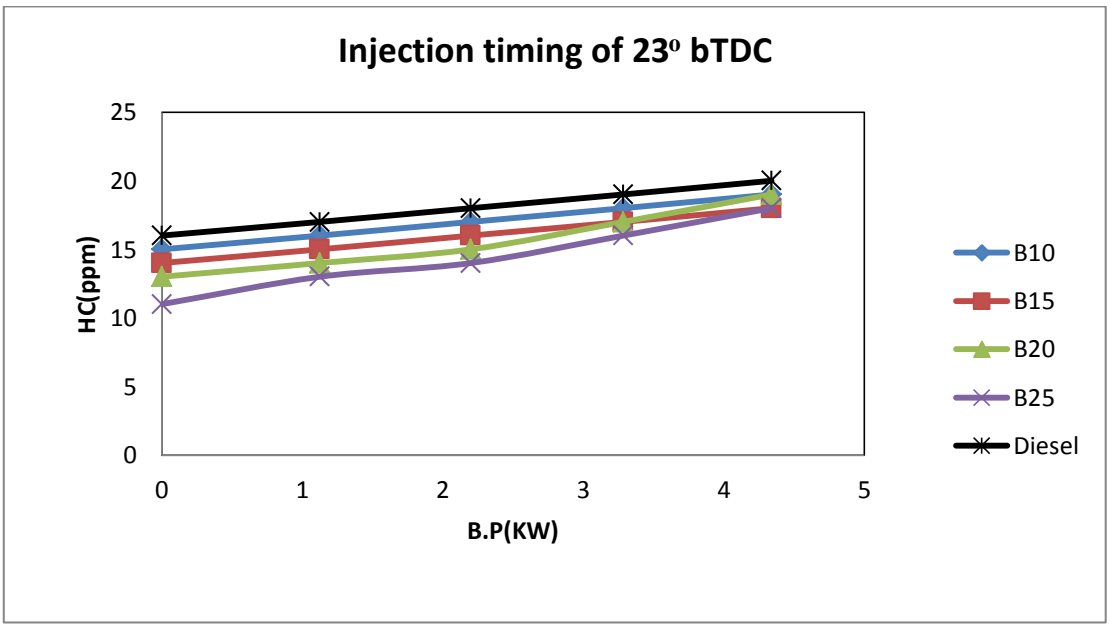

Fig 6.10 Variation HC emission for fuel blends at 180 bar Injection pressure.

6.2.1.7 Smoke emission

Variation in soot density for biodiesel blends is shown in Fig 6.11. It is observed that particulate matter (PM)is more in diesel exhaust compared with blends. At 75% load,

smoke density increases by 100%, 100%,100%,300% for blends B10, B15, B20, B25 respectively when compared with diesel. Since the biodiesel is an oxygenated fuel and during pre mixed combustion more heat is released for biodiesel blends and combustion is more complete for biodiesel blends(Raheman, H et al,2007) Due to increased after burning due to early combustion disassociation reactions occur and CO_2 splits into C and O_2. Hence soot concentration increases with blending concentration. As load increases it can be observed that soot or PM increases in the exhaust due to incomplete combustion at higher loads. Filter smoke number(FSN) is a measure of smoke density. Fig 6.12 shows the Variation of FSN for blends which is similar to smoke density for various blends.

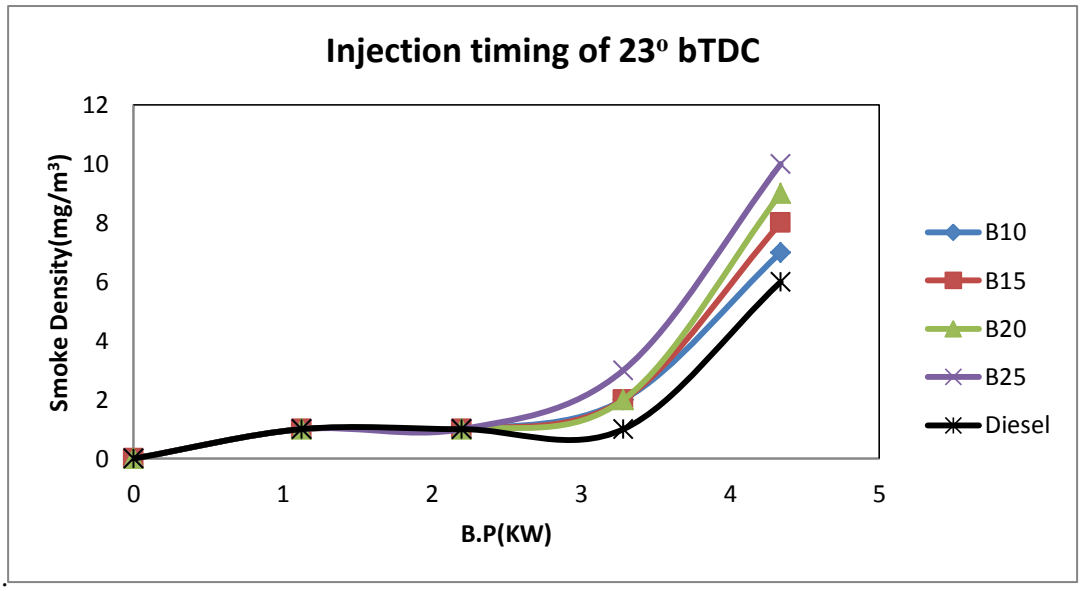

Fig 6.11 Variation of smoke density for fuel blends at 180 bar Injection pressure

6.2.1.8 CO_2 emission

The variation of CO_2 emission of the engine for different fuel blends is depicted in Fig 6.13. It can be observed that CO_2 emission increases for all fuel blends as the load is increased. At higher loads rich mixtures are burned and hence combustion will be incomplete. Hence CO_2 emission increases at higher loads. But because of more pre mixed combustion is occurring due to decreased delay period for blends, fuel gets more time for after burning phase in which disassociation of CO_2 occurs to produce carbon and oxygen. As the biodiesel concentration is more in higher blends this

phenomena is more. Hence higher blends emit more of soot and less of CO_2. At 75% Load CO_2 emission is increases by 13%, 7.4%, 7.4%, 3.7% compared to diesel for blends B10, B15, B20, B25 which phenomena supports the above argument. But diesel has less CO_2 emission compared to blends which indicates less disassociation reaction.

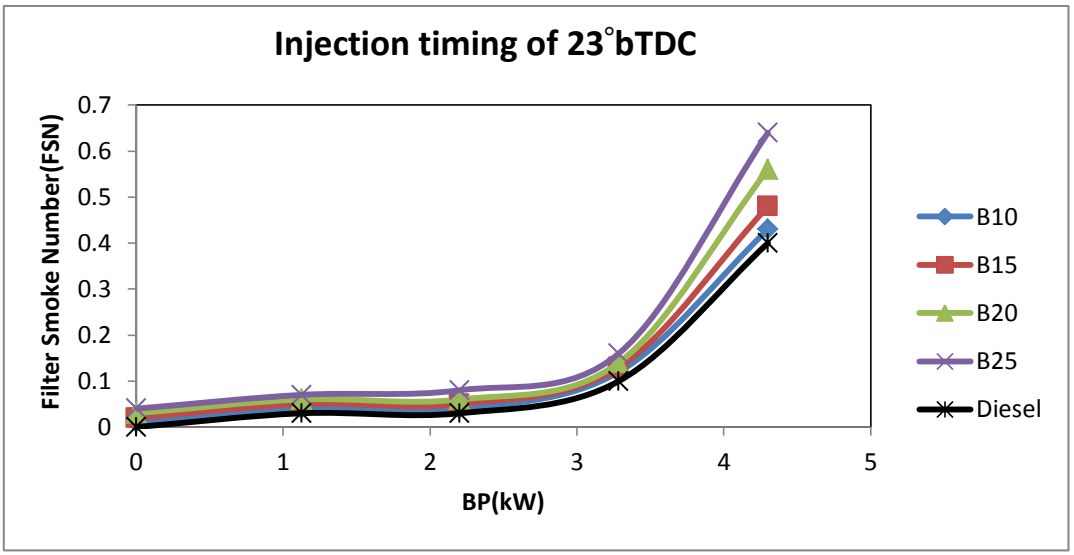

Fig 6.12 Variation of Filter Smoke Number (FSN)for fuel blends at 180 bar Injection pressure

6.2.2 200 bar injection pressure

This section gives the results of the experiments conducted with diesel and various blends of *Vateria Indica* biodiesel with diesel viz B10, B15, B20, B25 at 25, 50, 75, 100% Loads.. The combustion, performance and emission characteristics are investigated at injection pressure of 200 bar and injection timing is kept at standard timing of 23°bTDC. The results are presented and discussed with graphs.

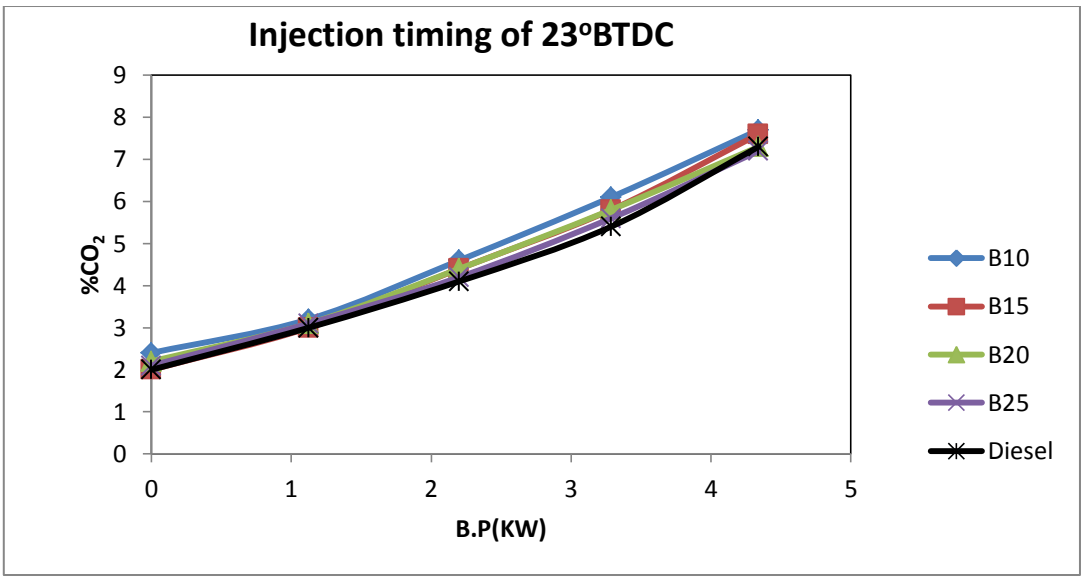

Fig 6.13 Variation of CO_2 for various fuel blends at 180 bar Injection pressure

6.2.2.1 Cylinder Pressure and Heat release rate

The comparison of the cylinder gas pressure for the test fuels at 75% Load condition is shown in Fig 6.14 and fig 6.15. Diesel has least cylinder peak pressure compared with the blends. There is no trend could be observed because of pressure perturbations which are may be due to knocking tendency. Premixed combustion is proceeding well incase of B25 which can be also concluded from heat release rate curve from Fig 6.16. The cumulative heat release graph shown in Fig 6.17 indicates even though maximum cumulative heat release occurs for B20 more cylinder pressure occurring for B10. This is because early pre mixed combustion for B10. B15 has least pressure release and cumulative heat release. Main reason for that is its highest ignition delay. B10 has been found to have better combustion characteristics compared to B15 for this reason. Detailed structural analysis is required to be done for B15 blend to find out why it has got longer delay period than B10. It can also be observed that no appreciable increase in cumulative heat release occurs when injection pressure is increased from 180 bar to 200 bar. In view of cylinder pressure and combustion characteristics B25 is the best blend. The variation of the exhaust temperature with the depicted in Fig 6.18 and table 6.2. The Exhaust Temperature is more for blends than diesel. This is because more heat release in the premixed phase for blends because

they have got lesser delay period. The exhaust temperature increases with the load because of rich mixture burning.

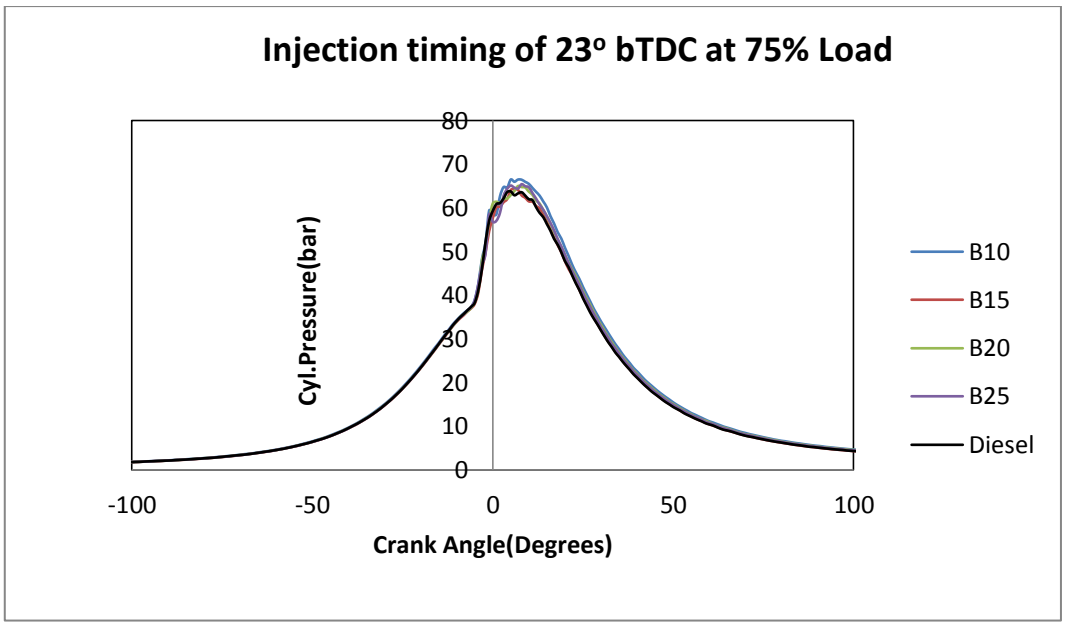

Fig 6.14 Variation of cylinder pressure for various blend at 75% Load and 200 bar injection pressure

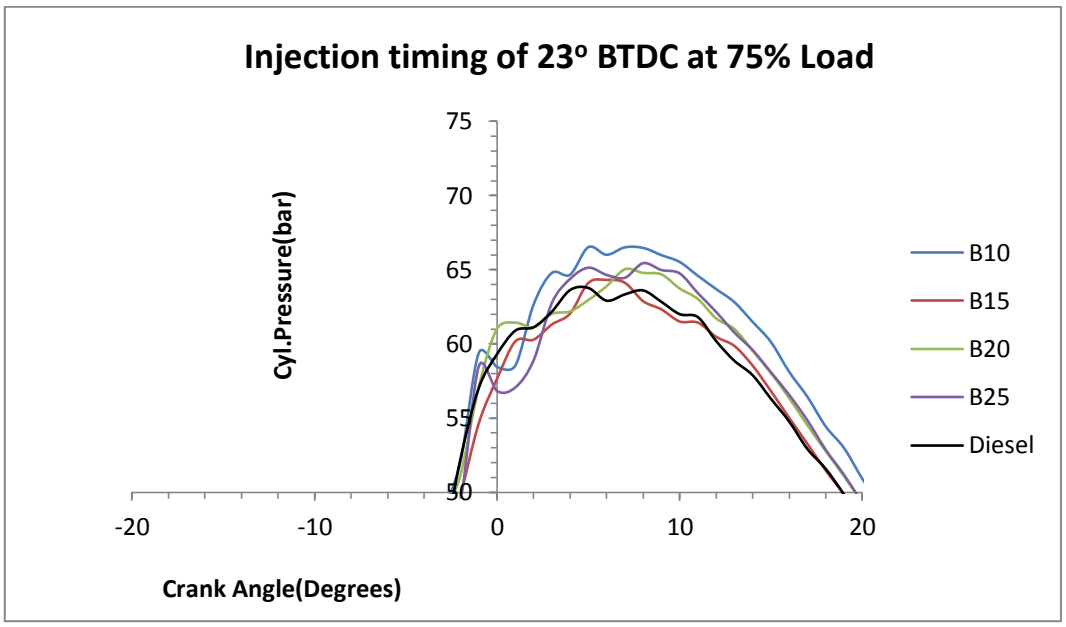

Fig 6.15 Enlarged peak of 6.14

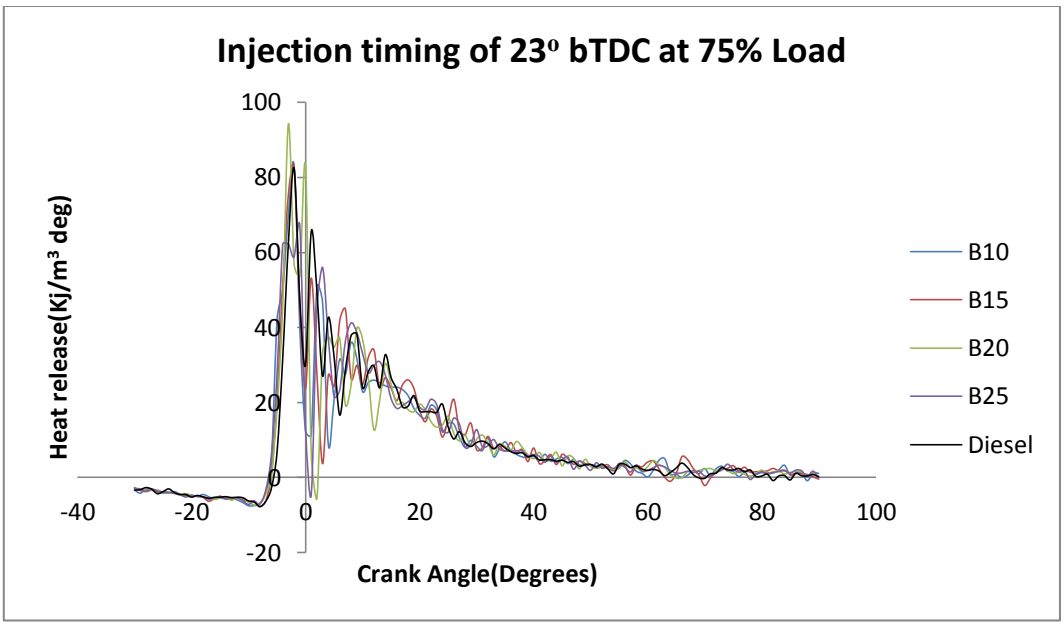

Fig 6.16 Variation of Heat release rate for various blend at 75% Load and 200 bar injection pressure

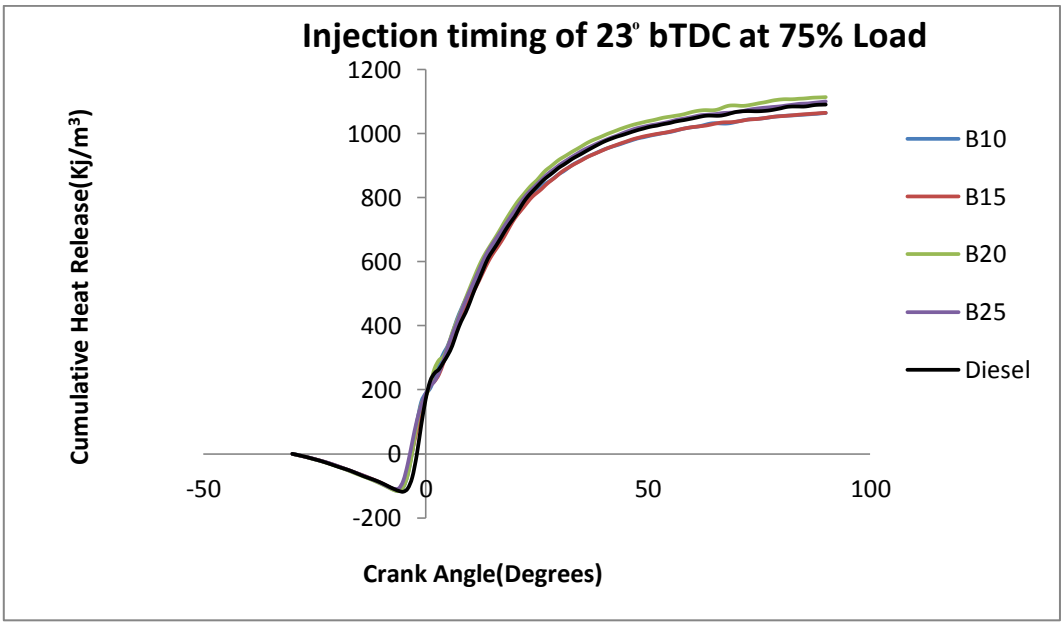

Fig 6.17 Variation of cumulative Heat release rate for various blend at 75% Load and 200 bar injection pressure

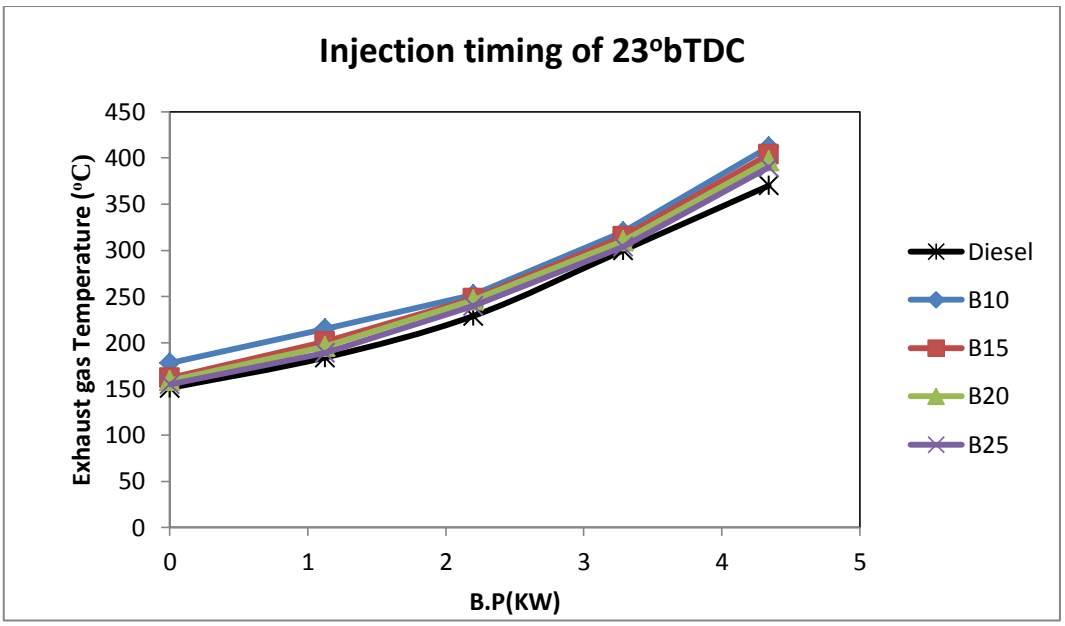

Fig 6.18 Variation of Exhaust temperature for various blends with varying load at 200 bar injection pressure

Table 6.2 Variation of Exhaust temperature for various fuels at 75% load for 200 bar injection pressure.

Fuel	B10	B15	B20	B25	Diesel
Temperature of the Exhaust Gas (^{o}C)	320	315	310	304	300

6.2.2.2 Brake Specific Energy Consumption

The fig 6.19 shows the variation of brake specific energy consumption(BSEC) for various fuel blends at different load conditions. For all blends specific energy consumption decreases upto part load and there on it remains almost constant. The BSEC at 75% Load for diesel is 12702.89 kJ/kW-hr. whereas it is 13367.99kJ/kW-hr, 12994.13kJ/kW-hr, B10,B15 which is more by5.2%, 2.3% compared to diesel and it is 12162.16kJ/kW-hr and 11601.68kJ/kW-hr which are less by 4.3% and 8.7% compared to diesel. Diesel found to perform poorly compared with B20 and B25

which may be due change in injection pressure which is different from standard operating injection pressure. B25 is good blend because it has least BSEC.

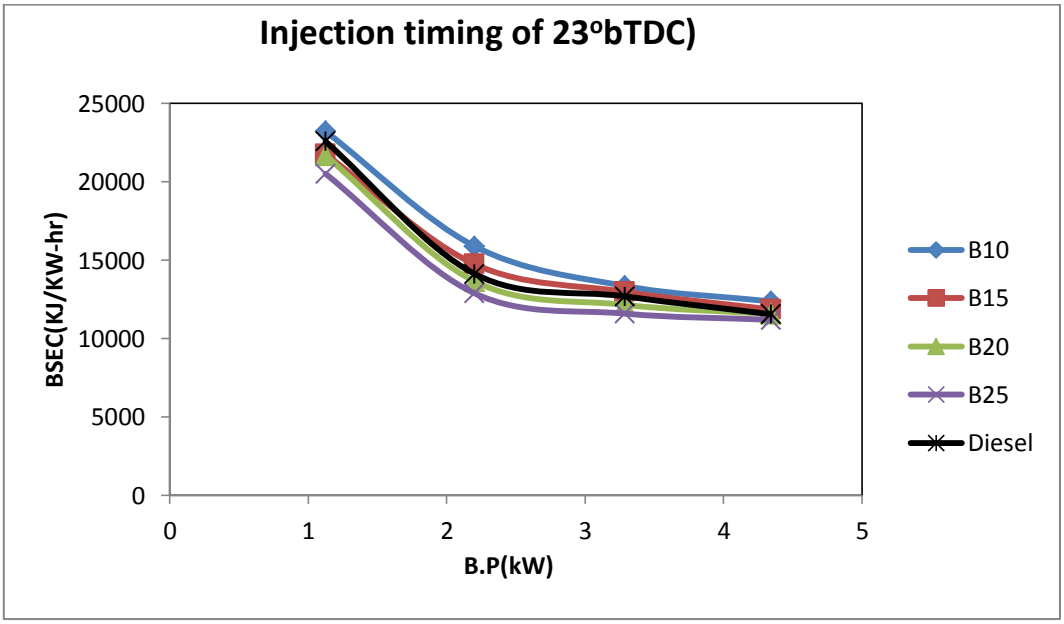

Fig 6.19 Variation of BSEC for various blends with varying load at 200 bar injection pressure

6.2.2.3 Brake Thermal Efficiency

Fig 6.20 depicts the variation of brake thermal efficiency(BTE) at varying engine loads. The BTE generally increases with load for all the fuels. It is observed from the figure that BTE for blend increase with biodiesel concentration. BTE is 25.23%, 26.50%, 27.23%, 28.04%, 23.93% for B10, B15, B20, B25 and diesel respectively at 75% load. The BTE increases with load because increased mixture strength.

6.2.2.4 NO_X emission

Fig 6.21 shows the variation of NO_X emission for various fuel blends at different load conditions. The NO_X emission increases as the load is increased, and maximum NO_X is obtained at full load condition. It is detected that 0.22%, 6.7%, 8.3%, 9.1% higher NO_X emission is obtained for B10, B15, B20,B25 blends than diesel. Higher NO_X emission is observed for blends rather than diesel because of better oxygen content in the blends.

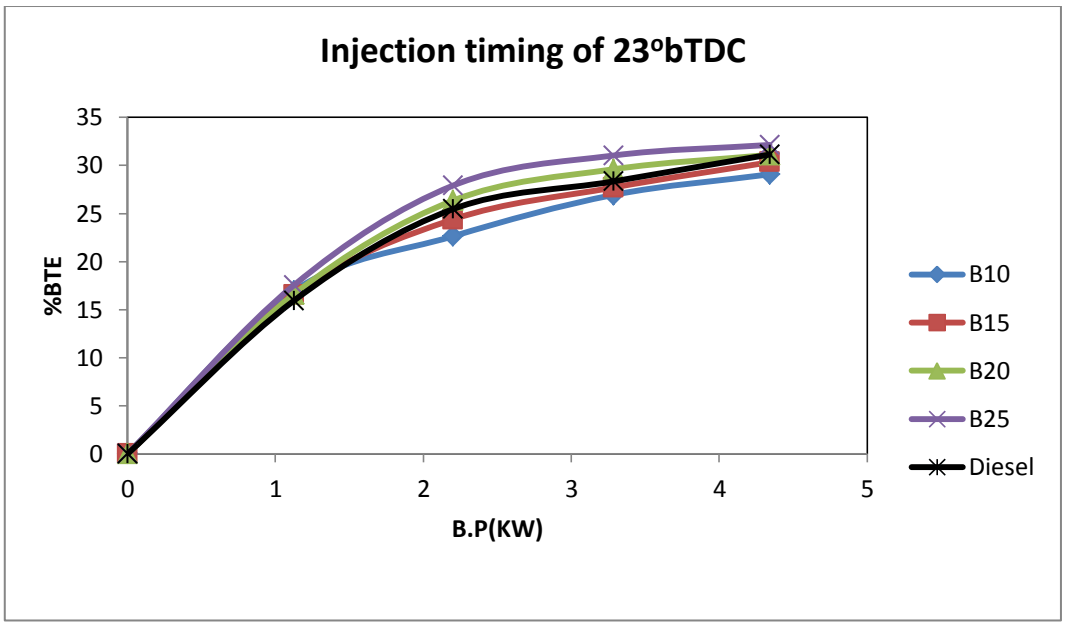

Fig 6.20 Variation of BTE for various blends with varying load at 200 bar injection pressure

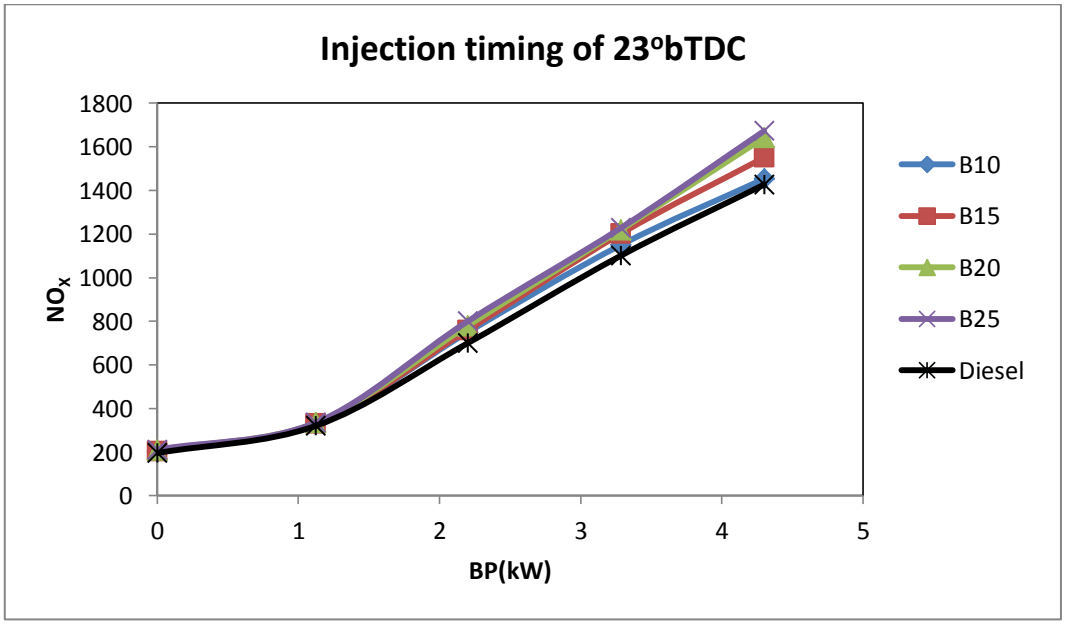

Fig 6.21 Variation of NO_X(ppm) for various blends with varying load at 200 bar injection pressure

6.2.2.5 CO emission

It is observed from Fig 6.22 that CO emission increases as the engine load increased due rich mixture requirements during high load conditions. Compared to diesel all biodiesel blends have lesser CO emissions. Blend B25 has minimum CO emissions because of high oxygen content in the blend. It is observed that at 75% load blends B10, B15, B20, B25 blends have 16.7%, 33.3%, 50%, 66.7% less CO emission respectively compared with diesel. Since blends are high oxygen content fuels combustion is more complete and hence lesser concentrations of CO are observed.

