Experimental Investigation on Performance and Emission Characteristics of CI-DI VCR Engine using Biodiesels and their Blends

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CERTIFICATE

This is to certify that **B.R.Hosamani** bearing university seat number **2BL10PMN04** has worked under my supervision for his doctoral thesis titled **"Experimental Investigation on Performance and Emission Characteristics of CI-DI VCR Engine using Biodiesels and their Blends".** I also certify that the work is original and has not been submitted to any other university wholly or in part for any other degree.

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Declaration

I, hereby declare that the entire work embodied in this doctoral thesis has been carried out by me at, BLDEA’s V.P.Dr.P.G.H. College of Engineering and Technology, Vijayapur, Karnataka, India, under the supervision of **Dr. V.V.Katti** **BE.,M.Tech.,Ph.D.** This thesis has not been submitted in part or full for the award of any Diploma or Degree of this or any other university.

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ABSTRACT

The development of any nation depends on the energy availability and consumption. As per Indian scenario the fuel consumption is increasing year by year because of improved economy. The researchers and technocrats are striving hard to find the energy sources which can be a substitute for petroleum derived fuels. The biofuels are gaining importance as a substitute fuel for petroleum derived diesel fuel. Biodiesels are renewable, biodegradable, non toxic, environmental friendly fuels which could be used in present day automobiles with or without modification.

The biodiesels used in the present experimental investigation are Pongamia, Jatropha and Simarouba. These biodiesel are prepared with their respective oils by transesterification method. The three biodiesels considered are mixed two at a time and in the different volume ratios i.e. 75:25, 50:50 and 25:75. The Pongamia and Jatropha are mixed in the ratio 75% Pongamia+25% Jatropha (P75+J25) and designated as M1, similarly the mixture (P50+J50) as M2, and (P25+J75) as M3 respectively. In the same way Pongamia and Simaruoba are mixed in different volume ratio and designated as M4, M5, and M6. The Jatropha and Simarouba are mixed and designated as M7, M8 and M9. These prepared mixtures are blended with diesel in different volume ratio. The B20M1 is the blend of 20% of M1 +80% of diesel fuel, similarly B40M1, B60M1, B80M1 and B100M1 which is mixture of two biodiesel.

Fuel properties play an important role in the combustion, performance and emission characteristics of engines. Properties of biodiesel are within ASTM and European standards and comparable with diesel fuel. The flash and fire points are higher, having lesser heating value and higher viscosity. New correlations are developed to find the density and viscosity of mixture of two biodiesel at elevated temperatures. Using these correlations the density and viscosity of the mixture of two biodiesel can be found for any temperature and for any volume fraction of biodiesel in the blends.

The mathematical correlations are established to find the density and viscosity of Simarouba biodiesel and diesel blends at different temperatures for any volume fraction of biodiesel. The mathematical correlations are also established for the density, flash point and heating values with viscosity of fuels used.

The aim of the present study is to experimentally investigate the combustion, thermal performance and emission characteristics of single cylinder, four stroke, DI VCR diesel engine using the mixture of two biodiesel in blend with diesel fuel. The investigation is carried out by operating the engine at different compression ratios of 16, 17 and 18 using the various blends. The load on the engine is varied from zero to the rated load increasing in the interval of 20% of rated load.

The combustion characteristics investigated and analysed are cylinder pressure, maximum cylinder pressure using P-V plot, net and cumulative heat release, mass fraction burned and rate of pressure rise. The thermal performance parameters evaluated are BTE, BSFC, EGT. The various exhaust emissions measured are CO, HC, NOx and Smoke intensity.

The cylinder pressure increases with increase in CR and maximum at the rated load for all the blends and diesel fuel. For all the compression ratios used cylinder pressure increases with increase in load. The start of injection and combustion are advanced for the blends compared to diesel fuel. The ignition delay for the all the blends is shorter in duration compared to diesel fuel. The heat releases are lesser for blends compared to the diesel fuel at the rated load for all the CR. The MFB are higher for diesel fuel. The combustion duration increases for the blends. The rate of pressure rise is higher for the blends.

The BTE increases with increase in load for the compression ratios used. The engine tests revealed that BTE is lower to a maximum of about 4% for the blends compared to diesel fuel at CR18. The blends up to 40% have comparable BTE with diesel fuel. The BSFC of biodiesel blends are increased to a maximum of about 6% compared to diesel fuel. The exhaust gas temperatures are increases with increase in load for the fuels used. The exhaust gas temperatures are lower by about 5% for the blends for the CR used.

The various exhaust emissions are measured using the five gas analyser and smoke meter. The exhaust emissions increases with increase in load for the all the fuels and CR used. The CO, HC and smoke emissions are decreased to a maximum of about 45%, 50% and 15% respectively for the various blends at higher CR for the rated load compared to the diesel fuel. The NOx emissions increase for higher CR for the blends to a maximum of about 25% compared to the diesel fuel. The CO, HC and smoke emissions are increases at lower CR which may be due to lower combustion temperature.

Artificial Neural Network (ANN) model is used to get the output parameters for the optimised input parameters. ANN modelling is a complex technique capable of modelling the various functions and methods. The different softwares can be used for the ANN model. The MATLAB®2014 software is used for the analysis. The parameters predicted by ANN model are found to be quite close to experimental values with reasonable accuracy.

From the experimental investigation, it is summarised that the engine can be operated at various compression ratios without problem. The mixture of two biodiesel in blend with diesel fuel can be used as an alternative fuel in VCR diesel engine. The combustion characteristics are reasonably comparable with diesel fuel at various compression ratios. Performance of the engine is marginally lower for the lower blends. The CO, HC and particulate emissions are decreases for the blends compared to diesel fuel whereas NOx emission increases. Based on combustion analysis, thermal performance and emission analysis, it is experienced that CR18, combination of any of the mixture, the blend B40 is a better substitute for the diesel fuel.

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NOMENCLATURE

ANN	Artificial neural network
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
CA	Crank angle
CI	Compression ignition
CHR	Cumulative heat release
CO	Carbon monoxide
CN	Cetane number
DI	Direct injection
EGT	Exhaust gas temperature
FP	Plash point
HC	hydrocarbon
HV	Heating value
J	Jatropha biodiesel
J-S	Jatropha +Simarouba biodiesel
MLNN	Multi layer neural network
MSE	Mean square error
NHR	Net heat release
NN	Neural network
P-J	Pongamia + Jatropha biodiesel
P	Pongamia biodiesel
PM	Particulate matters
P-S	Pongamia + Simarouba biodiesel
p	Cylinder pressure
NOx	Nitrogen oxides
RPR	Rate of pressure rise
S	Simarouba biodiesel
VCR	Variable compression ratio
TDC	Top dead centre
aTDC	After top dead centre
bTDC	before top dead centre

SYMBOLS

ρ	Density
ν	Viscosity
Ɵ	Crank angle
±	Plus or minus
¶$(\mathbf{w})$	Cost function
$\mathbf{w}$	Weight factor
	Weight decay term

Chapter-I

Introduction

Development of any nation is measured by their energy consumption. Building strong economy of any nation it needs the energy in different forms. Building strong energy is a must for sustainable economic and social development [1]. Energy demand is growing throughout the World at rapid rate because of increasing industrialisation and mechanisation with improved economy.

World's energy demand is increasing continuously since from number of years. Energy consumption is in different forms. Energy demand has increased by many folds since from the year 2000, because of increased economy of the various countries. India and China are showing the increasing trend of energy consumption due to their improved economy. Every sector of energy consumption such as oil, coal, gas, electricity, solar, wind markets are in the increasing trend. Energy consumption is expected not to decrease in the years to come, throughout the world, because of improved economy of the developing countries and increase in population throughout the world.

The renewable energy sources like solar, wind, hydropower geothermal power are gaining importance. These are renewable and environmental friendly energy sources. These energy resources can be considered as zero polluting. Until now facts shows that oils are the most dominating energy sources used throughout the world because of their exploration and easy availability. The major conventional sources of energy are petroleum fuels. Petroleum resources are seems to be limited and are available in particular parts of globe. Nations with no petroleum sources are facing energy crisis and spending largely their foreign exchange on heavy import of the petroleum products. Because of increased consumption of fossil fuel, increases extraction in crude petroleum products is leading to depletion of underground petroleum mineral deposits. These factors have increased the cost of petroleum product.

Presently the petroleum sources are the dominant source of environmental pollutions globally. CO_2, green house gaseous emissions are the dominant source in global warming. Combustion of petroleum fuels is causing strong environmental problems to the earth. Most serious problems of global warming emissions are threat to the environment. Therefore many countries put their hands together in reducing these problems they have signed the UN agreement to prevent imbalance in the climate change, and to reduce the harmful emissions. The percentage of serious pollutants concentration in the environment is the subject to be debated. Globally temperature is rising by 2% every year and is considered to be a high risk level by Stockholm Environmental Institute. It means that more than 2% rise in temperature is affecting the environment to maximum extent. To limit the rise in temperature, the carbon emissions from different sources have to be reduced by 75% from the most industrialized nations by 2050. In spite of the consensus on the basic problem, emissions are continuously rising, which are warming environment from energy production. For the security of civilization, it is duty of stake holders to stop increasing emissions regardless of population and economic development of the state.

The petroleum fuel resources are available only in particular part of the world, the general agreement among all the nation is that they are not secured oil sources and not economical. Several alternative energy sources are available currently and they are to be explored. The alternate energy resources available including renewable fuels and is free from carbon (nuclear power, hydraulic, wind, hydrogen, tidal) is an attempt to replace the conventional fuels such as coal, gas which are used in electrical energy sector. None of the fuels are available to replace the petroleum fuels which are extensively used in transport sectors such as road, rail and air. Electrical /hybrid vehicles are still under innovation and development and hence there is a long way to bring them in to a reality.

India is a fast developing country in the world. Lot of energy is being consumed in the different forms to meet the energy demand of the nation. Oil is the primary source of energy for any country. India is not self sufficient with petroleum fuels [2, 3]. Transport sector play an important role in the development of any nation. Due to the growing Indian economy its transport sector in the form of road, rail and air are increasing day by day and year by year. To satisfy the growing need of automobile industry it is essential to find an alternate fuel which can be used in existing engines with or without modifications. India is fourth highest petroleum fuel consumer in the world and is not self sufficient with petroleum fuels. Around 70% to 80% of the petroleum fuels are imported. The huge amount of its foreign reserves is spent on importing of petroleum products.

There are many sources of energy available which can be used for different purpose. The main source of energy for automobiles is petroleum fuels which can be readily stored and carried on the automobiles. Petroleum fuels are depleting at faster rate due to their usage. Petroleum fuels are consumed at the faster rate due to the increased number of automobiles and increase in population throughout the world. The consumption of petroleum fuels is depleting the limited available resources.

Short term and medium term alternatives are needed. Oils extracted from different crops as alternate fuels are denoted as biofuels these includes biodiesel and bio ethanol, are the real alternative fuels to be used in place of gasoline and conventional diesel for transportation. Consumption of these biofuels has increased exponentially since from last decade in some of the countries like Germany, France, and United States. Ideally these biofuels or bio oils as alternatives must decrease or even can mitigate the dependence of natural fuels such as gasoline and diesel fuel. These biofuels can contribute in the reduction and achieving the target of green house gas emissions. However, it is a joint effort of different stakeholders such as consumer, supplier, technocrats, regulatory bodies and political will is required to promote independent oil or green house gas controlled scenario in future. It is needed to produce bio fuels to replace at least part of petroleum fuel for secured energy supply for transportation makes it essential. Biofuel is the alternative to natural petroleum based fuels addressing and evaluating environmental consequences and socio economics originated in their implementation.

To help the society in larger way, mainly there are three aims for the biofuels; they are promotion, development, and implementation. In total these are giving energy independence, helps in changing the climate and rural development. The promotion of biofuel arises from each individuals or the combination of them. The main reason for promoting the biofuels are summarised as below,

- Energy independence with more security can be achieved by producing biofuels.
- Biofuels reduce green house gas emissions and contribute to the save earth policy.
- Bio fuels will enhance agriculture activities and increase economy of farmers and contribute to rural development [4, 5, 6].

India is not self sufficient with petroleum based fuels, most of the petroleum fuels are imported spending huge amount of foreign exchange. Improvement in local and national energy production will avoid the dependence on the imported oils. In addition, oil demand is increasing in an exponential way globally. Therefore there is an urgent need to find an alternate source of energy to replace the fossil fuels derived from petroleum sources. This increases the energy independence of the nation and for its economic growth.

The total emissions from biofuels have been reported to be considerably lesser than diesel fuel [7, 8, 9, 10]. Green house gas emissions from biofuels are the key issue and it requires careful attention as they come from growth of plants to seed production, storage, transportation, extraction of oil and to biofuel and their combustion. In country like India large manual labours are used for larger part of their cultivation, growth and collection of seeds etc. hence green house gas emissions are lower compared to natural diesel fuel.

With an increasing growth of biofuel market, India may be able to cultivate different types of biofuel plants and trees to cover the national demands on energy crops. India is an agriculture based country, most of its population depend on agriculture based income. Growth of agriculture improves the economic status of the people and at large the country. It is not only improves the economic status of the country it can be energy independent. India has large amount of waste land, it can be utilised to cultivate the plants and the trees which can produce the biofuel seeds in turn to biofuels.

Diesel engine inventor Rudolf diesel used vegetable oil to demonstrate his first research engine in France. With advantage of cheap petroleum fuels and diesel fuels and diesel engines developed together. During the world war-II due the shortage of petroleum fuels and diesel, vegetable oils and gaseous fuels are used again. Because of limited resources of fossil fuel, increase in prices of petroleum fuels and environmental pollution, there has been renewed focus on vegetable oil production. Biodiesel basically contain 10-12 % of oxygen in its chemical structure and has the ability to reduce the pollution level and global warming. As per the International Energy agency report, biofuel has the great potential to meet the fuel demand more than quarter of the of world energy of different transportation sector by 2050.

Biodiesels are considered to be one of the potential substitutes for diesel fuel. It can be produced from oils and fats using different processes. The different manufacturing processes are used to produce the biodiesel; most widely used method is transesterification process [11, 12]. In the transesterification process oils are made to react with alcohols to form their esters which are called biofuels or biodiesel. Any type of vegetable oils can be used for biodiesel production. The edible oils like Soybean, Palm, Sunflower, Safflower, mustard, etc can be used. Any type of non edible tree born oils can be used to produce biodiesels. The oils of non edible types are Pongamia, Jatropha, Simarouba, Mahua, Hazelnut, Honne, Rubber seed, etc can be considered for biodiesel production. Biodiesel is a liquid fuel its properties are similar to diesel fuel . Biodiesel is consisting of fatty acids of methyl or ethyl esters. Different biodiesel properties have to meet the American Standard for Testing of Materials (ASTM). Many developed and developing countries have introduced policies to encourage for the use of biodiesel produced from vegetable oils in different energy sectors. Biodiesel use in different energy consuming sector the following aim can be achieved.

- Import of petroleum fuels can be reduced and also reducing expenditure on foreign exchange and can achieve energy independence.
- Support the agriculture sector by increasing their farm income with biodiesel seeds production and to achieve economical independence.
- Prevent environmental degradation by using cleaner fuels such as biodiesels and alcohols in energy consuming sectors by reducing the emissions.
- Waste land can be utilized for planting trees and promote agro based industries.
- Create jobs for the rural people and earn their lively hood.

There are many advantages of biodiesels

- ➢ Biodiesels are renewable, biodegradable, environmental friendly, indigenous and their properties are similar to conventional petroleum diesel fuel, therefore it will be a potential replacement for diesel fuel in the near future [13-16].
- ➢ The use of biodiesel, country can attain energy independence in transport, power, agriculture and other energy sectors which are using diesel as fuel. It can increase the rural economy by generating employment to the rural people.
- ➢ Waste land can be utilised in growing non edible oil seed producing trees and plants which gives major thrust to the agriculture and agro based industries.
- ➢ Biodiesel can be stored like petroleum diesel; it does not need any separate storage tanks. Storage time for biodiesel is up to six months, it starts oxidation and forms gel if it is stored beyond six months.
- ➢ Production of biodiesel on large scale can bring down the cost of production nearer to the diesel fuel, consuming less time for production than other alternate energy sources.
- ➢ Biodiesel can be used in diesel engine alone i.e. in its pure form or it can blend with diesel in any proportion without any modification to the engine.

Because of these advantages biodiesel can be considered as one of the promising alternate fuel which can replace the petroleum diesel fuel in transport, power, railways and other energy sectors.

India has huge potential for biodiesel production, because it is mainly agriculture based country, and has large waste land which could be utilised to grow plants and trees which can provide biodiesel producing seeds. India has 17% of words population, and fossil fuel available with India is only 0.8% of Worlds natural fuel availability and natural gas resources. Annually India's requirement is 125 metric tonnes of oil. Most part of this fuel is consumed in transport sectors like road, rail, air and sea. India is producing only about 25% of its energy requirements. India is spending around 2, 25,000 corers of rupees only for importing oil and natural gas. Oil and gas prices are increasing continuously due to the non stable market prices. India has nearly 60 million hectares of waste land, about 50% of this land is available for energy tree plantations such as Pongamia, Simarouba, Mahua, Jatropha, etc. once the trees are planted they start yielding seed from fifth year and they have life of 60-80 years. They can grow in any type of climate extreme rainy areas to low rain fall areas. Each hectare of land can produce around 2 tonnes of biodiesel. Biodiesel is called to be carbon neutral fuels because they neither add nor decreases the carbon to environment. India is having the potential for producing around 60 million tonnes of different types of biofuel, thus making an important significant contribution to the energy sector and creates energy independence to the nation, boosting the agro based industries and increasing the rural economy of the nation.

India being prominent agriculture dependent nation needs major attention for satisfying the energy needs of farmers. Irrigation is the main problem for agriculture in India; it is to be developed in a big way, keeping the diesel consumption to a minimum level because of its depletion and scarcity. Finding an alternate energy sources for diesel engines is gaining importance because of the nation's fuel security and economy. The total substitution for oil imports by alternate indigenous fuel for transportation sector is biggest challenge to the Indian technologist and engineers.

Indian government has decided to cut down the oil imports petroleum fuels to 50% by 2020. Hence systematic planning is to be made by the Indian government to get the substitution from different sources. So it needs the systematic planning and implementation to produce these biofuels such as biodiesel, alcohols, biogas etc. for substituting in place of petroleum derived fuels. Producing biodiesel from edible oils cause the scarcity of eatable oils in populated country like India. Therefore India cannot offer to produce the biodiesel from edible oils. In turn India can produce the biodiesels from non edible oils. Vegetable oils used to made biodiesel are of non edible type. The non edible oils considered in Indian context are Pongamia, Jatropha, Simarouba, Rubber seed; Mahua, Nagachampa, etc. are used for biodiesel production. Vegetable oils used to produce biodiesel are made from renewable sources and environmental friendly, biodegradable, non aromatics and sulphur is absent in biodiesel fuel.

Almost all non edible oils are having medicinal properties being used in pharmaceutical industries and soap making. Now they are considered to be used in engines as biofuel. Hence different types of non edible vegetable oils are to be used to produce biodiesels. The non edible vegetable oils considered here are Pongamia, Simarouba, and Jatropha. Pongamia and Jatropha oils are easily available in different regions of India and they are cheaper than other non edible oils. Simarouba oil is available in southern part of India and it has medicinal properties used in the treatment of cancer. These can be cultivated on any type of land from fertile to waste land and in any type of climatic conditions and can be also cultivated all along the boundary of the fields (bunds) that may give an additional income to the farmers. Pongamia and Simarouba are the trees, they starts giving seeds after 5 years of their plantation. They have life around 60-80 years. Jatropha are the plants grow around 3-4.5 metres high and these can be cultivated all along the road side and even on the bunds of fields. Jatropha starts yielding seeds from third year on words. They are liable to get spoiled from cattle and humans easily.

Many types of alternate fuels have unable to gain the acceptance as an alternate fuel due to their inability to give the same performance like petroleum fuels. Neat biodiesel or blend of biodiesel with diesel fuel gives almost the same brake power, torque, little lesser mileage compared to diesel fuel. Pure biodiesel in its pure form may have around 10% lesser energy content compared to diesel fuel. However it is to be noted that there is variation of energy content of 15% from one supplier to other in petroleum diesel fuel. When biodiesel is used in its purest form it may provide slightly reduced performance because of lesser energy content of biodiesel, users report there is a little noticeable change in mileage. With B20 blend less than 2% change in energy content, no noticeable change in mileage or fuel economy are observed by the user.

Biodiesel have higher lubricating ability than diesel because of their higher viscosity. The fuel injection components present in the diesel injection system relies on the lubrication by the fuel. The degree to which fuel provides the lubrication is its lubricity. Biodiesel provide excellent lubrication to the fuel injection system.

Biodiesel is the only alternate fuel to successfully complete the EPA’s emission and health effects study under Clean Air Act [17]. Biodiesel provides significantly reduced carbon monoxide emissions, particulate matters, unburned hydrocarbons, and sulphates than diesel fuel. Additionally, biodiesel reduce the emission of carcinogenic compounds by 85% than diesel fuel. When biodiesel is used in the form of blends the reduction in the emissions are generally directly proportional to the amount of biodiesel in the blend.

Biodiesel and its blends with diesel fuel can be used in engines with or without modification [18, 19, 20]. Diesel engine is basically said to be a dirty engine. Diesel engines with catalytic converter and particulate filters give the clean diesel technology with incredible fuel economy and with ultra low emission levels. Biodiesels used in old and new engines can reduce the emissions significantly, including particulate matters.

Study of biodiesel emissions are carried out since from last 20 years. Biodiesel has subjected to the most rigorous testing compared to any other alternate fuel. It is the first and only the fuel be evaluated by EPA under Clean Air Act. Potential effects and their impact on health because of these hundreds of regulated and non regulated emissions are examined. Some of the results are as below. Average exhaust emissions for 100% biodiesel compared to petroleum diesel is given in the table-1 [21].

Table 1. Emissions for 100% biodiesel used engine

Regulated exhaust for B100	
PM	-47%
CO	-48%
UBHC	-67%
NO_x	+/-
Unregulated Emissions	
sulphates	-100%
PAH	-80%
nPAH	-90%
Special Hydrocarbon Ozone Forming Potential	50%

1.1 Aim of the research work

The main aim of this work is to investigate experimentally combustion, thermal performance and emission characteristics of DI VCR diesel engine using the mixture of two biodiesel in blend with diesel fuel and the impact of these blends on the combustion, performance characteristics, and emission constituents. The engine thermal performance and emission constituents are modelled by using artificial neural net work (ANN).

1.2 Organization of the thesis

The thesis start with brief introduction to the topic relating the availability of biodiesel seeds and their types, production of biodiesel, advantages, use in engines, its effect on pollution. Then follow the exhaustive literature review about the research carried out by the number researcher’s use of biodiesel in diesel engines. The material and methodology used in the present investigation. Then chapter 4 and deals with the results and discussion of fuel properties mixtures of two biodiesels and biodiesel and diesel blend, and the investigation of combustion, performance and emission characteristics of engine. ANN modelling for the thermal performance and emission constituents is discussed in chapter 6 and followed by brief conclusions of the work. References and annexure are towards the end.

Chapter-2

Review of Literature

2.1 Introduction:

Energy is the life line of the people and the society. Cannot think of the world without energy, hence it is the duty for every individual to think and use the energy available carefully. Energy has become so precious and has become part of the life. World cannot be imagined without automobiles and has become life line of the people and the society. To drive the automobiles needs energy in the form of fuel; hence use of liquid fuel to drive the automobile is must for present internal combustion engines.

Use of vegetable oils in diesel engine is not a new concept. Inventor of diesel engine 'Rudolf Diesel' used pea nut oil to initiate the combustion in his first research engine exhibited at Paris in the year 1900. Due to the advantages and easy availability of petroleum fuels, research activities and use of vegetable oils has been slow down.

Present energy sources for automobiles are the fossil fuels; these fuels are most extensively used throughout the world. Petroleum fuels are depleting rapidly due to their consumption. Use of petroleum fuels continued with the same phase it may lost only for few decades. Hence it is a must situation for the researchers and the scientific community to find alternate fuels which could be used in present day diesel engines without or with modification to present diesel engines.

Biodiesel is considered as one of the alternate fuel which can be used in diesel engines without or with little modifications. Biodiesel has many advantages over the petroleum diesel fuel. Biodiesel is a renewable fuel produced from biomass and bio resources such as vegetable oils by different process methods. Biodiesel used engine will have many benefits to the environments with reduced emissions. Performance of biodiesel used engines will give the comparable performance of petroleum diesel fuel. Emissions such as CO, HC, particulates matters, are reduced; NO_x and CO_2 emissions are increased with biodiesel used engines. Biodiesel used engines have an added advantage of having free from sulphur, higher flash point, no aromatics, higher Cetane number and with improved lubricity. Performances of biodiesel used engines are similar to the petroleum diesel used engines with increased fuel consumption, reduced thermal efficiency and with reduced emissions.

Combustion characteristics of biodiesel used engines are studied by number of researchers and they found that combustion characteristics are similar to the petroleum fuel used engines. Review of fuel properties was reported by Anjana Srivastav and Ram Prasd (1999), Michal Helcapek *et al*. (1999). Review of performance, emissions and combustion parameters using biodiesel and diesel blends were reported by number of researchers

In the present literature review first it is the study of fuel properties of different biodiesel and their blends with diesel. Correlation developed to find the viscosity and density of blends. This is followed by the performance and emission characteristics of engines with biodiesel and diesel blends with a constant compression ratio. Then, literature review is on performance and emission characteristics of engines with variable compression ratio engine. Literature review is followed by combustion characteristics of engines with constant compression ratio and variable compression ratio. Finally it is on the performance emission characteristics on two biodiesel blends with diesel.

2.2 Fuel properties:

Properties of fuel play an important role in the performance, emission and combustion characteristics of engines. Therefore the detailed study of properties such as density, viscosity, heating value, flash point, fire point, pour point of fuels were studied by number of researchers and some of the studies are listed below

Rushang Joshi et al. [2] studied the biodiesel flow properties of at lower temperatures. Dynamic viscosities of biodiesel derived from ethyl esters of fish oil, and diesel, and blends were measured from 298 K down to their respective pour points. Blends of B80 (80 vol. % biodiesel and 20 vol. % diesel), B60, B40, and B20 were investigated. An empirical equation was developed to find dynamic viscosity of blends as a function of temperature and blend fraction is $\ln(\eta_{\max}) = A + \frac{B}{T} + CV_B$ Where A, B and C are correlation constants and V_B is the volume fraction of the biodiesel in the blend. Based on kinematic viscosity and density measurements an empirical equation for predicting the dynamic viscosity of pure biodiesel for temperatures from 277- 573 K was given. $Ln(\eta) = -2.4343 + \frac{216.66}{T} + \frac{293523}{T^2}$. An empirical equation for calculating viscosity of individual blends as function of temperature was given by $\eta = e^{\left(\frac{A}{T} - B\right)}$ where η is the dynamic viscosity (MPa s), T was the temperature (K) and A and B were correlation constant. In all cases CP and PP of biodiesel decreased with increase in concentration of diesel. Empirical equation to predict PP $T_{pp} = 256.4 + 0.1991\ V_B + 0.000223\ V_B{}^2$ and PP of biodiesel and its blends with diesel fuel $T_{cp} = 253.9 + 0.1865V_B + 0.000335V^2{}_B$ have been developed.

Erton Alptekin and Mustapa canaki [22] studied the determination of the density and viscosity of biodiesel-diesel blends. Generalized equation for predicting density and viscosities for the blends were given $D = Ax + B$ where D is density, A and B are coefficients and x was the biodiesel fraction and $\eta = Ax^2 + Bx + c$ where η was kinematic viscosity(mm^2/Sec) A, B and C are coefficients and x was the biodiesel fraction. A mixing equation, originally proposed by Arrhenious and described by Grunberg and Nishan, $Log(\eta_B) = m_1 Log(\eta_1) + m_2 Log(\eta_{2)}$ were used to predict the viscosities of blends. Variation of viscosity of biodiesels was between 3.97 to 4.34 mm^2/sec and these were higher than diesel fuel. The maximum absolute error between the measured and calculated values of viscosity of biodiesel blends and diesel was 1.58% and 1.48% respectively.

Seung Hyun Yoon et al. [23] studied the experimental investigation on the fuel properties of biodiesel and its blends at various temperatures. Investigation was performed to find out the fuel properties including specific gravity, density and viscosity of diesel and biodiesel in the temperature range of 0 to 200° C. The density value measurement was correlated as a function of fuel temperature and blending ratio by empirical equation, $\rho_{cal} = 845.7616 + 0.4871r_{mix} - 0.7011r_{mix} + 5.844 \times 10^{-4} r_{mix}T$ where ρ_{cal} is the density (kg/m^3), r_{mix} is the blending ratio of biodiesel (%), and T is the fuel temperature in ° C. An empirical equation for kinematic viscosity test fuel as function of temperature is given by $\eta_{emp} = \alpha_{exp}(-\frac{T}{}) + \gamma$ where η is kinematic viscosity (mm^2/sec), T is fuel temperature °C and α, β and γ are correlation constants that are correlated with fuel type.

Amit sarin et al. [24] studied Palm, Jatropha , Pongamia biodiesel blends on cloud point and pour point. Palm biodiesel was blended with tree born biodiesels of non edible oil seeds, Jatropha, Pongamia to examine the effect on cloud point (CP) and pour point (PP) of PBO. The cloud point was 16° C, 4° C, and -1° C and pour points was 12° C, -3° C and -6° C respectively for palm, Jatropha and Pongamia biodiesel respectively. Therefore CP and PP was PBD > JBD > PoBD. When PBD and JBD were blended, higher CP of PBD was reduced by adding JBD having lower CP. Similarly when PBD was blended with PoBD CP of blended biodiesel was improved. PP of PBD was reduced by 3° C when PoBD added was more than 40% by weight in the blends. When JBD added with PoBD in different weight ratios, JBD improve its CP when PoBD was 80% by weight in the blends. Dependence of CP and PP on esters of fatty acid composition was also examined and good co-relation between CP and palmatic acid methyl ester (PAME) and between PP and PAME were obtained. Blending Jatropha and Pongamia with Palm biodiesel respectively, remarkably improved CP and PP of palm biodiesel.

G. R. Moradi et al. [25] studied densities and kinematic viscosities in biodiesel and diesel blends at various temperatures. The equations for density are $\rho_m = v_1 \rho_1 + v_2 \rho_2$ where ρ_m is the density of mixture, ρ_1 and ρ_2 are densities of components 1 and 2, v_1 and v_2 are the volume fractions, and other equation is $\rho_m = \alpha V + \beta T + \delta$ where ρ_m is density, V is the volume percentage of biodiesel blends, and, α, β, and δ are adjustable parameters that vary with the type of biodiesel and diesel. The equations for viscosity are $ln(v) = A + \frac{B}{T} + \frac{C}{T^2}$ where v is the kinematic viscosity, T is the temperature in K, A, B, and are constants and $\ln(v_m) = v_1 \ln(v_1) + v_2 \ln(v_2)$ where v_m is the kinematic viscosity of the mixture, v_1 and v_2 are the kinematic viscosity of components 1 and 2. These five biodiesels (SOB, COB, SFOB, WOB, and ETB) are compounded with diesel in various volume fractions. Results showed that, by reducing temperature and increasing the volume fraction of biodiesel, density and kinematic viscosity was increased.

Saeid Baroutian et al. [26] studied densities and kinematic viscosities in biodiesel diesel blends at various temperatures. In this work, density ρ and dynamic viscosity η of the binary mixtures of methyl esters, ethyl esters and ternary blends of methyl esters, ethyl esters, and diesel fuel were measured at various compositions and temperatures. The binary and ternary blends demonstrate temperature-dependent behaviours, and viscosities and densities decreased respectively nonlinearly and linearly with temperature. The results indicated that the increase in methyl ester contents increased the densities of the binary and ternary blends. The results also indicated that the blends of Jatropha esters have higher densities and viscosities in comparison with those obtained from palm oil. In addition, with the decrease in the diesel fuel the blends viscosities and densities increased due to the higher viscosities and densities of methyl and ethyl esters.

Table-2.1 Summary of literature review on fuel properties

Sl. No	Authors	Year	Fuel	Type of properties	Remarks
1	Rushang Joshi et al.	2007	Ethyl esters of fish oil	Dynamic Viscosity, cloud point, pour point	Correlation was established to find dynamic viscosity of biodiesel blends, DV was found from KV and density with established relation. CP, PP was determined the established correlation.
2	Erton Alptekin and Mustapa canaki	2008	Sunflower, Canola, soybean, cotton seed, corn, waste palm oil & two types of diesel	Density and viscosity	Relation was established to find density and viscosity of biodiesel blends for various percentage of biodiesel in the blends. Maximum and minimum viscosity between 3.97 to 4.34 mm^2/sec and was higher than diesel fuel.
3	Seung Hyun Yoon et al.	2008	--	Spe. gravity, density and viscosity	Correlation was established to find density and KV as a function of blending ratio and temperature. KV decreases linearly with increased temperature & decreased blending ratio.
4	Amit sarin et al.	2009	Palm, Jatropha , Pongamia biodiesel	Cloud point and pour point of PBO	PBD was blended with POBD cloud of blend was improved. PP of PBD was reduced by 3° C when PoBD added was more than 40% by wt. By blending one biodiesel with other properties of blends was improved. Correlation was established to find PP, CP.
5	G. R. Moradi et al.	2012	SOB, COB, SFOB, WOB, and ETB	Density and KV	Correlation was established to find density and viscosity of blends as function of blend percentage and temperature. Reducing temperature and increasing % of biodiesel in the blend density and KV of biodiesel blends increases.
6	Saeid Baroutian et al.	2012	Jatropha and Palm biodiesel	Density and DV	Density and DV of binary and ternary blends was determined at various temperatures and blend percentages. They show the temper. Dependent behaviors'. Density and viscosity decreases linearly and nonlinearly with temperature

2.3 Experimental investigations using biodiesel blends

2.3.1 Thermal performance and emission characteristics of engines

Vegetable oil was used as fuel in agricultural tractors and oil engine pump set. Use of vegetable for long term was created problems in the operation due to many reasons. Researchers identified the cause of problem and rectified by converting vegetable oils to their esters by different methods. Transesterification process was widely used due to it has advantage over other methods. Detail literature review was carried out on engine performance and emission characteristics using different biodiesels and their blends with diesel.

H. Raheman and Phadatare, [27] studied properties of Karanja methyl esters and its blends and their use in diesel engines. The minimum and maximum CO emissions were measured for the blends B20 and B100 and were found that reduction of 76% and 94% respectively, and smoke density were reduced 80% and 20% respectively compared to diesel. NO_x emissions for the above blends were reduced by an average of 26% compared to diesel. Torque produced were higher for blends B20 and B40 by 0.1- 13% than diesel. For B60 and B100 blends torque is reduced by 4-23% compared to diesel. BSFC for blends are higher than diesel. For B20 and B40 blends reduction in BSFC was 0.8-7.4% than diesel. For B60 and B100 blends BSFC was 11-48%. Brake thermal efficiency for B20 and B40 blends was 26.79% and 26.19% respectively, which were higher than diesel (24.62%). S Suresh Kumar [28] also worked on Karanja biodiesel.

N Usta, [29] studied use of Tobacco seed oil as alternate fuel for engines. Tobacco seeds contain oil and have lower heating value, density and kinematic viscosity of TOSME were 39811 KJ/KG, 886.8 Kg/m^3 and 3.98 mm^2/sec. TSOME and diesel blends were prepared by adding 10%, 17.5% and 25% of TSOME to diesel. Torque and power output were measured for engine speed of 1500 and 3000rpm at full load and partial load. There was no significant difference in engine power and torque of the engine up to 25% blends of TSOME with diesel fuel though heating value of TSOME is 10.8% less than diesel. Maximum torque was at the speed of 2200 rpm at full load. At partial load torque, power output and thermal efficiency were decreased marginally than diesel. CO emissions were reduced for blends and SO_2 emissions were also less than diesel fuel. There is no much difference in NO_x emission for blends and diesel at partial load, however there was an increased NO_x emission for the blends than diesel at full load.

Cherng Yaun Lin and Hsiu-An Lin, [30] studied the performance and emission characteristics of engine using biodiesel produced from peroxidation process. Four types of diesel and biodiesel with and without peroxidation process and petroleum diesel and ASTM 2D diesel were compared for their properties. Soybean oil methyl esters were considered for the test. Peroxidation process was used to modify the biodiesel, in this technology 1% of hydrogen peroxide (H_2O_2) is added to biodiesel and stirred well in reactor tank at 60º C, reaction time was 10 minutes and it is called biodiesel sample-2, sample-1 was biodiesel from soybean. The biodiesel used increases fuel consumption, BSFC, BTE and reduced CO, CO_2 emissions and lower exhaust gas temperatures than ASTM 2D diesel. Biodiesel from peroxidation process was found to have oxygen content, BSFC, fuel consumption rate were higher than biodiesel produced without peroxidation process. Biodiesel produced from peroxidation process, have BTE, equivalence ratio, were lower and emission of CO, CO_2 and NO_x were lower among all the test fuels.

Deepak Agarwal and Avinash Kumar Agarwal [31] studied the use of vegetable oils in diesel engines. Heating Jatropha oil viscosity effect on combustion and performance characteristics was eliminated. Presence of oxygen in Jatropha oil improves combustion and emission properties, reduces calorific value of fuel. Experiments were carried out using diesel, preheated Jatropha oil and unheated Jatropha oil and blends of Jatropha oils with diesel fuel at various loads and constant speed. Various acquired parameters were analyzed such as brake thermal efficiency, BSFC, and exhaust gas temperature of unheated Jatropha oil are higher than diesel and heated Jatropha oil. Thermal efficiency was lower for Jatropha oil than diesel fuel. Emissions such as CO, CO_2, HC and smoke density were higher for Jatropha oil than diesel fuel. Emissions were close to diesel for preheated Jatropha oil. Jatropha oil can be an alternate fuel without any modification to the engine. K. Pramanik [32] studied the same.

P.K.Sahoo et al. [33] studied use of Polanga biodiesel in diesel engine and their effect on performance and emission characteristics. Different blends used were B0, B20, B40, B60, B80, and B100 for testing performance and emissions over the entire range of varying condition of speed and load. Brake specific fuel consumption, brake thermal efficiency, brake energy consumption, smoke density, and exhaust emissions such as NO_x were better for the entire engine operation range. This was because of presence of oxygen in biodiesel played the role for improving the performance and emissions of the engine. It was said that thermal efficiency was improved by 0.1% for 100 % biodiesel (B100) fuel. Similar trend was seen in brake specific energy consumption. 35% less smoke opacity were found for B60 blends than diesel fuel. NO_x emissions were decreased by 4% for B100 fuel at full load.

S Murillo et al. [34] studied the performance and emission of CI DI engine using the blends of biodiesel and diesel and diesel. Waste cocking oil was used for producing biodiesel. For 100 % biodiesel used engine gives 7.14 % less power at full load conditions at rated speed.10% to 30% blends gives comparable power output with diesel fueled engines. BTE was compared with diesel rather than BSFC because of their energy discrimination between diesel and biodiesel. BTE is higher for 100% biodiesel than diesel, for other blends considered in the study have lesser thermal efficiency than diesel. It was reported that emission of CO are reduced by using biodiesel and reduction are reported to be 3% to 10%. It was explained by author that prevailing conditions are the important for the performance and emissions from the engines. NO_x emissions increase with increased volume fraction of biodiesel in the blends and can be reduced with correction to engine.

Banapurmath et al. [35] studied the performance and emission characteristics of engines using different vegetable oils and diesel blends. High viscosity of vegetable oils was creating in pumping and spray characteristics of fuels. Inefficient mixing of oil with air is causing the problems like incomplete combustion and increased emissions. Better method is to reduce viscosity of vegetable oils and convert it in to their biodiesel. Oils considered in this work were Pongamia, Jatropha, Rubber seed, Calophyllum Inophyllum. Biodiesel can be used in blends with diesel fuel or biodiesel alone. Brake thermal efficiency for biodiesel fuel was lesser than diesel fuel. Smoke opacity, were higher for biodiesel than diesel fuel because of heavier molecular structure and higher viscosity and lower volatility of biodiesel fuel. CO, HC emissions are more for methyl esters than diesel fuel. NO_x emissions were higher for diesel than biodiesel fuel. Heat release rate were lower during premixed combustion for biodiesel.

M.A. Kalam and S.S. Masjuki [36] studied the effect of additives to the biodiesel and diesel blends on performance and emission characteristics of engines. A computer controlled dynamometer is used for loading and speed is varied between 1000-4000 rpm. Three types of fuels were considered for tests, diesel, B20 blend and B20 blends with x% (B20x) additives. The B20x is additive-added biodiesel, where x is the percentage of additive (x = 1% of B20) in B20 blend. It was found that B20x blends gave better performance such as improved brake power, lesser specific fuel consumption, reduced emissions such as CO, HC, and $NOx_.$ 1% to 3% of B20x contaminated fuels in to lubricants reduces friction acting as anti wear agent and increasing flash temperature parameter. The specific objective of the work was adding in house developed additives to B20 blends to improve the performance and reduce emissions of diesel.

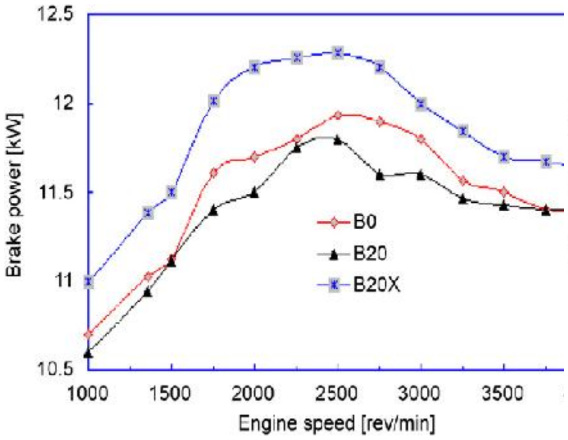


Fig. 2.3.1. BP output vs. engine speed.

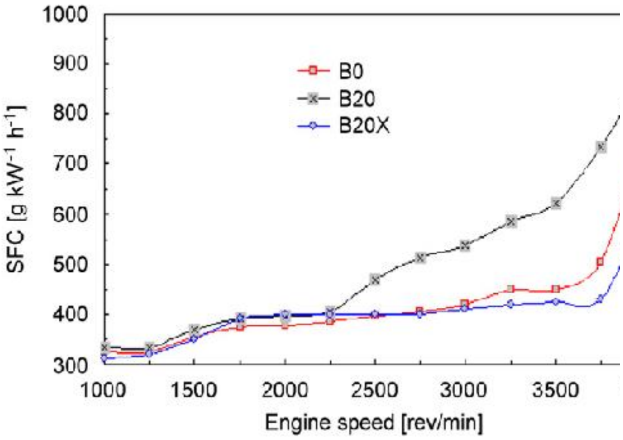


Fig. 2.3.2. BSFC vs. engine speed.

P.K.Sahoo et al. [37] studied the performance and emission characteristics of diesel engine using blends of biodiesel and diesel. Jatropha, Pongamia, Polanga methyl esters were produced and blended with petroleum diesel. The data generated were at full and part throttle position at various speeds (1200, 1800, 2200 rev/min) with emission measurements. Full throttle operation of engine no change in power were seen for lower speed of 1200rpm and 1400 rpm for biodiesel blends. Slight reduction in power output was observed at all speeds of tractor engine for biodiesel blends of KB20, KB100, JB100, PB20 and PB100. Maximum power output was observed for JB50 blends at 2000rpm and 2100 rpm. Part throttle operation increases the fuel economy for JB20, PB20 and PB50 blends than diesel. Smoke density was reduced for all the biodiesel blends than diesel at all the speeds. JB20 gives better BSFC among all the blends and diesel. It was observed there was noticeable reduction in the HC, particulate matter emissions for biodiesel and blends. Increase in NO_x and CO_2 was observed with the blends. M. Pandian et al, [38].

Murat Karabekas [39] studied the effect of turbocharger on the performance and exhaust emission of diesel engine with biodiesel blend. The rape seed biodiesel and their blends were used for testing. Performance parameters studied were brake power, brake torque, BSFC, BTE at full load and between 1200 to 2400 rpm. Turbocharged engine were having considerably lower BSFC than naturally aspirated engine for diesel and biodiesel for all the speeds. Similarly brake power and BTE was higher for turbocharged engine compared to naturally aspirated engines for both fuels and speeds. Brake torque was higher for the turbocharged engine than natural aspirated engine. BSFC is higher for biodiesel for both turbocharged engine and naturally aspirated engine compared to diesel. Naturally aspirated and turbocharged engines were having higher BTE for biodiesel than diesel. CO emissions reduced and NO_x emissions increased for turbocharged engines.

Bupendra singh Chauhan et al. [40] studied the use of Jatropha oil as an alternate fuel in diesel engines. The first approach was to modify the engine and second is to modify the fuel which suits the engine. The first approach was to blend Jatropha oil with diesel and use it in engine. In second approach, reduce viscosity of oil by transesterification process which could be used directly in engine or blending with diesel. Thermal performance of Jatropha fuel used engines such as brake thermal efficiency was lower, brake specific fuel consumption were higher throughout the operation range of engine than diesel fuel. Emissions such as CO, HC and CO_2 were increased for Jatropha oil used engine in comparison with diesel fuel. Whereas NO_x emissions were reduced with Jatropha oil fuelled engine than diesel fuel.

Jincheng Huang et al. [41] studied use of biodiesel blends in diesel engine for performance and emissions parameters. Two different biodiesels considered were Chinese Pistache oil and Jatropha oil. Engine was tested at two different speeds, for maximum torque at 1500 rpm and for maximum power at 2000 rpm for performance emissions characteristics of engine. Engine model was ZS195 diesel engine with single cylinder water cooled, direct injection, CR 17:1. Engine running with biodiesel fuel were having higher thermal efficiency than diesel fuel. Brake specific fuel consumption were higher both the biodiesel than diesel fuel for both test conditions. Emissions of CO were lower for the higher engine loads. CO and HC emissions were same for both biodiesel. HC emissions were lesser for both higher load and lower load than diesel fuel. NO_x emissions were lower for both biodiesel than diesel fuel especially at higher loads. Smoke emissions were lower both biodiesel than diesel fuel for all range of engine tested.

Lupetra et al. [42], studied emissions of diesel engine using blends of biodiesel and diesel fueled engine for fulfilling Euro emission norms. Biodiesel considered were transesterified soybean methyl esters added with additives such as pour flow depressants and oxidation stabilizers to satisfy Euro emission norms. Another biodiesel was considered in this study was gas to liquid biodiesel (GTL) fuel. Brake specific fuel consumption was higher for biodiesel than reference fuel and slightly lower for GTL fuel. For G30B70 blend was in between the two fuels. CO emissions were detectable for the blends and reference fuel and undetectable for GTL fuel at low load. It was because of combustion effects and improved efficiency of diesel oxidation catalyst contributes in reduced emissions from engine. NO_x emissions were slightly lower for tested fuel than diesel fuel. Significant reduction in smoke opacity, particulate matter, and particulate number was observed using GTL fuelled engine than diesel fuel. Particulate matter emissions were quite similar for biodiesel and GTL fuel in spite of its low soot emissions because of lower volatile organic fraction of PM in the GTL fuel. Blending of biodiesel and gas to liquid fuel reduce emissions which were satisfying the Euro emission standards were considered as second generation bio fuels.

M.A.Kalam et al. [43] studied the performance and emission characteristics of indirect injection diesel engine using Coconut oil and Palm oil biodiesel as fuel. Multi cylinder diesel engine was used for testing at two speeds of 1500 rpm and 3500 rpm at 85% throttle position. Engine was more stable at 85% throttle position rather than at 100% throttle position. Fuels were tested for their properties C5 have better heating value than P5, these properties gives better power from the engine and were lower than diesel fuel. Brake power was marginally higher for B0 than C5 and P5 fuels at 3000rpm. If the speed was increased beyond 3000rpm power output were reduced. Exhaust temperature were lower for C5 fuel followed by B0 and P5 fuels. Both fuels contain inbuilt oxygen and fatty acid in coconut oil is highly saturated (92%) than palm (50%). Emissions for biodiesel were lesser than diesel fuel. CO_2 emissions were higher for biodiesel blends than diesel. Emission of HC was less for C5 fuel than diesel and P5 have highest HC emissions less than even diesel fuel. NO_x emissions were lower for C5 fuel than diesel and P5 have higher NO_x emissions than diesel fuel. It was said that C5 is alternate fuel could be used in diesel engine than P5 because of its advantage over other fuel.

Jo-Han Ng et al. [44] studied three types of biodiesels were considered using in engine. Three biodiesel considered were Coconut methyl ester, Palm methyl ester and Soybean methyl ester. There was difference in specific fuel consumption, equivalence ratio and exhaust emissions such as CO, HC, and smoke opacity for different fuels. The properties of fuels such as kinematic viscosity, oxygen content, density, air fuel ratio and spry of fuel, were effecting the performance and emission of CO, HC and smoke density. In second phase of test of different blends were used in the steps 10% volume interval under steady state operating condition of engine. Using biodiesel of low and moderate unsaturated fuel was given out the reduced regulated emissions of UHC and smoke opacity. Highly unsaturated Soybean methyl esters were having higher emission of CO, UHC, NO, smoke opacity, than diesel fuel. Use of biodiesel in blends in different ratio was able to reduce the NO emissions and smoke opacity by blending 1% vol. of PME or 50% volume of CME with diesel fuel.

M.Mafijur et al. [45] studied thermal performance exhaust emissions of direct injection diesel engine using blends of Linseed biodiesel and diesel. Various blends used in engine testing were B5, B10, B15 and B20. Brake specific fuel consumption for different blends used was lesser than diesel fuel at rated load of engine. B10 blend has least BSFC at rated load and increases with increase in volume fraction of biodiesel in the blends. Brake thermal efficiency was higher for the blend B20 than diesel and other blends. At rated load of the engine emission of CO, HC and smoke opacity decreases with increase in biodiesel blends up to B10. HC emissions were lesser for all the blends tested than diesel fuel. Smoke opacity reduces with increased volume fraction of biodiesel in the blends. NO_x and CO_2 emissions increase with increase in volume fraction of biodiesel in the blends.

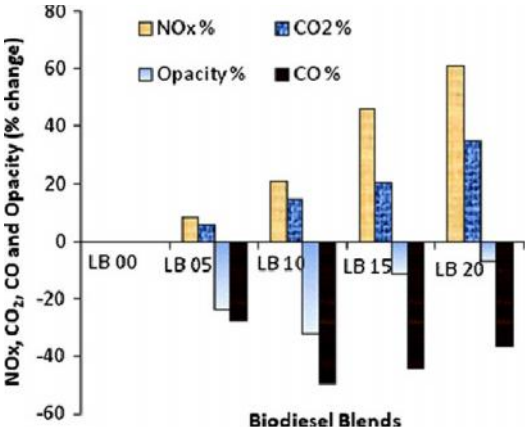


Fig.2.3.5 Change in emission with biodiesel blends as compared to diesel fuel

Peak pressure was higher for biodiesel blends B10 than diesel fuel. Rate pressure rise was found to be better for B10 blends than diesel fuel because of better combustion of biodiesel fuel.

Soham Chattopadhyay and Ramakrisna Sen [46] studied the performance and emission characteristics of engine using biodiesel and its blends. BSFC for B10 and B20 blends were 0.415 and 0.418 gm/kW hr, for petroleum diesel it was 0.407 gm/kW hr. Mean value of BSFC were higher for biodiesel blends than diesel by 2.3%. BTE for diesel, B10 and B20 fuel were 23.09%, 22.8% and 22.7% respectively. Exhaust gas temperature were lesser for biodiesel blends than diesel the values for the blends were 275° C and 271° C whereas for diesel fuel 277° C.

Emission of CO was reduced for biodiesel blends by 33.3% than diesel. CO emissions for B10, B20 and diesel were 0.033%, 0.029% and 0.046% respectively. Mean reduction of CO_2 mission for biodiesel blends were reduced by 8.4% than diesel. NO_x for B10, B20 and diesel was 330.33, 336.67 and 284.42 ppm respectively. The average increase in NO_x emissions for biodiesel blends were 17.3% higher than diesel. HC emission for B10, B20 and diesel was 70.58, 65.25 and 96.25% respectively. Mean reduction in HC emission for biodiesel blends was 29% than diesel. The average reduction of smoke for biodiesel blends were 43.4% lesser than diesel. C Ilkilic and R Behcet [47] is also worked on cotton seed oil biodiesel blends.

M.Mafijur et al. [48] studied performance and emission characteristics of biodiesel and diesel blends in multi cylinder diesel engines. Moringa Oleifra oil were converted to their biodiesel was used in engine testing. Various blends of biodiesel and diesel prepared were B10 and B20. Experimental investigations were carried out using Mitsubishi Pajero (Model 4D46T), multi cylinder, and variable speed engine. Brake power output from engine was found to be 28.72, 27.51 and 26.41 kW respectively for diesel, B10 and B20 fuels. Decrease in BP for B10 and B20 blends was 4.22% and 8.03% than diesel fuel. BSFC was 0.386, 0.406 and 0.418 Kg/kWh for diesel, B10 and B20 blends respectively. BSFC of blends B10 and B20 was 5.13% and 8.39% higher than diesel.

CO emissions for B10 and B20 blends were 10.60% and 22.93% lesser than diesel fuel. Emission of HC for the blends B10 and B20 were lesser than diesel fuel during the entire range of operation of the engine. Reduction in HC emissions was 9.21% and 23.68% lesser for B10 and B20 blends than diesel fuel. Emission of NO_x for B10 and B20 blends were higher than diesel fuel by 8.46% and 18.56%.

I.M. Rizwanul Tattah et al. [49] studied the performance and emission characteristics of engine using Coconut and Jatropha B20 blends with added antioxidants. Biodiesel were susceptible to oxidation degradation due to its oxidation in presence of oxygen present in the atmosphere affecting the use of biodiesel as an alternate fuel. The antioxidants considered were low cost synthetic antioxidant, 2(3)-tert-butyl-4-methyxiphenol(BHA) and 2,6-di-tert-butyl-4-methylphenol (BHT), at a concentration of 2000ppm were used. Adding antioxidants to biodiesel fuel increases the oxidation stability of biodiesel fuel.

Addition of antioxidants increases density and increases the quantity of fuel injection increases BP. BSFC for biodiesel blends with and without antioxidants were higher than diesel fuel for the whole engine operation range. BSFC for different blends JB20, JB20 BHA, JB20 BHT, CB20, CB20 BHA, CB20 BHT, and diesel fuel were 364, 361.13, 361.14, 363.08, 360.64, 361.07 and 346.60 gm/kWh respectively. BTE of biodiesel blends with and without antioxidants was lesser than diesel fuel over the entire engine operation range. Maximum BTE for diesel was 28% whereas that of JB20 and CB20 was 27.04% and 27.9% respectively. BTE for different blends JB20, JB20 BHA, JB20 BHT, CB20, CB20 BHA, CB20 BHT, and diesel were 23.20, 23.38, 23.36, 23.51, 23.69, 23.65 and 23.82% respectively. BTE of CB20 was higher than JB20.

NO emissions were lesser for the biodiesel with antioxidants added blends and were comparable with diesel. Mean increase of NO was 5.52% and 8.02% respectively for

JB20 and CB20 blends. Adding 2000ppm of BHA and BTH to JB20 and CB20 reduce average emission NO by 4.8%, 3.9%, 5.0% and 2.6% respectively. Emissions of CO and HC were lesser with or without antioxidant biodiesel blends than diesel. Average reduction in CO emission for different blends JB20, JB20 BHA, JB20 BHT, CB20, CB20 BHA, CB20 BHT were 22.3%, 17.5%, 40.7%, 35.8%, 37.7% and 31.7% respectively than diesel. Average reduction in HC for JB20 and CB20 were 40.1% and 49.6% respectively.

S.M.Plash et al. [50] studied thermal performance and emission characteristics of diesel engine using blends of Aphanamixis Polystachya biodiesel blend with diesel fuel. Biodiesel blends were prepared from APME fuel were blended with diesel fuel in different volume fractions and are B5, B10, B20,B30, B40, B60, B80. Experimental investigations were carried out using 2.5L, four cylinders, turbocharged diesel engine. The reduction in torque for the same amount of fuel injected for B5 and B10 were lower by 0.9% and 1.81% respectively than diesel. Average reduction in BP for blends B5 and B10 compared to diesel fuel were 0.9% and 2.1% respectively. Average increase in BSFC for B5 and B10 were 0.87% and 1.78% than diesel.

Reduction in CO emissions was found up to 2000rpm engine speed and then increases marginally at maximum speed of 4500rpm. B5 blend there was no much difference in CO emission compared to diesel for B10 blends reduction in CO emissions were 4.69% compared to diesel. Average reduction of HC was 9.86% and 22.32% respectively for B5 and B10 blends compared to diesel. The average increase in NO emissions was 2.18% and 7.32% than diesel for B5 and B10 blends respectively.

Satputaley et al. [51] investigated thermal performance and emission characteristics of diesel engine using micro algae oil and micro algae methyl ester blends. Micro algae oil and micro algae methyl esters properties were meeting the ASTM standards. These fuels were used in the engine testing. The results showed the reduction in CO, unburnt HC, NOx and smoke emissions compared to diesel fuel. The brake thermal efficiency of the engine was decreased with the use of micro algae oil and micro algae methyl esters.

Ozer Can et al [52] investigated the combustion, performance and emission characteristics of single cylinder four stroke CI DI engine using canola biodiesel and diesel blends. Comprehensive combustion characteristics investigations revealed the marginally reduced cylinder pressure and pressure rise rate. Maximum heat release rate for the canola biodiesel with diesel blends were reduced compared to diesel because of decrease in premixed combustion and increased diffusion combustion. The decreased premixed combustion for the blends is because of reduced ignition delay for blends. The increase in volume fraction of biodiesel in the blend ignition delay decreases further. The centre of maximum heat release is retarded for the blends compared to diesel fuel. The combustion duration increases for the blends compared to diesel fuel. BSFC for the blends increases and brake thermal efficiency decreases for the blends. The emission of CO, HC and particulate were lesser for the blends and NO and CO_2 emission increases for the blends because of increased combustion temperature for the blends.

The outcome of detailed literature review on thermal performance and emission characteristics of various researchers using different biodiesels and their blends with diesel was compared with petroleum diesel. Almost all the researchers have claimed that increase in fuel consumption for biodiesel and its blends and increased BSFC with reduced BTE. Emissions such as CO, HC and smoke opacity were lesser for biodiesel blends compared to diesel fuel. NO_x and CO_2 emissions were measured for diesel and various blends and were higher compared to diesel fuel.

Tabl-2.2 Summary of literature review on thermal performance and emission characteristics

Sl.No.	Authors	year	Fuel	Type of study TP and EC	Remarks
1	K. Pramanik	2003	Jatropha oil	TP	Heating Jatropha oil to 75° C viscosity was reduced and comparable results were obtained blending up to 50% Jatropha oil with diesel.
2	H. Raheman and Phadatare	2004	Karanja Biodiesel	TP and EC	Viscosity of oil was 10.7 times and 2.9 times for biodiesel than diesel. Higher BSFC and BTE lower for higher blend ratios. CO, HC, NO_x emissions were reduced
3	N. Usta	2005	Tobacco seed biodiesel	TP and EC	Up to 25% blend no reduction in power and torque of the engine. Slightly increased power and torque with TSOME than diesel fuel. CO emissions were reduced and NOx emissions were increased.
4	Cherng Yaun Lin and Husian Lin	2006	Soybean biodiesel	TP and EC	Increases BSFC and TE and reduces the CO, CO_2 and NO_x emissions for biodiesel from preoxidation process compared to transesterified biodiesel.
5	D.K.Agarwal and A. K.Agarwal	2007	Jatropha oil pre heated	TP and EC	Jatropha oil has higher BSFC lower TE and increased emissions such as CO, CO_2, HC and smoke. Preheated Jatroph oil has comparable results with diesel fuel, increased % may affect adversely.
6	S. Murillo et al.	2007	WCOME	TP and EC	Up to 30% blend gave comparable performance with increased thermal efficiency and reduced emission of CO, increased NO_x emissions.
7	P.K.Sahoo et al.	2007	Polanga biodiesel	TP and EC	BTE was 0.1% increased for B100 than diesel; other blends performance was better than diesel with reduced emission and smoke,

Sl.No.	Authors	year	Fuel	Type of study TP and EC	Remarks
					increased NO_x.
8	Banapurmath et al.	2008	Pongamia, Jatropha, Rubber Calo. Ino phyllum	TP and EC	Brake thermal efficiency was less compared to diesel for all the fuels and smoke density, HC, CO emissions was higher and NOx emissions were reduced.
9	Suresh kumar et al.	2008	Pongamia biodiesel	TP and EC	B20 and B40 blends have lower and equal BSFC to diesel fuel and BSEC was less for blends. CO, HC, NO_x emissions was reduced and CO_2 emissions were increased and reduce the global warming gases.
10	M.A. Kalam and S.S. Masjuki	2008	Palm oil biodiesel	TP and EC	Adding in house developed additives the performance of engine was improved with reduced emissions and wear of engine parts. In 20x out of 20% biodiesel x=1% additive was added.
11	P.K.Sahoo et al.	2009	Jatropha, Polanga Pongamia, methyl esters	TP and EC	Power was almost similar with diesel fuel, BSFC was higher for increased % of biodiesel in the blends for all the biodiesels, emissions of HC, PM was reduced and CO, NO_x was increased.
12	Murat Karabekas,	2009	Rape seed biodiesel	TP and EC	Turbocharged engine having lesser BSFC, increased power and BTE than natural aspirated engine. CO emissions were less for turbocharged engine and NOx emissions was increased for natural aspirated engine.
13	Bupendra singh	2010	Jatropha oil	TP and EC	BSFC was higher, BTE was lesser for Jatropha oil than diesel fuel,

Sl.No.	Authors	year	Fuel	Type of study TP and EC	Remarks
	Chauhan et al,				emissions CO, HC, CO_2 was increased and NO_x emissions were reduced.
14	C Ilkilic and R Behcet	2010	Cotton seed oil biodiesel	TP and EC	Using B20 blend CO, CO_2 and NO_x emissions was reduced by 33%, 13% and 15% respectively and increases engine life due to their higher lubrication properties.
15	Jincheng Huang et al.	2010	Chinese pistache and Jatropha oil	TP and EC	Brake thermal efficiency was higher for biodiesel blends than diesel and BSFC was higher for the blends. CO, HC emissions was lower at higher loads and NO_x emissions and smoke was lesser for blends than diesel.
16	Lupetra et al.	2010	Soybean and gas to liquid biodiesel (GTL)	TP and EC	BSFC was higher for biodiesel fuel and GTL, BTE similar to diesel. CO emissions were detectable for soybean and undetectable for GTL fuel, reduced smoke and PM for both the fuels and NO_x was reduced for both fuels than diesel.
17	M. Pandian et al.	2011	Polanga biodiesel	TP and EC	Injection timing, injection pressure and protrusion of injector was varied, advancing IT emissions such as CO, HC, Smoke was reduced and NOx was increased. BSEC was reduced where as BTE increased.
18	M.A.Kalam et al.	2011	Waste cocking oil and Palm biodiesel	TP and EC	Engine was running more stable at 85% throttle position than 100%. Reduced power at lower speed and still less power at higher speed of the engine. HC, CO, NO_x emissions was less and CO_2 was higher.

Sl.No.	Authors	year	Fuel	Type of study TP and EC	Remarks
19	Jo-Han Ng et al.	2011	Coconut, Palm and Soybean methyl ester	TP and EC	Higher fuel consumption for the blends used. Emissions were affected by the properties of fuels. SOME has higher emission of CO, UBHC, NO, and smoke than diesel and other fuels. Blending different volume of biodiesels NO emissions can be reduced.
20	M.Mafijur et al.	2013	Linseed oil biodiesel	TP and EC	At rated load BSFC for the blends was less, BTE was higher for B20 blends than other blends and same as diesel, CO, HC, smoke opacity was less up to B10 blend and NO_x, CO_2 emissions was higher.
21	Soham Chattopadhyay, Ramakrisna Sen	2013	Cotton seed oil biodiesel	TP and EC	Mean BSFC was higher for B10, B20 blends by 2.3% than diesel, BTE was marginally lesser for the blends, EGT was less for biodiesel, CO, HC, smoke emissions was less for blends and NO_x emissions was higher.
22	M.Mafijur et al.	2014	Moringa oleifra oil biodiesel	TP and EC	Brake power output was less for biodiesel blends than diesel, BSFC was higher for B10, B20 blends and BTE was less for the blends. CO, HC emissions was less whereas NO_x emission increases for blends.
23	I.M.Rizwanul Tattah et al.	2014	Coconut and Jatropha with antioxidents	TP and EC	BP for blends was reduced for blends, adding antioxidents BP was increased for JB20 and CB20 by 0.82% and 3.68%, BSFC was higher for blends with or without antioxidents BTE was lesser for both. Less CO, HC, increased NO_x emissions for both fuels with or without antioxidents.

Sl.No.	Authors	year	Fuel	Type of study TP and EC	Remarks
24	S.M.Plash et al. (2015)	2015	Aphanamixis Polystachya	TP and EC	Power and torque output was less for B5, B10 blends than diesel fuel. BSFC was higher for biodiesel blends for all the speeds. Emission of HC, CO was lesser and NO_x and CO_2 were higher for the blends.
25	Satputaley et al.	2016	Micro algae oil and methyl esters	TP and EC	The BSFC were higher and BTE were lower for micro algae oil and methyl esters compared to diesel. Emissions of CO, UBHC, NOx and smoke were reduced compared to diesel fuel.
26	Ozer Can	2017	Canola biodiesel	TP, and EC	The BSFC were increased and BTE were decreased compared to diesel fuel. The CO, HC and smoke emissions were decreased and CO_2 and NOx emissions were increased.

2.3.2 Combustion, thermal Performance and Emission and Characteristics of Engines

In this part of literature it is the study of performance, emissions and combustion characteristics of engine using various biodiesel and their blends with diesel fuel were compared with pure diesel as fuel. Emissions effects caused by burning the various fuels and the associated environmental problems were studied. The combustion parameters such as cylinder pressure and heat release rate and effect of injection timing, injection pressure on different types of blends with varying load were investigated by number of researchers and compared with diesel fuel.

Ekrem Buyukkaya [53] studied the performance, emission and combustion characteristics of diesel engines using rapeseed oils and its blends with diesel. Power output for diesel fuel and B5 blends were similar. Maximum reduction in the power output of engine for increased volume fraction of biodiesel in the blends (B20, B70, B100). At higher speeds torque for B5 blends was slightly higher than diesel. Brake thermal efficiency for biodiesel blends was higher than diesel for all the speeds. Smoke opacity was lower for biodiesel and their blends than diesel. Exhaust gas temperature for biodiesel and their blends were higher than diesel fuel for all the engine speeds. NO_x emissions were higher for biodiesel and its blends for all the engine speeds. Carbon monoxide and hydrocarbon emissions were lesser for biodiesel and its blends than diesel. Peak cylinder pressure was lesser for biodiesel and its blends than diesel. Combustion characteristics for these blends and diesel were similar. Cylinder pressure was higher for diesel fuel followed by B5, B20 and so on. Heat release for biodiesel and diesel blends were less than diesel. Ignition delay was lesser for biodiesel and its blends than diesel.

Agarwal and Dhar [54] studied the use of biodiesel in diesel engines. Experimental investigations were carried out using rice bran oil (RBO20) and rice bran methyl esters RBME20)at two different speeds 1800rpm and 2400rpm for thermal efficiency, emissions and combustion characteristics of diesel engine. BSFC was higher for rice bran oil than rice bran methyl esters (B20) at 1800 rpm whereas for rice bran methyl ester has better thermal efficiency than mineral diesel at 2400rpm. Brake thermal efficiency was higher for mineral diesel at 1800rpm. Emissions were reducing because of better combustion with rice bran methyl ester blends. CO_2 emissions were lower for mineral diesel where as for rice bran methyl esters (B20) are close to mineral diesel. NO_x emissions were comparable for mineral diesel and rice bran methyl ester blends (B20). CO emissions were lesser for rice bran methyl ester blends (B20) and rice bran oil at lower loads than mineral diesel. At higher loads CO emissions were similar for all the fuels used in the tests. Smoke emissions were lower for B20 blends of rice bran biodiesel whereas it was highest for diesel fuel. Cylinder pressure was almost same for all the fuels used in the tests. Peak cylinder pressure for fuels used was 4-8 degree after TDC for speed of 1800 rpm, and for 2400 rpm peak pressure was 4-9 degree after TDC. Heat release was higher for mineral diesel compared to the other blends used.

Sukumar Puhan et al. [55] studied performance, emission and combustion characteristics using blends of biodiesel and diesel fuel. There were three types of oils namely Jatropha, Coconut, Linseed considered for the tests. Coconut methyl esters have more favorable properties such as heating value, viscosity, density, Cetane number than JOME and LOME fuels. BSEC were higher for all three biodiesel than diesel. LOME was having marginally higher BSEC than other two methyl esters. Brake thermal efficiency of LOME ester was less than COME and JOME fuels. JOME have higher brake thermal efficiency than other two methyl esters. CO emissions were less for COME at lower loads than JOME and LOME and these two almost similar, at higher loads CO emission for LOME were more than other two methyl esters. CO_2 emissions of COME and JOME were comparable and were higher for LOME for all the loads. HC emissions were highest for LOME and least for COME and JOME is in between the two fuels. NO_x emissions were higher for LOME, least for JOME and between these two fuels for COME. Smoke was more for LOME and least for COME and JOME at lower loads. Heat releases rate were almost similar for all the fuels used at lower loads. Highly unsaturated LOME was having longer ignition delay and longer premixed burning. The net heat release rate was almost comparable for all the fuels used for testing. Cumulative heat release rate for all test fuels were same for lower loads. It is higher for JOME and LOME than COME at higher loads.

Rao [56] studied use of Jatropha biodiesel in compression ignition engine. Experiments were carried out using with different operating condition of engine with preset injection pressure set by engine supplier. Tests were carried out using Jatropha biodiesel, preheated Jatropha biodiesel and petroleum diesel. BSFC for Jatropha biodiesel was more than diesel and preheated biodiesel. BTE of diesel was higher than Jatropha biodiesel and pre heated Jatropha biodiesel. Brake specific energy consumption was higher for Jatropha biodiesel than diesel and preheated Jatropha biodiesel. Peak cylinder pressure was higher for Jatropha biodiesel and burning closer to TDC than diesel and preheated Jatropha biodiesel. Net heat release rate were higher for biodiesel than diesel and preheated biodiesel. Cumulative heat release were higher for Jatropha biodiesel than diesel and preheated biodiesel during premixed combustion stage, where as in diffusion combustion stage it was lower than diesel and pre heated Jatropha biodiesel. NO emissions were higher for JBD than other two fuels. HC emissions were higher for diesel than Jatropha biodiesel and preheated biodiesel. Emissions of CO were similar for diesel and Jatropha biodiesel at lower loads and less for preheated Jatropha biodiesel. Smoke density was lower for both biodiesel than diesel from medium and higher loads.

Jaichchanrda et al. [57] studied effect of injection timing and combustion geometry on performance biodiesel fueled CI engine. In the experimental study the aim was to optimize and improve performance and emission of engine using combined effect of injection timing and combustion chamber geometry. Combustion chamber geometry used was Toroidal Re-etntrant combustion chamber (TRCC) and Hemispherical combustion chamber (HCC). Tests were carried out using petroleum diesel and Pongamia methyl ester blends B20 varying the injection timing between 20° and 24° before TDC. BSFC was better for TRCC than HCC at standard injection timing. BTE for B20 blends were lower compared to ultralow sulfur diesel with HCC because of lesser ignition delay for B20 fuel. BTE for B20 blend was higher for TRCC than HCC. Emissions were lower for B20 blend than diesel for both type of combustion chamber with different injection timing. Addition of Pongamia biodiesel to ULSD reduces CO emission significantly. NO_x emissions were higher for B20 with TRCC than HCC was because of higher combustion temperature with B20 blend with improved combustion. Retarding the injection timing decreases the NO_x emissions was due to shorter ignition delay gave lesser premixed combustion temperature. Smoke emissions were lower for B20 blends than diesel for both TRCC and HCC. Cylinder pressure for B20 blends was lower than diesel. Peak pressure was higher for TRCC than HCC for diesel. Peak cylinder pressure was marginally less for retarded injection timing. Heat release rate was higher for diesel than B20 blends.

Orkun Ozner [58] studied the use of soybean biodiesel blends (B10, B20, B50) and diesel fuel in variable speed CI engines. Torque increases approximately up to 2000rpm, then it starts reducing for all the fuels used in the tests, it follows similar trend for blends and diesel fuel. BSFC increases for all the fuels used with increase in speed of the engine. HC and CO emissions decrease considerably for biodiesel blends than diesel. Carbon dioxide emissions were increased with biodiesel fuel than diesel. Exhaust gas temperature for biodiesel fuel were lesser than diesel fuel. NO_x emissions were higher for biodiesel blends than diesel. Smoke opacity was lower for biodiesel and its blends than diesel. Peak pressure for diesel fuel was marginally higher for diesel fuel than biodiesel and its blends. Ignition delay was lesser for biodiesel and its blends because of their higher Cetane number. Heat release rate were shown in Fig. 2.3.1. b. Heat release was higher for diesel fuel than biodiesel and its blends. D.H.Qi et al [59]

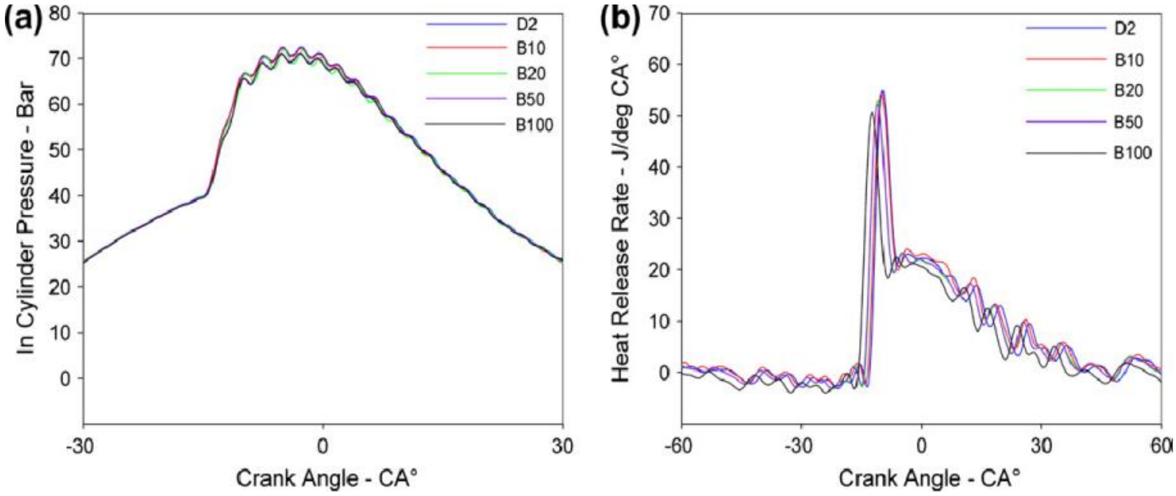


Fig 2.4.1 (a) Measured In-cylinder pressures for the diesel fuel and blends. @2000 rpm-Max. Torque (b) calculated heat release rates for the diesel fuel and blends. @2000 rpm-max. Torque.

Prabu et al. [60] studied the use of biodiesel from plants and animal fat as alternate fuel in diesel engines. BSFC for diesel was less than 20% NOME and 100% NOME. BTE was lower for B100 than B20 and petroleum diesel. Lesser BTE for biodiesel were due to lower heating value biodiesel. Exhaust temperature were higher for biodiesel and blends than diesel. CO emissions were less for biodiesel and their blends than diesel. As biodiesel volume fraction increases CO emission decreases. HC emissions were higher for B100 than B20, B40 blends and diesel. NO emission for NOME and its blends were higher than diesel. Smoke emissions were lower for NOME and its blends than diesel. Combustion starts for NOME and 20% NOME blends earlier than diesel. 20% NOME were having higher cylinder pressure than 100% NOME and diesel. Heat release rate were higher for diesel than 20% NOME and 100% NOME at rated load.

Abhishek Sharma et al. [61] studied use of Tyre Pyrolysis oil and Jatropha methyl esters blend in diesel engine. BTE was higher for diesel than other fuels used in the testing of engine. BTE of JMETPO20 was better than the other blends used in testing of the engines. BSFC was lesser for diesel followed by JME and blends of JMETPO. Increased TPO volume fraction in the blends of JMETPO increases BSEC of blends. Exhaust gas temperature for the blends were more than diesel and JME fuels.CO and HC emissions were lesser for JME, JMETPO10, and JMETPO20 than diesel. Increased percentage of TPO in the blends increases the HC emissions. Nitrogen oxide emission increases for JME and its blends with increased BP. NO emissions decreases with increased volume fraction of TPO in the blends. Smoke emissions were lesser for JME, JMETPO10 and JMETPO20 than diesel. The pattern of cylinder pressure was similar for different blends and diesel at full load. Cylinder pressure was higher for diesel followed by JME fuel and JMETPO10 was least. Ignition delay was lesser for JME than TPO, increased percentage of TPO in bends of JMETPO ignition delay increases. Heat release rate were maximum for diesel and minimum foe JMETPO50. Heat release for JME was next to diesel, with increased volume fraction TPO in blends of JMETPO heat release rate decreases. Combustion duration is lesser for JME, JMETPO10, and JMETPO20 than diesel. Rate of pressure rise were maximum for diesel followed by JME and other blends.

H. An et al. [62] studied performance and emission characteristics of diesel engine using blends of waste cocking oil biodiesel and diesel blends. Experiments were carried out using Euro IV, turbocharged diesel engine. Performance emissions were obtained at four different engine speeds, four different fuels used i.e. diesel, B10, B50 and B100. Blends B50 and B100 were having less than diesel for all the speeds. For B50 and B100 blends power were reduced by 5.6% and 9.7% respectively at 3600rpm speed. Among the fuels used in the tests diesel has least BSFC and B100 was highest at all the speeds, B10 has lower BSFC at 3600rpm speed. BTE for all the blends was higher for biodiesel and its blends at rated load at all speeds. At 2400rpm speed BTE was higher, if the speed is increased beyond 2400rpm BTE decreases. For 25% load B100 has least BTE than other fuels, B10 and B50 was having BTE same as that of diesel. CO emissions were negligible at 50% and 100% loads and gave different results at 25% load for four speeds; emissions for B100 were higher than diesel. HC emissions were lesser at all operating conditions of the engine except at 800rpm and 25% load on engine. Lesser NO_x emission was lower for B100 than diesel except 800rpm at 50% and 100% load and 1200rpm at 100% load. For diesel and B100 peak cylinder pressure drops from 1.6% to 5.8% for three different engine loads and at speed of 1200rpm. The highest drop of pressure was at 50% loads and it was 5.2% and 5.8% from first peak to second peak. Ignition delay was shorter for B100. Maximum heat release for B100 at 800rpm, 1200rpm and 2400rpm were 4.8%. 1.2% and 4.2% lesser than diesel.

Viramuthu et al. [63] studied performance, emission and combustion characteristics of diesel engine using biodiesel and its blends. Colaphyllum and Inophyllum seed oils were considered as a source of biodiesel in his work. Biodiesel blends B25, B50, B75 and B100 and petroleum diesel were used in testing of engine. BTE of diesel was higher than biodiesel and its blends at lower loads. At higher loads B25 blend were having higher BTE than diesel because better mixture formation for B25 blend. HC and CO emissions were higher for biodiesel and diesel blends for all operating conditions. B25 blend was having lower CO emission than diesel, HC emissions were less at lower and higher loads and higher at mid range loads. NO_x emissions for biodiesel and its blends were lesser than diesel. Smoke density was higher for biodiesel and its blends for all operating conditions of engine. Heat release rate for B25, B50, B75 were higher than diesel fuel. Increased ignition delay contributes to the higher rate of heat release for the blends. Cylinder pressure was higher for B75 blends than diesel and for other blends marginally lower than diesel. Cumulative heat release rate were higher for biodiesel blends than diesel.

M.S.Shehata et al. [64] studied the thermal performance, emission and combustion characteristics of diesel engine fuelled with biodiesel and diesel blends with different injection pressures. Biodiesel considered in their study were Corn and Soybean biodiesel and their blends used and they were C20 and S20 blends. BSFC at higher load and medium load for C20 has lesser than S20 and diesel. BTE of biodiesel blends C20 and S20 were higher than diesel. Engine performance was better with C20 and S20 blends than diesel. For the same operating condition of engine cylinder pressure were higher for C20 blends than diesel and S20 blends because of its higher Cetane number and reduced delay period. Cylinder pressure was higher for diesel fuel at 200 bar injection pressure than C20 and S20 blends. Maximum cylinder pressure was 14-18° aTDC for the fuels tested for all the loads and injection pressure. Increased injection pressure reduces the combustion duration and increases maximum cylinder pressure and heat release rate and 50% heat release were close to TDC.

A. Gharehghani et al [65] studied the combustion characteristics of single cylinder E6 Recardo engine using waste fish oil biodiesel. Higher cylinder pressure lesser heat release for waste fish oil biodiesel compared to diesel fuel. More stable combustion was observed using blends. Higher thermal efficiency and lesser combustion loss were observed for the blends compared to diesel fuel. The CO and HC emissions were reduced for the biodiesel blends compared to diesel fuel. There was increase in CO_2 and NOx emission for the biodiesel blends when compared to diesel fuel.

The outcome of the literature study by various researchers was claimed that BSFC of biodiesel and their blends were higher than diesel for most of the biodiesel blends. Some of the researcher’s were claimed BSFC for B20 blends were less than diesel. BTE of biodiesel B20 blends were higher than diesel, as the percentage of biodiesel increases in the blends BTE decreases. Emissions such as HC and CO were lesser and NO_x, CO_2 were higher. Researchers claimed that smoke opacity were lesser than diesel and higher by some researchers. Cylinder pressure were depends on the type of biodiesel and the volume fraction of the biodiesel and their blends. Ignition delay was lesser for biodiesel and its blends than diesel. Heat release rate were depends on the ignition delay for the biodiesel blends. Increased injection pressure, timing and CR increases BTE, decreases BSFC and reduces CO, HC, and smoke density for blends.

Table-2.3 Summary of literature review on combustion, thermal performance and emission characteristics

Sl.No.	Authors	year	Fuel	Study of TP& EC	Remarks
1	Ekrem Buyukkaya	2010	Rapeseed oils	TP, EC and Comb.	BSFC was higher and BTE was higher for blends than diesel. Emissions of CO, HC smoke was lesser for blends than diesel, NO_x emissions was higher. Peak cylinder pressure and heat release rate was less for biodiesel than diesel; ignition delay was less for biodiesel fuel blends.
2	Agarwal and Dhar	2010	Rice bran methyl esters	TP, EC and Comb.	B20 have higher BSFC than diesel, BTE was higher for B20 at 2400rpm than diesel which was at 1800rpm. CO and smoke was less for B20 blends, NO_x emissions was lesser for B20. Peak cylinder pressure was almost same for diesel and B20, heat release rate was higher for diesel than B20, ignition was earlier for B20 blends than diesel
3	Sukumar Puhan et al.	2010	Jatropha, Coconut, Linseed, biodiesel	TP, EC and Comb.	BSEC was higher for three biodiesel blends; BSEC for LOME was higher than other two methyl esters. BTE was less for LOME was lesser than other two fuels used. CO, smoke was less for blends and NO_x was higher. Higher peak pressure for the blends, heat release rate was almost same with diesel, LOME have higher ignition delay.
4	Rao	2011	Jatropha biodiesel	TP, EC and Comb.	Jatropha biodiesel and pre heated Jatropha biodiesel have higher fuel consumption than diesel; BTE was higher for diesel than two fuels used. HC, CO emission for biodiesel was less, NOx emissions was higher for JBD. Peak cylinder pressure, heat release rate was higher for

Sl.No.	Authors	year	Fuel	Study of TP& EC	Remarks
					JBD than other two fuels, EGT was higher for diesel.
5	Jaichchanrda et al.	2012	Pongamia biodiesel	TP, EC and Comb.	BSFC was better for TRCC than HCC combustion chamber, BTE was less for B20 blends than diesel. BTE was better for TRCC than HCC. CO emissions was reduced for B20, NOx emissions was higher for B20 blends for TRCC than HCC, Peak cylinder pressure, heat release rate was less for B20 blends, peak pressure was higher for TRCC than HCC for diesel.
6	Orkun Ozner	2012	Soybean biodiesel	TP, EC and Comb.	Lesser torque and higher BSFC for the blends than diesel fuel. CO, HC emissions was lesser for blends and NO_x was increased, EGT was lesser for the blends than diesel. Peak cylinder pressure and heat release rate was lesser for biodiesel blends; ignition delay was reduced for blends.
7	D.H.Qi et al.	2009	Soybean Biodiesel	TP, EC and Comb.	Power and torque almost same for biodiesel and diesel, higher BSFC for biodiesel blends, BSEC was closer to diesel fuel, at higher speed BSEC was less for biodiesel. CO, HC and NO_x emissions was less for biodiesel. Peak pressure, heat release, pressure rise was higher for blends.
8	Prabu et al.	2013	Neem oil biodiesel	TP, EC and Comb.	BSFC was higher for B20 and B100 biodiesel than diesel; BTE was less for blend B20 and B100 than diesel. CO and smoke was less for blends than diesel and NO_x emissions was higher. Cylinder pressure was higher for blends than diesel whereas heat release rate was less for

Sl.No.	Authors	year	Fuel	Study of TP& EC	Remarks
					blends.
9	Abhishek Sharma et al.	2013	Tyre Pyrolysis oil with Jatropha methyl esters	TP, EC and Comb.	BTE was better for JMETPO20 than other fuels. BSEC was lesser for diesel followed by JME and JMETPO. CO, HC, NO_x and smoke was less for all the blends. Peak cylinder pressure, heat release rate and rate of pressure rise was less for blends, ignition delay was less for JME.
10	H.An et al.	2013	Waste cocking oil biodiesel	TP, EC and Comb.	Power was higher for B10 blends and B50, B100 power was lesser than diesel. BSFC for B10 was lesser, for other blends it was higher. BTE was higher for all the blends. CO, HC, NO_x emissions was lesser for blends. Peak cylinder pressure and heat release was less for blends.
11	Viramuthu et al.	2015	Colaphyllum, Inophyllum seed biodiesel	TP, EC and Comb.	BTE was higher for diesel fuel than blends; BSFC was less for diesel than biodiesel. CO, HC, smoke density was higher for biodiesel blends than diesel fuel, NO_x emissions was lesser for blends. Peak cylinder pressure and heat release rate was higher for biodiesel blends than diesel.
12	M.S.Shehata et al.	2015	Corn and Soybean biodiesel	TP, EC and Comb.	BSFC was higher for B20 blends of both biodiesels and BTE was higher for blends than diesel. Cylinder pressure was higher for diesel than blends; increased injection pressure increases the cylinder pressure and was higher for blends than diesel.
13	Ayatallah Gharehghani et al.	2017	Waste fish oil biodiesel	TP, EC and Combustion	Higher cylinder pressure and lower heat release were observed for the blends. Thermal performance was improved for the blends. CO, HC emissions were reduced and NOx and CO_2 were higher.

2.3.3 Combustion characteristics of engine

The combustion characteristics were investigated by few numbers of researchers. The detailed study of combustion parameters was very much essential to study the performance and emission characteristics of the engines. In addition to the detailed investigation of combustion characteristics, effect of injection pressure and injection timing were investigated by the number of researchers.

Sinha and Agarwal [66] studied combustion characteristics of transportation diesel engine using rice bran biodiesel and its blends in diesel engine. Different fuels were used in testing were diesel B00, blends B10, B20, B100 biodiesel at speed different speeds and the pressure variation were measured for 50 cycles. Peak pressure was higher at low loads for biodiesel blends than diesel. At higher loads peak pressure were higher for diesel than biodiesel Heat release rate were higher for diesel than biodiesel and its blends. Cumulative heat release was higher at lower engine loads for biodiesel and its blends than diesel fuel. 5% mass fraction burned for biodiesel and its blends were earlier than diesel. Whereas 90% mass fraction burned was earlier for diesel than biodiesel with increased load on engine Increased engine load increases combustion duration for all the fuel used and increases with increased volume fraction of biodiesel in the blends. Sinha and Agarwal [67].

P. K. Sahoo and L.M. Das [68] studied combustion analysis of using three type biodiesel and its blends in diesel engine biodiesel considered are Jatropha, Karanja, and Polanga. Peak cylinder pressure and heat release rate were analyzed at zero load, half load and full load of engine they gave very similar results for all the blends and diesel fuel. For full load peak pressure for three fuels are higher for B100, B50, and B20 fuel than diesel fuel. Heat release rate of biodiesel and its blends were lower than diesel fuel was because of reduced ignition delay for biodiesel and its blends makes less intense burning of biodiesel fuel in premixed combustion stage than diesel. Increased delay period of diesel accumulate more fuel during premixed combustion stage increases the heat release of diesel fuel than biodiesel. Biodiesel were not derived from petroleum fuel opposite trend were observed for biodiesel and its blends. Ignition delay was shorter for JB100 4.2°, for KB100 4.5° and for PB100 4.2° lesser than diesel fuel. Complex chemical reaction with biodiesel and its blends releases gases of volatile combustion compounds and ignites earlier that reduces the delay period.

Gumus [69] studied combustion characteristics of hazelnut biodiesel and diesel blends in diesel engines. Comprehensive investigation of different combustion parameters were carried out varying volume fraction of biodiesel in the blends, engine load, injection pressure, injection timing and compression ratio of engine. Cylinder pressure was higher for diesel than biodiesel and its blends. Cylinder pressure was reduced with increased volume fraction of biodiesel in the blends and peak pressure move away from TDC. Modification of injection timing, injection pressure, compression ratio increases the cylinder gas pressure. Maximum cylinder gas pressure was for B00 at engine load of 20 Nm and for CR20. Minimum cylinder gas pressure was for B100 for engine load of 10 Nm for injection timing of 15°. Increasing CR was the most effective method to improve the cylinder gas pressure. Rate of pressure rise were lower for biodiesel and its blends than diesel because of lesser ignition delay and lesser premixed combustion of biodiesel and its blends. Increasing injection pressure, injection timing and compression ratio improve combustion rate, increases fuel burned in premixed combustion and increases rate of heat release. Higher Cetane number ignites the biodiesel blends earlier and reduces ignition delay.

Nicati and canakci [70] studied combustion, injection and performance of engines using blends of biodiesel and diesel. Two types of biodiesel were considered canola, waste (frying) palm oil were converted in to their methyl esters and used in engines testing. Full load combustion characteristics were obtained for canola oil methyl esters and palm oil methyl esters at different speeds of engine. Cylinder gas pressures were higher for COME fuel than WPOME and diesel, because of higher BSFC and higher

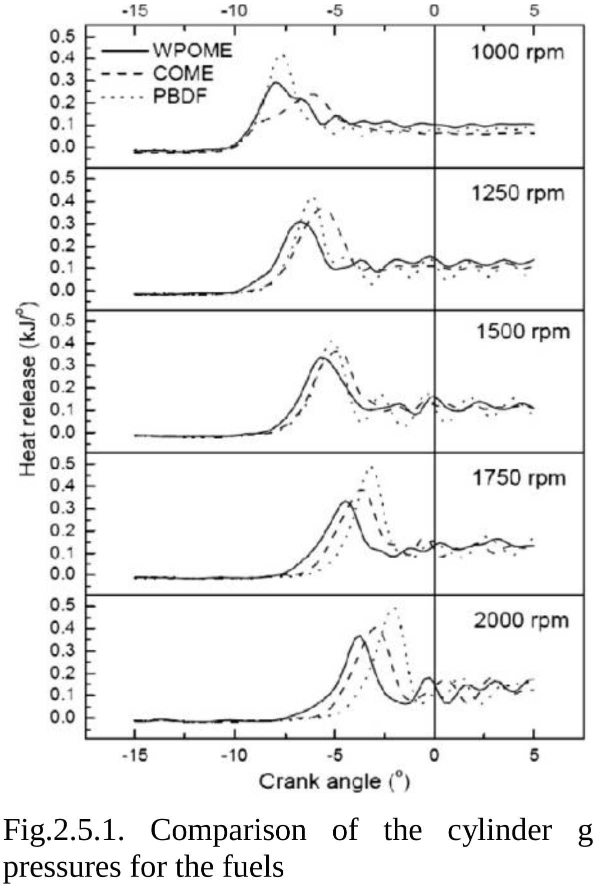


Fig.2.5.1. Comparison of the cylinder gas pressures for the fuels

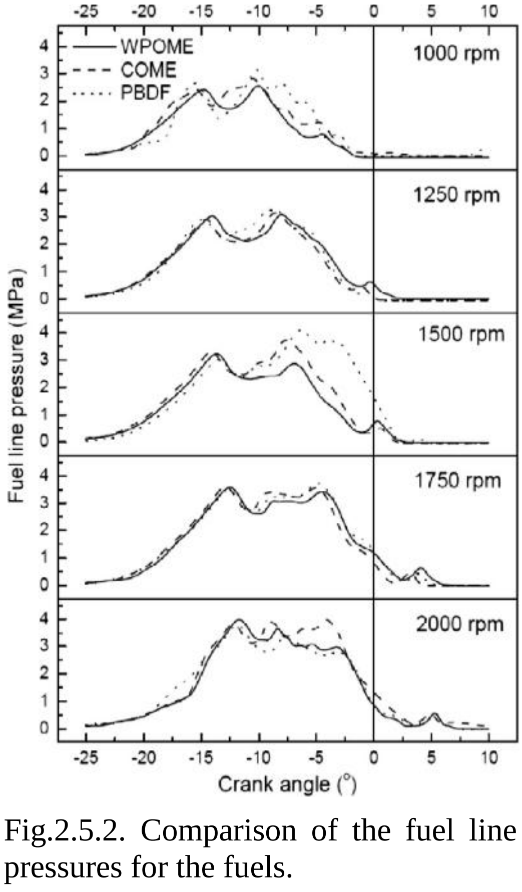


Fig.2.5.2. Comparison of the fuel line pressures for the fuels.

Cetane number, oxygen content and early start of injection with biodiesel fuels. Peak pressure was occurring at earlier crank angle degree for COME than WPOME and diesel fuel. Heat release rate were indicating rapid release of heat during premixed combustion phase for all the fuels used in the tests. Another parameter considered were ignition delay in combustion process which were lesser for WPOME and COME than diesel fuel.

Brake specific fuel consumption was higher for both biodiesel and their blends than diesel fuel. Higher BSFC for biodiesel fuel were because their lesser energy content of biodiesel fuel considered for the tests. BTE was lesser for biodiesel than diesel. CO, HC, and smoke opacity emissions were lesser for biodiesel fuels than diesel. NO_x and CO_2 emissions were higher for biodiesel fuel than diesel.

B. Tesfa et al. [71] studied the effect of biodiesel type and properties on the engine combustion performance and emission characteristics. Experimental investigations were carried out on four cylinders, four strokes, turbocharged, direct injection diesel engine coupled to AC dynamometer. In this investigation three types of biodiesel, rape seed oil, corn oil and waste oil were considered. Cylinder pressure was increased with increasing engine speed. Cylinder pressure was higher for ROB and COB than diesel. Engine running with WOB shows the inconsistent variation in cylinder pressure for all the engine speeds. Variation of fatty acids in WOB has non uniform combustion characteristics for different operating condition of engines. Neat biodiesel has higher peak cylinder pressure than diesel. At lower engine loads cylinder pressure for diesel were higher than biodiesel because of less quantity of fuel injected at lower loads. Heat release rate were higher for biodiesel than diesel. Cumulative heat release rate for biodiesel blend B50 was higher than diesel at all loads. B50 has better combustion than B100.

BSFC was higher for biodiesel and their blends than diesel. At lower engine speed BSFC were higher because of more heat were lost during combustion in cooling.

Harun Mohamed Ismail et al. [72] studied the difference in the combustion characteristics of diesel and biodiesel. Three types of methyl esters were considered for the study are coconut, palm and soybean methyl ester. Experimental investigations were carried out using three biodiesel blends in different proportions as B0, B50 and B100 constant speed on diesel engine. Bowl in piston type light duty diesel engine having CR19 with variable speed coupled to asynchronous dynamometer. Computational mesh and codes were used for simulation of the combustion characteristics of engine. Six types of fuels were considered for testing B50 and B100 of CME, PME and SME. Cylinder pressure of experimental values and calculated values using the modules and they were

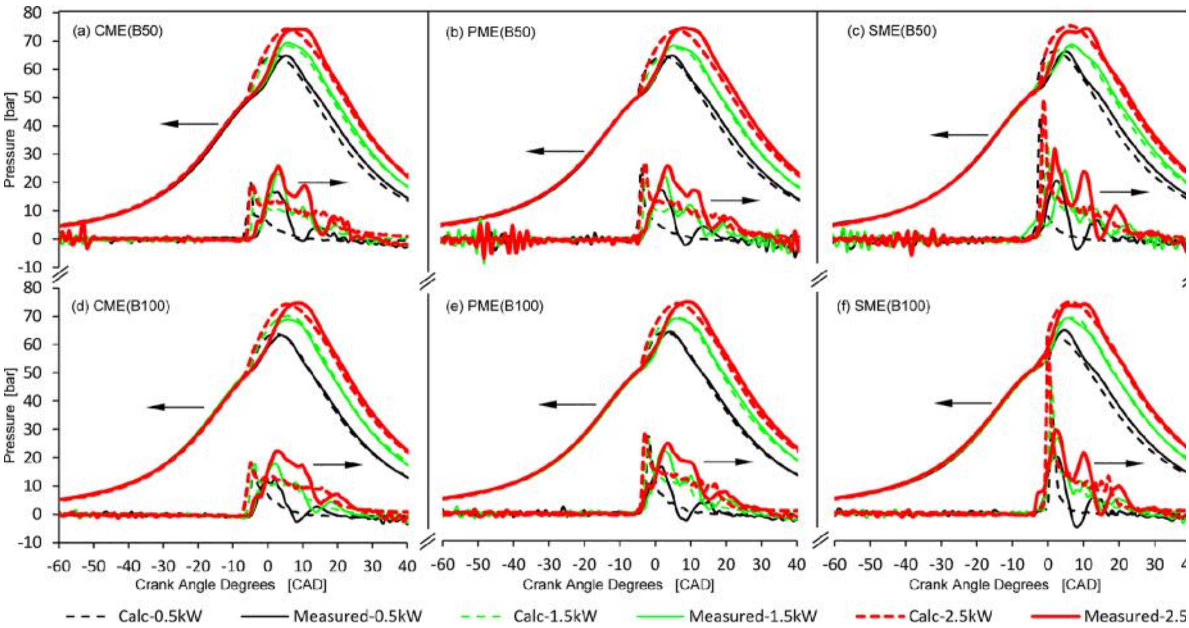
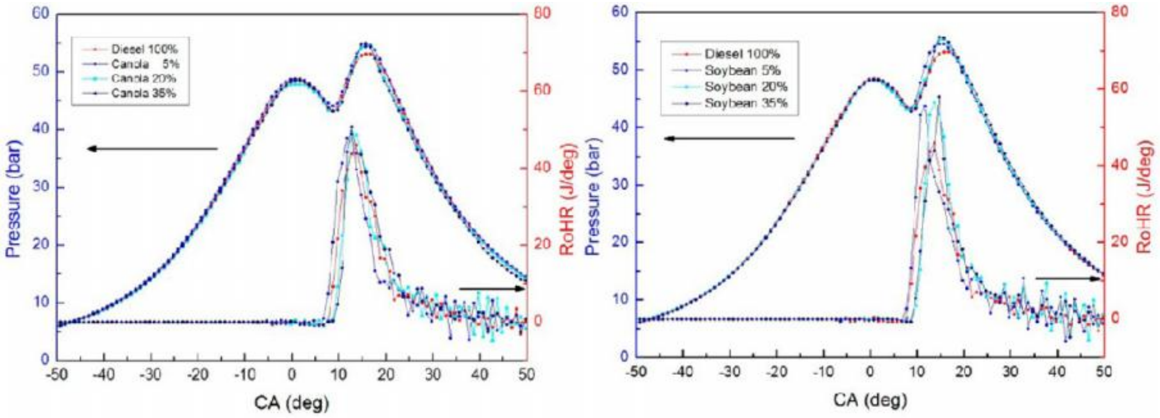


Fig.2.5.2. Pressure traces and HRRs for low, medium, and high loads at 2000 rpm for (a) CME (B50), (b) PME (B50), (c) SME (B50), (d) CME B100), (e) PME (B100), and (f) SME (B100).

compared, were in good agreement for premixed combustion and mixing controlled combustion for all the fuels for the engine speed of 2000 rpm. Ignition delay and peak pressure were accurately predicted for all the loads. Ignition delay was lesser for B50 blends of CME, PME, and SME than diesel. Heat release rate for premixed combustion were longer significantly for biodiesel blends at low load than medium load and high loads More amount of heat was released in mixing controlled combustion when loads were changed from low to high loads for all the fuel blends.

Hyungik Kim et al. [73] studied spray, combustion and emission characteristics of soybean and canola biodiesel fuels. Two biodiesel considered for the tests were mixed with diesel in the volume fraction of 5%, 20% and 35% and totally there were six fuel blends and petroleum diesel used in engine testing. Spray uniformity and atomization were analyzed using the designed spray visualization device to simulate the temperature and pressure in the cylinder. Temperature and pressure were controlled by electronic heater and N_2 gas respectively. High speed camera with xenon lamp as light source was used for visualization of spray and penetration. Seven hole injector placed at 148° apart were used. Temperature was 60° C maintained while carrying out the spray of fuel. Injection delay for diesel was less than biodiesel and distribution at each hole was regular. 5% canola blends with diesel show the similar results as diesel. 20% and 35% blends show small difference than diesel. Combustion visualizations were measured with crank angle. Both the biodiesel were having higher peak pressure and heat release rate than diesel is shown in figure 2.5.4. For 5% soybean and canola biodiesel ignition were advanced compared to diesel. NOx emissions were higher and CO emissions were lesser for biodiesel than diesel. THC was less because of less impingement of biodiesel fuel due to shorter penetration.



(a) Diesel and Canola (b) Diesel and Soybean

Fig.2.5.4. Combustion pressure and RoHR for different fuel types.

Muhammad Islam et al. [74] studied the biodiesel properties and effect of blends of methyl esters and diesel on combustion characteristics. Experimental investigation were carried out using four cylinders, direct injection turbocharged diesel engine using microalgae methyl esters. Different methyl esters used were D90A10, D80A20, and D50A50, waste cocking oil methyl esters D80WC20 and diesel. Peak cylinder pressure was higher for diesel at 25% of loading than other blends. Waste cocking oil methyl esters was having higher pressure for 50% and for 100% load. Diesel was having higher heat release rate than microalgae and waste cocking oil biodiesel for 25% load. The difference in heat release rate was eliminated with increased load. As load increases BSFC of diesel were lower than biodiesel, BSFC of D50A50 were highest and other biodiesel blends were almost similar and higher than diesel. For 50% and above loads BTE for diesel was higher than biodiesel and its blends. NO and NO_x emissions were higher for biodiesel than diesel except for D90A10 lesser emissions of NO_x than diesel. Unburned HC were less for algae fuel blends and for waste cocking biodiesel it was same as that of diesel.

Wood et al. [75] studied the combustion and performance of biodiesel as fuel for motorsports engine. Methyl esters from rapeseed, soybean and sunflower were used along with EN590 diesel for comparison. Automotive engines were used for the tests with B100 soybean; beef tallow B50 and diesel EN590 to know the performance. Tests were carried out at 2000rpm speed depressing the accelerator by 63% this speed gave accurate measurements. B80 blend of soybean methyl esters gave torque of 26.4 Nm between the speed of 2390 to 2510rpm and at 2800rpm gave maximum power of 7.5 kW. Rapeseed B80 blends produced maximum torque at lesser speed than other fuels used and it was 25.3 Nm at 1860rpm and maximum power of 6.8 kW at 2810rpm. B80 sunflower oil methyl esters gave torque output of 25.68 Nm at 1870rpm and maximum power of 7.1 kW at 2850rpm. Fuel consumption for two different fuels was shown in figure with their heating values. Difference in the maximum torque and power were 7.76% and 10.30% respectively. The second engine was used in testing was under electronically controlled; it was more accurately controlled and used for motorsports. Requirement of motorsports engine were to get higher speed which was possible with biodiesel because of improved quality combustion than diesel. The reason for considering B50 for beef tallow was it gets solidified at lower temperature. The tests were carried out at 2000rpm speed of engine, for this speed ignition delay in seconds can be obtained. B100 was having shorter ignition delay followed by B50 and EN590 diesel. Higher viscosity of B100 has increases ignition delay. 0.1 milliseconds (ms) ignition delay was seems too insignificant but in terms of crank angle at 2000 rpm was 12°/ms.

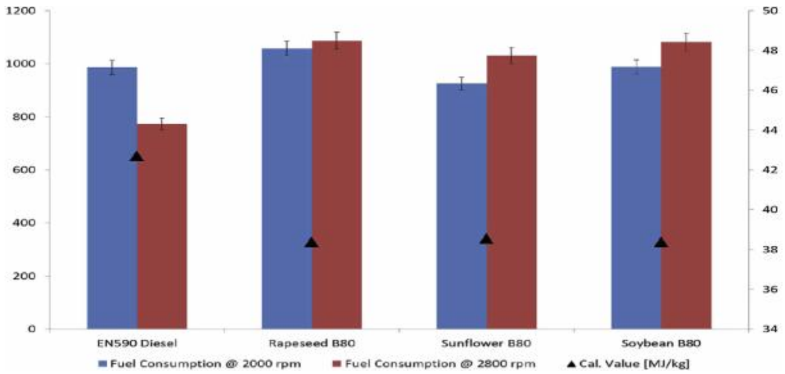


Fig.2.5.5. Comparison of fuel consumption and gross calorific values.

R. SenthilKumar and M. Loganathan [76] investigated the combustion characteristics of CI engine using the blends of biodiesel with diesel. The heat release decreases for the blends compared to diesel fuel. The cylinder pressure is higher for the blends. Ignition delay for the blends decreases. Combustion duration increases with increase in load for the blends with increase percentage of biodiesel in the blends. Cumulative heat release increases for the blends. The rate of pressure rise increases for the blends compared to diesel.

The outcome of the above literature reviews show that the peak cylinder pressure for biodiesel blends was higher than diesel fuel. Some of authors claim the contrary. Similar observations were noted with respect heat release rate and rate of pressure rise. All researchers reported that injection and ignition were advanced for biodiesel blends than diesel. Increasing injection pressure, injection timing and CR increases the peak pressure, heat release rate, rate of pressure rise and reduces combustion duration for both blends and diesel.

Table-2.4 Summary of literature review on combustion characteristics

Sl.No	Authors	year	Fuel	Type of study	Remarks
1	Sinha and Agarwal	2006	Rice bran Methyl ester	Combustion characteristics	Peak pressure was higher for B20 blends than diesel at zero loads and was higher for diesel at rated load. Heat release rate was lesser for B20 than blends. Ignition delay was less for B20. 90% mass fraction burned was earlier for diesel than biodiesel.
2	Sinha and Agarwal	2007	Rice bran Methyl ester	Combustion characteristics	Peak pressure was higher for B10, B20 B100 fuels than diesel at lower loads and less at higher load than diesel fuel. Heat release for biodiesel blends was lesser than diesel. Ignition delay was less for blends and combustion duration was higher for blends.
3	P. K Sahoo and L.M. Das	2009	Jatropha, karanja, and Polanga oil biodiesel	Combustion characteristics	Peak cylinder pressure and heat release rate was higher for B20, B50, B100 fuels than diesel. Maximum heat release was earlier for the blends. Increased volume of biodiesel in the blend reduces the heat release rate. Start of combustion was advanced for biodiesel blends.
4	Gumus	2010	Hazelnut biodiesel	Combustion characteristics	Peak cylinder gas pressure was higher for diesel than biodiesel blends. Changing injection pressure, angle and CR peak pressure increases for diesel than biodiesel at 20Nm load. Rate of pressure rise and heat release was less for biodiesel blends; heat release rate was lesser for the blends at all CR and injection pressure and injection timing. Ignition delay was lesser for blends.
5	Nicati and	2011	canola,	Combustion	Peak cylinder pressure was higher for COME than diesel and WPOME and

Sl.No	Authors	year	Fuel	Type of study	Remarks
	canakci		waste palm oil	characteristics	earlier crank as well. Injection starts earlier for biodiesel blends than diesel due to higher bulk modulus of biodiesel. Ignition delay was less for biodiesel fuel.
6	B.Tesfa et al.	2013	Corn, waste oil biodiesel	Combustion characteristics	Peak pressure, heat release rate, rate of pressure rise was higher for the blends than diesel fuel. At lower loads heat release rate was higher for diesel.
7	Harun Mohamed Ismail et al.	2013	coconut, palm and soybean oil biodiesel	Combustion characteristics	Six fuels were analyzed for experimental and computation data they were in agreement with each other. Ignition delay was reduced for B50 blends than diesel fuel. Heat release rate was longer at low loads than medium and higher loads. Biodiesel burns slower than diesel fuel.
8	Hyungik Kim et al.	2013	soybean and canola biodiesel	Combustion characteristics	Quantity of fuel injected was varies with injection pressure and injection timing. Biodiesel blends was having higher peak pressure and heat release rate. Even 5% of biodiesel in the blends advance the ignition.
9	Muhammad Islam et al.	2015	Microalgae and waste cocking oil methyl ester	Combustion characteristics	Peak pressure was higher for diesel at 25% load; WCOME has peak cylinder pressure at 50% and 100% load than diesel. Heat release rate at 50% and 100% loads was comparable for diesel and biodiesel blends. At rated load WCOME has higher heat release rate than diesel fuel.
10	Benjamin M.	2015	Rapeseed,	Combustion	Peak pressure was higher with advanced injection timing for both the fuels,

Sl.No	Authors	year	Fuel	Type of study	Remarks
	Wood et al.		Soybean, Sunflower	characteristics	i.e. at 11° bTDC, this inject more fuel for combustion and increases peak pressure. Peak pressure was different for different injection angles.
11	Senthil Kumar and Loganathan	2016	Corn biodiesel	Combustion, characteristics	The cylinder pressures were higher for the blends and heat releases were lesser for the blends compared to diesel fuel. Ignition delay decreases for the increased in load. Maximum cylinder pressures were higher for the blends. The rate of pressure rise was higher for the blends. combustion duration increases with increase in engine load.
12	H. V.Pali and N.Kumar	2016	Sal methyl ester	Combustion, and emission characteristics	The cylinder pressures and heat release were lower for the blends compared to diesel. The pressure rise rates were higher for the blends and combustion duration decreases for the lower blends and increases for the higher blends.

2.3.4 Thermal performance and emission characteristics of VCR engine

Few researchers worked on VCR engine to study the performance, emission and combustion characteristics of engine. Compression ratio is one of the main variables of the engines affecting the performance and emission characteristics. Hence the details of some reviews in this study are as below

Raheman and Gadage [77] studied performance of diesel engine using biodiesel fuel varying the compression ratio of engine and ignition timing. Experimental investigations were carried out on constant Ricardo E6 engine, varying the compression ratio from 18-20. The other parameters varied during the tests were blends, injection timing and loads. Mahua oil biodiesel and is blended with diesel. B20 blends were having lower BSFC than high speed diesel. For any combination of blends IT and CR B20 blend has lesser BSFC than that of HSD. Increasing biodiesel in blend beyond 40% effect was negated. At full load conditions, increase in CR 18 to 20 reduces BSFC of biodiesel and its blends. Advancing injection timing 35° to 45° bTDC BSFC was reduced by 15.8% for blends than diesel fuel and 11% when advanced 40° bTDC. Advancing IT combustion initiates earlier and more fuel burned before TDC peak pressure were close to TDC. Advancing IT by 5° reduces the fuel consumption for all CR used in the tests. Further advancement by 5° reduces BSFC by another 5% for CR20, the same trend even CR 18 and 19. BSFC at full loads were reduced by 60% than part load operation. Advanced injection timing increases the BTE. Advancing injection from 35° to 40° increases BTE by 13.7% and further 45° increases BTE by 4.7%.

Reduction in EGT was 23% when CR was increased from 18 to 20. Exhaust gas temperature decreases continuously as IT was advanced 35° to 40° and to 45° bTDC. Increasing injection advance was depends on CR, CR18, advance in IT from 35° to 40° was reduces EGT by 4.7%, further advance from 40° to 45° reduces EGT by 8.9%.

S. Jindal et al. [78] studied the effect of compression ratio and injection pressure injection timing on direct injection diesel engine using Jatropha methyl esters. Compression ratio were varied from 16 to 18, compression ratio below16 gave poor performance of the engine. BSFC for Jatropha biodiesel was higher than diesel and decreases with increase in compression ratio for both the fuels, because of increase in brake power at higher compression ratio. Injection pressure affects BSFC significantly; lowest BSFC was obtained at 200 bar injection pressure up to 50% load and 250 bar for higher loads. It was found that CR 18 at 250 bar injection pressure gave minimum BSFC for all the loads. BTE for diesel was higher than B100 fuel at all the loads and at CR18 BTE increases by

5.5%. Combination of CR and IP gave better BTE were CR18 at injection pressure of 250 bars improve BTE by 8.2% higher than standard engine settings.

Emissions were measured at full loads only for B100 and diesel. Smoke opacity was lesser for B100 than diesel whereas CO and CO_2 emissions were increased at standard engine settings. HC was reduced by 50%, NO_x by 25% and EGT by 10% and smoke opacity by 20%. CO and CO_2 emissions were increased by 38% and 2%. Lowest HC emission was CR17 with injection pressure 200 bars. Increases in CR decreases CO emissions and smoke opacity whereas increased IP for given CR, CO emission increases and smoke opacity decreases. Higher NO_x emissions were obtained for CR at lower IP. Performance of engine was improved with increased CR and IP, with increased emissions.

Cenk Sayin and Metin Gumus [79] studied the performance of and emission characteristics of direct injection diesel engine and influence of CR, injection pressure and injection timing using biodiesel and diesel blends. Experiments were carried using preset condition by manufacturer of the engine, i.e. CR18, 20 MPa, 20° bTDC. Performance and emission analysis for different fuels used in the tests at 20 Nm engine torque at 2200 rpm. NO_x emissions increase with increased compression ratio for 17, 18 19, and with increased volume fraction of biodiesel in the blends. Increased injection timing increases the NO_x emissions. Increased compression ratio, IT and injection pressure decreases the smoke opacity and HC emissions for B20 blends compared to original engine settings. CO emissions were reduced with increased biodiesel percentage in the blends. Increased CR, IT and reduces CO emissions compared to original engine settings.

BSFC was increased with increased percentage of biodiesel in the blends. Increased CR decreases BSFC for B50 blend compared to diesel and original engine settings. Increase in CR, increases the maximum cylinder pressure and decreases BSFC. Increased and decreased IT increases BSFC compared to original engine settings. BTE decreases with increase in biodiesel volume fraction in the blend. Increase in CR and IP increases the BTE due to improved combustion. Increased injection timing reduces the BTE of biodiesel and its blends than diesel. BSEC was higher for biodiesel and its blends than diesel. Increased injection pressure gave good result for BSFC, BTE and BSEC than original engine settings and reduces emissions with increased NO_x.

H.K. Amaranath and P. Prabhakaran [80] studied the performance emission characteristics of engine using blends of Karanja biodiesel and diesel. BSFC increases with Karanja biodiesel and its blends. For CR18 and IP 200 bar were almost close to diesel fuel. B100 (100% pure Karanja biodiesel) was having 9% higher BSFC than diesel fuel. Increase in CR decreases BSFC for all the blends and the loads; decrease in BSFC was 15 to 20% for all the fuels. BSFC was higher for B100 at CR14 and at no load. Increased injection pressure reduces BSFC because of increased IP. BTE of biodiesel blends B20 and B40 were higher than diesel fuel at all the loads than diesel. For other blends BTE was lesser at all the loads. Increased compression ratio increases the BTE of all the fuels used in testing. CR 18 gave highest BTE for all the fuels. Diesel has maximum BTE at all the CR was considered in the investigation. B100 fuel has least BTE at all CR and IP. There was not much difference in the EGT of different fuels used in the tests. EGT were lesser for biodiesel than diesel at all the loads.

Increased CR and IP reduce smoke opacity for all the fuels used. Increase of CR from 14 to 18 there was reduction in smoke density by 45%. CO emissions were less for biodiesel blends than diesel at all the loads and increased CR and IP reduces CO. NO_x emissions were higher for biodiesel and its blends at all the loads. With increase in compression ratio above 17 increases NO_x emissions and were more than diesel. NO_x emissions were increased with increased in IP. HC emissions were lesser for biodiesel and its blends for all the loads than diesel.

Mohammad and Medhat [81] studied the performance and emission characteristics of diesel engine using blends of Waste cocking oil biodiesel and diesel fuel. Tests were carried out for thee compression ratio 14, 16 and 18. Torque was higher for diesel than biodiesel blends at all the speeds and for all compression ratios. Increase in percentage of biodiesel in the blends decreases torque of engine, and increasing compression ratio increases the torque. Increased compression ratio performs better for biodiesel blends because of improved combustion for biodiesel blends. BTE of biodiesel blends was lower than diesel and decreases with increased percentage of biodiesel in blends. BTE for B20 blends was higher than diesel at CR18. BTE increases with increase in compression ratio; improvement in BTE was 18.5% when CR was increased from 14 - 18. CO emissions were lower for biodiesel than diesel, increased volume fraction of biodiesel in blends increases in CO emissions. HC emissions were also lesser for biodiesel blends than diesel fuel. There was 37.5% reduction in CO emissions when CR was changed from 14 to 18 for the blends B30. NO_x emissions were higher for all the biodiesel blends than diesel and for all compression ratios. Increased compression ratio increases NO_x emissions, 36.8% increase in NO_x emission when CR changed from 14 to 18. Cylinder pressure was higher for biodiesel blends than diesel at all the speeds and compression ratio. Cylinder pressure increases with increased percentage of biodiesel in blends. Delay was consistently lesser for B50 blends. 13.9% decrease in delay was observed when CR changed from 14 to 18. Dawoody and Bhatti [82] studied the effect of compression ratio on performance emissions and combustion characteristics of diesel engine using blends of soybean biodiesel and diesel blends. Standard compression ratio set for the engine was 17.5 and tests were carried out for different compression ratios 15, 16, 17.5 and 19 for the engine. Different fuels for tests were soybean biodiesel and diesel blends B20, B40, B100. Diesel-rk software was used for calculation and optimization of the internal combustion engines and also it is a tool for multi parameter optimization. Experiments were carried out at constant speed of 1500 rpm at 220 bar injection pressure at 20° CA before TDC injection timing at various compression ratios. Results obtained from simulation software Diesel-rk. Increased compression ratio increases HC emissions. CO emissions decrease with increased volume fraction of biodiesel in the blends and with increased compression ratios for biodiesel and its blends. NOx emissions were higher for biodiesel and its blends at all compression ratios than diesel. Smoke opacity was lesser for biodiesel and its blends than diesel. In this study experimental results were compared with the calculated values using Diesel-rk software, these two results were in better agreement with each other. The higher cylinder pressure ensures better combustion and heat release. Cylinder pressure for B20 SME blends were increases as result of increasing compression ratio 15-19 by 37.45%. Supriya Chavan et al. [83] studied the emission characteristics of VCR engine using blends of biodiesel and diesel. Synthesized Jatropha oil was used to carry out the tests. The different blends were used in engine testing and were called JB00, JB10, JB20, JB30 and JB100. HC emissions for biodiesel blends were lower up to 6 Kg load, for compression ratio of 15 and 16. Compression ratio has different effect on HC emissions at higher loads diesel fuel was having lesser HC emissions for CR 14 to16. For CR17 it was JB30 was comparable with diesel fuel. At CR18 HC emissions were lowest for 6-12 Kg loads for biodiesel blends. NO_x emissions were increased with increased volume fraction of biodiesel in the blends. NO_x emissions were lower at every CR except CR18 and CR15, for these CR NO_x were higher for JB100 and JB30 than diesel fuel. CO emissions were lowest at loads 9 kg and 12 Kg, CO emissions for diesel fuel were comparable with biodiesel blends for every compression ratio. At CR 18 all blends and diesel emission of CO were almost similar, therefore at higher CR effect of load and blend ratio can be ignored for CO emissions. For JB30 blends shown least emissions of CO at CR 14, 15 and 16. Increasing CR 14 to 17 CO emissions for JB30 blends were lower at higher loads.

Amarnath et al. [84] studied the thermal performance and emissions of DI diesel engine using Karanja and Jatropha methyl esters as alternate fuel for diesel engines. Brake specific fuel consumption of for both biodiesel and their blends was higher than diesel fuel. Increases in injection pressure decreases BSFC for all the fuels. BTE increases with increase in compression ratio; it is highest for CR 18 for the fuels used in the engine testing. BTE increases with increase in IP increase in IT. Exhaust gas temperature increases with increase in torque. CO emissions for both biodiesels were lesser than diesel. Increased compression ratio and injection pressure decreases the CO emissions. NO_x emissions were higher for biodiesel than diesel. Increased CR and IP reduce the HC emissions. Smoke opacity was higher for both biodiesel than diesel.

Mohit Vasudev et al [85] studied the performance and exhaust emissions of VCR engine using crude methyl esters of rice bran oil. Average decrease in BSFC were 18.75%, 18.97%, 18.28% and 18.42% respectively for B10, B20, B40 and diesel with increased compression ratio from 15 to 18. Decrease in BSFC was higher for biodiesel blends than diesel fuel except B40 with increased compression ratio. BTE of biodiesel blends B10, B20 were slightly lower than diesel. Average increase in BTE was 14.21%, 16.44%, 13.56% and 14.43% respectively for B10, B20 B40 and diesel fuel, when compression ratio changed from 15 to 18.

Average reduction in HC emissions for B10, B20, B40 and diesel fuel were 37.42%, 42.83%, 41.17%, 31.8% and 37.42% respectively when CR changed from 15 to 18. Average reduction in CO emissions for B10, B20, B40 and diesel fuel were 22.54%, 24.46%, 20.22% and 21.9% respectively when CR was increased from 15 to18. Average increase in NO_x emission for the blends B10, B20, B40 and diesel was 24.71%, 31.96%, 18.26% and 16.11% respectively with increased CR from15 to18. For CR15 peak pressure for diesel was 55.98 bars at 11° aTDC, for biodiesel blends B10 and B20 was 57 bars, 56.7 bars respectively at 8° aTDC. When CR was increased from 15 to 18 the increase in cylinder pressure was 17.04%, 16.44%, 9.98% and 16.75 for B10, B20, B40 and diesel.

Biswajit De and R.S. Panau [86] studied the performance and emission characteristics of VCR engine using Jatropha biodiesel with diesel blends. The effect of CR on fuel consumption and cylinder pressure and emissions were investigated. The results were better at CR18 with improved thermal performance, reduced emissions without modification to existing diesel engine with 30% Jatropha biodiesel with diesel blend (B30).

B. Singh and S.K. Shukla [87] investigated the combustion characteristics of engine using castor biodiesel and diesel blends using VCR engine. The mean gas temperature increases with increase in compression ratio and were higher for diesel fuel. The cylinder gas pressure increases with increase in CR and were higher for the blends. The maximum cylinder pressure for the lend B50 at CR18. The net heat release decreases for the blends and is higher for diesel fuel at CR15. The mass fraction burned is better for B20 blend and comparable with diesel. Combustion duration increases with increase in volume fraction of biodiesel in the blends.

The outcomes of the above literature review were that with increase in CR, IP and IT BSFC reduces and increases the BTE for all the biodiesel blends and diesel. Emissions such as CO, HC, smoke reduces and NO_x increases. Increased CR, IP and IT were improving every parameter of engine performance and reducing emissions for biodiesel than diesel except for NO_x. Peak cylinder pressure, heat release rate, rate of pressure rise increases with increase in CR.

Table-2.5 Summary of literature review on thermal performance, emission and combustion characteristics of VCR engines

Sl.No.	Authors	year	Fuel	Type of study	Remarks
1	Raheman and Gadage	2008	Mahua oil	TP	BSFC for B20 blends was lesser than diesel, increased % biodiesel beyond 40% increases BSFC of blends. Increasing CR 18 to 20 reduces BSFC of the blends. Advancing timing from 35° to 45° reduces BSFC by 15.8% for biodiesel than diesel and 11% when it was 40°. Advancing timing from 35° to 40° increase BTE by 13.7% for biodiesel and 4.7% advanced to 45°.
2	S. Jindal et al.	2009	Jatropha methyl ester	TP and EC	Combination of CR18 and 250 bars gave least BSFC at all the loads. BTE of diesel was higher than B100, CR18 and 250 bars gave 8.2% higher BTE than standard setting. CO, CO_2 increased for standard setting, NO_x, HC, smoke was reduced.
3	Cenk Sayin and Metin Gumus	2011	--	TP and EC	Biodiesel blends increases BSFC, BSEC and NO_x while BTE, CO, HC, smoke opacity decreases for standard setting of the engine with increased % of biodiesel in the blends. Increased CR, IP, IT reduces BSFC, HC, CO, smoke opacity and increases NO_x emissions.
4	H.H. Amaranath and P. Prabhakaran	2012	Karanja biodiesel	TP and EC	With increased CR, IP, IT BSFC reduces for the blends and BTE increases. With increased CR 14 to 18 decreases BSFC and increases BTE and reduce CO, HC, smoke opacity and increases NO_x emissions.
5	Mohammad and Medhat	2014	WCOME	TP, EC and Combustion Charact.	BSFC was higher for biodiesel blends and BTE was reduced for blends than diesel. Increased CR reduces BSFC and increases BTE of biodiesel blends than diesel for B20. CO, HC emissions was reduced increase in

Sl.No.	Authors	year	Fuel	Type of study	Remarks
					NO_x emissions. Cylinder pressure was higher for all CR for biodiesel blends.
6	Dawoody and Bhatti	2014	Soybean biodiesel	TP, EC and Combustion Charact.	BTE was less for biodiesel than diesel and reduces further with increased % of biodiesel in the blends. HC, CO, smoke was reduced for biodiesel than diesel and NO_x was increased. Increased CR 15 to 19 increases cylinder pressure by 37.45 %. Heat release rate increases with increase in CR.
7	Supriya Chavan et al.	2015	Jatropha biodiesel	EC	HC and CO emissions were less for biodiesel blends decreased further with % increase in biodiesel and CR reduces HC emissions for blends and diesel fuel. NO_x emission was increased with increased CR and increased % of biodiesel in the blends. CO emission was least for JB30 at CR 14, 15,16.
8	H.K.Amarnath et al.	2012 and 2015	Karanja & Jatropha methyl esters	TP and EC	CR18 gave least BSFC for all the fuel used. BTE was less for biodiesel blends than diesel at all CR. BTE increases with IP, IT and CR for all the fuels. EGT was less for biodiesel. CO, HC emission reduces at higher CR, increases at lower CR. NO_x emissions was higher for biodiesel blends.
9	Mohit Vasudev et al.	2016	Crude rice bran oil	TP, EC and Combustion Characteristics.	Increase in CR reduces BSFC of all the blends and diesel fuel. BTE was higher for B10, B20 blends than diesel. HC, CO emission decreases with biodiesel blends than diesel and NO_x emission increases. Peak cylinder pressure was higher for B10, B20 blends than diesel.

Sl.No.	Authors	year	Fuel	Type of study	Remarks
10	Biswajit De and R.S. Panau	2016	Jatropha biodiesel blends	TP, EC and combustion characteristics	Improved thermal performance and reduced emissions at CR18 for the blends as well as diesel fuel. The 30% blend gave the better results for the thermal performance and emission characteristics of the engines.
11	B. Singh and S.K. Shukla	2017	Castor biodiesel	Combustion characteristics	Mean gas temperature increases for diesel fuel compared to the blends. Cylinder pressures were higher for the blends compared to diesel fuel. The cylinder pressure is higher for B50 blend at CR18 compared to diesel. The mass fraction burned for B20 blends were comparable with diesel. Combustion duration increases for the blends.

2.3.5 Performance and emission characteristics of engines using blends two biodiesels and diesel

In this part of literature review two biodiesels are blended in various volume percentages with diesel and used in investigation of engine performance and emission characteristics. Researchers used mixture of two different biodiesels with diesel and used in engine tests.

H.Yogesh et al. [88] studied thermal performance and emission characteristics of engine using the blends of two biodiesel and diesel. Biodiesels were produced by mixing two vegetable oils namely Jatropha and Pongamia and they are named as M1(J90+P10), M2(J80+P20), M3(J70+P30), M4(J60+P40), and M5 (J50+P50). Blends of biodiesel and diesel were prepared and they were B10, B20, B30, B40 and B50. Experimental investigations were carried out at two injection pressures 160 bars and 180 bars for different mixture blends for 300 trials. Fuel consumption for composite biodiesel blends was 20% lower than diesel for 180M4B20. The values were 0.48 Kg/hr for M4B20 blends and it was 0.6 Kg/hr for diesel at 180 bar injection pressure at full load. BSFC for diesel at 160 bar and 180 bar injection pressure were 0.23 kg/kWh and 0.25 Kg/kWh respectively. Whereas for biodiesel blends M4B20 it was 0.19 Kg/kWh at 180 bar injection pressure at full load was minimum compared to diesel and other blends. BTE for M4B20 were highest 45% at 180 bar injection pressure and 36.4% for 160M3B30 blends. For diesel it was 36.3% at injection pressure of 180 bars. 180M4B20 composite blends have higher BTE than to diesel and other blends. The blend M4B20 emits 4.3% CO_2 whereas diesel

it is 4.7% CO_2 for the injection pressure of 180 bars. Biodiesel fuel M4B20, CO emissions were 0.04% was lowest among all the fuels used whereas for diesel it was 0.07% at 180 bars. Lower premixed combustion temperature with composite biodiesel blends may be reason for lesser NO_x emissions for blends. HC emission was less by 17.35 % than diesel.

K.Srithar et al. [89] studied thermal performance and emission characteristics of low heat rejection engine using combination two biodiesel with diesel. Piston surface and cylinder head were coated with aluminium titanate. Two biodiesel considered were Pongamia Pinnata and Neem biodiesel were mixed in different proportions and blended with diesel. The various blends prepared were DPN 1 (Diesel 75% + Pongamia Pinnata 22.5% + Neem 2.5%), DPN 2 (D 50%+ P 45% + N 5%) DPN 3 (D 25% +P 67.5% +N 7.5%) and DPN 4 (D 0% +P 90% +N 10%) were used in engine testing. BTE increased significantly with coated engine compared to base line engine. BTE of base line engine was 26.3% whereas coated engine has 30.3%. BTE of DPN 1, DPN 2 and DPN 4 were 26.4% 25.3%

and 23.6% respectively for base line engine, whereas for coated engine they were 29.3%, 28% and 24.6% respectively. Thermal efficiency of DPN 1 was higher than other blends and was closer to base line diesel. Difference in the BTE for coated engine and base engine was 3.1%. BSFC for low heat rejection engine was lesser than diesel. The value of BSFC for DPN 1 CE, DPN 2 CE and DPN 4 CE were 0.31, 0.37 and 0.37 Kg/kWh respectively whereas for petroleum diesel in baseline engine was 0.36 Kg/kWh. Exhaust gas temperature were higher for LHR engine than baseline engine.

Emissions of HC for coated engine were lower by 4.8% than non coated engines and 8.3% lower than reference fuel. For rated load NO_x emissions for diesel, DPN 1CE, DPN 2 CE and DPN 4 CE were 2.4%, 8%, 13% and 25% higher than baseline. At rated load smoke emissions was lesser than baseline engine for DPN 1, DPN 2, DPN 3 and diesel for coated engines were 16.6%, 10.8% 4.6% and 19.4% respectively.

Hifjur Rehaman et al. [90] studied performance, emissions of engine using mixture of two biodiesel blends in diesel engine. Experimental investigations were carried out using 10.3 kW single cylinder engine. Two oils Mahua and Simorouba were mixed in the ratio of 50:50 and prepared the biodiesel. BSFC for B10 and B20 were higher than diesel by 2.44% and 5.63%. B10 has minimum BSFC. BSFC at rated load were 274.29, 281.05 and 290 gm/kW h respectively for diesel, B10 and B20 blends. BTE for 20% loads were 16.72%, 16.50% and 16.80% respectively for diesel, B10 and B20 respectively. BTE were 30.89% 30.50% and 29.99% respectively for the fuels used for rated. Exhaust gas temperature for B10 and B20 were higher than diesel 4.44% and 5.12% respectively.

For B10 blends mean reduction in CO emissions was 0.031% at 20% of load whereas at 60% load the reduction was 0.014% and increased to 0.071% at rated load. For B10 and B20 blends reduction in mean emissions were 38.76% and 47.60% respectively than diesel. Mean NO_x emissions for B10 and B20 were 5.57% and 11.45% higher than diesel.

Ganesh Shirsath et al. [91] studied the use of two biodiesel blended with diesel and used in engine. Combination of two biodiesels produced from Jatropha and Karanja oils. Other blends were KB20, KB40, KB80 and JB20, JB40, JB80. In KB20 blends 20% karanja and 80% diesel. Fuel was injected at three different crank angles were 19°, 23° and 27° bTDC. BTE at 23° bTDC were 30.9% for diesel. For the HOME and JOME blends were less than diesel. Maximum BTE for HOME were 29.5% at 19° bTDC and minimum were 27.96 at 27° bTDC, for JOME fuel maximum 29.31% and minimum 26.6% at 19° and 27° bTDC respectively. Retarded injection timing 19° bTDC was better for HOME and advanced injection timing 27° bTDC was better for JOME fuel. HC and CO emissions were higher for HOME and JOME fuels. NO_x emissions were lesser for JOME and

HOME than diesel. Peak cylinder pressure was decreased slightly for retarded injection timing. Heat release was reduced at retarded injection timing, gave lesser efficiency. Advanced injection timing increases ignition delay, increases heat release rate gave higher cylinder pressure.

K. Srithar et al. [92] studied use of two biodiesel blended with diesel in compression ignition engine. Two biodiesel were produced from Pongamia pinnata oil and Mustered oil. The two biodiesels blended in different volume fractions and named them as blend A-diesel90%, PPEE5% and MEE5%; blend B-Diesel80%, PPEE10% and MEE10%; blend C-diesel60%, PPEE20% and MEE20%; blend D-diesel40%, PPEE30% and MEE30%; blend E-diesel 20%, PPEE40% and MEE40%, and blend F-diesel00%, PPEE50% and MEE50%. BSFC for different blends was 0.32kg/kWh, 0.35 kg/kWh and 0.37 kg/kWh for Blend A, B and C respectively whereas for diesel it was 0.31 kg/kWh. BSFC for the all the blends were higher than diesel. Smoke percentage for diesel was 60%, 64%, for blend A and 68% for blend B for maximum load. CO and CO_2 emissions for blend A and blend B were lesser than diesel at rated load. For all other blends they were higher than diesel. NO_x emissions were increases with increased volume fraction of biodiesel in the blends. NO_x emissions for blend A were 166ppm whereas for diesel it was 150ppm, for blend B180 ppm, and for blend C 200ppm.

Srinivas Kommana et al. [93] studied use of two biodiesel blends in diesel engine for thermal performance, emission and combustion characteristics of engines. Two biodiesel considered were Eucalyptus oil blended with Palm oil methyl esters. Palm oil was used as major fuel and eucalyptus oil in blended in small quantity with POME. At full loads CO emissions were reduced considerably compared to diesel, 41.09% reduction in CO emissions for B15 blends. HC emissions lesser 42.99% compared to diesel. NO_x emissions were higher by 9.02% for B15 blends. Maximum reduction in Smoke opacity was observed to be 37.05% at full load on the engine. Cylinder pressure increases increased volume fraction of Eucalyptus oil in Pongamia methyl esters. Maximum cylinder pressure were observed for B15 blends and followed by B10, B5 and diesel.

The outcome of above literature are mixing of two biodiesel and blended with diesel gave the almost similar performance as that of single biodiesel blend with diesel or in between the two biodiesel blends with diesel. Emissions were reduced for blends. Some of the properties such as KV, CP, PP, CFPP, FP can be improved by adding one biodiesel with other, these improved fuel property of blends is an advantage of mixing of one biodiesel with other and mixtures used in engine testing under different atmospheric conditions.