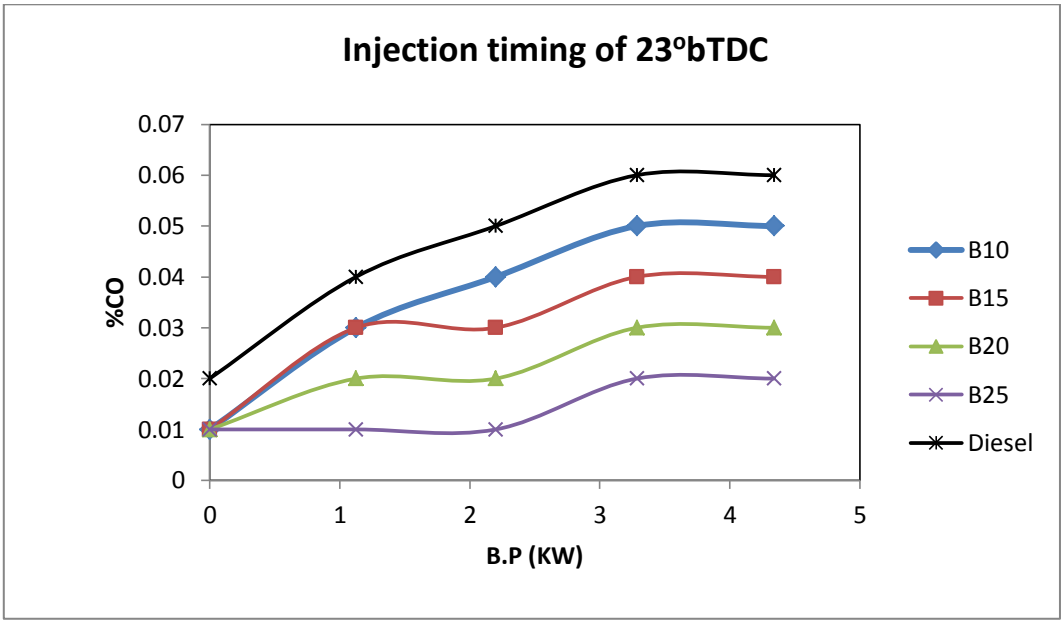

Fig 6.22 Variation of CO(%v) for various blend with varying load at 200 bar injection pressure

6.2.2.6 HC emission

The variation of HC emission at different loads for different blends is shown in Fig 6.23. It is observed that for all blends HC emission is lesser than diesel at all loads. The HC emission of diesel is 28 ppm at 75% Load whereas it is 21, 20, 18,15 ppm for B10, B15, B20, B25 blends respectively at 75% load. It is observed that 21.7%, 26.1%, 30.43%, 34.8% less HC emission occurs for blends B10, B15, B20, B25 when compared to diesel at 75% Load. Decreased HC emission occurs for higher blends because better combustion due to increased oxygen content (A. Engin Ozcelik,2015).

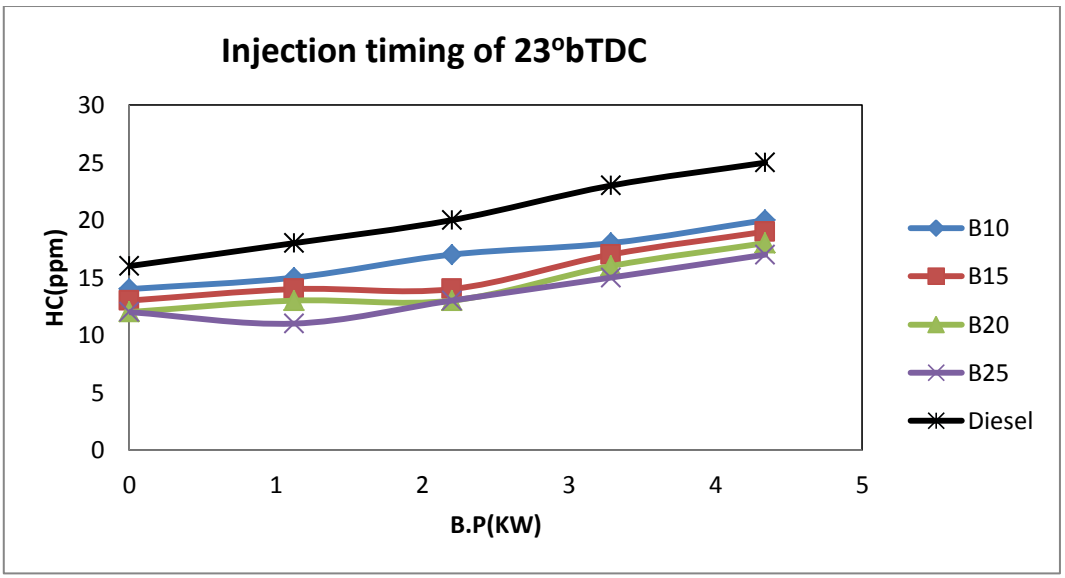

Fig 6.23 Variation of HC (ppm) for various blend with varying load at 200 bar injection pressure

6.2.2.7 Smoke emission

Variation in smoke density is shown in the Fig 6.24. Unlike for 180 bar injection soot formation is more at all loads for all the fuels. Diesel has lower soot formation because better combustion due to higher injection pressure even though it is not an engine standard. For Biodiesel blends formation of nonuniform fuel air mixture regions give out smoke. At 75% load smoke density increases by 250%, 150%, 100%, 50% for blends B10, B15, B20, B25 when compared with diesel. Formation of rich mixture fuel regions is less because of larger oxygen content at higher blends. Even though combustion is more complete for biodiesel blends, some cool fuel rich mixture regions may be formed near the bowl wall due to deeper fuel penetration at higher injection pressure. This region may cause higher soot formation. As the load increases smoke density increases because of poor combustion. Filter smoke number characteristics are similar to those of smoke density as can be concluded from Fig 6.25

6.2.2.8 CO_2 emission

Variation of CO_2 emission for various blends is shown in Fig 6.26. It can be observed that increases with increase in load. CO_2 emission is least for B25 blend and Maximum for B10. CO_2 emission is more that for diesel compared to B25. This is

because non standard operating condition for diesel. CO_2 emission increases by 7%,3.6%,1.7%,-1.8% for blends B10, B15, B20, B25 respectively. For B25 blend emits least CO_2 may be because for this blend at higher rate of combustion leading to diaassociation reaction occurring for CO_2, due little early combustion.

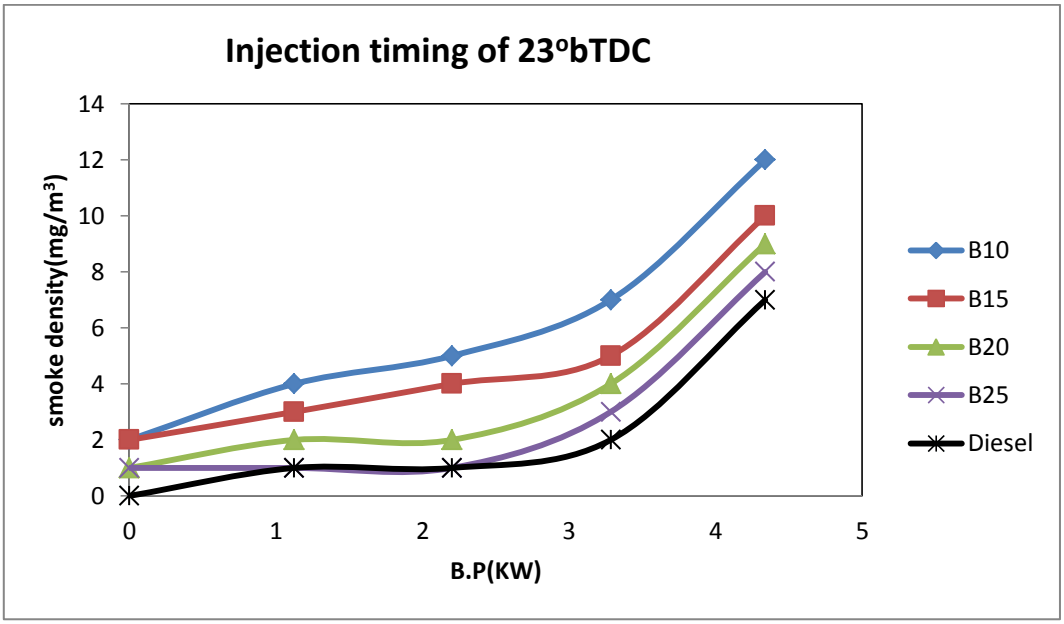

Fig 6.24 Variation of smoke density(mg/m^3) for various blend with varying load at 200 bar injection pressure

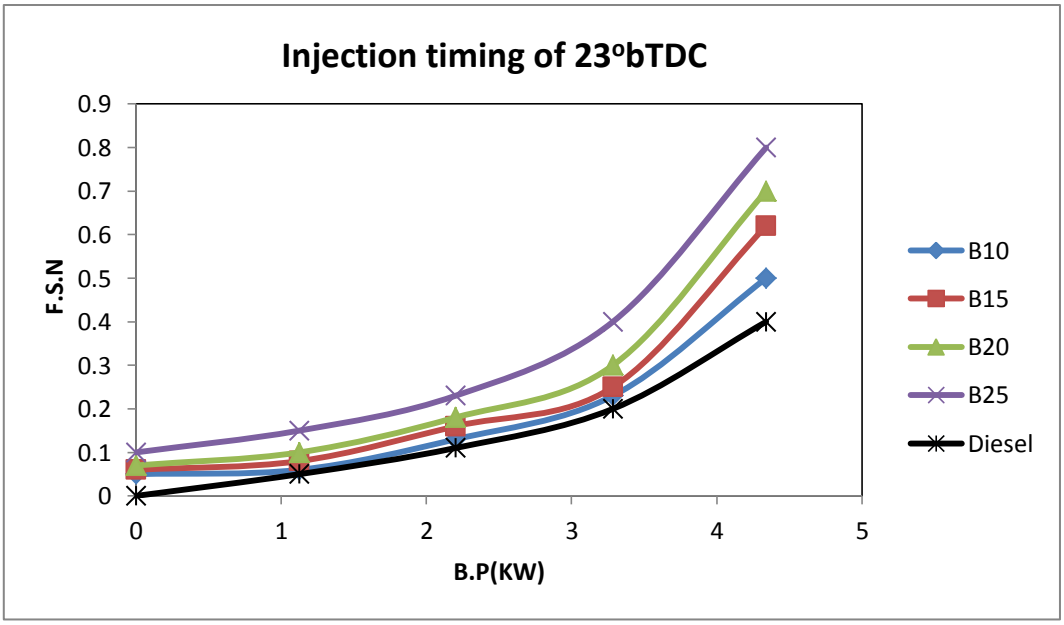

Fig 6.25 Variation of Filter smoke number(FSN) for various blend with varying load at 200 bar injection pressure

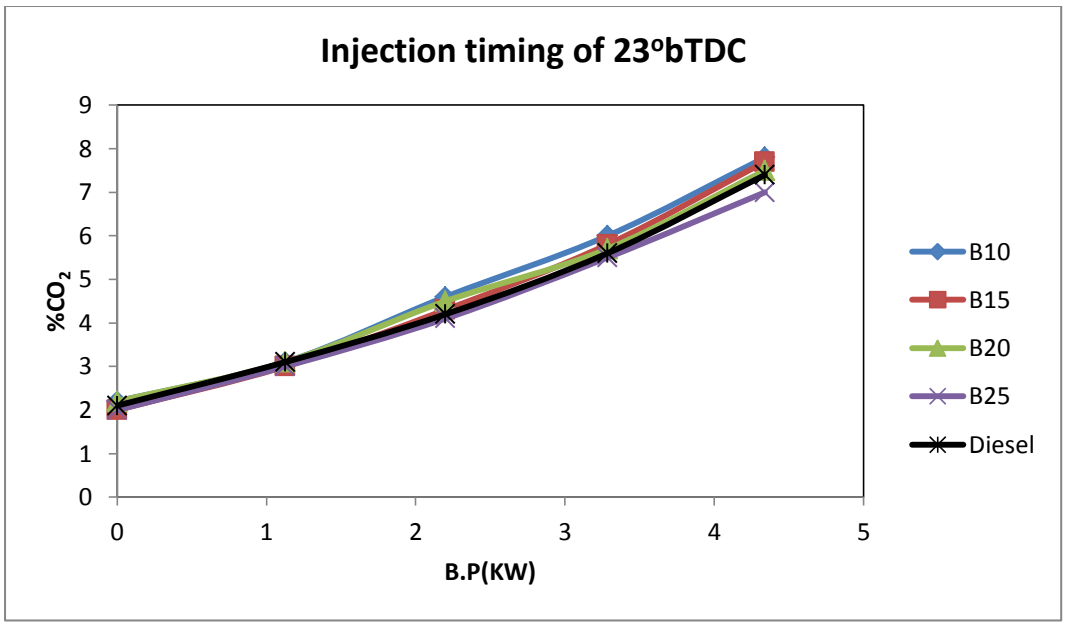

Fig 6.26 Variation of CO_2(%v) for various blend with varying load at 200 bar injection pressure

6.2.3 220 bar injection pressure.

This section gives the results of experiments conducted with diesel and various blends of *Vateria Indica* biodiesel namely, B10, B15, B20, B25. The combustion, performance, and emission characteristics are investigated at injection pressure of 220 bar and the fuel injection timing is kept at standard condition of 23°bTDC. The results are presented and discussed with graphs.

6.2.3.1 Cylinder Pressure and Heat release rate

Bio fuel blend give higher cylinder peak pressure which can be concluded from fig 6.27 and Fig 6.28. For B25 blend, in-cylinder pressure, and heat release are better compared to other blends(Fig 6.29). There is no much variation in the cumulative heat release for different blends in premixed combustion regime (Fig 6.30). Combustion Occurs early for B25 blend as shown in fig 6.29. Exhaust Gas is comparatively cooler for B25 blend compared with other blends and diesel in general. This may be due to combustion is better and more of the heat released is transferred to piston as more time is available after main combustion which can be concluded from table 6.5. It can also be observed that exhaust gas temperature increases with load (Fig 6.31) due to rich fuel burning releasing larger heat.

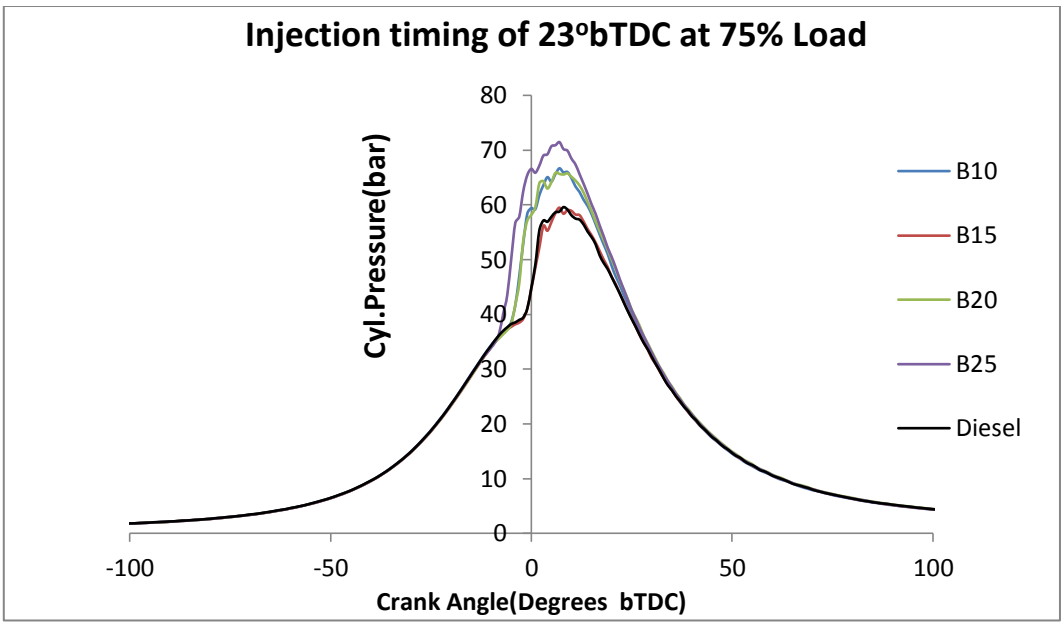

Fig 6.27 Variation of Cylinder pressure for various blends at 75% Load at 220 bar injection pressure

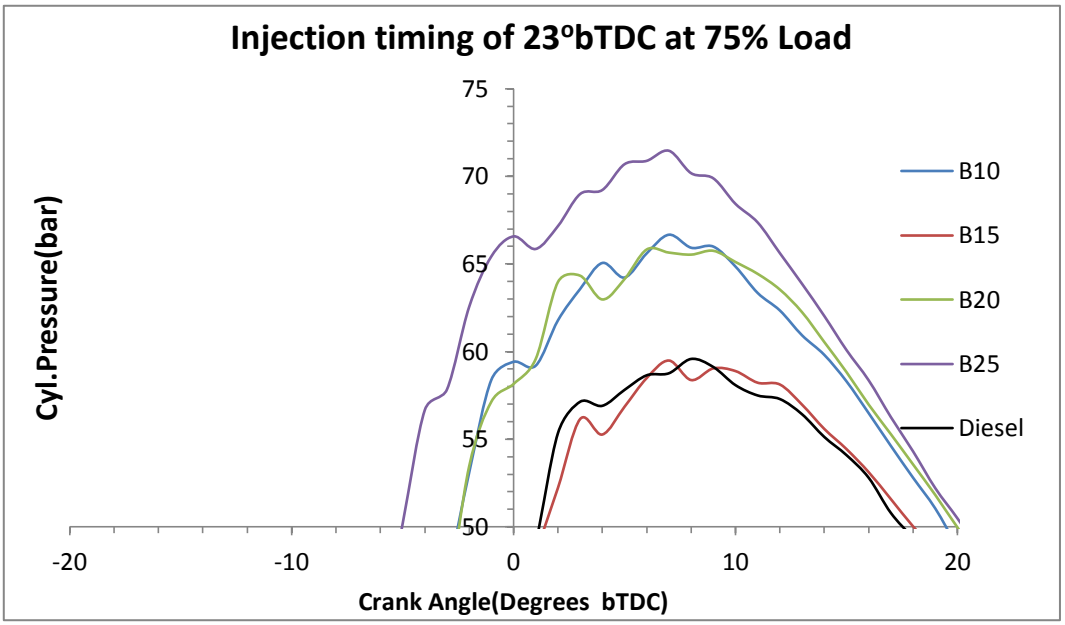

Fig 6.28 Enlarged view of peak of figure 6.27

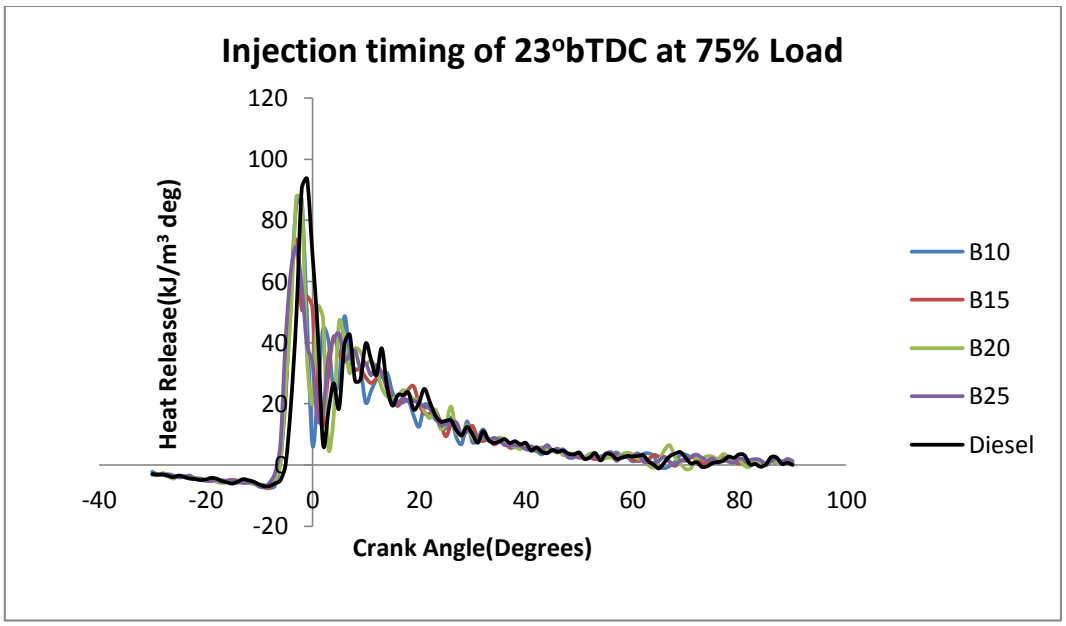

Fig 6.29 Variation of Heat release for various blends at 75% Load at 220 bar injection pressure

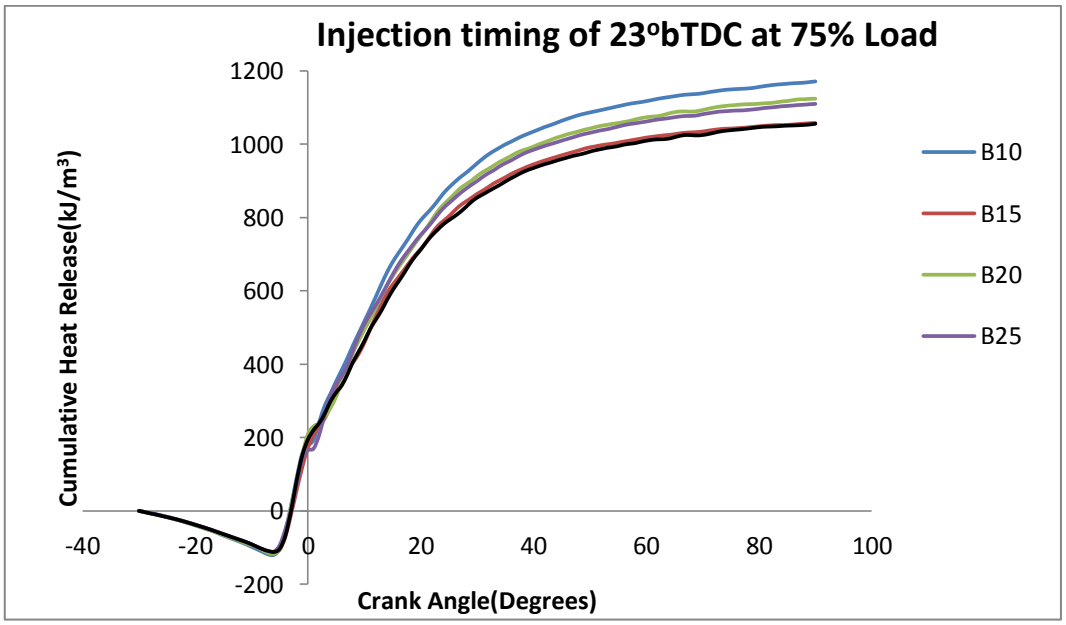

Fig 6.30 Variation of Cumulative heat release for various blends at 75% Load at 220 bar injection pressure.

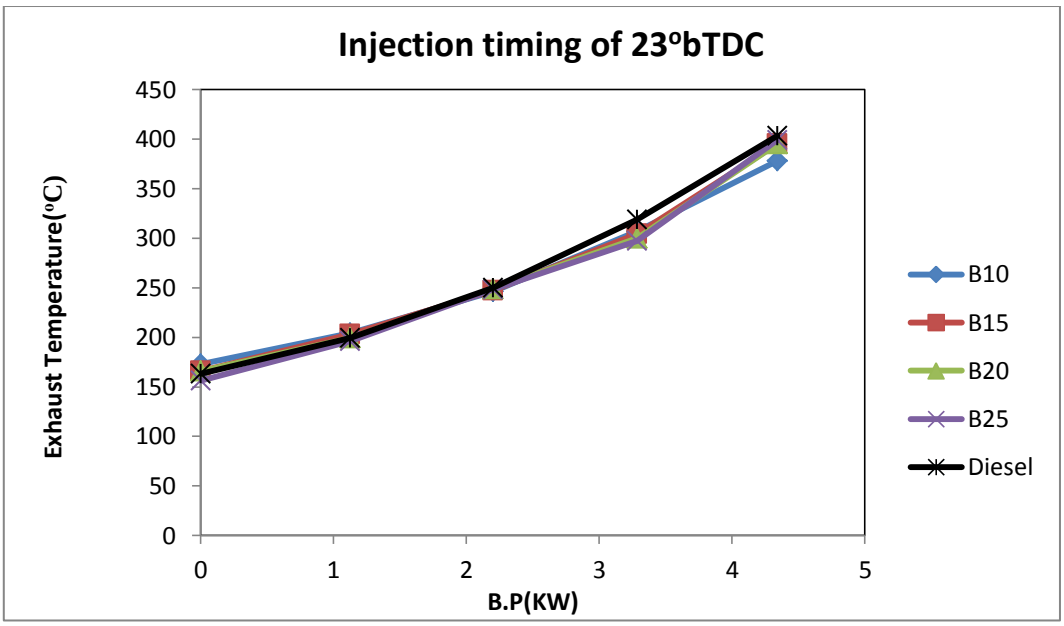

Fig 6.31 Variation of Exhaust gas temperature for various blends with varying load at 220 bar injection pressure

Table 6.3 Variation of exhaust gas temperature for various fuels at 75% load and 220 bar injection pressure.

Fuel	B10	B15	B20	B25	Diesel
Temperature of the Exhaust(^{o}C)	307	304	300	297	310

6.2.3.2 Brake Specific Energy Consumption

Fig 6.32 shows the variation of brake specific energy consumption (BSEC) for the various fuel blends at different load conditions. For all the blends, specific energy consumption decreases upto part load and then remains almost constant. The BSEC at 75% load for diesel is 13323.46kJ/kW-hr, whereas it is 13124.32kJ/kW-hr,12526.12kJ/kW-hr,11908.7kJ/kW-hr ,11601.67kJ/kW-hr respectively for B10, B15, B20, B25 fuel blends.. The BSEC decreases by 1.5%, 6%, 10.6%,12.9% respectively for B10, B15, B20, B25 when compared with diesel. BSEC is BSEC is

less for biodiesel blends may be because improved combustion characteristics and decreased ignition delay.

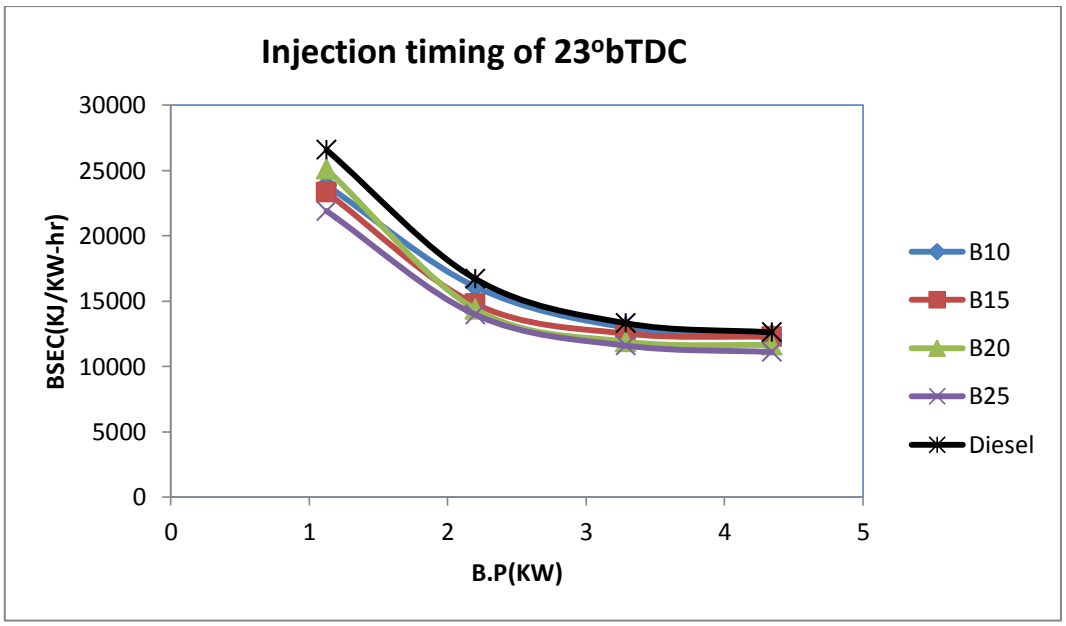

Fig 6.32 Variation of brake specific energy consumption (BSEC) with load for various blends at 220 bar injection pressure

6.2.3.3 Brake Thermal Efficiency

Fig 6.33 shows the variation of brake thermal efficiency(BTE) with varying loads. BTE generally increases with load for all fuels. It can be observed from the figure that the BTE of biofuel blends increases as biodiesel concentration increases. The BTE of diesel is 27.02% at 75% load whereas it is 27.43%,28.74%, 30.23%, 31.03% for blends B10, B15, B20, B25 respectively. It increases by 1.5%, 6.4%, 11.9%, 14.8% for B10, B15, B20, B25 respectively at 75% load compared to diesel. The BTE increases for higher blends because of better combustion due to increased oxygen content.