Table-2.6 Summary of literature review on thermal performance, emission characteristics of engines using mixture of two biodiesel in blend with diesel

Sl.No	Authors	year	Fuel	Type of study	Remarks
1	H.Yogesh et al.	2012	Jatropha and Pongamia biodiesel	TP and EC	Fuel consumption for M4B20 was 0.19 Kg/kWh, and for diesel 0.23 kg/kWh at 180 bar injection pressure. 20% lesser for blends than diesel fuel, brake power was higher for M4B20 at 180bar injection pressure. M4B20 were highest 45% and for diesel 36.3% at 180 bar injection pressure. M4B20, CO emissions were lowest 0.04% for all the fuels used and for diesel 0.07%. HC 100 ppm for the blends whereas for diesel it was 121 ppm at 180 bar injection pressure. NO_x emissions were less for composite biodiesel.
2	K.Srithar et al.	2013	Pongamia Pinnata and Neem biodiesel	TP and EC	Thermal efficiency of DPN 1 was higher than other blends and was closer to base line diesel. Difference in the BTE for coated engine and base engine was 3.1% for all the fuels. BSFC for DPN1 0.31 Kg/kWh and for diesel 0.36 Kg/kWh. HC, CO emissions was lesser for coated engine than baseline engine. NO_x emissions were higher for coated engine than base line engine.
3	Hifjur Rehaman et al.	2013	Mahua and Simorouba biodiesel	TP and EC	BSFC for the blends was higher than diesel fuel. BTE for diesel and B10 blends was comparable, for other blends it was lesser. EGT was higher for the blends. CO and HC emission was lesser for blends. Increased percentage of biodiesel in the blends reduces CO and increases HC beyond 60% load. NO_x emission was higher for biodiesel, soot deposits was lesser

					for B10 blends than diesel.
4	Ganesh Shirsath et al.	2014	Jatropha, Karanja and Honge oil methyl esters	TP and EC Combustion characteristic	BSFC was higher for all the methyl ester blends with diesel and two methyl ester blends with diesel. BTE was lesser for the blends and two methyl ester blends. CO, HC, NO_x emissions was higher for methyl esters. Peak pressure was higher for diesel than blends; heat release was less for methyl esters.
5	K. Srithar et al.	2014	Pongamia Pinnata oil and Mustered oil biodiesel	TP and EC	BSFC and BSEC were higher for all the blends than diesel. EGT was lesser for blends than diesel. CO and CO_2 were lesser for blend A and B, for other blends they were higher. HC, Smoke %, No_x emission was increased with increased percentage of biodiesel in the blends.
6	Srinivas Kommana et al.	2016	Eucalyptus oil and Palm oil biodiesel	TP, EC and Combustion characteristic	CO and HC emissions Smoke opacity were reduced with blends than diesel. NO_x was increased for the blends. Cylinder pressure engine power, torque was higher for the blends than diesel fuel.

2.4 ANN modelling for the thermal performance and emissions characteristics of the engine

Artificial neural net work is the simulation of the experimental engine behaviour to predict the engine output with respect to the optimized engine operating parameters. This is powerful modelling method employed for the engine research by the investigators. Some of the ANN model applied for the engine by the researchers for predicting the thermal performance parameters such as BTE, BSFC, EGT, and emission constituents such as CO, HC, NOx and smoke of the engine. In this part of the study presents some of the work on ANN modelling developed ANN modelling for light duty diesel engine using biodiesel and diesel blends. The ANN modelling technique was used for predicting the nine output of the engine for the different input. The engine outputs parameters are CO, CO_2, NOx, UBHC and maximum cylinder pressure, location of maximum pressure, maximum HRR, location of Maximum HRR and CuHRR. The input operating parameters of engine were speed, torque, mass flow rate of fuel, type of biodiesel and blends. The achievability of using ANN model for predicting the outputs for the given inputs were assessed. The ANN technique used here was able to predict the accurately seven output parameters out of nine parameters with high degree of accuracy. Applying ANN modelling for the engine testing phase, the number of experimental runs can be reduced considerably. Only few trails trial was required for construction of the ANN modelling. Once the technique was established the engine combustion and emissions behaviour can be predicted by the model.

Kumar R.S. et al (2013) proposed a back propagation ANN modelling for the prediction of thermal performance and emission characteristics of the diesel engine using Pongamia biodiesel in blend with diesel fuel. The model was sufficient for predicting the output torque, SFC and various exhaust components for the inputs of engine speed and for the various blends.

Sarala et al (2013) was developed a neural network modelling for the prediction of emissions from the engine using Nakthmala oil biodiesel fuel in diesel engine. The emissions predicted were CO, CO2, NOx, and HC for the given input parameters were the load and the blends. The developed model results into the better relation between the input and output parameters.

Channapattan et al (2017) was developed multilayer neural network for predicting the performance and emissions from the engine using the experimental data. Four different categories of transfer functions were attempted to develop the model and one which yields the minimum absolute error percentage and higher predicting accuracy were chosen. The Artificial neural network tool was observed to be suitable for the engine applications. The ANN model can be applied during the engine testing phase and the number of experimental trials can be reduced noticeably. Once the accurate ANN technique is established, the performance and emissions behaviour for the various operating condition of the engine can be predicted accurately. This approach is also applicable to other combustion systems when input output relation are required.

Table-2.7 Summary of ANN modelling

Sl.No	Authors	year	Fuel	Type of study	Remarks
1	Kumar R.S. et al	2011	Waste cocking oil biodiesel and diesel blends	Thermal performance and emission constituents	Developed ANN model for the experimental work on VCR diesel engine. The results confirm that the training algorithm proposed a back propagation was sufficient for the predicting the outputs for the given input speed and blends.
2	Harun Mohamed Ismail et al**.**	2012	Biodiesel and diesel blends	Combustion and emissions characteristics	Developed an ANN model for light duty diesel engine using biodiesel and diesel blends. The nine output parameters are predicted using four inputs. Out of nine outputs seven of them can be predicted with high degree of accuracy.
3	Sarala et al	2013	Nakthmala biodiesel with diesel blend	Emission constituents	Developed ANN model for predicting the output of the engine for the given inputs of diesel engine using biodiesel and diesel blends. The emissions predicted using the models were in better agreement with the experimental results.
4	Channapattan et al	2017	Honne oil biodiesel with diesel blend	Thermal performance and emission characteristics	Developed an ANN model for DI diesel engine using Honne biodiesel and diesel blends. Four different transfer functions were used for the model. A model which gives absolute mean error and higher prediction accuracy was chosen. ANN tool was observed to be suitable for the engine applications.

2.5 Summary of literature review

Various observations were made by the researchers in their respective studies and some of the of the common observations made by the researchers from their studies are listed as follows

Fuel property studies:

Density and viscosity of biodiesel fuels were higher than diesel and decreases with increase in temperatures.

Properties of biodiesels such as density, viscosity, pour point, cloud point and CFPP can be modified by blending one biodiesel with other.

Properties of biodiesel were comparable with the diesel fuel, biodiesel fuels can be blended with diesel in any volume fractions.

Thermal performance and emission characteristics:

Brake specific consumption was higher for biodiesel and their blends compared to diesel fuel.

Brake thermal efficiency was lesser compared to diesel fuel.

Thermal performance emission and combustion characteristics:

In addition to the above thermal performance and emission characteristics, some of the observations made by number of researchers on combustion characteristics were as follows

Cylinder pressures were higher for the diesel fuel compared to biodiesel blends.

Cylinder pressure and heat release rate was higher for lower percentage of biodiesel in the blends and decreases with increased percentage of biodiesel in the blends.

Ignition delay was reduced for biodiesel blends compared to diesel.

CO, HC emissions and particulate matters are reduced whereas NO_x and CO_2 are increased for biodiesel blends than diesel.

Combustion characteristics:

Peak cylinder pressure and heat release rate was higher for diesel fuel was claimed by some researchers because of increased ignition delay for diesel compared to biodiesel fuel.

The number of other researchers claimed peak cylinder pressure and heat release rate was higher for biodiesel blends compared to diesel fuel because of improved combustion due to presence of oxygen in biodiesel blends.

Pressure rise rate was higher for the biodiesel blends compared to diesel fuel.

Start of injection and combustion are advanced for biodiesel blends compared to diesel fuel.

Combustion duration is higher for biodiesel blends compared to diesel fuel.

Thermal performance emission and combustion characteristics of VCR engines:

Brake specific consumption was increased for biodiesel and their blends compared to diesel fuel.

Brake thermal efficiency is lesser compared to diesel fuel.

Increased compression ratio improves brake specific fuel consumption and brake thermal efficiency for both biodiesel blends as well as diesel fuel.

Increased compression ratio gives higher peak cylinder pressures for diesel compared to the biodiesel blends.

Cylinder pressure and heat release rate was increased with increase in compression ratio for lower percentage of biodiesel in the blends.

At lower compression ratio the performance of the engine decreases for the fuels used.

Increased percentage of biodiesel in blends cylinder pressure and heat release rate decreases for the various fuels used.

Ignition delay was reduced for biodiesel blends compared to diesel fuel.

CO, HC emissions and particulate matters are reduced for higher CR whereas NO_x and CO_2 emissions were increased for biodiesel fuel compared to diesel fuel.

Thermal performance emission and combustion characteristics of engines with two biodiesel blends with diesel:

Few numbers of researchers worked on blend of two biodiesel with diesel fuel and the outcomes of their researchers are as follows

In addition to the above thermal performance and emission characteristics observation made by number of researchers on combustion characteristics are

Cylinder pressures were higher for the diesel compared to biodiesel blends.

Cylinder pressure and heat release rate were higher for lower percentage of biodiesel in the blends and decreases with increased percentage of biodiesel in blends.

Ignition delay was reduced for biodiesel blends compared to diesel fuel.

CO, HC emissions and particulate matters were reduced whereas NO_x and CO_2 were increased for biodiesel blends compared to diesel fuel.

Mixture of two biodiesel blends with diesel performance is same as single biodiesel blend.

ANN modelling for the thermal performance and emission characteristics of engine

The ANN model was developed for the prediction of outputs for the various inputs of the engines.

The various outputs predicted were thermal performance, combustion and emission constituents of the engines.

The predicted results were having better agreement with the optimum inputs given to the engine.

2.6 Conclusions from literature review

- Various types of biodiesels are considered by number of researchers which were used in the investigation for the thermal performance, emission and combustion characteristics of engine.
- Most of the investigators considered were the blends of single biodiesel with diesel.
- Few studies were reported in the open literature on blending of two biodiesel with diesel.
- Few researchers investigated the detailed combustion characteristics of the engines with blends of biodiesel and diesel fuel.
- Little work is available in open literature on the Simarouba biodiesel blends.
- Few studies were reported on VCR engines using mixture of two biodiesel in blend with diesel fuel.

The shortfall of the literature:

- Few researchers used mixture of two biodiesel in blend with diesel as fuel in diesel engines.
- Few researchers carried out the detailed study of combustion characteristics of engine using biodiesel blends.
- Few of the researchers investigated the combustion characteristics using mixture of two biodiesel in blend with diesel fuel in VCR engine.
- Few studies were reported using Simarouba biodiesel blend with other biodiesel or diesel fuel and Simarouba biodiesel alone as fuel in diesel engines.
- No study seems to be reported in the available literature on blends of Simarouba and Pongamia, Simarouba and Jatropha and Pongamia and Jatropha.

Objective of the present study

From the exhaustive review of the literature most of the study were on thermal performance and emission characteristics of engine and were restricted to constant compression ratio engine using biodiesel and diesel blends as fuel. Few researchers studied the detailed combustion characteristics of engines such as cylinder pressure, heat release rate, and rate of pressure rise, mass fraction burned and combustion duration using biodiesel. No researchers carried out the study of combustion characteristics of engine using the mixture of two biodiesel in blend with diesel fuel in VCR engine. From the open literature little work is available on the use of Simarouba biodiesel and diesel blends in VCR engine.

The objective of the present work is to carry out the thermal combustion characteristics, performance, and emission characteristics of direct injection VCR diesel engine using blends of mixture of two biodiesel in blend with diesel fuel. **B**iodiesels considered for this study have good potential from Indian perspective and less explored till today.

1. The study of the properties of fuels used in the investigation.
2. The present work is to study the performance of the engine using the mixture of two biodiesel in blend with diesel fuel using VCR engine.
3. The study the influence of mixture ratio and blend ratio on the combustion, thermal performance and emission characteristics of engines.
4. The study the effect of compression ratio on combustion, thermal performance and emission characteristics of engine.
5. Detailed combustion, thermal performance and emissions analysis of engine using blends of mixture of two biodiesel in blend with diesel fuel as the fuel.
6. The study of the effect of compression ratio and blend ratio on emission characteristics of engine.
7. The ANN model is to be developed for the predicting the accuracy of the experimental data and validate the same.

Chapter-3

Methodology and Experimental setup

Experimental investigation is carried out to evaluate combustion, thermal performance, and exhaust emission characteristics of variable compression ratio, CI DI VCR engine using mixture of two biodiesel in blend with diesel fuel. Section 3.1 deals with the experimental set up and details of the equipments of the engine for the investigation of combustion characteristics, thermal performance, and emission constituents of engine. Brief procedure of experiment is explained in section 3.2 and details of the components in the subsequent sections.

3.1 Experimental setup

The Kirloskar TAF1 make, single cylinder, four stroke, water cooled, CI DI VCR coupled to eddy current dynamometer and generate 3.5 kW at constant rated speed of 1500 rpm engine is used. Engine is fully computerized, loaded with ‘Engine soft-9’ software. It is also fitted with pressure sensors to measure on line cylinder gas pressure, fuel injection pressure and thermocouple to measure various temperatures for the performance and assessment of losses occurred in the engine.

Engine is fitted with calibrated pressure sensors for acquiring the various pressures. One of the sensors is positioned on the cylinder head to measure cylinder gas pressures; another sensor is placed on injector for fuel injection pressure measurement. Temperatures of the sensors are to be within the limit and are cooled by circulation of water for better life and thermodynamic behaviour. Frequency response and operating range of pressure sensors is an advantage to use them in pressure measurement. Specially designed cylinder block is used to vary the compression ratio of the engine. Compression ratio can be varied within the minimum and maximum limit of 12 to 18. Compression ratio of the engine can be changed during the running condition, with the help of adjusting screw provided on the engine. Compression ratio can be changed by tilting the cylinder block without affecting the combustion chamber geometry. A pump is used to circulate the water to cool the engine and calorimeter. The detailed specification of the engine is given in Table-1.

Eddy current dynamometer is used to load the engine. Dynamometer consists of basically a rotor mounted on the shaft which rotates within casing on ball bearings trunnions mounted on the bed plate. There are two fields coils connected in series placed inside the casing when these coils are supplied with direct current, magnetic field is developed on either side of the rotor inside the casing. When the rotor rotates in the magnetic field, eddy current are induced creating braking effect between rotor and casing. Strain gauge load cells are fitted on the restraining member between the casing and dynamometer bed plate to measure the torque. To avoid the overheating of eddy current dynamometer it is circulated with water for cooling with electrical motor and pump.

The engine is fitted with transmitters to measure flow of air and fuel. Cooling water flow to engine and calorimeter is measured and controlled by rotameter. Numbers of thermocouples are fitted on to the engine and calorimeter for measurement of different temperatures such as water inlet and outlet to the engine and inlet and outlet to calorimeter, and the exhaust gas temperature. Water flow rate, air flow rate, speed and load on engine are measured online. These online measured data signals are acquired by data acquisition system. The data acquisition is loaded with “Engine soft-9” software and system software supported by Windows-10 is used for online performance and combustion data acquisition.

Exhaust emissions of the engine are measured using Marsh five gas analyser and AVL 437 smoke meter with help of specially designed measuring unit. The measuring system is fed with the exhaust gas from the engine through designed unit without creating the back pressure on the engine and without affecting the operation of the engine. The main exhaust emissions measured using the gas analyser are CO %, CO_2 %, HC ppm, NO_x ppm. Smoke density is measured using smoke meter and is in percentage.

3.2 Experimental procedure

Diesel and alternate fuels are stored in two separate fuel tanks. The valve is located between the diesel and alternate fuel tanks which supply the fuel from one of the tanks as per the requirements. The fuel measuring system consists of a burette fitted with two optical sensors one at the higher level and other at the lower level of the tank. As the fuel passes the higher optical sensor gives signal to data acquisition system to start the counter time. As the fuel pass the lower optical sensor, gives signals to the data acquisition system for the end of counter time. From this time for the fuel consumption for one minute is recorded and brake specific fuel consumption is estimated. The next process is to fill the burette for the next operation of the engine. Diesel or alternate fuel is injected in to the cylinder with injector fitted on to the engine. Air box is used to damp out the pulsation caused by the engine intake of the air through the air box. The pulsations are reduced to make the air flow to be smooth and steady through the intake manifold. Quantity of air consumed is measured by differential manometer fitted on the air box. Thermocouples are fitted on to the engine to measure various temperatures. The temperatures measured are cooling water inlet and outlet to engine and calorimeter, exhaust gas temperature and ambient temperature.

The cylinder pressure is measured using piezo sensors models HSM111A22 and M108A02. The range is 5000 psi (345 bars) mounted on the cylinder head. The diaphragm is of stainless steel and is of sealed type. The piezo electric sensor produces the charge output and is proportional to cylinder gas pressure. The piezo sensor consists of quartz crystal and is exposed to cylinder pressure through the diaphragm. With the increase in cylinder pressure in the cylinder the diaphragm is compressed and it is proportional to the gas pressure inside the cylinder. The piezo sensors generate an output which is proportional to the pressure in the cylinder. The output from the piezo sensor is small and it cannot be measured hence an amplifier is incorporated to amplify the output and can be measured and it is proportional to the cylinder pressure.

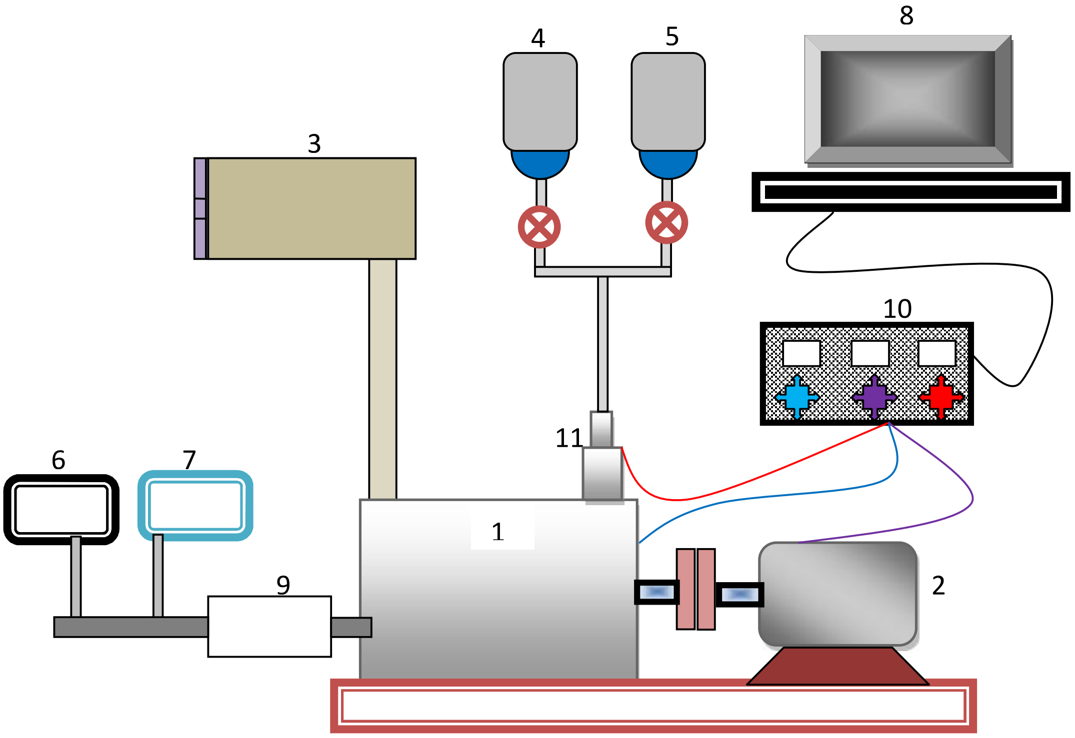


Fig.3.2 Schematic of experimental layout

1. Engine 2. Dynamometer 3. Air box 4. Diesel tank 5. Biodiesel tank 6. Smoke meter 7. Five gas analyzer 8. Computer 9. Calorimeter 10. Control panel 11. Fuel injector

Table-3.1 Detailed Engine Specifications

Type of engine	Kirloskar, TV-1
Number of Cylinders	One
Power at rated speed of 1500 rpm	3.5 kW
Stroke x Bore	110mmx 87.5mm
CR	17.5 (12-18)
Injection pressure	200 bars
Injection timing	23° bTDC
Dynamometer	Eddy current type

It is important to check the quantity of lubricating oil and cooling water in the test bench before the starting of engine. Once these quantities are found to be correct then switch on the power supply. Water pump is started and adjusted the quantity of water supply as 250 L/h to engine cooling and 80 L/h to calorimeter. Computer is started and interfaced with the engine. The engine soft software is made ON and configured by entering the parameters such as compression ratio, ambient temperature, density and calorific value of different fuels used one at a time. First experiment is carried out with neat diesel as a fuel. The results obtained using diesel fuel is the baseline results which are used for comparison with blends. Then experimental investigation is carried out using various blends of mixture of two biodiesel with diesel. Different blends used in engine testing are B20, B40, B60, and B100 and are prepared using nine different mixtures prepared with diesel fuel.

Engine is started using starter motor and it is allowed run for few minutes without load to attain stable operating condition. Once the stable operating condition is achieved the measurements of different parameters such as fuel consumption in 60 seconds and various temperatures are recorded. Same procedure is repeated for various blends and the loads and for different compression ratio. Compression ratio is altered with the help of Allen bolts provided on the tilting block and also clamp it to the engine. Allen bolts are loosened and tilting block is adjusted to any required compression ratio by adjusting the screw which is provided to adjust the compression ratio. After adjusting the required compression ratio Allen bolts are tightened. Experiments are repeated three times and average of the three reading is noted.

Performance of the engine is obtained by estimation of brake thermal efficiency, brake power, brake specific fuel consumption, exhaust gas temperature and brake torque, volumetric efficiency. Various exhaust emissions are measured such as CO, HC, CO_2, and NO_x using 'MARS five gas analyser'. Smoke emissions from engine are measured using 'AVL 437' make smoke meter.

3.3. Thermal performance

Thermal performance is carried out in three different experimental programs

1. Diesel as fuel for three different compression ratios and load is changed each time.

2. Two biodiesel blends as fuel following the same procedure as diesel fuel.

The mixture of two biodiesel is prepared using considered biodiesels for the study. Two biodiesels are mixed in different volume fractions for example (P75+J25), (P50+J50), (P25+J75) and designated as M1, M2 and M3 respectively, similarly for other two biodiesels and these mixtures are designated as B100. Using B100 different blends B20 (20% M1+ 80% diesel), B40M1, B60M1, B80M2 are prepared.

The first experimental work is validation test for ensuring the correctness of the experimental setup. Experimental procedure is undertaken for validation of the tests, using diesel fuel, next the mixture of two biodiesel in blend with diesel.

3.3.1 Validation of Tests

The validation tests are carried out using diesel as fuel, the procedure is explained step by step as below

1. Check the lubricating oil, cooling water and adequate quantity of fuel in the test set up.
2. Switch on the power supply and it is to be seen that every measuring parameter are on.
3. Engine is to be started and allow it to run for few minutes with no load conditions for warm up and reach the steady state operating conditions.
4. Set the required compression by tilting the cylinder block following the usual procedure.
5. Record the data for no load for the thermal performance through the data acquisition system interfaced with computer. Computer is loaded with 'Engine soft-9' software and is used for data acquisition with system software and analyse.
6. Adjust the load to 5 kg using loading unit, run the engine with this load for few minutes to stabilise and record the data and analyse. This gives the repeatability of the data acquired and validates the setup.
7. Repeat the tests with different loads following the same procedure as above.

8. Repeat the experiments varying the compression ratio 16, 17 and 18.
9. After completions of the tests reduce the load to zero before the engine is stopped and continue to run the water pump for few minutes to cool the engine and the sensors.

3.3.2 Mixture of two biodiesel in blend with diesel

Experiments are carried out using mixture of two biodiesel in blend with diesel fuel using the step wise procedure as explained in the above section 3.3.1.

3.7 Emission characteristics

Experimental studies of emission tests are carried out in three different ways

1. Using diesel as fuel for testing the emissions of the engine for various blends, loads and for different CR.
2. Using mixture of two biodiesel only varying the loads and compression ratios.
3. Using mixture of two biodiesel in blend with diesel, for different blends, loads and at different compression ratios.

3.8 Combustion Characteristics

Combustion characteristics of the engine for diesel fuel, mixture of two biodiesel and mixture of two biodiesel in blend with diesel and combustion data are acquired by data acquisition from ‘engine soft version-9 software’. The combustion characteristics acquired are cylinder pressure, P-V diagram, net heat release, cumulative heat release rate, and mean gas temperature, rate of pressure rise, mass fraction burned, and fuel line pressure. These combustion parameters are taken for all three compression ratio i.e. 16, 17 and 18 for various loads and blends.

3.9 Data acquisition system (DAS)

Data acquisition system can explained as the process of acquiring the various data which are measured. The acquired data like cylinder pressure, P-V diagram, heat release, mass fraction burned, rate of pressure rise, mean gas temperature, fuel line pressure, etc. The data signals comes from the various sensors in the experimental setup, then converting the signals into digital values of measurements that can be acquired by data acquisition system with system software windows 10. Data acquisition system typically convert analogues wave form in to digital signal and stored in the system. DAS products centrally connect the entire component such as sensors, pressure, flow, temperature, performance and combustion parameters etc. The average data of pressure crank angle values and occasion of the peak pressure, heat release, rate of pressure rise and mass fraction burnt data are recorded by the DAS stored in the computer as an excel sheet and some of them are in the form of world file.

The each of the combustion experimental data's are collected for number of cycles. The combustion data are collected for 10 cycles the average of 10 cycles is taken for analysis. The first signal sent by the TDC indicator system is taken as TDC position.

Inlet manifold pressure is used as reference pressure. The mean of intake pressure is the accurate indicator of cylinder pressure when the piston is at bottom dead centre. The variation of in cylinder pressure with change in crank angle is collected by the data acquisition system. The collected data are extracted and used for the plot of graphs to check whether the acquired data are correct or not.

The cylinder pressure and injection pressure with change in crank angle variation is large from cycle to cycle hence one such cycle cannot be used to present the data for particular operating condition. Hence the data are collected for minimum of 10 cycles to and ensemble average is taken as the pressure of the cylinder for one cycle of operation of the engine.

Experimental procedure involved in this work is divided in to three parts namely thermal performance evaluation, exhaust emission evaluation and exhaustive combustion characteristics analysis. The flow of experimental investigation is following the above said stages one by one in a systematic manner. The first section explains about the combustion characteristics analysis and the second section explains about the thermal performance of the engines, followed by exhaust emissions in the third section of engine.

3.10 Smoke meter

The AVL437 model smoke meter is used to measure the smoke emissions. The basic principal involved is that fixed quantity of exhaust gas is allowed to pass in the course of measurement through the filter paper fixed in the smoke meter. The densities of smoke stain the filter paper its readings are functions of the mass of the carbon present in the volume of exhaust gas [98] and are evaluated optically to measure the smoke density of exhaust gas from the engines. In the recent modification these smoke meters are developed to measure the smoke stains on the filter paper. The Fig.3.10 shows the detailed photographic view of the AVL437 smoke.

The measuring system consists of a measuring probe draw the fixed quantity of exhaust gas through white filter paper within the smoke meter. The reflection of the paper is measured with smoke meter as density of smoke. This smoke meter consists of light source and annular photo detector that illuminates the filter paper to measure the reflected light. Before the start of next sample measurement, one has to see that the sample smoke from the previous sample should be completely driven out [99].

Fig.3.10 AVL Smoke meter

Calibration of smoke meter is done periodically. Heating the element up to 70º C the calibration is done. The heater was designed to prevent the temperature below dew point of smoke to avoid the error in measurement. The fresh air is allowed to draw in to the chamber through filter paper, and then it undergoes the measurement for calibration process. The halogen bulb current irradiates column of fresh air volume, and the signal from the detector is measured by microprocessor and the reference value is set as 0% opacity. The linearity can be checked by smoothly linearity check knob up/down to its end position. The calibration plate is measured in front of the detector; the measured opacity value is indication of smoke density of exhaust. The probe is connected to the exhaust pipe of the engine through non return valve of which the measurements are carried out. Once the engine reached stable operating condition for particular load non return valve is turned to the positions which send the whole of the exhaust gas of the engine to smoke meter and the measurements are taken.

3.11 Exhaust Gas analyser

The instrument used for the chemical analysis of flue gas or exhaust gas is called exhaust gas analyser. The five gas analyser manufactured by MARS, company is used for measurement of various exhaust constituents from the engine. The photographic image of exhaust gas analyser is shown in Fig. 3.11 and range of data measurement and the resolution and accuracy of measurement is given in the table 3.4.

The instrument measures different composition of exhaust gas such as CO (carbon monoxide), HC (hydrocarbon), CO_2 (carbon dioxide), NO_x (oxides of nitrogen) and O_2. The CO, CO_2, O_2 are measured in %, and HC, NOx are measured in ppm.

Exhaust emissions are measured and recorded by using the gas analyser. The exhaust emissions are tapped from the specially designed T-joint fitted between the outlet from the engine and smoke meter. The exhaust emissions are diverted in the direction of gas analyser and the probe is inserted to measure the exhaust emissions. The various exhaust emissions are measured and analysed.

The gas analyser uses NDIR principal for the measurement CO, HC and electrochemical principal to measure NOx and O_2. In NDIR technique, infrared light is made to pass through the exhaust gas. Molecules of flue gas absorbs the infrared light, the amount of light absorbed by the gas molecules is proportional to the concentration of the exhaust gas [98]. The incandescent bulb is used as the source infrared light. NO are measured by electrochemical principal, in this measurement the nitrogen reacts with ozone and forms nitrogen dioxide, it is oxidised in the electrochemical cell [100].

Fig.3.11 MARS five gas analyser

Table 3.3 Range and resolution of gas analyser

Exhaust Emissions	Range	Resolution
HC	0-1500ppm	1ppm
CO	0-10% volume	0.001%
CO_2	0-20% volume	0.01%
NO_x	0-5000ppm	1ppm
O_2	0-25% volume	0.01%

Chapter 4

Investigation of Fuel properties of blends

4.1 Blends Preparation

Pongamia, Jatropha, Simarouba oils are procured from Agricultural University Dharwad and converted to the respective biodiesel at BVV's STEP Bagalkot. The diesel fuel is procured from local petroleum dealer.

The non edible oils considered for the experimental investigation are Pongamia, Jatropha, and Somarouba. These oils are converted to their respective biodiesel. The processed fuels are called biodiesel or methyl esters of Pongamia, Jatropha, and Somarouba respectively or simply biodiesel with their names ex. Pongamia biodiesel. The biodiesel considered are mixed in different volume fractions and designated them as M1, M2, M3, M4, M5, M6, M7 M8 and M9. The content of nine mixtures is presented in table-1.

Table-4.1 Mixture of two biodiesel in different volume ratio and their designation

Biodiesels used	Volume % of two biodiesel	Designation
Pongamia + Jatropha	75+25 (P75+J25)	M1
Pongamia + Jatropha	50+50 (P50+J50)	M2
Pongamia + Jatropha	25+75 (P25+J75)	M3
Pongamia + Simarouba	75+25 (P75+S25)	M4
Pongamia + Simarouba	50+50 (P50+S50)	M5
Pongamia + Simarouba	25+75 (P25+75)	M6
Jatropha + Simarouba	75+25 (J75+25)	M7
Jatropha + Simarouba	50+50 (J50+50)	M8
Jatropha + Simarouba	25+75 (J25+75)	M9

These nine mixtures are used to prepare the different blends and they are named them as B20M1, B40M1, B60M1, and B80M1 respectively. B20M1 indicates 20% of M1 + 80% of diesel fuel. The same procedure is used for the other eight mixtures to prepare the blends and named them as B20M2, B40M2 etc for the other blends. 20% biodiesel may be from any one of the nine mixtures prepared from the above and presented with particular mixture designation such as M2, M3, and M4 etc. Similarly B40M2, B60M2 and B80M2 blends are prepared and used for the testing of their properties and as well as engine testing.

4.2 Fuel property measurement

The fuel property plays the significant role on the performance and emission characteristics of engines. The chemical and physical properties of biodiesel and diesel blends investigated are density, viscosity; flash point, fire point, and heating value of mixture of two biodiesel blends at various temperatures.

4.2.1 Materials and methods

The test fuels are methyl esters of Pongamia, Jatropha and Simarouba. The mixture of two methyl-esters is prepared in 500 ml. flask. During mixture preparation two methyl-ester of different volume fractions are added and stirred continuously to ensure the uniformity of two methyl-esters. The mixtures prepared are P-J, J-S and P-S. The prepared mixture is stored in a closed container for 24 hours to test the miscibility. It is observed that there is no separation of methyl-esters. The methyl-esters and blends considered are heated from 25° C to 95° C in the steps of 15° C, using standard Red Wood viscometer to determine the viscosity of the methyl-esters and their blends using the standard method. The temperature variation is controlled by dimmer stat. Once the temperature is stabilised the measurements are taken. Measurements are repeated thrice and the mean of three measurements is taken as the result. The density of the various mixtures is measured by gravimetric method. The various mixtures are heated and weighed for measuring their density at various temperatures. The density and viscosity of mixture of two biodiesel mixtures at different temperature for various percentage volume of two biodiesel are measured.

Table 4.2 List of equipments used for fuel testing

Properties	Equipment	Manufacturer and Model	Test Method
Kinematic viscosity	Red-Wood viscometer	Advance Research Instruments, FRW-2	ASTM D445
Density	Relative density method	Gravimetric	ASTMD1298
Flash Point	Cleveland apparatus	Advance Research Instruments	ASTM D92
Calorific value	Bomb calorimeter	Advance Research Instruments, BC 80118	ASTM D240

4.3 Results and discussions of fuel Properties

The present work investigates the influence of blend percentage and temperature on the fuel properties density, kinematic viscosity and dynamic viscosity of neat esters of Pongamia, Jatropha and Simarouba and their blends. The various empirical models and were developed by the researchers for density and viscosity with temperatures and volume fraction of biodiesel in the blends [101, 102, 103]. Blend temperatures are varied from 25 ºC to 95 ºC. The results so obtained are discussed and analyzed.

4. 3.1 Density Measurements

Densities and viscosities of Pongamia, Jatropha and Simarouba methyl-esters and blends of two different methyl-esters like P-J, J-S and P-S are considered in present work. The considered methyl-esters are blended in different volume fractions. The measurements are made at different temperatures. During the measurements the temperature are controlled with the help of dimmer-stat which controls the flow of current to the heater. Once the stable temperature is reached the measurements are taken and recorded. The measurements are the average of the triplicate determinations.

The variation of density of methyl-esters and their blends with change in temperature range of 25° C to 95° C is shown in Fig.4.3.1.1.

Fig.4.3.1.1 shows the variation of density of neat Pongamia and Jatropha methyl-esters and their blends of 10 to 90 %. The results show that density of liquid methyl-esters of Pongamia, Jatropha and blends decrease with rise in temperature. The decrease in density for both the methyl-esters and blends is linear. The decrease in density is due to the increased volume of methyl-esters and their blends at higher temperatures. The Fig.4.3.1.1 indicates that the density of P-J blends increases with the increase in volume percentage of Pongamia methyl-esters in the blends. This is because of higher density of Pongamia methyl ester. The density variation of blends of Pongamia + Jatropha methyl-esters at any temperature for any volume fraction may be determined by a correlation established as function of percentage volume of Pongamia methyl-ester in the blend and temperature is presented in the form of equation (4.3.1.1).

$$^{\circ}_{P-J} = [0.200(X_{P-J}\%) + 862][-0.00058\ (T) + 1.02324] \quad \text{kg/m}^3 \qquad (4.3.1.1)$$

Where X_{P-J} = % of Pongamia in P-J blend (volume %)

and T = temperature (degree centigrade)

Experimental values agree with values estimated from correlations and vary within 0.4%.

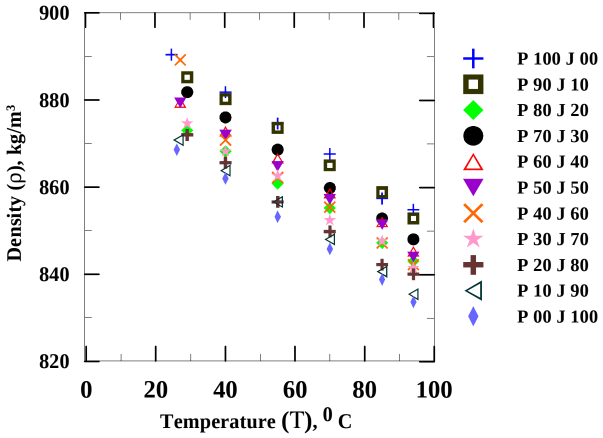
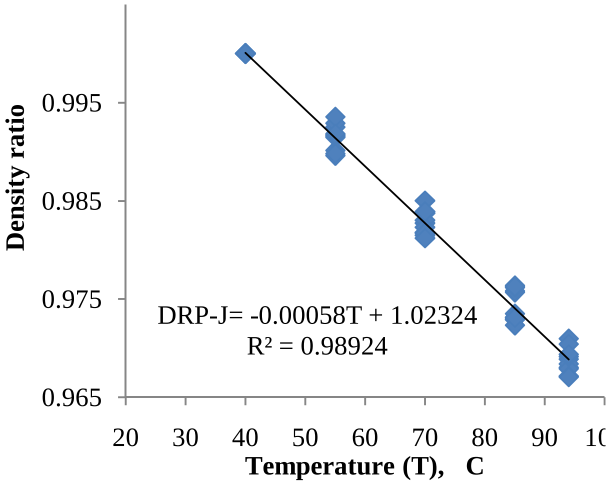


Fig. 4.3.1.1 Influence of temperature on density of P-J biodiesel blends

The correlations established for Pongamia, Jatropha methyl-esters and their blends, referring to the two figures shown below.

The correlation is established for the blends of P-J using Fig. 4.3.1.2 and 4.3.1.3. The Fig. 4.3.1.2 shows the variation of density ratio with temperature from 25° C to 95° C, the first term of the Eq. (4.3.1.1), in the correlation is taken from Fig. 4.3.1.3 and second term from the Fig. 4.3.1.2. The Figure 4.3.1.3 presents density variation with the change in percentage of Pongamia biodiesel in P-J blend at reference temperature of 40° C. The straight line fit suits the trend for both the graphs. The effect of variables upon density is analyzed using regression analysis. In regression, R^2 value is the measure of how best the regression line approximates actual data. The value of R^2 is 0.989 and 0.997 respectively.



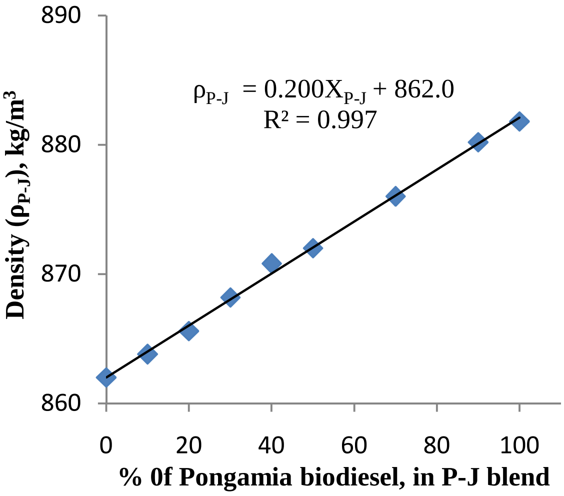


Fig. 4.3.1.2 Influence of temperature on density ratio of P-J blends

Fig. 4.3.1.3 Influence of % pongamia biodiesel on density of P-J blend at reference temperature of 40° C

The correlation for other two blends viz. J-S and P-S is also established using same method.

The Fig. 4.3.1.4, shows the variation of density of Jatropha, Simarouba methyl-esters' blends with temperature change between 25° C to 95° C. Increase in volume percentage of Jatropha methyl-esters' blend increases density of J-S methyl-esters. This is because of higher density of Jatropha methyl-esters. The density variation at any temperature and at any given fraction of methyl-esters' blend is determined by a single correlation established as function of volume percentage of Jatropha methyl-esters in the blend and temperature as seen in Eq. (3.3.2).

$$\circ_{J-S} = [0.029(X_{J-S}\%) + 859.3][-0.00061(T) + 1.02413] \qquad \text{kg/m}^3 \qquad (4.3.1.4)$$

Where X_{J-S} = % of Jatropha in J-S blend (volume %)

and T = temperature (degree centigrade)

Experimental values agree well with estimated values from correlations and vary within 0.23 %.

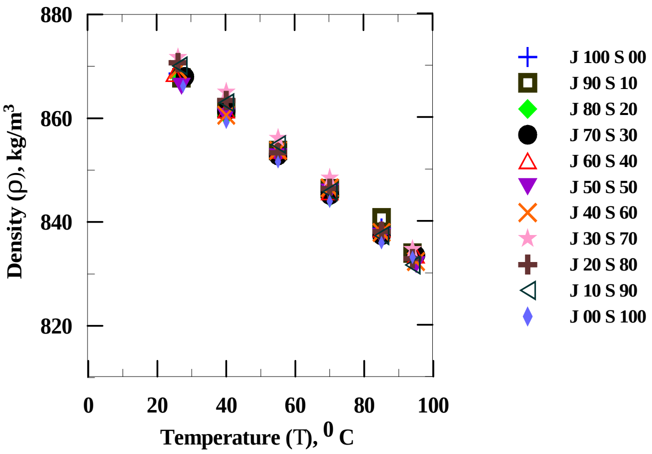


Fig. 4.3.1.4 Influence of temperature on density of J-S biodiesel blends

The Fig. 4.3.1.5 shows the variation of density of Pongamia-Simarouba methyl-esters and their blends with the change in temperature in the range of 25° C to 95° C. The density of blends of methyl-esters increases as the volume percentage of Pongamia methyl-ester increases in the blends of P-S methyl-esters. This is due to higher density of Pongamia methyl-ester compared to Simarouba methyl-esters. The density variation is the function of volume percentage of Pongamia methyl-ester in the blend and temperature. Density is determined form the correlation established for any volume percentage of Pongamia methyl-esters in the blend and at any temperatures. The correlation is given in the form of equation (4.3.1.5).

$$^{\circ}{}_{P-S} = [0.225(X_{P-S}\%) + 859.1][-0.00060(T) + 1.0239] \qquad \text{kg/m}^3 \qquad (4.3.1.5)$$

Where X_{P-S} = % of Pongamia in P-S blend (volume %)

and T = temperature (degree centigrade)

Experimental values agree with values estimated from correlations and vary within 0.17%

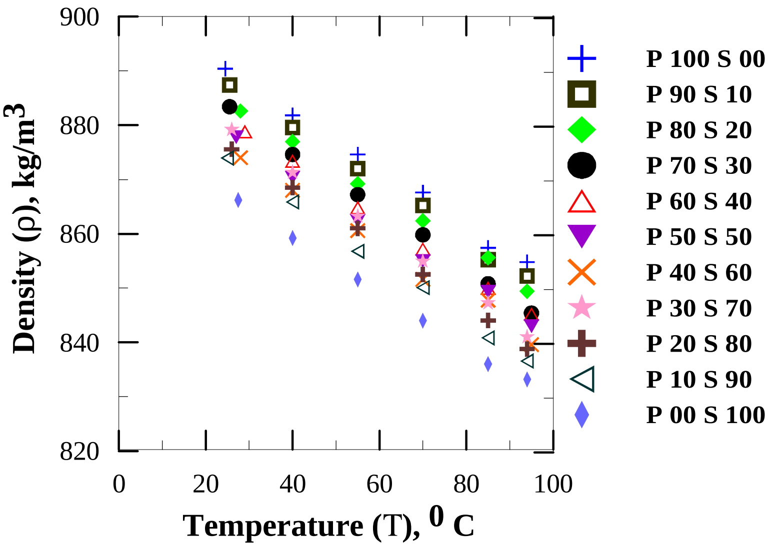


Fig. 4.3.1.5 Influence of temperature on density of P-S biodiesel blends

Density of Pongamia, Jatropha and Simarouba methyl-esters at 40^0 C are 881.8 kg/m^3, 868.6 kg/m^3 and 859.2 kg/m^3 respectively where as the density of these methyl-esters at 95^0 C are 854.8 kg/m^3, 833.6 kg/m^3 and 833.2 kg/m^3 respectively.

4.3.2 Viscosity measurements

The variation of kinematic viscosity of three methyl-esters and their blends are measured between temperatures 25°C to 95°C are shown in the Fig. 4.3.2.

The Fig.4.3.2.1, shows the variation of kinematic viscosity of Pongamia-Jatropha methyl-esters’ blends with change in temperatures. The results indicate, as temperature increases, kinematic viscosity of P-J methyl-esters’ blends decreases. The decrease of kinematic viscosity with increase in temperature is due to reduced resistance to the flow of liquid of methyl-esters at higher temperatures. Increase in percentage of Pongamia methyl-esters in the blends of P-J methyl-esters kinematic viscosity increases. This is due to higher kinematic viscosity of Pongamia methyl-esters compared to Jatropha methyl-esters. It is also observed that decrease in viscosity is more at lower temperature than at higher temperatures. The correlation are established to find kinematic viscosity of P-J methyl-esters' blends. The correlation established as the function of percentage of Pongamia methyl-ester and temperature of blends. Established correlation is given as in equation (4.3.2.1).

$$\nu_{P-J} = [0.014(X_{P-J}\%) + 4.540][-0.78\ln(T) + 3.875] \quad \text{mm}^2/\text{sec} \qquad (4.3.2.1)$$

Where X_{P-J} = % of Pongamia in P-J blend (volume %)

and T = temperature (º C)

Experimental values agree with values estimated from correlations and vary within 5%.

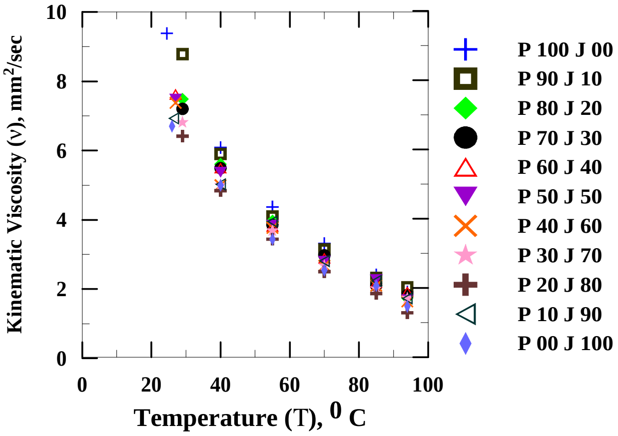


Fig. 4.3.2.1 Influence of temperature on kinematic viscosity of P-J biodiesel blends

The correlations for kinematic viscosity of the P-J blends are established using the Figs.4.3.2.2 and 4.3.2.3 The Fig. 4.3.2.3 shows the variation of viscosity ratio with temperature from 25° C to 95° C. The first term of the Eq. (4.3.2.1) is taken from the Fig. 4.3.2.3, and second term from the Fig. 4.3.2.2. The Fig. 4.3.2.3 presents the kinematic viscosity to the % of Pongamia biodiesel in P-J blend at reference temperature of 40º C. The logarithmic fit suits the trend for the variation of ratio of viscosity to the change in temperature. The straight line fit is best suits for the trend of viscosity to the change in volume percentage of Pongamia methyl-esters in P-J blends. The effect of variables upon the viscosity is analyzed using regression analysis. In the regression, the value of R^2 is measure of how best the regression line approximates the actual data. The value of R^2 is 0.99 and 0.974 respectively. The correlation for other two blends *viz*. J-S and P-S is also established using the same procedure.

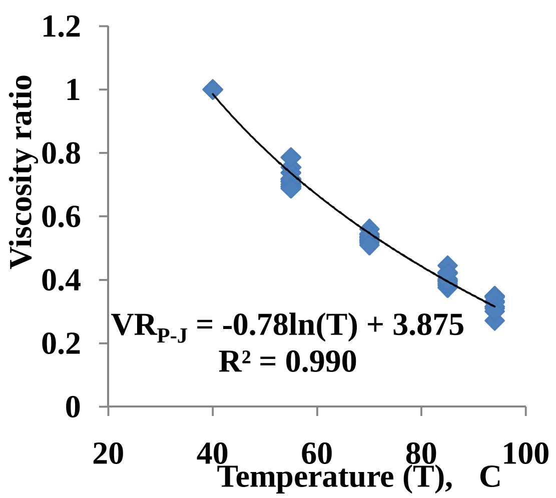


Fig. 4.3.2.2 Influence of temperature on viscosity ratio of P-J blends

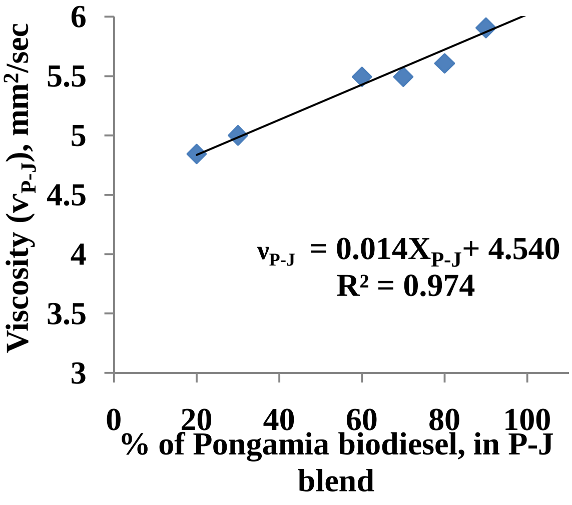


Fig. 4.3.2.3 Influence of % Pongamia biodiesel on viscosity of P-J blend at reference of temperature of 40° C

The Fig. 4.3.2.4 shows the variation of kinematic viscosity of blends of Jatropha, Simarouba methyl-esters with change in temperatures. It is noticed that as the temperature increase kinematic viscosity of Jatropha-Simarouba biodiesels' blends decreases. As the volume fraction of Simarouba bio diesel increases in J-S blend, viscosity of the blend increases, due to higher viscosity of Simarouba methyl-esters. A correlation is established as the function of percentage of Simarouba methyl esters in the blend and temperature. From the established correlation the viscosity of the J-S blends and pure methyl esters can be estimated for any percentage of Jatropha methyl ester and for any given temperature. The correlation is presented as given in the eq. (4.3.2.2).

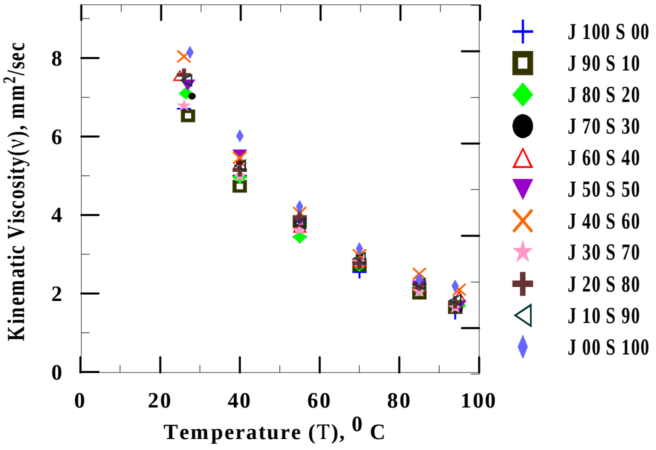


Fig. 4.3.2.4 Influence of temperature on kinematic viscosity of J-S biodiesel blend

$$\neg_{J-S} = [-0.009(X_{J-S}\%) + 5.964][-0.76\ln(T) + 3.802] \quad \text{mm}^2/\text{sec} \qquad (4.3.2.2)$$

Where X_{J-S} = % of Jatropha in J-S blend (volume %)

and T = temperature (degree centigrade)

Experimental values agree with values estimated from correlations and vary within 5%. The Fig.4.3.2.5 shows the variation of kinematic viscosity of Pongamia-Simarouba methyl-esters and their mixture with increase in temperature. It is indicated from the figure that as the temperature of the methyl esters increases viscosity decreases. Increase in Pongamia methyl ester volume percentage in the blends increases the viscosity of P-S methyl-ester. This increase in viscosity is because of higher viscosity of Pongamia methyl-ester. It is observed that decrease in viscosity is more at lower temperatures compared to higher temperatures. A correlation is established as a function of volume percentage of Pongamia methyl-ester and temperatures in the blend of P-S. The correlation is presented as given in the eq. (4.3.2.3).

$$\neg_{P-S} = [0.012(X_{P-S}\%) + 4.977][-0.77\ln(T) + 3.862] \ \text{mm}^2/\text{sec} \qquad (4.3.2..3)$$

Where X_{P-S} = % of Pongamia in P-S blend (volume %)

and T = temperature (degree centigrade)

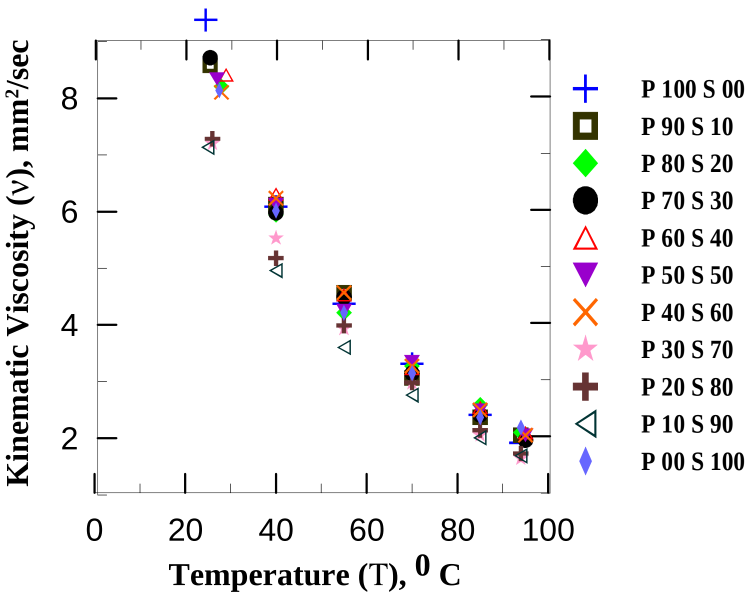


Fig. 4.3.2.5 Influence of temperature on viscosity of P-S biodiesel blends

Experimental values agree with values estimated from correlations and vary within 5%. Kinematic viscosity of Pongamia, Jatropha and Simarouba methyl-esters at 40^0 C are 6.08 mm^2/Sec, 5.0 mm^2/sec and 6.01 mm^2/sec respectively where as at 95^0 C are 1.91 mm^2/sec, 1.5 mm^2/sec and 2.9 mm^2/sec respectively.

4.4 Summary

The influence of percentage biodiesel in the blend and temperature on the fuel properties such as density and kinematic viscosity of neat esters of Pongamia, Jatropha and Simarouba and their blends is investigated. Blend temperatures are varied from 25° C to 95° C and the following conclusions are drawn

Density and viscosity of P-J and P-S blend increases with the increase in volume fraction of Pongamia methyl-ester in the blends. For J-S blends, density increases as the volume percentage of Jatropha methyl-ester increases where as kinematic viscosity decreases. Decreases in density are linear whereas kinematic viscosity is logarithmic with increase in temperature. Correlations are established to find the density and kinematic viscosity of two methyl-ester blends; calculated results are in confirmation with experimental values.

4.5 Properties of Simarouba and diesel blends

The test fuels are Simarouba methyl ester (100%) and its blend of 10% to 90% with diesel fuel. The Simarouba methyl ester and diesel mixtures are prepared in 500 ml flask. During mixing of Simarouba methyl ester and diesel fuels are stirred continuously to ensure the uniformity in the mixture of biodiesel and diesel. Mixtures are stored in the closed containers for 24 hour for observing the separation of blends. It is observed that there is no separation of blended fuels. The blends are prepared and named as per the ASTM standards of methyl ester fuels (B00-B100).

The various properties tested are viscosity, density, flash point, fire point, heating value of the different blends. Standard red wood viscometer is used for testing viscosity of blends at various temperatures. The temperatures variation is controlled using dimmer stat once the temperatures are stabilised the measurements are taken. Cleveland’s open cup apparatus is used to measure the flash point and fire point of different blends with standard procedure. Heating value of different fuel mixture is measured using Bomb Calorimeter with standard procedure. Density of various blends is carried out by gravimetric method.

Experiments are carried out to measure the physico-chemical properties of neat Simarouba methyl-ester and its blends with diesel and neat diesel. The important fuel properties measured are density, viscosity, flash point, fire point and heating value of Simarouba methyl-esters and their blends with neat diesel at various temperatures.

4.5.1 Influence of temperature on density of blends

Density of Simarouba methyl esters and diesel blends at various temperatures for different blends measured are presented in Fig. 4.5.1.1. Density measurements at various temperatures are the mean of triplicate determination. The results indicate that with increase in methyl-esters volume fraction in the blends, density increases. Increase in density may be attributed to increased volume of methyl esters in the blends. Density of methyl esters and their blends decreases with increase in temperature. Decrease in density of blends with increased temperature is attributed to increase in volume of methyl ester blends. Density of methyl esters and their blends are measured and correlated by least square regression analysis.

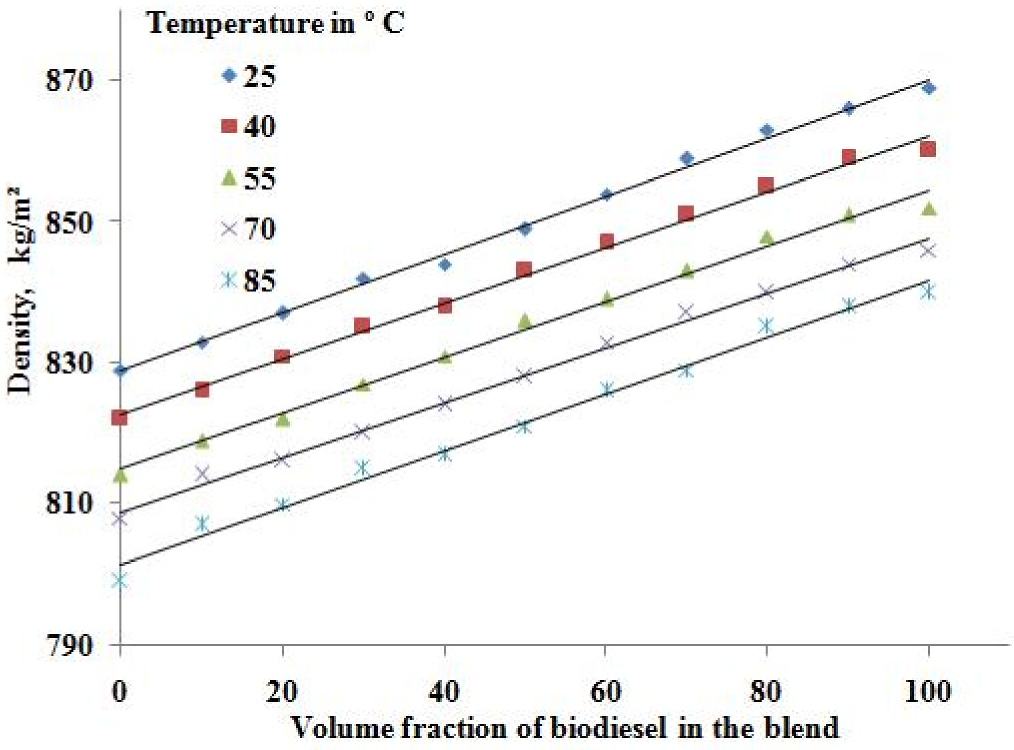


Fig.4.5.1.1 Influence of temperature on density blends.

Various correlations are established and are in the form of equations (3.6.1.1) to (3.6.1.4). Regression coefficient is between 0.996 - 0.990. This shows that there is good agreement between the experimental results and calculated values.

at 40°C $\rho = 0.395x+822.6$ $0 \leq x \leq 100$ $R^2 = 0.995$ (4.6.1.1)

at 55° C $\rho = 0.396x+814.9$ $0 \leq x \leq 100$ $R^2 = 0.993$ (4.6.1.2)

at 70° C $\rho = 0.386x+808.8$ $0 \leq x \leq 100$ $R^2 = 0.995$ (4.6.1.3)

at 85° C $\rho = 0.400x+801.5$ $0 \leq x \leq 100$ $R^2 = 0.990$ (4.6.1.4) 'x' is the volume fraction of methyl ester in blends.

4.5.2 Influence of temperature on kinematic viscosity of blends

Kinematic viscosity of methyl-ester-diesel blends and neat diesel is measured at various temperatures is presented in Figs. 4.5.2.1. Kinematic viscosity increases with increase in methyl-ester volume fraction in blends. It is indicated from the experimental results that the kinematic viscosity decreases nonlinearly with increase in temperature. The decrease in kinematic viscosity of methyl ester blend with diesel is due the decreased resistance to the flow of fuel with increase in temperatures. The viscosity of methyl ester and their blends are measured and correlated by polynomial least square regression analysis. Various correlations are established for kinematic viscosity of methyl esters-diesel blends referring to the Fig.4.5.2.1, for different volume fractions of Simarouba methyl ester-diesel blends for various temperatures. Correlations established are in the form of equations (4.5.2.1) - (4.5.2.5). Regression coefficient R^2 is between 0.991 - 0.996 at different temperatures. It shows better agreement between the measured values and calculated results.

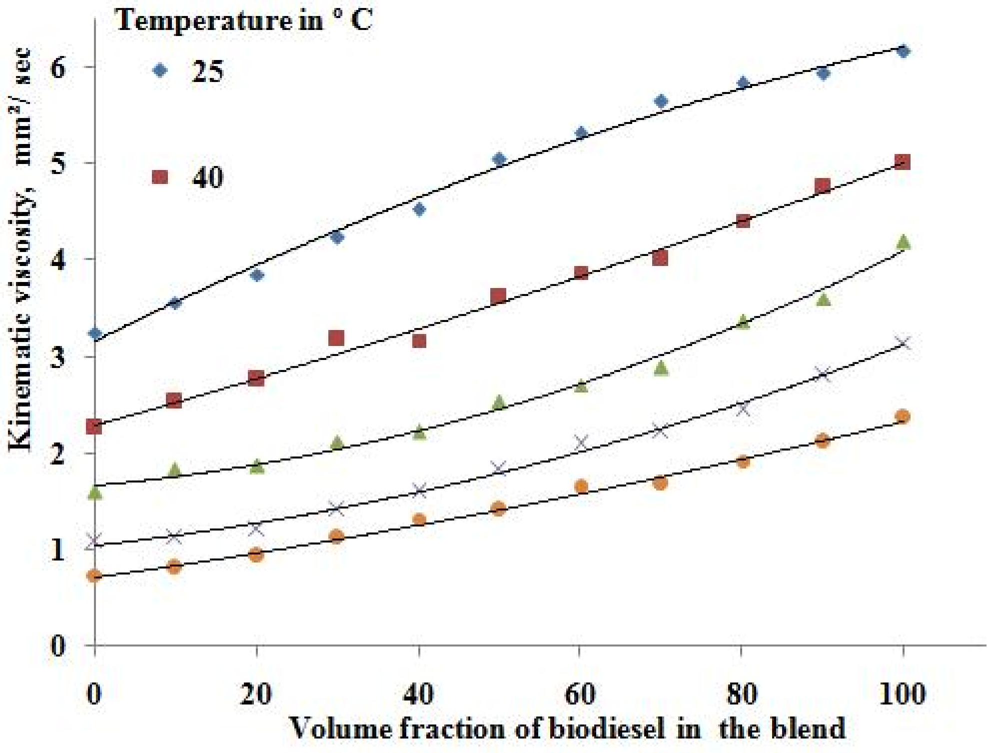


Fig.4.6.2.1 Influence of temperatures on kinematic viscosity of blends.

at $25^{0°}$C $\nu = -0.000011x^2 + 0.04181x + 3.153$ $0 \le x \le 6$ $R^2 = 0.993$ (4.5.2.1)

at $40^{°}$ C $\nu = 0.00004x^2 + 0.02341x + 2.296$ $0 \le x \le 6$ $R^2 = 0.993$ (4.5.2.2)

at $55^{°}$ C $\nu = 0.00017x^2 + 0.00739x + 1.667$ $0 \le x \le 6$ $R^2 = 0.991$ (4.5.2.3)

at $70^{°}$ C $\nu = 0.00012x^2 + 0.00934x + 1.037$ $0 \le x \le 6$ $R^2 = 0.996$ (4.5.2.4)

at $85^{°}$ C $\nu = 0.00004x^2 + 0.01172x + 0.723$ $0 \le x \le 6$ $R^2 = 0.995$ (4.5.2.5)

‘x’ is volume fraction of methyl-ester in blends.

It is observed from the figure that decease in kinematic viscosity of blends at lower temperature is higher compared to higher temperatures. This may be attributed to decreased resistance of flow at higher temperatures.

4.6 Influence of volume fraction of biodiesel on flash point and heating value of blends

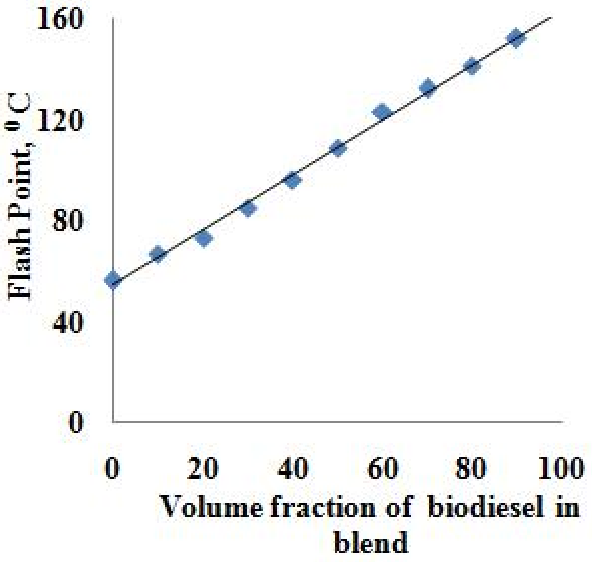
The variation of flash point and heating value for different blends are shown in the Figs. 4.6.1 and 4.6.2. The correlation exists between the heating, flash point with volume fraction of biodiesel in the blends [104, 105]. There is an increase in flash point with increase in volume fraction of methyl ester in blends. It is indicated from results that flash point of blends increases linearly. Flash point of methyl ester-diesel blends are much higher compared to diesel fuel. The increase in volume fraction of methyl-ester in the blends, heating value deceases. The decrease in heating value is linear. The correlations are established in the form of equations (3.6.1) and (3.6.2). Regression coefficients for the correlations are 0.994 and 0.997 for flash point and heating value respectively.

$FP = 1.686x + 54.40$ $0 \le x \le 100$ $R^2 = 0.994$ (4.6.1)

$HV = - 0.0045x + 45.10$ $0 \le x \le 100$ $R^2 = 0.997$ (4.6.2)

x’ is the volume fraction of biodiesel in blends.

It is observed from figures that density, viscosity and flash point increases with increase in volume percentage of Simarouba biodiesel in blends, where as heating value decreases.



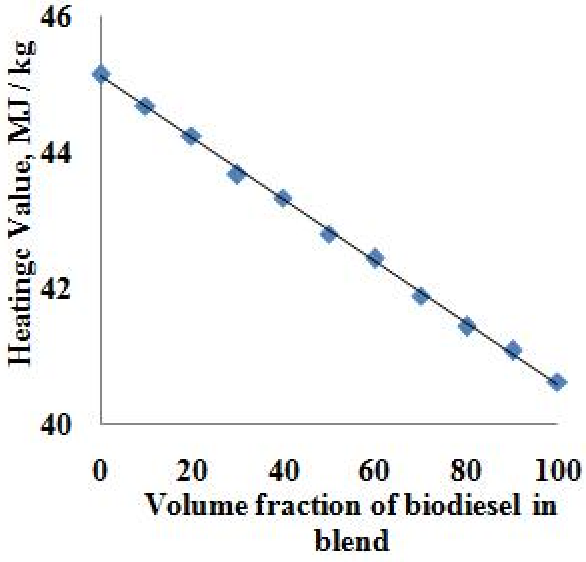


Fig. 4.6.1 Influence of volume fraction of biodiesel on flash point of blends

Fig. 4.6.2 Influence volume fraction of biodiesel on heating value of blends

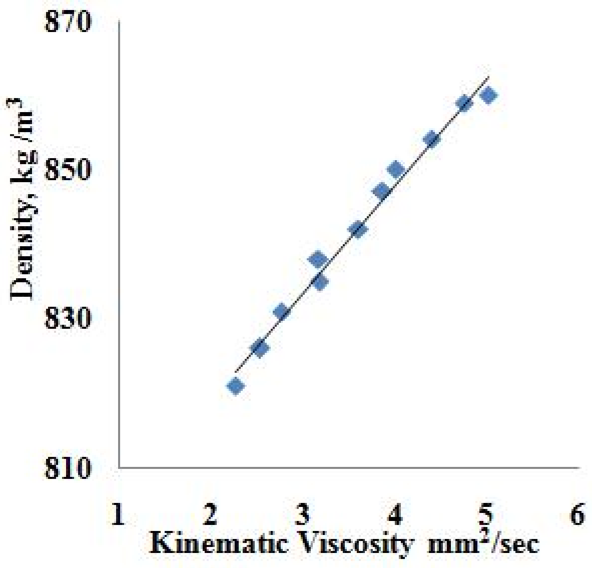
4.7 Influence of viscosity on density, flash point and heating value of blends

Fig.4.7.1 shows variation of density of methyl-ester-diesel blends for various viscosities of blends. It is indicated from the figure that with increase in viscosity density of blends increase. The Correlation relation is established between viscosity and density of the blends, straight line fit is used for the same. From the correlation the density of methyl-ester-diesel blends can be estimated.

Fig.4.7.2. shows the variation in flash point of methyl-ester-diesel blends and neat diesel with change in kinematic viscosity. It may be observed that flash point of blends increase with increase in viscosity of methyl-esters-diesel blends. The mathematical relation is established for the viscosity and flash point of methyl-ester-diesel blends, straight line fit method is used. Mathematical relation is used to validate the flash point of methyl-ester-diesel blends.

The Fig.4.7.3 shows the change in heating value of methyl-ester-diesel blends with change in kinematic viscosity. It is observed from figure that with the increase in kinematic viscosity of blends heating value decreases. Mathematical relation is established between kinematic viscosity and heating value of the blends, to verify heating value of methyl-ester-diesel blends. Correlations established are in the form of equations

(4.7.1) to (4.7.3). The number of correlation exists between the properties of biodiesel and heating value [106, 107].



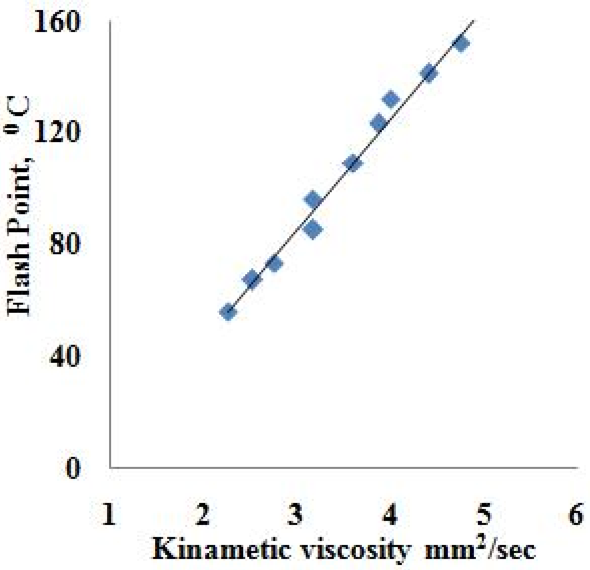


Fig. 4.7.1 Influence of viscosity on density **Fig. 4.7.2 Influence of viscosity on FP**

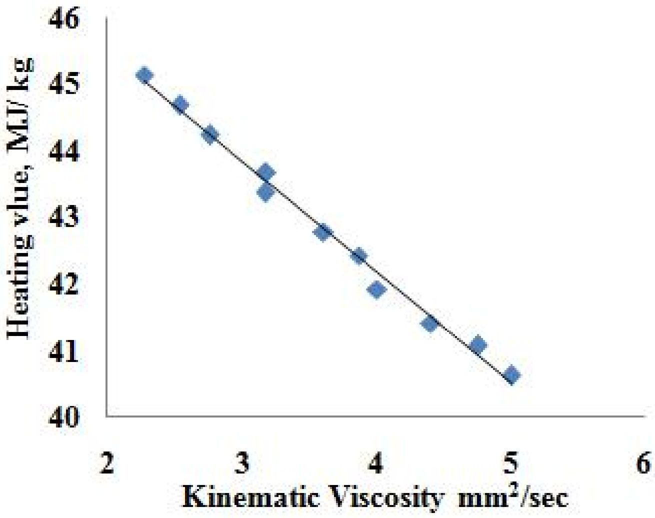


Fig. 4.7.3 Influence of viscosity on heating value of blends

Correlations established to find the density, flash point and heating value of methyl-ester-diesel blends from kinematic viscosity of various blends is given below,

Density,	$\rho = 14.43672x + 790.13185$	$1 \leq \nu \leq 6$	$R^2 = 0.987$	(4.7.1)
Flash point,	$FP = 39.63928x - 33.93812$	$1 \leq \nu \leq 6$	$R^2 = 0.988$	(4.7.2)
Heating value	$HV = -1.652x + 48.79$	$1 \leq \nu \leq 6$	$R^2 = 0.992$	(4.7.3)

'ν' is the viscosity of methyl ester in mm^2/sec.

4.8 Summary

Density, viscosity of blends increases with increase in volume fraction of methyl-esters in the blends and also decreases with increase in temperature. Flash point of blends increases with increases in volume fraction of methyl-ester in blends. Heating value of blends decreases with increased volume fraction of methyl-esters in the blends. The correlations are established for density, kinematic viscosity, flash point and heating value of methyl-ester-diesel blends. Regression coefficient is higher (R^2) for established correlations for various blends at various temperatures. The results from the correlations compare well with the experimental values. Flash point of methyl-ester is almost three times higher as compared to diesel fuel. Heating value of methyl-esters is 10 to 15 % lower compared to diesel fuel.

Chapter-5

RESULTS AND DISCUSSIONS

5.1 Combustion, Performance and Emission characteristics analysis of Pongamia- Jatropha biodiesel blends with diesel

The combustion characteristics, thermal performance and exhaust emissions of single cylinder, four stroke, DI VCR, water cooled diesel engine using mixture of two biodiesel in blend with diesel is investigated and analysed. The Pongamia and Jatropha biodiesels are mixed in the ratio of 50:50 (P50 + J50) and the mixture is designated as M2. The various blends are prepared using the mixture M2 with diesel. The combustion parameters investigated are cylinder pressure, net and cumulative heat release, rate of pressure rise, and mass fraction burned. The results are compared with base line results of diesel fuel at the same operating conditions. The thermal performance parameters investigated are brake thermal efficiency, brake specific fuel consumption, and EGT. The emissions constituents measured are CO, HC, NOx, and smoke. The results for various biodiesel mixtures are discussed.

5.1.1 Combustion analysis

5.1.1.1 Variation of cylinder gas pressure with CA

The cylinder gas pressure variation for the crank angle for various blends at CR18 for the rated load of the engine is illustrated in the Fig. 5.1.1.1. The cylinder pressures of the various blends are following the similar trend as the diesel fuel which may perhaps be accredited to the comparable properties of biodiesel. The cylinder gas pressures of the biodiesel blends are higher in comparison with diesel fuel at the rated load [108, 109]. The higher cylinder pressure may perhaps be accredited to higher combustion temperature, higher temperature and density of the air at higher CR may enhance mixing of fuel-air and atomization of fuel contributes in complete combustion [110, 111]. This may perhaps be accredited to higher CN and inherent oxygen of biodiesel in the blend. The inherent oxygen and higher CN of biodiesel may enhance mixture formation of fuel-air and accelerate the combustion. It may be seen that maximum cylinder pressure for the B00 (diesel) is found to be 71.63 bar at the rated load and is at 10° aTDC. The maximum cylinder pressures for B20M2, B40M2, B60 M2 and B100M2 are 72.68 bars, 72.31bars, 72.21 bars and 70.72 bars respectively and at are 11°, 10°, 8°, 10° aTDC. The start injection and ignition for the various blends used are earlier in comparison with diesel fuel. The early start of injection may perhaps be accredited to high bulk modulus of biodiesel in the blends. The advanced ignition may perhaps be attributed to higher CN of biodiesel fuel. For the higher volume fraction of biodiesel in the blends, the cylinder pressure is lesser compared to diesel fuel which may perhaps be attributed to higher viscosity and inferior volatility biodiesel fuel may influence the mixture formation of fuel-air and consequently the process of combustion [112].

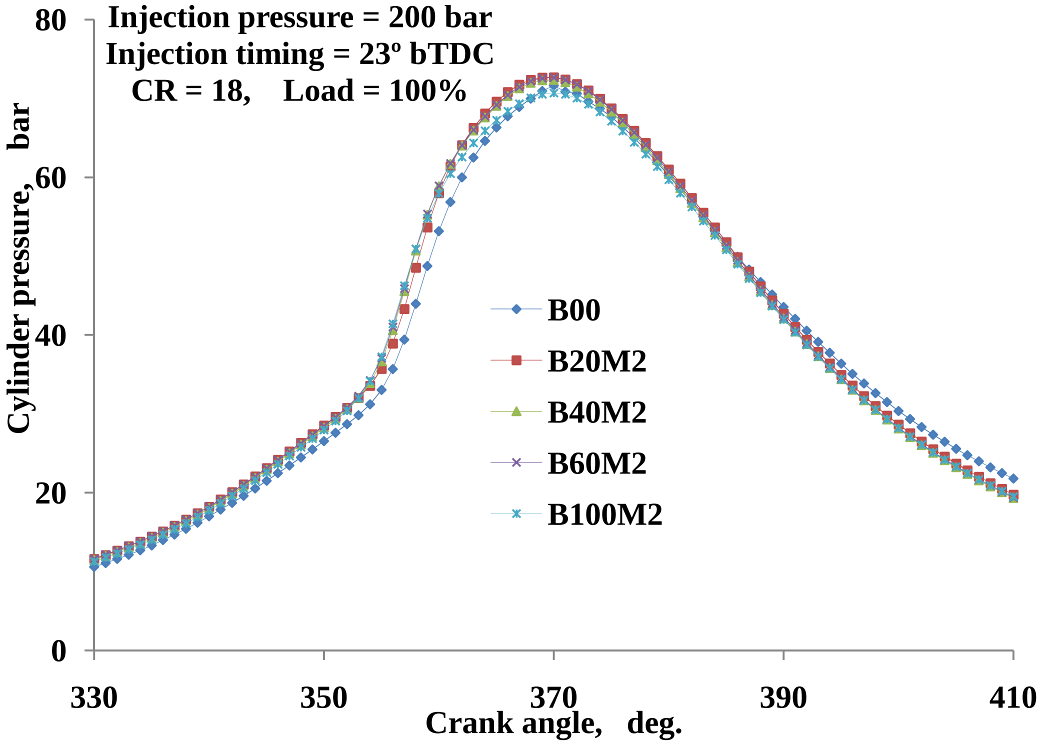


Fig. 5.1.1.1 Variation of cylinder pressure with CA

5.1.1.2 Maximum cylinder pressure with load

The maximum cylinder gas pressure is mainly depends on the quantity and quality of fuel burned all through the premixed combustion phase which results in to the engine output. The maximum gas pressures are taken from the pressure volume plot data acquired from the data acquisition system. The variation of maximum cylinder gas pressure for various blends and diesel fuel for the various loads is illustrated in Fig. 5.1.1.2. It is observed from the figure that the maximum cylinder gas pressures are higher for the blends for all the loads as compared to diesel fuel which may perhaps be accredited to higher combustion temperature, higher density and temperature of the air at higher CR may enhance mixing of fuel-air and atomization of fuel contributes in complete combustion [110]. The higher cylinder pressure may also be accredited to inherent oxygen and higher CN of the methyl esters in the blends. The higher inherent oxygen of biodiesel in the blends may perhaps enhance the mixture formation of fuel-air and accelerates the chemical reaction. Higher CN of biodiesel blends may accelerate the combustion process of various blends which contributes in higher maximum cylinder gas pressure. The maximum higher cylinder gas pressure for the diesel fuel is 71.4 bars for rated load at CR18. Maximum cylinder gas pressure for the blend B20M2, B40M2, B60M2 and B100M2 are 72.69 bars, 72.34 bars, 72.65 bars and 70.72 bars respectively at the rated load [113]. Maximum cylinder pressures for the blends are marginally higher in comparison with diesel fuel which may be attributed to enhanced combustion of blends. The higher maximum cylinder gas pressure for B100M2 is lesser compared to diesel fuel at the rated load which may well be accredited to lower heating value and higher viscosity, inferior volatility of biodiesel in the blends influence the mixing of fuel-air consequently the sluggish combustion.

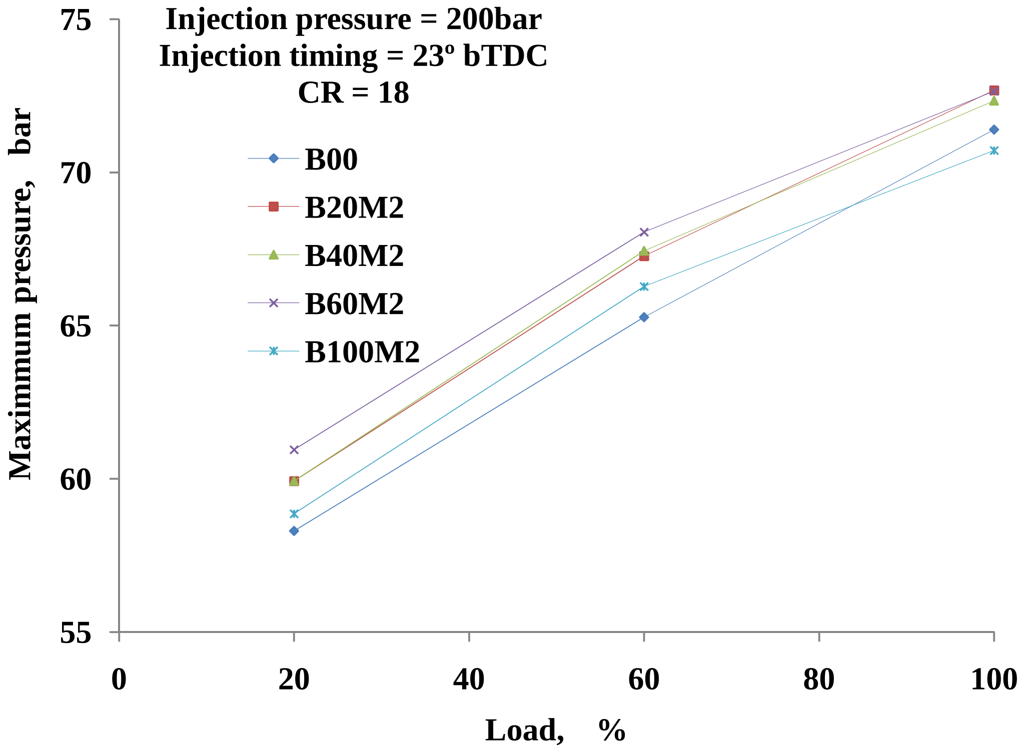


Fig. 5.1.1.2 Variation of maximum cylinder pressure with load

5.1.1.3 Net heat release (NHR) with CA

The NHR is the result of rapid burning of fuel-air mixture accumulated all through the ignition delay stage during the premixed combustion or uncontrolled combustion stage. The net heat release is the energy released from the chemical energy of the fuel [113]. The variation of net heat release for change in CA for different blends at CR18 for the rated load is illustrated in the Fig.5.1.1.3. The negative net heat release is observed initially for all the fuels used in the investigation which may perhaps be accredited to evaporation of the fuel which absorbs the heat from the hot air hence there may be negative heat release. Heat is consumed rather than generated all through the ignition delay period results into negative release. For the duration of the diffusion combustion phase fuel may be burned instantaneously as soon as injected into the combustion chamber. Start combustion of blends are earlier in comparison to diesel fuel which may perhaps be accredited to inherent oxygen and higher CN of biodiesel in the blends. The inherent oxygen and higher CN may improve the mixture formation of fuel-air and increases chemical reaction, accelerates the combustion. The net heat releases for the rated load are higher for diesel fuel in comparison to the blends which might be accredited to increased delay, higher heating value of diesel fuel, which is in good agreement with Mani et al., [114]. Higher net heat release for the blends is at earlier crank angles in comparison to diesel fuel could be attributed to early start of injection and advanced combustion of blends. The net heat release is lesser for the blends compared to diesel fuel [115]. Mixture B100M2 has the lesser net heat release in comparison to diesel fuel and other blends which may perhaps be accredited to lower energy content and higher viscosity of blends. The higher viscosity of B100M2 may perhaps be influence

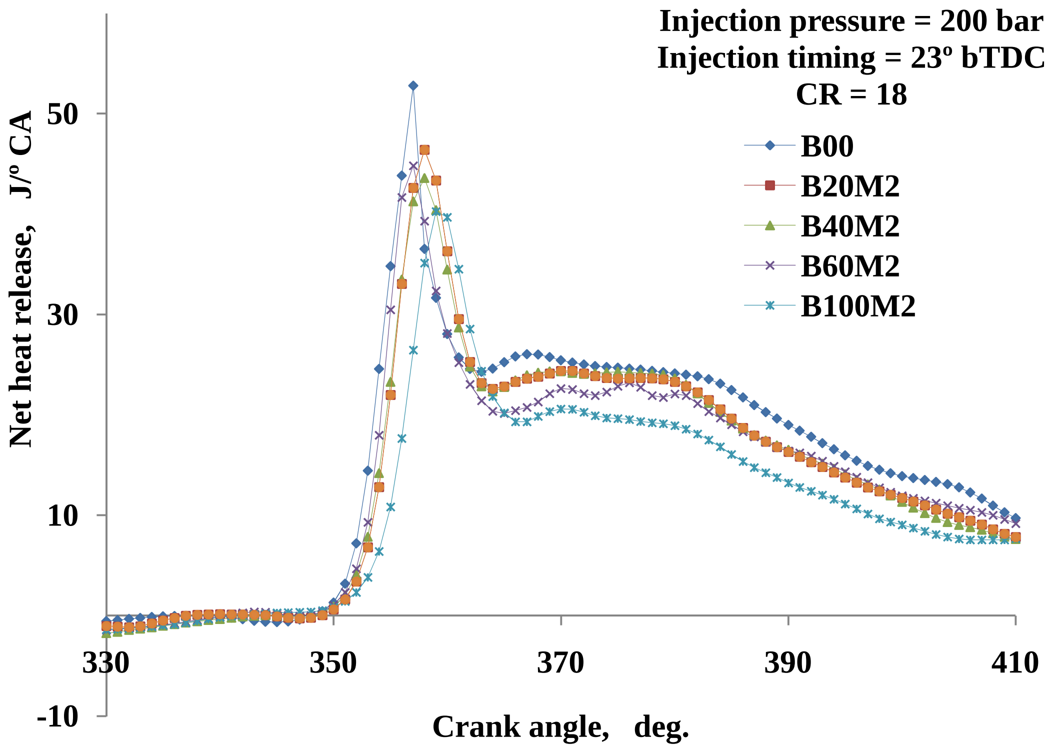


Fig. 5.1.1.3 Variation of NHR with crank angle

mixing of fuel-air consequently sluggish combustion hence lower net heat release. The maximum net heat release for B00, B20M2, B40M2, B60M2 and B100M2 are 52.79 J/º CA, 44.5 J/º CA, 43.97 J/º CA, 44.06 J/º CA and 39.88 J/º CA respectively [113].

5.1.1.4 Cumulative heat release (CHR) with CA

The cumulative heat release gives more information with reference to the progress of combustion of fuel-air mixtures. The cumulative heat release for various blends and diesel fuel with change in crank angle at CR18 for the rated load is shown in the Fig.5.1.1.3. The CHR of the blends is following the similar trend as those of diesel fuel because of the biodiesel properties are comparable with diesel. The cumulative heat release is the overall heat energy released from the chemical energy of the fuel. The CHR for the diesel fuel is lesser during the early phase of the combustion which may well be attributed to late start of combustion. As the combustion progresses CHR of diesel fuel surpass the blends. Over all the CHR of diesel fuel is higher in comparison to the blends which may perhaps be accredited to higher heating value and better combustible properties. The lesser CHR for biodiesel blends which might be accredited to lower heating value and higher viscosity, inferior volatility of biodiesel in the blends. The cumulative heat release are 1531 kJ, 1320 kJ, 1322 kJ, 1341 kJ, 1311 kJ for B00, B20M2, B40M2, B60M2 and B100M2 respectively. There is an increase in cumulative

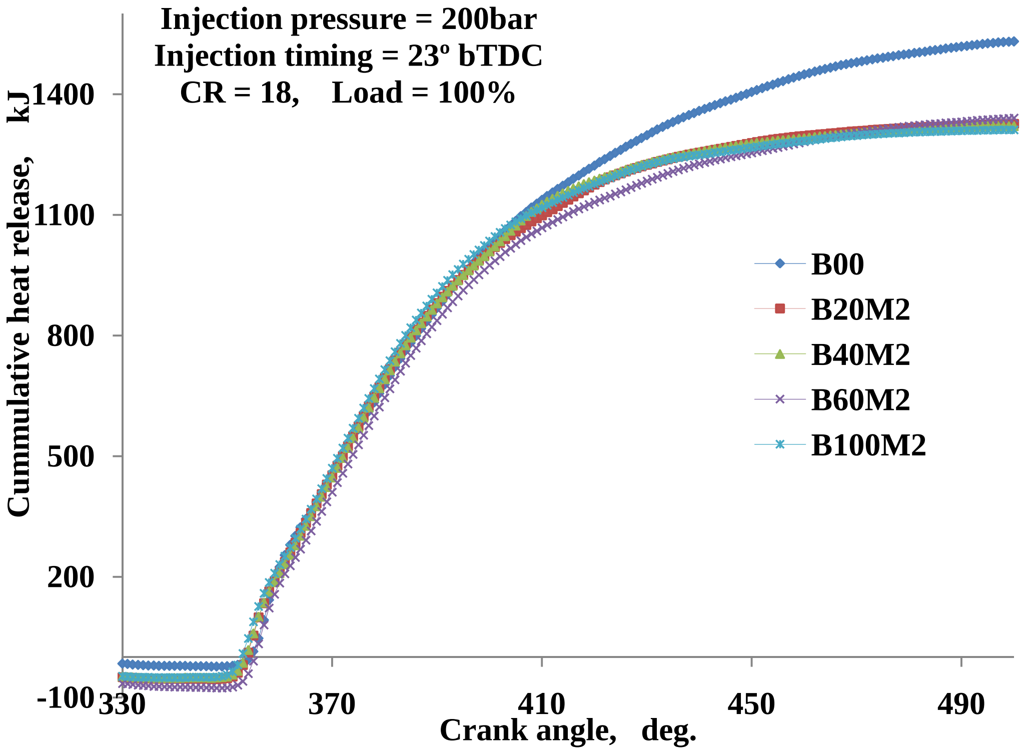


Fig. 5.1.1.4 Variation of CHR with CA

heat release up to B40M2 blends which may perhaps be attributed to enhanced combustion of blends. B100M2 blend has lower CHR which may perhaps be accredited to lesser energy content and sluggish combustion of mixture B100M2. The end of combustion is indicated by cumulative heat release curve [111].

5.1.1.5 Mass fraction burned (MFB) with crank angle

Mass fraction burned in each of the individual phase is a normalised quantity with the scale of 0-100%, unfolding the process of chemical energy released with change in crank angle [115]. The variation of MFB for diesel fuel and various blends at CR18 for the rated load of the engine is shown in Fig.5.1.1.5. Mass fraction burned for biodiesel blends exhibit the similar trend as that of diesel fuel. Initiation of burning of the blends starts earlier in comparison to diesel fuel which may perhaps be attributed to higher CN and inherent oxygen of biodiesel in the blends. Initially mass fractions burned are more rapidly for the blends which may be because of inherent oxygen and higher CN of biodiesel in the blends. The inherent oxygen enhances the mixture formation of fuel-air and accelerates the chemical reactions. The mass fractions burned at TDC are higher for the blends in comparison to diesel fuel which may be because of above explained reason.

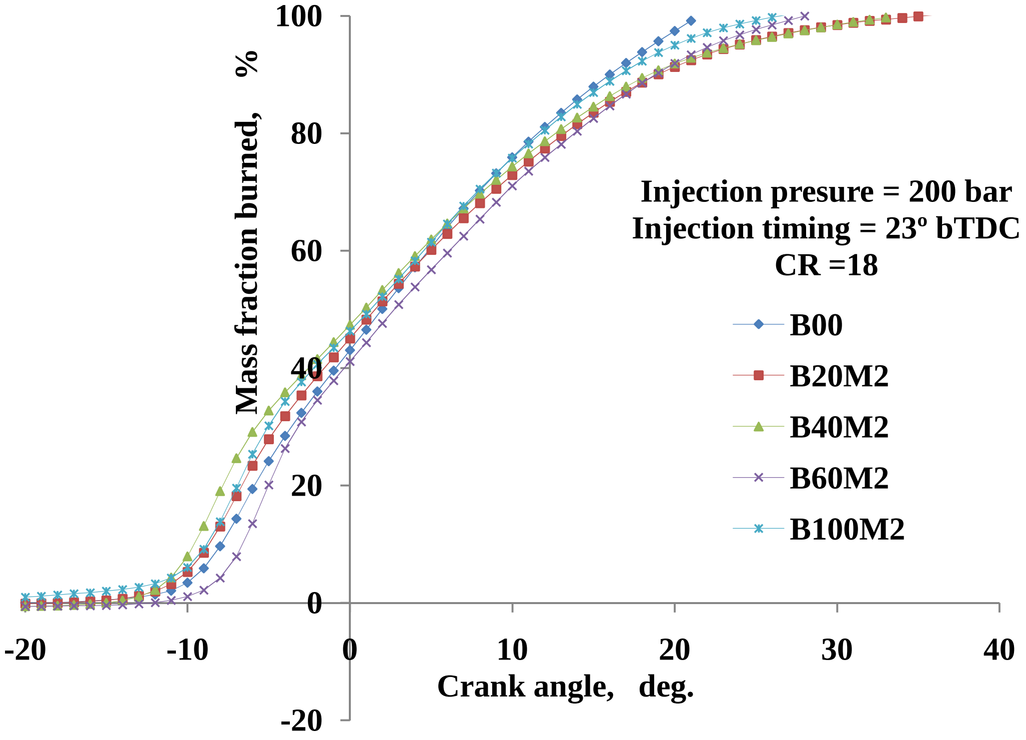


Fig. 5.1.1.5 Variation of MFB with CA

The higher CN enhance the chemical reaction of the fuels used and accelerate the combustion process. Combustion duration increases with the increased volume percentage of biodiesel in the blends which may be attributed to high viscosity and inferior volatility of biodiesel in the blends [112, 113]. The mass fraction burned at TDC for B00, B20M2, B40M2, B60M2 and M2 are 43.03%, 45.07%, 47.33%, 41.13% and 46.31% respectively.

5.1.1.6 Pressure rise rate (RPR) with load

The noise of any engine increases linearly for higher premixed combustion phase regardless of the fuel used and also for the maximum RPR in the engine testing. The pressure rise rate and premixed combustion phase are the critical factors to be considered for the engine noise [116]. The pressure rise rate is the first derivative of cylinder pressure with respect to CA or the time which relates towards the smoothness of engine operation. The maximum pressure rise rate for different load on the engine for various blends at CR18 is shown in the Fig 5.1.1.6. It is seen from the figure that with increase in load the rate of pressure rise increases which may perhaps be accredited to the more amount fuel supply to generate additional power to take the extra load. The maximum pressure rise rates for diesel fuel are found to be 4.79 bars/ ºCA at CR18 for the rated load.

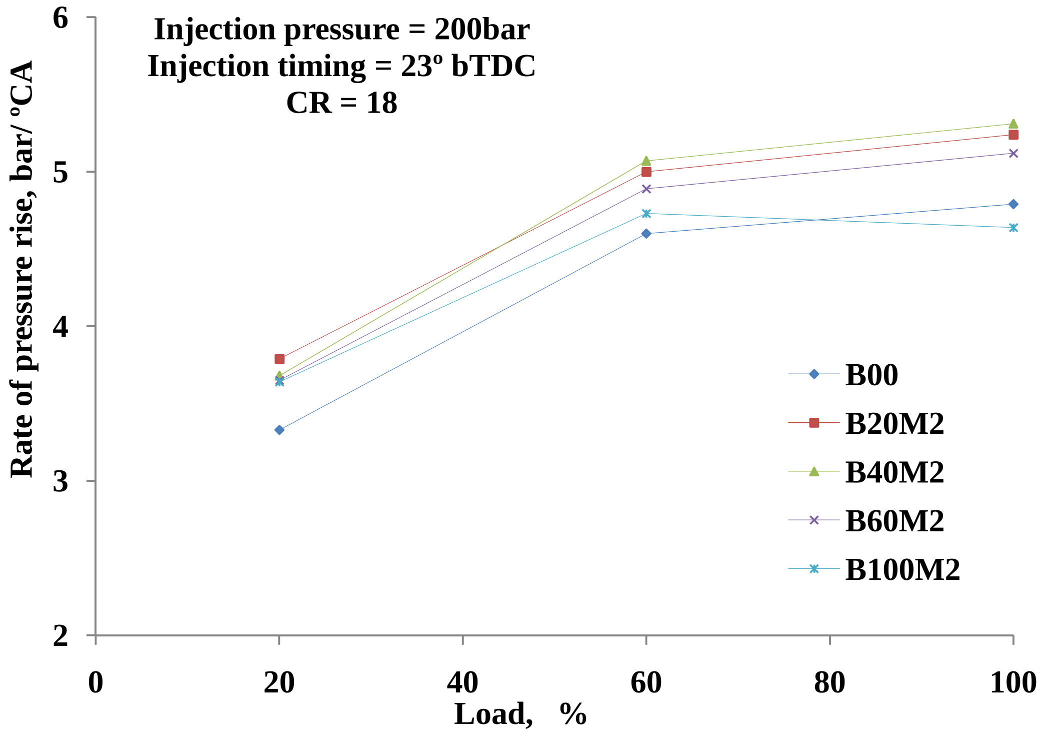


Fig. 5.1.1.6 Variation of RPR with load

The maximum RPR for B20M2, B40M2, B60M2 and B100M2 are 5.24 bars/ ºCA, 5.31 bars/ ºCA, 5.12 bars/ ºCA, 4.64 bars/ ºCA respectively. The pressure rise rate for biodiesel blends is higher compared to diesel fuel which may well be attributed to the better combustion of blends. The B100M2 has lower rate of pressure rise which may perhaps be attributed to higher viscosity and inferior volatility of biodiesel. The pressure rise rate specified for CI engine is 7 bars/ ºCA for single cylinder, four strokes, direct injection CI engine [117]. The pressure rise rates for diesel fuel and biodiesel blends used in the investigation are within the limit prescribed for the engine.

5.1.2 Performance analysis

5.1.2.1 Brake thermal efficiency (BTE) with load

The Change in BTE for the various blends as well as for the diesel fuel for different loads at CR18 is shown in the Fig.5.1.2.1. It is seen from figure that with increase in load BTE increases for the various blends and diesel fuel. The BTE is higher for diesel fuel for all the load which might perhaps be accredited to better mixture formation of fuel-air, higher heating value and better properties of diesel fuel contributes in complete combustion. The B20M2, B40M2 and B60M2 blend has almost similar brake thermal efficiency and are lesser compared to diesel fuel which may perhaps be accredited to higher viscosity and lower energy content of biodiesel in the blends. The same reason was explained by Nazzal for vegetable oils [118]. The BTE of B80M2 and B100M2 blends are lesser in comparison to diesel fuel and other blends might perhaps be accredited to lower heating

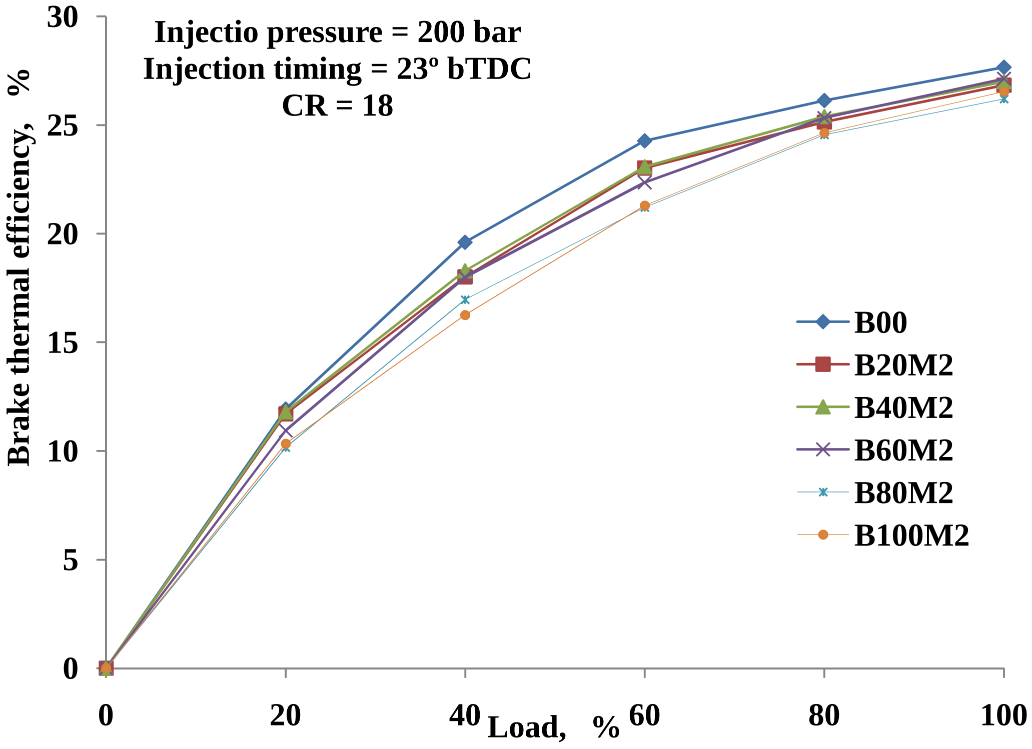


Fig. 5.1.2.1 Variation of BTE with load

value and higher viscosity, inferior volatility of biodiesel in the blends, may be the source of sluggish mixture formation of fuel-air and hence decelerate the combustion. The BTE for diesel fuel is found to be 27.66% for the rated load at CR18. BTE for B20M2, B40M2, B60M2, B80M2 and B100M2 are found to be 26.84%, 27%, 27.13%, 26.2%, and 26.55% respectively at CR18 for the rated load. The BTE for B80M2 and B100M2 are lesser and almost similar which may perhaps be attributed to higher volume fraction of biodiesel in the blends.

4.1.2.2 Brake specific fuel consumption (BSFC) with load

The variation of BSFC for diesel fuel as well as for the various blends for different load at CR18 is shown in the Fig.4.1.2.2. It is seen from the figure that BSFC for various biodiesel blends is following the similar trend as the diesel fuel. This may perhaps be accredited to the biodiesel properties are comparable with diesel fuel. The brake specific fuel consumption deceases with increase in load which might be accredited to increase in load on the engine increases the combustion temperature and decreases the heat lost to the cooling water hence increases the fuel efficiency. The BSFC of diesel fuel is the lower among all the fuels used which may perhaps be attributed to better mixture formation, and higher energy content of diesel fuel. The BSFC of biodiesel blends is higher in comparison to diesel fuel which may well be accredited to lower energy content and

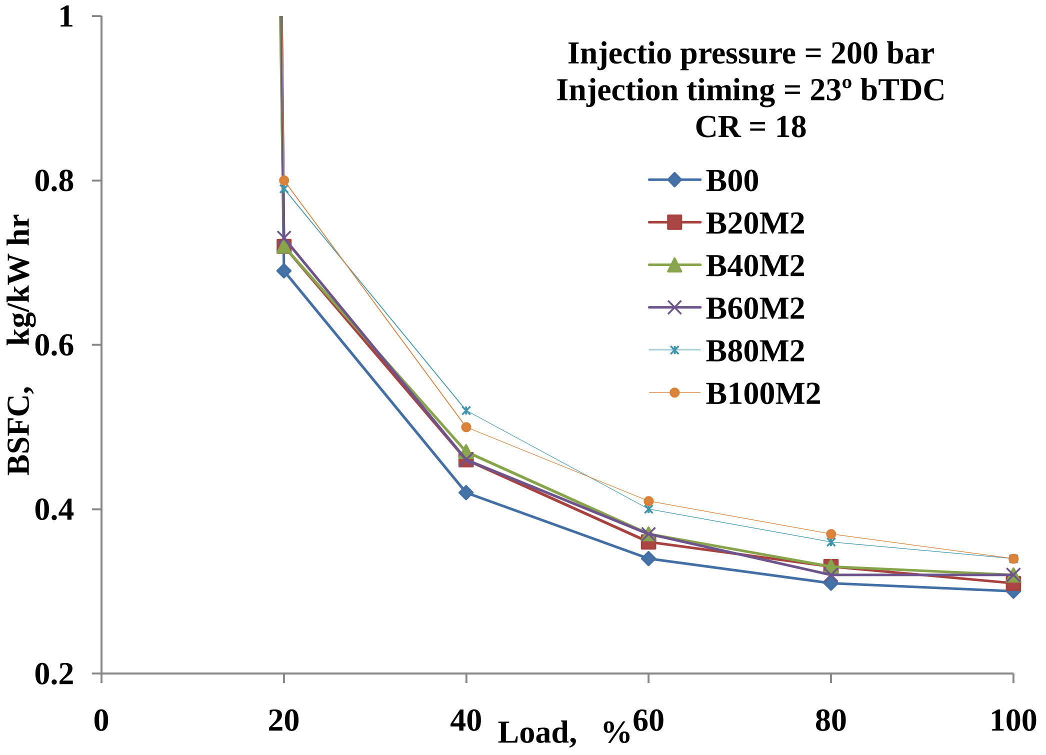


Fig. 5.1.2.2 Variation of BSFC with load

higher density of biodiesel in the blends. The similar reasons were quoted by Altun et al., [119] for the sesame oil diesel blends. The blends B20M2, B40M2 and B60M2 have almost similar brake BSFC which may perhaps be because of the increased volume fraction of biodiesel in the blends improve the combustion of blends. The improved combustion of blends may possibly be accredited to the inherent oxygen and higher CN of biodiesel though the energy content decreases. B80M2 and B100M2 blends have higher brake specific fuel consumption in comparison to diesel fuel and other blends. The brake specific fuel consumption of diesel fuel is 0.3 kg/kW hr which is the lower. The BSFC for B20M2, B40M2, B60M2, B80M2 and M2 are 0.31 kg/kW hr, 0.3 kg/kW hr, 0.32 kg/kW hr, 0.32 kg/kW hr, 0.34 kg/kW hr, 0.34 kg/kW hr respectively at CR18 for the rated load.

5.1.2.3 Exhaust gas temperature (EGT) with load

The variation of EGT of various blend as well as for diesel fuel for different load at CR18 are illustrated in the Fig.5.1.2.3. The EGT increases with increase in load for the fuels used. The exhaust gas temperature indicates the quantity of heat carried away through exhaust with the gasses [120]. The EGT increases with increase in load on the engine which may perhaps be attributed to increased fuel supply with increased load, to take the burden of extra load on engine. This is one of the reasons stated by the researchers in

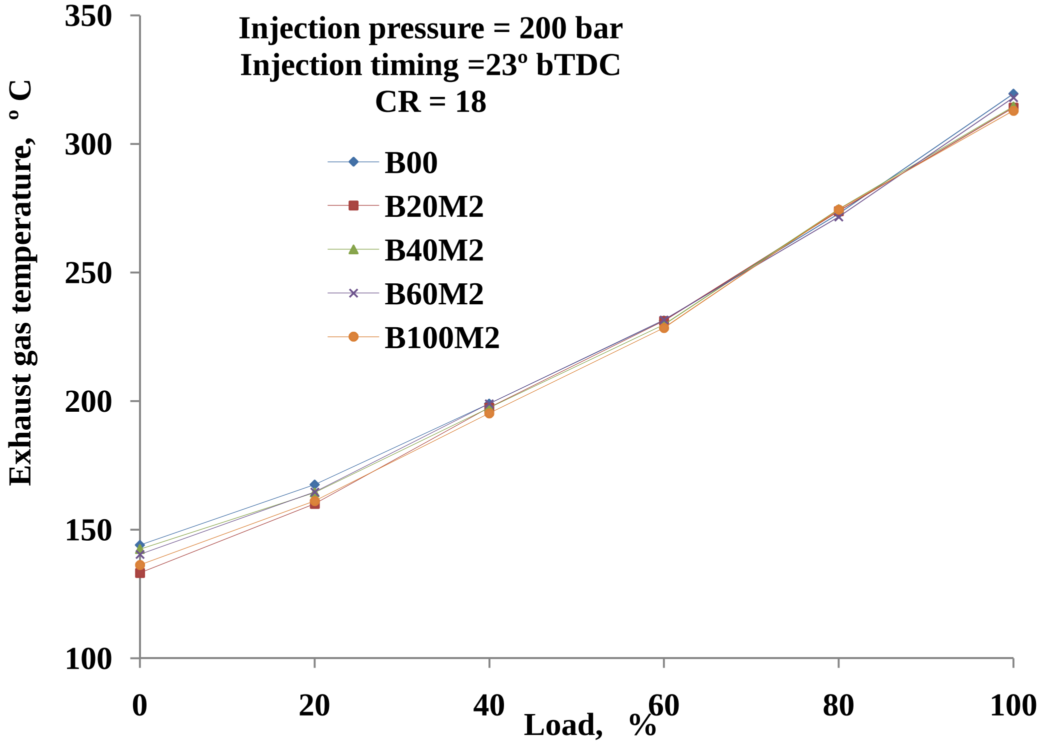


Fig. 5.1.2.3 Variation of EGT with load

common [121-123]. The EGT recorded for B00 (diesel), B20M2, B40M2, B60M2, B80M2 and B100M2 are 320º C, 314º C, 315º C, 321º C, 315º C and 313º C respectively at the rated load. The lower exhaust gas temperature for the blends may well be attributed to better combustion of blends. The lower EGT presents the less heat energy is carried away with the gas. The difference in the exhaust gas temperature can be observed initially for the various blends and diesel fuel may perhaps be because of sluggish combustion of blends.

5.1.3 Emission analysis

5.1.3.1 Carbon monoxide (CO) emissions with load

The combustion process of an ideal engine forms carbon dioxide using carbon and oxygen, if the combustion is complete. Incomplete combustion of fuels forms the carbon monoxide. Emissions of CO for diesel fuel and for the various blends at different load at CR18 are illustrated in the Fig. 5.3.1.1. The carbon monoxide is created all through the combustion process might perhaps be accredited to incomplete combustion because of insufficient oxygen for the complete combustion of the carbon particles present in the fuel. The increased load on the engine combustion temperature increases which leads to better combustion of fuel-air hence producing lesser carbon monoxide emission [123]. For the rated load of the engine fuel supply increases to take up the extra burden of increased load on the engine having the same amount of air causes the incomplete combustion hence increases the CO emissions. The CO emissions are decreased for all the blends and diesel fuel used in the investigations up to about 80% of the rated load. This may be an optimum load for better combustion for lesser CO emissions for all the fuels used. The emissions of CO for diesel fuel at the rated load on the engine are 0.046% which is higher compared to all other blends used. The higher CO emissions for the diesel fuel may be because of lack of oxygen. The similar reason is quoted by Xue et al., [125] in their work. The emissions of CO for B20M2, B40M2, B60M2, B80M2 and B100M2 blends are 0.026%, 0.025%, 0.027%, 0.028% and 0.029% respectively for the rated load. The emissions of CO are higher for diesel fuels at all the loads which may perhaps be accredited to incomplete combustion. The CO emissions for biodiesel blends are lesser which may perhaps be attributed to inherent oxygen and higher CN of biodiesel in the blends contributes in better combustion of blends consequently decreases the CO emissions. The CO emissions are decreased by 45.6% for the blends compared to diesel fuel [126]

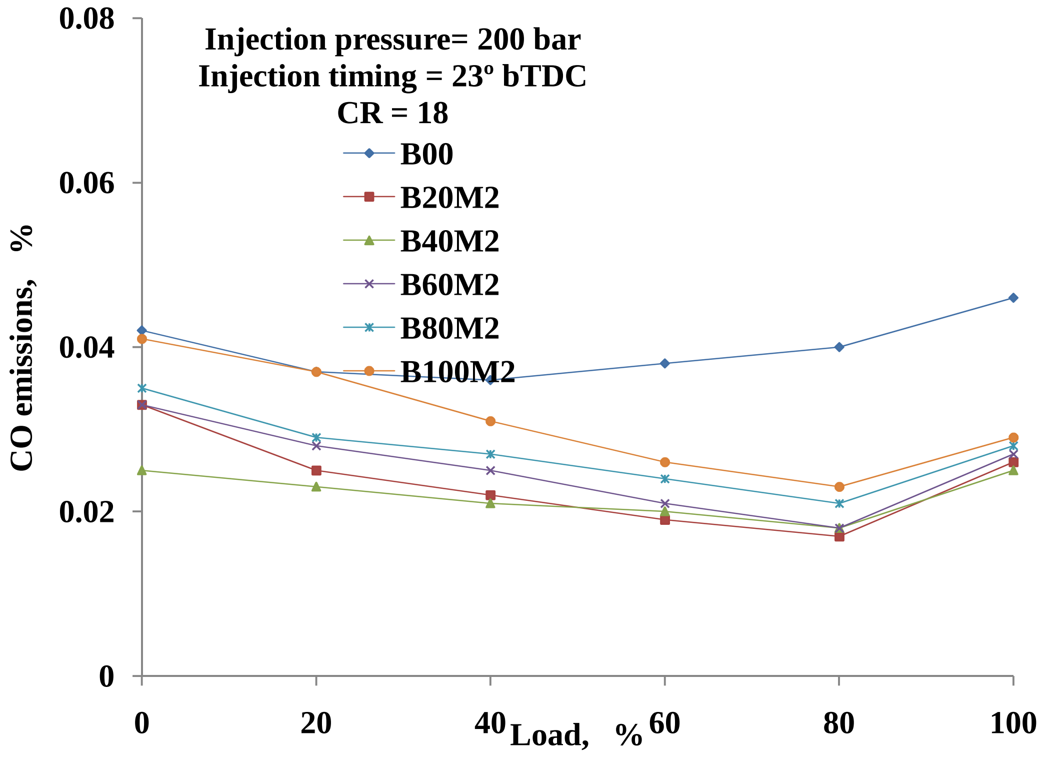


Fig. 5.1.3.1 Variation of CO emissions with load

5.1.3.2 Hydrocarbon (HC) emissions with load

The HC emissions for diesel fuel as well as for various blends used at CR18 for different load are illustrated in the Fig. 5.3.2. The HC emission is the result of incomplete combustion because of inefficient mixing of fuel and the air [127]. The emissions of HC are higher at lower load may perhaps be accredited to lower combustion temperature and is not being higher enough for sufficiently high evaporation of fuel and significant portion of the unburnt fuel may go through exhaust system in the form of HC. The concentration of unburnt HC emission deceases for all the fuels used with increase in load [128]. It may perhaps be observed from the figure that unburnt HC emission for blends is lesser compared to diesel fuel. This may possibly be attributed to inherent oxygen of biodiesel in the blends enhance the mixing of fuel-air consequently improve the combustion of blends hence decreases the unburnt HC emissions. For the rated load unburnt HC emission increases which may well be accredited to incomplete combustion of all the fuels used. This may also be attributed increased turbulence and reduced time for combustion. The unburnt HC emission for diesel fuel at the rated load on the engine at CR18 is 87 ppm. The HC emission for the blends B20M2, B40M2, B60M2, B80M2 and B100M2 are 46 ppm, 42 ppm, 51ppm, 62ppm, and 68 ppm respectively. HC emission for blend B20M2 and B40M2 blends is reduced by about 47.2% and 51.7% compared to diesel fuel for the rated load. At 80 % of the rated load of the engine unburnt HC emissions are least. for the rated load the HC emission increases which may well be accredited to increased fuel supply which may cause the incomplete combustion results into increase in the HC emissions.

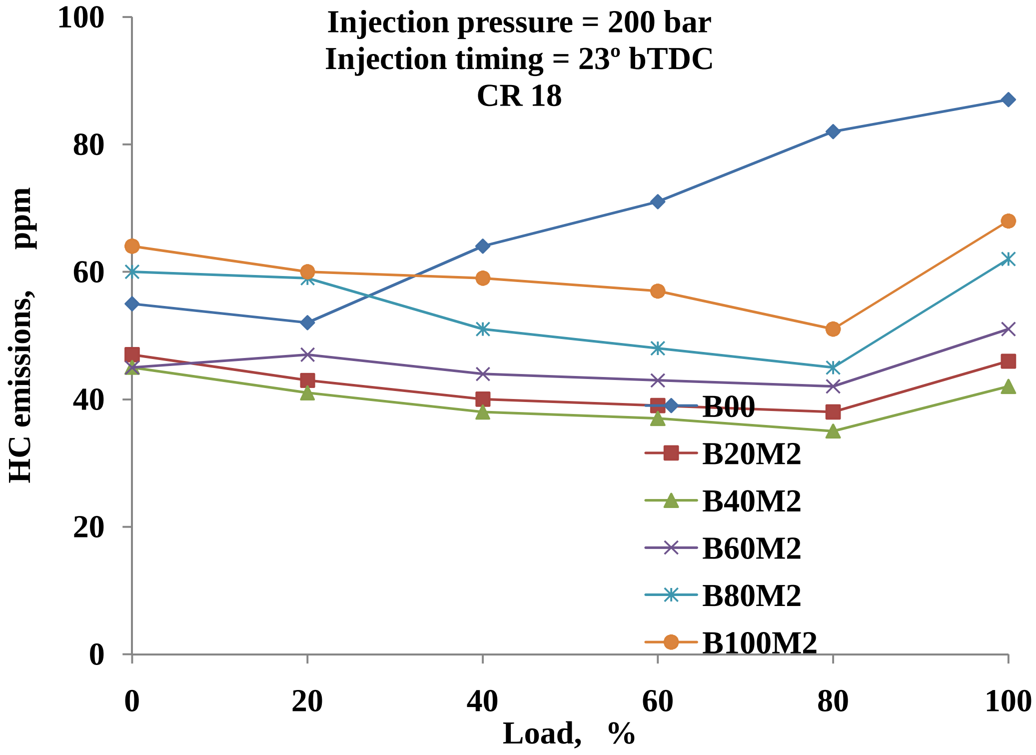


Fig. 5.1.3.2 Variation of HC emissions with load

5.1.3.3 Nitrogen oxide (NOx) emissions with load

The main factor which contributes for NOx emissions are higher temperature and oxygen availability. The NOx emission for diesel fuel as well as for various blends for different load at CR18 is shown in the Fig. 5.1.3.3. For the various loads the NOx emission for all the blends used in the investigation are following the similar trend as the diesel fuel. The NOx emissions are measured at the different loads at CR18 are higher for the blends compared to diesel fuel. The higher NOx emission for the blends may well be attributed to higher combustion temperature and inherent oxygen of biodiesel in the blends [129-131, 111]. The NOx emission for the blend B40M2 is highest which may be an optimum blend for higher NOx formation. As the volume percentage of biodiesel in the blends increases NOx emissions decreases which may perhaps affect the mixture formation. The higher viscosity of biodiesel in the blends may affect the mixture formation consequently the combustion hence decreases the NOx emissions. The NOx emission for diesel fuel at rated at CR18 is found to be 619 ppm. The NOx emission for B20M2, B40M2, B60M2, B80M2 and B100M2 blends is 745 ppm, 778 ppm, 728 ppm, 667 ppm and 632 ppm respectively. The NOx emission for B20M2 and B40M2 blends are 20.4% and 25.7% higher compared to diesel fuel [132].

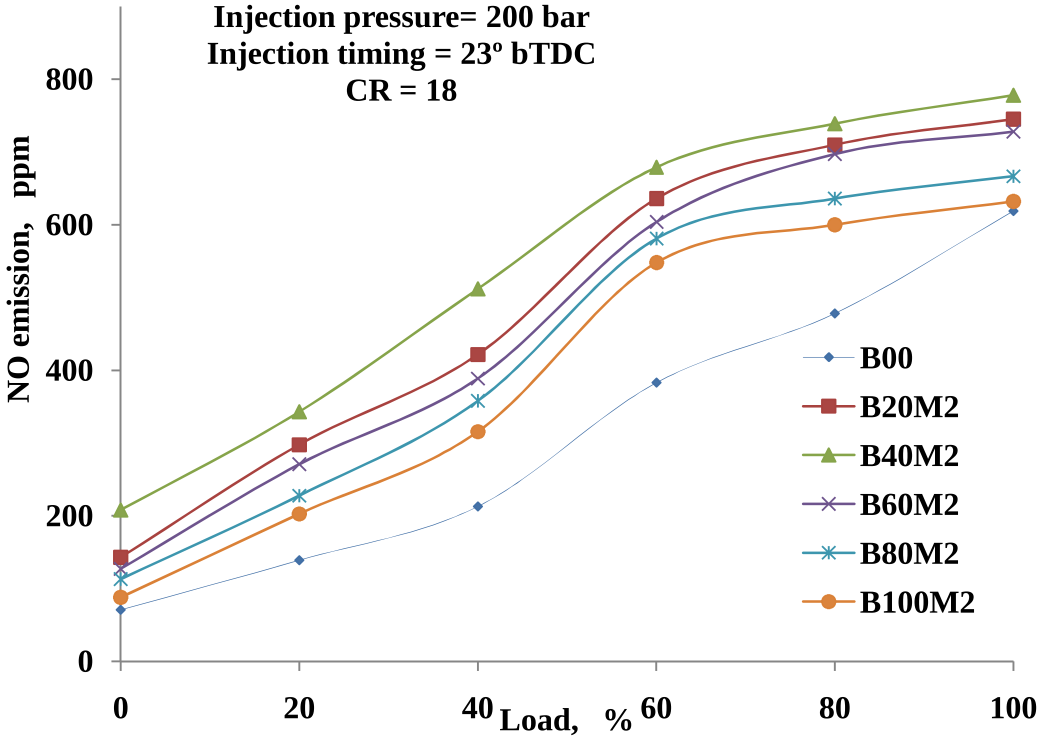


Fig. 5.1.3.3 Variation of NOx emissions with load

5.1.3.4 Smoke emissions with load

The smoke emissions for diesel fuel as well as for the various blends for different load at CR18 are shown in the Fig. 5.3.4. Smoke is solid soot particles formed during the combustion and suspended in the exhaust [111]. The smoke emission increases for diesel fuel as well as for the various blends used with increase in load which may perhaps be attributed to increased quantity fuel supply. The smoke densities for the blends B20M2, B40M2, B60M2, are lesser for almost all the loads in comparison to diesel fuel. This may be attributed to the higher CN and inherent oxygen of biodiesel fuel enhances the mixing of fuel-air and improves the combustion. For the blends B80M2 and B100M2 smoke emissions are higher which may perhaps be attributed to higher viscosity and inferior volatility of biodiesel. The higher viscosity and inferior volatility may affect the mixing of fuel-air consequently incomplete combustion hence decreases the smoke emissions. Higher smoke emissions may perhaps be attributed to unburned and partially reacted hydrocarbon and also the presence of higher density carbon particles present in the exhaust even after the combustion. For almost 60% and above load the smoke emission decreases for all the biodiesel blends used in the investigation in comparison to diesel fuel which may perhaps be attributed to increased combustion temperature. The smoke emissions for diesel fuel at CR18 are 93% for the rated load. The B40M2 blend has lower smoke emissions compared to diesel fuel and other blends used which may perhaps be an optimum blend which emits lesser smoke. Smoke emission for B40M2 blend at CR18 is 80.4% for the rated load. The reduction in smoke emissions for the blend B40M2 by about13.6% compared to diesel fuel.

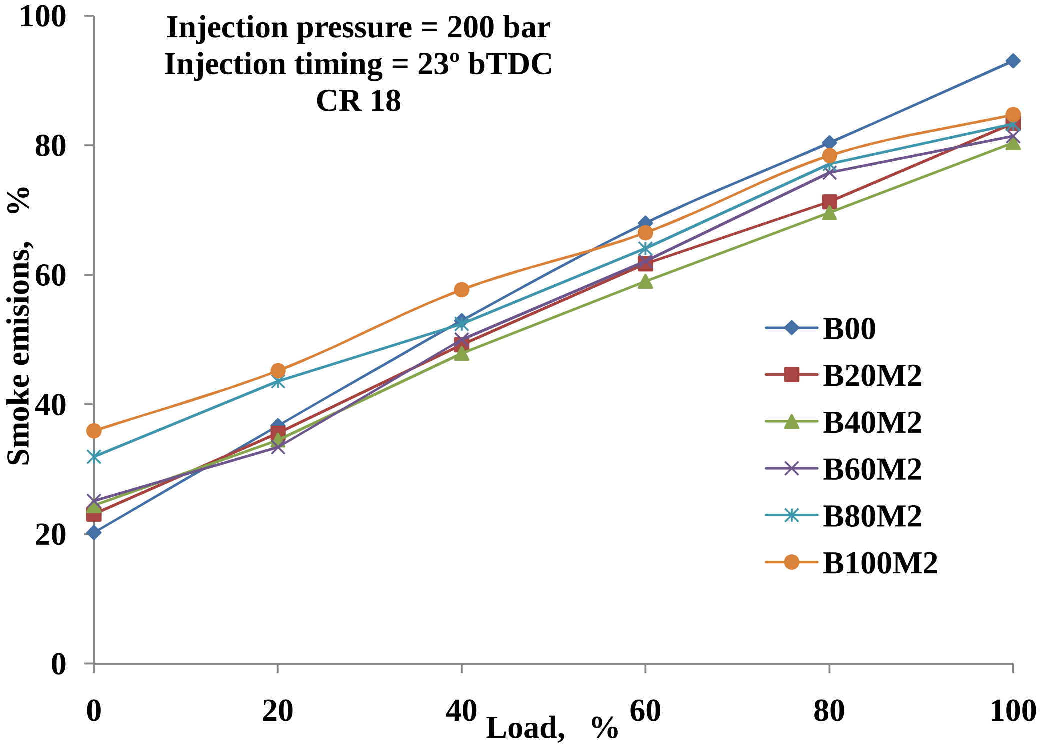


Fig. 5.1.3.4. Variation of smoke emissions with load

5.1.4 Summary

From the results of the experiments it is revealed that the engine can run with biodiesel and diesel blends without any alteration to the existing diesel engine. The engine can run with biodiesel either in blend with diesel fuel in any volume fraction or biodiesel alone without any modification. The detailed analysis of combustion, performance and emission characteristics of the engine using mixture of two biodiesel in blend with diesel give roughly similar performance with reduced CO, HC and smoke emissions in comparison with diesel. The use of various mixture of biodiesel in blend with diesel fuel has revealed, marginally inferior thermal performance with lower BTE and higher BSFC, which may be attributed to lower heating value and higher viscosity of biodiesel in the blend. The exhaust gas temperatures are lesser for the blends in comparison with diesel fuel. The engine can run efficiently with 40% blend of biodiesel with diesel. The maximum up to 40% diesel can be replaced with biodiesel.

Table-5.1.1 Results of engine parameters obtained for diesel and various blends for the rated load at CR18

Sl.No.		B00	B20M2	B40M2	B60M2	B100M2
Combustion Parameters						
1	Maximum pressure, bar	71.4	72.69	72.34	72.65	70.72
2	Max. heat release, J/ºCA	52.79	46.42	43.56	44.81	40.27
3	Max. rate of pr. rise bar/ºCA	4.79	5.12	5.31	5.12	4.64
Performance parameters						
1	Brake thermal efficiency %	27.66	26.84	27	27.13	26.55
2	BSFC kg/kW hr	0.3	0.32	0.32	0.32	0.34
3	EGT ºC	320	314	315	318	313
Emissions parameters						
1	CO emission, %	0.046	0.026	0.025	0.027	0.029
2	HC emission, ppm	87	46	42	51	87
3	NO emission, ppm	619	745	778	728	632
4	Smoke emission, %	93	83.4	80.4	81.4	84.7

5.2 Combustion, Performance and Emissions analysis of Pongamia and Simarouba biodiesel blends (P50+S50) with diesel

General

Pongamia and Simarouba biodiesel are mixed in the ratio of 50:50. The various blends are prepared using the mixture of P50+S50; the mixture of these biodiesels is designated as M5. The various blends are prepared using mixture M5 with diesel fuel. The blend B20M5 indicates, 20% of M5 + 80% of diesel. The other blends prepared are B40M5, B60M5, B80M5 using M5 with diesel fuel and B100M5 is the mixture of two biodiesel. These blends are used in the investigation of combustion, thermal performance and emission characteristics of DI VCR diesel engine. The various combustion characteristics investigated are cylinder gas pressure, net and cumulative heat release, mass fraction burned and pressure rise rate. The thermal performance parameters investigated are BTE, BSFC, EGT and emissions measured are CO, HC, NOx, smoke. The results are compared with the results of base line diesel fuel at the same operational condition all through the investigations. The results obtained for various blends and diesel fuel is discussed.

5.2.1 Combustion Analysis

5.2.1.1 Cylinder pressure with crank angle

The cylinder gas pressures with the change in CA for diesel fuel and for the various blends for rated load at CR18 are illustrated in Fig. 5.2.1.1. The cylinder gas pressure for various blends used in the investigation are following similar trend as diesel fuel which may be because of the biodiesel properties are comparable diesel fuel. The cylinder pressure are higher for the blends B20M5, B40M5 and B60M5 compared to diesel fuel at CR18 for the rated load which might be attributed to higher CN and inherent oxygen of biodiesel in the blends. The inherent oxygen and higher CN enhance the mixture formation of fuel-air and accelerate the combustion consequently the higher cylinder pressure. In addition the reason for higher cylinder pressure may perhaps be accredited to advanced start of injection and combustion. The advance start of injection may be because of higher bulk modulus of biodiesel in the blends. The advanced start of combustion of biodiesel blends may be because of higher CN of biodiesel in the blends. The cylinder gas pressures for B100M5 mixture are lesser compared to diesel fuel and other blends which may well be accredited to lesser heat content and higher viscosity, inferior volatility of biodiesel in the blends. The higher viscosity and inferior volatility may affect the mixture formation of fuel-air hence incomplete combustion which decreases the cylinder pressure. The cylinder pressure for diesel fuel at CR18 is 70.63 bars for the rated load. The cylinder pressure for the blends B20M5, B40M5, B60M5 and B100M5 are 71.45 bar, 70.63 bar, 71.39 bar, and 66.78 bar respectively for the rated load. The maximum cylinder pressure for B00, B20M5, B40M5, B60M5 blends are at 10° aTDC whereas for B100M5 are at 9° aTDC. The premixed or uncontrolled combustion for the blends is better in comparison to diesel fuel which might be accredited to higher CN and oxygen content of biodiesel in the blends. The higher CN and oxygen content which may enhance the chemical reaction and initiate the combustion earlier for the blends. Mixing controlled combustion and after burning phase are higher for diesel fuel which may perhaps be accredited to delayed start of combustion of diesel fuel.

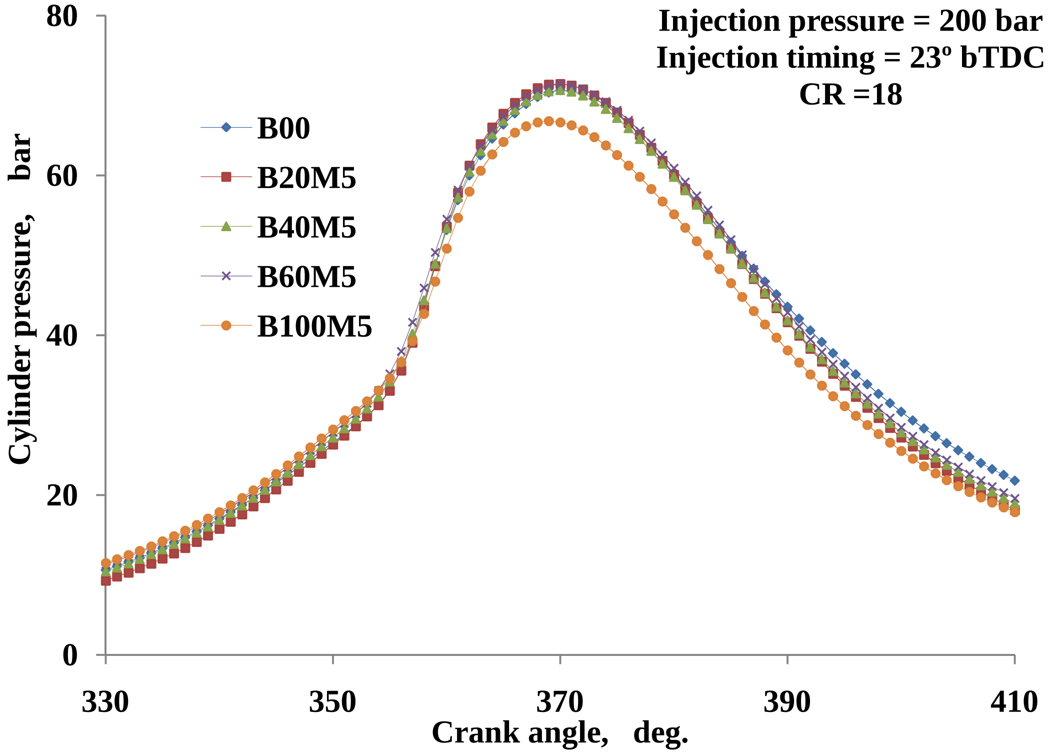
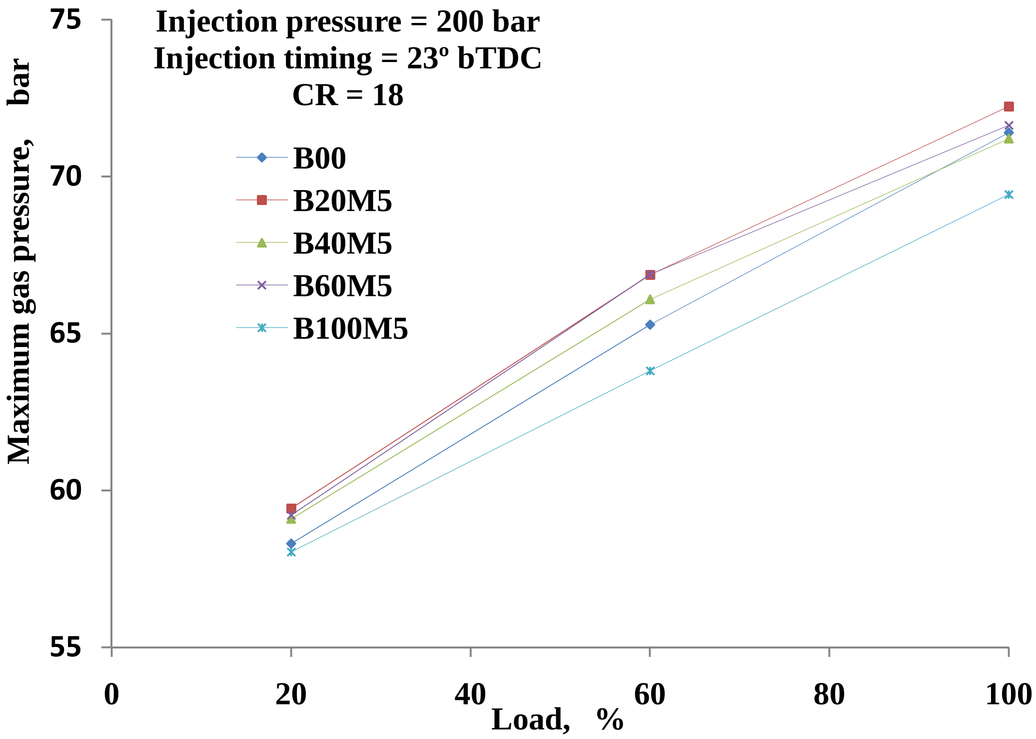


Fig. 5.2.1.1 Variation of cylinder pressure with CA

5.2.1.2. Maximum cylinder pressure with load

The maximum cylinder gas pressures are mainly depending on the quality and quantity of fuel burned in the premixed combustion stage which may results into the output of the engine. The values of maximum pressure are taken from the pressure volume plot data acquired from the data acquisition system. The change in maximum cylinder gas pressure for diesel fuel and for the various blends for different loads at CR18 is illustrated in Fig.5.2.1.2. The cylinder gas pressure increases with increase in load for diesel fuel and for the blends used in the investigation which may possibly be attributed to increased amount of fuel supply. The maximum cylinder gas pressure for the blends may perhaps be accredited to inherent oxygen and higher CN of biodiesel in the blends. The inherent oxygen and higher CN of biodiesel may enhance the mixture formation of fuel-air and accelerate the chemical reaction and the combustion. The maximum cylinder gas pressure of B20M5, B40M5 and B60M5 blends are higher compared to diesel fuel at CR18 for the rated load. The maximum cylinder gas pressure is lesser for the mixture B100M5 might be accredited to lesser heat value and higher viscosity, inferior volatility of the mixture of two biodiesel (B100M5). This may probably diminish the mixture formation of fuel-air and hence the sluggish combustion. The maximum cylinder pressure for diesel fuel is 71.4 bars at CR18 for the rated load. The maximum cylinder pressure for the blends for B20M5, B40M5, B60M5 and B100M5 are 72.3 bars, 71.2 bars, 71.63 bar and 69.43 bars respectively at CR18 for the rated load.



5.2.1.2 Variation of maximum pressure with load

5.2.1.3 Net heat release (NHR) with CA

The fuel injected in to the combustion chamber will not burn instantly. The injected fuel will go through atomisation, evaporation and then mixed with air before it ignites. All these process is called ignition delay. The net heat released is the result of rapid burning of air-fuel mixture accumulated all through the delay period is called premixed combustion or uncontrolled combustion stage. The maximum heat energy released during the premixed combustion by burning of the fuel is called the net heat release. The net heat release for diesel fuel as well as for the various blends used at CR18 for the rated load is illustrated in Fig. 5.2.1.3. Net heat releases for the diesel fuel are higher which may perhaps be accredited to better mixture formation of fuel-air and higher heating value of diesel fuel. The lower net heat release for biodiesel blends may perhaps be accredited to reduced ignition delay and lower heat value of the blends. The maximum net heat release for diesel fuel at CR18 is 52.79 J/º CA for the rated load and is at 3º bTDC. The maximum net heat release for blends B20M5, B40M5, B60M5 and B100M5 are 45.79 J/º CA, 40.56 J/º CA, 40.04 J/º CA, and 42.08 J/º CA respectively and are at 3º bTDC, 3º bTDC, 4º bTDC, and 5º bTDC. Biodiesel blends have lesser net heat release compared to diesel fuel which may be accredited to lower heat value and higher viscosity of biodiesel in the blends.