6.2.3.4 NO_X emission

Fig 6.34 shows the variation of NO_X emission for various fuel blends at different load condition. NO_X emission is found to increase with load for blends as well as diesel because increased temperature inside the combustion chamber. NO_X emission for

diesel at 75% load is 1090 ppm whereas it is 1100ppm, 1120ppm, 1150ppm, 1180ppm for blends B10, B15, B20, B25 repectively. NO_X emission is observed to increase by 1%, 2.75%, 5.5%, 8.25% for B10, B15, B20, B25 blends respectively compared to diesel. NO_X is formed through high temperature oxidation of nitrogen N_2 in the combustion chamber. The formation of NO_X depends on in- cylinder temperatures, oxygen concentrations and residence time for the reaction to take place. In addition at high combustion temperatures, N_2 and O_2 in the combustion chamber disassociate into their atomic states and participate in a series of reactions. When compared to diesel *Vateria Indica* biodiesel blends have more oxygen in them. Hence NO_X emission is considerably more for blends B25, B20, B15, B10 blend in order. This may be due to increased oxygen concentration with increased blending percentage.

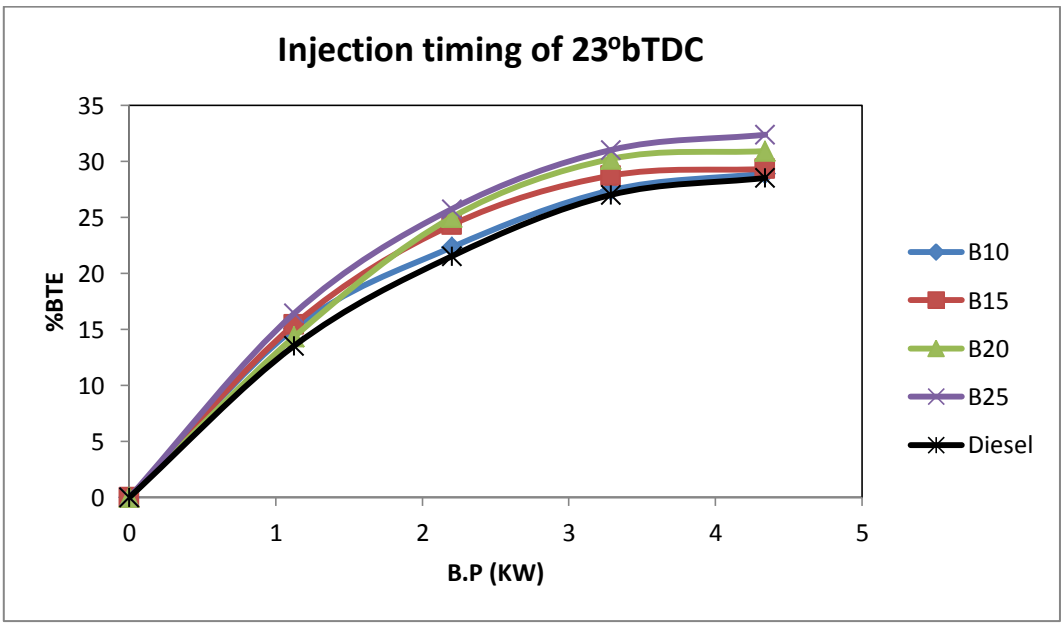

Fig 6.33 Variation of Brake thermal efficiency(%) for various blends at 220 bar injection pressure

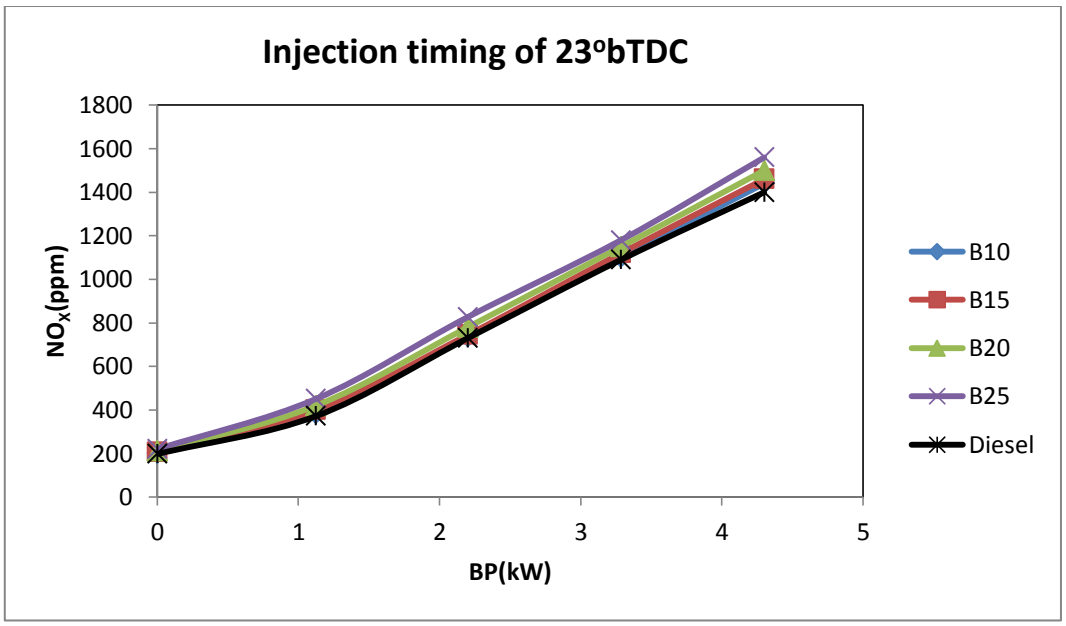

Fig 6.34 Variation of NO_x emission for various blends with varying load at 220 bar injection pressure

6.2.3.5 CO emission

The variation of CO emission for different fuels with varying load is shown in the fig 6.35. It is observed from Fig 6.34 that CO emission increases as the engine load increased due rich mixture requirements during high load conditions. Compared to diesel all biodiesel blends have lesser CO emissions. Blend B25 has minimum CO emissions. It is observed that at 75% load blends B10, B15, B20, B25 blends have 16.7%, 33.3%, 50%, 66.7% less CO emission respectively compared with diesel. Since blends are high oxygen content fuels combustion is more complete and hence lesser concentrations of CO are observed. CO emission becomes lesser when biodiesel concentrations increase. Higher concentrations oxygen in higher blend lead to better combustion and hence lesser CO emissions. Increase of injection pressure found to be ineffective as for as CO emissions are concerned.

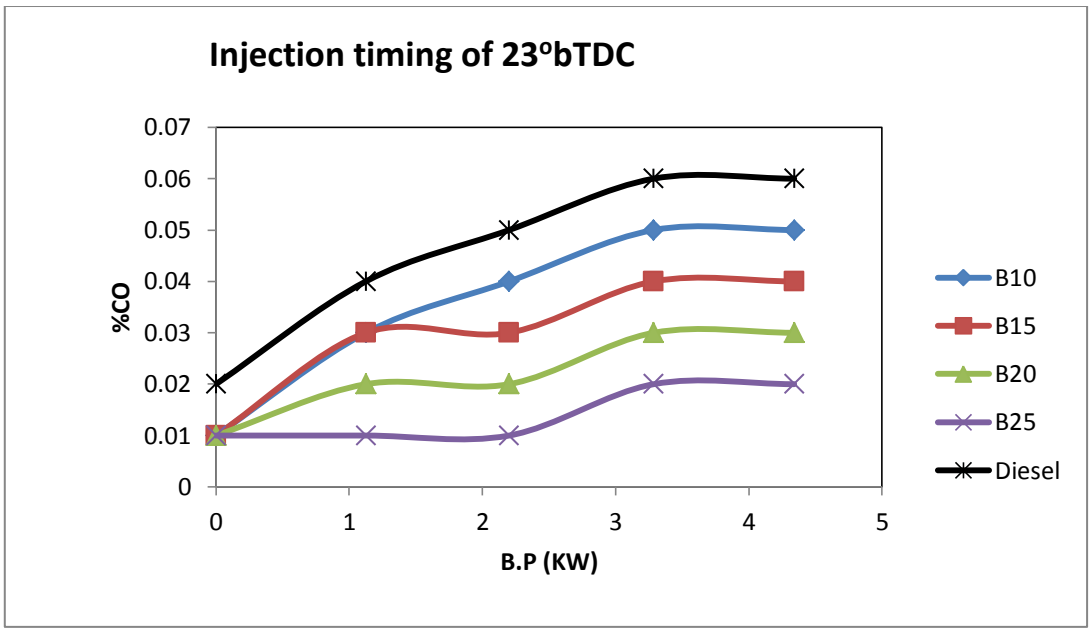

Fig 6.35 Variation of CO(%v) emission for various fuels with varying load at 220 bar injection pressure

6.2.3.6 HC emission

The variation HC emission with varying load is shown in Fig 6.36. The HC emission increases with increasing load for all the fuels because of increased richness of the mixture and incomplete combustion. As the biodiesel concentration increases in the blend the amount of HC emission decreases at all the loads. This is mainly because of excess oxygen available in the higher blends leading to better combustion. For all the blends increased injection pressure decreases the HC emission because of better atomization of the fuel at higher injection pressure.

6.2.3.7 Smoke emission

The variation of smoke density(mg/m^3) is depicted in Fig 6.37 for various fuels with varying load. It can be observed that smoke density increases by 150%, 116%, 100%, 67% for B10, B15, B20, B25 blends respectively compared with diesel. As the biodiesel concentration in the blends increase the smoke emission decreases because of less chances for dissociation reaction of CO_2 into atomic states C and O_2 which is indicated by exhaust gas temperature. Hence soot formation tendency decreases. Filter smoke number is showing similar tendency as soot density as depicted by Fig 6.38.

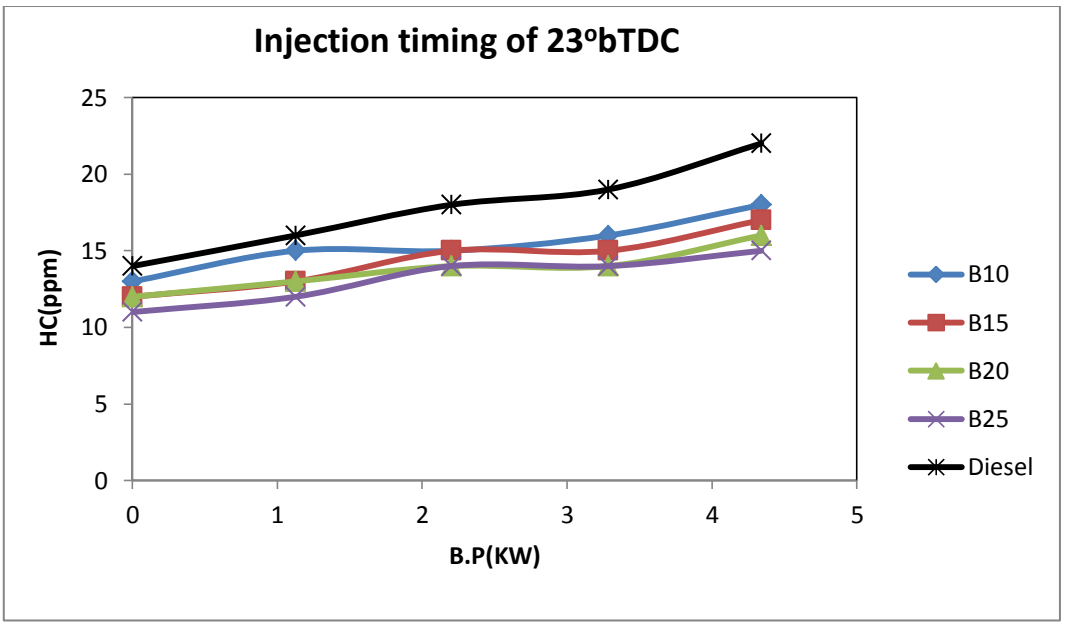

Fig 6.36 Variation of HC(ppm) emission for various fuels with varying load an 220bar injection pressure.

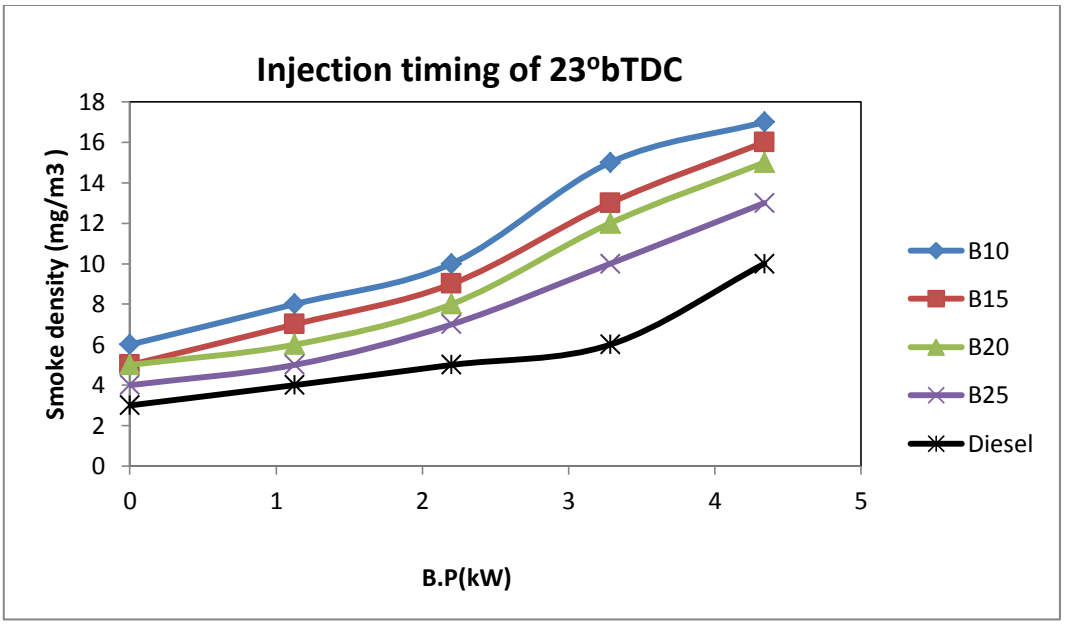

Fig 6.37 Variation of Smoke Density(mg/m^3) for various fuels with varying load and 220 bar injection pressure.

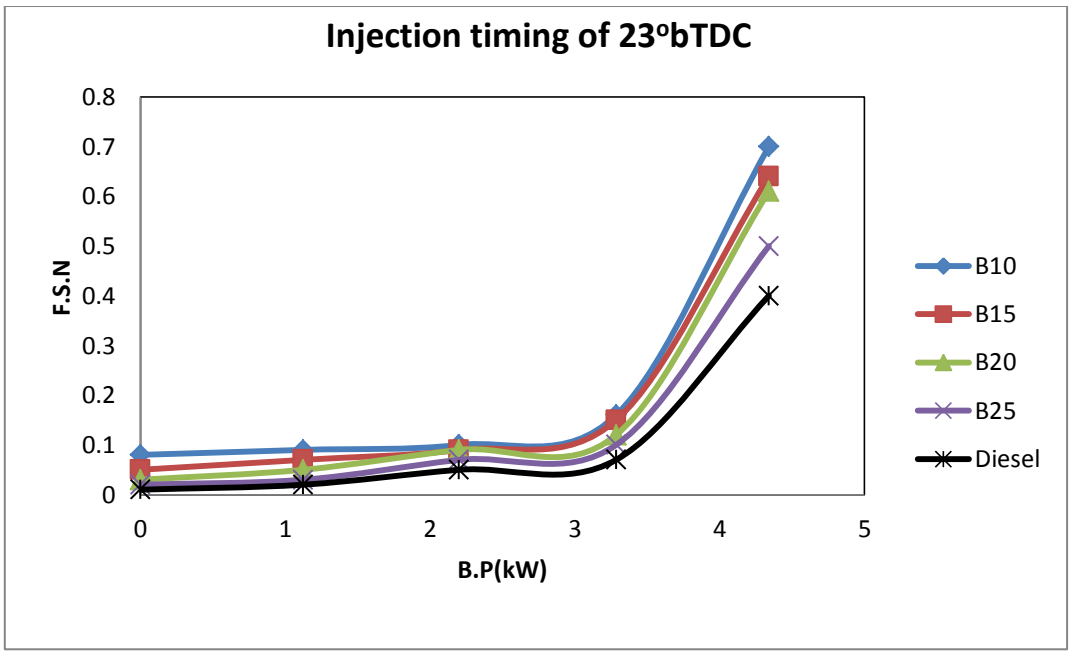

Fig 6.38 Variation of Filter smoke number (FSN) for various fuels with varying load and 220 bar injection pressure.

6.2.4 Comparison of injection pressure on performance and emission characteristics of various blends of *Vateria Indica* biodiesel.

This section gives a comparison of the results of the experiments conducted with diesel and various blends of *Vateria Indica* biodiesel with diesel namely B10, B15, B20, B25. At different injection pressures under 75% load. The effect varying injection pressure on the combustion, performance, emission characteristics of diesel and various blends on CI engine is studied. A comparative study of the combustion, performance, emission characteristics are made at injection pressure levels of 180, 200, 220 bars and the fuel injection timing is kept standard at 23°bTDC. The results are presented and discussed with graphs.

6.2.4.1 Combustion Characteristics

Figure 6.39 shows the comparison of in-cylinder pressure variation for different *Vateria Indica* biodiesel blends for various injection pressures. It can be inferred from the Figure 6.40 that average in-cylinder pressure increases as the injection pressure is increased. This may be due to improved combustion due to reduced droplet size. Figure 6.40 presents the variation of cumulative heat release with crank angle for

different injection pressures for *Vateria Indica* biodiesel blends at 75% load. It can be noted that as the IP is increased the cumulative heat release rate marginally increases indicating better combustion due to the larger surface area of fuel droplet at higher IP.

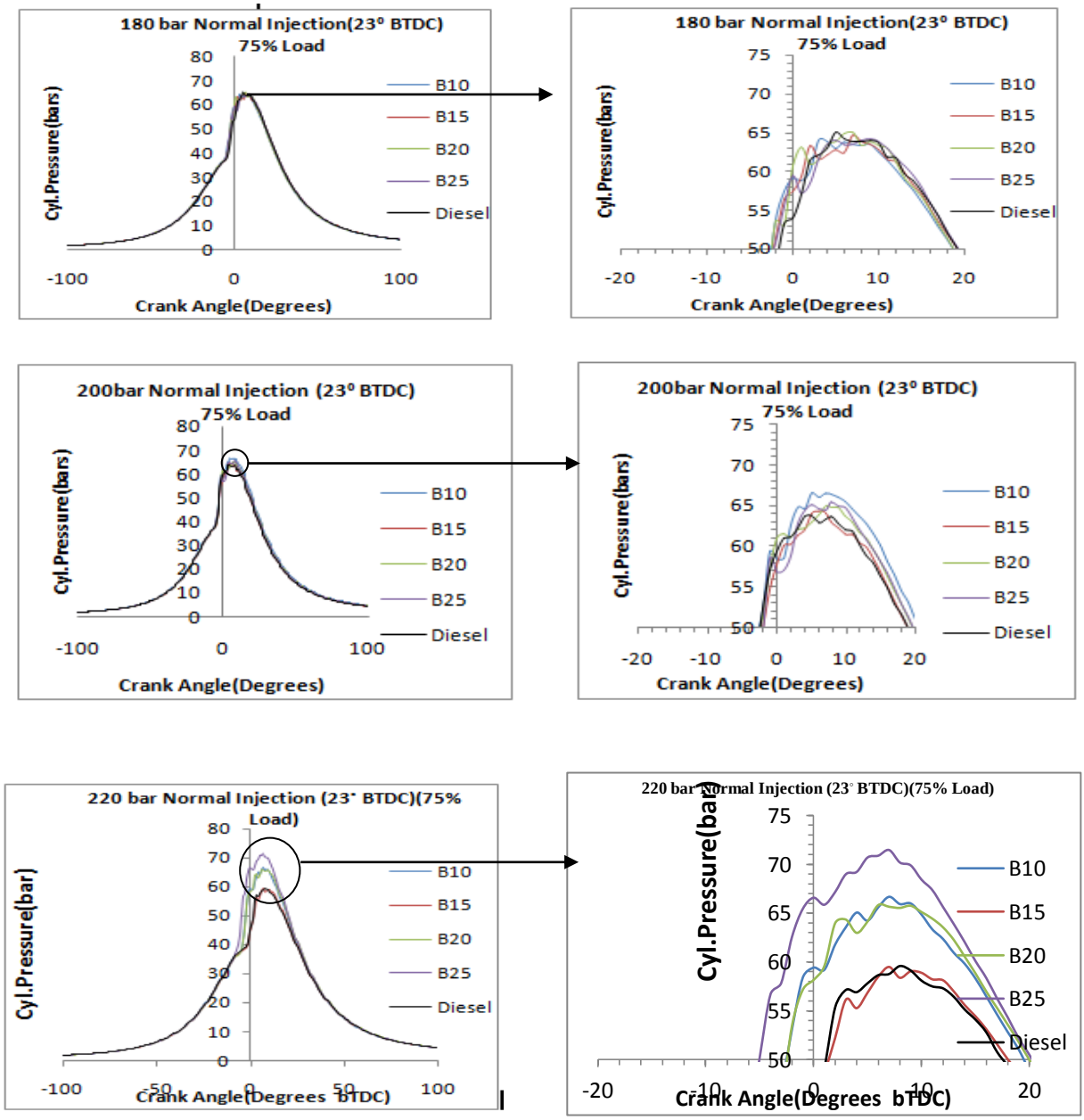

Fig 6.39 In-cylinder pressure Vs crank angle for test fuels at different injection Pressures(peeks are shown at right)

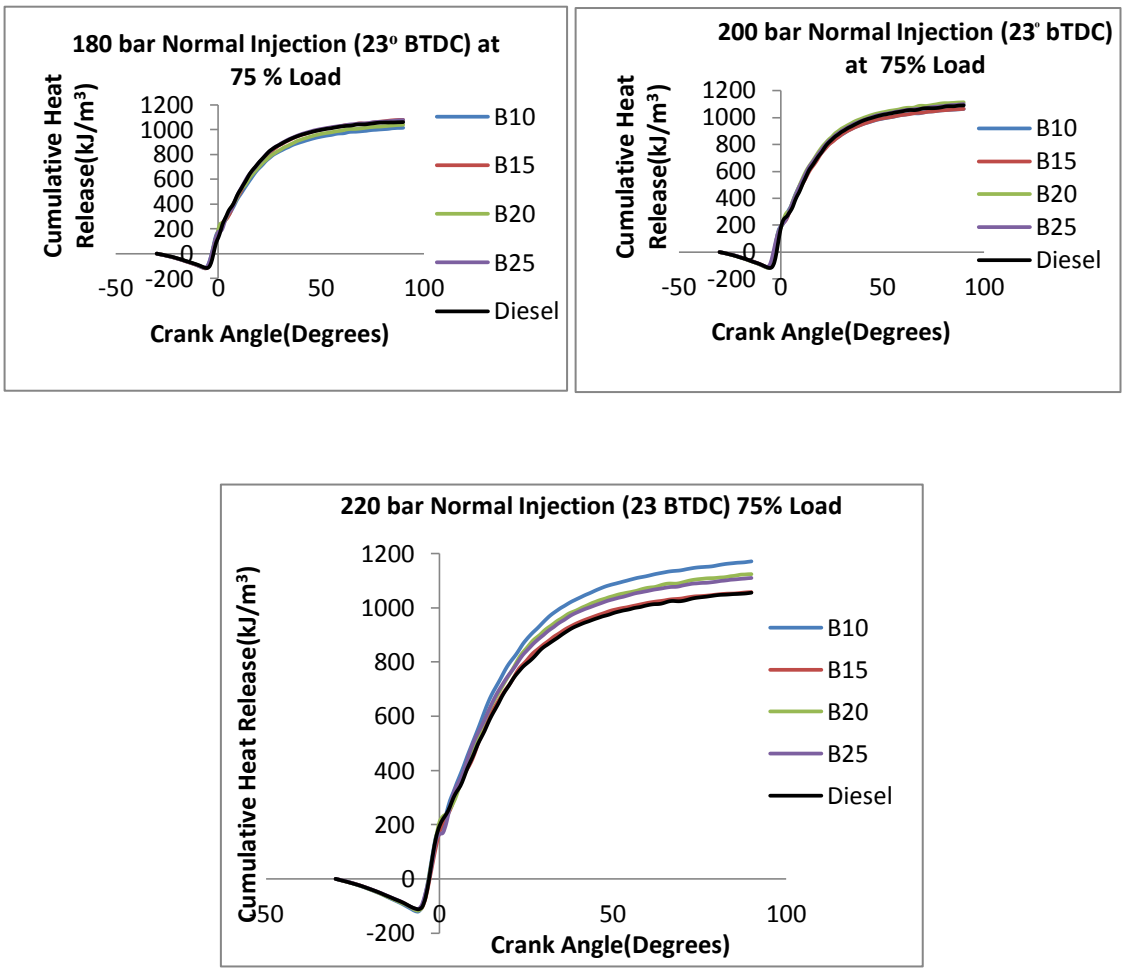

Figure 6.40 Cumulative heat release rate Vs crank angle for test fuels at different injection pressure

6.2.4.2 Brake Specific Energy Consumption

Fig 6.41 shows the variation of brake specific energy consumption at various injection pressures for different test fuels. It is observed from the Fig that the BSEC decreases as the injection pressure increased from 180 bar to 220 bars. At 180 bar injection pressure, the BSEC of 14268.72, 13584.90, 13220.71,12837.54, 15043.87 kJ/kW-hr obtained for B10, B15, B20, B25, Diesel respectively. Whereas BSEC of 13071.9, 12907.85, 12186.87, 11695.9,13564 kJ/kW-hr are respectively obtained at 200 bar injection pressure. When the injection pressure increased to 220 bar, the BSEC values for all the test fuels reduce to the minimum. It can be observed from the figure that lower BSEC levels of 8.86%, 8%, 10%, 9.62%, 11.43% are obtained respectively for

B10, B15, B20, B25, diesel fuels at 220 bar injection pressure compared to the 180 bar injection pressure. The reason for lower BSEC at higher injection pressure is better atomization and better distribution of fuel droplets inside the combustion chamber. Thus at a particular load a less quantity of fuel is consumed. Similar results were observed by Venkatraman M and Devaradjane G (2010) when tested with Pungam oil methyl ester.

6.2.4.3 Brake Thermal Efficiency (%BTE)

Fig 6.42 shows the variation of brake thermal efficiency at various injection pressures for the test fuels. It is observed from the Fig that BTE increases as the injection pressure increased from 180 bar to 220 bar. Maximum BTE is obtained at 220 bar injection pressure for all blends excepting diesel. For diesel there is a decrease in BTE when injection pressure is increased from 200 bars to 220 bars. For diesel there is a decrease because 220 bar is not standard injection pressure. For 180 bars injection pressure BTE obtained are 25.23%, 26.5%, 27.23%, 28.04%, 23.93% respectively for B10, B15, B20, B25, diesel fuels where as it is 27.43%, 28.74%, 30.23%, 33.03%, 27.02 % respectively. It increases by 8.7%, 8.4%, 11%, 17.8% respectively for B10, B15, B20, B25 but for diesel it decreases by 12.93%. In different studies on various biodiesels the injection pressure is found to increase the BTE when tested for blends of Canola oil methyl ester and cotton seed oil methyl ester & Thevetia Peruviana seed methyl ester and honne oil methyl ester respectively (Anbarasu A & Karthikeyan A (2016), Suresh G et al (2014), Balusamy T and Marappan R(2010), Channapattana S V et al(2015)).This was attributed to improved atomization leading to better combustion. In the present study same phenomena is observed.

6.2.4.4 NO_X Emission

NO_X emission is found to increase with injection pressure as depicted by figure 6.43. It is observed that NO_x emission of 1175,1120,1080,1028,1024ppm are obtained at 180 bars whereas 1228,1220,1202,1150,1126 ppm are obtained for 200 bar injection pressure and 1180,1150,1120,1100,1090 ppm are observed for 220 bar injection pressure for B25,B20, B15, B10 and diesel respectively at 75% load. NO_x emission is

found to increase in general with injection pressure but it is maximum for 200 bars not for 220bar pressure. As pressure is increased from 200 bar to 220 bars due to decreased In-cylinder peak temperature. In a study conducted by Balaji G and Cheralathan M (2015) on neem oil biodiesel as injection pressure is increased NO_X emission increased upto to 240 bars and later decreased. Increase in NO_X emission is attributed to increased peak pressure and heat release. But beyond 240 bars why NO_X emission decreases is not clear. It may be due to disassociation reactions as stated above.

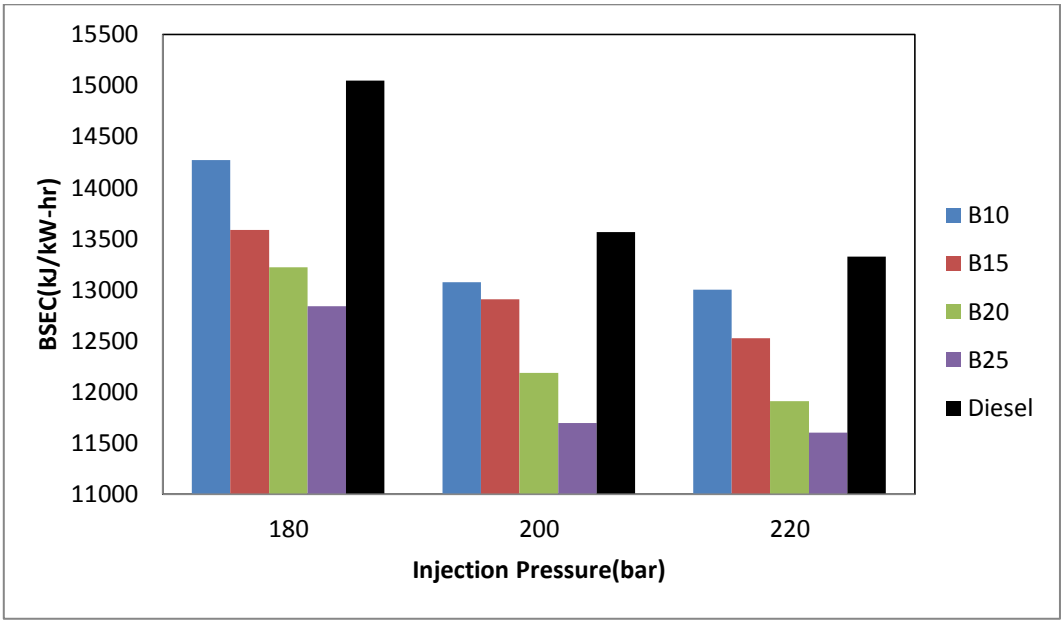

Fig 6.41 Comparison of BSEC for various test fuels for various injection pressure

6.2.4.5 CO Emission

The variation of CO emission with Injection pressure is depicted in Fig 6.44. It can be observed that the CO emission is generally low for all blends. This may be due to complete combustion of these oxygenated fuels. Also oxidation of CO to CO_2 at the after burning stage. But Injection pressure seem not to effect the CO emission. Since CO is already low at low injection pressure there is no appreciable effect on CO emission with increased fuel injection pressure. In many studies, increasing IP reduces CO emission as it causes increase in surface area of the fuel droplet and better air–fuel mixing, and hence, better combustion (Niraj Kumar et al, 2016). But in the present study it is observed that IP has no role to play in CO emission. The effect of

better atomization may be offset due to increased bulk of fuel induced. Hence even though IP is increased CO emission remains unchanged.