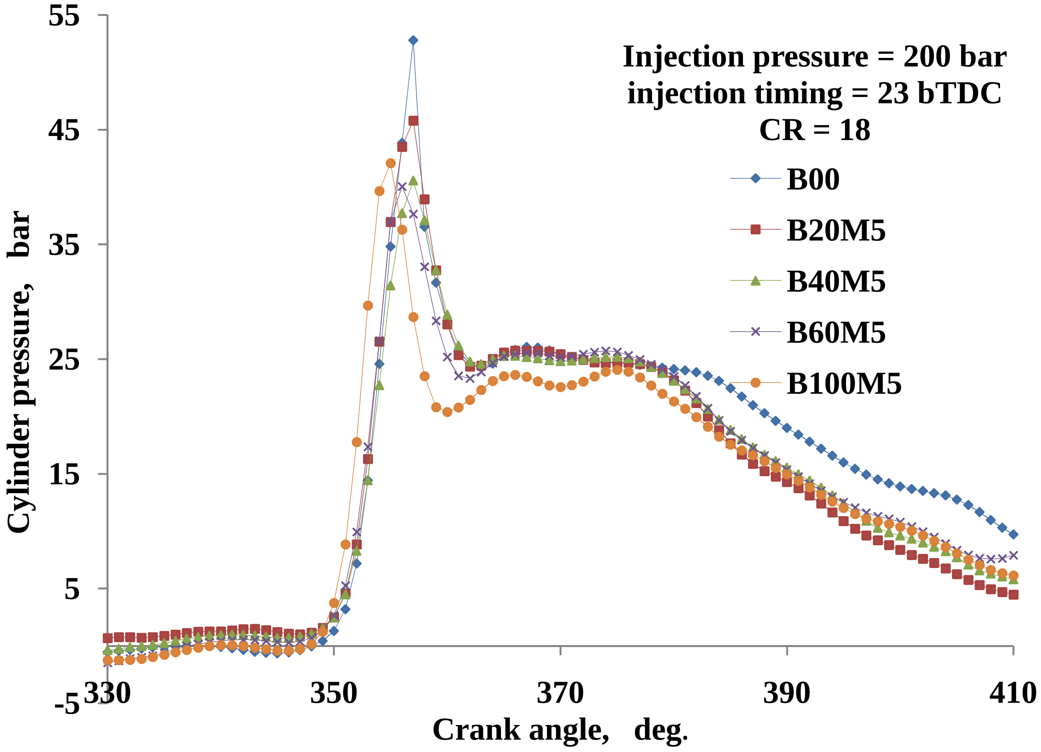


Fig. 5.2.1.3 Variation of NHR with CA

5.2.4.1 Mass fraction burned (MFB) with CA

Mass fraction burned in each of the individual cycle of the engine is normalised quantity with a scale of 0 to 100%, describing about the progress of chemical energy released as the function of CA. The variation of mass fraction burned for various blends and diesel at CR18 for the rated load is shown in Fig 5.2.1.4. It might be seen from the figure that burning of all the biodiesel blends starts earlier in comparison to diesel fuel which may well be accredited to higher CN and oxygen content of biodiesel in the blends. At TDC the mass fraction burned for diesel fuel at CR18 for the rated load is 25.47%. The mass fraction burned for the blends B20M5, B40M5, B60M5 and B100M5 at TDC are 32.64%, 29.8%, 23.69% and 29.71% respectively at CR18 for the rated load. The 50% mass fraction burned for various blends and diesel fuel are varies in the range of 3° CA. However combustion for diesel fuel starts later compared to the blends, completion of 100% burning (combustion) is at earlier crank angle compared to the blends which may perhaps be attributed to better combustible properties of diesel fuel. Increase in volume fraction of biodiesel in the blend the duration of mass fraction burned increases in terms of crank angle. The duration of mass fraction burned for B20 blend is less compared to other blends which may perhaps be attributed lower volume fraction of biodiesel in the blends; hence B20 blend may well be used in the existing diesel engine without any modification.

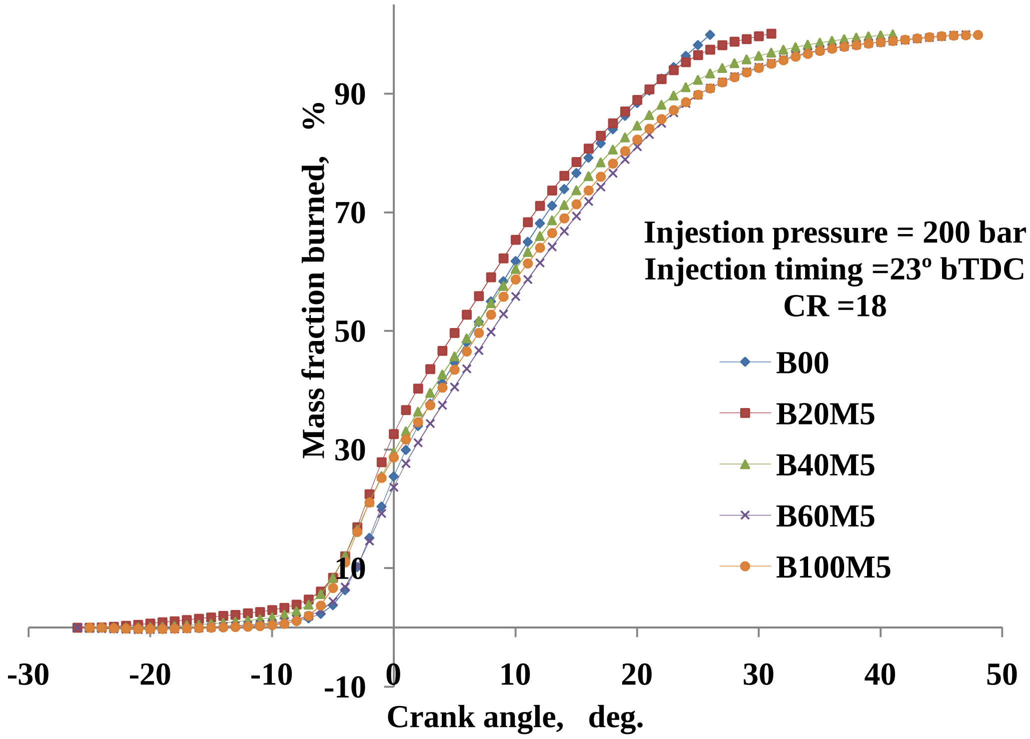


Fig. 5.2.1.4 Variation of mass fraction burned with crank angle

5.2.1.5 Maximum rate of pressure rise (RPR) with CA

The increase in magnitude of premixed combustion, the rate of pressure rise increases regardless of the fuels used hence the noise of the engine increases linearly. The RPR indicates the smoothness of engine operation and it is the first derivative of cylinder gas pressure with respect to CA. Thus the control of maximum RPR and the magnitude of uncontrolled or premixed combustion are the essential factors in controlling the noise of the engine and consequently the vibrations. The variation of RPR diesel fuel and for the various blends used at CR18 for different load is illustrated in Fig. 5.2.1.5. It may perhaps be observed from figure that as the load on the engine increases the rate of pressure rise increases for the diesel fuel and as well as for the blends. The highest RPR for the diesel fuel is found to be 4.79 bar/ ºCA at CR18 for the rated load. The RPR for B20M5, B40M5, B60M5 and B100M5 are 5.02 bars/ ºCA, 4.72 bars/ ºCA, 4.63 bars/ ºCA, 4.42 bars/ ºCA respectively at CR18 for the rated load. At lower load the rate of pressure rise rate is higher for diesel fuel which may possibly be accredited to better combustible properties of diesel fuel. The pressure rise rate for single cylinder four stroke direct injection diesel engine is prescribed to be 7bars/ºCA. The rate of pressure rise for biodiesel blends is within the prescribed limit for the said engine.

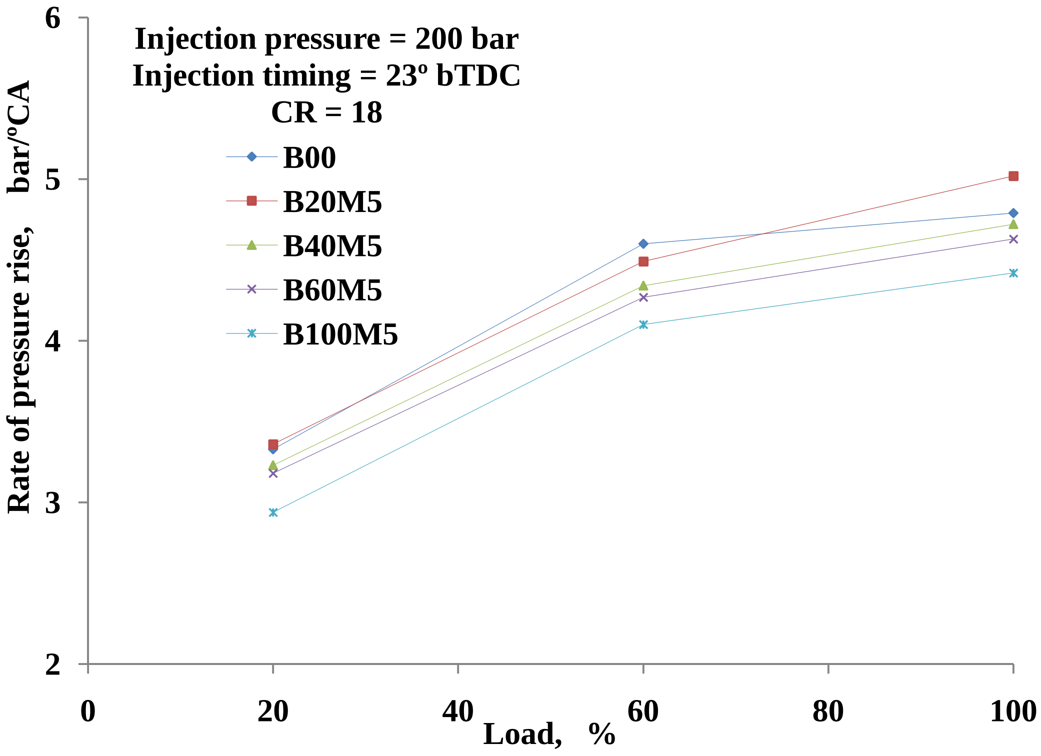


Fig. 5.2.1.5 Variation of rate of pressure rise with CA

5.2.2 Performance analysis

5.2.2.1 Brake thermal efficiency (BTE) with load

The change in BTE for diesel fuel as well as for various blends for different loads at CR18 is shown in Fig 5.2.2.1. The BTE increases with increase in load for diesel fuel as well as for the various blends used. The BTE of diesel fuel is higher for entire load range which may be attributed to higher heating value and the better combustible properties of diesel fuel which contribute in complete combustion. The BTE for the various blends are lesser in comparison to diesel fuel which may perhaps be accredited to lower heat value and higher viscosity, inferior volatility of biodiesel in the blends. The BTE for the lower blends are higher which may perhaps be accredited to higher CN and inherent oxygen of biodiesel in the blends. The inherent oxygen may improve the mixture formation of fuel-air which increases the chemical reactions and higher CN number may accelerate the combustion hence higher BTE. The BTE for diesel fuel at CR18 is 27.66% for the rated load. The BTE at CR18 are 27.32%, 28.49%, 27.63% for the blends B20M5, B40M5, and B60M5 for the rated load respectively. The higher BTE for the blends B40M5 and B60M5 may possibly be accredited to better and complete combustion of blends.

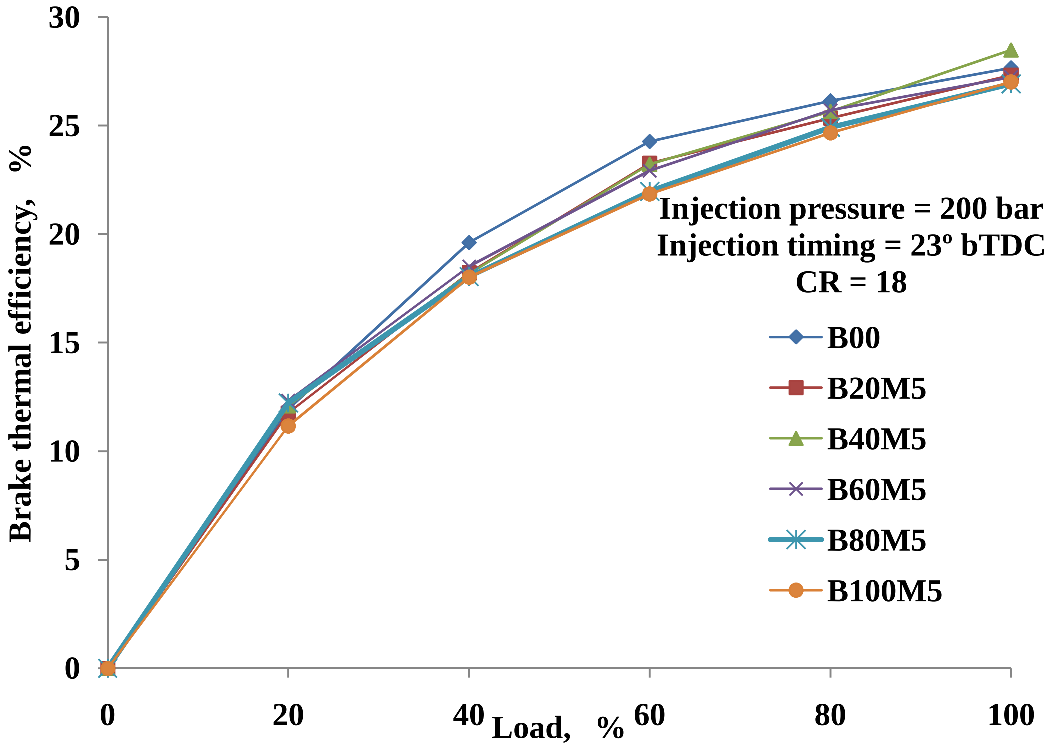


Fig. 5.2.2.1 Variation of BTE with load

This may be because of higher CN and inherent oxygen of biodiesel in the blends. The blends B80M5 and B100M5 have the lower BTE in comparison to diesel fuel and the other blends which might perhaps be accredited to lower heating value accompanied with increased viscosity, reduced volatility of the blends. Higher viscosity of the blends B80M5 and B100M5 may affect the mixture formation of fuel-air which causes the sluggish combustion consequently lower brake thermal efficiency.

5.2.2.2 Brake specific fuel consumption (BSFC) with load

The variation of BSFC for diesel fuel as well as for various blends for different load at CR18 is shown in Fig. 5.2.2.2. BSFC decreases with increase in load for diesel fuel and as well as for various blends which may perhaps be accredited to increased combustion temperature with increased in load and also the decrease in heat loss to the cooling water. The BSFC of different biodiesel blends following the similar trend as that of diesel fuel which may perhaps be accredited to the properties of biodiesel fuel are comparable with diesel fuel. The BSFC of diesel fuel is lesser in comparison to the blends which may perhaps be accredited to the higher energy content. The BSFC of B20M5, B40M5, B60M5 blends are marginally higher compared to diesel fuel which may perhaps be accredited to lesser heat content and inferior volatility, higher viscosity of biodiesel in the blends. The BSFC of blends B20M5, B40M5 and B60M5 are closer to diesel fuel at 80% and above of the rated load which may perhaps be accredited to increased combustion temperature. The higher combustion temperature may complete the combustion of blends

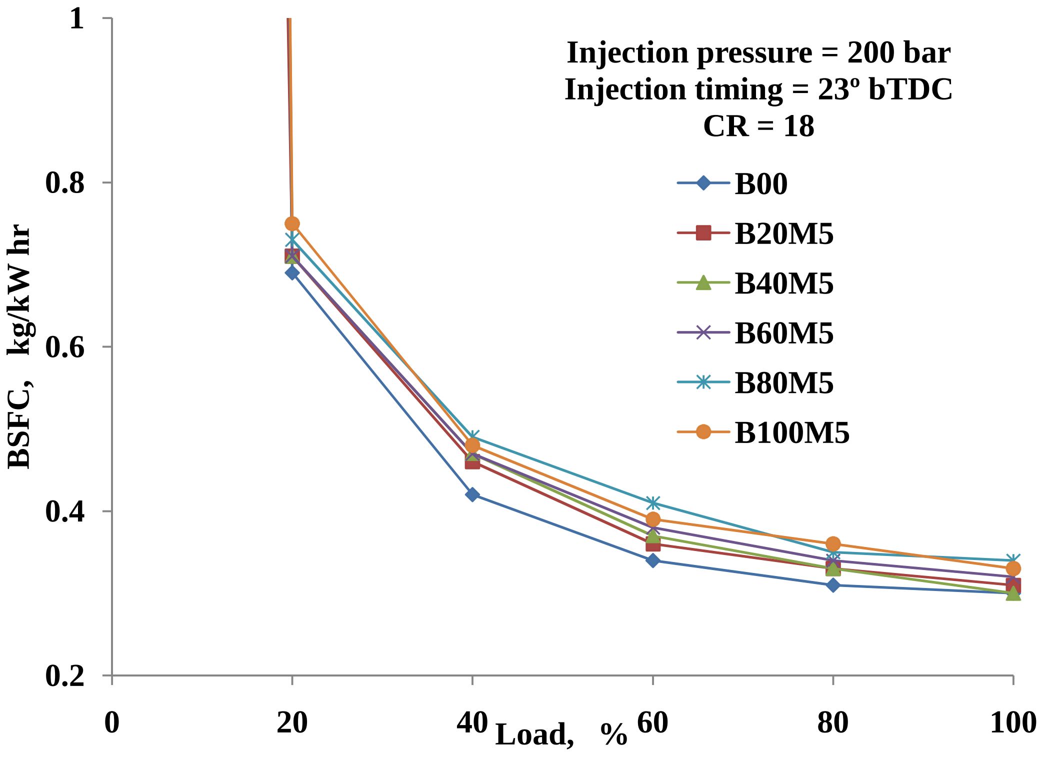


Fig. 5.2.2.2 Variation of BSFC with load

consequently the lower BSFC and are closer to diesel fuel. The BSFC for the blends B80M5 and B100M5 are higher in comparison to diesel fuel and other blends which may perhaps be accredited to lower heat content and higher viscosity, inferior volatility of biodiesel in the blends. The higher viscosity and lower volatility may perhaps be affecting the mixture formation of fuel-air which in turn causes the incomplete combustion. The BSFC are 0.3 kg/kW hr, 0.31 kg/kW hr, 0.3 kg/kW hr, 0.32 kg/kW hr, 0.34 kg/kW hr, 0.33 kg/kW hr for B00, B20M5, B40M5, B60M5, B80M5 and B100M5 respectively.

5.2.2.3 Exhaust gas temperature (EGT) with load

The EGT for diesel fuel and as well as for the various blends for different load at CR18 is illustrated in the Fig. 5.2.2.3. The EGT indicates the amount of heat carried away through the exhaust gases. It may perhaps be observed from the figure that EGT increases for increased load on the engine which may perhaps be accredited to increased amount of fuel supply to sustain the increased load. The EGT for the different biodiesel blends may perhaps be following the comparable trend as that of diesel fuel. The exhaust gas temperature for diesel fuel at the rated load is 320º C and for the blends B20M5, B40M5, B60M5, B80M5 and B100M5 are 306º C, 310º C 308º C, 314º C, and 309º C respectively. The exhaust gas temperature for diesel fuel is higher in comparison to biodiesel blends for entire operating conditions of engine. The higher exhaust gas

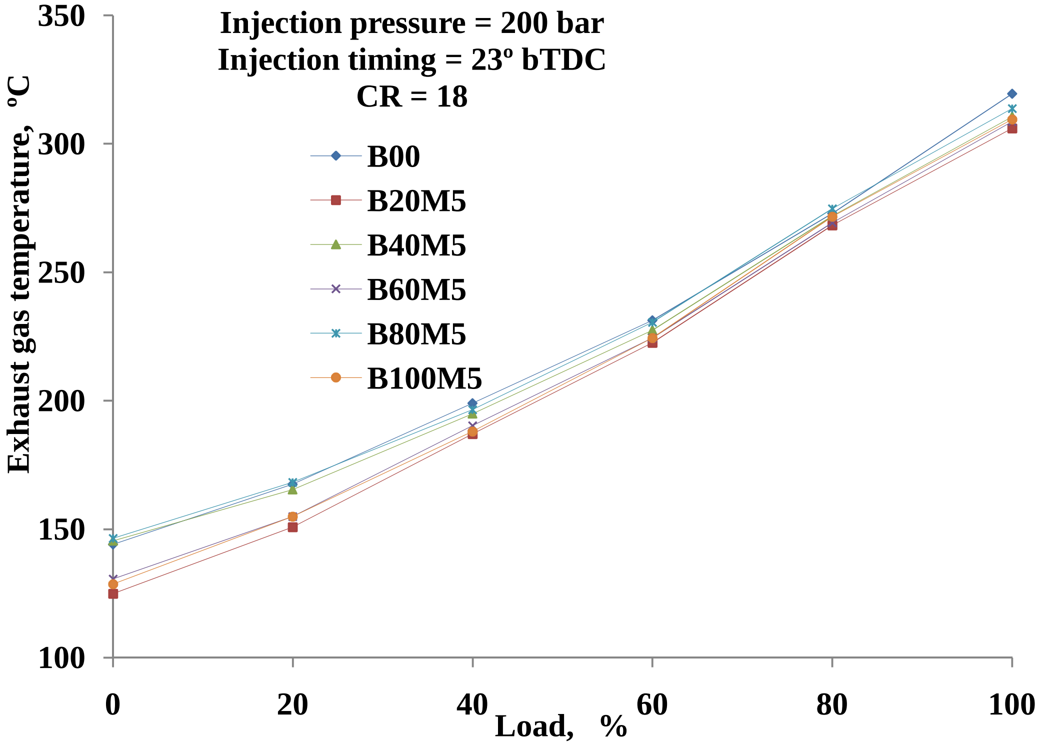


Fig. 5.2.2.3 Variation of EGT with load

temperature for diesel fuel shows the heat lost through exhaust is higher compared to the blends. The heat lost through the exhaust for the blend B20M5 is reduced by about 4.4% compared to diesel fuel.

5.2.3 Emission analysis

5.2.3.1 Carbon monoxide (CO) emissions

The Carbon monoxide emissions are because of inefficient combustion of fuel supplied to the engine. The incomplete combustion of fuel may be because of lack of oxygen or less time available for complete combustion of fuels. In general CI engines are supplied with lean mixture hence they emit less carbon monoxide. The emissions of CO are quite lower for diesel engine in comparison with spark ignition engines. The emissions of CO for diesel fuel and as well as for the various blends at different load at CR18 is illustrated in the Fig.5.2.3.1. The emissions of CO for diesel fuel are higher compared to the blends which may perhaps be accredited to incomplete combustion of diesel fuel. The incomplete combustion of diesel fuel may be because of lack of oxygen. The emissions of CO for the entire range of blends are lesser in comparison to diesel fuel which may perhaps be attributed to complete combustion of blends. Complete combustion of blends may possibly be accredited to inherent oxygen of biodiesel in the blends which may enhance the mixing of fuel-air consequently improve the combustion results into decrease of CO emissions. The blend B40M5 gives least CO emissions which may perhaps be an optimum mixture for complete combustion compared to other blends and diesel fuel. The CO emissions for diesel fuel at CR18 are 0.046% at the rated load and for the blends B20M5; B40M5 blends 0.032%, 0.026%, respectively for the rated load. For B60M5 and above blends emission of CO increases which may be attributed to poor mixing of fuel-air for the reason that of higher viscosity and inferior volatility of biodiesel in the blends consequently sluggish combustion. The CO emissions for the blends for B60M5, B80M5, and B100M5 are 0.042%, 0.045%, 0.046% respectively. The emissions of CO are decreased for the blend B40M5 by about 43.5% compared to diesel fuel.

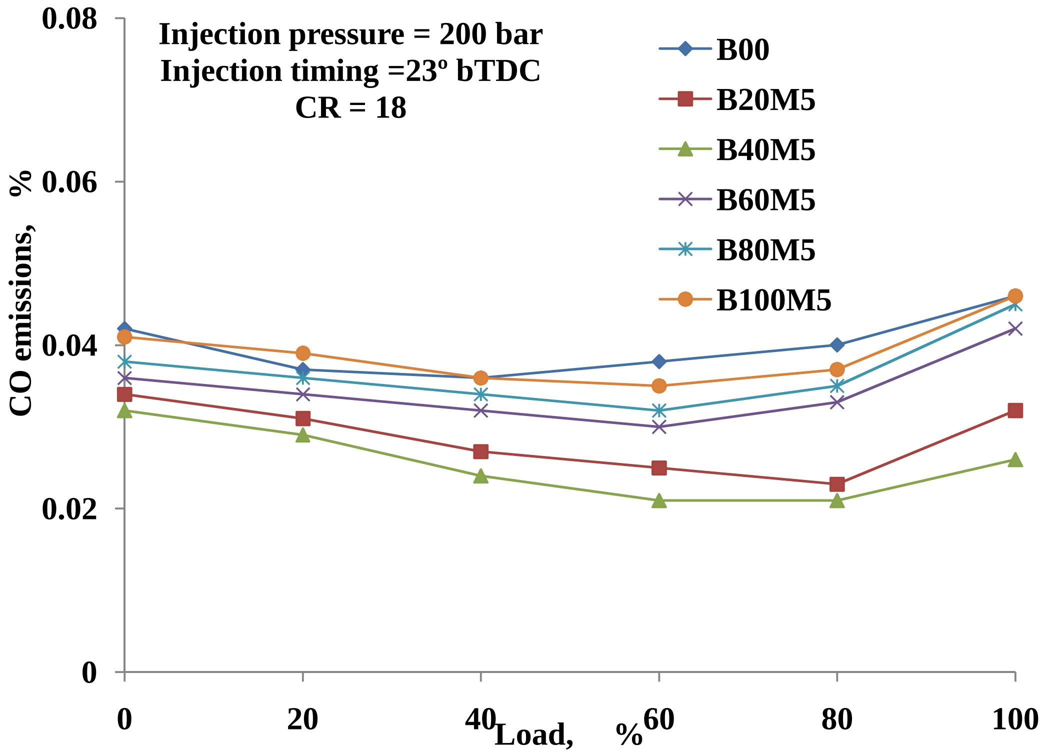


Fig. 5.2.3.1 Variation of CO emissions with load

5.2.3.2 Hydrocarbon (HC) emissions

The hydrocarbon emissions are formed because of inefficient combustion of fuel supplied to the engine which may perhaps be accredited to the poor mixing of fuel-air or the lesser time available for the combustion of fuel. The concentration of hydrocarbon increases for increase in load on engine which may perhaps be attributed to increased fuel supply to carry the burden of increased load. The emission of HC diesel fuel and for the various blends for different load at CR18 is illustrated in Fig. 5.2.3.2. It may be seen from the figure that hydrocarbon emissions for diesel fuel are higher in comparison to blends which may perhaps be accredited to incomplete combustion. The incomplete combustion of diesel fuel may perhaps be accredited to lack of oxygen. The hydrocarbon emission is lesser for biodiesel blends may perhaps be accredited to inherent oxygen and higher CN of biodiesel in the blends. The inherent oxygen and higher CN of biodiesel in the blends may improve the mixing of fuel-air and complete the combustion. The HC emissions for the blend B20M5 are 47 ppm at rated load and are least among the blends. The CO emissions increased for the increased volume fraction of biodiesel in the blend which may possibly be accredited to higher viscosity and inferior volatility of biodiesel in the blends. The HC emissions for diesel fuel are 87 ppm for the rated load. The HC emissions for the other blends are in between the blend B20M5 and diesel fuel. The reduction in HC emissions for the blend B20M5 are by about 46% compared to diesel fuel.

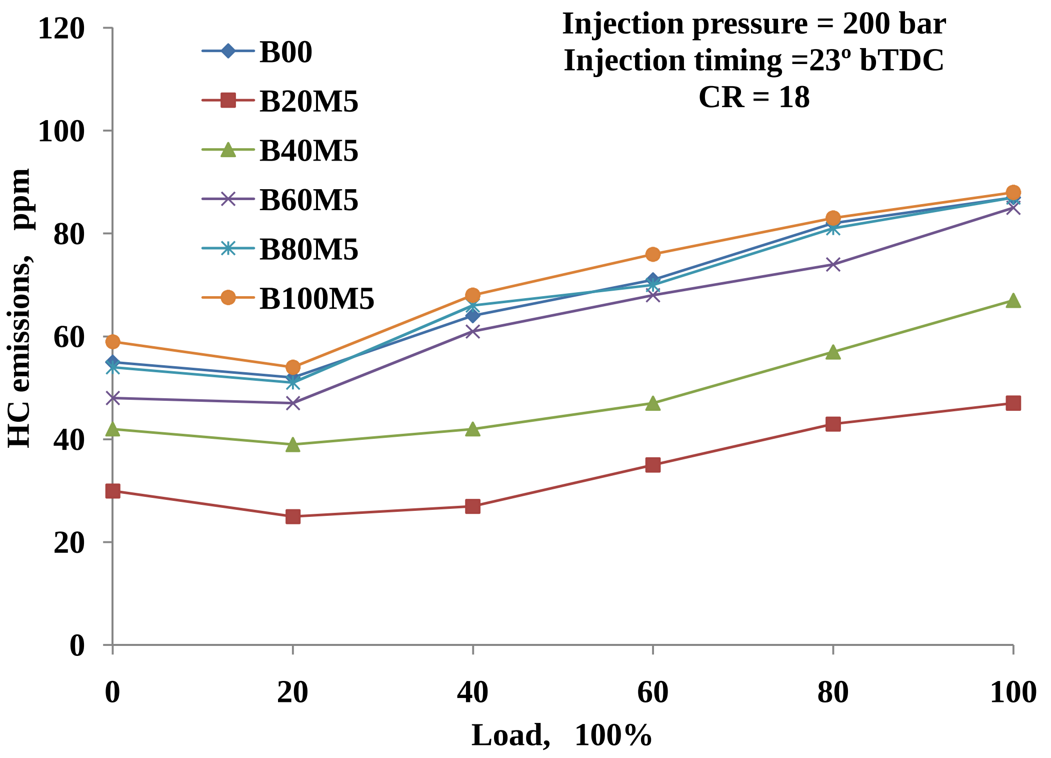


Fig. 5.4.2.2 Variation of HC emissions with load

5.2.3.3 Nitrogen oxide ($NO_{x)}$ emissions

The nitrogen oxide emissions for the various blends and diesel fuel for different loads at CR18 is illustrated in Fig.5.2.3.3. The nitrogen oxide emission increases for the increase in load which may perhaps be accredited to increased combustion temperature. The increased combustion temperature may be because of the higher heat release throughout the uncontrolled combustion stage. Moreover the same may be observed from the heat release for the various blends and diesel fuel. The emissions of NOx are higher for the biodiesel blends which might be attributed to complete combustion. The complete combustion of biodiesel blends may perhaps be accredited to inherent oxygen and higher CN of biodiesel in the blends. The NOx emissions are higher at CR18 for blend B40M5 for the rated load compared to diesel fuel and as well as for the other blends used. The NOx emissions for diesel fuel are 619ppm whereas for the blend B40M5 are 787ppm for the rated load. The NOx emissions for the blends B80M5 and B100M5 are lesser which may be attributed to increase in viscosity and lower volatility of the biodiesel in the blends causes the incomplete combustion. The NOx emissions for B40M5 blend are higher by about 22.1% compared to diesel fuel for the rated load.

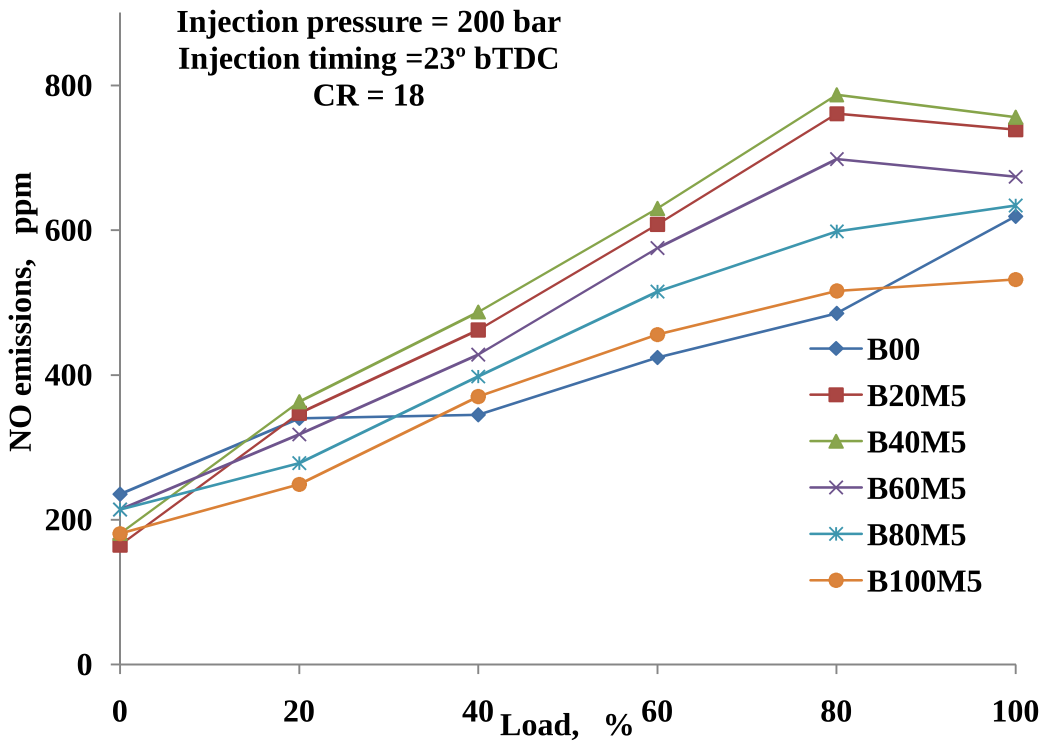


Fig. 5.2.3.3 Variation of NOx emissions with load

5.2.3.4 Smoke emissions

The smoke emissions results because of the incomplete combustion of fuel-air mixture supplied to the engine. The smoke emission for diesel fuel as well as for the various blends used in the investigations for different load is illustrated in Fig. 5.2.3.4. It is observed from the figure that with increase in load on the engine the smoke emissions increases. Increase in smoke emission with increased load on the engine may perhaps be accredited to increased fuel consumption to take up the additional load on the engine. The smoke emissions for diesel fuel are lesser for the lower load in comparison to the blends which may possibly be accredited to better combustion of diesel fuel. Improved combustion of diesel fuel at lower load may perhaps be accredited to better combustible properties. The increased load on the engine the smoke emissions decreases for the blends which may perhaps be accredited to increased combustion temperature. Higher combustion temperatures improve the mixture formation of fuel-air and combustion of the blends results into decrease in smoke emissions. The smoke emissions for diesel fuel are higher in comparison to blends for 50% and above of the rated load of the engine which may perhaps be accredited to improved combustion of blends. It might be observed from the figure that as volume fraction of biodiesel in the blends increases the smoke emission increases which may perhaps be accredited to the higher viscosity and inferior volatility of biodiesel in the blends. The higher viscosity and inferior volatility of biodiesel may affect the atomization, vaporization and mixture formation of fuel-air consequently the combustion process. The smoke emissions for diesel fuel at CR18 are 93%, whereas for B20M5 blend smoke emissions are 78.1% for the rated load. The reduction in smoke emissions for B20M5 blend is by about 19%, which is significant.

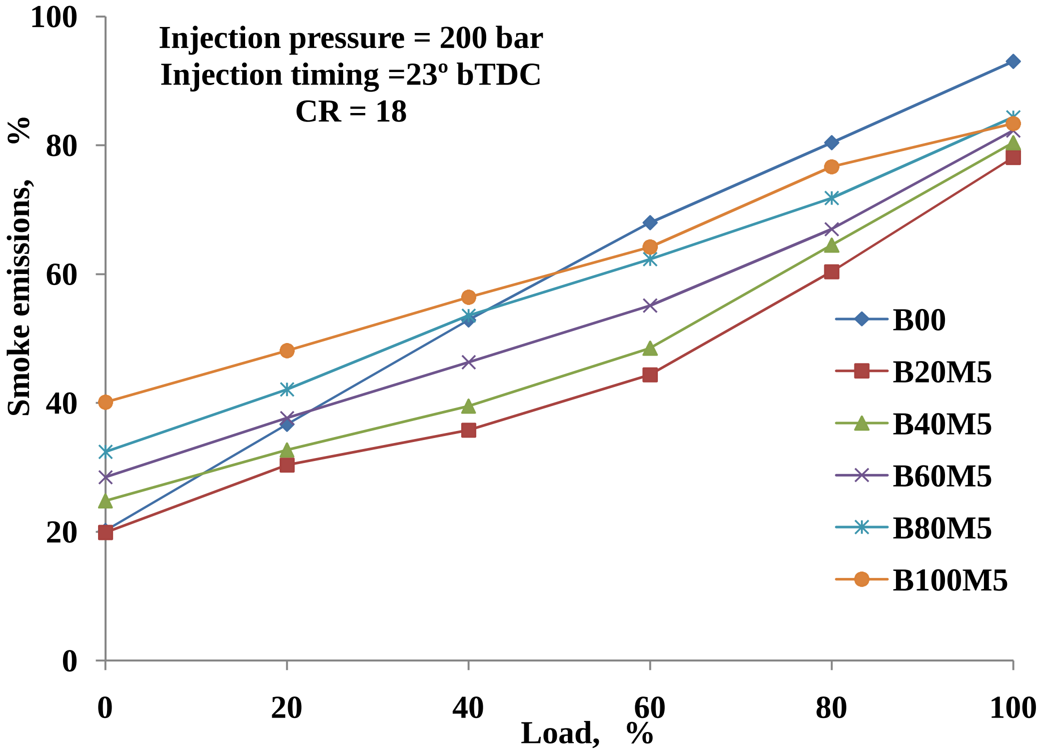


Fig. 5.2.3.5 Variation of smoke emissions with load

5.2.4 Summary

The experimental investigation and from the results it is summarised that the engine can run with mixture of two biodiesel M5 (P50+S50) in blend with diesel fuel without any modification to the existing diesel engine. The mixture of two biodiesel M5 (P50+S50) can be used in any volume fraction in blend with diesel or the mixture of biodiesels i.e. M5 alone in the diesel engine. The analysis of combustion, performance and emission characteristics investigation it gives roughly similar combustion and performance with reduced CO, HC and smoke emissions in comparison with diesel. The biodiesel blends gives marginally lower BTE and higher BSFC; lower exhaust gas temperature compared to diesel fuel which may be attributed to lower heating value and higher viscosity, inferior volatility of biodiesel fuel. The engine can run efficiently with 40% biodiesel blend with diesel. The maximum up to 40% diesel can be replaced with mixture of two biodiesel.

Table-5.2.1 Results of engine parameters obtained for diesel and various blends at CR18 for the rated load

Sl.No.		B00	B20	B40	B60	B100
Combustion Parameters						
1	Maximum pressure, bar	71.4	72.2	72.02	71.63	69.43
2	Max. heat release, J/°CA	52.79	45.79	40.56	40.04	42.08
3	Max. rate of pressure rise bar/°CA	4.79	4.79	5.02	4.72	4.63
Performance parameters						
1	Brake thermal efficiency %	27.66	27.32	28.49	27.23	27.01
2	BSFC kg/kW hr	0.3	0.31	0.3	0.3	0.33
3	EGT °C	320	314	315	315	313
Emissions parameters						
1	CO emission, %	0.046	0.032	0.026	0.042	0.046
2	HC emission, ppm	87	47	67	87	88
3	NO emission, ppm	619	739	756	674	532
4	Smoke emission, %	93	78.1	80.4	82.3	83.4

5.3 Combustion, Performance and Emission characteristics and analysis of Jatropha and Simarouba biodiesel blend (J50+S50) with diesel

Jatropha and Simarouba biodiesel are mixed in the proportion of 50:50 (J50+S50) and the mixture of the two biodiesel is designated as M8. The various blends are prepared using the mixture M8 in blend with diesel fuel. The prepared blends are used in the engine to investigate and analyse the different combustion, thermal performance and emission characteristics of DI VCR diesel engine. The various combustion characteristics investigated are cylinder pressure, maximum cylinder pressure, net heat release, mass fraction burned and rate of pressure rise. The thermal performance parameters investigated are BTE, BSFC, EGT, and emissions measured are CO, HC, NOx, and smoke. The results obtained are compared with the results of base line diesel fuel for the same engine and with similar operational settings all through the investigations. The results obtained for different blends and diesel fuels are discussed.

5.3.1 Combustion analysis

5.3.1.1 Cylinder pressure with crank angle

The cylinder pressure of diesel engine is the result of the fuel accumulated and prepared for the combustion throughout the delay period and the rate of combustion for the period of premixed combustion stage. The premixed combustion stage is mainly depends on the quality of fuel used and the preparation of fuel-air mixture all through the delay period. The change in cylinder gas pressure with CA for different blends at CR18 for the rated load is illustrated in the Fig.5.3.1.1. The variation of cylinder gas pressure with respect to CA for the various blends follow the similar trend as that of diesel fuel which may well be accredited to comparable properties of biodiesel with diesel fuel. The cylinder gas pressures for lower volume fraction of biodiesel in the blends at CR18 for the rated load are higher in comparison with diesel fuel. The higher cylinder gas pressure for biodiesel blends may possibly be accredited to inherent oxygen and higher CN of biodiesel in the blends. The inherent oxygen of biodiesel in the blends enhances the mixing of fuel-air, chemical reactions and higher CN accelerate the combustion of blends in comparison to diesel fuel. The maximum cylinder gas pressure for diesel fuel at CR18 is 71.94 bars for the rated load. The start of combustion for all the biodiesel blends is earlier in comparison with diesel fuel which may possibly be accredited to inherent oxygen of and higher CN of biodiesel in the blends. The maximum cylinder gas pressure for the blends B20M8, B40M8, B60M8 and B100M8 are 72.42 bars, 71.54 bars, 73.26 bars and 71.54 bars respectively. The premixed combustion for biodiesel blends is higher compared to diesel fuel which may perhaps be accredited to advanced start of injection and combustion of the blends. The mixing controlled combustion and after burning period for diesel fuel are higher compared to the blends which may possibly be accredited to increased ignition delay and delayed start of combustion in comparison to biodiesel blends. B100M8 blend has lower cylinder pressure which may perhaps be accredited to lower heating. The lower cylinder pressure for B100M8 may perhaps also because of higher viscosity and inferior volatility. The higher viscosity and inferior volatility may affect the mixing of fuel-air and consequently sluggish combustion of blends results into lesser cylinder pressure for the mixture of two biodiesel i.e. B100M8.

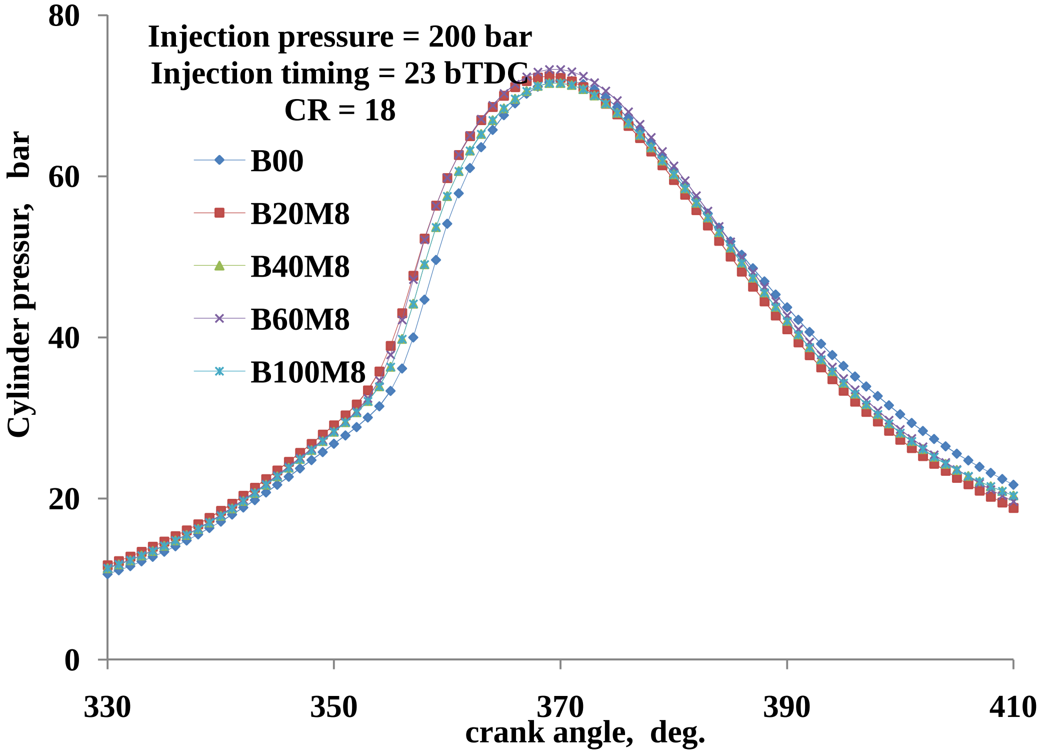


Fig. 5.3.1.1 Variation of cylinder gas pressure with CA

5.3.1.2 Maximum cylinder gas pressure with load

The properties of fuel such as viscosity, volatility, flash point and cetane number may possibly influence the delay period in compression ignition engines. The atomization, vaporisation and mixing of fuel-air may perhaps be influenced by the viscosity and volatility of the fuel. The start of ignition is mainly influenced by the cetane number of the fuel used. The maximum cylinder gas pressure data are collected from pressure volume (P-V) plot data; these data are acquired from the data acquisition system software. The maximum cylinder gas pressure for diesel fuel as well as for the various blends at CR18 for the rated load is illustrated in the Fig.5.3.1.2. The cylinder pressure increases with increase in load on the engine which may perhaps be accredited to increased fuel supply for the reason to generate additional power to carry the extra load. The increase in load on the engine demands more fuel to be supplied and burned which may well be increasing the cylinder gas pressure and the engine power. The maximum cylinder gas pressure for the diesel fuel at CR18 is 71.4 bars for the rated load. The cylinder gas pressure for B20M8, B40M8, B60M8 and B100M8 blends are 72.12 bars, 70.85 bars, 70.20 bars, and 70.32 bars respectively. The higher cylinder gas pressure for the blend B20M8 for all the loads may possibly be accredited to complete combustion. The complete combustion of B20M8 may perhaps be accredited to inherent oxygen and higher CN of biodiesel in the blend. The lower cylinder gas pressures for B60M8 and B100M8 blends at CR18 for the rated load may perhaps be accredited to higher viscosity and inferior volatility of biodiesel in the blends. The higher viscosity and inferior volatility may affect the mixing of fuel-air consequently sluggish combustion which causes the lower maximum cylinder pressure.

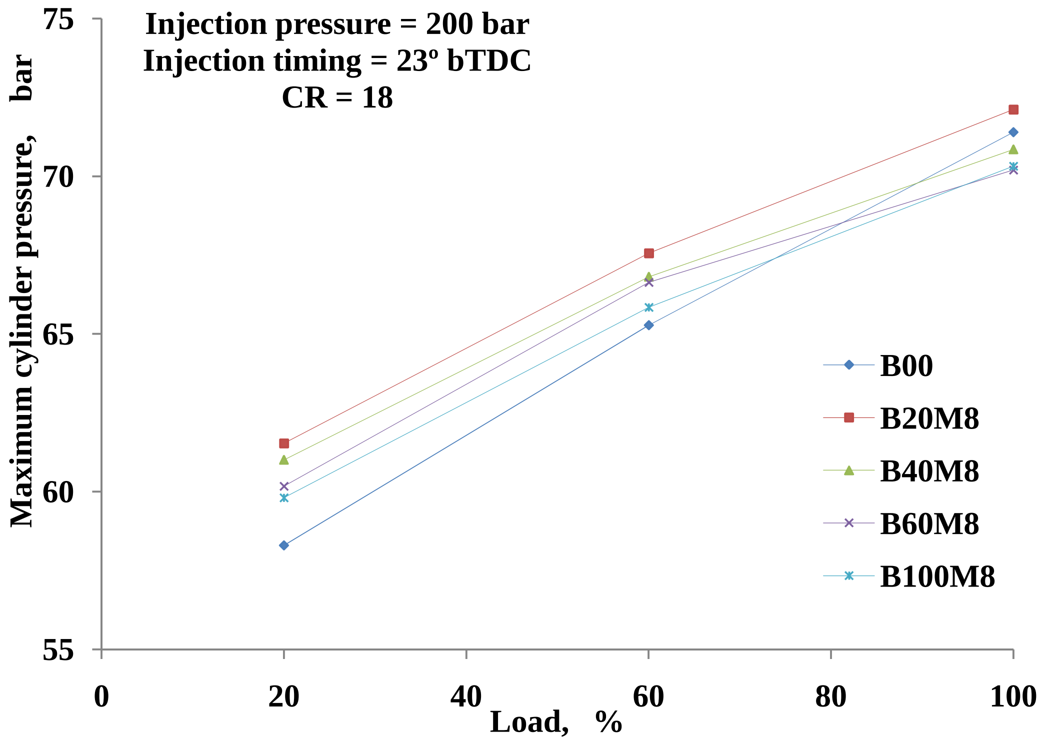


Fig. 5.3.1.2. Variation of maximum cylinder pressure with load

5.3.1.3 Net heat release with crank angle

The net heat release for any diesel engine is depends on the ignition delay, the amount of fuel burned and the commencement of combustion for the various fuels used. The net heat release is also depends on the quantity of fuel burned during the premixed combustion phase and burning rate. The fuel injected into the combustion chamber does not ignite instantaneously. The fuel droplet injected in to the hot compressed air has to evaporate and get mixed with air, raised in temperature then ignites. The process of preparing the mixture is called ignition delay which is depends on the physical and chemical properties of fuel and the type of engine used. The net heat releases are negative for the initial period which may perhaps be accredited to, the heat is absorbed by the fuel from the hot air rather than generating the heat. The net heat releases for the diesel and for the various blends at CR18 for the rated load is illustrated in the Fig.5.3.1.3. The higher net heat release for diesel fuel which may perhaps be accredited to higher heating value and increase in the ignition delay. Increase in ignition delay for diesel fuel may contribute in better mixture formation and complete combustion of diesel fuel. The net heat releases for diesel fuel at CR18 is 52.79 J/º CA for the rated load. The net heat release for biodiesel blends is lower compared to diesel fuel which may possibly be attributed to lower heating value of biodiesel in the blends as well as the reduced ignition delay.

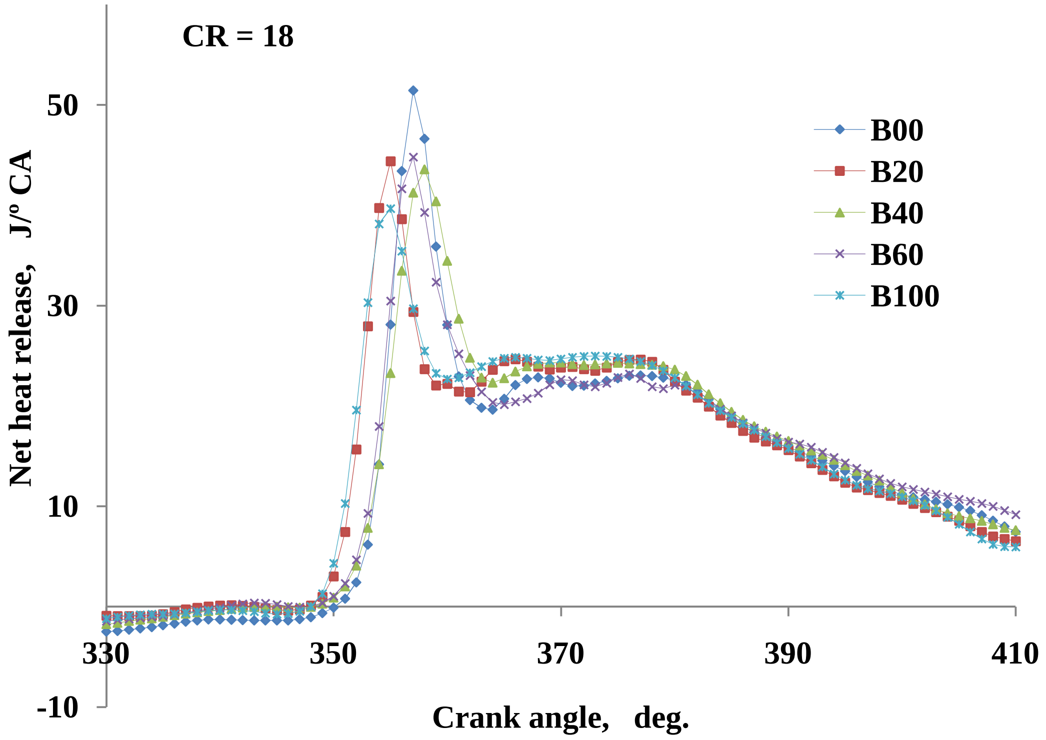


Fig. 5.3.1.3 Variation of net heat release with CA

The net heat release for the blends B20M8, B40M8, B60M8 and B100M8 are 44.4 J/º CA, 43.56 J/º CA, 44.81 J/º CA, and 39.71 J/º CA respectively. The blend B100M8 has lower net heat release compared diesel and the other blends which may possibly be accredited to lower heating value and higher viscosity, inferior volatility of mixture of two biodiesel. The higher viscosity and inferior volatility of biodiesel may affect the mixing of fuel-air consequently sluggish combustion hence lower net heat release.

5.3.1.4. Mass fraction burned (MFB) with crank angle

The mass fraction burned in each particular cycle is normalised quantity with scale of 0-100%. The mass fraction burned indicates the chemical energy of the fuel released with change in CA. The mass fraction burned for diesel fuel and various blends at CR18 for the rated load is illustrated in the Fig.5.3.1.4. It is observed from the illustration that MFB for biodiesel blends is following the similar trend as that of diesel fuel which may perhaps be accredited to comparable properties of biodiesel with diesel fuel. Though the start of combustion of diesel fuel might be delayed, the completion of combustion for diesel fuel is earlier in comparison to biodiesel blends. This may be attributed to better combustible property of diesel fuel. Start of combustion for the blends is earlier compared to diesel fuel which may perhaps be accredited to inherent oxygen and higher CN of biodiesel in the blends. The duration of combustion for biodiesel blends are higher compared to diesel

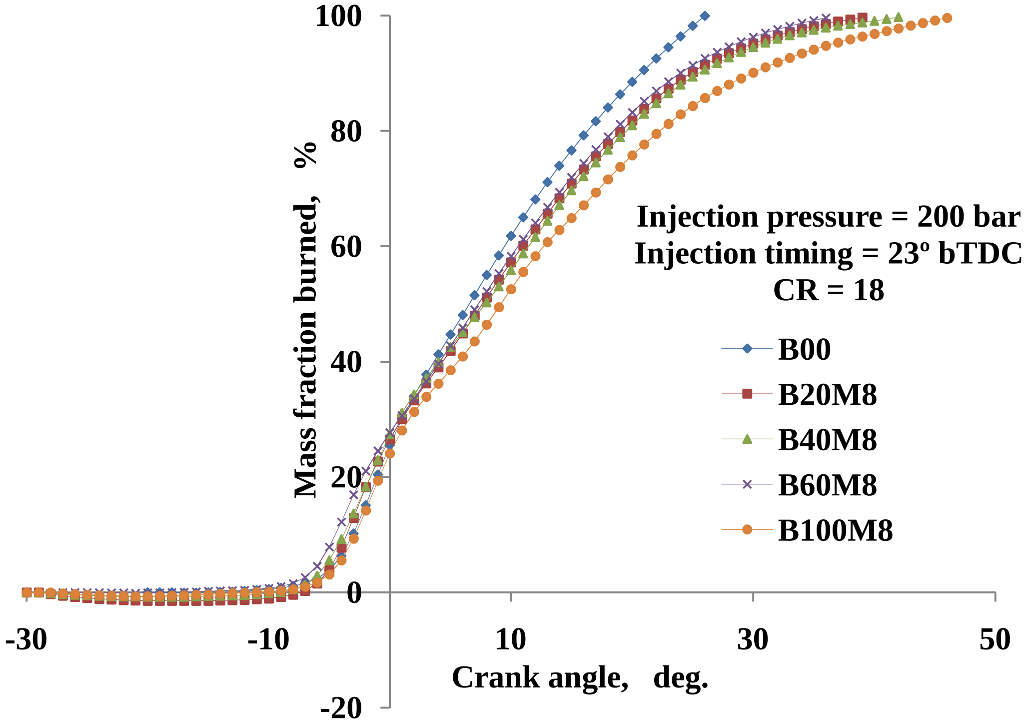


Fig. 5.3.1.4 Variation of mass fraction burned with CA

fuel which may possibly be accredited to higher viscosity and inferior volatility of biodiesel in the blends. The higher viscosity and inferior volatility may affect the mixing of fuel-air and the chemical reaction consequently the sluggish combustion. The slow combustion of blends increases the combustion time. Higher volume fraction of biodiesel in the blends increases the combustion duration for reason as explained earlier.

5.3.1.5. Maximum rate of pressure rise (RPR) with load

The maximum rate of pressure rise increases with increase in load on the engine for diesel fuel as well as for the various blends used. The increased RPR with increase in the load on the engine which may perhaps be accredited to increased amount of air-fuel mixture burned for the higher engine load. For the increased load on the engine more fuel is to be supplied and burned to take the burden of extra load which may perhaps increases the RPR. The maximum pressure rise rate for diesel fuel as well as for the various blends for various loads at CR18 is illustrated in the Fig.5.3.1.5. The maximum RPR for diesel fuel are 4.79 bars/ ºCA for the rated load. The rate of pressure rise for the blends B20M8, B40M8, B60M8 and B100M8 are 5.43 bars/ ºCA, 5.24 bars/ ºCA, 4.98 bar/ ºCA. 4.64 bar/ ºCA respectively at CR18 for the rated load.

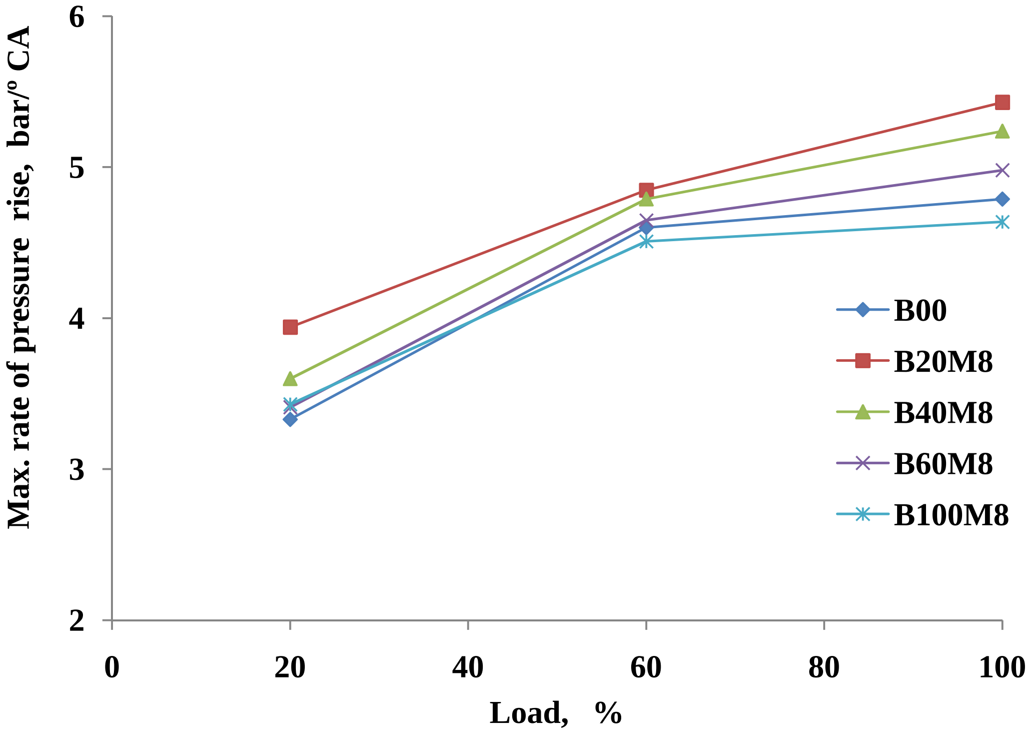


Fig. 5.3.1.5 Variation of maximum rate of pressure rise with load

The higher RPR for the blends B20M8, B40M8 and B60M8 may perhaps be accredited to complete combustion of blends. The complete combustion of blends may perhaps be accredited to inherent oxygen and higher CN of biodiesel in the blends. The mixture of two biodiesel, B100M8 has lower rate of pressure rise at CR18 for various loads which may perhaps be accredited to higher volume fraction of biodiesel in the blends. The biodiesel has higher viscosity and inferior volatility which may affect the mixing of fuel-air consequently combustion process results into lesser rate of pressure rise.

5.3.2 Thermal performance analysis

5.3.2.1 Brake thermal efficiency (BTE) with load

The BTE of diesel fuel as well as for the various blends at different loads at CR18 is illustrated in the Fig. 5.3.2.1. The BTE increases with increase in load for all the fuels used in the investigation. The BTE of diesel fuel are higher in comparison to the various blends which may perhaps be accredited to higher heating value and complete combustion of diesel fuel. The Brake thermal efficiency for the blends B20M8, B40M8 and B60M8 are almost comparable for 80% and above of the rated load of the engine at CR18.

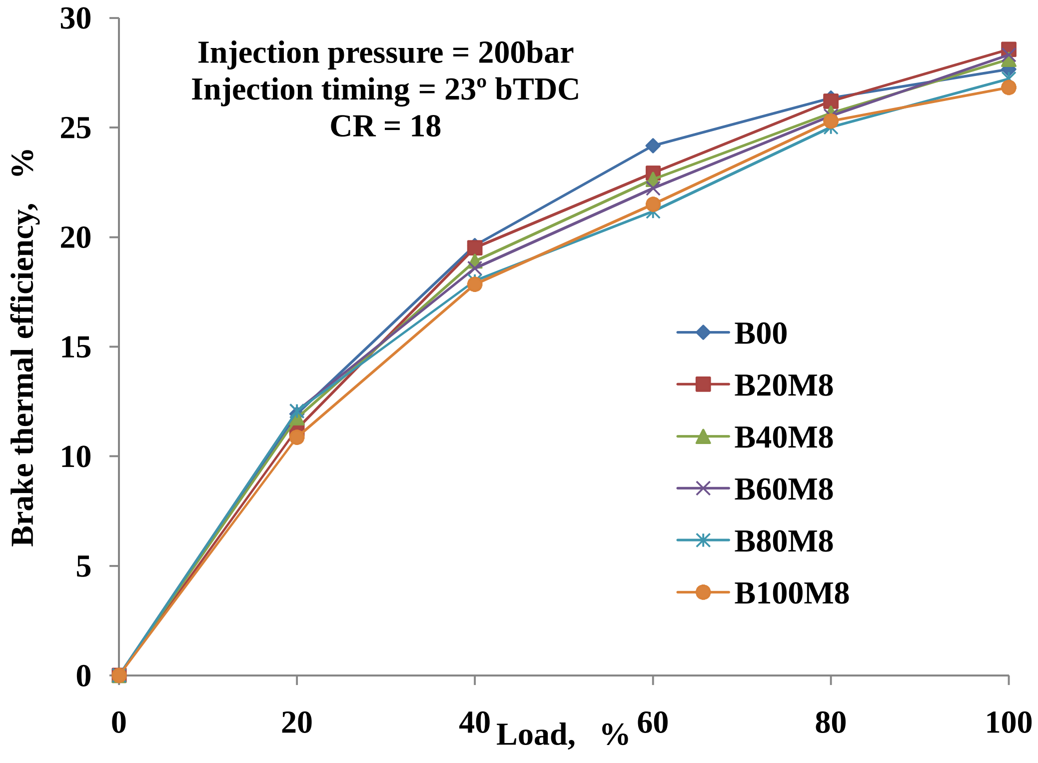


Fig. 5.3.2.1 Variation of brake thermal efficiency with load

This may perhaps be accredited to higher combustion temperature, higher density, and temperature of the air may complete the combustion of the blends hence higher brake thermal efficiency. The lower BTE of the blends at lower load compared to diesel fuel may perhaps be accredited to lower heating value of biodiesel in the blends. As the volume percentage of biodiesel in the blend increases brake thermal efficiency decreases which may possibly be accredited to lower energy content and higher viscosity of biodiesel fuel. Brake thermal efficiency for diesel fuel at CR18 is 27.66% for the rated load. The brake thermal efficiency for the blends B20M8, B40M8, B60M8 are 28.56%, 28.11%, 28.31% at CR18 for the rated load of the engine. The brake thermal efficiency of B80M8 and B100M8 are lesser and are 27.22% and 26.82% respectively for the rated load. The lesser BTE for the blends B80M8 and B100M8 may perhaps be attributed to lower heating value and higher viscosity, inferior volatility of biodiesel fuel in the blends. The higher viscosity and inferior volatility may affect the mixing of fuel-air hence the sluggish combustion results in to lesser BTE for higher blends.

5.3.2.2 Brake specific fuel consumption (BSFC) with load

The BSFC for diesel as well as for the various blends for different load at CR18 is illustrated in the Fig. 5.3.2.2. The brake specific consumption of biodiesel blends is following the similar trend as that of diesel fuel which may possibly because of comparable properties of biodiesel. The BSFC of diesel fuel as well as for the various blends decreases with the increase in load which may possibly be accredited to increased combustion temperature and reduced heat loss to the cooling. Higher combustion temperature improves evaporation, mixing of fuel-air and burning rate of fuels which may decrease the BSFC. The BSFC of diesel fuel is lesser which may perhaps be accredited to higher heating value and better combustible properties of diesel fuel which contributes in complete combustion. The brake specific fuel consumption of B20M8, B40M8, B60M8 blends are more or less comparable with diesel fuel for the rated load which may possibly be accredited to inherent oxygen and higher CN of biodiesel in the blends. The inherent oxygen and higher CN of biodiesel in the blends may enhance the mixing of fuel-air, chemical reaction and accelerate the combustion. The BSFC of diesel fuel at CR18 is 0.3 kg/kW h for the rated load. The BSFC for B20M8, B40M8 and B60M8 blends are 0. 3 kg/kW h, 0.3 kg/kW h, 0.31 kg/kW h respectively for the rated load. BSFC for the blends B80M8 and B100M8 are higher at the rated load which may perhaps be accredited to lower heating value and higher viscosity, inferior volatility of the biodiesel in the blends. The higher viscosity and inferior volatility biodiesel in the blends may affect the mixing of fuel-air consequently sluggish combustion results into increase in BSFC.

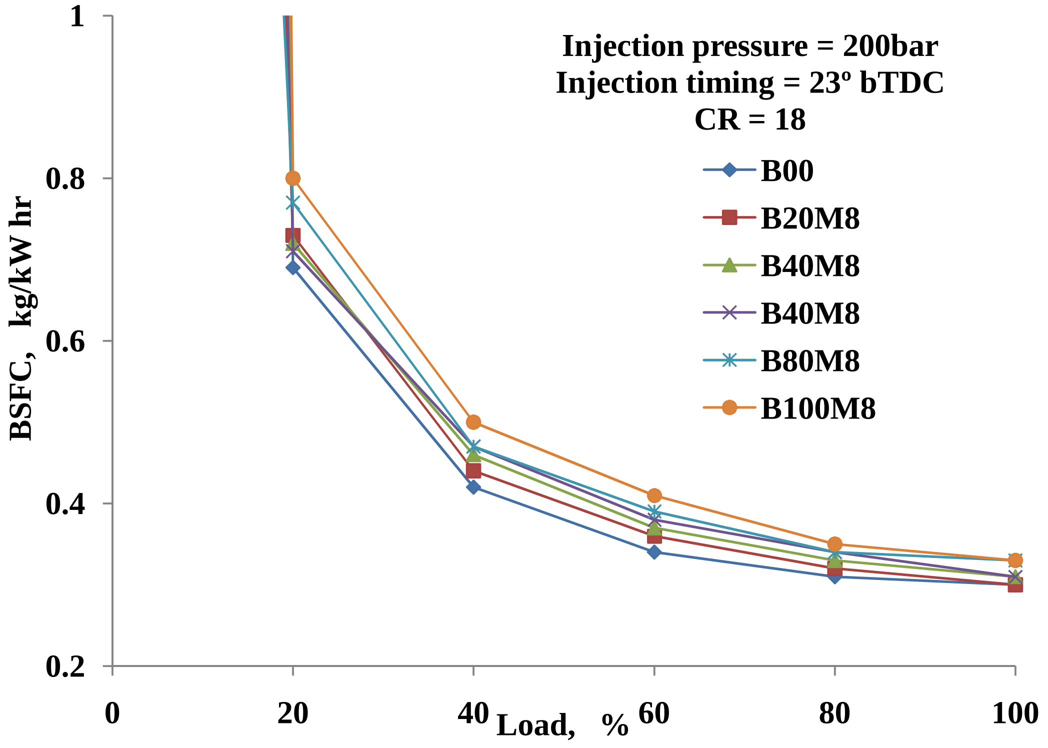


Fig. 5.3.2.2 Variation of BSFC with load

5.3.2.3 Exhaust gas temperature (EGT) with load

The exhaust gas temperatures for diesel fuel and for the various blends for different load at CR18 are illustrated in the Fig.5.3.2.3. The quantity of heat carried away with the exhaust gas may perhaps be indicated by the EGT. The EGT increases for diesel fuel as well as for the various blends with increase in load which may well be accredited to increase in fuel consumption. The fuel consumption increases with increase in load may perhaps be accredited to more amount of fuel is to be supplied and burned to generate additional power to carry the burden of increased load. The exhaust gas temperatures for various blends used in the investigation are following the similar trend as that of diesel fuel. The exhaust gas temperature of diesel fuel at CR18 is 320º C for the rated load. The EGT of blends B20M8, B40M8, B60M8 and B100M8 are 316º C, 309º C, 309º C and 310º C respectively. The exhaust gas temperatures for the different blends are less compared to diesel fuel which results in to improved fuel efficiency and brake thermal efficiency for the blends.