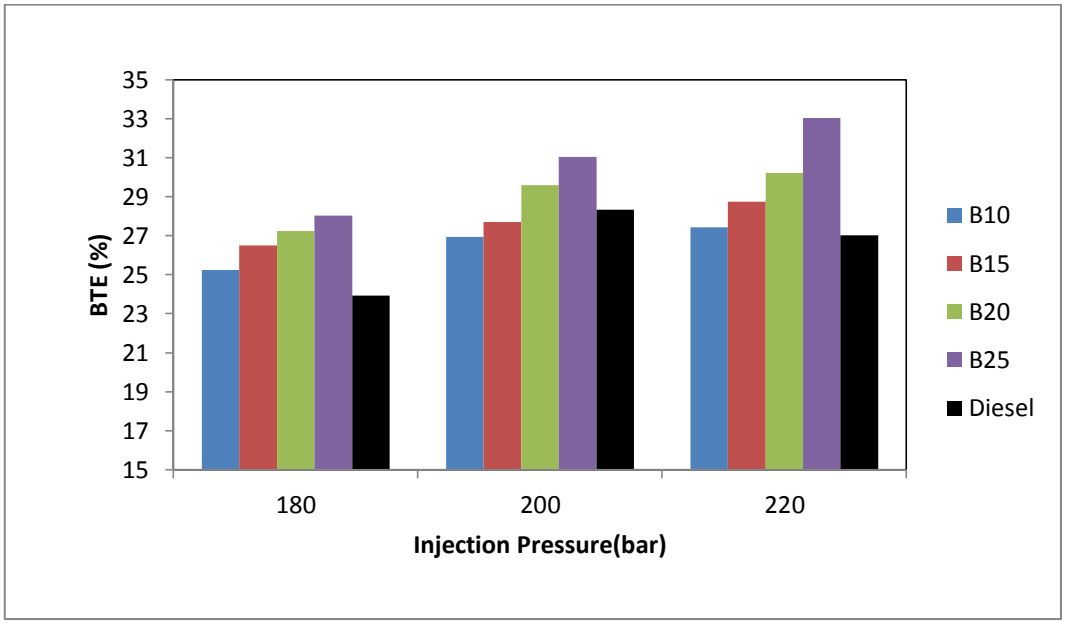

Fig 6.42 Comparison of Brake thermal efficiency for various test fuels for various injection pressure

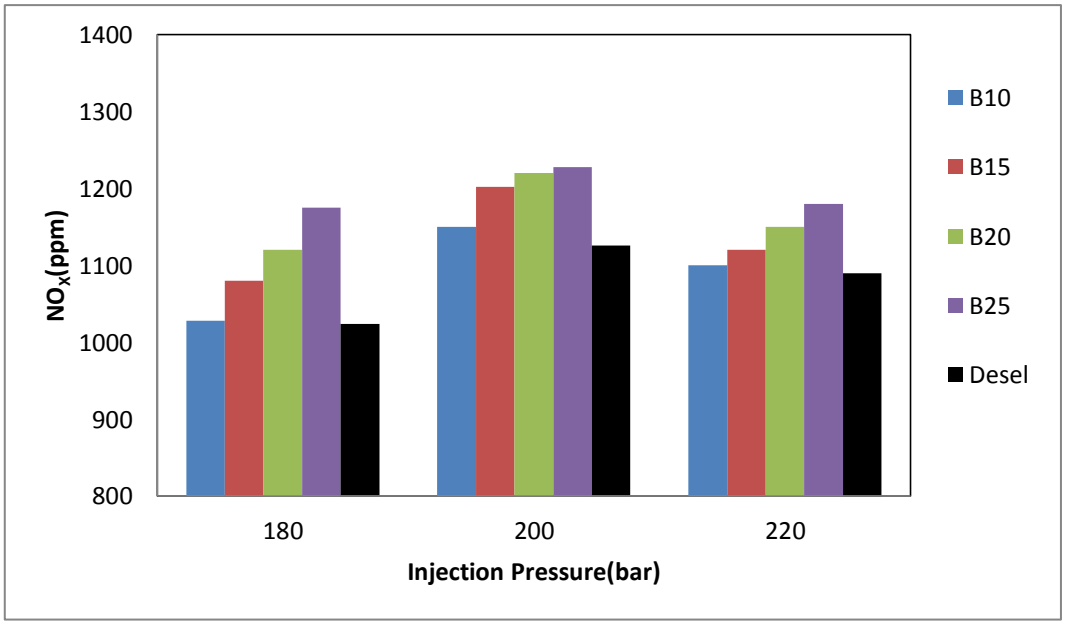

Fig 6.43 Comparison of NO_X(ppm) for various test fuels for various injection pressure

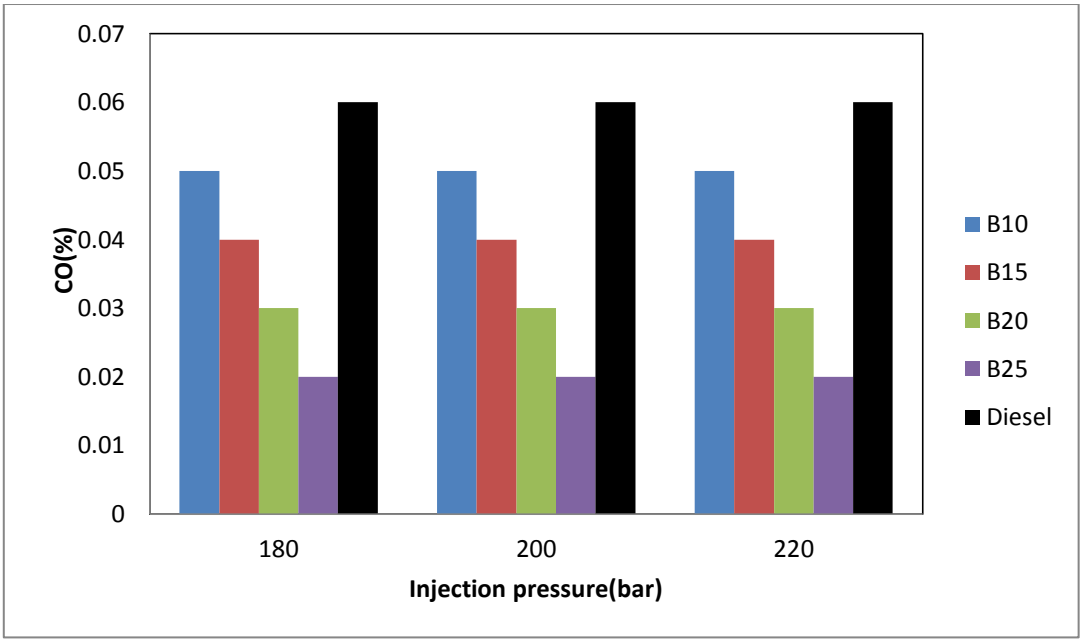

Fig 6.44 Comparison of CO(%) for various test fuels for various injection pressure

6.2.4.6 HC Emission

The HC emission is observed to decrease as injection pressure is increased as depicted in Fig 6.45. HC emission is 18, 17, 17, 16, 19 ppm for 180 bar injection pressure whereas it is 18,17,16,15,23 ppm for 200 bar injection pressure and it is 16, 15, 14, 14, 19 ppm for 220 bar injection pressure respectively for B10, B15, B20, B25 blends. Diesel shows deviation from biodiesel blends because 200 and 220 bar injection pressures are not set standard operating pressures for diesel. As injection pressure increases better atomization and evaporation leads to better combustion for the blends. HC emission is minimum for B25 because of complete combustion due available oxygen. The similar results were obtained by many investigators when conducted tests on Mahua oil methyl ester and cotton seed, honne, honge oil methyl ester respectively(Sonar D et al,2015& Wategave S P et al,2014).

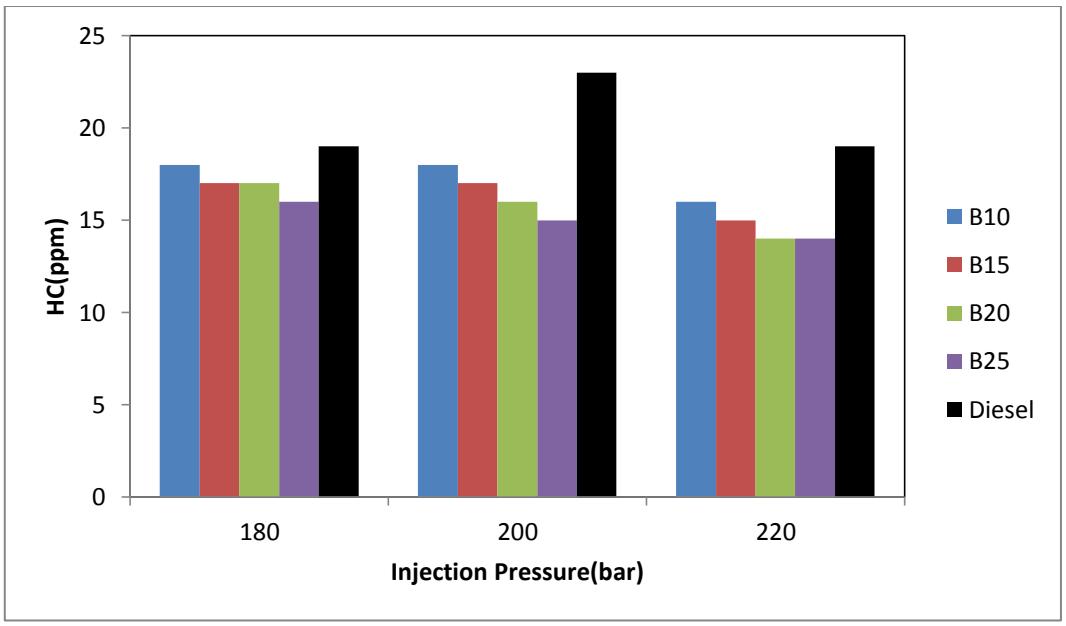

Fig 6.45 Comparison of HC(ppm) for various test fuels for various injection pressure

6.2.4.7 Smoke Emission

Variation of smoke density for different injection pressure is shown in Fig 6.46. It can be observed that a large increase of smoke emission occurs as the injection pressure is increased from 200 bar to 220 bars. There is an increase of 114%, 160%, 200%, 233%, 200% of smoke emission for B10, B15, B20, B25, diesel fuels respectively when injection pressure is increased from 200 bar to 220 bars. In general as the injection pressure is increased from 180 bars to 220 bars the soot density in the exhaust is increasing. As the IP is increased due to sharp fuel penetration fuel droplets reach cool bowl wall. Near the bowl wall Fuel rich cool regions are formed and from these regions soot formation takes place. This phenomena is pronounced at higher IP. It is generally found that increasing IP decreases the smoke opacity. The increased IP increases the surface area of the fuel due to smaller fuel droplet diameter. This results in better mixing of fuel and air and hence lower smoke opacity (Raheman and Ghadge 2008, N Kumar et al, 2016) but in the present study a reverse phenomena is observed due to liberation of soot in the diffusion part of combustion.

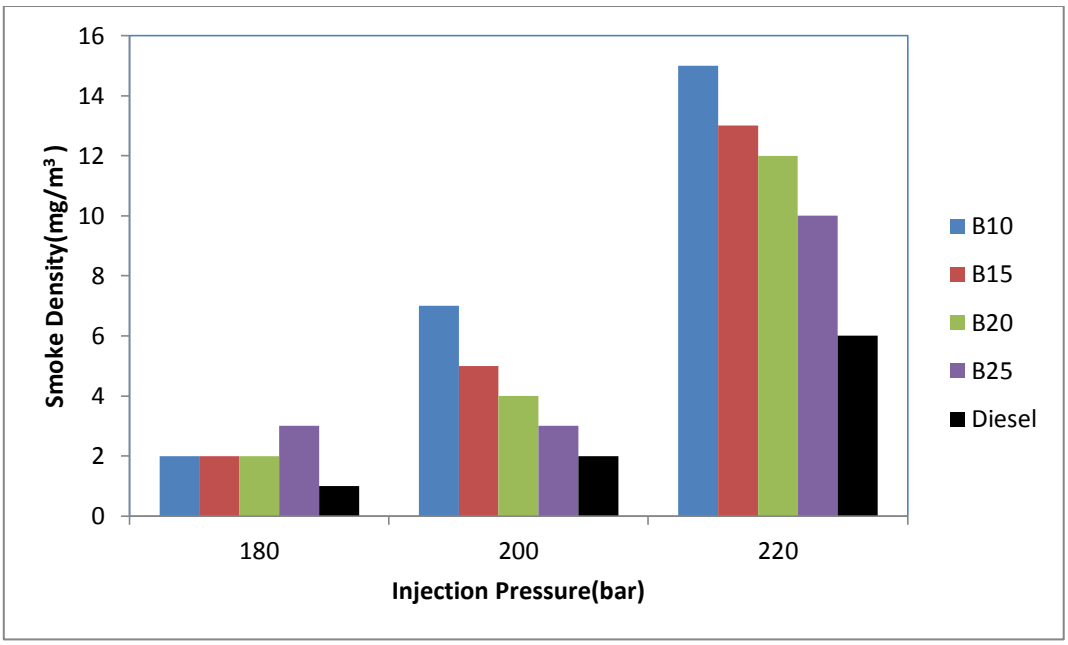

Fig 6.46 comparison of smoke density(mg/m^3) for various test fuels for various injection pressure

The results of experiments of comparison of injection pressure can be summarized as follows.

- Results have shown that among the various injection pressures, 220 bar is the most suitable from the engine performance and emission point of view. Hence it can be taken as optimized injection pressure at 23^{o}bTDC injection timing.
- The Engine performance improved at 220 bar injection pressure with8.86%, 8%, 10%, 9.62%, 11.43% lower BSEC respectively for B10, B15, B20, B25 and diesel as compared to 180 bar injection pressure. BTE increases by 8.7%, 8.4%, 11%, 17.8% respectively for B10, B15, B20, B25 but for diesel it decreases by 12.93%.when injection pressure increased from 180 bar to 220bar.
- NO_X emission increased for all fuels when injection pressure increased from 180 bars to 200 bars but it is decreased when injection pressure is increased from 200 bar to 220 bar. This is due to reduced peak In-cylinder temperature . This indicated that as long as NO_X emission is concerned 220 bar injection pressure is best. There are no significant changes in CO emissions as injection pressure is varied from 180 bar to 220 bars. HC emission, is decreased by

11.1%, 11.7%, 17.64%, 12.5%, as injection pressure increased from 180 bar to220 bar for B10, B15, B20, B25 blends. For diesel it remains unchanged. There is an increase of 114%, 160%, 200%, 233%, 200% of smoke emission for B10, B15, B20, B25, Diesel fuels respectively when injection pressure is increased from 200 bar to 220 bars. 220 bar injection pressure is optimum as for as performance and emission characteristics are concerned excepting smoke emission.

From the experimental findings, it is clear that the higher injection pressure(220 bar) gives better combustion, performance and emission characteristics for the tested fuels as compared to 180 bar and 200 bar injection pressure.

6.3 PERFORMANCE, COMBUSTION AND EMISSION CHARACTERISTICS OF VARIOUS BLENDS OF *VATERIA INDICA* BIODIESEL AND DIESEL AT 220BAR INJECTION PRESSURE UNDER VARYING INJECTION TIMING

The results of previous section reveals that the 220 bar injection pressure gives best performance, combustion and emission charactereristics for the fuels tested. Hence, 220 bar injection pressure is selected as optimized condition. In this section the test results are presented by conducting the experiments with diesel and various blends of *Vateria Indica* biodiesel and diesel viz. B10, B15, B20, B25 and diesel at varying injection timings. The combustion, performance and emission characteristics are investigated at injection pressure of 220 bar and fuel injection timing by retarding by 4^{o}. and advancing by 4^{o}. from standard injection timing of 23^{o}bTDC. So the injection timing used for the present investigations are 19^{o}bTDC and 27^{o}bTDC. The results are presented and discussed with graphs.

6.3.1 Combustion, performance and emission characteristics of various blend of Vateria Indica Biodiesel and diesel at 220 bar injection pressure and at injection timing of 19^{o}bTDC.

This section gives the results of the experiments conducted with diesel and various blends of diesel and *Vateria Indica* biodiesel B10,B15,B20, B25 at 0,25,50,75,100% of full load conditions. The combustion, performance and emission characteristics are

investigated at injection timing of 19^{o}bTDC and injection pressure of 220 bar. The results are presented and discussed with graphs.

6.3.1.1 Cylinder pressure and Heat release rate

The variation of cylinder pressure with crank angle is shown in Fig 6.47 and Fig 6.48.It can be observed that all the test fuels give almost same peak pressure. It can be clearly observed that ignition delay for B25 is minimum. Therefore there is early combustion for B25 which can be concluded from Fig 6.49. It can be observed from the figure that with increase in the biodiesel concentration ignition delay is less and early combustion occurs because biodiesel has lesser ignition delay compared to diesel. Cumulative heat release can be observed to be more for B25 in the early part of the curve as depicted from Fig 6.50. In the latter part of combustion B15 and B20 show better heat release. But late heat release for these fuels results in hot exhaust and waste of heat in the exhaust gasses as depicted in table 6.4. Exhaust gas temperature is not showing much variation for retarded injection because of marginal increase in performance and exhaust temperature increases with the load because of rich mixture burning at higher loads. B25 has cool exhaust gas and better combustion in the early part with better heat release. From Fig 6.51 it can be seen that exhaust gas temperature increases with increase in load due to rich mixture burning at higher loads.

6.3.1.2 Brake Specific Energy Consumption

Variation of brake specific energy consumption is with load is shown in Fig 6.52. For all blends specific energy consumption decreases upto part load and remains same thereon. The BSEC at 75% Load for diesel is 13650.32kJ/kW-hr whereas it is 13071.89kJ/kW-hr, 12702.89KJ/KW-hr, 12244.89KJ/KW-hr, 11824.12kJ/kW-hr respectively for blends B10, B15, B20, B25. The BSEC decreases by4.2%, 6.9%, 10.29%,13.37% for B10,B15,B20, B25 respectively when compared with diesel. BSEC decreases foe blends in the order of biodiesel concentration. Lower BSEC for blends is due to better combustion due to increased oxygen content in the blends.

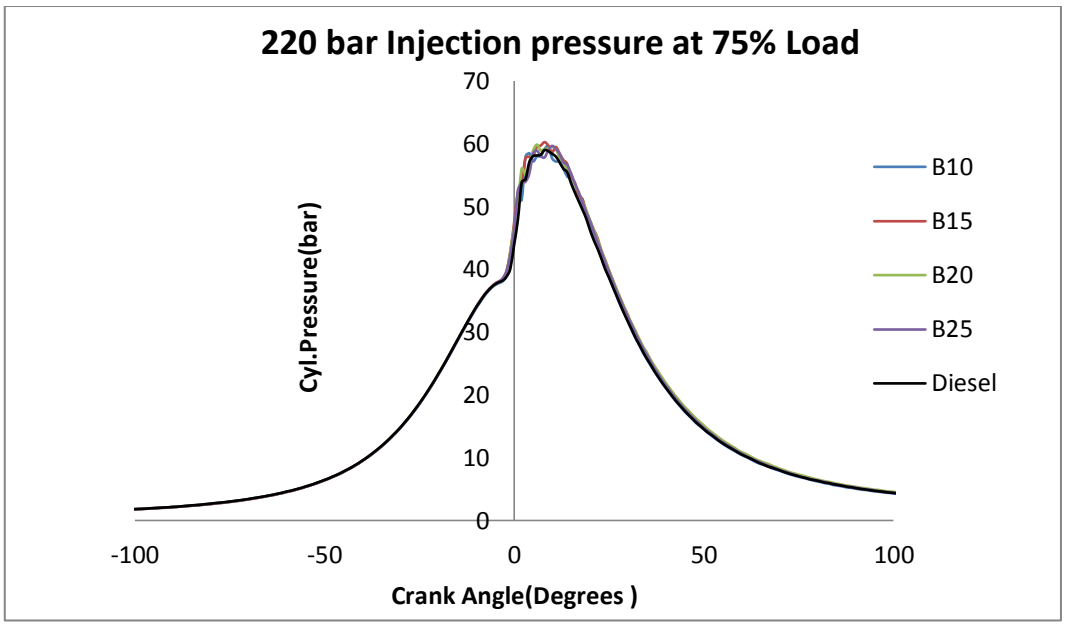

Fig 6.47 Variation of Cylinder pressure with crank angle for test fuels at 220 bar injection pressure and 19^{o}bTDC injection timing

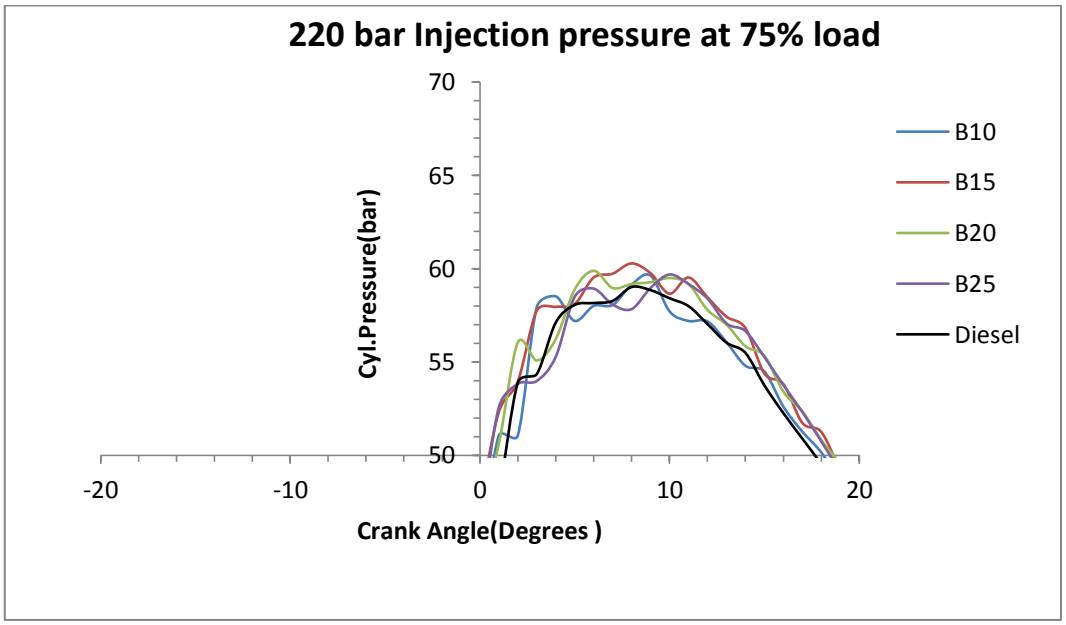

Fig 6.48 Enlarged view of the peak pressure of Fig 6.58

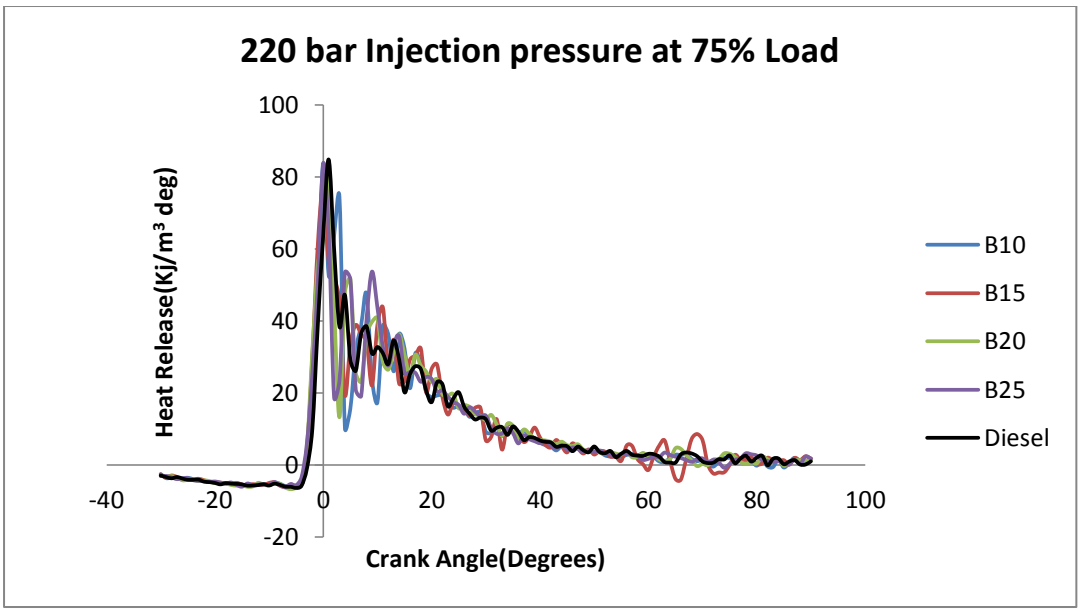

Fig 6.49 Variation of Heat release with Crank angle for 220 bar injection pressure and 19^{o}bTDC injection timing

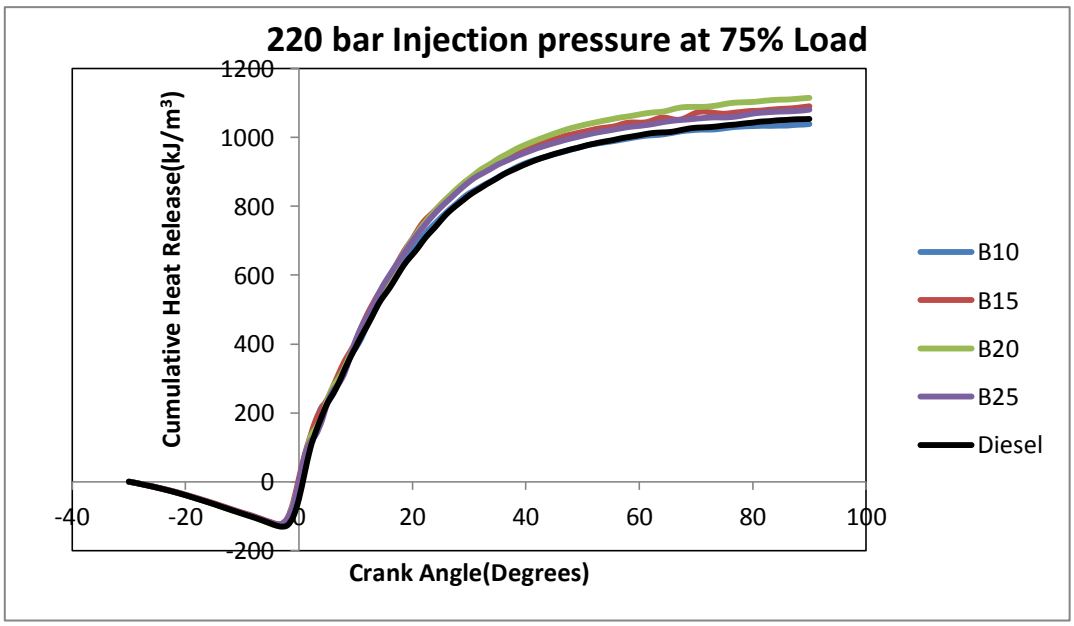

Fig 6.50 Variation Cumulative Heat release for various test fuels at 220 bar injection pressure and 19^{o}bTDC injection timing.

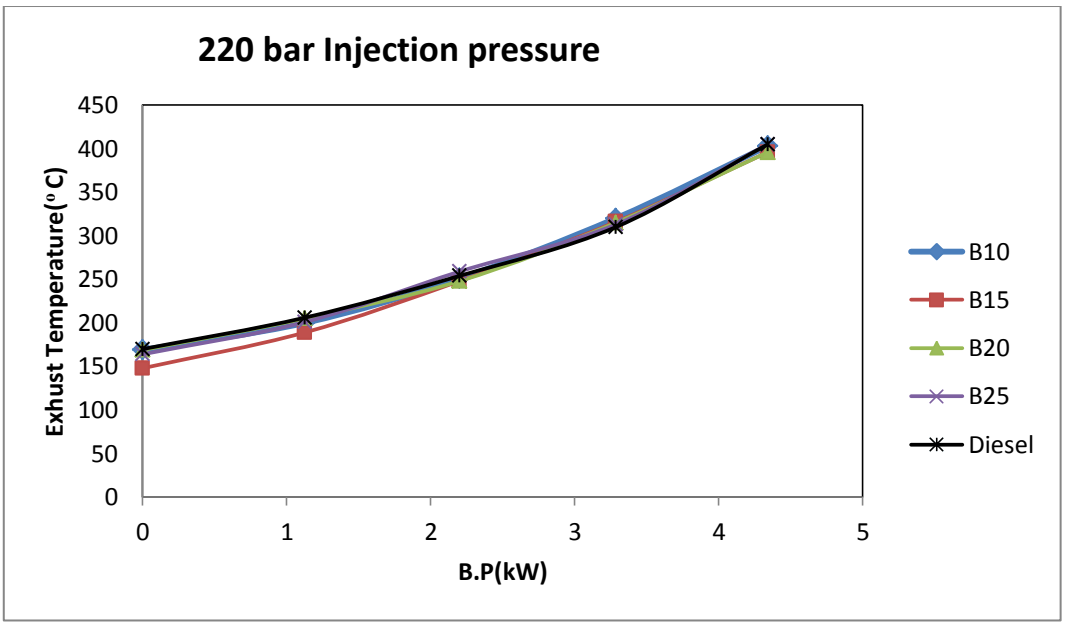

Fig 6.51 Variation of Exhaust Gas temperature with varying load at 220 bar injection pressure and 19° bTDC injection timing.

Table 6.4 Variation of Exhaust temperature for various fuels at 75% load for 220 bar injection pressure and 19°bTDC injection timing.

Fuel	B10	B15	B20	B25	Diesel
Temperature of the Exhaust(°C)	320	316	315	313	310

6.3.1.3 Brake Thermal Efficiency

Fig 6.53 shows the impact of engine load on brake thermal efficiency(BTE). The BTE generally increases with increasing engine load for all fuels. It is maximum for 75% load. It is observed from the figure that the BTE for blends increases with increase with biodiesel concentration.

The BTE of Diesel is 26.37% at 75% load whereas it is 27.54%,28.34%, 29.42%, 30.44% for blends B10,B15,B20,B25 respectively at same load. For all blends BTE is more than diesel because of better combustion and early combustion due to reduced delay period. BTE is maximum for B25 and it increases with increasing biodiesel

concentration in the blend. This characteristic is observed because increased oxygen content and better combustion for higher blends.

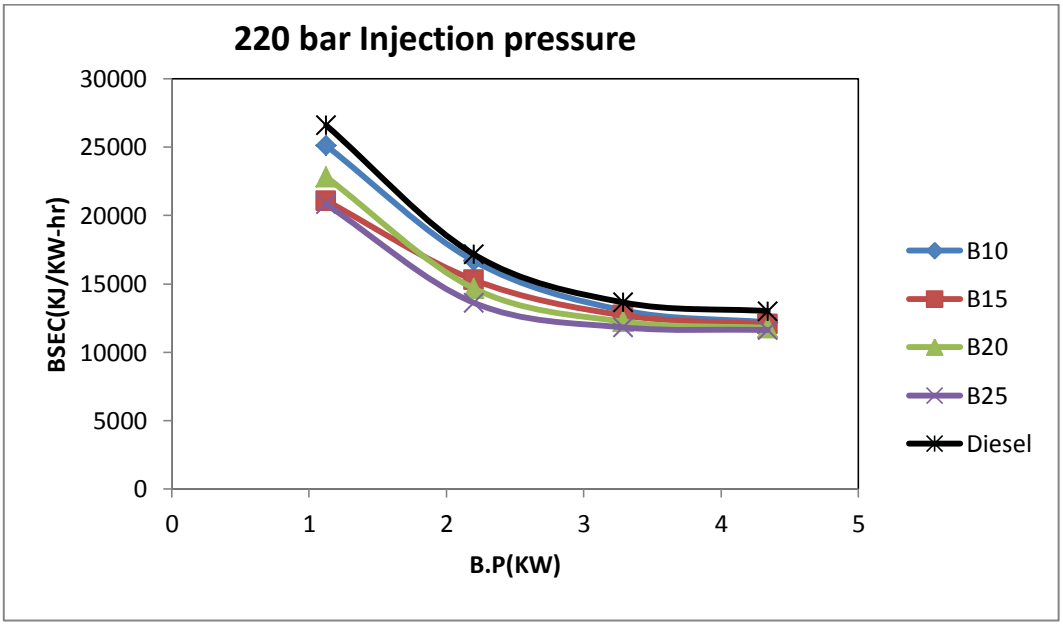

Fig 6.52 Variation of Brake specific energy consumption(BSEC) with load at 220 bar injection pressure and19^{o}bTDC injection timing.

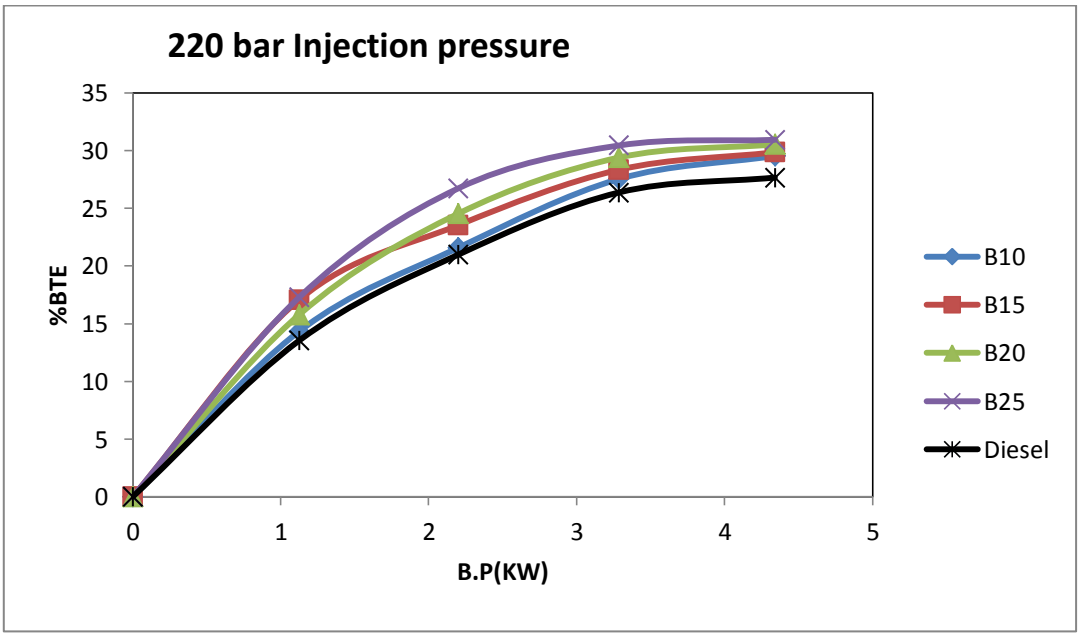

Fig 6.53 Variation of Brake thermal efficiency(BTE%) with load at 220 bar injection pressure and 19^{o}bTDC injection timing.

6.3.1.4 NO_X Emission

Fig 6.54 shows the variation of NO_X emission for various fuel blends at different load conditions. NO_X increases as the load is increased and maximum NO_X is obtained for full load conditions. NO_X for diesel is 812 ppm .NO_X emission is 820ppm, 828ppm, 834ppm, 836ppm for B10, B15, B20, B25 blends respectively. Diesel shows increased NO_X because of nonstandard operating conditions. With increase in Biodiesel concentrations NO_X emission increases B25 results in maximum NO_X emission. All blends have lesser ignition delay hence better combustion leading to higher peak In-cylinder temperature and hence increased NO_X emission.

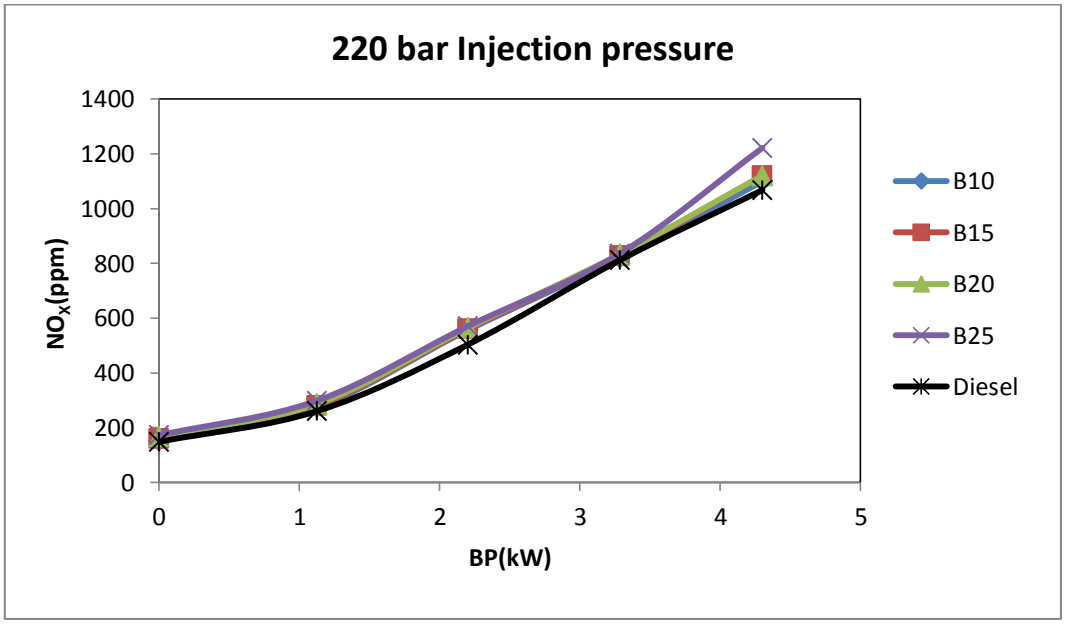

Fig 6.54 Variation of NO_X(ppm) emission with load at 220 bar injection pressure and19^{o}bTDC injection timing.

6.3.1.5 CO Emission

It is observed from Fig 6.55, that CO emission increases as the engine load is increased due to rich mixture requirement during higher load conditions. Compared to Diesel all blends have lesser CO emission and B25 has minimum CO emission. It is observed that 12.5%, 25%, 37.5%, 50% less CO emission is observed for B10, B15, B20, B25 blend respectively at 75% load. Since blend are oxygenated fuels complete

combustion occurs and lesser CO emission is obtained. As the blending ratio is increased more oxygen becomes available and lesser CO results.

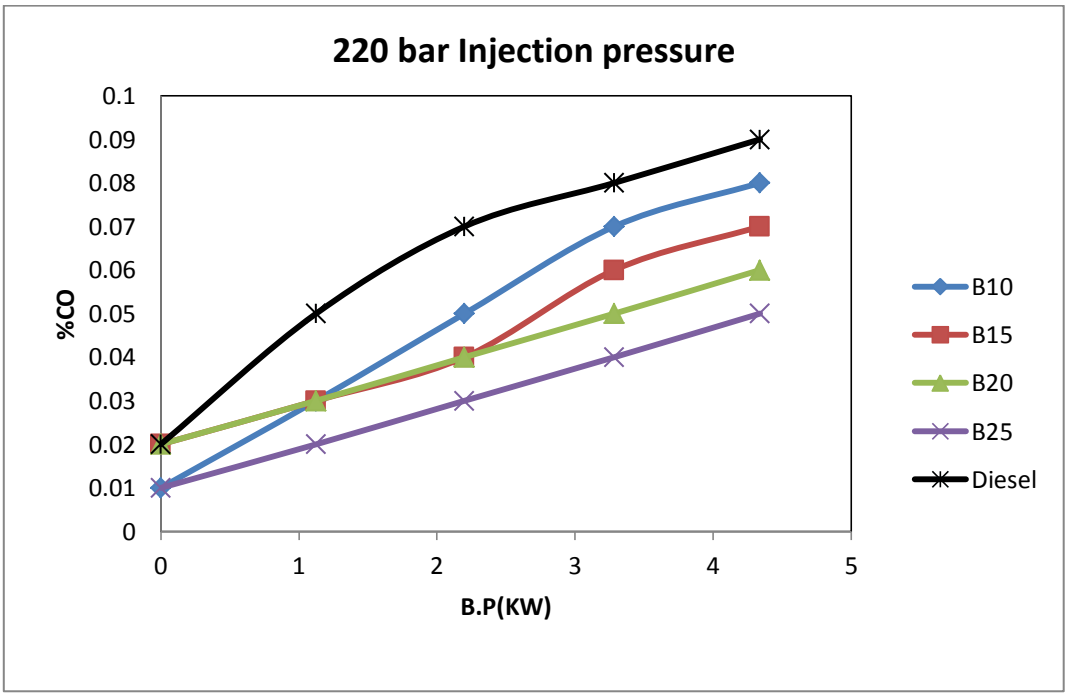

Fig 6.55 Variation of CO(%v) emission with load at 220 bar injection pressure and19^{o}bTDC injection timing.

6.3.1.6 HC emission

The variation of HC emission at different loads for different blends is shown in Fig 6.56 Hydrocarbon emission increases as the engine load increases and maximum HC emission is observed for 100% Load. In addition HC emission decreases as the Biodiesel concentration increases in the blends. It can be observed from the figure that 12.51%, 15.62%, 21.87%, 28.13% lesser HC emission is obtained for B10, B15, B20, B25 blends compared to diesel at 75% load respectively. Additional oxygen content and reduced delay period both lead to early and better combustion resulting in reduced HC emission for all the blends.

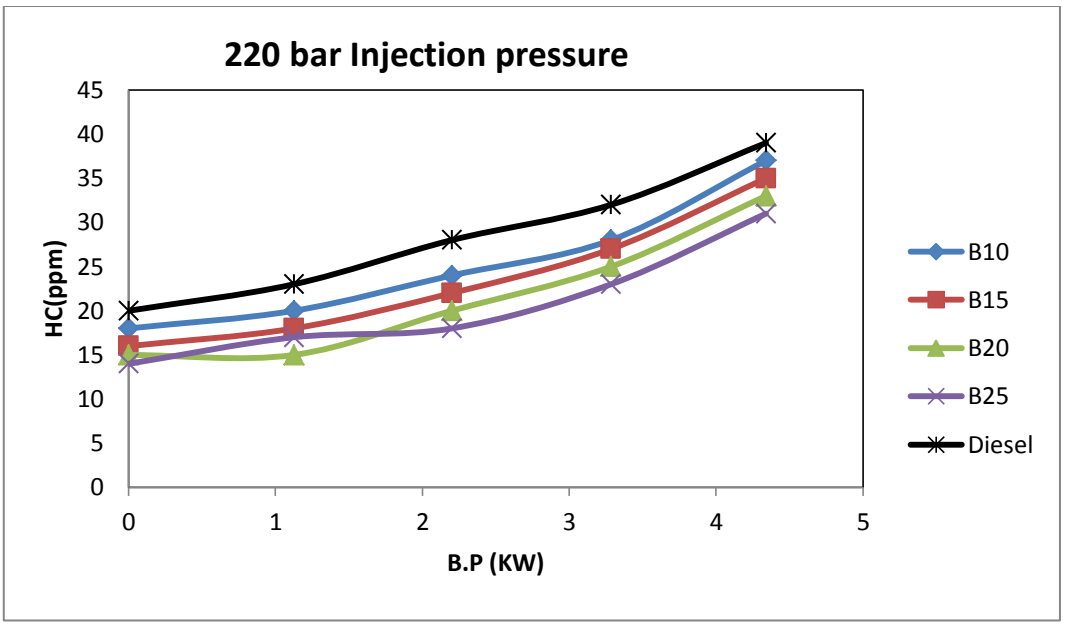

Fig 6.56 Variation of HC(ppm) emission with load at 220 bar injection pressure and19^{o}bTDC injection timing.

6.3.1.7 Smoke emission

The variation in smoke density with load is shown in the Fig 6.57 for all the test fuels. There is a decrease of 12.5%, 25%, 37.5%%, 50% when compared with diesel for 75% load for B25, B20, B15, B10 respectively. As the biodiesel concentration increases the smoke emission increases. The trend is reverse of that of normal injection. When retarded injection takes place higher blends burn early due to decrease in delay period. Due to complete combustion occurring particulate matter is less compared to diesel but, higher blends there is more PM because poor combustion occurring at retarded injection timing due to reduced bulk of fuel and lesser time for combustion.

6.3.2 Combustion, performance and emission characteristics of various blends of *Vateria Indica* biodiesel with diesel at 220 bar injection pressure and 27^{o}bTDC injection timing.

This section gives the results of experiments conducted with diesel and various blends of *Vateria Indica* biodiesel with diesel namely B10, B15, B20, B25 at 0, 25, 75,

100% of full load conditions. The combustion, performance and emission characteristics are investigated at advanced injection timing of 27^{o}bTDC and the fuel injection pressure is kept at 220 bar. The results are presented and discussed with graphs.

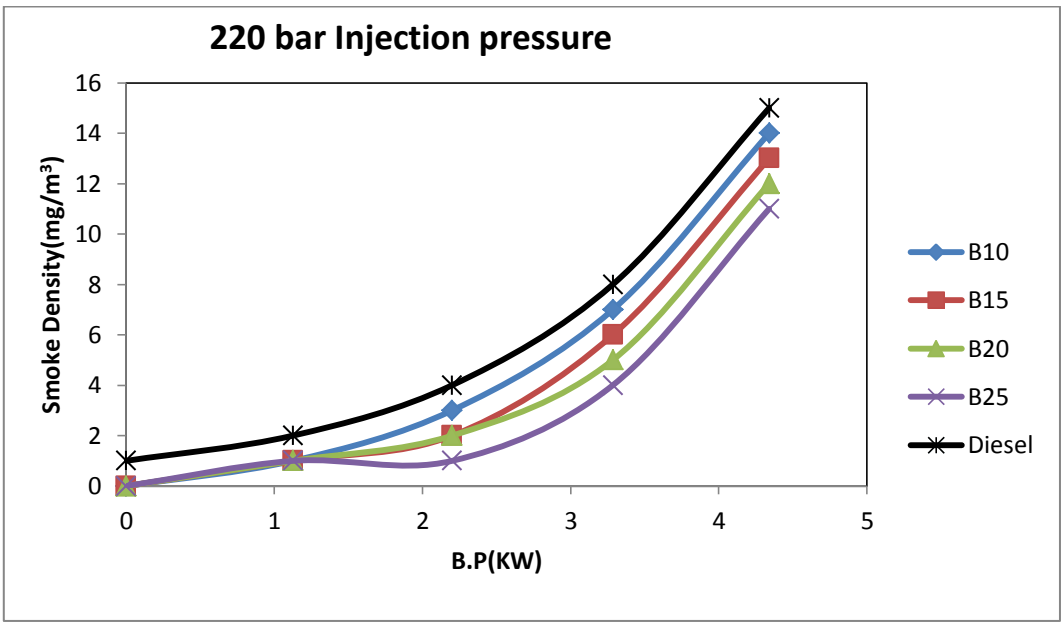

Fig 6.57 Variation of smoke density(mg/m^{3}) with load at 220 bar injection pressure and19^{o}bTDC injection timing.

6.3.2.1 Cylinder pressure and Heat release rate.

The comparison of Variation of cylinder gas pressure vs crank angle for the test fuels at 75% load condition is shown in Fig 6.58 and 6.59. It can be observed that maximum cylinder pressure occurs for B25 blend. B15 blend gives minimum cylinder peak pressure. Peak cylinder pressure of 72 bar, 69 bar,69 bar, 68 bar,67bar obtained for B25, B20, Diesel, B10, B15 respectively. B25 and B20 are the much oxygenated fuels and having lesser ignition delay therefore more cylinder peak pressure. The advanced injection timing of 27^{o}bTDC results in higher peak cylinder pressure due to increased time availability for combustion. Advancing the injection advances the cylinder peak pressure and increased peak pressure. Premixed combustion phase rigorously occurs due to accumulation of fuel drops due to decreased delay period. That is the reason for increase of cylinder peak pressure. Due to the earlier start of

injection, the detailed combustion and engine performance results in case of waste cooking oil biodiesel showed that the ignition delay with the biodiesel addition was decreased for the all engine loads with the earlier combustion timings due to higher cetane number of biodiesel (Ozer Can 2014). Same phenomena observed in present study.

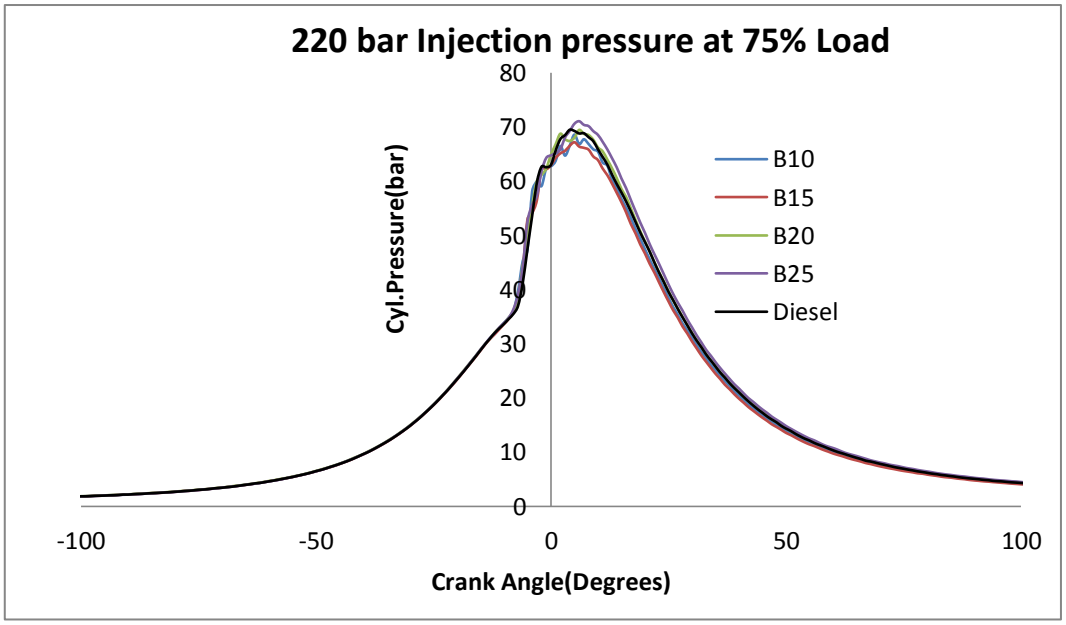

Fig 6.58 Variation of Cylinder pressure with crank angle for test fuels at 220 bar injection pressure and 27^{o}bTDC injection timing

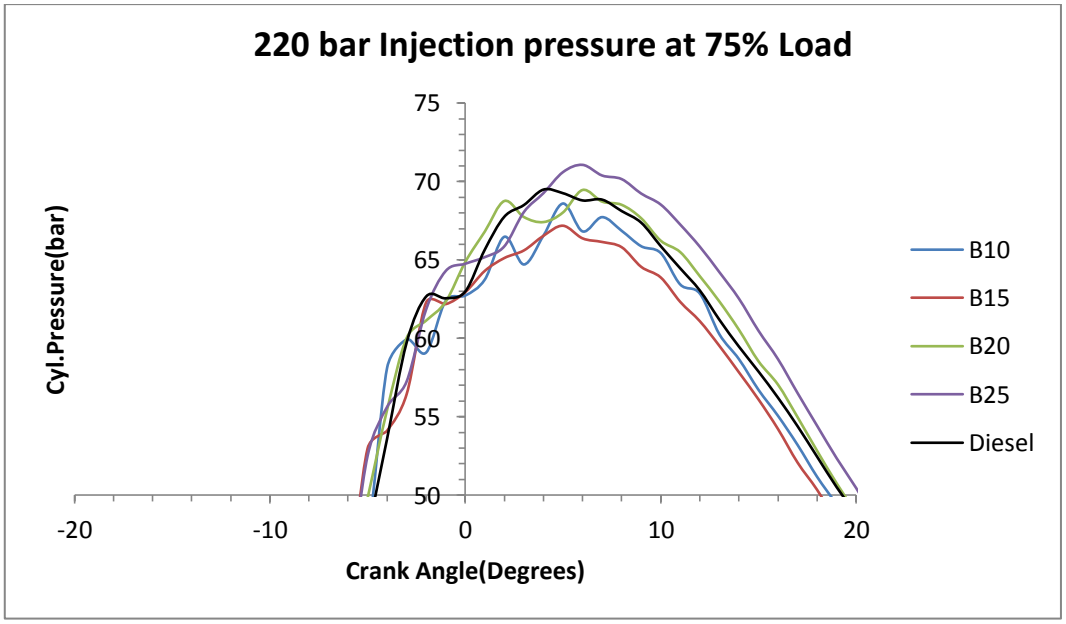

Fig 6.59 Enlarged view of the peak pressure of Fig 6.69

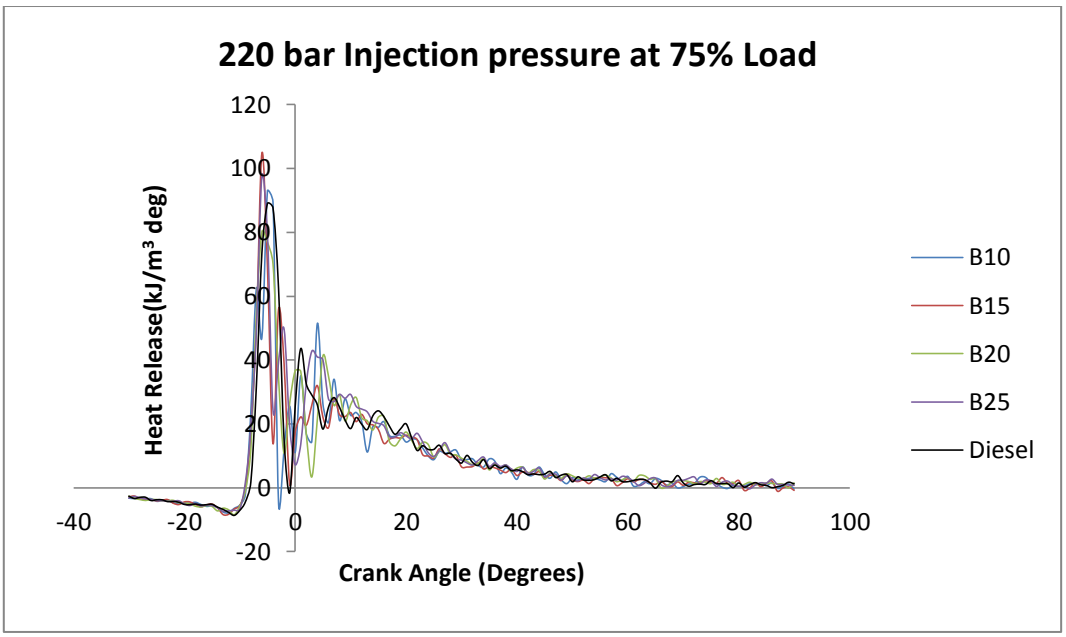

Fig 6.60 Variation of Heat release rate with crank angle for test fuels at 220 bar injection pressure and 27^{o}bTDC injection timing

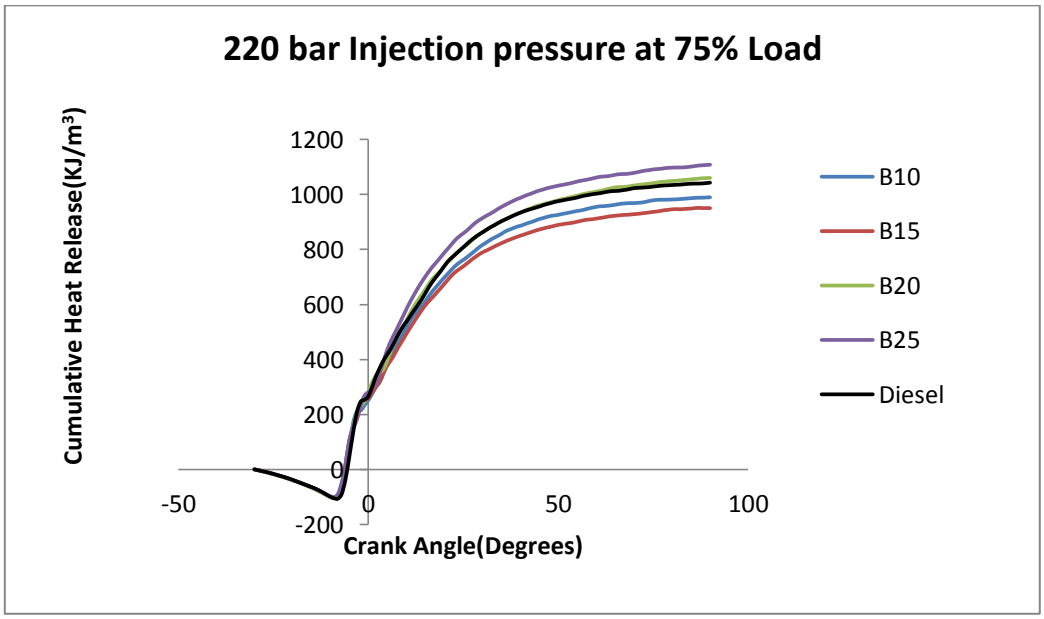

Fig 6.61 Variation of Cumulative Heat release rate with crank angle for test fuels at 220 bar injection pressure and 27^{o}bTDC injection timing

Table 6.5 Variation of Exhaust temperature for various fuels at 75% load for 220 bar injection pressure and 27^{o}bTDC injection timing.

Fuel	B10	B15	B20	B25	Diesel
Temperature of the Exhaust(^{o}C)	322	318	305	300	298

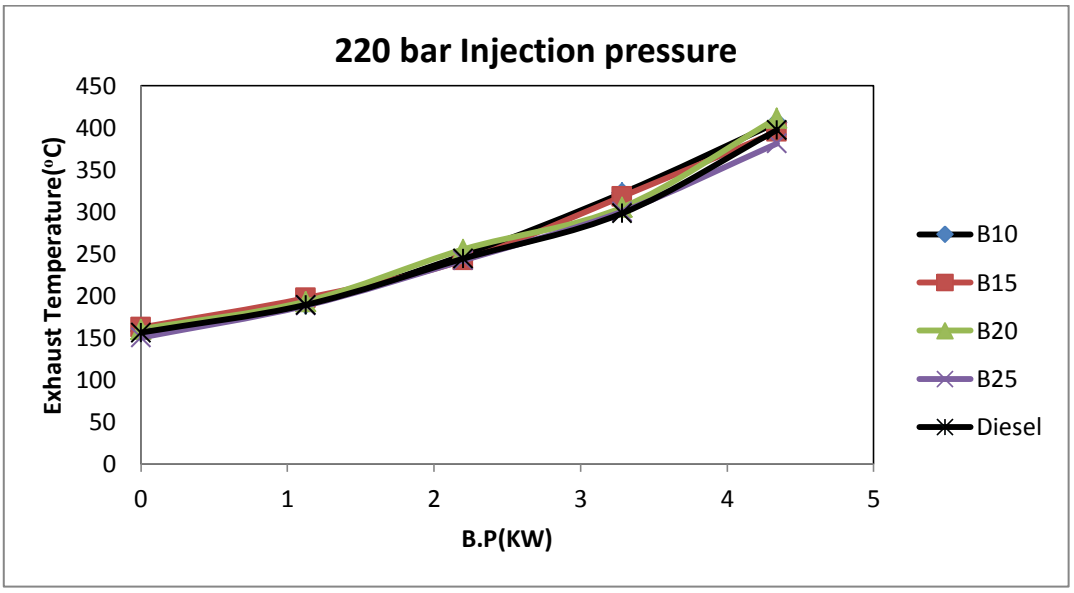

Fig 6.62 Variation of Exhaust Temperature with load for test fuels at 220 bar injection pressure and 27^{o}bTDC injection timing

Fig 6.60 and Fig 6.61 depicts the variation of heat release rate and cumulative heat release rate with the crank angle. From Fig 6.60 it can be concluded that most of the combustion occurs in the late part of compression stroke and early part of power stroke. More time is available for the transfer of heat to the piston in power stroke. Combustion is complete for all the test fuels and maximum heat release occurs for B25 blend. Cumulative heat release occurs in the decreasing order of B25,B20 Diesel, B10, B15. This order is same as that for cylinder peak pressure. The ignition delay for the test fuels is in this order. Detailed chemical structural evaluation is recommended for B10 & B15 blends to find out why ignition delay is more for these blends.