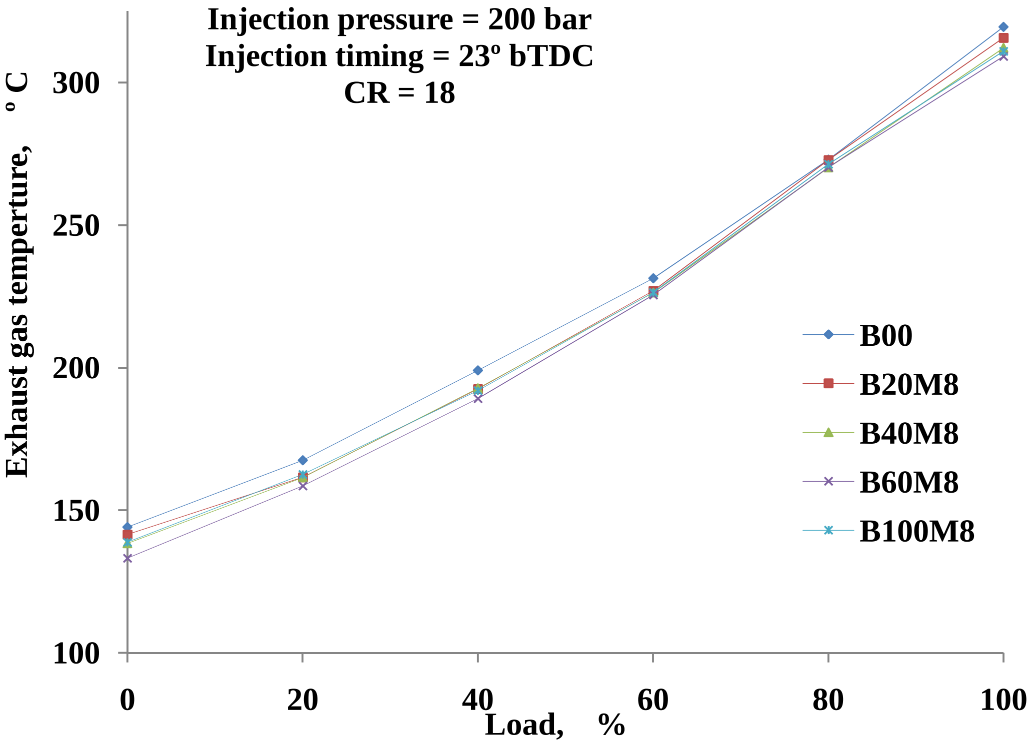


Fig. 5.3.2.3 Variation of exhaust gas temperature with load

5.3.3 Emission analysis

5.3.3.1 CO emission with load

The carbon monoxide emissions are because of incomplete combustion of fuel supplied to the engine because of deficient amount air available for combustion or may perhaps be less time available for complete of combustion. Diesel engine are operated with lean mixture i.e. more air and less fuel hence carbon monoxide emissions are lesser for given load on the engine in comparison with spark ignition engine. The CO emission for diesel fuel and various blends at CR18 for the rated load is illustrated in the Fig.5.3.3.1. The emissions of CO decreases for diesel fuel as well as for the various blends for increase in load which may perhaps be accredited to increased combustion temperature. The increased combustion temperature for higher loads results into improved combustion which results in lesser CO emissions. The emissions of CO for diesel fuel is higher compared to blends which may perhaps be accredited to incomplete combustion of diesel fuel because of lack of oxygen. The CO emissions for diesel fuel at the rated load are 0.046%. The CO emission for biodiesel blends are lesser compared to diesel fuel which may possibly be accredited to the inherent oxygen and higher CN of biodiesel in the blends. The inherent oxygen enhance the mixing of fuel-air, chemical reaction and CN accelerates the combustion consequently decreases the CO emissions. The emissions of

CO for the blends B20M8, B40M8, B60M8, B80M8, and B100M8 are 0.026%, 0.025%, 0.029%, 0.034% and 0.036% respectively for the rated load. It is seen from the figure that with increased volume fraction of biodiesel in the blends increases the CO emission which may well be accredited to increased viscosity and inferior volatility of biodiesel in the blends. The increased viscosity may affect the mixture formation which may slowdown the combustion hence increases CO emission.

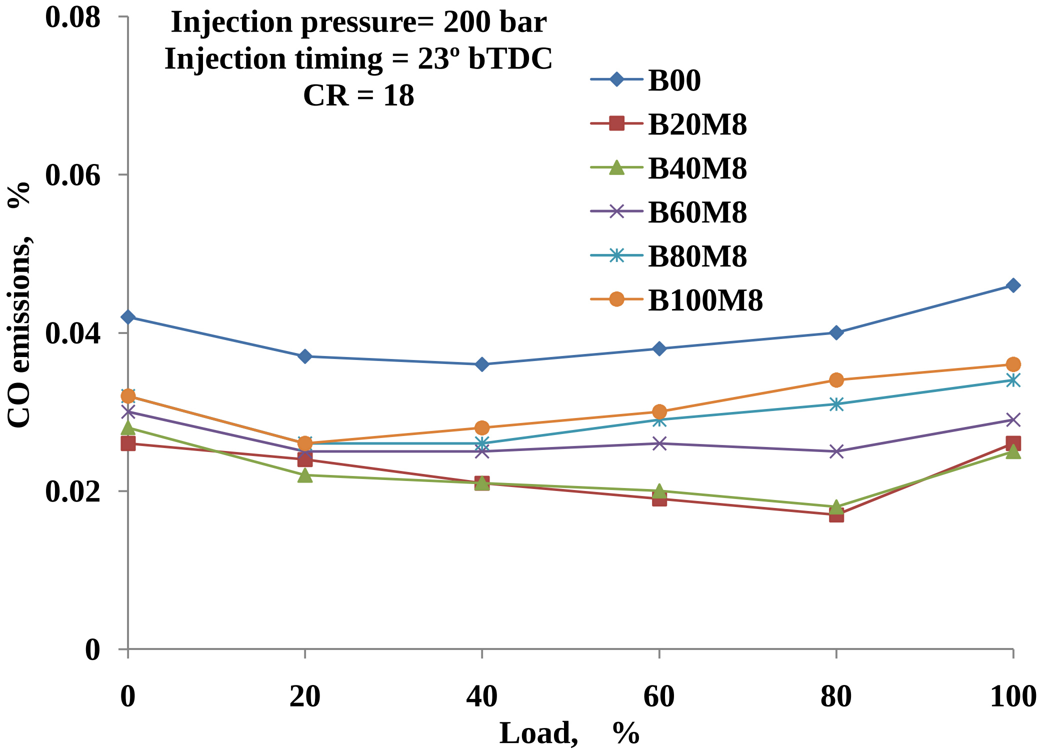


Fig. 5.3.3.1 Variation of Carbon monoxide emission with load

5.3.3.2 HC emission with load

The unburnt hydrocarbon emissions are the product of incomplete combustion of fuel-air mixture which may perhaps be because of insufficient oxygen or time available for combustion or inefficient mixing of fuel-air. The HC emissions for diesel fuel and for the various blends for different load at CR18 are illustrated in the Fig. 5.3.3.2. The higher HC emissions for diesel fuel which may perhaps be accredited to incomplete combustion because of deficient oxygen. The HC emissions are lower for biodiesel blends which may perhaps be accredited to inherent oxygen and higher CN of biodiesel in the blends. The inherent oxygen of biodiesel enhances the mixture formation of fuel-air, chemical reaction and higher CN accelerate the combustion of blends hence lesser HC emission for the blends. For the higher volume fraction of biodiesel in the blends the HC emissions increases which may possibly be accredited to higher viscosity and inferior volatility of biodiesel in the blend. The higher viscosity and inferior volatility may affect the atomisation and mixture formation of fuel-air for the blends consequently the combustion process. HC emission for diesel fuel for the rated load at CR18 is 87 ppm. The HC emission for the blends B20M8, B40M8, B60M8, B80M8 and B100M8 are 53 ppm, 58 ppm, 61 ppm, 79 ppm and 88 ppm respectively. HC emissions are reduced by 39% for B20M8 blends in comparison with diesel fuel.

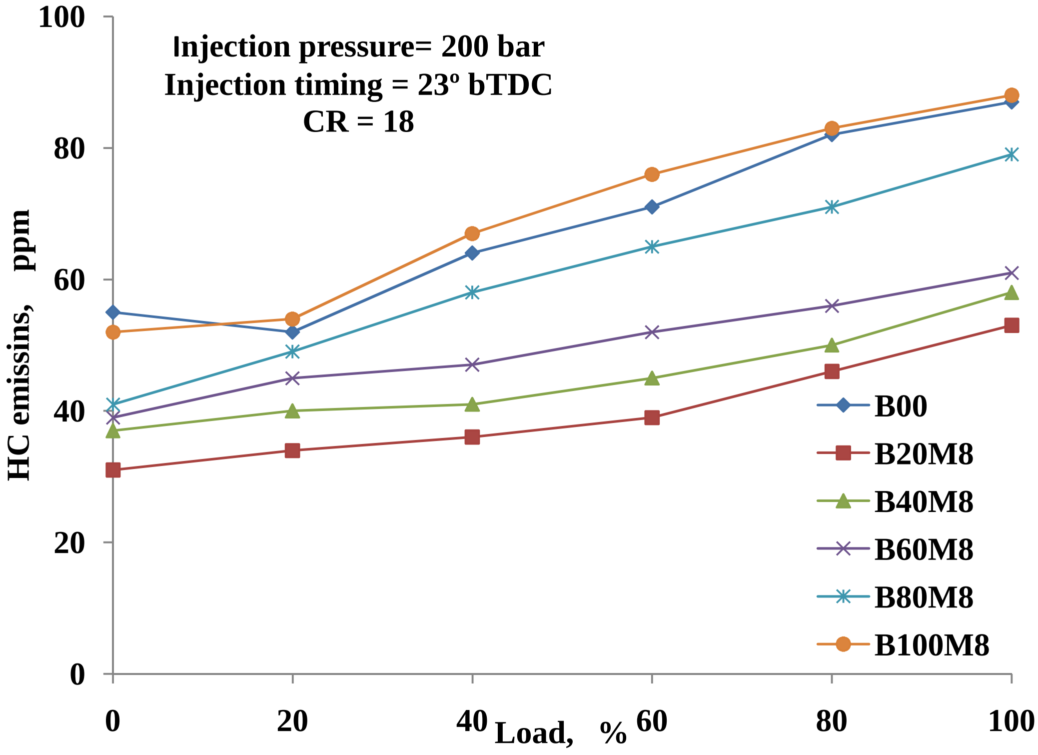


Fig. 5.3.3.2 Variation of hydrocarbon emissions with load

5.3.3.3 NOx emissions with load

The NOx emissions for CI engine are always on the higher side compared spark ignition engine which may possibly be attributed to higher CR of CI engine. The components which contribute for the NOx formations are higher combustion temperature and oxygen availability. The NOx may not be created if any one of the two is not available. The NOx emissions for diesel fuel and for the various blends at CR18 for different load are illustrated in the Fig. 5.3.3.3. The NOx emissions increases with increase in load on the engine which may perhaps be accredited to increased amount of fuel supplied and burnt which increases the combustion temperature. At lower load NOx emission for diesel fuel is higher which may perhaps be accredited to better and complete combustion of diesel fuel. Complete combustion of diesel fuel increases the cylinder pressure and temperature hence higher NOx formation. The emissions of NOx for biodiesel blends are higher which may probably be accredited to inherent oxygen and higher CN of biodiesel in the blends. The inherent oxygen and higher CN may enhance mixing of fuel-air and complete combustion which increases the temperature hence higher NOx. For increased volume fraction of biodiesel in the blends, NOx emission decreases which may probably because of higher viscosity and inferior volatility of the biodiesel in the blends. The higher viscosity and inferior volatility may decelerate the mixture formation consequently the combustion. The NOx emissions for diesel fuel are 619 ppm at CR18 for the rated load. The NOx emission for the blends B20M8, B40M8, B60M8, B80M8 and B100M8 are 650 ppm, 699 ppm, 592 ppm, 533 ppm, and 505ppm respectively at the rated load. The NOx emissions are increased by about 12.9% for the blend B40M8 compared to diesel fuel.

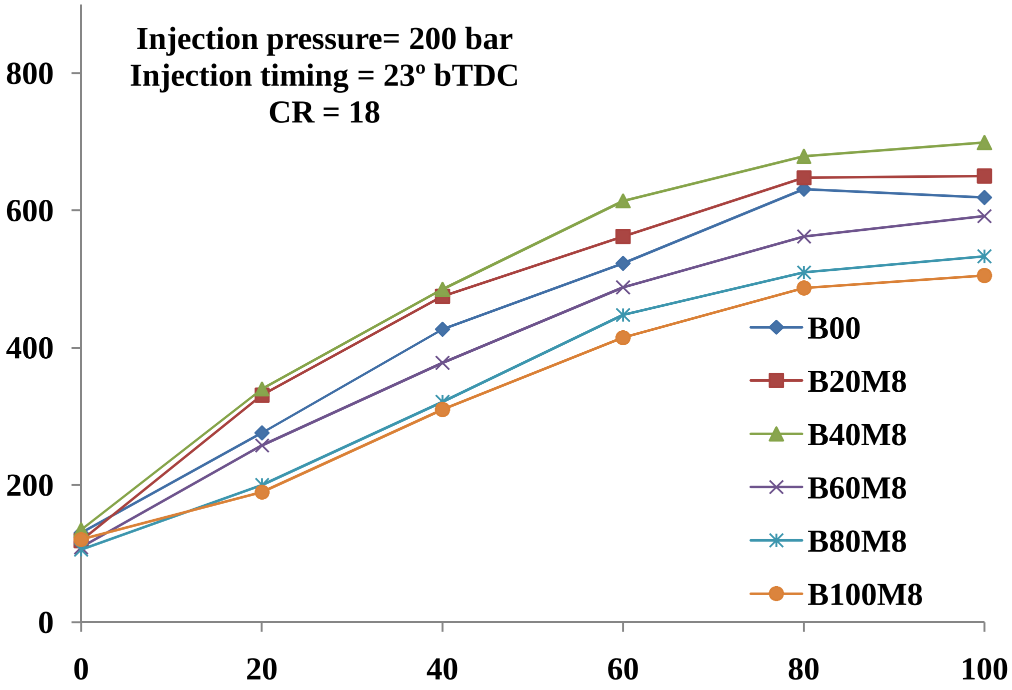


Fig. 5.3.3.3 Variation of nitrogen oxide emissions with load

5.3.3.4 Smoke emissions with load

The smoke emissions are cause of soot particles present in the exhaust. The smoke emssion for diesel fuel and for the various blends for different load at CR18 is llustrated in the Fig.5.3.12. The smoke emissions increases with increase in load which may probably be accredited to increased quantity of fuel supplied with increase in load. Smoke emissions for diesel fuel at lower load are lesser which may perhaps be accredited to less amoount of fuel supply and burnt. The smoke emissions for biodiesel blends is lesser for higher load which may perhps be accedited to improved combustion of blends.

The improved combustion of blends which may be because of increased combustion temperature and inherent oxygen, higher CN of biodiesel in the blends. The smoke emissions of the diesel fuel are 93% for the rated load of the engine. The smoke emission for the blends B20M8, B40M8, B60M8, B80M8, and B100M8 are 84.9%, 84.5%, 86.2%, 93.8% and 94.6% respectively for the rated load at CR18. The higher smoke emission for the blends B80M8 and B100M8 may probably be accredited to higher viscosity and inferior volatality of biodesel in the blends. The said properties of biodesel might be affecting the mixing of fuel-air consequntly the combustion of blends which results in the increases of the smoke emissions.

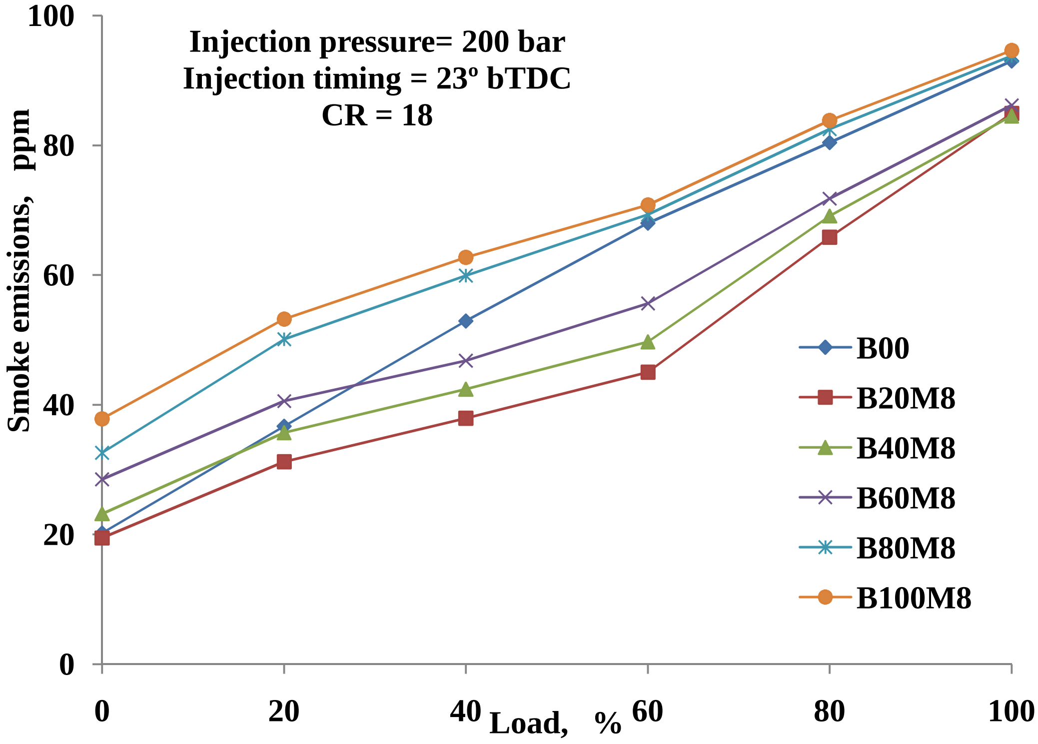


Fig. 5.3.3.4 Variation of smoke emission with load

5.3.4 Summary

The two biodiesel considered are Jatropha and Simarouba are mixed in the ratio of 50:50 (J50+S50) and designated as M8. The mixture two biodiesel i.e., M8 is used in the preparation of blends. The blend B20M8 indicates, 20% of M8 + 80% of diesel fuel. From the results of the experiments it is revealed that the engine can run with mixture of two biodiesel in blend with diesel fuel without any modification to the existing diesel engine. The engine can run with mixture of two biodiesel either in blend with diesel fuel or mixture of two biodiesel without any modification. It is observed from the combustion analysis that cylinder pressure is higher for the blends and heat release is lesser. The maximum cylinder pressures are higher for the blends compared to diesel fuel. The pressure rise rates are higher for the blends compared to diesel fuel. The combustion duration is increased for the blends. The BTE for the blends is lesser and BSFC of the blends are increased for the blends compared to diesel fuel. The exhaust gas temperatures are lesser for blends compared to diesel fuel. The CO, HC and smoke emissions are lesser and NOx emissions are higher for the blends compared to diesel fuel. The engine can run efficiently with 40% blends of mixture of two biodiesel with diesel fuel. The maximum up to 40% diesel may be replaced with mixture of two biodiesel.

Table-5.3.1 Results of engine parameters obtained for diesel and various blends of M8 at CR18 for the rated the load

Sl.No.		B00	B20	B40	B60	B100
Combustion Parameters						
1	Maximum pressure, bar	71.4	72.12	70.85	70.2	70.32
2	Max. heat release, J/ºCA	52.79	44.4	43.56	44.8	39.7
3	Max. rate of pressure rise bar/ºCA	4.79	5.43	4.94	4.72	4.64
Performance parameters						
1	Brake thermal efficiency %	27.66	28.56	28.31	28.11	26.82
2	BSFC kg/kW hr	0.3	0.3	0.31	0.31	0.32
3	EGT ºC	320	315	313	309	311
Emissions parameters						
1	CO emission, %	0.046	0.026	0.025	0.027	0.036
2	HC emission, ppm	87	53	58	61	88
3	NO emission, ppm	619	650	699	592	505
4	Smoke emission, %	93	84.9	84.5	86.2	94.6

5.4 Effect of compression ratio, mixture ratio and blend ratio on Combustion, Performance and Emission characteristics using Pongamia and Jatropha biodiesel blend with diesel

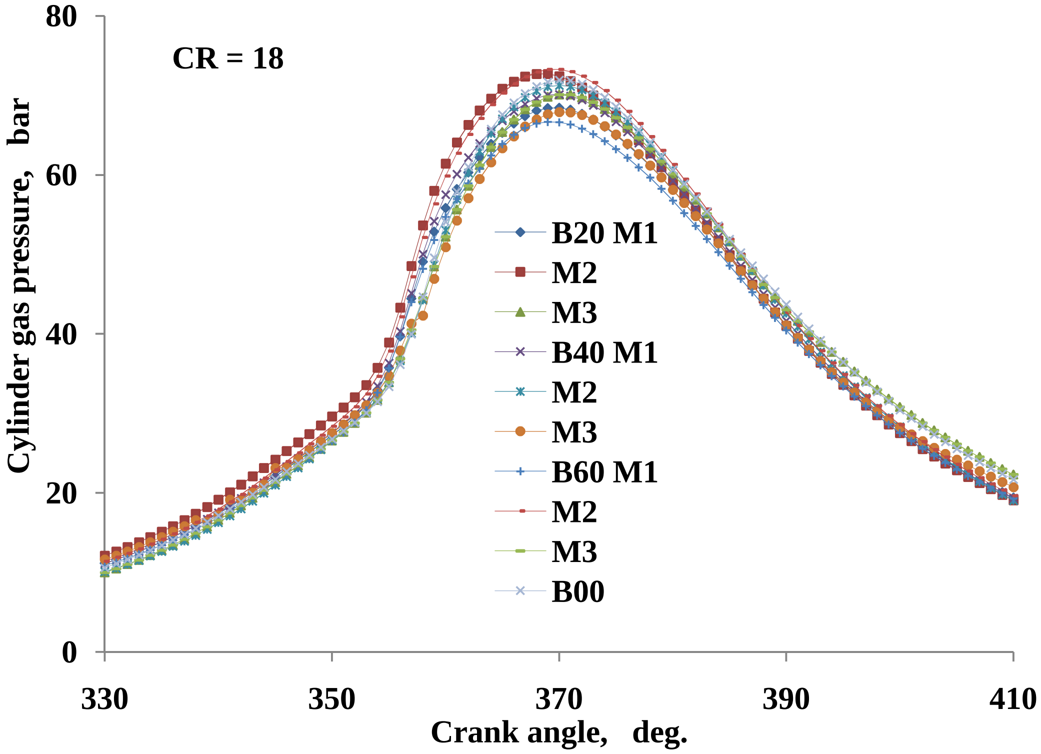
Pongamia and Jatropha biodiesel are mixed in different volume ratios of 75:25 (P75+J25), 50:50 (P50+J50) and 25:75 (P25+J75). The mixture of two biodiesel in different volume ratios are designated as M1 for (P75+J25), M2 for (P50+J50), and M3 for (P25+J75). These mixtures are used for the preparation of various blends with diesel fuel. The blend B20M1 indicates 20% of M1+80% diesel fuel. Similarly the other blends prepared are B40M1, B60M1 using M1 with diesel fuel and B100M1 is the mixture of two biodiesel. The blends are also prepared using mixture of M2 and M3. These blends are used in the investigation of combustion, thermal performance and exhaust emission characteristics varying the load and compression ratio of the engine. The results of the blends are compared with the results of base line diesel fuel.

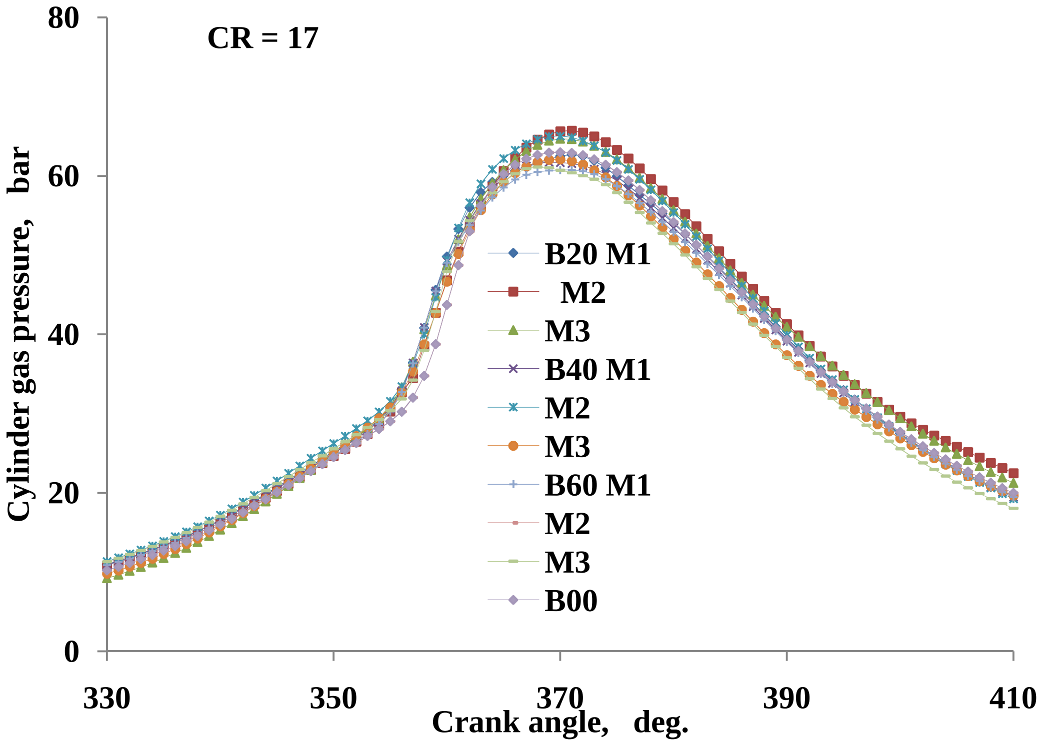
5.4.1 Combustion analysis

5.4.1.1 Cylinder pressure with CA

The change in cylinder gas pressure with CA for various blends prepared using the mixture of two biodiesel in blend with diesel fuel for the rated load at different compression ratio are illustrated in the Fig. 5.4.1.1. The cylinder pressures are depends on the premixed combustion stage of the cycle which is depends on the type of fuel used and the CR. It might be seen from the figure that the cylinder gas pressure is higher at higher CR for all the blends. The higher cylinder gas pressure for the blends may perhaps be accredited to increased combustion temperature and higher temperature of the air at higher CR. Higher temperature and density of air helps in enhanced atomization of fuel and mixing of fuel-air and contributes for the complete combustion of fuels used [111, 133]. The cylinder gas pressures are higher for blend B20M2 is 72.95 bars and are at 8º CA aTDC. The higher cylinder pressure for B20M2 blends may conceivably be accredited to inherent oxygen and higher cetane number of the biodiesel in the blends. It may well be observed that start of combustion for the blends are earlier compared to the diesel fuel which may be accredited to higher combustion temperature and reduced exhaust gas dilution [134, 135]. The variation of maximum cylinder gas pressure for various blends as well as diesel fuel varies in the range of 4º of crank angle. The maximum cylinder gas pressure for diesel fuel is 71.94 bars and is at 10º aTDC. The cylinder gas pressure for B60M2 blend is lesser compared to other blends and diesel fuel which may possibly be accredited to high viscosity and inferior volatility of biodiesel in the blends. The high viscosity and inferior volatility of B60M2 blends may affect the mixing of fuel-air and consequently the combustion of the said blends. The blend B20M2 is better fuel at CR18 which gave higher cylinder gas pressure in comparison to diesel and other blends.

The variation of cylinder gas pressure at CR17 are lesser compared to CR18 for diesel fuel as well as for the various blends at the rated load. The cylinder gas pressures are higher for the blends B60M3 which may possibly be accredited to inherent oxygen. The higher CN of biodiesel in the blends which may contribute in enhanced mixture formation of fuel-air hence improve the combustion. The value of cylinder gas pressure for B60M3 blends is 61 bars at rated load and is at 9° CA aTDC. The cylinder gas pressure at CR17 is lower compared CR18 which may perhaps be because of decreased combustion temperature, lower density and temperature of the air. The decreased combustion temperature and lower density, temperature of the air in the cylinder at CR17 may affect the vaporization and mixing of fuel-air consequently the combustion process. The maximum cylinder gas pressure at CR17 is reduced by about 10% compared to CR18 and is at 3° CA aTDC.





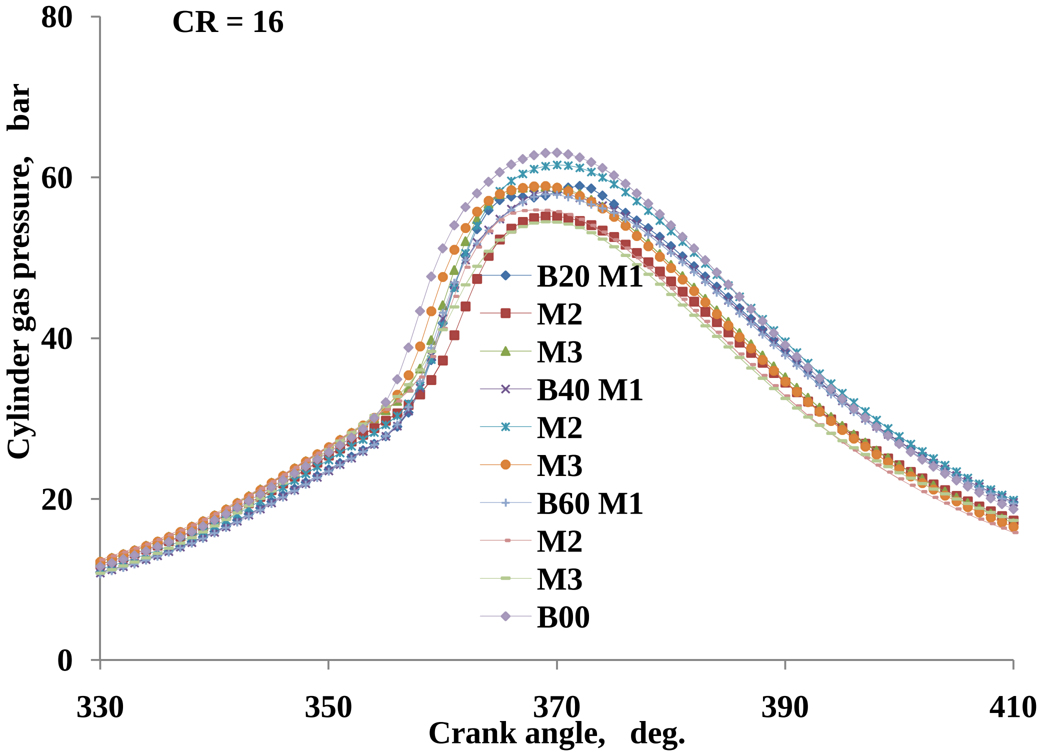


Fig. 5.4.1.1 Variation of cylinder pressure with crank angle

The variation of cylinder gas pressure at CR16 are lesser compared to CR17 and CR18 for diesel fuel as well as for the various blends used. The premixed combustion stage increases for CR16 which may be possibly be attributed to lower combustion temperature, and temperature of the air at lower CR. The lower combustion temperature, And temperature of the air may influence the atomisation of fuel and mixture formation subsequently incomplete combustion hence lower cylinder pressure at CR16. The cylinder pressure for the diesel fuel is higher in comparison to the blends and its value is 63.07 bars at the rated load and is at 9º CA aTDC. The higher cylinder gas pressure for the blend B20M2 blend is 55.93 bars at 10º CA aTDC and for the blend B40M2 is 61.56 bars at the rated load. The cylinder pressure at CR16 is decreased by about 23.7% compared to CR18 and 15.3% compared to CR17 for B20M2 for the rated load.

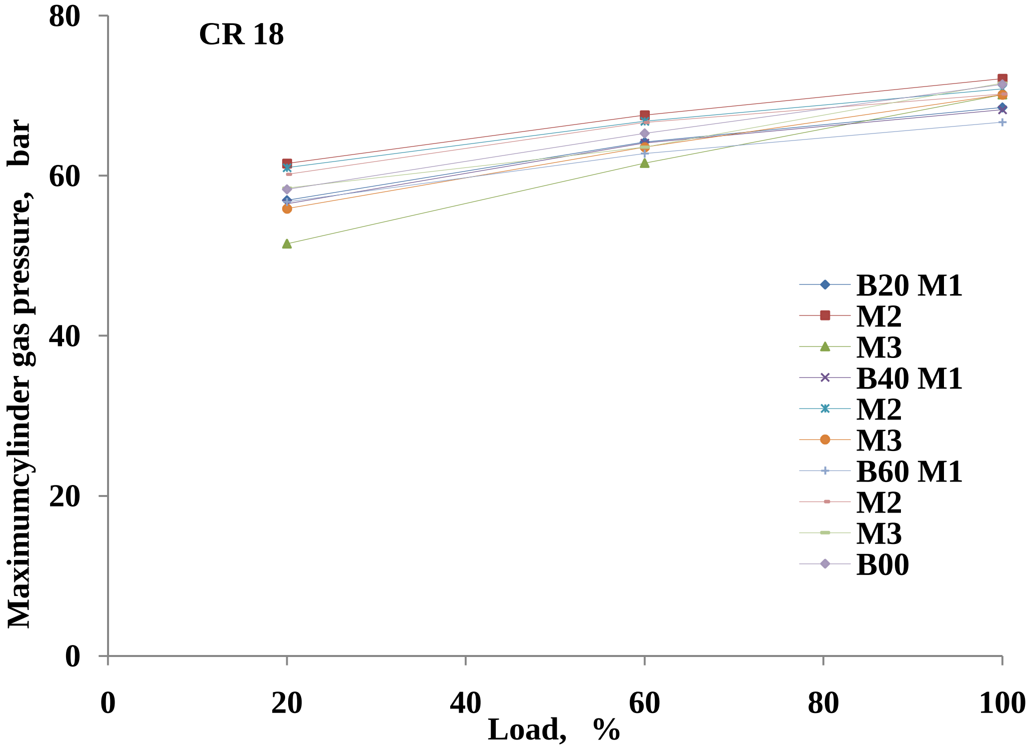
The above discussions has made it clear that with increase in CR the combustion of mixture of two biodiesel in blend with diesel improve the combustion, provide the higher cylinder pressure and are also at earlier crank angle in comparison to diesel fuel which may increase the power output of the engine.

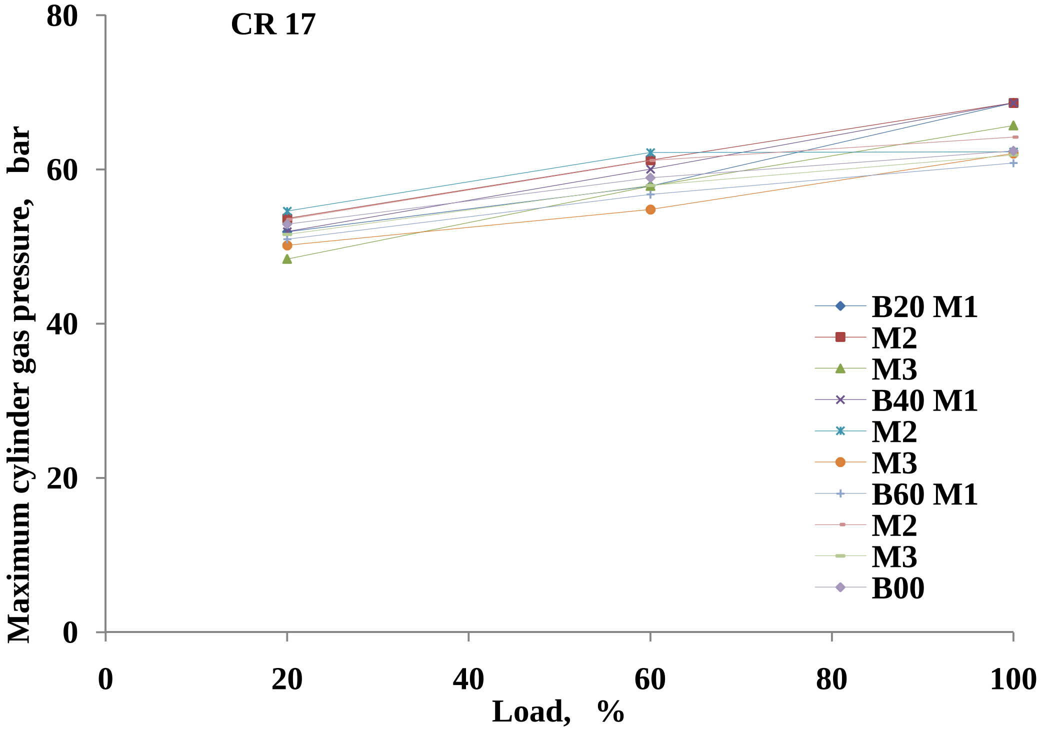
5.4.1.2 Maximum cylinder gas pressure with load

The maximum cylinder gas pressure for diesel fuel and various blends at different load at compression ratio 16, 17 and 18 are illustrated in the Fig.5.4.1.2. The maximum cylinder pressure data are taken from the P-V plot data acquired from the data acquisition. The maximum cylinder pressure for various blends increases with the increase in load for diesel fuel and for the various blends used for the different CR. The increase in cylinder pressure may possibly be attributed to increased fuel supply to produce additional power to take the burden of increased load on the engine. The more quantity fuel supplied and burnt may perhaps increases the cylinder gas pressure. The maximum cylinder pressure is higher for diesel fuel for the rated load at CR18 which may perhaps be attributed to higher heating value. The maximum cylinder pressure for diesel fuel at CR18 for the rated load is 71.4 bars. The maximum higher cylinder pressure for the blend B20M2 is 72.12 bars are higher compared to diesel fuel which may well be accredited to complete combustion of the blends. The complete combustion of blend may be accredited to inherent oxygen and higher cetane number of biodiesel in the blends. The cylinder pressures for all other blends used in the investigation are lesser compared to B20M2 blend. The maximum cylinder pressure are lower for blend B60M1 which may possibly attributed to lower heating value and higher viscosity of the biodiesel in the blend which may affect the combustion efficiency subsequently lower cylinder pressure.

The maximum cylinder pressures at CR17 are lesser compared to CR18 which may possibly be accredited to lower combustion temperature, lesser density and temperature of the air which may influence the mixture formation consequently the combustion process.

The value of maximum higher cylinder pressure for the diesel fuel is 68.65 bars which is same as that of B20M2. Though the heating value of blend B20M2 is lower, cylinder pressures is same as the diesel fuel because of better and complete combustion of blend.





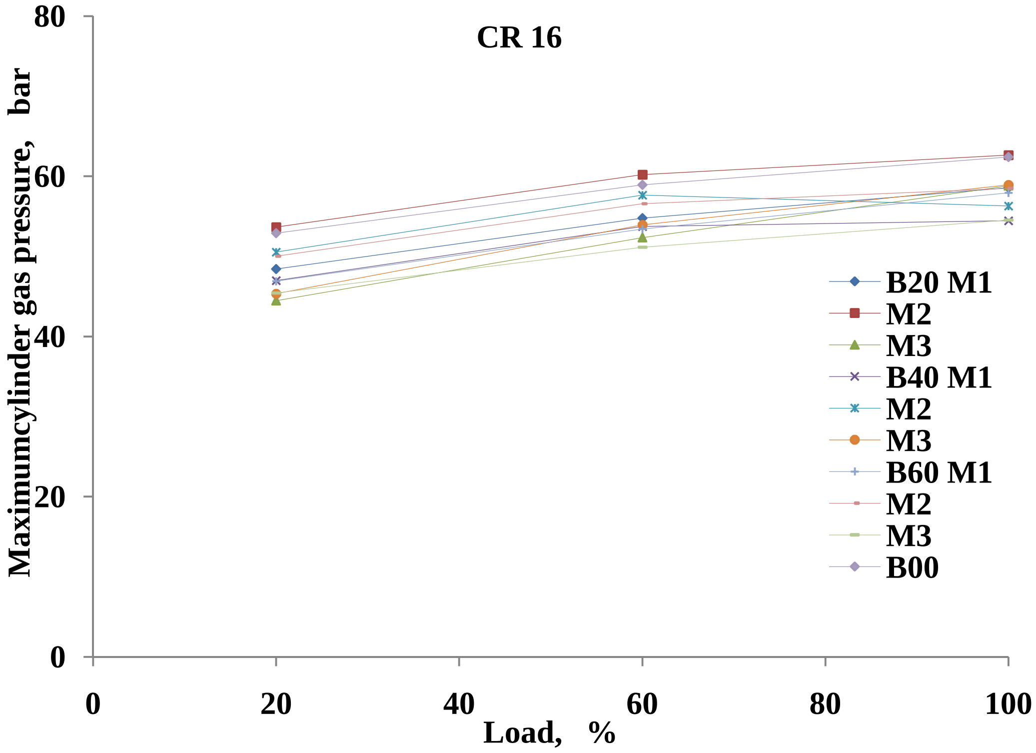


Fig. 5.4.1.2 Variation of maximum cylinder gas pressure with crank angle

The maximum cylinder gas pressures are lesser for the blend B60M1 which may possibly be accredited to lower heat value and higher viscosity of biodiesel in the blends. The higher viscosity of the blends may perhaps be affecting the mixture formation of fuel-air which influences the combustion process consequently the lower maximum cylinder gas pressure.

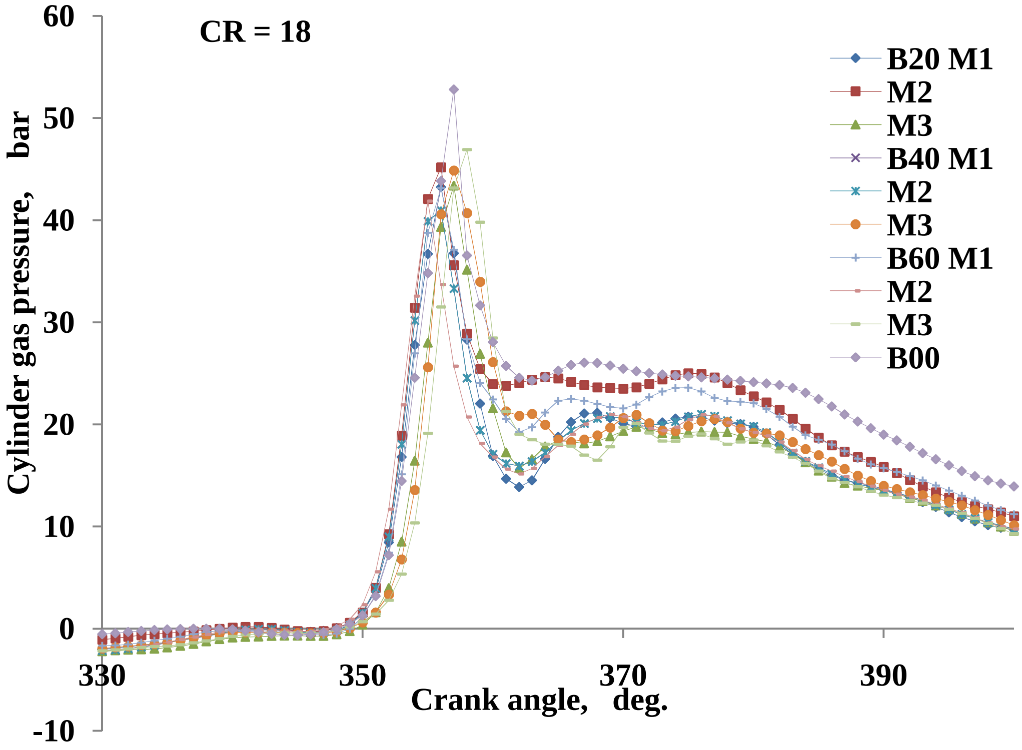
The maximum cylinder gas pressures are lower at CR16 compared to CR17 and CR18 which may perhaps be accredited lower combustion temperature, lesser density and temperature of the air in the cylinder which may delay the start of combustion increasing the premixed combustion stage. The lower combustion temperature, lesser temperature and density of the air at CR16 may have an effect on the mixture formation which in turn influence the combustion hence lesser maximum cylinder pressure.

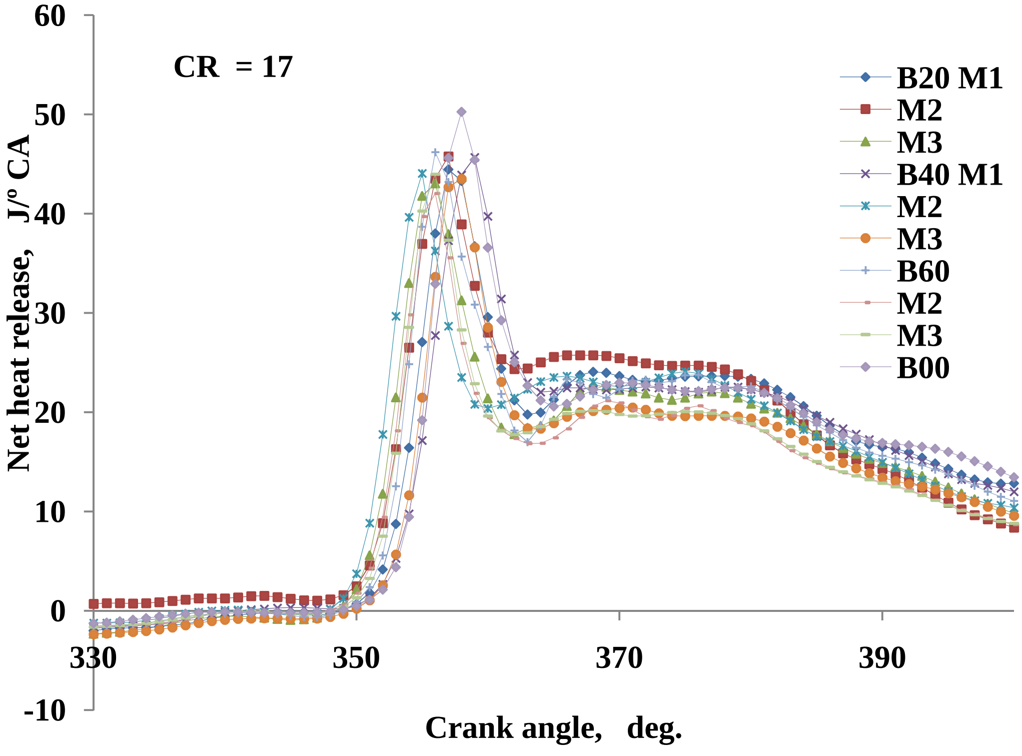
5.4.1.2 Net heat release with crank angle

The variations of net heat release for the diesel fuel as well as for the various blends for the rated load for the CR of 16, 17 and 18 are illustrated in the Fig. 5.4.1.3. The net heat release is the heat released by burning the air-fuel mixture which is accumulated throughout the ignition delay. It is seen from the figures that there is a negative net heat release for all the blends and diesel fuel which may perhaps be because of heat is absorbed for evaporation of the fuel rather than generating the heat. The initiation of ignition changes the net heat release from negative to positive since the heat is released after the start of combustion. The net heat release for the diesel fuel is higher compared to other blends which may perhaps be accredited to higher heating value as well as better combustible properties of diesel fuel. The higher net heat release for the diesel fuel may possibly be accredited to increased delay. The value of net heat release for diesel fuel is 52.79 J/º CA and is at 4º CA bTDC. The net heat release for all the blends are lesser compared to diesel fuel which may perhaps be accredited to lower heating value and reduced ignition delay for the blends. It is seen from the figure the net heat release is higher at CR18 compared to other two CR 17 and 16 for the rated load [136]. The higher net heat release at CR18 which may be possibly be because of increased combustion temperature, higher temperature and density of the air inside the cylinder. The higher combustion temperature, higher temperature and pressure of air at CR18 which may contribute in improved mixture formation and complete combustion of fuels. The higher net heat release for B60M3 blend which may perhaps be accredited to the intrinsic oxygen, higher CN of biodiesel in the blends. The inherent oxygen enhances the mixing of fuel-air and higher cetane number accelerates the combustion of the blends. The value of NHR for B60M3 is 46.89 J/º CA and is at 2º CA bTDC. The NHR for the blend B40M1 is lower and is 40.95 J/º CA and is at 4º CA bTDC. The maximum higher net heat release varies in the range of 5-2 º CA bTDC. The higher CR decreases the combustion duration and improve the performance of the engine for the fuels used [137].

The net heat release at CR17 is to be lower at the rated load compared to CR18 which may well be accredited to reduced combustion temperature, lesser density and temperature of the air inside the cylinder. Though the ignition delay increases because of lower temperature, and density of the air and lower combustion temperature at CR17 which may perhaps affects the mixture formation consequently the premixed combustion phase. The lower combustion temperature and density of the air may contribute to the lower net heat release. The maximum net heat released is marginally lower for CR17 compared to CR18. The maximum NHR for the diesel fuel are higher and is 50.28 J/º CA for the rated load and at 2º CA bTDC. The higher net heat release for the blend B60M1 is 46.19 J/º CA for the rated load. The blend B40M2 has lesser maximum net heat release and its value is 42.08 J/º CA for the rated load and is at 5º CA bTDC. The net heat release for the blends and petroleum diesel fuel varies in the range of 5º CA bTDC to 1º CA bTDC which is higher compared to CR18.

The ignition delay is increased at CR16 the net heat releases are to be higher for blends in comparison to CR17 and CR18. The increased ignition delay increases premixed combustion stage hence the higher net heat release. However the net heat release for the blends at CR16 are lower compared to CR17 and CR18 which may be accredited to decreased combustion temperature, lower temperature and density of air which may





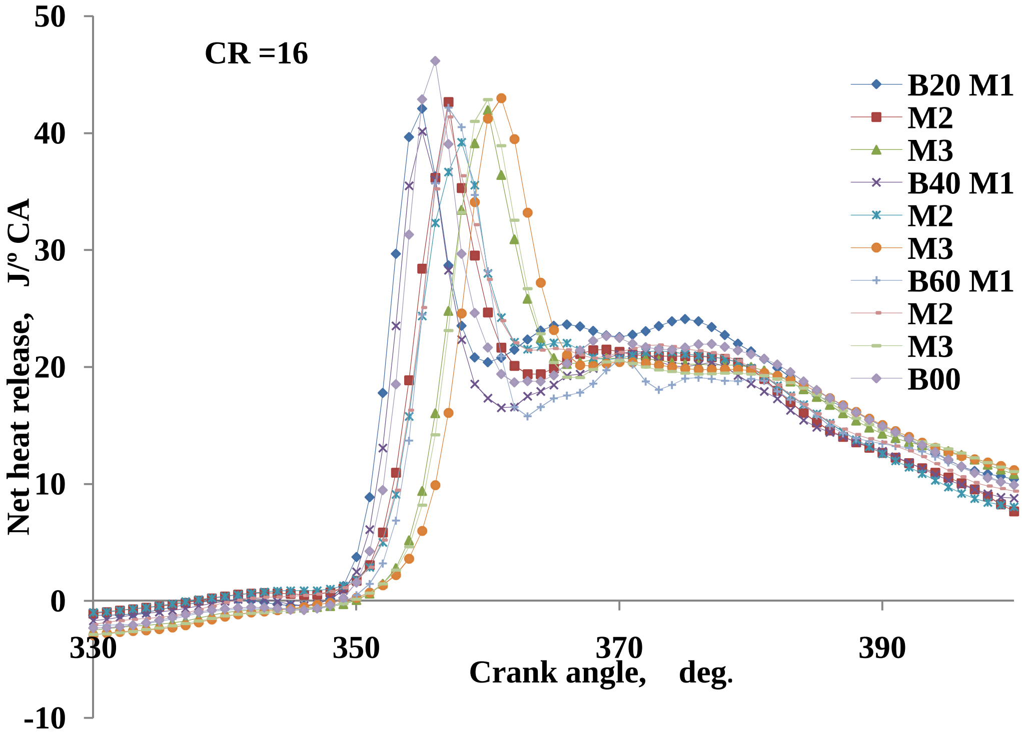


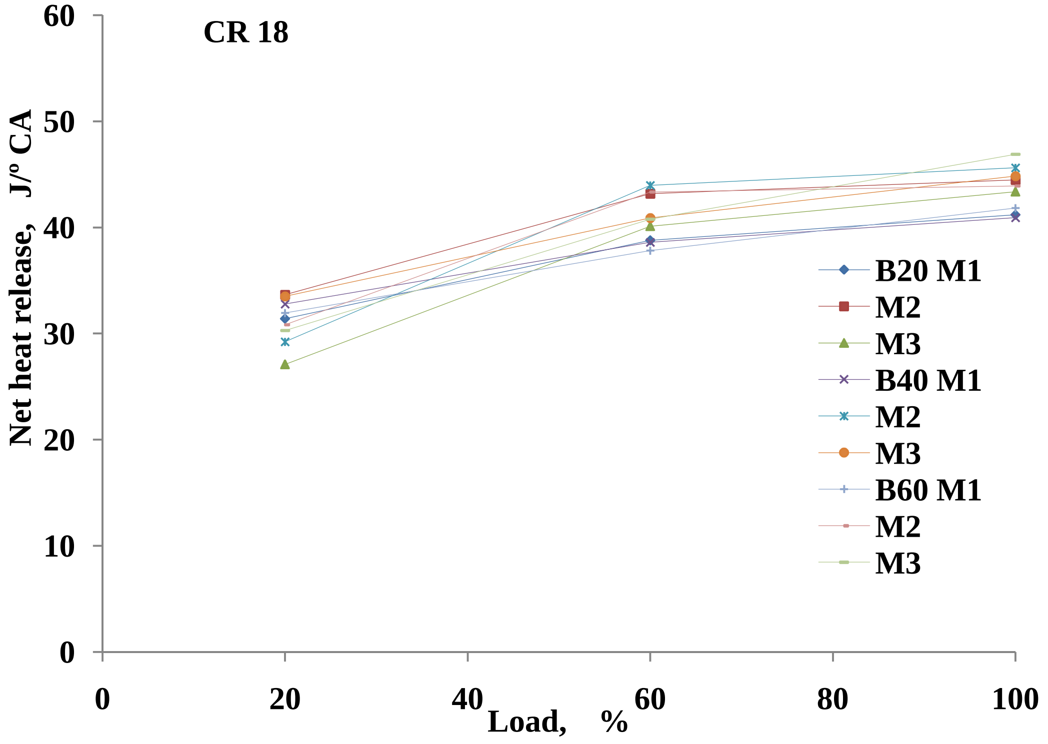
Fig. 5.4.1.3 Variation of net heat release with crank angle at rated load

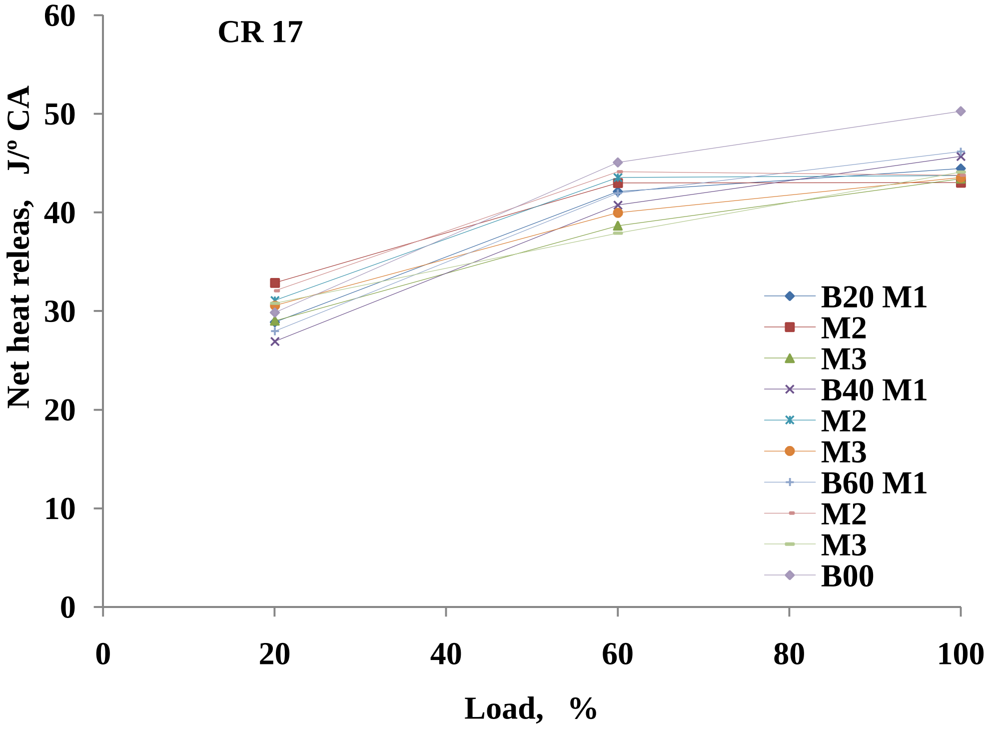
perhaps be influence the vaporization and mixing of fuel-air consequently the incomplete combustion. Incomplete combustion of fuels decreases the net heat release at CR16. The maximum net heat release for diesel fuel is higher; its value is 46.16 J/° CA at the rated load and is at 4° CA bTDC. The maximum NHR for all blend are varying in the range of 5° CA bTDC to 1° CA aTDC. The maximum higher net heat release at CR16 is later in terms of cark angle compared to CR17 and CR18.

5.4.1.4. Maximum heat release with load

The maximum heat release for the diesel fuel as well as for the various blends for different loads for compression ratio 16, 17 and 18 are illustrated in the Fig. 5.4.1.4. The heat release gives more information regarding the progress of combustion in the engine. It is observed from figure the heat release increases with increase in load for all the compression ratios used. It can be observed from the figure that the maximum heat release rate for the various blends follow the similar trend as diesel fuel which may perhaps be attributed to the properties of biodiesel and are comparable with diesel fuel. The highest heat release is found to be for the diesel fuel and is 52.79 J/° CA which is higher in comparison to the blends. The maximum heat release for the blend B60M2 is 46.38 J/° CA at CR18 for the rated load. The heat release for the blend B20M3 is 42.16 J/° CA for the rated load. The lesser heat release for the blends may perhaps be accredited to lesser heat value and high viscosity of the biodiesel in the blends. The heat release at rated load might be still higher compared to the values obtained which may perhaps be accredited to incomplete combustion of fuels used. The incomplete combustion at the rated load may perhaps be accredited to increased turbulence and decreased time for the combustion which causes the lower heat release for the rated load at CR18.

The maximum heat release at CR17 is lesser compared to CR18 for the rated load for diesel fuel and for the various blends used for different load. For the CR17, the maximum heat release for the diesel fuel is 50.28 J/ ºCA for the rated load which is higher compared to the blends. The maximum higher heat release for the diesel fuel may be possibly accredited to high heating value and complete combustion of diesel fuel at CR17. The heat release for biodiesel blends is lower compared to diesel fuel which may be well be accredited to lower heating value and higher viscosity of biodiesel in the blends. The higher viscosity of blends may affect the mixing of fuel-air which may perhaps be contributes towards the incomplete combustion hence lower heat release. The maximum heat release for the blends B20M1 and B20M2 is 46.19 J/º CA and 42.3 J/º CA respectively for the rated load.





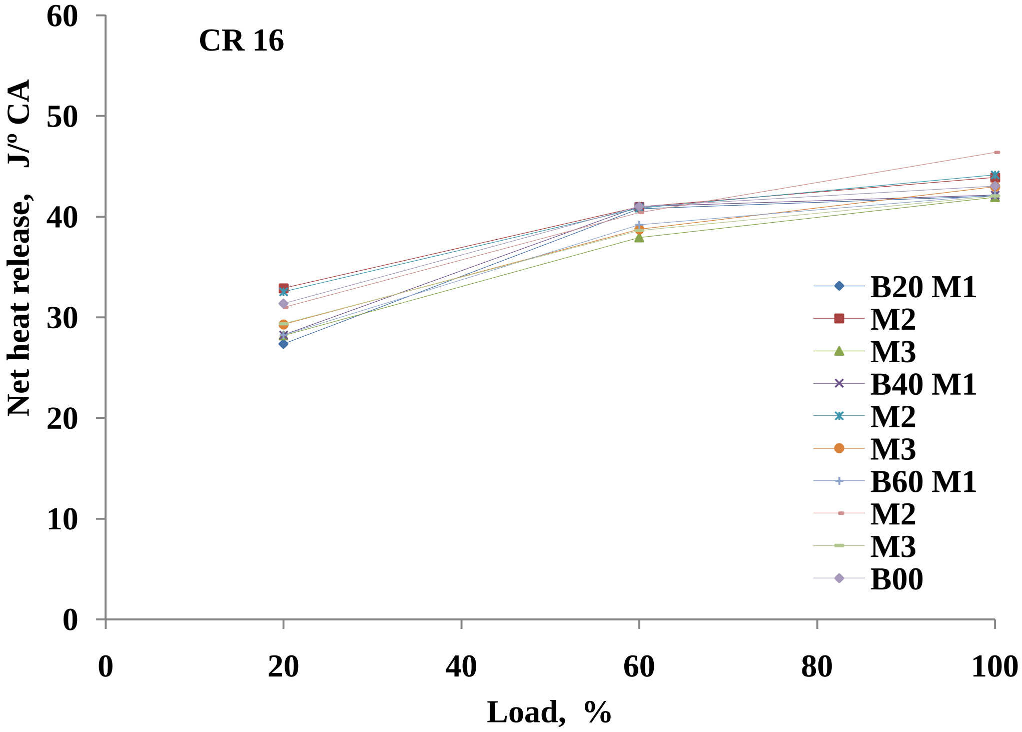


Fig. 5.4.1.4 Variation of net heat release with CA at the rated load

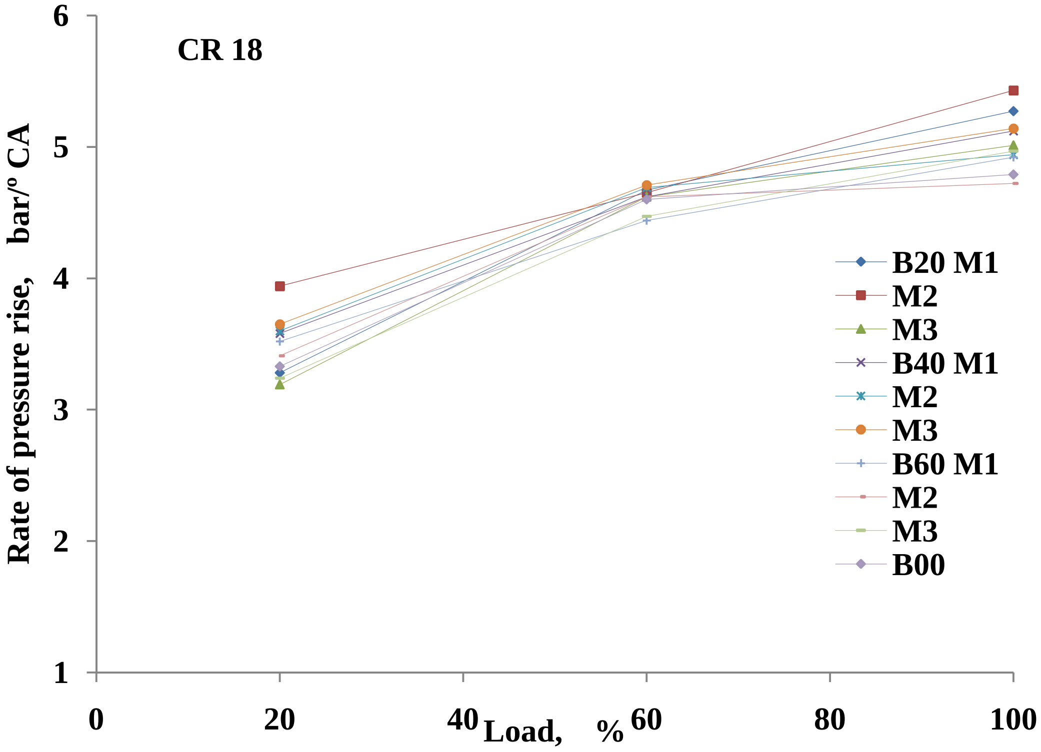
The heat releases for the diesel fuel are higher in comparison to the blends at CR16 which may be attributed to higher heating value and complete combustion. The maximum heat released for the blends are lesser which may possibly be accredited to reduced combustion temperature, lower temperature and density of the air which may have an effect on the atomisation and mixing of fuel-air consequently the combustion. The lower combustion temperature and temperature of the air at CR16 may contribute into incomplete combustion hence decreases the maximum heat release.

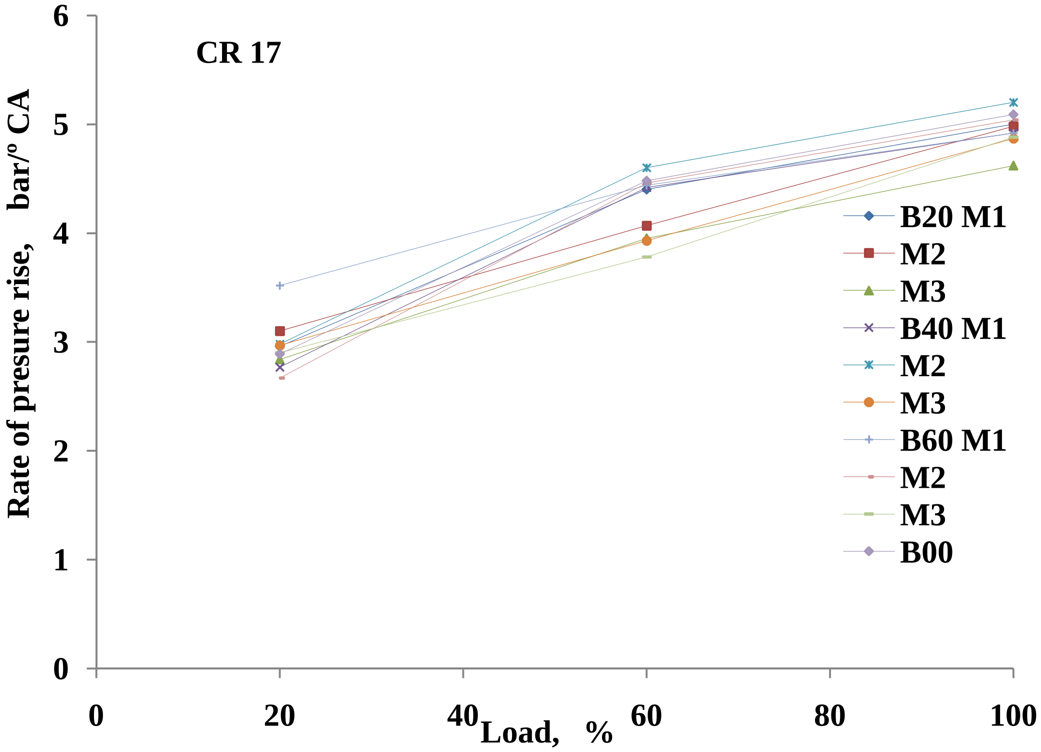
5.4.1.5 Rate of pressure rise (RPR) with load

The change in RPR for diesel fuel and for the various blends for the different load is illustrated in the Fig.5.4.1.5. It is seen with the figure that the RPR increases with increase in compression ratio for diesel fuel as well as for the various blends. The RPR is depends on the premixed or uncontrolled combustion stage. The RPR increases with increase in compression ratio which may possibly be accredited to increased combustion temperature, higher temperature and pressure of the air which may perhaps improve the mixture formation of fuel-air, subsequently complete combustion. This may also perhaps be accredited to increased chemical reactions and accelerate the combustion of the blends. The RPR is higher for the blend B20M2 at CR18 which may perhaps be accredited to complete combustion of blends. The complete combustion of blends may perhaps be because of natural oxygen content and higher CN of biodiesel in the blends. The maximum RPR for the B20M2 blend is 5.12 bars/ ºCA for the rated load where as for diesel fuel it is found to be 4.79 bars/ ºCA for the rated load at CR18.