It can be observed from Fig 6.62 that exhaust temperature increases with increase in load. At higher loads rich mixture is burnt and exhaust temperature increases. From table 6.5 it is clear that B25 blend gives cool exhaust which means maximum energy transfer to the piston.

6.3.2.2 Brake Specific Energy Consumption(BSEC)

Fig 6.63 shows the variation of Brake specific energy consumption for the various blends of *Vateria Indica* Biodiesel with diesel at various loads. BSEC decreases for all blends up to part load and remains constant thereon. The BSEC is 11737.85kJ/kW-hr for diesel and it is 11142.06kJ/kW-hr,10486.45kJ/kW-hr, 10092.51kJ/kW-hr, 9782.61kJ/kW-hr respectively for B10, B15, B20, B25 blends. BSEC decreases by 5.07%, 10.66%, 14.01%,16.65% for B10, B15, B20, B25 blends respectively when compared with diesel. Biodiesel blend have excess oxygen in their structure and heat release advances when injection is advanced which results in better combustion and hence leads to lesser BSEC. Higher the blend lesser the BSEC and B25 has minimum BSEC because of above reason (Venkatra man M. S et al,2015)

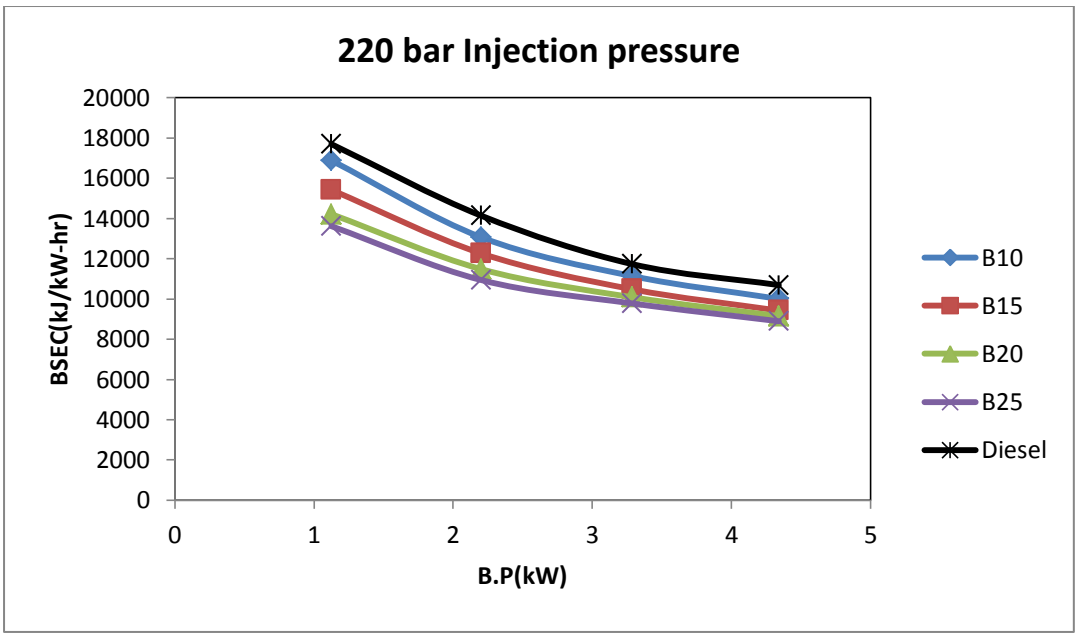

Fig 6.63 Variation of Brake specific energy consumption(BSEC) with the load for test fuels at 220 bar injection pressure and 27^{o}bTDC injection timing

6.3.2.3 Brake thermal Efficiency (BTE)

Fig 6.64 shows the variation of brake thermal efficiency (BTE) at varying engine loads. The BTE generally increases with increasing engine load for all fuels and is maximum for full load. It can be observed that the BTE increases with increase in biodiesel concentration in the blends. The BTE of Diesel is 30.67% whereas it is 32.11%, 34.33%, 35.67%,36.8% for B10, B15, B20, B25 respectively at 75% Load. The BTE is more for higher blends because of interaction of many reasons like availability of oxygen and early premixed combustion and more heat release and cool exhaust gasses.

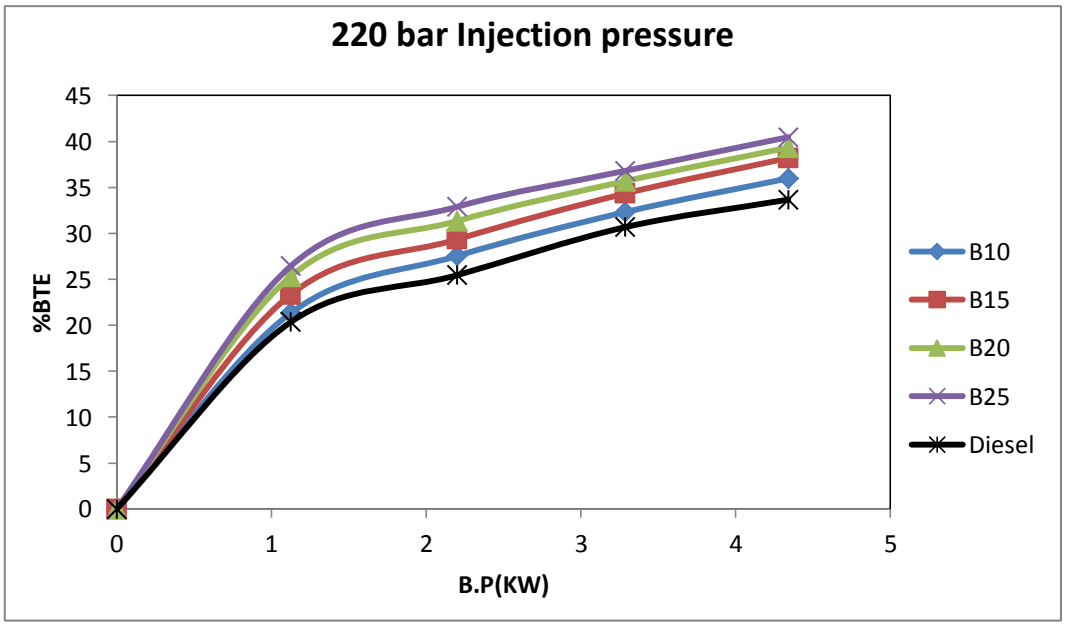

Fig 6.64 Variation of Brake thermal efficiency(BTE) with the load for test fuels at 220 bar injection pressure and 27^{o}bTDC injection timing

6.3.2.4 NO_X emission

Fig 6.65 shows the variation of NO_X emission for various fuel blends at different load conditions. NO_X emission increases as the load is increased and maximum NO_X emission occurs for full load. NO_X emission of diesel is 1536 ppm for 75% load, whereas it is1545ppm, 1560ppm,1582ppm,1590ppm for B10, B15, B20, B25 blends respectively at same load. As biodiesel concentration increases NO_X emission incresases. Since The Availability of Oxygen in Blend makes combustion better and

higher blends higher NO_X emission. B25 is the coolest exhaust highest NO_X emission. Diesel has slightly more NO_X because non standard operating parameters.

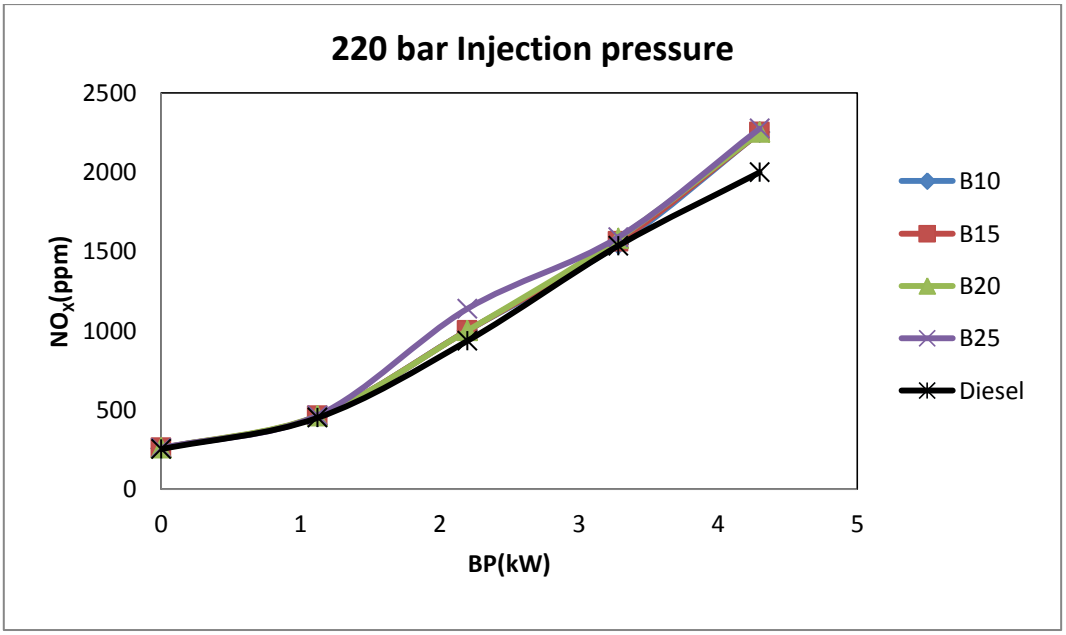

Fig 6.65 Variation of NO_X(ppm) with the load for test fuels at 220 bar injection pressure and 27^{o}bTDC injection timing

6.3.2.5 CO emission

It is observed from Fig 6.66 that CO emission increases with engine load due to rich mixture requirements during higher load conditions. The CO of diesel is 0.05% at 75% load whereas it is 0.04%, 0.03%, 0.02%, 0.01% for blends B10, B15, B20, B25 respectively at the same load. It can be observed that 20%,40%, 60%, 80% less CO emission is observed for B10, B15, B20, B25 blends respectively when compared with diesel for 75% load. Biodiesel blends are oxygenated fuels and advancing the injection burns them early leading to complete combustion which results in lower CO emissions. Higher blends have lower CO emissions because they contain more oxygen.

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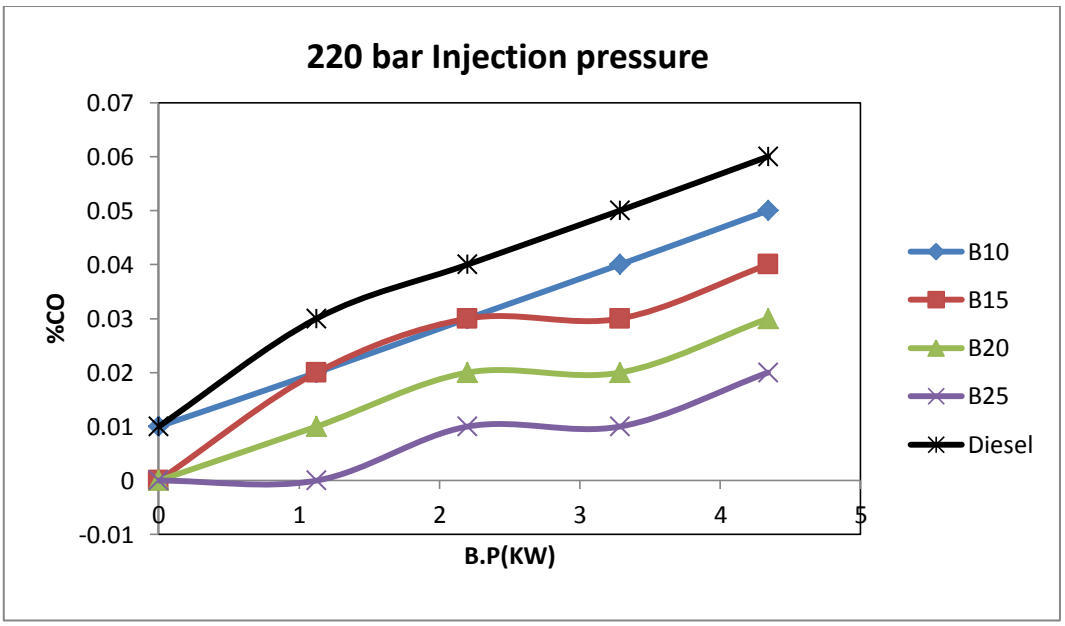

Fig 6.66 Variation of CO(%v) with the load for test fuels at 220 bar injection pressure and 27^{o}bTDC injection timing

6.3.2.6 HC emission

Variation of HC emission at different loads for different blends is shown in figure 6.67. Hydrocarbon emission increases as the engine load is increased and maximum for full load. HC emission decreases as the biodiesel concentration increases in the blend. Biodiesel found to burn more completely because of advanced high pressure injection. Better atomization and advancing the injection leads to better evaporation and early combustion leading to complete combustion. Complete combustion ensures lesser HC emissions for blends. Higher blends burn more completely because of increased oxygen content in them. At 75% load diesel has 17ppm HC emission and B10, B15, B20, B25 have 15ppm, 14ppm, 13ppm, 12ppm HC emission respectively 11.76%, 17.64%, 23.52%, 29.41% reduced HC emissions are observed for B10, B15, B20, B25 respectively. The reason for lower emissions for blends already stated (Venkatraman M. S et al,2015).

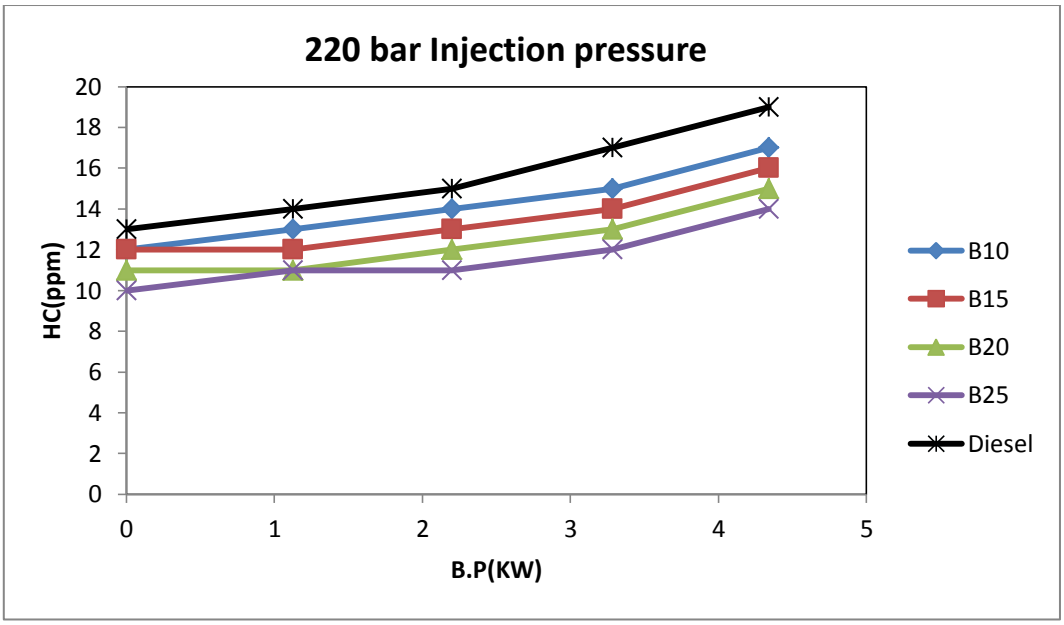

Fig 6.67 Variation of HC(ppm) with the load for test fuels at 220 bar injection pressure and 27^{o}bTDC injection timing

6.3.2.7 Smoke emission

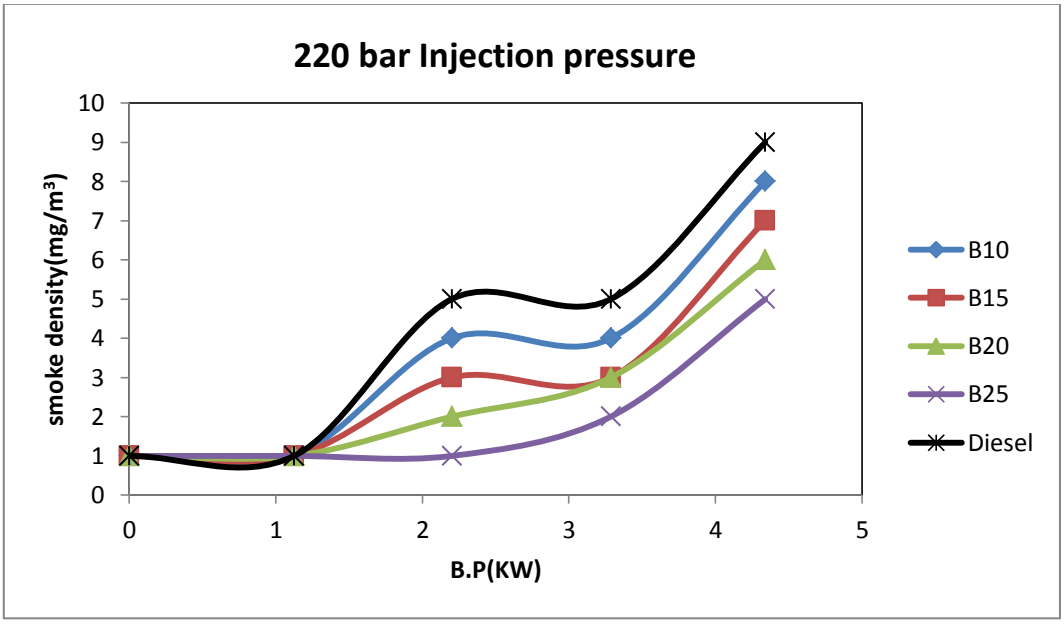

Fig 6.68 Variation of smoke density(mg/m^{3}) with the load for test fuels at 220 bar injection pressure and 27^{o}bTDC injection timing

The variation of smoke density with engine load is shown in Fig 6.68. It can be observed from the figure that the smoke density values tend to decrease for blends when compared with diesel. From the figure it can be observed for B10, B15, B20, B25 blends smoke density decreases by 20%, 40%, 40%, 60% respectively when compared with diesel. The smoke becomes opaque for diesel and lower blends compared with higher blends. Higher blends burn more completely compared with lower blends because of lesser delay period and more oxygen content with them. When combustion is complete carbon gets converted into CO_2. Hence lesser Particulate Matter compared to diesel obtained for all blends more particularly for B25.

6.3.3 Comparison of effects of injection timing on performance and emission characteristics of *Vateria Indica* Biodiesel blends

This section gives the comparison of the results of experiments conducted with diesel and various blends of *Vateria Indica* Biodiesel viz, B10, B15, B20, B25 at different injection timing at 75% Load condition. The effect of injection timing on the combustion, performance, and emission characteristics of diesel and various biofuel blends on CI engine is studied. A comparative study of the combustion, performance and emission characteristics are made at injection timings of 19^{o}bTDC, 23^{o}bTDC, 27^{o}bTDC for the optimized fuel injection pressure of 220 bar. The results are presented and discussed with graphs.

6.3.3.1 Combustion Characteristics

Figure 6.69 shows the variation in-cylinder pressure for different injection timing for all the blends. B25 gives maximum in-cylinder pressure at advanced fuel injection. In-cylinder pressure increases as injection is advanced for all the blends. The Figure 6.70 shows the impact of variation of injection timing on cumulative heat release as the crank angle changes. It can be observed that there is no considerable difference in heat release that is occurring when injection is advanced from 19°bTDC to 27°bTDC. Cumulative heat release slightly increases when the injection is advanced which may be because of decreased ignition delay which gives smoother combustion.

6.3.3.2 Brake specific energy consumption (BSEC)

Figure 6.71shows the variation of brake specific energy consumption at various injection timings for the test fuels.It is observed from the figure that the BSEC decreases as the injection timing is advanced. At 19^{o}bTDC injection timing BSEC of 13650.32, 13071.89, 12702.89, 12244.89, 11824.12 KJ/KW-hr are obtained respectively for diesel, B10, B15, B20, B25 fuels whereas 13323.46, 13000.78, 12526.12, 11908.70, 11601.67 KJ/KW-hr BSEC are respectively obtained for the same test fuels at 23^{o}bTDC injection timing. When injection timing is advanced to 27^{o}bTDC from 19 ^{o}bTDC, the BSEC values for all test fuels decrease. It can be observed from Fig 4.64 that 14.01%, 14.76%,17.44%,17.57%,17.86% reduction of BSEC can be observed for diesel, B10, B15, B20, B25 test fuels when injection timing is advanced from 19^{o}bTDC to 27^{o}bTDC.The reason for lower BSEC is that as injection timing is advanced combustion duration increases and improved combustion occurs.Thus for a given power output minimum quantity of fuel isconsumed. Similar result is obtained for BSFC by Hariram Venkatesan &Vagesh Shangar Ramani (2015) for petrodiesel and Ganapathy T et al(2011) for Jatropha biodiesel blends. S Jindal(2011) observed to the contrary that on advancing IT BSFC increased when tested with Karanj oil methyl ester blends.It is reasoned as on retarding the injection, the delay period increases but fuel delivery to the cylinder reduces with a higher mean effective pressure in the cycle maintaining the power, thereby reducing the specific fuel consumption.

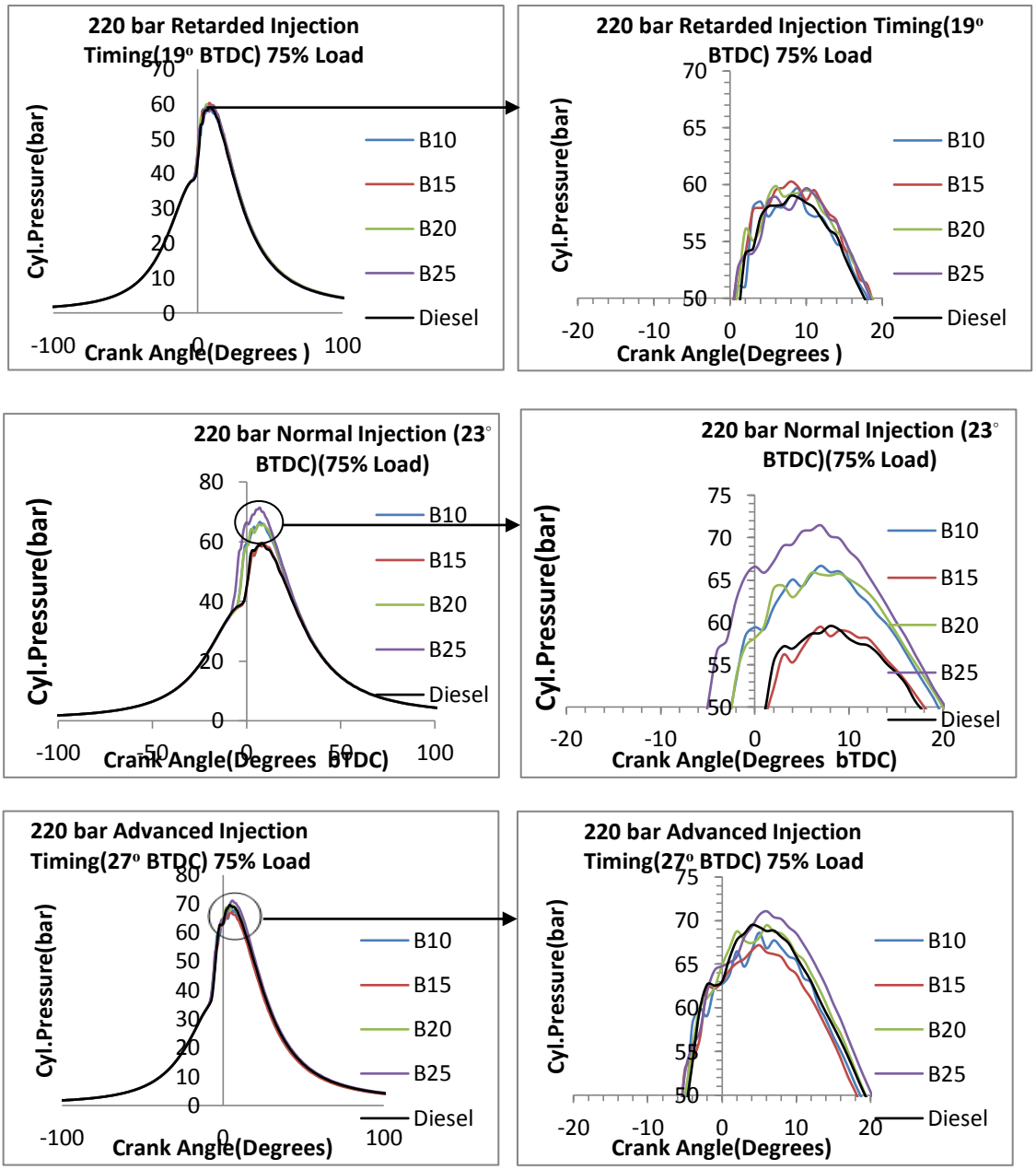

Figure 6.69 In-cylinder pressure Vs crank angle for various injection timing (peeks at the right)

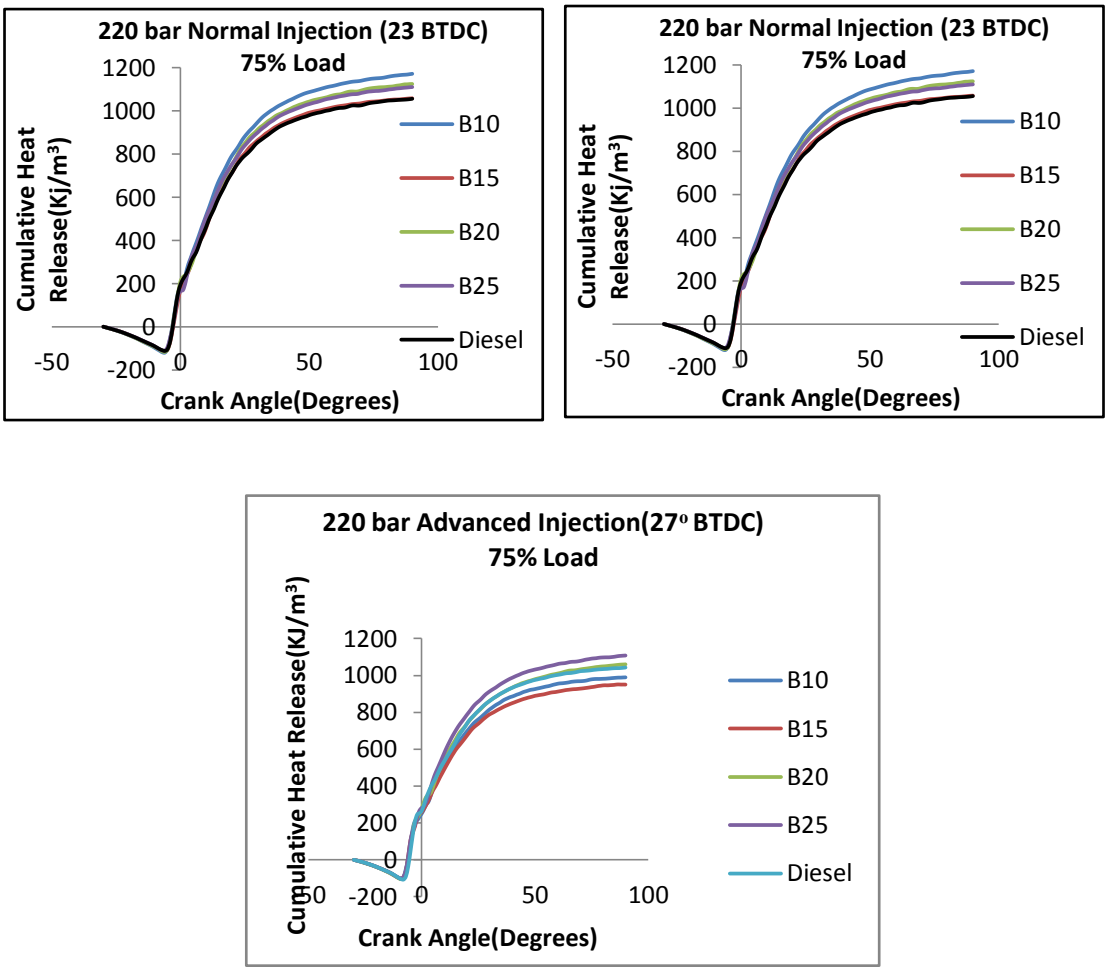

Figure 6.70 Cumulative heat release Vs crank angle for test fuels at different injection timings

6.3.3.3 Brake Thermal Efficiency (BTE %)

Fig 6.72 shows the variation of brake thermal efficiency at various injection timings for the test fuels. It is observed from the figure that the BTE increases as the injection timing is advanced from 19^{o}bTDC to27^{o}bTDC.The Maximum BTE is obtained for 27^{o}bTDC injection timing for all the test fuels at 75% loading condition. At 19^{o}bTDCinjection timing, brake thermal efficiency of 26.37%, 27.54%,28.34%, 29.40%, 30.44% BTE is obtained for Diesel, B10, B15, B20, B25 respectively whereas 30.67%, 32.31%, 34.33%, 35.67%, 36.8% BTE are obtained respectively for 27^{o}bTDC injection timing.

The reason for higher BTE may be the advancing the injection timing leads to higher combustion duration resulting in better utilization of the fuel which helps improved

reaction between fuel and air. This enhances the combustion and in turn improves brake thermal efficiency. Similar results were obtained by Suresh G et al(2014),But Tumbal A V et al, 2016 obtained reverse results were obtained ie BTE decreased on advancing the injection timing when tested with Honge oil methyl ester blends. Suryavamshi J G & Deshpande N V,2006 also observed the same trend when tested with Jatropha biodiesel. When compared to diesel BTE is better for blends because blends are oxygenated fuels which give better combustion. Higher blends better oxygenated fuels hence better BTE.