The RPR for the diesel fuel and for the various blends at CR17 are lesser compared to CR18 which may perhaps be accredited to reduced combustion temperature and lower temperature, pressure of the air. The reduced combustion temperature, lower temperature and density of the air may perhaps be affecting the atomization, mixing of fuel-air subsequently the combustion process. The RPR for diesel fuel at CR17 is 5.09 bars/ ºCA for the rated load. The maximum higher rate of pressure rise at CR17 for the blend B40M2 is 5.2 bars/ ºCA at the rated load. The higher RPR for the blend B40M2 may well be accredited to increased ignition delay at CR17 which may increases the RPR. The RPR for the diesel fuel and for the various blends is in the range of 4.62 to 5.2 bars/ ºCA for the rated load.

The RPR for diesel fuel at CR16 is 4.92 bars/ ºCA which is less compared to CR17. This may perhaps be accredited to reduced combustion temperature, lower temperature and density of the air in the cylinder which may delay the start of ignition and slow combustion consequently lesser RPR. The RPR for the blends are lesser at CR16 compared to CR17 and CR18 which may possibly because of lower combustion temperature, lesser temperature and pressure of the air at CR16. The lower combustion temperature at CR16 may influence the atomisation, evaporation of the fuel hence affect the mixing of fuel-air which may contributes towards the incomplete combustion hence lower RPR.





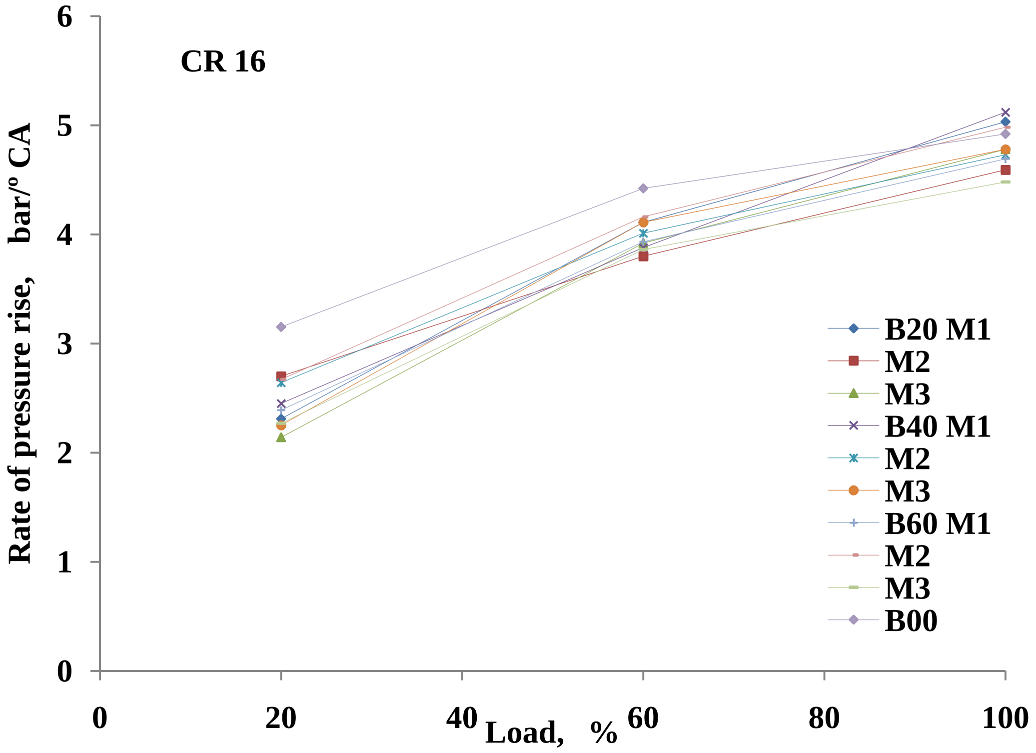


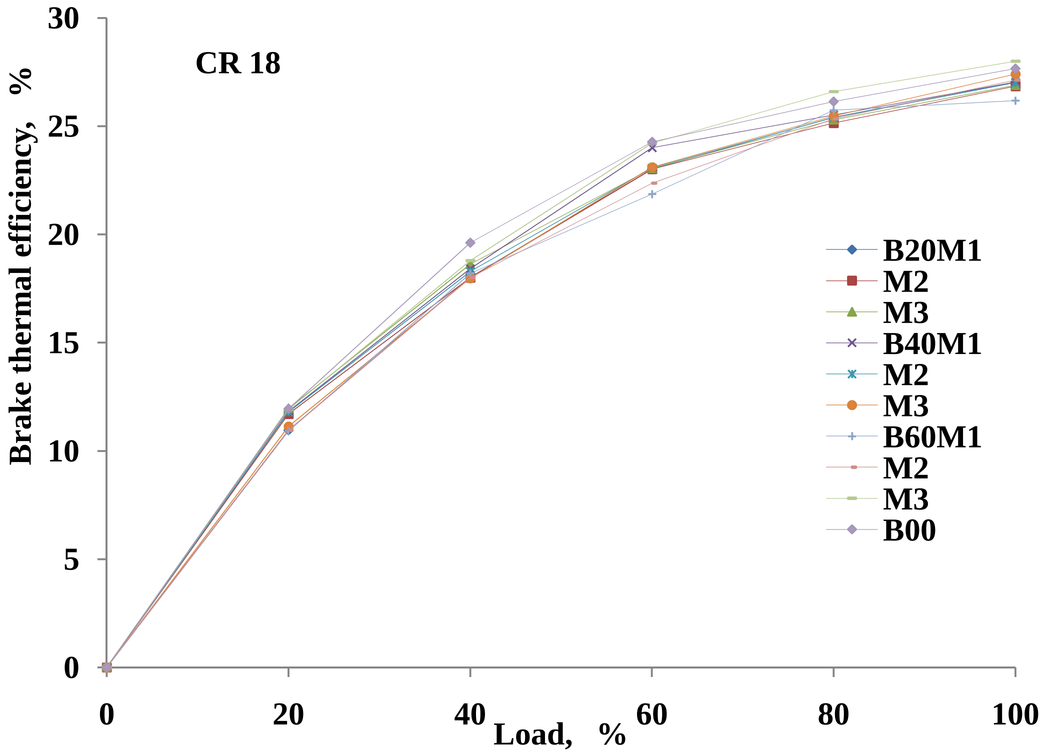
Fig. 5.4.1.5 Variation of rate of pressure rise with CA at rated load

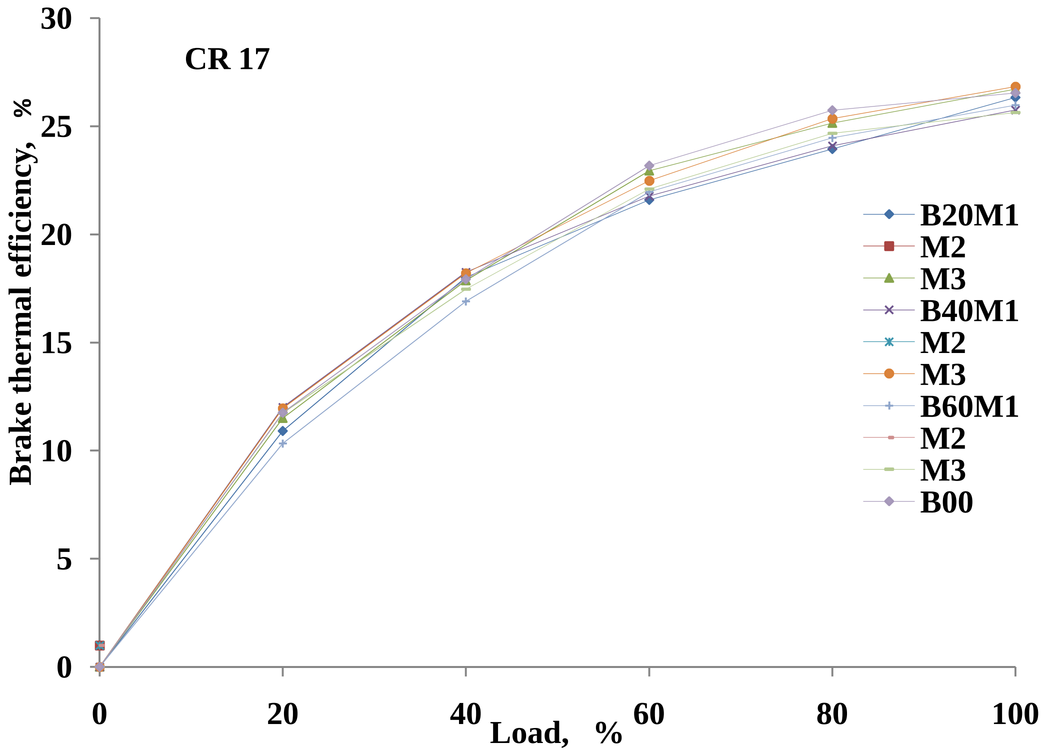
5.4.2 Performance analysis

5.4.2.1 Brake thermal efficiency

The variation of BTE with load for diesel fuel as well the various blends at compression ratio 16, 17 and 18 is illustrated in the Fig. 5.4.2.1. The BTE increases with increase in load for the fuels used for the different CR. The BTE are higher at CR18 for the diesel fuel and for the various blends used. The higher BTE at CR18 for the diesel fuel and various blends may possibly accredited to increased combustion temperature, higher temperature and pressure of the air in the cylinder [137]. The increased combustion temperature, higher temperature and density of the air which may perhaps improve the mixture formation and complete combustion results in to increases the thermal efficiency of engine. The BTE increases for the increase in CR for the fuels used which might increase the thermal efficiency of the engine [138]. It is observed that BTE of diesel fuel is higher compared to the blends which may perhaps be accredited to higher heating value and better combustible properties of diesel fuel. The better properties of diesel fuel may contribute in complete combustion hence increases the BTE. The blend B60M3 has higher brake thermal efficiency compared to diesel fuel for the rated load which may perhaps be accredited to inherent oxygen and higher CN of biodiesel in the blends contributes for the complete combustion of blends. The BTE of diesel fuel is 27.66% at

CR18 whereas for B60M3 blend BTE is 27.99% for the rated load. The BTE for the blend B60M1 is least and its value is 26.18%. The higher BTE for the blend B60M1 may perhaps be because natural oxygen and higher CN contribute in complete combustion of





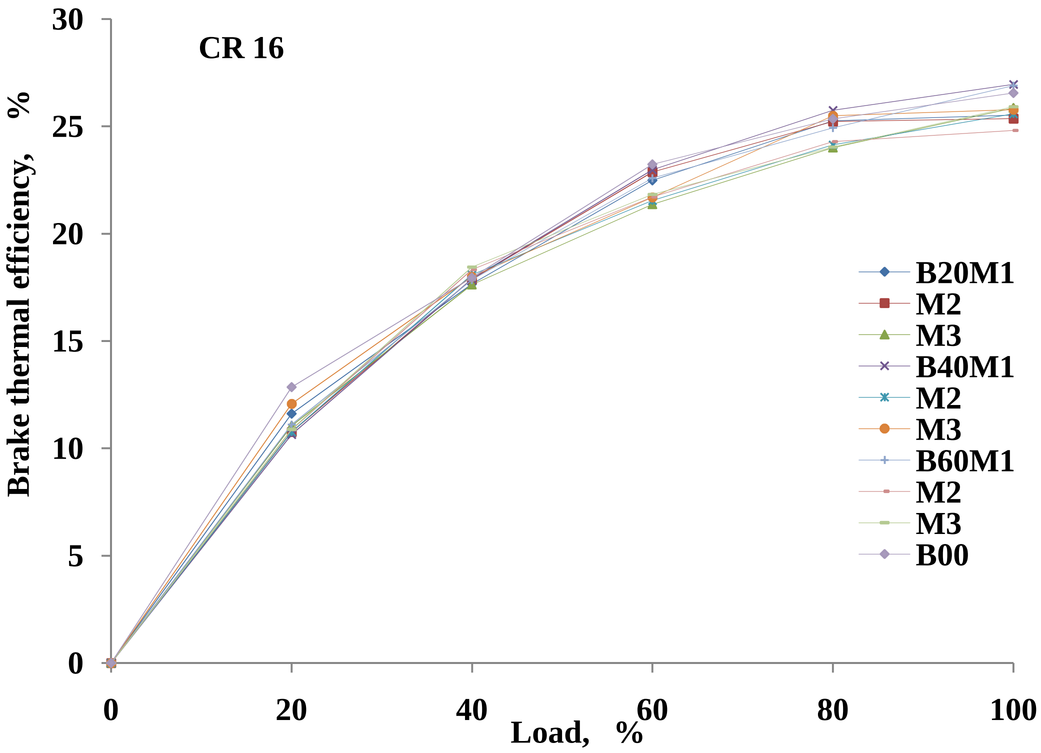


Fig. 5.4.2.1 Variation of brake thermal efficiency with load

the blends. The BTE for the blend B20M2 is decreased by 1.9% and for the blend B60M3 blend is increased by about 1.3% compared to diesel fuel for the rated load.

The BTE at CR17 for diesel fuel as well as for the various blends are lesser compared to CR18 which may possibly accredited to lower combustion temperature, lesser temperature and density of the air in the cylinder. The lower combustion temperature, lesser density and temperature of the air at CR17 which may influence the mixture formation consequently the combustion process hence lower BTE. The lower combustion temperature at CR17 may influence the fuel atomisation and vaporisation and mixture formation which contribute towards incomplete combustion. The BTE of diesel fuel is 26.54% at the rated load. BTE of diesel fuel is higher for almost for all the load compared to the blends which may perhaps be accredited to higher heating value of diesel fuel. The blend B40M3 has higher BTE compared to diesel fuel and other blends for the rated load and it is 26.84% which may be accredited to inherent oxygen and higher cetane number of the biodiesel in the blend may complete the combustion.

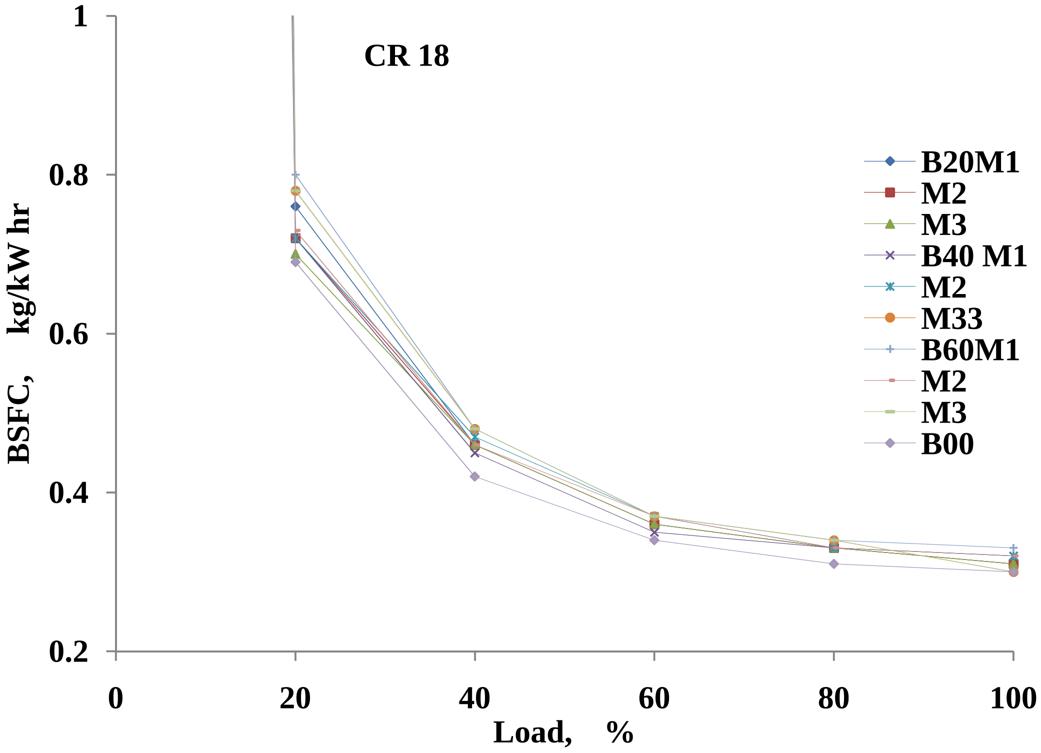
The BTE are lesser for CR16 compared to the CR17 and CR18 for diesel as well as for various blends used. The lesser BTE at CR16 may possibly be because of lower combustion temperature, lesser density and temperature of the air in the cylinder may possibly be accredited to sluggish mixture formation consequently the incomplete combustion [139]. The BTE for diesel fuel at CR16 is higher compared to the blends which may be perhaps be accredited to better combustible properties of diesel fuel compared to the blends.

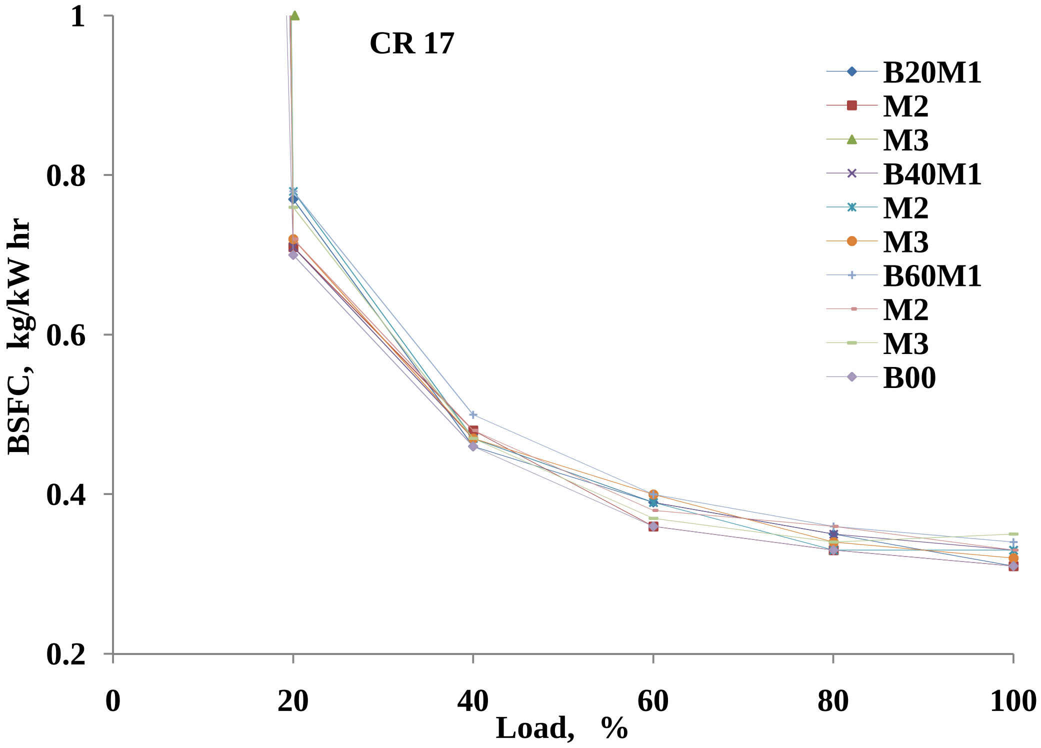
5.4.2.2 Brake specific fuel consumption with load

The variation of BSFC with load for diesel fuel and for the various blends for different loads at compression ratio of 16, 17 and 18 are illustrated in the Fig. 5.4.2.1. The BSFC decreases for diesel fuel as well as for the various blends with the increase in load which may probably be accredited to increased combustion temperature and higher temperature of the air, results in improving the fuel efficiency. The similar trend is followed by the various biodiesel blends used which may perhaps be accredited to biodiesel properties are comparable with diesel fuel. The BSFC for diesel fuel is 0.3 kg/kW hr for the rated load at CR18. The BSFC for the blend B20M3 is 0.3 kg/kW hr are same as that of diesel fuel. The inherent oxygen and higher CN of biodiesel in the blends, contribute in the complete combustion of blends hence increases the fuel efficiency. The BSFC of blend B60M1 is higher compared to diesel fuel and other blends which might be accredited to lower heating value and higher viscosity, inferior volatility of biodiesel in the blends. The higher viscosity and inferior volatility of biodiesel in the blends may affect the mixture formation of fuel-air consequently the combustion. The blend B60M1 has 9% higher fuel consumption compared to diesel because of lower heating value and higher viscosity of biodiesel in the blends.

The BSFC of diesel fuel as well as for the various blends at CR17 are higher compared to CR18 which may possibly be attributed to decreased combustion temperature, lower pressure and temperature of the air. The lower pressure and temperature of the air have an effect on the atomization and mixture formation of fuel-air subsequently the sluggish combustion which in turn increases the BSFC at CR17. The BSFC of diesel fuel at CR17 is 0.31 kg/kW hr at the rated load. The BSFC for the blend B60M3 is higher and its value is 0.35 kg/kW hr for the rated load. The blend B60M3 has 12.9% higher fuel consumption compared to diesel fuel which may possibly be accredited to lower heating value and inferior fuel properties of biodiesel in the blends. Higher viscosity and inferior volatility of biodiesel in the blends may affect mixture formation and the combustion of the blends which may increases the BSFC of the blends.

The BSFC of the diesel at CR16 are lesser compared to the blends which may be accredited better combustible properties of diesel fuel. The BSFC of diesel fuel is 0.31 kg/kW hr at the rated load. BSFC of the blends and diesel fuel are higher at CR16 compared to CR17 and 18 because of lower combustion temperature, lesser pressure and temperature of the air which might possibly affect the mixture formation and the





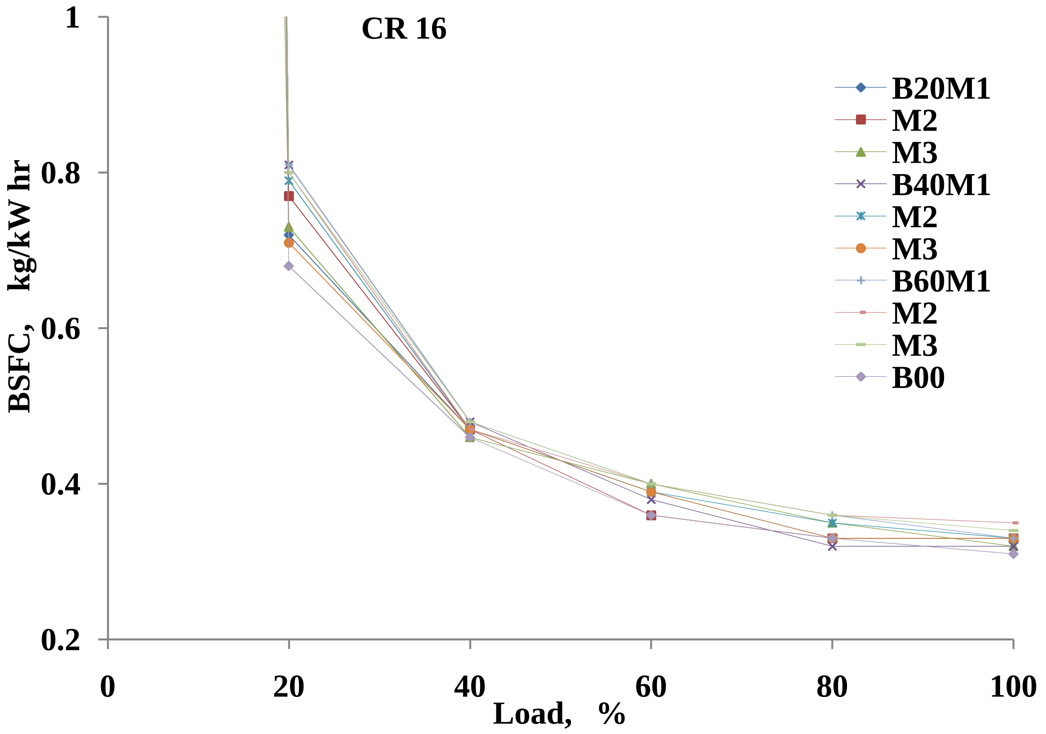


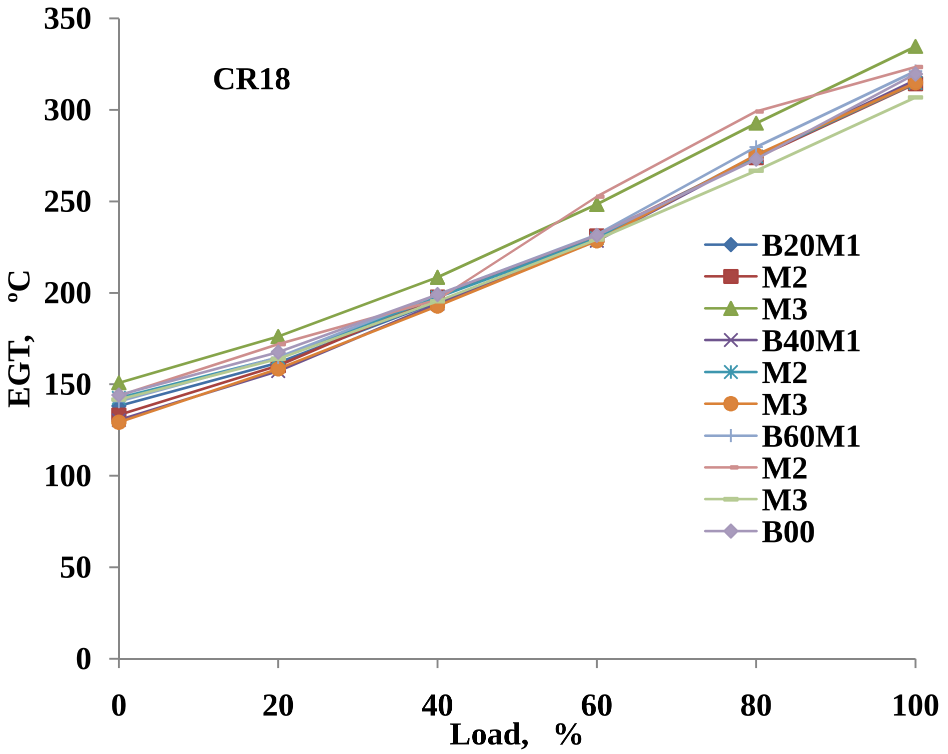
Fig. 5.4.2.2 Variation of BSFC with load

combustion process of blends. The decreased combustion temperature, lower temperature and density of the air which may affect the mixing of fuel-air results in incomplete combustion hence increase the fuel consumption. The BSFC of diesel fuel at CR16 is 0.32 kg/kW hr at the rated load. The BSFC for the blend B40M2 is 0.35 kg/kW hr which is higher compared to diesel fuel and other blends. The blend B40M2 has higher BSFC and it increased by about 12.9% compared to diesel fuel.

5.4.2.3 Exhaust gas temperature (EGT) with load

EGT for the diesel fuel and for the various blends at different load at CR 16, 17 and 18 are illustrated in the Fig. 5.4.2.3. The EGT increases for the increased load on engine because of increased quantity of fuel supply and burned to take the burden of additional load on the engine. The EGT for diesel fuel and for the various blends decreases with increases in compression ratio. It is observed from the figure that EGT for the blend B60M3 is found to be lower by about 4% compared to diesel fuel at CR18. The lower EGT for the higher CR which may perhaps be attributed to increased combustion temperature, higher temperatures and pressure of the air which may increases the burning speed and reduce the combustion time results into reduced EGT for the blends [140]. This increased combustion temperature enhance the mixing of fuel-air and chemical reaction and accelerate the combustion of blends results into decrease in the EGT [141]. The EGT for diesel fuel is 320º C and for the blend B60M3 is 306º C. The reduction in EGT for the blends B60M3 is by about 4.1% compared to diesel fuel. The higher exhaust gas temperature for some of the blends may perhaps be accredited to the higher viscosity and inferior volatility of the blends. The inferior fuel properties of blends may influence the mixture formation of fuel-air and the combustion hence it results into the increase of EGT for the higher blends.

The EGT for the diesel fuel and for the various blends for different load at CR17 are found to be higher compared to CR18. The higher EGT at CR17 may be accredited to lower combustion temperature, lesser density and temperature of the air in the cylinder. The lower combustion temperature may affect the mixing of fuel-air and combustion process hence increases the exhaust gas temperature. The EGT at CR17 is higher by about 5% for the rated load compared to CR18. The EGT for biodiesel blends are lesser compared to diesel fuel which may possibly be accredited to complete combustion of blends. The higher temperature of exhaust gas may perhaps be because of incomplete combustion of blends and diesel fuel at CR17.



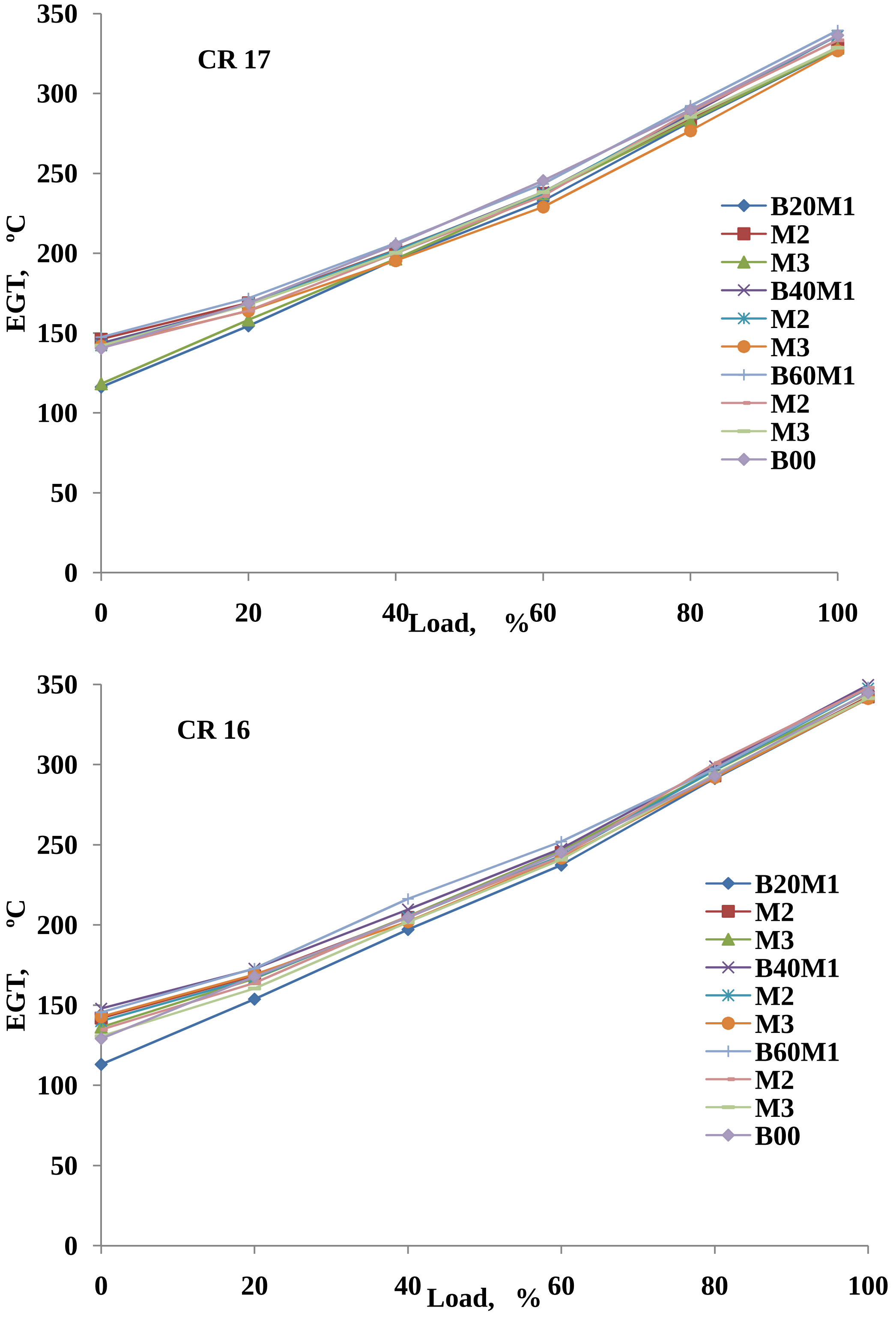


Fig. 5.4.2.3 Variation of exhaust gas temperature with load

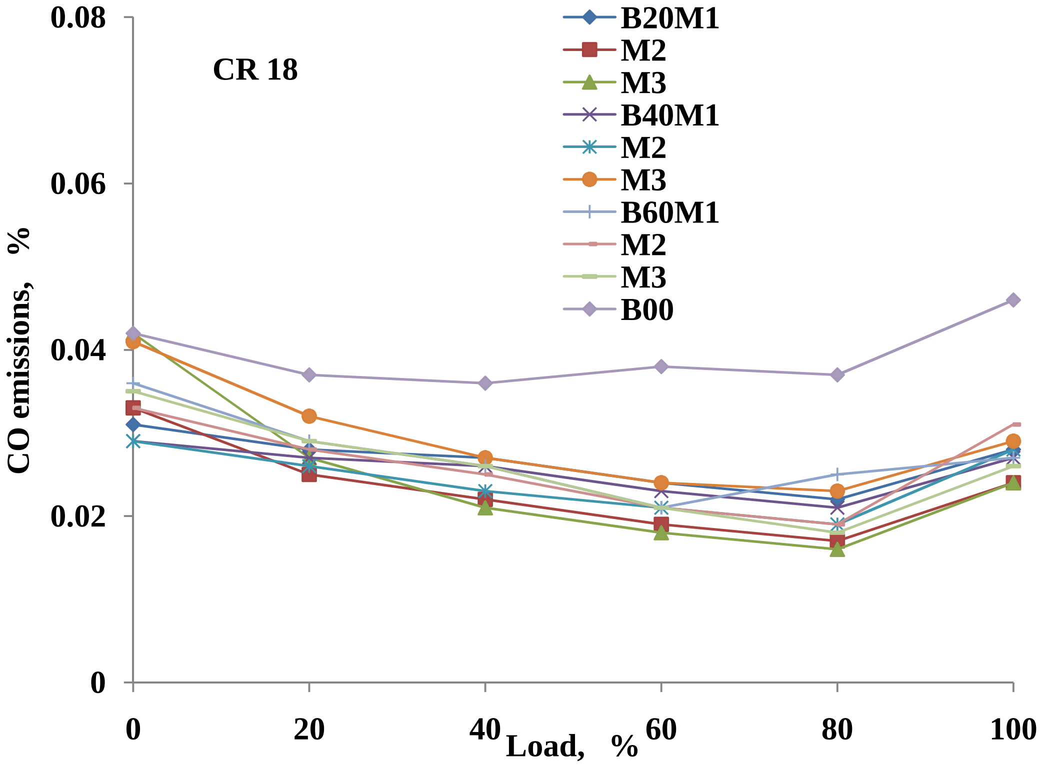
The EGT of the diesel fuel and various blends at CR16 are higher compared to CR17 and CR18 which may possibly accredited to lower combustion temperature, lesser pressure and temperature of the air in the combustion chamber when the fuel is injected. The lower combustion temperature, density and temperature of the air at CR16 may perhaps delay the mixture formation causes the sluggish combustion subsequently increases the EGT. The higher the EGT indicates the higher energy is carried away by the gases through the exhaust.

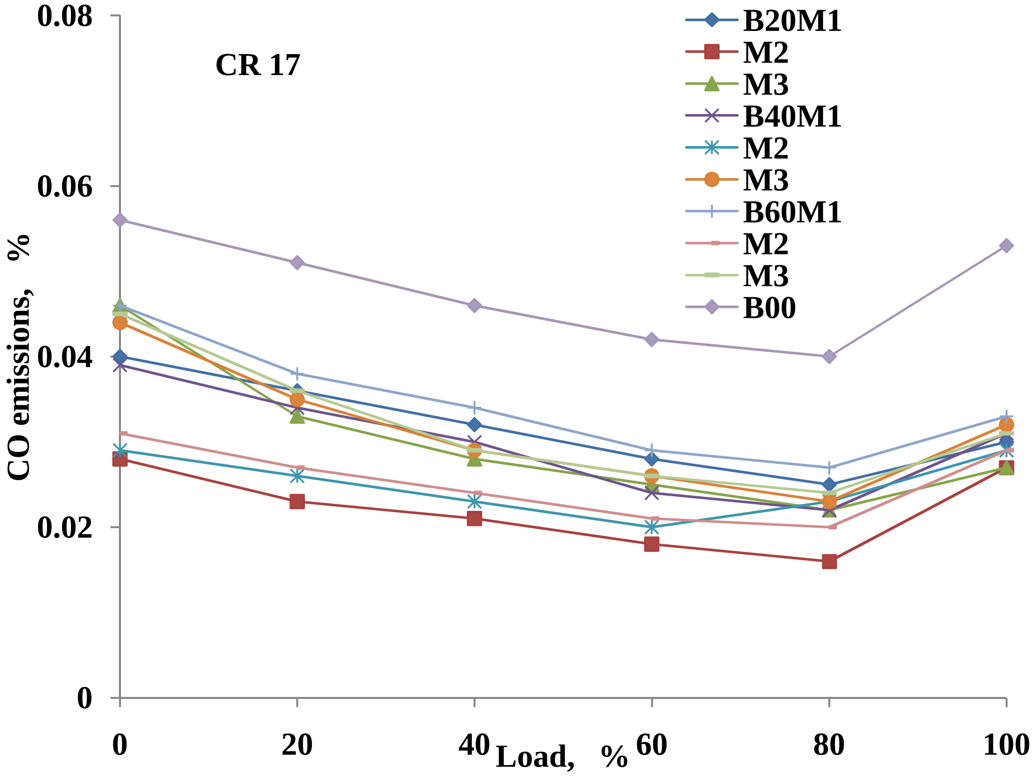
5.4.3 Emission analysis

5.4.3.1 CO emissions with load

The CO emissions for the diesel fuel and for the various blends for different load at compression ratio 16, 17 and 18 are illustrated in the Fig.5.4.3.1. The CO emissions decrease with increase in CR for diesel fuel as well as for the various blends. The increase in CR increases the combustion temperature, density and temperature of the air in the cylinder. The higher combustion temperatures improve the mixture formation of fuel-air and accelerate the combustion which results into reduction of CO emissions [138]. The CO emissions are lesser for the blends in comparison with diesel fuel which may be accredited to inherent oxygen and higher CN of biodiesel in the blends. The inherent oxygen and higher CN may perhaps enhance the mixture formation of fuel-air which contributes in complete the combustion of blends. At lower loads CO emission are higher for the fuels used in the investigation which may perhaps be accredited to lesser combustion temperature. As the load on the engine increases the CO emissions decreases which may perhaps be because of increased combustion temperature, enhance the burning and complete the combustion results into decrease of CO emissions. It is seen that CO emissions are higher for the rated load which may perhaps be because of enhanced turbulence and speed of combustion at higher load. Because of enhanced speed of combustion the time available for conversion of CO to CO2 is less which increases the CO emissions. It is observed from the figure that CO emissions are lesser at CR18 compared to CR17 and CR16 for the rated load. The CO emissions are found to be 0.046% for diesel fuel for the rated load. The CO emission for blend B40M2 is the lowest 0.024% and the blend B60M1 is the highest which is 0.031% for the rated load. The CO emissions are decreased by 47.8% for the blend B40M2 and 32.6% for the blend B60M1 compared to diesel fuel for the rated load. Decrease in CO emissions for the other blend is in between B40M2 and B60M1 blends.

The CO emission for CR17 is found to be higher compared to CR18 which may possibly accredited to lower combustion temperature, temperature and pressure of the air in the cylinder influence the mixture formation consequently affect the combustion process. The CO emissions are found to be higher for diesel fuel which is 0.053%. The CO emissions are lower for the blend B40M3 and are found to be 0.027%. The maximum higher CO emissions for the blends are found to be for the blend B60M1 and its value is 0.033%. The higher CO emission for the blend B60M1 may perhaps be accredited to higher viscosity and lower volatility of the biodiesel in the blend. The higher viscosity and lower volatility may affect the combustion which increases CO emissions. The decrease in CO





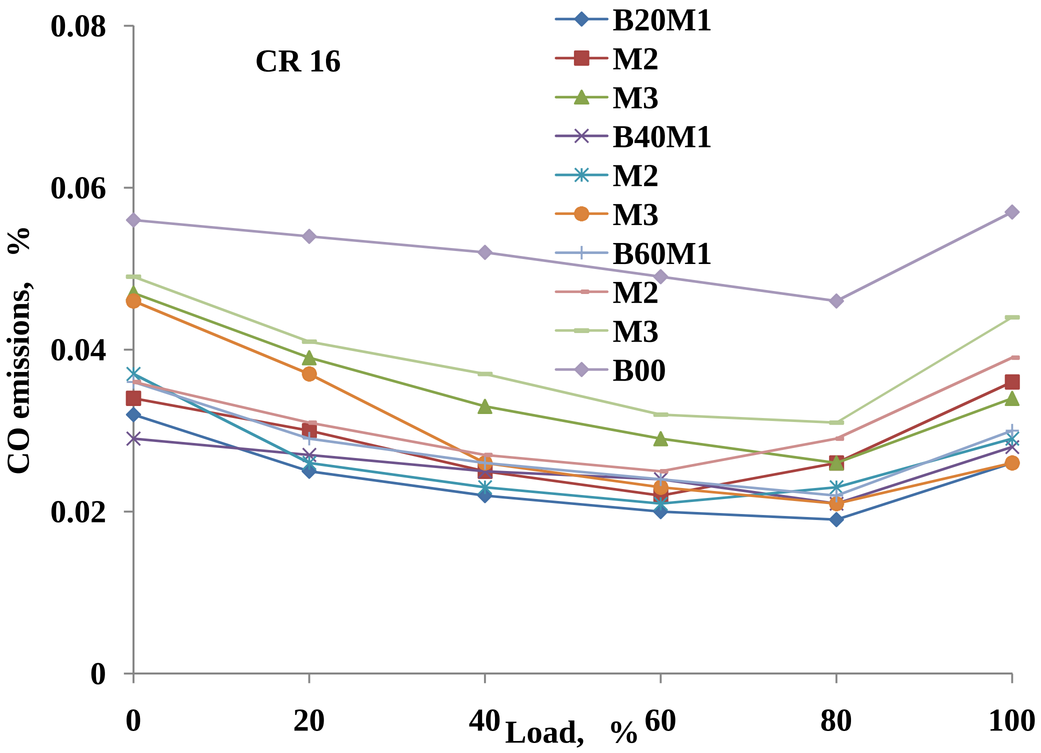


Fig. 5.4.3.1 Variation of CO emissions with load

emissions for the blend B40M3 is 49% where as for the blend B60M1 reduction is 37.7% compared to diesel fuel. The lower CO emission for the blends is because of improved combustion of blends.

The CO emissions at CR16 are higher compared to CR17 and CR18 for the diesel fuel as well as for the various blends. The higher CO emissions at CR16 which may be accredited to lower combustion temperature, lesser density and temperature of the air inside the cylinder may influence the mixing of fuel-air consequently the combustion process. The CO emissions at CR16 for diesel fuel are 0.057% at the rated load. The least CO emissions for the blend B40M3 is 0.026% for the rated load.

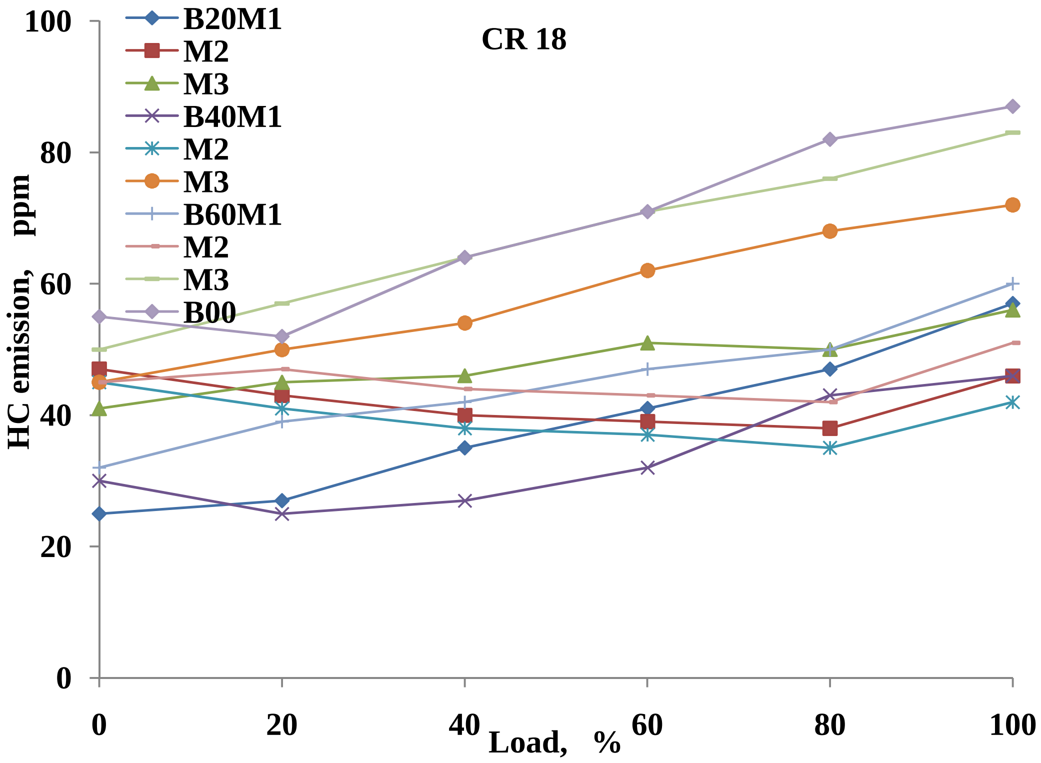
5.4.3.2 Hydrocarbon emissions with load

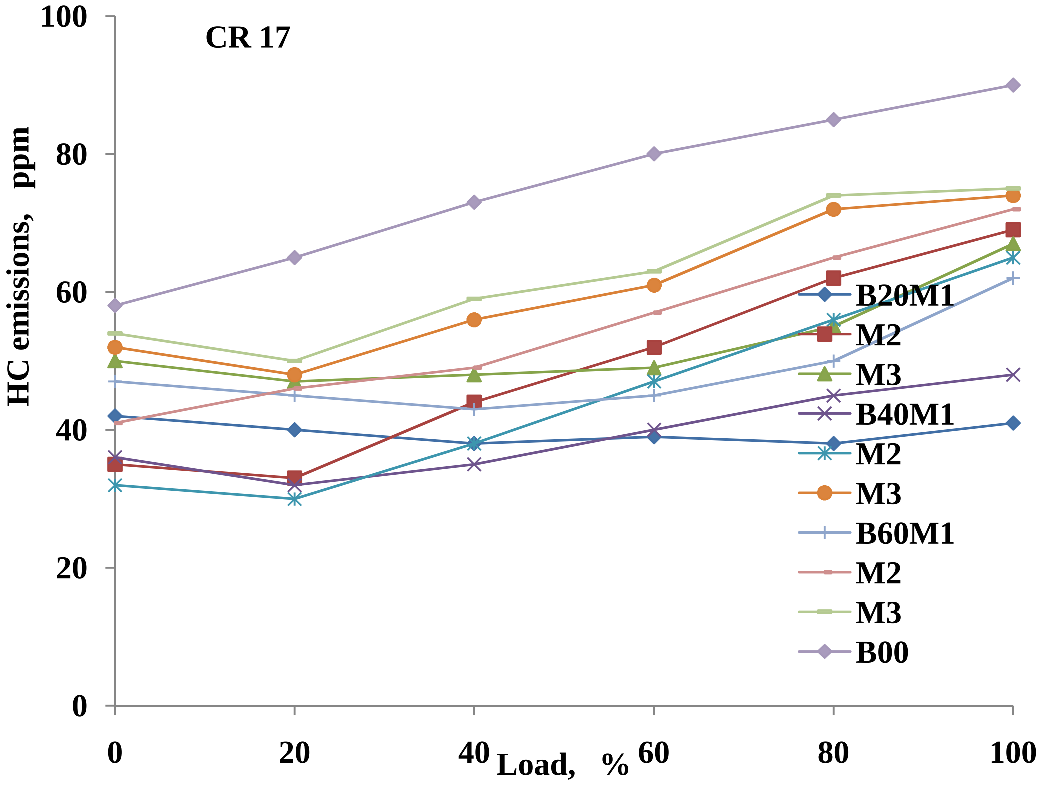
The HC emissions for diesel fuel as well as for the various blends for different loads at CR 16, 17 and 18 are illustrated in the Fig. 5.4.3.2. The unburned HC emissions are formed because of the incomplete combustion of the fuel supplied. The hydrocarbon emission decreases with increase in CR for the fuels used in the investigation. This is because of increased combustion temperature and increased burning rate of fuel and reduced diffusion combustion [142]. The hydrocarbon emission increases with increase in load because of increased amount of fuel supply.

It is seen from the figure that hydrocarbon emissions are lesser for the blends and diesel fuel at CR18 which may possibly be accredited to higher combustion temperature, higher temperature and pressure of the air which may enhances mixture formation and complete the combustion of the blends [143]. The HC emissions for the blends are lesser in comparison to diesel fuel which may perhaps be attributed to inherent oxygen and higher cetane number of biodiesel in the blends. The inherent oxygen and higher CN of blends which may enhance the chemical reactions and accelerate, complete the combustion hence decreases the HC emissions. The HC emission for diesel fuel is higher compared to biodiesel blends which may perhaps be attributed to incomplete combustion. The incomplete combustion of diesel fuel may possibly be accredited to lack of oxygen which increases the HC emissions. The HC emission at CR 18 for diesel fuel is 87 ppm for the rated load which is higher compared to the blends. The HC emission is least for the blend B40M2, and is 42 ppm at the rated load. The HC emission for the blend B60M2 is higher among the blends used and it is 83 ppm. The higher HC emission for the blend B60M2 may be accredited to higher viscosity and inferior volatility of the biodiesel in the blend. The higher viscosity and inferior volatility of biodiesel may affect the mixture formation of fuel-air consequently the combustion process. The HC emissions are decreased by about 53.3% for B40M2 blend and 7.8% for B60M2 blend compared to diesel fuel. The HC emissions for all other blends are in between the above two blends and are lesser compared to diesel fuel.

The HC emission for the diesel fuel and for the various blends are found to be higher at CR17 compared to CR18 which may be accredited to lower combustion temperature, lesser temperature and density of the air in the cylinder. The lower combustion temperature, lesser temperature and density of the air may perhaps influence the mixture formation subsequently the combustion process. The HC emission for the diesel fuel is higher compared to the blends and its value is 90 ppm which is higher compared to the blends used. The HC emission for the blend B20M1 is less and its value is 41 ppm which is least among the blends used. The HC emissions for the blend B60M3 are higher and its value is 75 ppm. The HC emissions are reduced by about 57.3% for B20M1 and 27.6% for the blend B60M3 compared to diesel fuel for the rated load. The HC emission for the other blends is between the above two blends.

The HC emissions for diesel fuel as well as for the various at CR16 are higher compared to CR17 and CR18. The higher HC emission for the blends may perhaps be accredited to lower combustion temperature, lesser density and temperature of the air in the cylinder may influence the mixture formation of fuel-air which causes the incomplete combustion [140]. The emission of HC for the diesel fuel at CR16 is 99 ppm. The emissions of HC are less for the blend B40M3 and are 45ppm. The HC emissions are higher among the





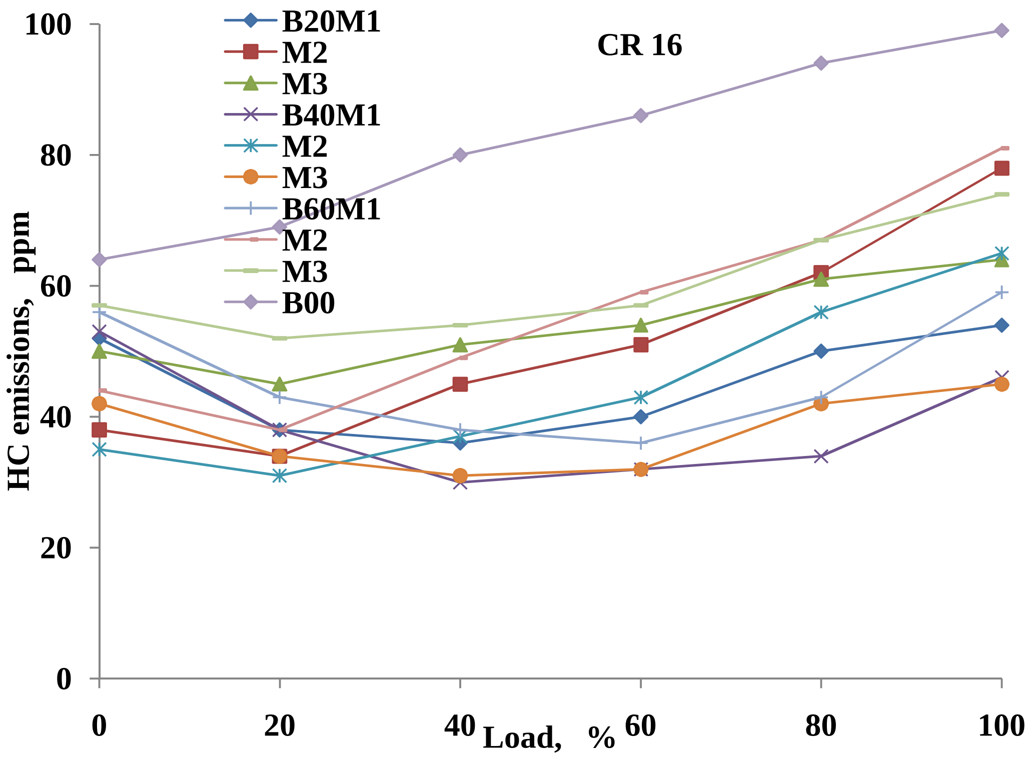
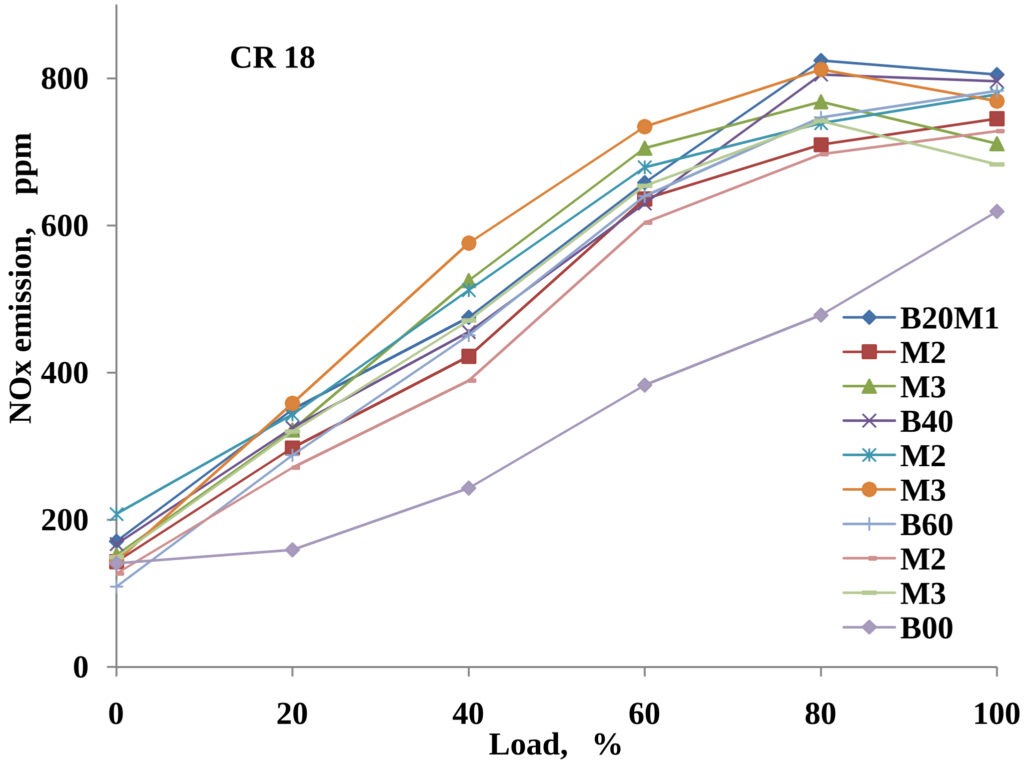


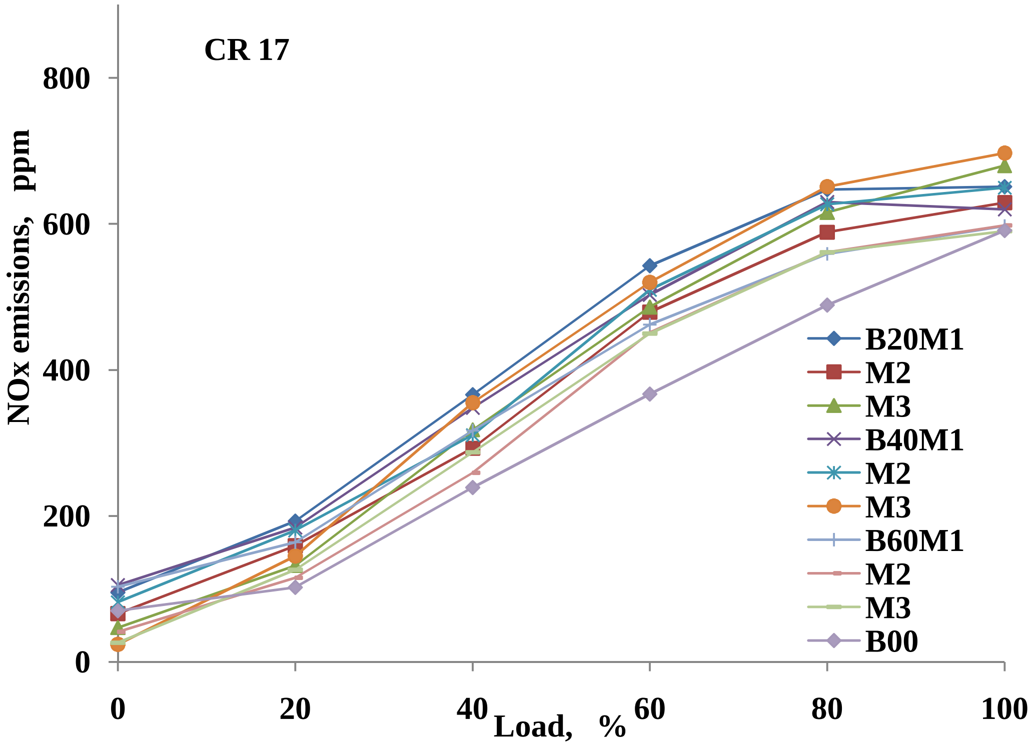
Fig. 5.4.3.2 Variation of CO emissions with load

blends for B60M2 and it is 81 ppm. The reduction in HC emission for the blend B40M3 is 48.3% and for the blend B60M2 is 6.9% compared to diesel fuel for the rated load.

5.4.3.3 NOx emission analysis with load

The emission of NOx for the diesel fuel and for the various blends for different loads at CR 16, 17 and 18 are illustrated in the Fig.5.4.3.3. The NOx emissions increase with increase in load for the fuels and the compression ratio used in the investigation. The NOx emissions are higher for the blends at CR18 which may perhaps be accredited to increased combustion temperature, higher temperature and density of the air in the cylinder. The higher combustion temperature, density and temperature of the air may contribute in the better mixture formation and improve the combustion of the blends which results in to higher temperature and higher NOx emissions. It is observed from the figure that the NOx emissions are lower for the diesel fuel compared to the blends at CR18. The NOx emissions for diesel fuel are 619 ppm for the rated load. The NOx emission for the blend B20M1 is higher and it is 805 ppm and NOx emissions are least for the blend B60M3 and it is 683 ppm at the rated load. The increased NOx emissions for the blends may possibly be accredited to oxygen content and higher CN of biodiesel in the blends. The natural oxygen content and higher CN of biodiesel in the blends may improve the mixing of fuel-air and enhance the chemical reaction, accelerate the combustion which results into increased temperature and higher NOx emissions. The NOx emission for the blends is higher by about 23.2% for B20M1 and 9.4% for B60M3 for the rated load. The NOx emissions for the other blends are between the two blends.





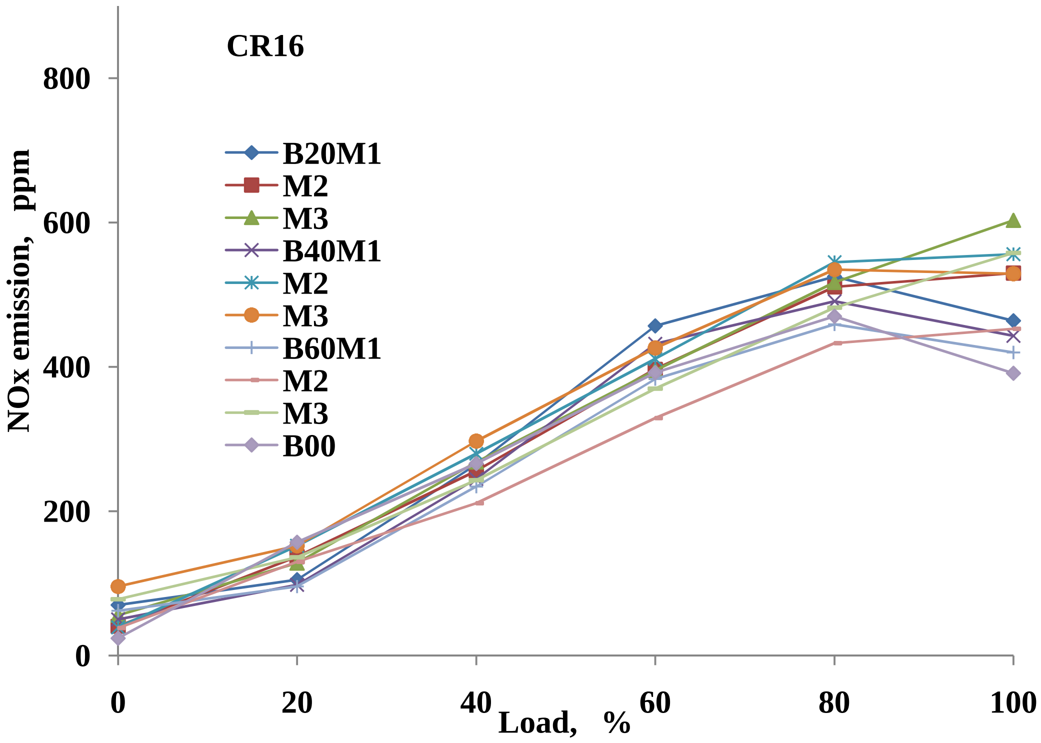


Fig. 5.4.3.3 Variation of NOx emissions with load

The emissions are lesser at CR17 compared to CR18 for diesel fuel and for the various blends used. The lower NOx emissions at CR17 may possibly be accredited to lower combustion temperature, lesser temperature and density of the air in the cylinder which may influence the mixture formation and hence combustion. The lower temperature, pressure of the air at CR17 may delay the combustion which results into lesser combustion temperature and lesser NOx emissions. The NOx emission for the diesel fuel at CR17 is 591 ppm at the rated load. The NOx emission for the blend B20M1 is 697 for the rated load which are higher compared to diesel fuel. The NOx emission for the blend B60M3 is 590 ppm for the rated load which is lower among the blends. The NOx emission for the other blends is in between the above two blends. The NOx emissions for the blends are increased by about 15.2% for the blend B20M1 compared to diesel fuel at the rated load.

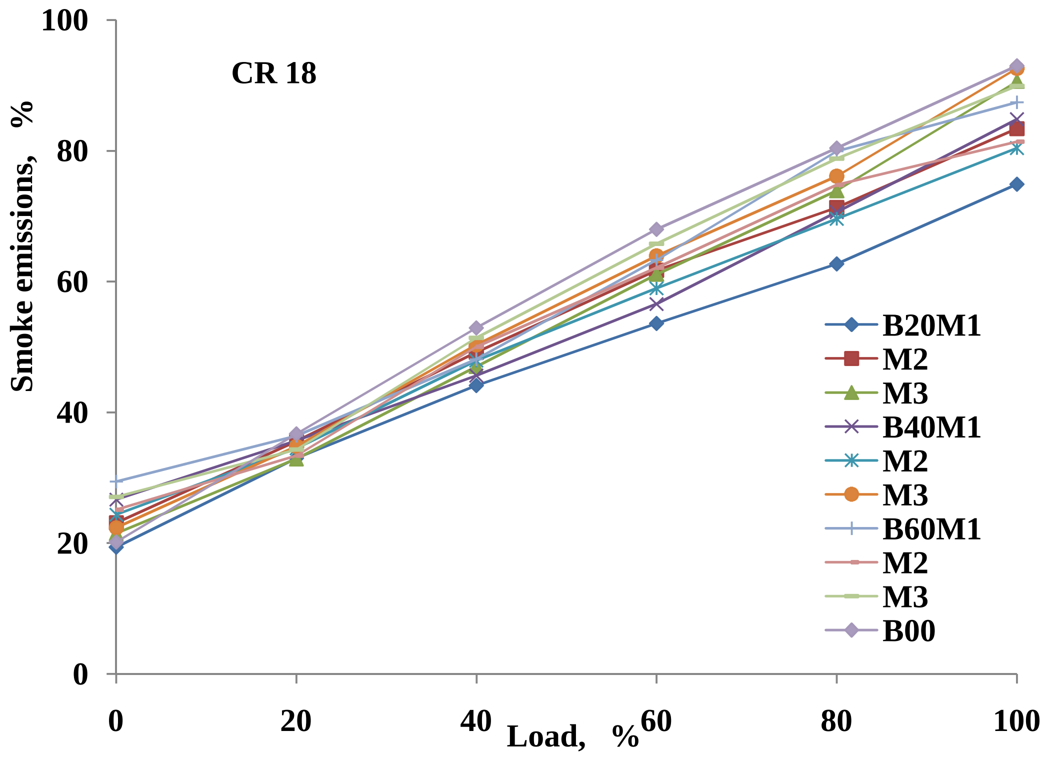
The NOx emissions are lesser at CR16 compared to CR17 and CR18 for the diesel fuel and as well as for the various blends used. The lower NOx emission for the blends may possibly be accredited to lower combustion temperature, lesser temperature and density of the air which may affect the mixture formation of fuel-air and consequently the combustion process. The lower combustion temperature, lesser temperature and density of the air at CR16 may perhaps be the region for the lesser NOx formation at CR16. The emission of NOx for diesel fuel is 391 ppm for the rated load. The NOx emission for the blend B20M3 is higher and its value is 603 ppm for the rated load. The NOx emission for the blend B60M1 is the least among the blends and its value is 420 ppm.

5.4.3.4 Smoke emissions with load

The smoke emission for diesel fuel as well as for the various blends for different load at CR of 16, 17 and 18 are illustrated in the Fig. 5.4.3.4. The smoke emissions are formed mainly because of incomplete combustion of hydrocarbon fuel supplied and to some extent partly reacted carbon elements in the liquid fuel. The smoke emissions increase with increase in load for the fuels used. The increase in smoke emission with increase in load may be accredited to increased fuel supply to carry the burden of increased load on the engine to generate additional power. The smoke emissions are higher for the diesel fuel at CR18 compared to the various blends used. The lesser smoke emission for the blends at CR18 may possibly be accredited to increased combustion temperature, higher temperatures and density of the air [144]. The higher combustion temperature, increased density and temperature of the air speed up the mixture formation which accelerates and complete the combustion. The lesser smoke for the blends may also possibly be accredited to oxygen content and higher CN of biodiesel in the blends. The oxygen content and higher CN of biodiesel in the blends may improve the mixture formation of fuel-air, accelerate the chemical reaction and complete the combustion of blends. The smoke emissions for the diesel fuel are higher at CR18 which may perhaps be accredited to incomplete combustion because of lack of oxygen for the complete combustion. The smoke emission for diesel fuel is 93% at the rated load. The smoke emissions for the blend B20M1 are the least among all the blends and it is 74.9% at the rated load. The smoke emissions are higher for blend B40M3 which is 92.6% at the rated load. The decrease in the smoke emissions for the blend B20M1 is 19.8% compared to diesel fuel. The smoke emissions increases for all the blends for the rated load which may perhaps be accredited to increased turbulence thus lesser time for the complete combustion of the fuels used.