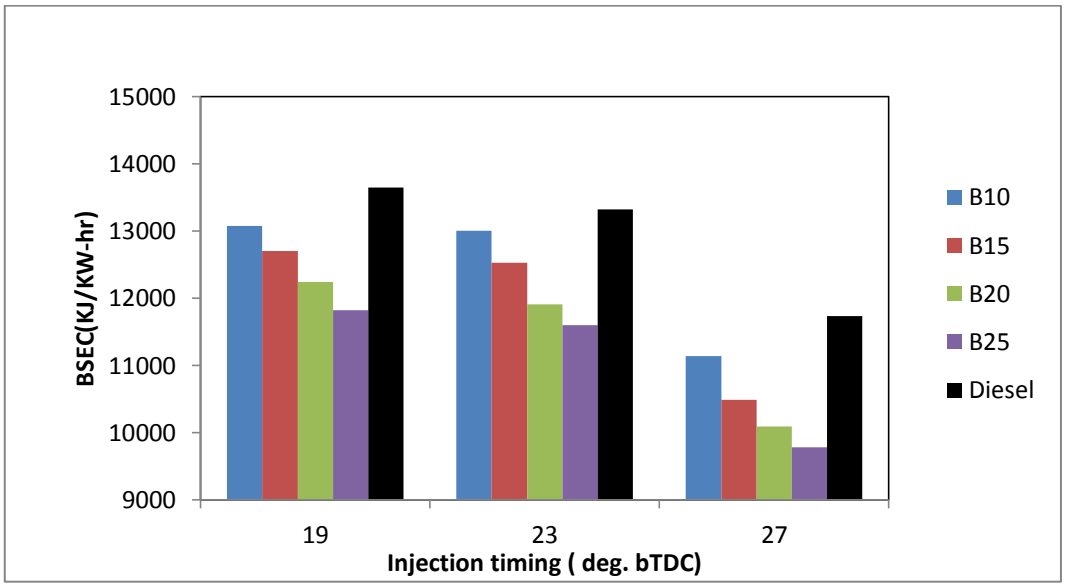

Fig 6.71 Variation of BSEC(KJ/KW-hr) with the Injection timing for test fuels at 220 bar injection pressure at 75% load

6.3.3.4 NO_X emission

The variation of NO_X emission at various injection timings for the test fuels is shown in Fig 6.73. NO_X emission increases as the injection is advanced and Maximum NO_X emission is obtained at 27^obTDC injection timing. It is observed from the figure that 812, 820, 828, 834, 836 ppm of NO_X emission is obtained for diesel, B10, B15, B20, B25 respectively at 75% load whereas 1536, 1545, 1560, 1582, 1590ppm of NO_X emission is obtained for same fuels at same load, when the injection timing is advanced from 19^obTDC to 27^obTDC. NO_X emission increases by 89.16%,90.2%,

88.40%,89.68%,90.2% respectively for diesel, B10, B15, B20, B25 test fuels respectively. The reason for higher NO_X emission is that at advanced injection timing, larger quantities of fuel will burn in the premixed combustion phase resulting in higher peak in-cylinder temperature. It is also observed that NO_X emission decreases as the injection timing is retarded. This may be due to the corresponding changes in the in cylinder gas temperature and lower intensity of heat release rate in the premixed combustion phase and longer combustion duration. The NO_X is formed due to oxidation of N_2 and O_2 at high in-cylinder temperature. but NO_X increases as blending ratio is increased that the biodiesel concentration increases in the blends due to increased availability of oxygen. Jaichander S et al (2012) observed similar phenomena with Pongamia oil methyl ester.The NO emission level increases with increasing injection timing in a study by Kannan G R & Anand A (2012) for waste cooking oil biodiesel blends. This is reasoned for faster combustion and higher cylinder gas temperature due to peak pressure which occurs at earlier crank angle.

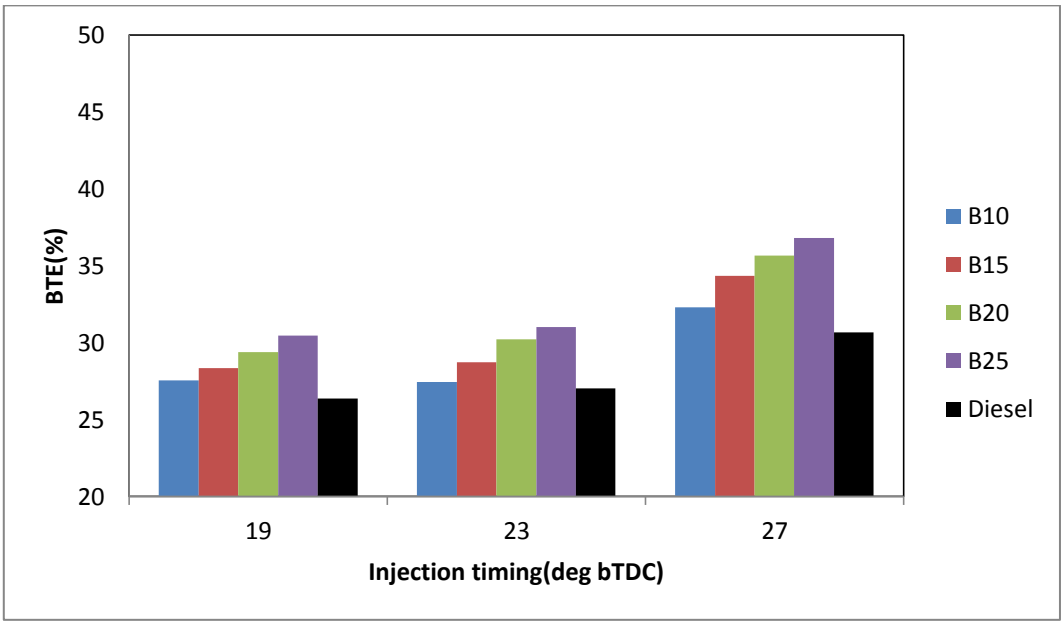

Fig 6.72 Variation of BTE(%) with the Injection timing for test fuels at 220 bar injection pressure at 75% load

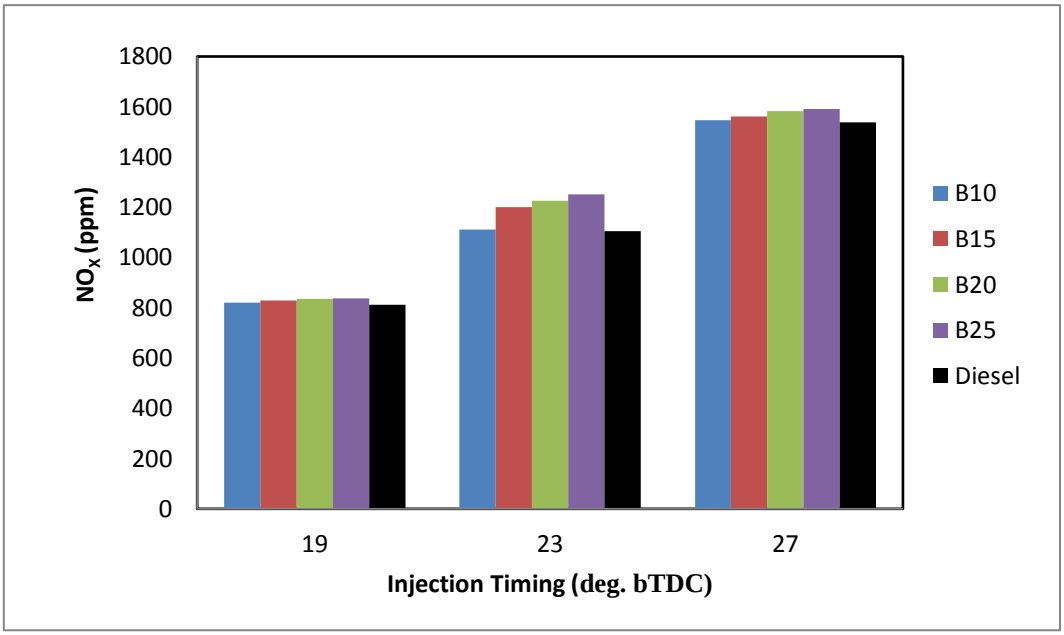

Fig 6.73 Variation of NO_X(ppm) with the Injection timing for test fuels at 220 bar injection pressure at 75% load

6.3.3.5 CO emission

The variation of CO emission at various injection timings for the test fuels is depicted in Fig 6.74. At 19^{o}bTDC injection timing CO emission of 0.08%, 0.07%, 06%, 0.05%, 0.04% obtained for diesel, B10, B15, B20, B25 respectively whereas CO emissions of 0.05%, 0.04%, 0.03%, 0.02%, 0.01% obtained for same fuels at 27^{o}bTDC injection timing. It is observed that 37.5%,42.85%, 50%, 60%, 75% less CO emissions are obtained when injection timing is advanced from 19^{o}bTDC to 27^{o}bTDC.The test results show that the lower CO emission is obtained at advanced injection timings. At higher injection timing the injected fuel will undergo improved combustion due to increased time availability in terms of crank angle for the combustion. The fuel will burn completely and formation of CO_2 takes place instead of CO(Wamankar Arun Kumar et al,2015, Jindal S,2011).

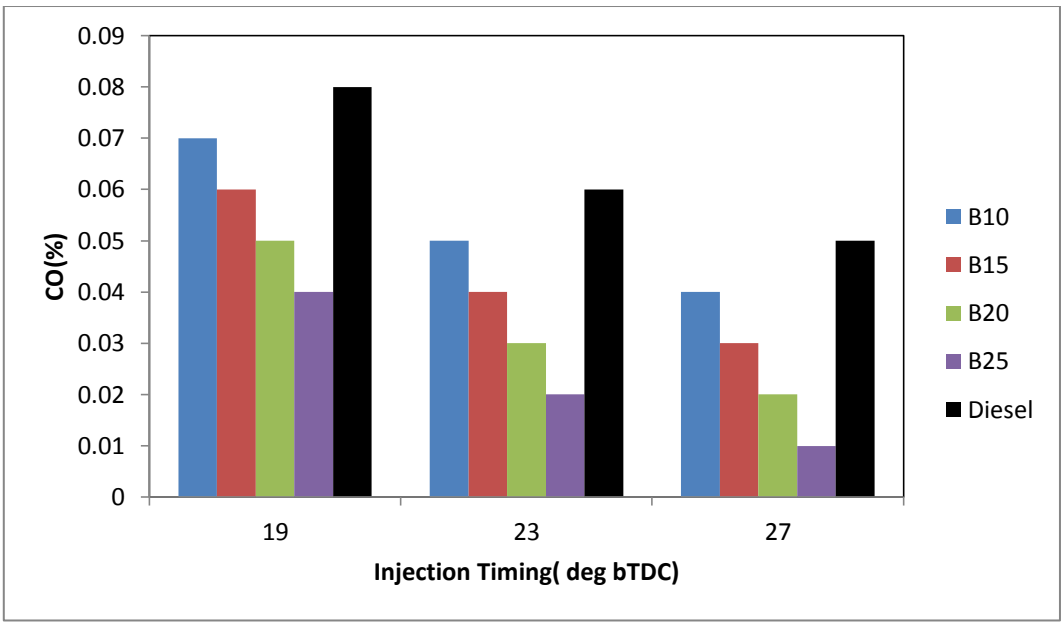

Fig 6.74 Variation of CO(%v) with the Injection timing for test fuels at 220 bar injection pressure at 75% load

6.3.3.6 HC emission

Fig 6.75 shows the variation of HC emission at different injection timings for the various test fuels. It can be observed that 40.64%, 46.15%, 44.45%, 44%, 64.28% reduction in HC emission takes place when injection timing is advanced from 19^{o}bTDC to 23^{o}bTDC whereas HC emission reduces by 46.8%, 46.43%, 48.14%, 48%, 47.82% when fuel injection time is advanced from 19^{o}bTDC to 27^{o}bTDC at 75% loading condition. HC emission is minimum for 27^{o}bTDC injection timing. As the injection is advanced longer combustion duration is obtained and complete combustion occurs which results in less HC emission. Advancing the injection timing causes earlier start of combustion relative to the TDC. Because of this, the cylinder charge, being compressed as the piston moves to the TDC, had relatively higher temperatures, and thus lower the HC emissions (Cenk Sayin, 2009). But a converse result is observed by Tumbal A V et al, (2016), for Honge oil methyl ester.

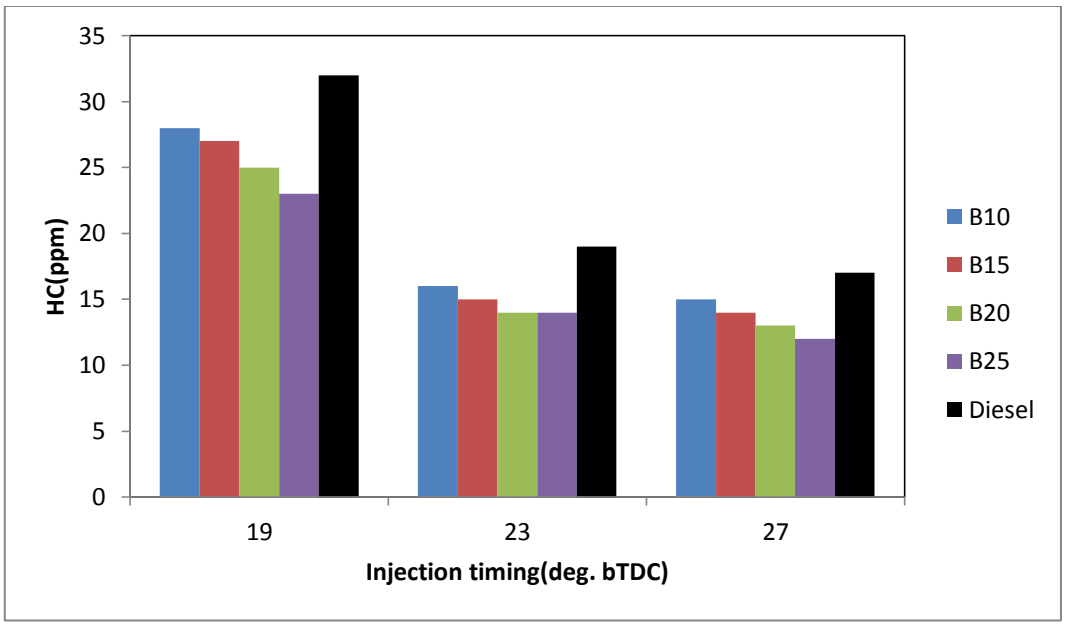

Fig 6.75 Variation of HC(ppm) with the Injection timing for test fuels at 220 bar injection pressure at 75% load

6.3.3.7 Smoke emission

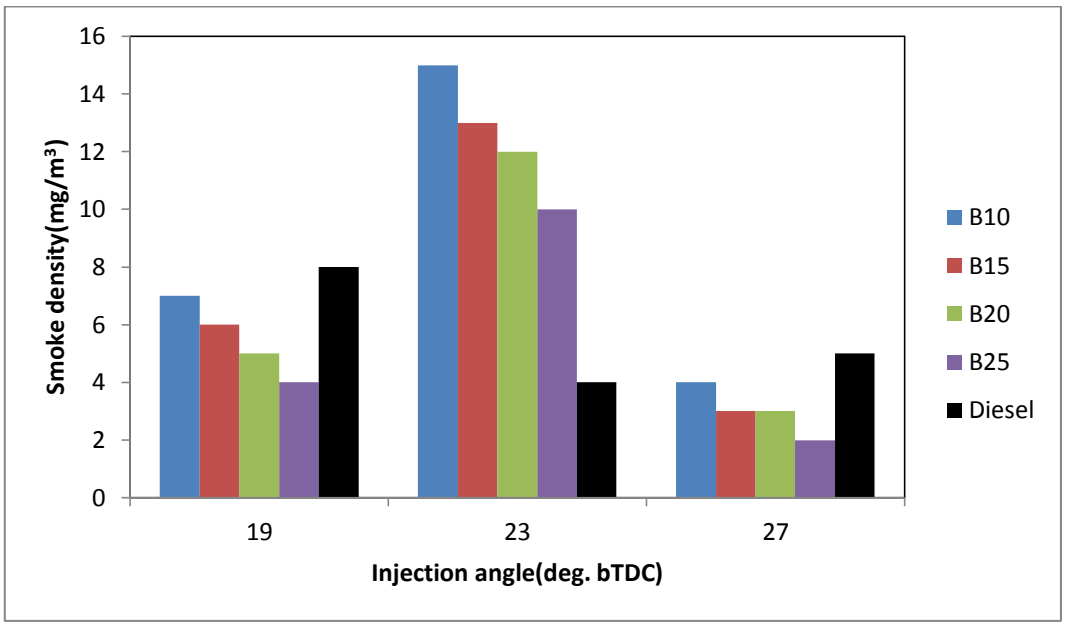

Fig 6.76 Variation of smoke density(mg/m^3) with the Injection timing for test fuels at 220 bar injection pressure at 75% load

Fig 6.76 shows the variation of smoke emission at various injection timings for the test fuels. From the figure it is clear that smoke density is maximum in case of injection timing of 23°bTDC. The normal injection of 23°bTDC proves to be inferior when the smoke emission is considered. The smoke emission increases when the injection timing is advanced from 19°bTDC to 23°bTDC. But smoke density decreases and it becomes less opaque when injection timing is advanced from 23°bTDC to 27°bTDC. It decreases by 37.5%, 42.85%, 50%, 40%, 50% for B10, B15, B20, B25, Diesel respectively when injection timing is advanced from 19°bTDC to 27°bTDC.when injection is advanced to 27°bTDC combustion duration increases and complete combustion occurs and smoke emission is less. But for 23°bTDC smoke emission is maximum because combustion is less complete and after burning phase adds more Particulate matter because of reduction of CO_2, CO to its atomic states. Retarded injection of 19°bTDC gives lesser smoke compared to 23°bTDC injection timing. This may be due to less of after burning phase. Many studies reveal that smoke level decreases when the injection is advanced.(Balusamy T & Marappan R,2010,)Advancing IT decreases smoke emission for all conditions. Reason may be higher cylinder temperature due to increase in premixed combustion phase as a result of longer ID. Lower pressure and temperature inside the combustion chamber during injection of fuel, increase the ID. The high temperature of combustion promotes the oxidation of soot which causes reduction in smoke (Kumar Niraj et al,2016). In the present study Smoke emission increases first and decreases for further increase in IT.

The results of experiments of the comparison of fuel injection timings can be summarized as follows.

- Results have shown that among various injection timings 27°bTDC is the most suitable from the engine performance and emission point of view. Hence it can be taken as optimized injection timing at optimized injection pressure of 220 bars.
- The engine performance improved at 27°bTDC injection timing with lower BSEC and Higher BTE obtained for diesel, B10, B15, B20, B25 fuels when compared to 23°bTDC injection timing. At advanced injection timing and higher injection pressure improved fuel spray and atomization results in better distribution throughout the combustion chamber during the prolonged

combustion duration. This phenomena is observed in pistacia lentiscus biodiesel(K. Khiari et al,2016)

- Considerable reduction of CO, HC, and smoke emission are achieved, while NO_X emission showed an increasing trend with 27^{o}bTDC injection timing and 220 bar injection pressure. It can be observed that 16.67%, 20%, 25%, 33.33%, 50% lower CO emission is obtained for diesel, B10, B15, B20, B25 fuels respectively when injection timing is advanced from 23^{o}bTDC to 27^{o}bTDC. It can be observed that 39.25%, 45.45%, 46.05%, 49.69%, 51.82% more NO_X emission is observed for diesel, B10, B15, B20, B25 test fuels respectively when fuel injection timing is changed from 23^{o}bTDC to 27^{o}bTDC.The reasons for higher NO_X and lower CO and HC emissions are at advanced emission timing resulting in simultaneous improvement in fuel spray characteristics and extended combustion duration.
- A 37.5%,42.85%, 50%, 40%, 50% less smoke emission is obtained for Diesel, B10, B15, B20, B25 test fuels at 75% load when injection timing is advanced from 19^{o}bTDC to 27^{o}bTDC at 220 bar injection pressure.

From experimental findings it is clear that the advanced injection timing 27^{o}bTDC under 220 bar injection pressure gives better combustion, performance and emission characteristics for fuels tested compared to retarded injection timing of 19^{o}bTDC and standard injection timing 23^{o}bTDC.

6.4 OPTIMIZATION OF *VATERIA INDICA* BIODIESEL AND DIESEL BLEND

The results of the present investigation of *Vateria Indica* biodiesel and diesel blends show the considerable variation in performance, combustion and emission characteristics between B10, B15, B20 blends when compared with B25 blend. It is observed that3.17% less BSEC, 3.18% more BTE and 50% less CO,7.69% less HC and 33.34% less smoke is obtained for B25 blend compared with B20 blend under 220 bar injection pressure and 27^{o}bTDC injection timing. Hence B25 is taken as optimized blend for further investigation.

6.5 EFFECT OF EGR ON PERFORMANCE, PERFORMANCE AND EMISSION CHARACTERISTICS OF *VATERIA INDICA* BIODIESEL AND DIESEL BLEND

This section presents the EGR effect on engine characteristics of B25 blend under 220 bar injection pressure and 27^{o}bTDC injection timing. The EGR is carried out by considering mass flow rate of atmospheric air as reference and engine tests are conducted by supplying the mass flow of 5% and 10% EGR concentration. The combustion, performance and emission results are presented and discussed with graphs.

6.5.1 Cylinder pressure and heat release.

Fig 6.77 shows the variation of cylinder pressure with crank angle varying with EGR. It can be observed that minimum cylinder pressure occurs with 10% EGR. As EGR percentage increases cylinder pressure decreases for optimum blend B25. EGR dilutes the charges and some energy is absorbed by the exhaust gasses reducing the maximum in cylinder pressure. The similar result is observed by Donghui Qi et al, (2011).Exhaust gas recirculation reduces the availability of extra oxygen and absorbs the heat during combustion thereby reduces the temperature during timeof combustion. Since the specific heat capacity of the exhaust gas is more it absorbs more heat thereby reducing the high temperatures available at the time of combustion which reduced the net heat release(Suryawamshi G J and Deshpande N V,(2006).

Fig 6.78 shows the variation of heat release rate for B25 varying with EGR. It can be observed from the figure that maximum heat release occurs for B25 without EGR. But minimum heat release occurs for 5% EGR whereas for 10% EGR more heat release occurs compared to 5% EGR. This may be due to exhaust gasses adding to the net heat. From Fig 6.78 it is evident that ignition delay for 5% EGR is same as NO EGR case and it is more for more 10%EGR compared to NO EGR case. When EGR is more absorbing of energy of the charge by exhaust gasses reduces the temperature of the charge increasing the ignition delay From Fig 6.79 it is clear that maximum cumulative heat release occurs for B25 without EGR in premixed combustion phase. But as the combustion proceeds in the diffusion stage is more cumulative heat release

occurs for 10% EGR. The minimum cumulative heat release occurs for 5% EGR in diffusion combustion stage. When large amount of exhaust gasses are present heat of exhaust gasses may be released to combustion products. But when only 5% gasses are present they may work as heat cushion leading to minimum heat release.

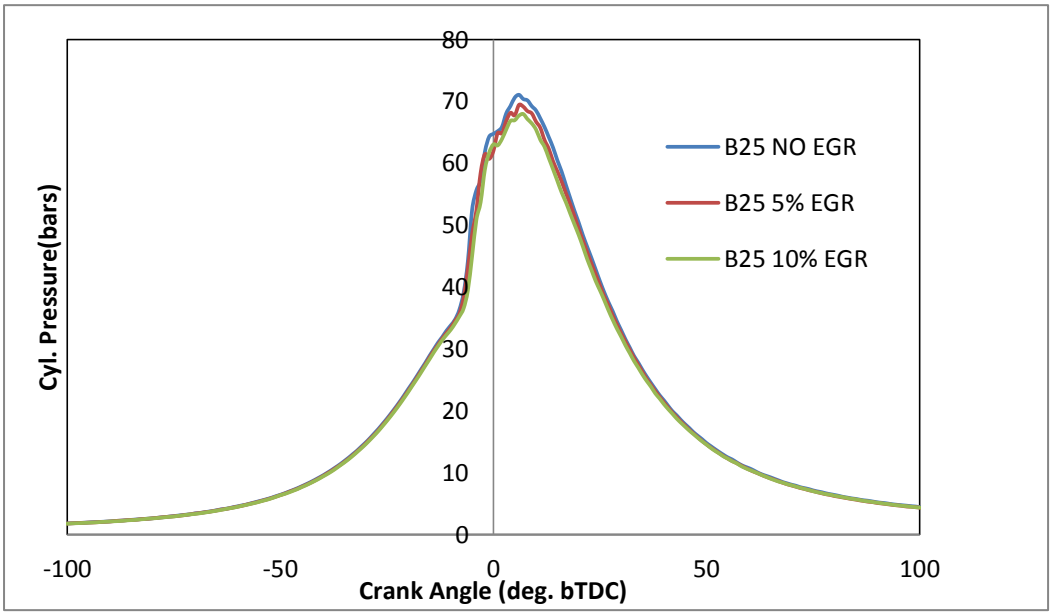

Fig 6.77 Variation of Cylinder pressure with crank angle for 75% load for B25 varying with EGR at 220 bar injection pressure and 27^{o}bTDC injection timing

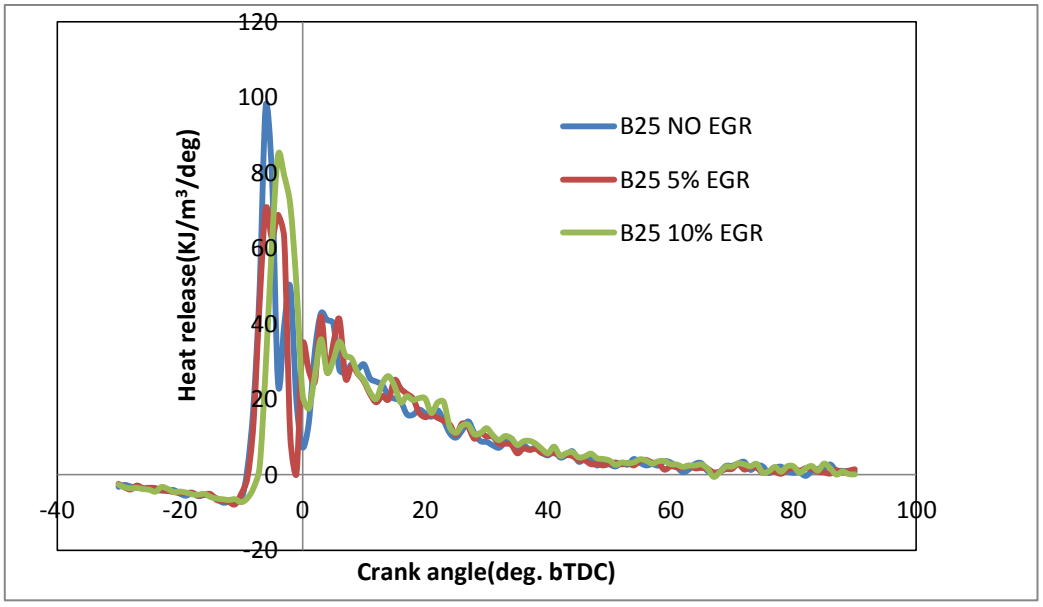

Fig 6.78 Variation of Heat release with crank angle for 75% load for B25 varying with EGR at 220 bar injection pressure and 27^{o}bTDC injection timing

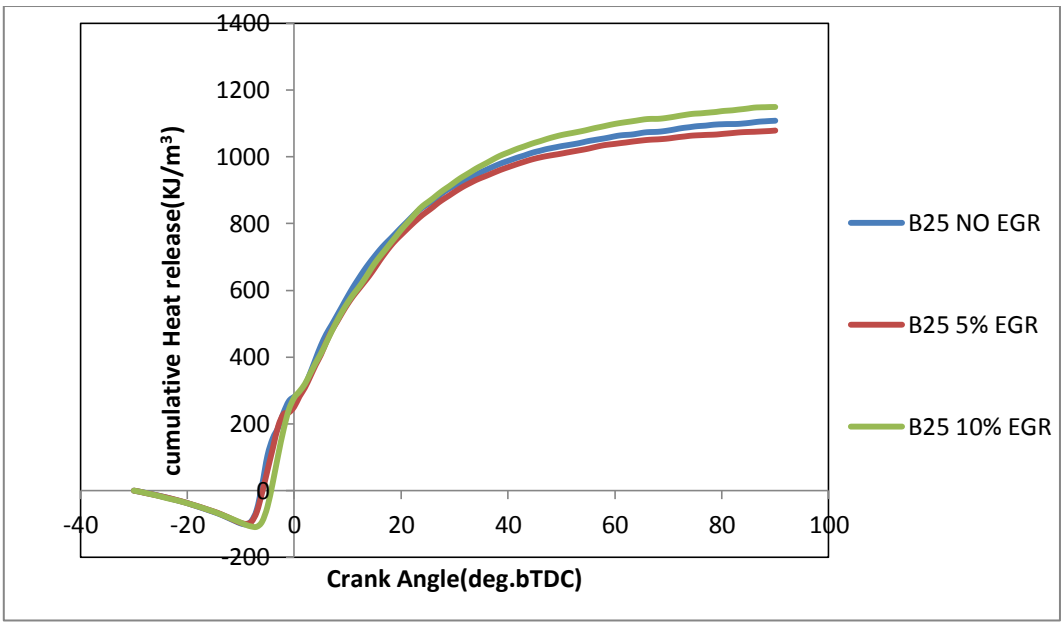

Fig 6.79 Variation of Cumulative Heat release with crank angle for 75% load for B25 varying with EGR at 220 bar injection pressure and 27^{o}bTDC injection timing

6.5.2 Brake specific Energy consumption (BSEC)

Variation of brake specific energy consumption with varying EGR is shown in Fig 6.80. Increased BSEC is observed as percentage of EGR is increased. An increase of 14.47% and 17.56% in BSEC is observed for 5% and 10% EGR with B25 when compared to B25 without EGR. Increase in EGR percentage decreases intake air. This will reduce the oxygen availability for the combustion by increasing the amount of CO_2. The EGR concentration in the intake air will increase the fuel consumption for all load conditions and higher BSEC is observed. The reason for higher specific fuel consumption values for bio-diesel is due to its lower calorific value and higher viscosity and higher boiling point(Vidya Sagar Polu et al,2013).

6.5.3 Brake thermal efficiency(BTE%)

The variation of brake thermal efficiency with varying EGR is depicted in Fig 6.81. Decreased BTE is observed as the percentage of EGR to the intake air is increased. A decrease of 12.66% and 14.9% in BTE is observed for 5% EGR and 10% EGR along with B25 blend when compared with NO EGR with B25.The performance of the engine decreases as percentage EGR increases. This may be due to decreased oxygen

availability with increased EGR percentage. However the blend B25 performs better than diesel even if EGR is done because biodiesel is a oxygenated fuel. At higher load conditions, exhaust gas has higher amount of CO_2, which decreases the combustion temperature. The increase in EGR percentage decreases the combustion temperature, and thereby, the decrease in BTE is obtained. Similar results were observed by Ozer Can et al,(2016) by using Soya bean biodiesel.

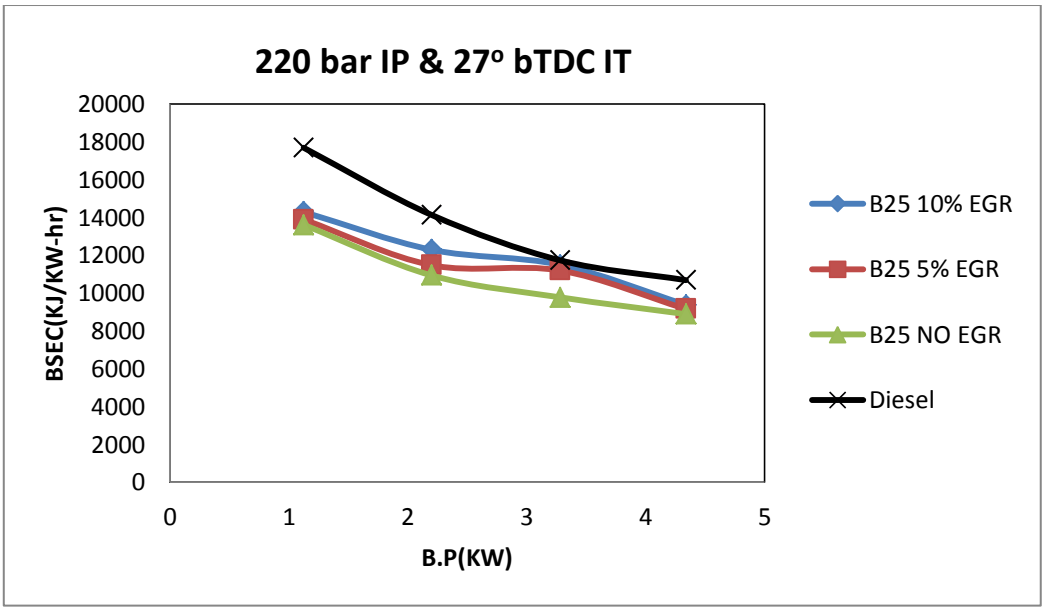

Fig 6.80 Variation of Brake specific fuel consumption with varying load and EGR at 220 bar injection pressure and 27^{o}bTDC.

6.5.4 NO_X emission

Variation of NO_X (ppm) emission with varying EGR is shown in Fig 6.82. It can be observed that when EGR is done with optimized B25 blend NO_X emission decreases. This reduction in NO_X emission increases as EGR percentage increases from 5% to 10% drastically at part and full loads. A decrease of 19.05% and 66.52% in NO_X emission is observed for 5% EGR and 10% EGR. When these results are compared with diesel 68.55% reduction is observed for 10% EGR. The reasons for decrease in NO_X emission using EGR in diesel engines are reduced oxygen concentrations and decreased flame temperatures. Therefore it can be observed that when EGR is applied

there is considerable decrease in NO_X emission(Saravanan S et al, 2016,Vidya Sagar Polu et al,2013,Suryawanshi G J et al, 2006,Donghui Qi et al,2011)

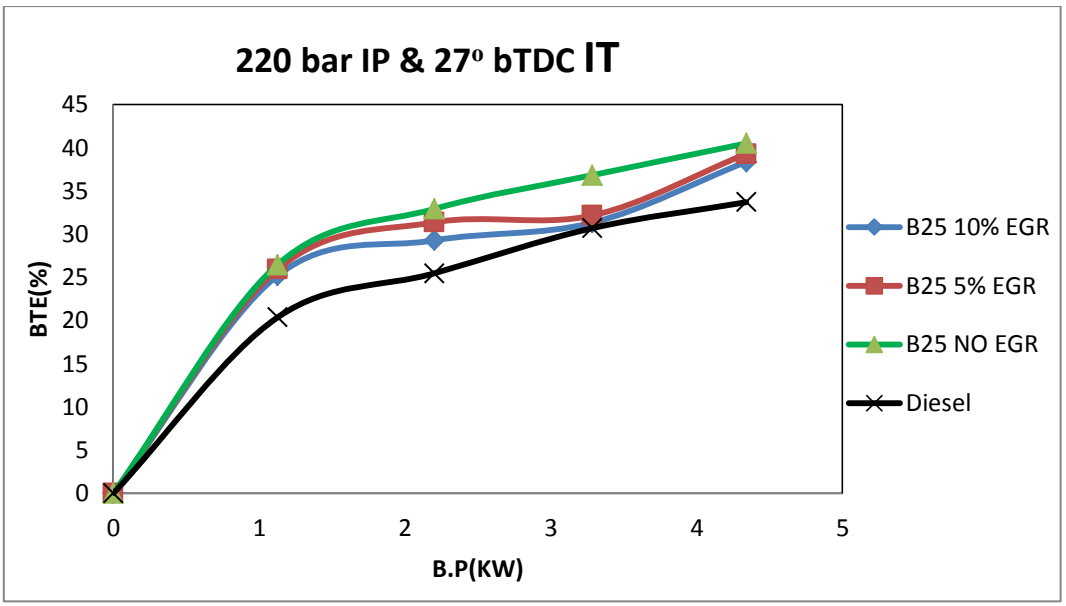

Fig 6.81 Variation of Brake thermal efficiency(BTE%) with varying load and EGR at 220bar injection pressure and 27°bTDC.

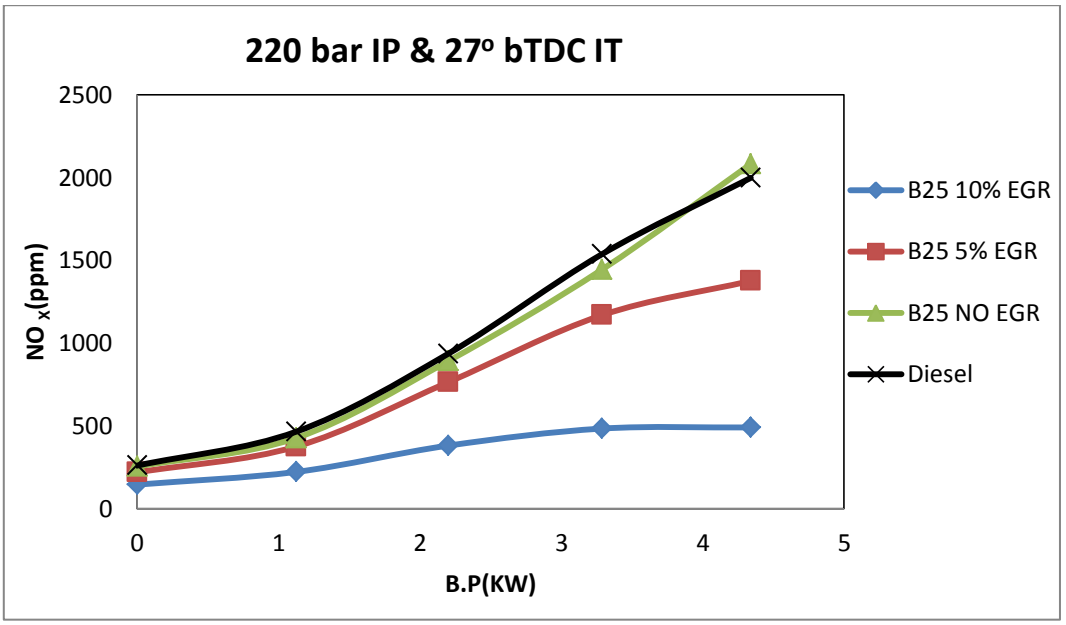

Fig 6.82 Variation of NO_X(ppm) with varying load and EGR at 220bar injection pressure and 27°bTDC.

6.5.5 CO emission

The variation of CO emission with varying EGR is depicted in Figure 6.83. The CO emission increases as the EGR to intake air increased from 5% to 10% . As the EGR supply is increased, the CO emission increases due to poor combustion. It can be seen from the figure that 300% to 400% increase of CO occurs when EGR increases from 5% and 10% respectively. The CO emission is found to be very less for this biodiesel whatever the operating conditions may be. Addition of EGR to intake air decreases the air fuel ratio and results in rich fuel air mixture. This fuel rich heterogeneous mixture follows poor combustion and results in CO formation, instead of CO_2

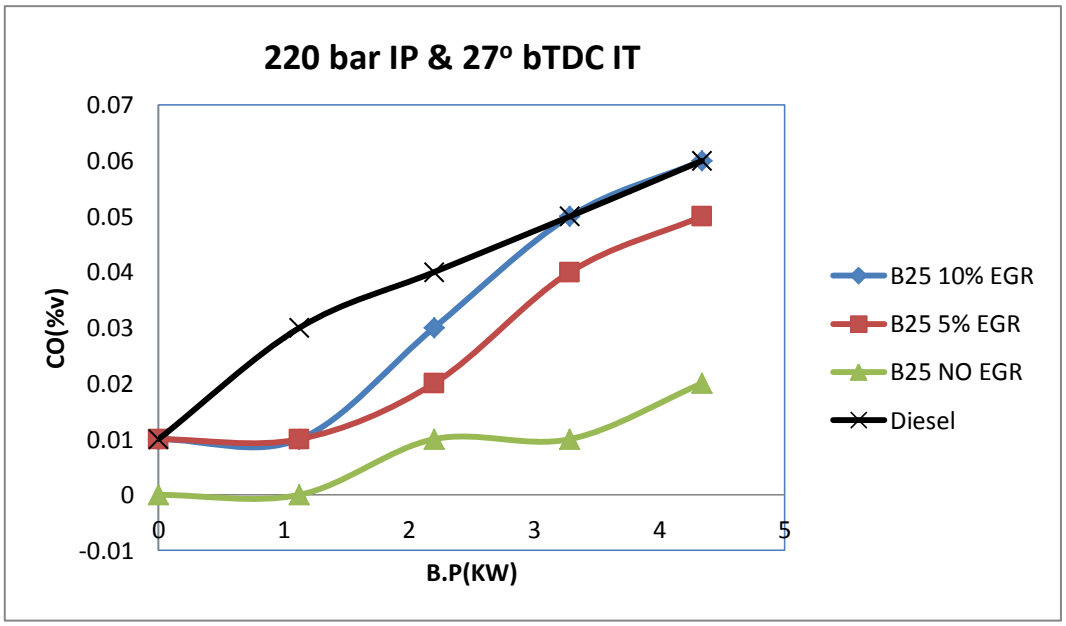

Fig 6.83Variation of CO(%V) emission with varying load and EGR at 220bar injection pressure and 27°bTDC.

6.5.6 HC emission

The variation of HC emission with varying EGR is shown in the Fig 6.84. It can be seen from the figure that there is 16.67% and 33.33% increase in HC emission occurs for 5% and 10% EGR along with B25 when compared with NO EGR for B25.The HC of B25 with 10% EGR is 5.88% less than that of base line diesel fuel. The possible reason for increased HC emission when EGR is done may be poorer surplus oxygen

available for the combustion mixture. Poorer excess oxygen concentration results in rich fuel air mixtures at different locations inside the combustion chamber. This fuel rich heterogeneous mixture does not combust properly, and results in poor combustion with higher HC emissions. However for all the biofuels give Lesser HC emission than that for base line diesel fuel.

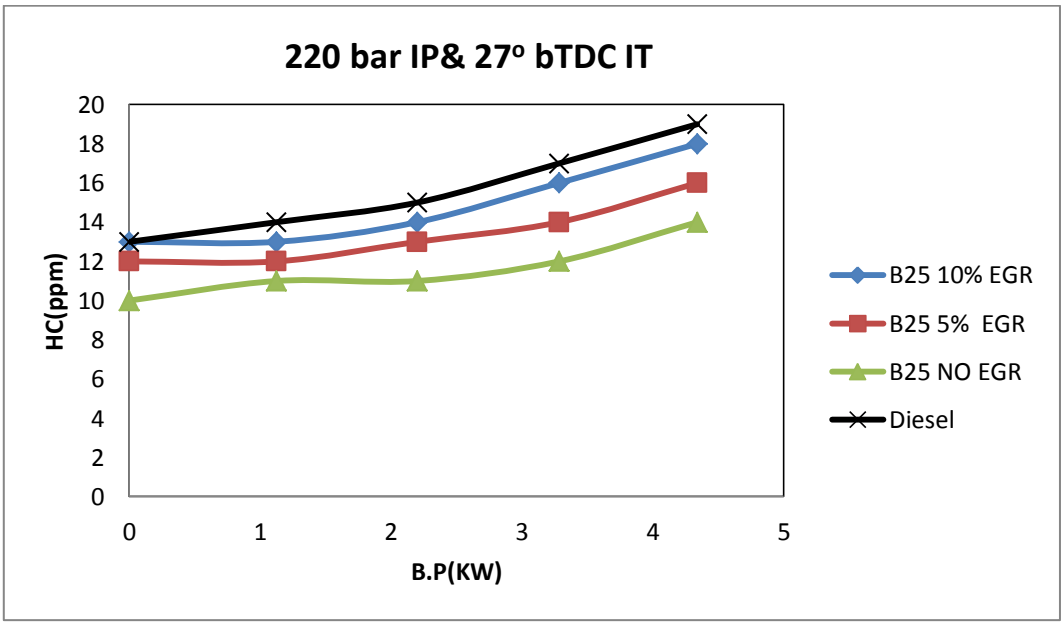

Fig 6.84 Variation of HC(ppm) emission with varying load and EGR at 220bar injection pressure and 27°bTDC.

6.5.7 Smoke emission

It is observed from the Fig 6.85 that smoke density and hence opacity increases with EGR. There is a increase of 33.3% and 50% smoke density with 5% and 10% EGR for B25 blend. When EGR is done oxygen availability decreases and combustion would be incomplete. Moreover soot in the EGR adds to combustion products. Therefore with EGR smoke density increases. However smoke density is still lesser that for base line diesel because B25 is heavily oxygenated fuel whereas oxygen availability is lesser for diesel.

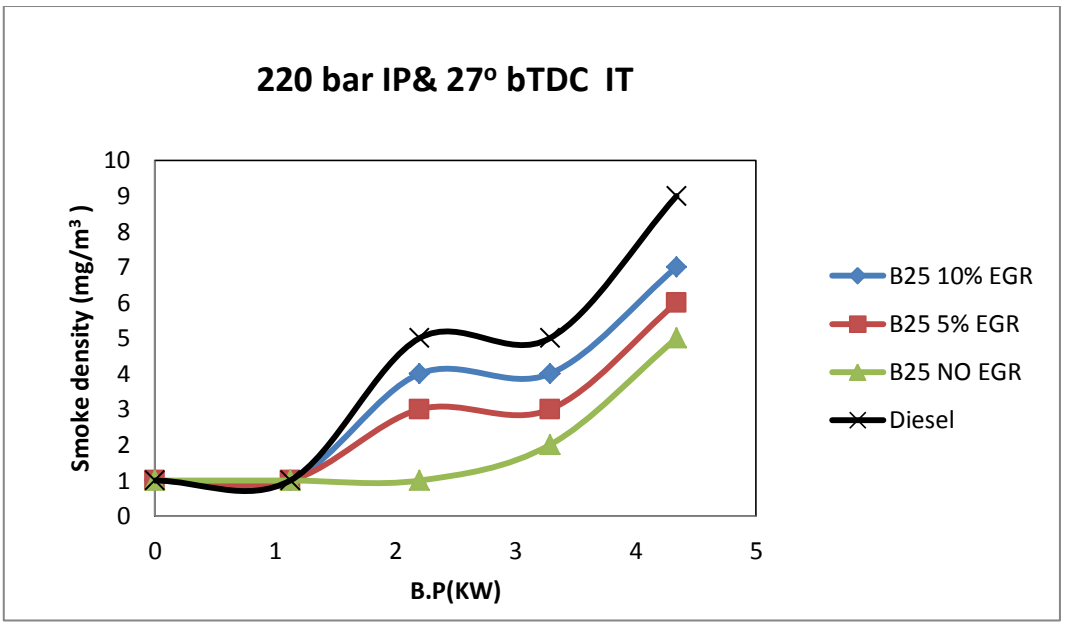

Fig 6.85 Variation of HC(ppm) emission with varying load and EGR at 220bar injection pressure and 27°bTDC.

Present study investigates the effect of EGR percentage along with optimum blend B25 at 220 bar injection pressure and 27°bTDC injection timing and compares with baseline diesel operation.

- A remarkable reduction in NO_X emission is obtained with EGR system when percentage is varied from 5% to 10%.This result is similar to results obtained by Ozer Can et al(Ozer Can et al,2016) for soybean biodiesel.
- EGR lowers performance and emission characteristics. A maximum increase in BSEC and maximum decrease in BTE are obtained when EGR percentage increased to 10%.
- Higher CO, HC and smoke emissions are observed for 10% EGR when compared to B25 without EGR This is similar to results obtained by Vidya Sagar Polu et al,(2013) for Jatropha biodiesel..

Even though EGR lowers performance and emission characteristics is better compared to base line diesel. Hence 10% EGR is recommended along with blend B25 at optimized operating parameters.

Chapter 7

CONCLUSIONS OF PRESENT WORK

The present research work has lead to many relevant conclusions in regarding biodiesel production from *Vateria Indica* oil/fat and its characteristics in a single cylinder CI engine as an alternative fuel. There were three stages in the present work. The conclusions drawn from these three stages is summarized separately in the following sections.

7.1 EXTRACTION OF *VATERIA INDICA* OIL/FAT AND ITS CHARACTERIZATION

The following conclusions are drawn from oil extraction studies

- Solvent extraction pilot plant is found to work satisfactorily as a viable alternative for conventional or traditional boiling water floating method or aqueous method.
- Solvent extraction is found to be economical in view of both cost and yield. But large scale production from present pilot plant is not possible.
- Physical nature of the oil is semisolid fat at room temperature.
- Solvent extraction suggests the use of the *Vateria Indica* oil as the possible economic feedstock for biodiesel preparation.

In the present work water extract is considered for further studies because easy availability in the market. Even though solvent extraction is economical option large scale production is yet to become viable for use further biodiesel preparation.

7.2 PRODUCTION OF BIODIESEL FROM WATER EXTRACTED *VATERIA INDICA* OIL/FAT AND ITS PHYSICAL AND CHEMICAL CHARACTERIZATION

From the investigations on production and characterization of *Vateria Indica* Methyl Ester(VIME) or *Vateria Indica* biodiesel many conclusions are drawn. They can be listed as below

1. Dhupa Fat or *Vateria Indica* oil obtained from water extraction method is a suitable starting material for biodiesel production.

2.A two step synthesis adopted for conversion of *Vateria Indica* oil into biodiesel is yields 85% conversion.

3. All the major Physical properties of VIME are within the limits set by ASTM standards.

4. Chemical Charecterization done by GC-MS and ^{1}H NMR and ^{13}C NMR done confirm that the product is the conventional biodiesel.

5. VIME consists of methyl myristate, Hexadecanoic acid Methyl ester or a palmitic acid methyl ester with chemical formula C17H34O2, Octadecanoic acid methyl ester or oleic acid methyl ester with a chemical formula C19H34O2 and Methyl stearate with Chemical formula C19H38O2.

6. The major chemical properties are at par with other conventional biodiesels like Jatropha and pongamia biodiesels.

7.3 PERFORMANCE, COMBUSTION AND EMISSION CHARACTERISTICS OF VATERIA INDICA BIODIESEL

7.3.1 Performance, combustion and emission characteristics of *Vateria Indica* biodiesel under varying injection pressure

Engine is operated with diesel and *Vateria Indica* Methyl Ester (VIME) blends at 25, 50,75% and full load conditions. The tests are conducted at standard injection timing of 23^{o}bTDC and varying injection pressures like 180, 200, 220 bar. The results are

discussed for optimizing injector opening pressure for better performance, combustion and emission characteristics of the engine. Major conclusions drawn are

- Among the various injection pressures, 220 bar is the most suitable from the engine performance and emission point of view. Hence it can be taken as optimized injection pressure at 23^{o}bTDC injection timing.
- The biodiesel blends found to perform better as injector pressure increased from 180 bar to 220 bar through 200 bar. Increase in BTE and decrease in BSEC are attributed to the fact that better atomization and improved evaporation of the fuel droplets due to increased surface area at higher injection pressure leading to better combustion.
- NO_X emission increased for all fuels when injection pressure increased from 180 bars to 200 bars but it is decreased when injection pressure is increased from 200 bar to 220 bar. This indicated that as long as NO_X emission is concerned 220 bar injection pressure is lowest. There are no significant changes in CO emissions as injection pressure is varied from 180 bar to 220 bars. HC emission, is decreased as injection pressure increased from 180 bar to 220 bar for B10, B15, B20, B25 blends. For diesel it remains unchanged. There is an increase smoke emission for B10, B15, B20, B25, Diesel fuels respectively when injection pressure is increased from 200 bar to 220 bars. 220 bar injection pressure is optimum as for as performance and emission characteristics are concerned excepting smoke emission.

From the experimental findings, it is clear that the higher injection pressure(220 bar) gives better combustion, performance and emission characteristics for the tested fuels as compared to 180 bar and 200 bar injection pressure.

7.3.2 Performance, combustion and emission characteristics of *Vateria Indica* biodiesel under varying injection timing at 220 bar injector opening pressure

The conclusions of experiments of the comparison of fuel injection timings can be summarized as follows.

- The engine performance improved at 27^{o}bTDC injection timing with lower BSEC and Higher BTE obtained for diesel, B10, B15, B20, B25 fuels when compared to

23^{o}bTDC injection timing. At advanced injection timing and higher injection pressure improved fuel spray and atomization which results in better distribution throughout the combustion chamber during the prolonged combustion duration. Retarding injection timing to 19^{o}bTDC leads to poor engine performance.

- Considerable reduction of CO, HC, and smoke emission are achieved, while NO_X emission showed an increasing trend with 27^{o}bTDC injection timing and 220 bar injection pressure.
- Results have shown that among various injection timings 27^{o}bTDC is the most suitable from the engine performance and emission point of view. Hence it can be taken as optimized injection timing at optimized injection pressure of 220 bars.

From experimental findings it is clear that the advanced injection timing 27^{o}bTDC under 220 bar injection pressure gives better combustion, performance and emission characteristics for fuels tested compared to retarded injection timing of 19^{o}bTDC and standard injection timing 23^{o}bTDC.

7.4 OPTIMIZATION OF VATAERIA INDICA BIODIESEL AND DIESEL BLEND

The results of the present investigation of *Vateria Indica* biodiesel and diesel blends show the considerable variation in performance, combustion and emission characteristics between B10, B15, B20 blends when compared with B25 blend. It is observed that3.17% less BSEC, 3.18% more BTE and 50% less CO, 7.69% less HC and 33.34% less smoke is obtained for B25 blend compared with B20 blend under 220 bar injection pressure and 27^{o}bTDC injection timing. Hence B25 is taken as optimized blend for further investigation.

7.5 EFFECT OF EGR ON COMBUSTION, PERFORMANCE AND EMISSION CHARACTERISTICS OF *VATERIA INDICA* BIODIESEL AND DIESEL BLEND

Present study investigates the effect of EGR percentage along with optimum blend B25 at 220 bar injection pressure and 27^{o}bTDC injection timing and compares with baseline diesel operation.

- A remarkable reduction in NO_X emission is obtained with EGR system when percentage is varied from 5% to 10%.
- EGR lowers performance and emission characteristics. A maximum increase in BSEC and maximum decrease in BTE are obtained when EGR percentage increased to 10%. From No EGR condition.
- Higher CO, HC and smoke emissions are observed for 10% EGR when compared to B25 without EGR This is similar to results obtained by Vidya Sagar Polu et al,(2013) for Jatropha biodiesel.

Even though EGR lowers performance and emission characteristics it is better compared to base line diesel. Hence 10% EGR is recommended along with blend B25 at optimized operating parameters of injector opening pressure of 220 bars and injection timing of 27^{o}bTDC.

Finally it can be concluded that *Vateria Indica* oil/fat can be more economically extracted by solvent extraction by building a larger plant taking the clues from the pilot plant developed in the present investigation. The traditionally extracted *Vateria Indica* oil/fat is easily available in the domestic marked can be transesterified by procedure mentioned in the thesis. The Vateria Indica Methyl ester best suits as blend with single cylinder diesel engine. Blend B25 found to be best blend as for as Performance, Combustion and Emission characteristics in a CI engine are considered under 220 bar Injector opening pressure and 27^{o}bTDC injection timing along with 10% hot EGR.

Chapter 8

FUTURE SCOPE OF PRESENT WORK

The present work carriedout throws light on many future research works that can be done with *Vateria Indica* fat/oil. They can be listed as

- The solvent extraction method for *Vateria Indica* oil/fat can be tested for large scale production by building large capacity plant.
- Optimization of yield of extracted oil can be done by using design of experiments technique. The particle size, particle size distribution, duration of maceration, extraction temperature can be taken as inputs that can be varied to give best oil yield..
- The research work can be done to develop a suitable method for trans esterification of solvent extracted *Vateria Indica* oil/fat.
- The method developed to extract biodiesel from solvent extracted *Vateria Indica* oil/fat can be modified for continuous large scale production of biodiesel.
- The remainants of powder of *Vateria Indica* seed after soaking can be explored for their uses such as firewood stics.
- Optimization of production of *Vateria Indica* biodiesel production can be done by using different techniques of design of experiments such as Taguchi method, Response surface method etc.
- The life cycle analysis of *Vateria Indica* species from plant to wheels can be conducted.
- The chemical kinetics of the reactions involved in production of biodiesel from water extracted biodiesel can be studied in detail so as to optimize and improve the particular method developed in the present work

Chapter 9

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APPENDIX I

ENGINE TEST RIG SPECIFICATIONS

Type:Four stroke, single cylinder vertical air cooled Diesel engine

Rated power	4.4KW
Rated speed	1500RPM
Bore dia	87.5mm
Stroke(L)	110mm
Compression Ratio	17.5:1
Orifice diameter-	29.06mm
Coefficient of Discharge(C_d)	0.6
Swing field electrical dynamometer	(KVA-5,Hz-50, Volt-240, Amps-21, RPM-1500)
Standard injection pressure	180 bar
Standard Injection Timing	23^{o}bTDC

APPENDIX II

SPECIFICATIONS OF PRESSURE TRANSDUCER

Make	AVL GH14D/AH01
Sensitivity	18.89pc/bar
Linearity	<±0.3%
Measurement Range	250 bar
Temp range	400^{o}C
Natural Frequency	115KHz

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APPENDIX III

SPECIFICATIONS OF THE EXHAUST GAS ANALYSER

Make: AVL Digas 444

Measured Values	**Measurement Range**	**Resolution**
CO	0-10%	0.01% Vol
HC	0-2000ppm	10ppm
CO_2	0-20% Vol	0.1% Vol.
O_2	0-22% Vol	0.01% Vol.
NO_X	0-5000ppm	1 ppm
Lambda	0-9.9999 calculated	0.001

APPENDIX IV

SPECFICATIONS OF AVL415 Smoke Meter

Measurement principle:	Measurement of filter paper blackening
Measured value output:	FSN (filter smoke number) or mg/m³ (soot concentration)
Measurement range:	0 to 10 FSN
Detection limit:	0.002 FSN or ~ 0.02 mg/m³
Resolution:	0.001 FSN or 0.01 mg/m³
Exhaust pressure ranges:	(-300*) -100 to 400 mbars (-500*) -200 to 750 mbars with the special sampling option 0 to 3000 mbars with the high-pressure option (*) with activated altitude simulation
Maximum exhaust temperature:	600 °C with standard 340 mm sample probe (800 °C with 780 mm long sample probe)
Interfaces:	2 serial RS232 interfaces with AK protocol Digital via Instrument Controller 4210 1 Ethernet interface with InPort option installed with AK protocol
Power supply:	100 – 115 VAC or 230 VAC, 50/60 Hz
Power consumption:	700 VA
Compressed air (for compressed air option):	~150l/min during purge
Compressed air quality required:	Grades 1.1.1 to 1.4.1 according to ISO 8573.1:2001(E) Recommended connection pressure on the AVL Smoke Meter: 5 to 8 bars at the measurement device input
Weight:	<40 kg
Dimensions (w x h x d):	560 x 620 x 300 mm
Sample flow:	~ 10 l/min
Ambient conditions:	5 to 55 °C / max.95 RH; without condensation Sea level -500 to + 5000 m
Repeatability:	Standard deviation 1 s = ± (0.005 FSN + 3 % of the measured value @ 10sec intake time)

List of Publications

S.No	Title of the paper	Authors(in the same order as in the paper,Underline the Research Scholar's name)	Name of the Journal/Conference, Vol.,No.,Pages	Month and Year of Publication	Category *
1.	Effects of Additives on Biodiesel/Diesel Performance, Emission Characteristics and Properties,	Gangadhara Rao, Kumar G.N, Mervin A Herbert	International Journal of Engineeing Trends and Technology, Special issue NCAMES May 2016, pp-22-27	May 2016	1
2.	Effect of Injection Pressure on the performance and emission characteristics of CI engine using VatariaIndica Biodiesel	Gangadhara Rao, Kumar G.N, Mervin A Herbert	International journal of Ambient Energy(Taylor & Francis) ISSN:0143(print) 2162-8246(online)	Jan 25th 2018	1
3.	Effect Of Fuel Injection Pressure And Injection Timing On Combustion Of *Vateria indica* Biodiesel	Gangadhara Rao, Kumar G.N, Mervin A Herbert	25thNational Conference on Internal Combustion Engines and Combustion. 15 - 17 December 2017 NITK Surathkal	Dec 2017	3
4.	Impact of Advancing and Retarding the Injection timing on the performance and emission characteristics of CI engine using *Vateria Indica* Biodiesel	Gangadhara Rao, Kumar G.N, Mervin A Herbert	International journal of Ambient Energy(Taylor & Francis)	April 2018 Under review	1

*Category: 1: Journal paper full reviewed 2: Jounal paper, Abstract reviews 3: Conference/ Symposium paper, full paper reviewed 4: Conference/Symposium paper, abstract reviewed 5: others(including papers in workshops,NITK Research Bulletins,Short notes etc.)

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- **Journals: 03 (**International – 1, National – 02**)**
- **Conferences: 02 (**International – 01, National – 01**)**