The smoke emissions for diesel fuel as well as for the various blends at CR17 are higher compared to CR 18. The higher smoke emission at CR17 for the fuels used may possibly be accredited to lower combustion temperature and lesser temperature of the air in the cylinder may affect the mixing of fuel-air consequently incomplete combustion. The smoke emission for the diesel fuel at CR17 is 94% for the rated load. The smoke emission for the blend B60M1 is 96.5% at the rated load which is higher compared to diesel fuel. The higher smoke emission for the blend B60M1 may possibly be attributed to higher viscosity and inferior volatility of biodiesel in the blends may influence the mixture formation results into incomplete combustion. The smoke emission for the blend B20M1 lower and is 86.6% at the rated load. The smoke emissions for the blend B20M1are decreases by about 10.2% compared to diesel fuel at the rated load.

The smoke emissions are higher at CR16 compared to CR17 and CR18 for diesel fuel as well as for the various blends and for all the loads. The higher smoke emission at CR16 may be accredited to lower combustion temperature, lesser temperature and density of the air in the cylinder may affect the mixture formation of fuel-air hence incomplete combustion. The smoke emission for diesel fuel at CR16 is lower compared to the blends which may possibly be accredited to better combustible properties and contributes in complete combustion. The smoke emission for the blends are higher at CR16 may possibly be attributed to higher viscosity and inferior volatility of blends which may affect mixture formation of fuel-air hence sluggish incomplete combustion.



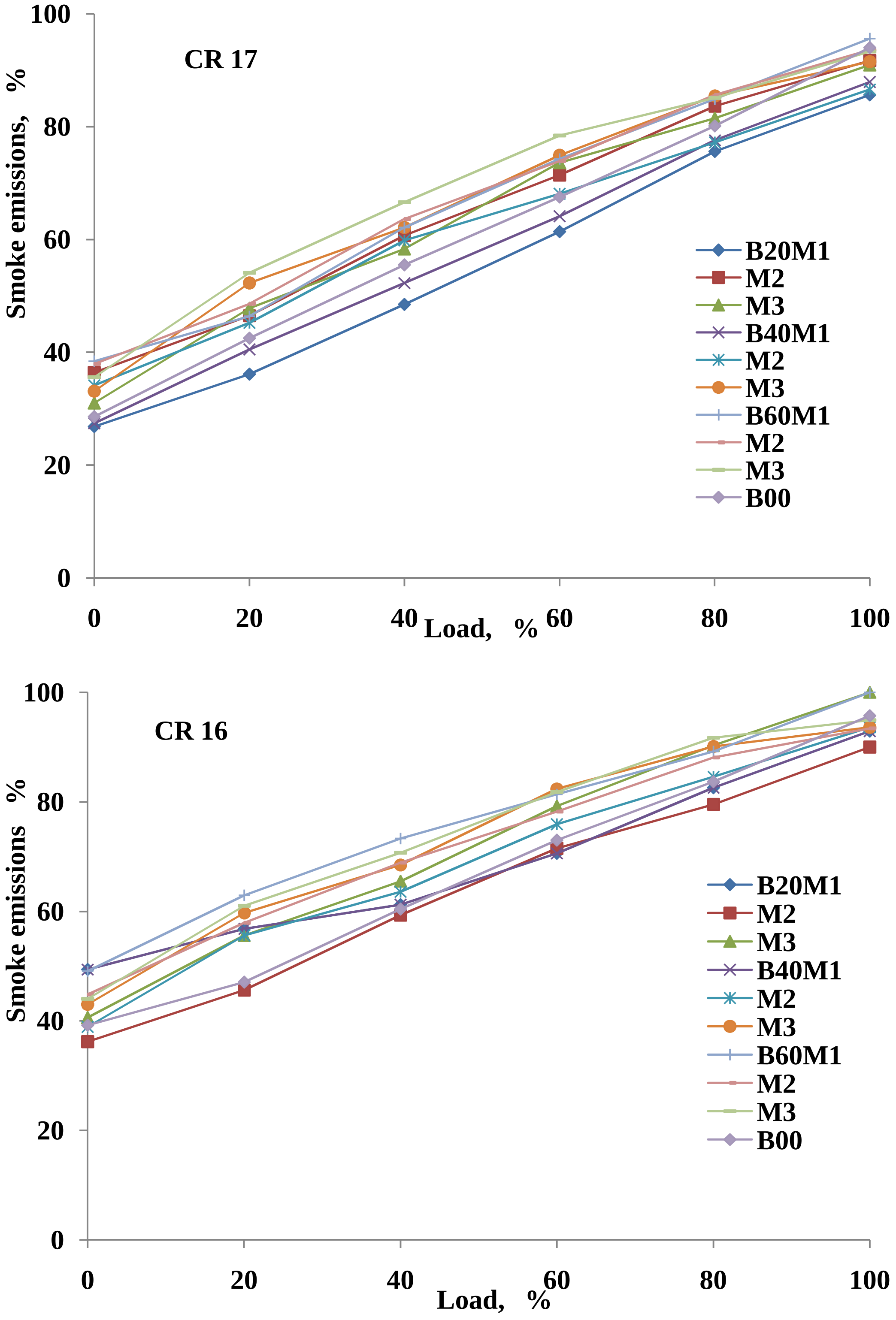


Fig. 5.4.3.4 Variation of smoke emissions with load

5.4.4 Summary

The summary of the combined results of the various blends and diesel fuel, for different compression ratio, loads, and for different mixture ratio on the combustion, thermal performance and emission characteristics of DI VCR diesel engine are presented and analysed. The results are towards the improved combustion characteristics for lower blends and comparable thermal performance with reduced emissions. The higher CR i.e. CR18 improve the combustion characteristics, thermal performance and reduces the emissions of various blends used compared to CR17 and CR16. The overall improvement at CR18 may be because of higher combustion temperature in addition to higher density and temperature of the air. The combustion and thermal performance, emission characteristics are decreases at CR16 and CR17 which may be attributed to decrease in combustion temperature in addition to decreased density and temperature of the air at lower CR which may influence the overall performance of the engine. The outcome of this analysis is that mixture of two biodiesel in any volume ratio can be blended with diesel and used in the DI diesel engine. The mixture of two biodiesel up to 40% in blend with diesel can be used in existing diesel engine without any modification. The mixture of two biodiesel can be blended with diesel up to 40% volume fraction which gives almost comparable performance with diesel fuel with reduced emissions at CR18.

Table 5.4.1 Results of engine parameters obtained for diesel and for the various blends at CR18 for the rated load

Sl.No.		B00	B20M1	B40M1	B60M1	B20M2	B40M2	B60M2	B20M3	B40M3	B60M3
Combustion Parameters											
1	Maximum pressure, bar	71.4	71.51	72.23	72.66	72.12	70.85	70.2	70.1	71.12	71.57
2	Max. heat release, J/°CA	52.79	41.22	40.95	41.84	44.5	45.63	43.91	43.37	44.87	46.89
3	Max. rate of pressure rise, bar/°CA	4.79	5.27	5.12	4.92	5.43	4.94	4.72	5.01	5.14	4.97
Performance parameters											
1	Brake thermal efficiency, %	27.66	27.04	27.04	26.18	26.84	27	27.13	26.89	27.46	27.99
2	BSFC, kg/kW hr	0.3	0.31	0.32	0.33	0.31	0.32	0.32	0.31	0.3	0.31
3	EGT , °C	320	315	316	315	314	315	323	324	314	316
Emissions parameters											
1	CO emissions, %	0.046	0.028	0.027	0.027	0.024	0.026	0.027	0.024	0.022	0.026
2	HC emissions, ppm	87	57	46	60	46	42	51	56	72	85
3	NO emissions, ppm	619	805	796	783	745	778	728	711	769	683
4	Smoke emissions, %	93	74.9	84.8	87.4	83.4	80.4	81.4	90.6	92.6	89.9

Table 5.4.2 Results of engine parameters obtained for diesel and for the various blends at CR17 for the rated load

Sl.No.		B00	B20M1	B40M1	B60M1	B20M2	B40M2	B60M2	B20M3	B40M3	B60M3
Combustion Parameters											
1	Maximum pressure, bar	63.58	68.65	68.65	65.03	68.63	62.31	64.19	65.68	62.08	61.89
2	Max. heat release, J/ºCA	50.28	44.45	45.69	46.19	43.02	43.75	43.78	41.95	42.99	42.06
3	Max. rate of pressure rise, bar/ºCA	5.09	5	4.92	4.92	4.98	5.2	5.04	4.62	4.87	4.88
Performance parameters											
1	Brake thermal efficiency, %	26.54	26.61	25.88	25.96	26.33	25.76	26.54	26.72	26.84	25.63
2	BSFC, kg/kW hr	0.31	0.31	0.33	0.34	0.31	0.33	0.33	0.31	0.32	0.36
3	EGT, ºC	336	328	336	339	329	336	333	328	327	329
Emissions parameters											
1	CO emissions, %	0.053	0.03	0.031	0.033	0.027	0.025	0.029	0.027	0.024	0.03
2	HC emissions, ppm	90	41	48	62	69	65	72	67	74	75
3	NO emissions, ppm	591	651	620	597	629	650	598	680	697	590
4	Smoke emissions, %	94	85.6	89.9	95.6	91.7	86.6	93.6	90.9	91.5	93.3

Table 5.4.3 Results of engine parameters obtained for diesel and for the various blends at CR16 for the rated load

Sl.No.		B00	B20M1	B40M1	B60M1	B20M2	B40M2	B60M2	B20M3	B40M3	B60M3
Combustion Parameters											
1	Maximum pressure, bar	62.4	56.57	54.44	57.91	62.63	56.28	58.48	58.8	58.93	54.51
2	Max. heat release, J/ºCA	43.03	42.08	42.16	42.16	43.04	44.14	46.38	41.95	42.99	44.12
3	Max. rate of pressure rise, bar/ºCA	4.92	5.03	5.12	4.69	4.59	4.73	4.98	4.78	4.78	4.48
Performance parameters											
1	Brake thermal efficiency, %	26.55	25.53	26.95	26.89	25.36	25.58	24.81	25.85	25.77	25.91
2	BSFC, kg/kW hr	0.31	0.33	0.32	0.33	0.33	0.33	0.35	0.32	0.33	0.34
3	EGT, ºC	346	349	348	348	342	347	348	344	341	344
Emissions parameters											
1	CO emissions, %	0.057	0.026	0.028	0.030	0.036	0.029	0.039	0.034	0.026	0.044
2	HC emissions, ppm	99	54	46	59	78	65	81	64	45	74
3	NO emissions, ppm	591	464	443	420	530	556	453	603	529	588
4	Smoke emissions, %	95.7	92.9	93.7	100	100	90	93.4	100	93.6	94.7

5.5 Effect of compression ratio, mixture ratio and blend ratio on Combustion, Performance and emissions characteristics using mixture of P-S biodiesel in blend with diesel

Pongamia and Simarouba biodiesel are mixed in different volume ratio and blended with diesel fuel. The two biodiesel mixed in the ratio of 75% Pongamia + 25% Simarouba, 50% Pongamia + 50% Simarouba and 25% Pongamia + 75% Simarouba. These mixtures are designated as M4 for (P75+S25), M5 for (P50+S50) and M6 for (P25+S75). The different blends are prepared using the M4, M5, and M6 with diesel fuel. The B20M4 is the blend of 20% of M4+ 80% diesel; using the same procedure the other blends are prepared such as B40M4, B60M4. The B100M4 indicates the mixture of two biodiesels. Similarly B20M5, B40M5, B60M5 and B20M6, B40M6, B60M6 are prepared. These blends are used in the investigations varying the load and CR of the engine. The obtained results are compared with the results of base line diesel fuel.

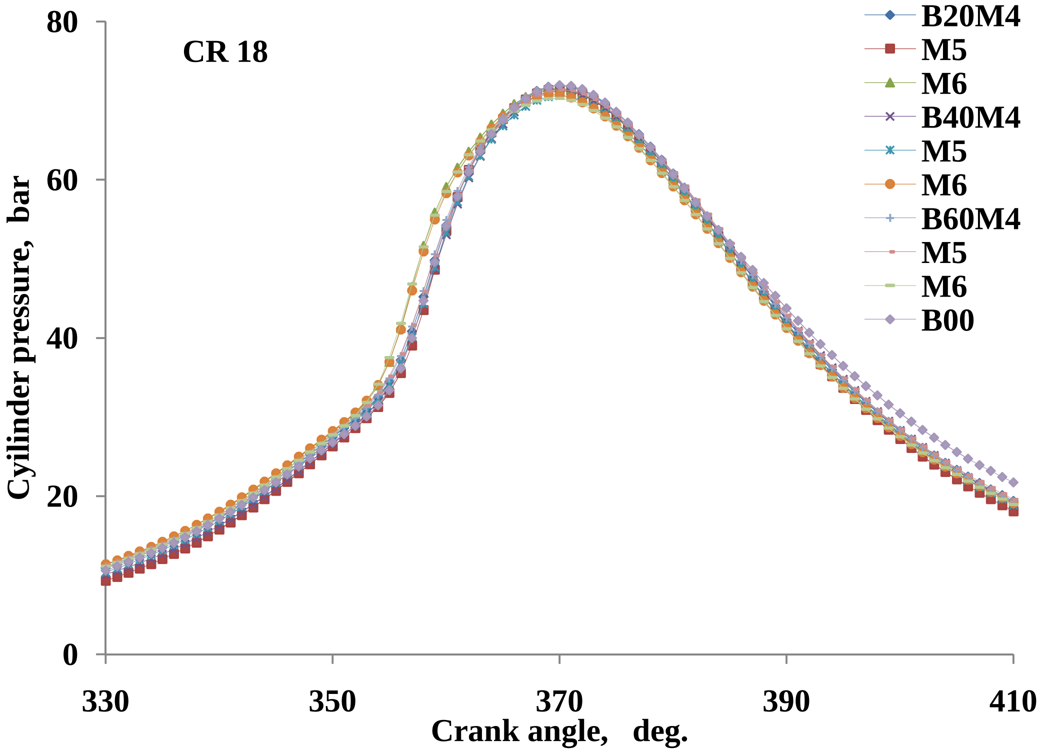
5.5.1 Combustion analysis

5.5.1.1 Cylinder pressure with CA

The change in cylinder gas pressure for diesel fuel as well as for the various blends for the rated load at the compression ratio of 16, 17 and 18 are illustrated in the Fig. 5.5.1.1. It is seen from the figures that the cylinder pressures are higher at the CR18 compared to CR16 and CR17 for diesel fuel as well as for the various blends used. The higher cylinder gas pressure may possibly be accredited to higher combustion temperature, increased density and temperature of the air at CR18. The increased combustion temperature, density the temperature of the air decreases the premixed combustion which contributes in the increase in cylinder pressure. The increase in combustion temperature and higher temperature of the air may contribute in better atomization; improved mixture formation of fuel-air which may contribute in the complete combustion which results into the increase in cylinder pressure and combustion temperature. The maximum higher cylinder gas pressure for the diesel fuel at CR18 is 71.85 bars at the rated load. The higher cylinder gas pressure for the blend B60M6 is 71.9 bars at the rated load. The marginal higher cylinder gas pressure for the blend may be perhaps be attributed to natural oxygen and higher CN of biodiesel in the blends which may contribute in better and complete combustion of blends. The cylinder gas pressure for the blend is least for the blend B20M6 which may perhaps be attributed to early initiation of combustion of the blends. The early start of combustion which means that less amount of fuel is available for the premixed combustion. The start injection and ignition for the blends are advanced compared to the diesel fuel which may perhaps be attributed to higher bulk modulus and higher CN of biodiesel in the blends. The cylinder gas pressure for the some of the blends are lower compared to the diesel fuel which may be accredited increased viscosity and inferior volatility of the biodiesel in the blends.

The cylinder pressure at CR17 are lesser compared to CR18 for the rated load for diesel fuel and for the various blends. The air is compressed to lesser level at CR17 which may have lower temperature and density of the air inside the cylinder may influence the mixture formation and the combustion process results into lesser cylinder gas pressure. It can be also observed from the figure that start of combustion for all the blends are advanced compared to diesel fuel which may be attributed to natural oxygen content and higher CN of biodiesel in the blends. The cylinder gas pressure for diesel fuel is 62.97 bars at the rated load. The higher maximum cylinder gas pressure for the blend B40M5 is 65.78 bars for the rated load which is higher compared to diesel fuel. The higher cylinder pressure for the blend B40M5 may perhaps be accredited to better and complete combustion of blends because of above said reason.

The cylinder pressures at CR16 are lesser compared to CR17 and CR18 for the rated load for the fuels used. The cylinder pressure for diesel fuel is higher compared to the various



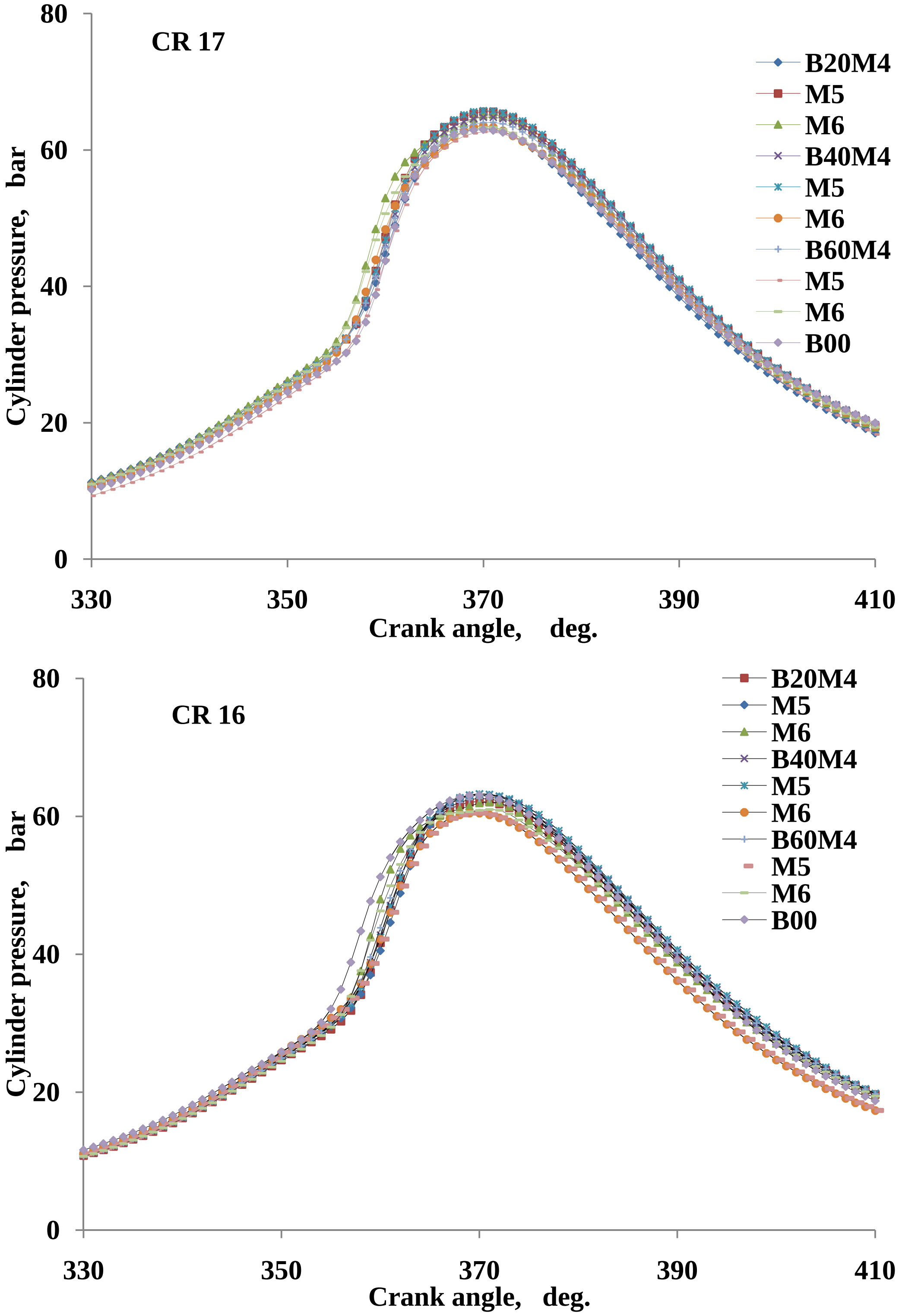


Fig. 5.5.1.1 Variation of cylinder pressure with crank angle at rated load

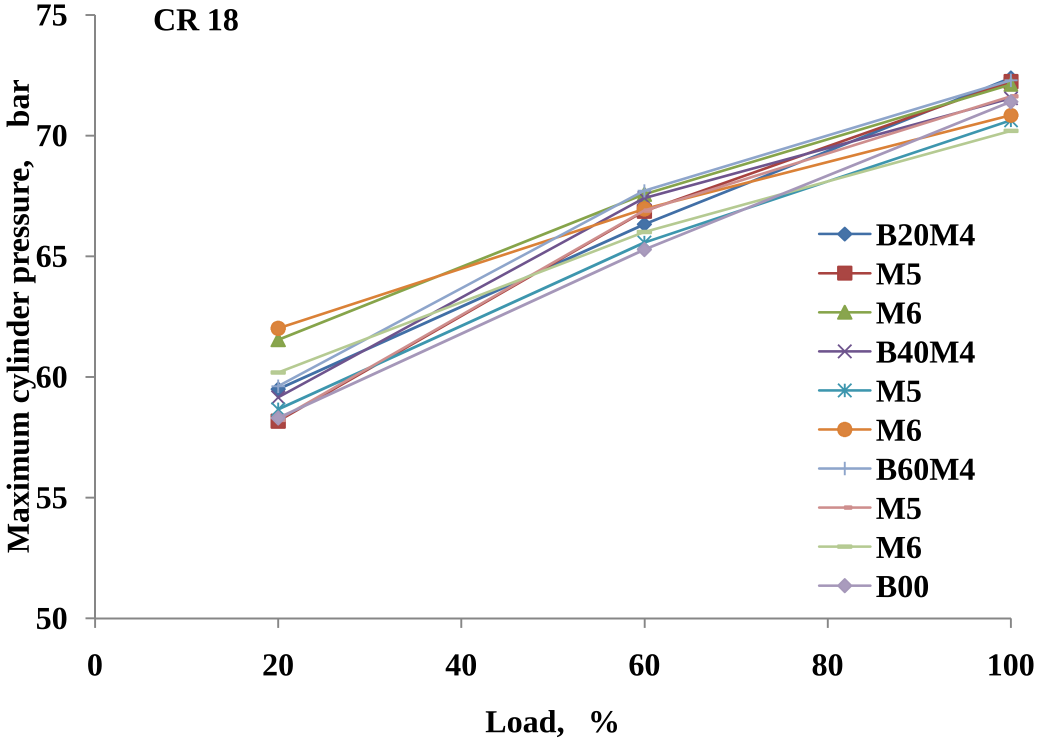
blends. The higher cylinder pressure for the blends may perhaps be accredited to better combustible properties of diesel fuel at CR16. The cylinder pressures are lesser for the blends compared to diesel fuel. The lower cylinder pressure for the blends at CR16 may be possibly accredited to decreased combustion temperature, lower temperature and density of the air in the cylinder. The lesser combustion temperature, lower temperature and density of the air inside the cylinder at CR16 at the time of injection may influence the mixture formation and incomplete combustion. The cylinder gas pressure for diesel fuel at CR16 is 63.07 bars at the rated load. The maximum cylinder gas pressure for the blend B40M5 is 63.26 bars for the rated load and comparable with diesel fuel. The start of combustion for the diesel is earlier compared to the blends which may be because of better combustible properties. The start of ignition for the blends at CR16 is delayed which may perhaps be accredited to lower combustion temperature and higher viscosity, inferior volatility of biodiesel in the blends

5.5.1.2 Maximum cylinder pressure with load

The maximum cylinder pressure for the change in CA for the fuels used for different loads at CR of 16, 17 and 18 are illustrated in the Fig.5.5.1.2. The maximum cylinder pressure values are taken from the pressure volume plots, these data are acquired by data acquisition system software. The maximum cylinder gas pressure increases with increase in load for diesel fuel as well as for the various blends at different compression ratios. The maximum cylinder pressures are high for the blends in comparison to diesel fuel at CR18 for almost all the loads. The higher cylinder pressure for the blends may perhaps be accredited to higher CN and natural oxygen content of biodiesel in the blends. The oxygen content and higher CN may improve mixture formation of fuel-air and complete the combustion of blends hence increases the maximum cylinder pressure. The higher maximum cylinder gas pressure at CR18 for diesel fuel is 71.4 bars for the rated load whereas for the blend B20M4 the pressure is 72.38 bars for the rated load which is higher compared to diesel fuel. The higher cylinder gas pressure for the blends may be due to the better and complete combustion of blends. The least cylinder pressure for the blend B60M6 is 70.2 bars for rated load. The lower cylinder pressure for the blend B60M6 may perhaps be attributed to lower heating value and high viscosity, inferior volatility of the biodiesel in the blends. The inferior properties of biodiesel in the blends may affect the mixing of fuel-air as a result the burning of the blends. The increase in cylinder pressure for the blendB20M4 is by about 1.3% compared to diesel fuel.

The cylinder pressure at CR17 are lesser compared to CR18 for diesel fuel and for the various blends for the different loads. The lesser cylinder pressure at CR17 may perhaps be accredited to lower compression of air at CR17 will have lower temperature and density of the air in the cylinder and also the lower combustion temperature. The lower combustion temperature, lesser temperature and, pressure of the air which may influence the mixture formation of fuel-air and hence the combustion of fuels used. The incomplete combustion at CR17 may contribute to the lower cylinder pressure. The higher maximum cylinder pressure for diesel fuel at CR17 is 62.4 bars for the rated load. The maximum cylinder pressure for the blends for the rated load are higher for almost all the blends used compared to diesel fuel. The higher maximum cylinder pressure for the blends may perhaps be attributed to higher combustion temperature and natural oxygen content of biodiesel in the blends may complete the combustion. The higher maximum cylinder pressure for the blend B20M6 is 66.37 bars. The cylinder pressure for the blend is increased by about 6.4% compared to diesel fuel.

The maximum cylinder gas pressures at CR16 are lower compared to CR17 and CR18 for diesel as well as for the various blends. The lower maximum cylinder pressure may perhaps be attributed to lower combustion temperature and lesser temperature, density of the air at CR16. The lower combustion temperature, density and temperature of the air may affect the mixture formation consequently the combustion of the fuels used. The maximum cylinder pressure for diesel fuel at CR16 is higher compared to the blends for all the loads which may well be accredited to better combustible properties of diesel fuel. The cylinder pressure for diesel fuel at rated load is 62.4 bars. The cylinder for some of the blends are higher in comparison with diesel fuel for the full load which may perhaps



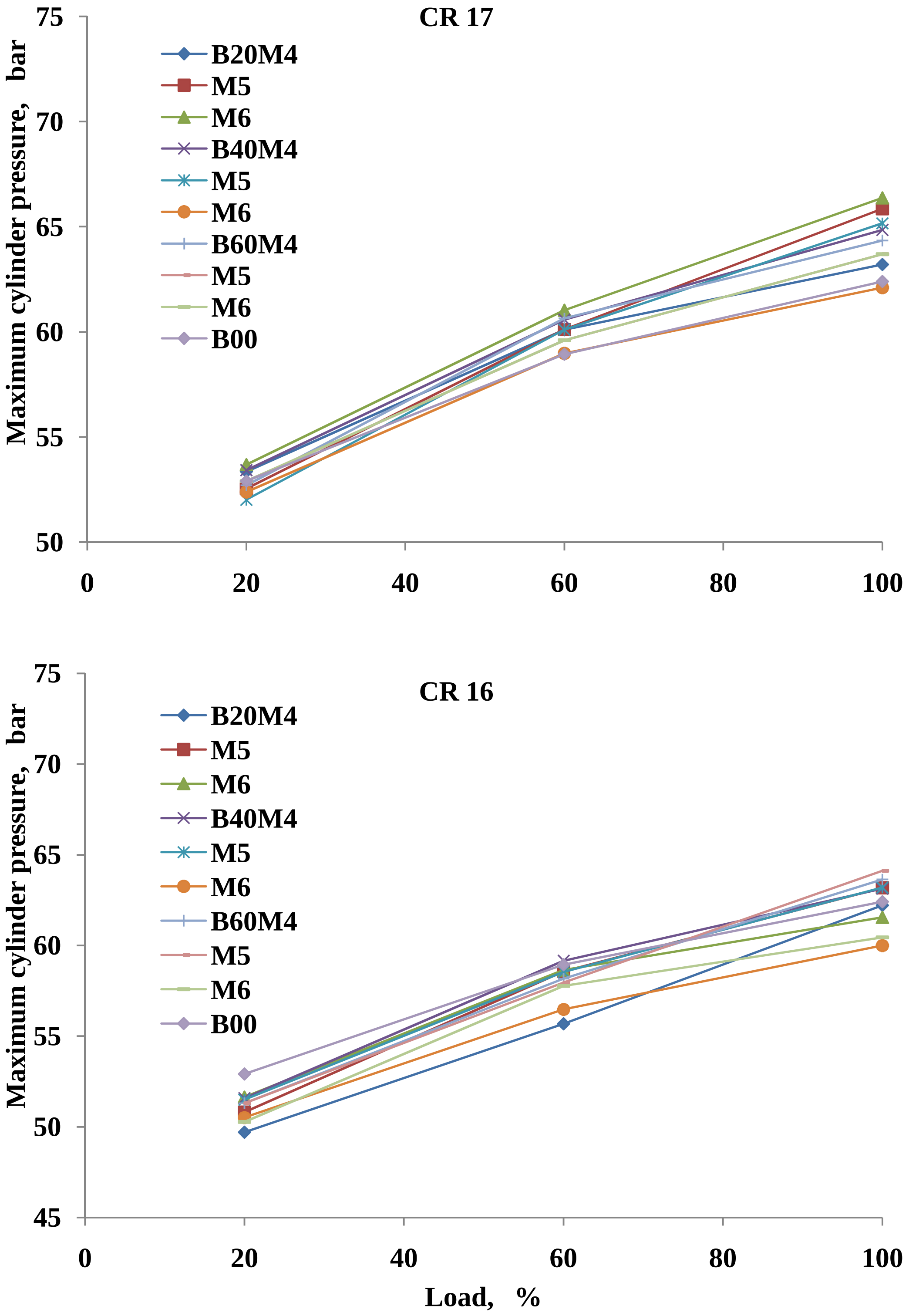


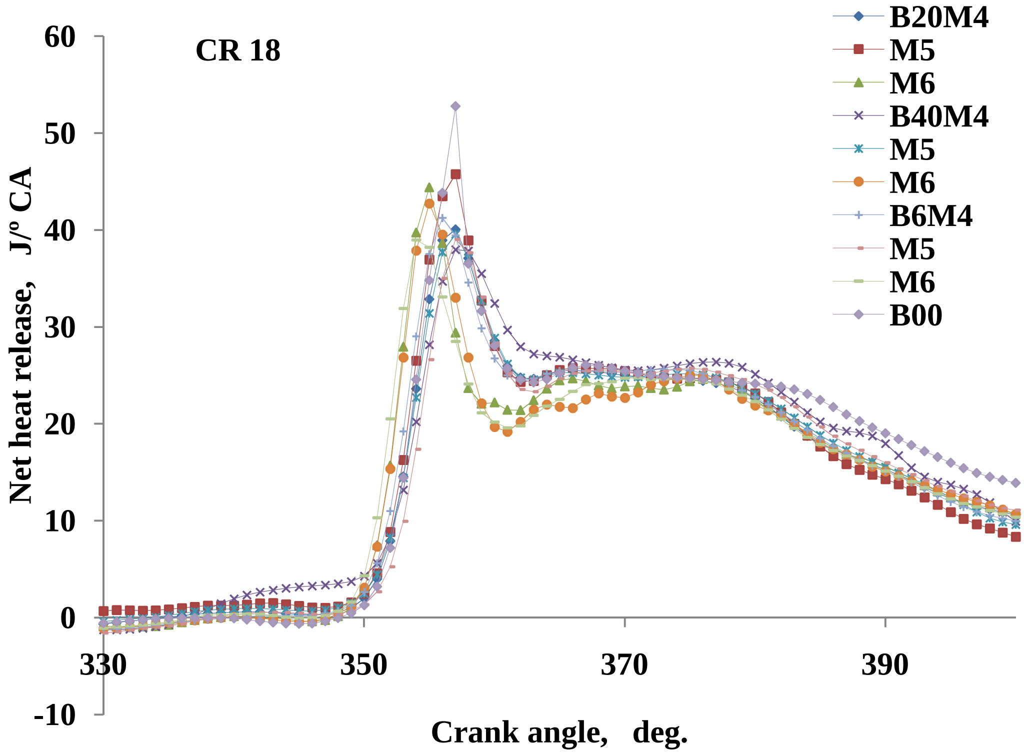
Fig. 5.5.1.2 Variation of maximum cylinder pressure with load

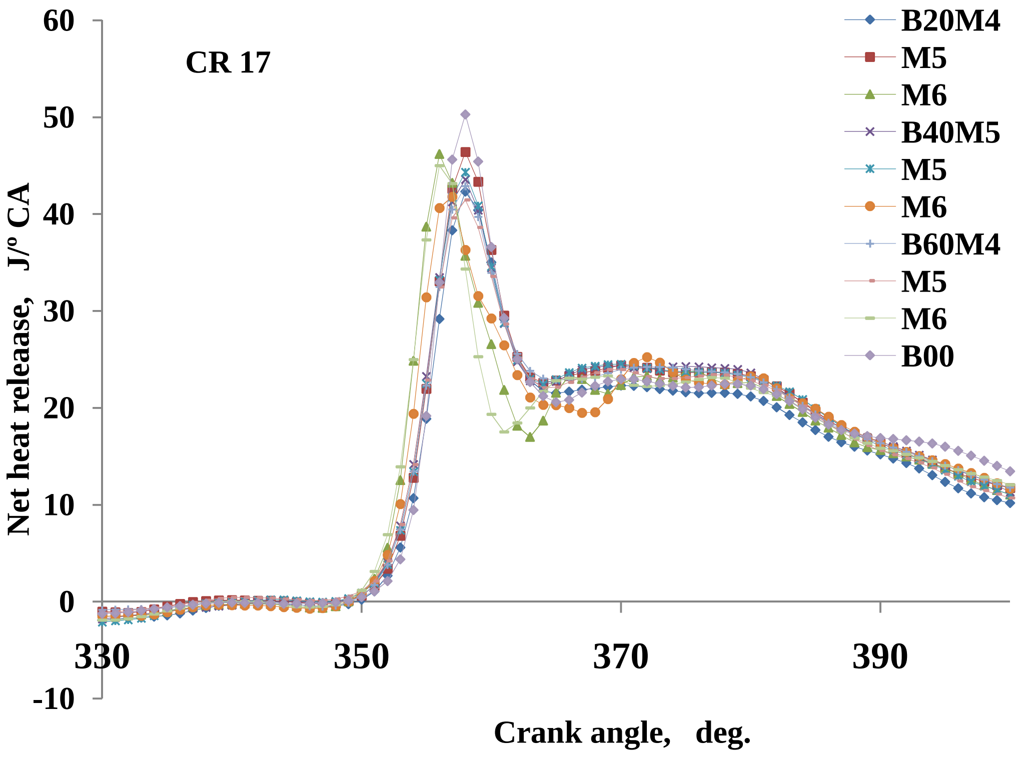
be accredited to better combustion of blends consequently have higher maximum cylinder pressure.

5.5.1.3 Net heat release with CA

The net heat releases for diesel fuel as well as for the various blends of biodiesel with diesel for different loads at compression ratio 16, 17 and 18 are illustrated in the Fig.5.5.1.3. The net heat release is the heat energy released from the chemical energy of the fuel throughout the premixed combustion stage. The fuel which is accumulated during the ignition delay is to be evaporated and get mixed with the air before the start of ignition. This process of evaporation of the fuel will absorbs the heat rather than generating the heat which shows the negative heat release at the beginning of heat release process. It is observed from the figure that the maximum net heat releases at CR18 are higher compared CR16 and CR17 for diesel fuel for the full load. The higher net heat released at CR18 may well be accredited to complete combustion of the diesel fuel at the rated load. The complete combustion the fuels at CR18 may possibly be accredited to higher combustion temperature, higher temperature and density of the air. Because of higher combustion temperature, fuel injected quickly evaporates and mixes with air and makes the mixture ready for burning. The net heat release for diesel fuel at CR18 at the rated load is 52.79 bar/ ºCA. The higher net heat release for diesel may perhaps be accredited to higher heating value as well as the increased ignition delay. The net heat release for the various blends are lesser compared to diesel fuel which may perhaps be accredited to lower heating value of biodiesel in the blends. The net heat release for the blend B20M5 is 45.79 J/ ºCA which is lesser in comparison to diesel fuel. The net heat release for blend B60M4 is the least which is 39.43 J/ ºCA at rated load. The maximum and minimum net heat releases are decreased for the blends by about 13.26% and 25.3% for the blend B20M5 and B60M4 compared to diesel fuel at the rated load. The higher reduction of net heat release for the blend B60M4 may be attributed to higher viscosity and lower volatility of the blends which may influence the mixture formation of fuel-air and hence the combustion.

The net heat release is lesser at CR17 for diesel fuel and for the various blends at rated load compared to CR18. The lesser heat release for the blends may perhaps be accredited to lower combustion temperature, lesser density and temperature of the air may influence the mixture formation consequently incomplete combustion. The higher viscosity of biodiesel in the blends at lower CR may also influence the mixing of fuel-air consequently slow combustion which releases lesser heat. The maximum net heat release for diesel fuel is 50.28 J/ºCA at the rated load. The higher maximum net heat release for the blend B20M5 is 46.42 J/ºCA at the rated load. The higher net heat release for the diesel fuel may be due to the increased ignition delay results into more fuel accumulation. The accumulated fuel burns suddenly releasing the heat during the premixed combustion stage. The net heat releases for some of the blends are higher compared to CR18 which may be because of increased ignition delay results into increase in the premixed combustion. The increase in ignition delay is because of lower combustion temperature





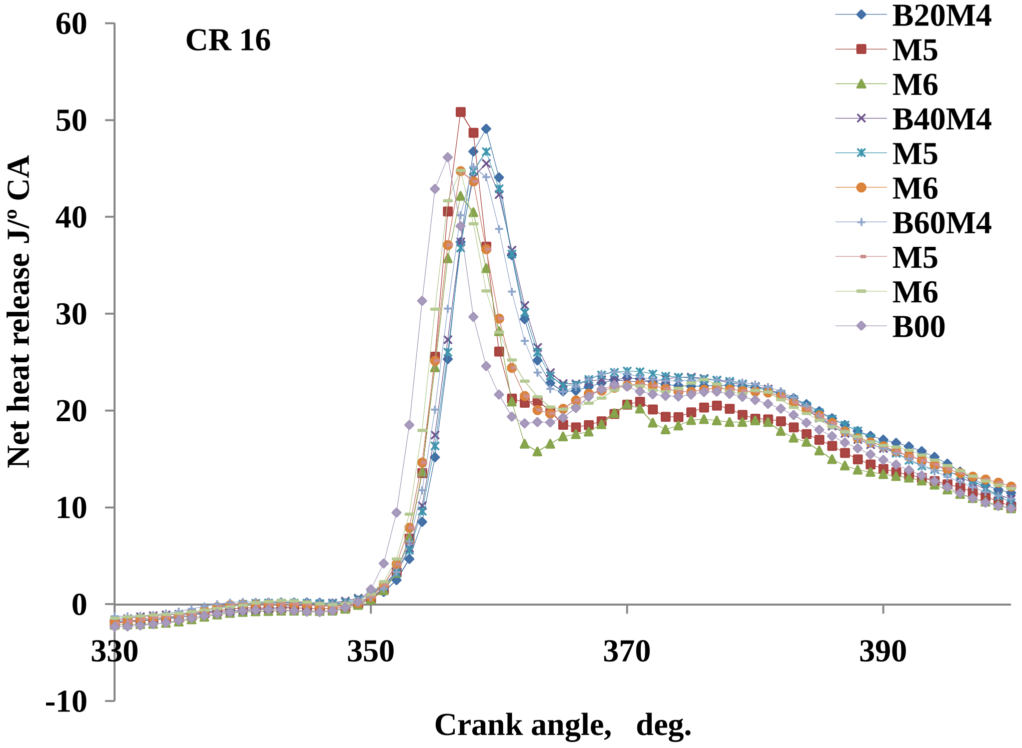


Fig. 5.5.1.3 Variation of net heat release with crank angle at rated load

and lesser temperature of the air at CR17 which increases the premixed combustion and hence the net heat release.

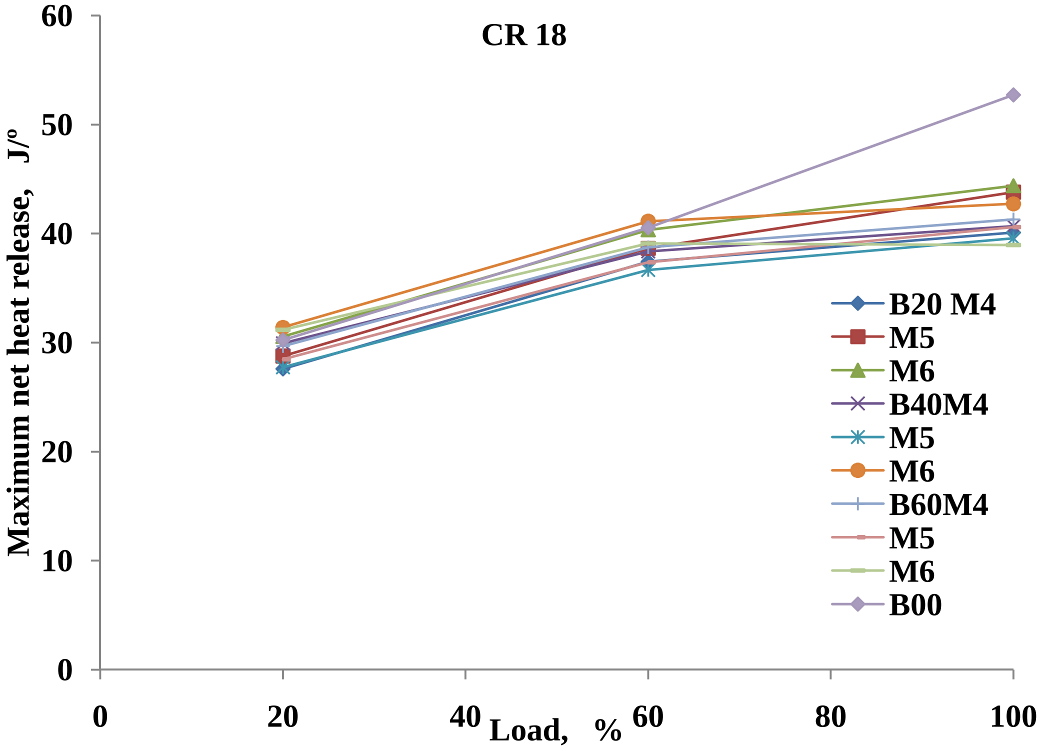
The heat release at CR16 is higher for the blends compared to CR17 and CR18 at the rated load. The higher net heat release at CR16 may perhaps be accredited to increased ignition delay at CR16 which increases the premixed combustion stage. The increased ignition delay for the blends may be attributed to lesser combustion temperature and lower temperature, density of the air in the cylinder. The increased ignition delay increases the amount of fuel accumulated which burns instantly increasing the heat release. The net heat release for diesel fuel at CR16 is 46.16 J/ºCA at the rated load. The higher net heat release for the blend B20M5 is 50.87 J/ºCA at the rated load.

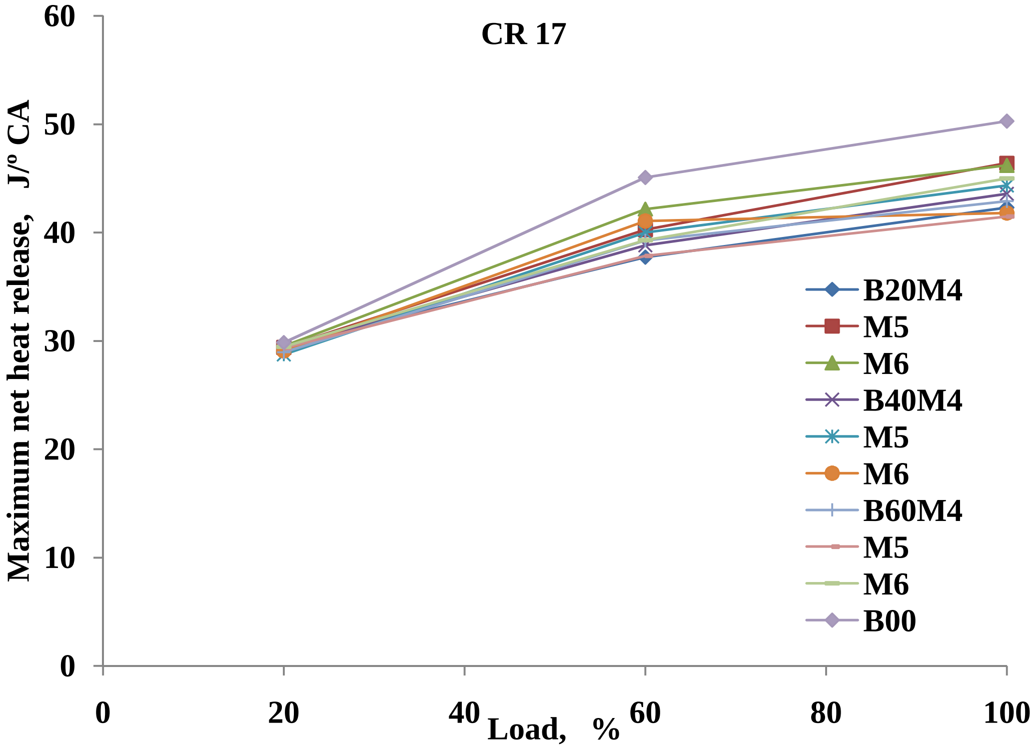
5.5.1.4 Maximum heat release with load

Maximum heat release for diesel fuel as well as for the various blends for different loads at compression ratio 16, 17 and 18 are illustrated in the Fig.5.5.1.4. The maximum heat release for the diesel fuel and for the blends are depends upon the quantity of fuel burned in the uncontrolled combustion stage, CR, type of fuel and load on the engine. The maximum net heat release increases with increase in load for diesel fuel and for the various blends for the different CR used. At lower load the maximum heat released is lesser because of the small amount of fuel is supplied and burned. The quantity of fuel required increases with increase in load that's why the maximum heat release increases for higher loads. The maximum heat release at the rated load is not proportionate to the amount fuel burnt which may perhaps be attributed to incomplete combustion. The incomplete combustion may well be attributed to increased turbulence which increases speed of combustion and decreases the time at the rated load. The incomplete combustion of fuel supplied decreases the maximum heat release at the rated load. The maximum heat release for diesel fuel for the rated load is higher and it is 52.79 J/ ºCA which may perhaps be attributed increase in premixed combustion for diesel fuel for the full load. The increased premixed combustion for diesel fuel may perhaps be accredited to increased ignition delay. The higher maximum heat release for the blend B20M6 is 44.4 J/ºCA at the rated load. The minimum heat release for blend B60M6 is 38.96 J/ºCA at the rated load. The heat release for all other blends are lesser compared to diesel fuel for the rated load. The increase in volume fraction of biodiesel in the blend the heat release decreases at the rated load which may be attributed to the lower heating value and higher viscosity of biodiesel in the blends affect the combustion. The reduction in the net heat release for the blend B20M6 is about 15.9% compared to diesel fuel. The maximum reduction in net heat release for the blend B60M6 is 26.2%.

The maximum heat release at CR17 for diesel fuel is less compared to CR18 at the rated load. The lesser heat release may perhaps be attributed to lower combustion temperature, temperature and density of the air at CR17 which may influence the mixture formation of fuel-air, contributes in the incomplete combustion. The some of the blends have higher maximum heat release at CR17 compared to CR18 which may be accredited to increased ignition delay because of the reason as discussed earlier. The increase in delay increases the premixed combustion of blends hence increases the maximum heat release. The maximum heat release at CR17 for diesel fuel is 50.28 J/ºCA at the rated load. The maximum heat release for the blend B20M5 is 46.42 J/ºCA at the rated load. The minimum heat release for the blend B60M5 is 41.47 J/ºCA at the rated load. The reduction in the net heat release for the blend B20M5 and B60M5 is by about 7.7% and 17.5% respectively compared to diesel fuel.

The maximum heat release at CR 16 for diesel fuel is lesser compared to CR17 and CR18 at the rated load. Though the premixed combustion increases with increase in delay period for CR16 the maximum heat release is lesser because of incomplete combustion. The lesser net heat release at CR16 may perhaps be accredited to lesser combustion temperature and lower temperature of the air insider the cylinder which may affect the mixing of fuel-air subsequently the combustion. The net heat release for diesel fuel at CR16 is 46.16 J/ºCA at the rated load. The higher maximum heat release for the blend B20M4 is 49.09 J/ºCA at the rated load. The higher maximum heat release for the blend may perhaps be accredited to natural oxygen and higher CN of biodiesel in the blends which increases the chemical reaction and accelerate the combustion of blends. The





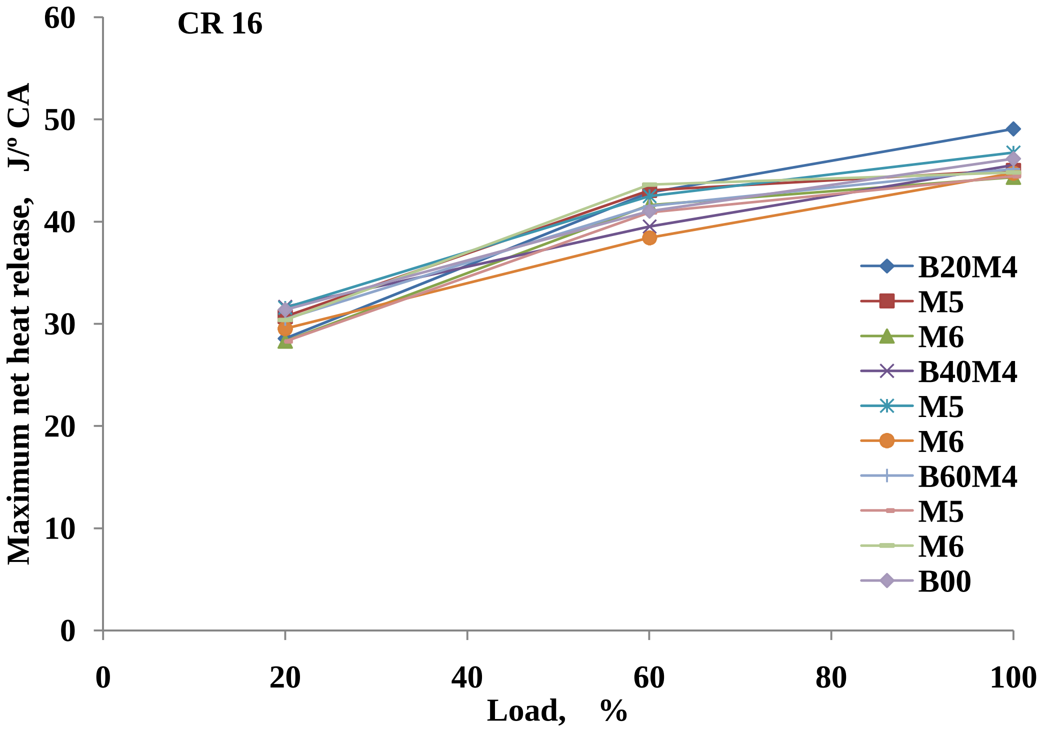


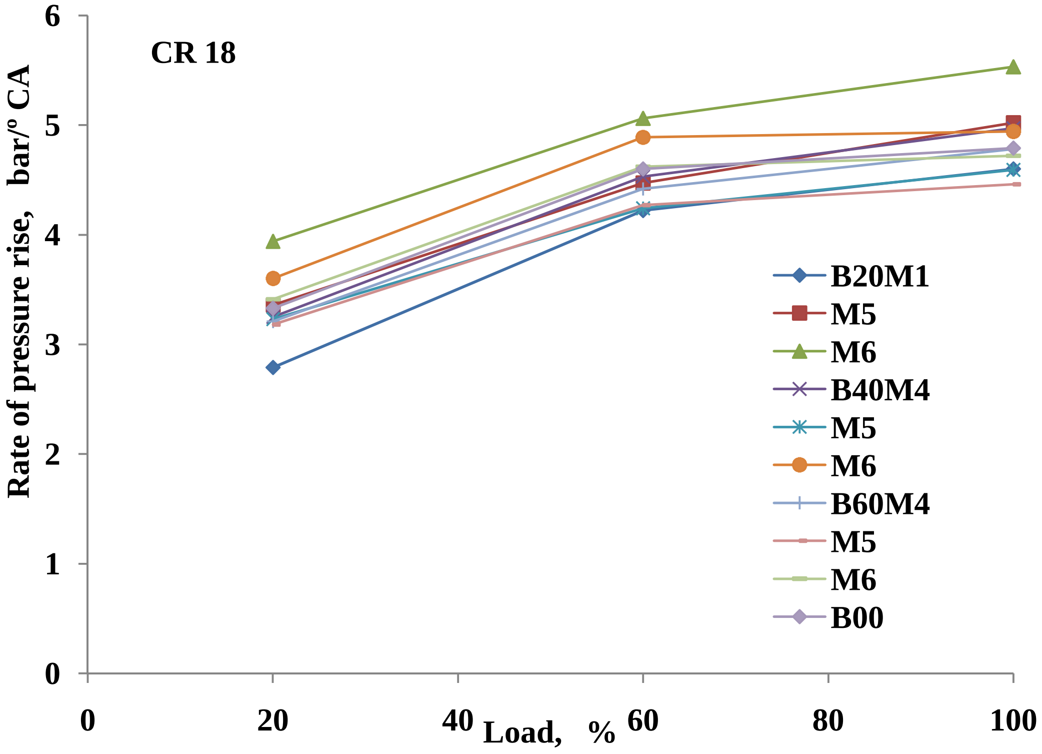
Fig. 5.5.1.4 Variation of maximum net heat release with load

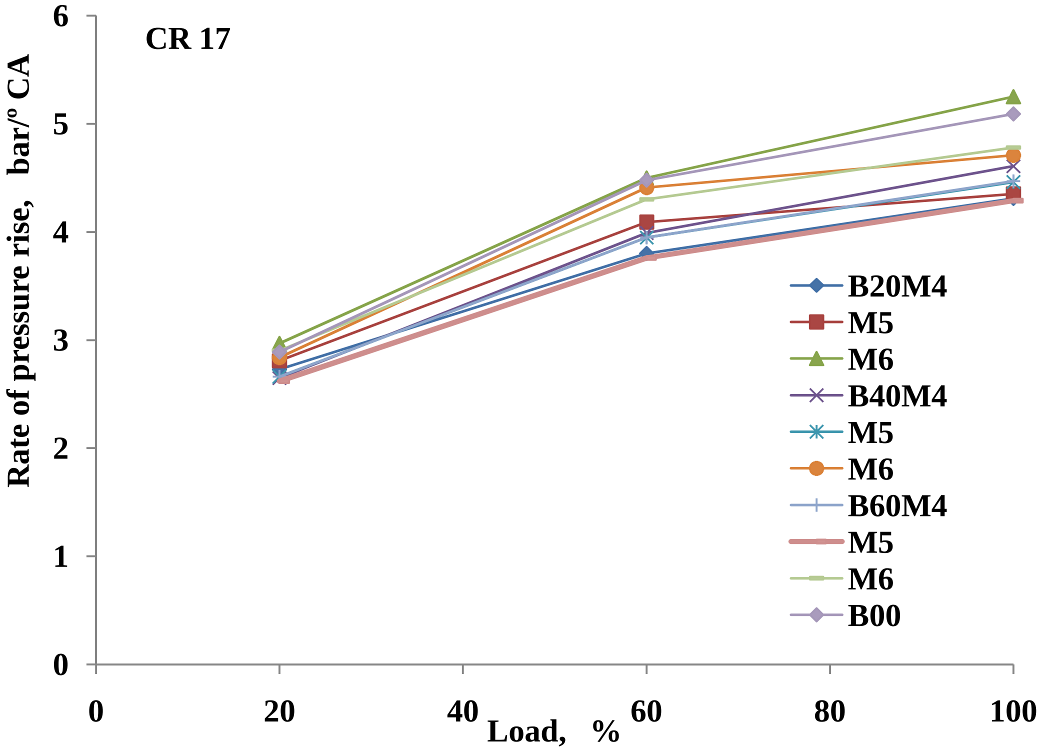
increased in maximum heat release for the blend B20M4 is about 6.3% in compared with diesel fuel.

5.5.1.5 Rate of pressure rise with load

The RPR for diesel fuel as well as for the various blends for various loads at compression ratio 16, 17 and 18 is illustrated in the Fig. 5.5.1.5. The RPR is depends on the amount of fuel burnt during the premixed combustion as well as the load on the engine and the type of fuel used. The RPR increases for the increased load for fuels and the compression ratio used. The RPR is lesser at lower load which may perhaps be accredited to lower combustion temperature and less quantity of fuel available for combustion at lower load for the CR used. However the RPR is higher for higher load for diesel and for the various blends. The RPR for diesel fuel at CR18 is 4.79 bar/ ºCA for the full load. The RPR for most of the blends is lower compared to diesel fuel which may perhaps be accredited to shorter ignition delay for the blends. The ignition delay for the blends is shorter because of higher cetane number of biodiesel in the blends. The higher maximum RPR for the blend B20M6 is 5.53 bar /ºCA at the rated load. The minimum RPR for the blend B60M5 is 4.46 bar /ºCA which is lower among all the blends used. The lower RPR for the blend B60M5 may perhaps be because of lower heating value and higher viscosity of blends influence the mixture formation and combustion of the blends. The RPR is increased for the blend B20M6 is by about 15.5% compared to diesel fuel at the rated load. The reduction in the RPR for the blend B60M5 is by about 6.9% compared to diesel fuel at the rated load.

The RPR at CR17 for the diesel fuel are higher for almost all the loads as well as for the blends. The higher RPR for diesel fuel at CR17 may be because of increased ignition





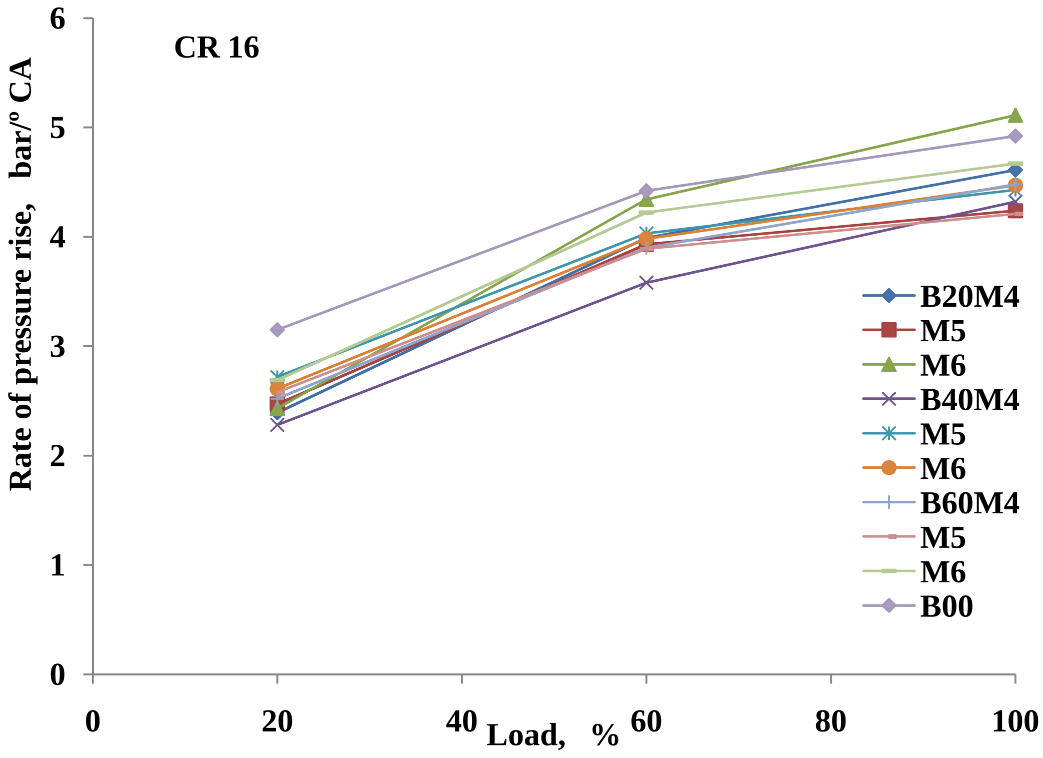


Fig. 5.5.1.5 Variation of rate of pressure rise with load

delay which increases the premixed combustion. The increase in ignition delay, increase the premixed combustion at CR17 which may possibly be accredited to lower combustion temperature, lesser temperature and density of the air inside the combustion chamber. The above two factors takes more time for the mixture formation which increases the accumulation fuel all through the delay period hence increases the RPR. The rate of pressure rise for diesel fuel at CR17 is 5.09 bar /ºCA at the rated load. The higher maximum rate of pressure rise for the blend B20M6 is 5.25 bar /ºCA at the rated load. The higher RPR for the blend B20M6 may perhaps be attributed to inherent oxygen and higher CN enhances the mixture formation of fuel-air and accelerate the combustion. The minimum RPR for the blend B60M5 is 4.29 bar /ºCA at the rated load. The lower rate of pressure for B60M5 may well be attributed to higher inferior properties of biodiesel in the blends. The RPR increases for the blend B20M6 is by about 3.14% compared to diesel fuel at the rated load. The reduction in RPR for the blend B60M5 is by about 15.7% at the rated load.

The RPR for CR16 is higher for diesel fuel for all the loads compared to biodiesel blends. The RPR for diesel fuel may perhaps be accredited to higher heating value and better combustible properties of diesel fuel at lower CR. The RPR for diesel fuel at CR16 is 4.96 bar /ºCA at the rated load. The maximum RPR for blend B20M6 is 5.11 bar /ºCA at the rated load. The least rate pressure rise for the blend B60M5 is 4.21 bar /ºCA at the rated load. The lower rate of pressure rise for higher blends may be accredited to inferior properties of biodiesel in the blend affects the mixture formation which results in the incomplete combustion.

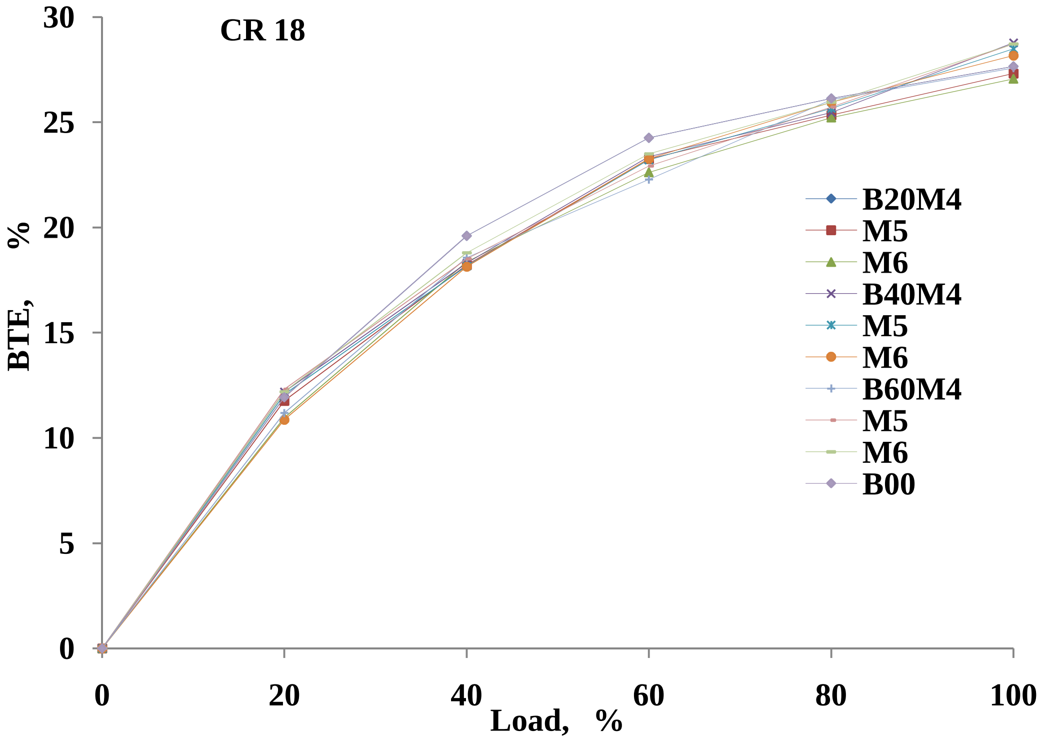
5.5.2 Performance analysis

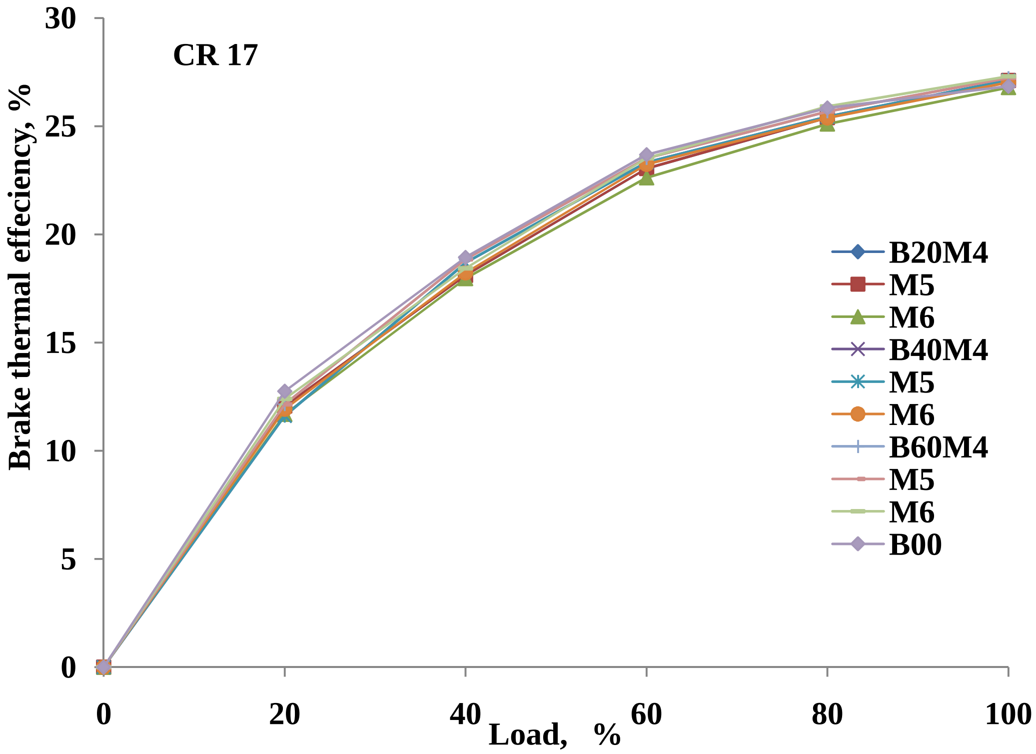
5.5.2.1. Brake thermal efficiency with load

The change in BTE for diesel fuel as well as for the various blends for different loads at compression ratio 16, 17 and 18 are illustrated in the Fig.5.5.2.1. The BTE increases with increase in load for the fuels used. The BTE of diesel fuel is higher at CR18 for the rated load. The higher BTE of diesel fuel may perhaps be accredited to higher heating value and better combustible properties of diesel fuel. The BTE of diesel fuel is 27.66% at CR18 for the rated load. The BTE for the blends are lesser compared to diesel fuel which might perhaps be accredited to lower heat value and higher viscosity of biodiesel in the blends. The inferior volatility, higher viscosity may influence atomization and mixture formation of fuel-air consequently the combustion process. The brake thermal efficiency of the blend B60M6 is comparable with diesel fuel up to 40% of the rated load which may perhaps be accredited to natural oxygen and higher CN of biodiesel in the blends. The natural oxygen content and higher CN of biodiesel in the blends may improve the mixture formation of fuel-air and the combustion. The brake thermal of the blends B40M5 is higher at the rated load which may perhaps be accredited to increased combustion temperature results into better thermal efficiency. The BTE of the blend B40M5 is 28.78% for the rated load. The BTE of some of the other blends are also higher compared to diesel fuel which may perhaps be because of above explained reasons. The blend B20M6 has the lower BTE and is 27.07% at the rated load. The BTE of the blend B20M6 is lower by about 2% compared to diesel fuel at the rated load.

The BTE at CR17 are lesser compared to CR18 for the diesel fuel and for the various blends used. The lesser BTE at CR17 may possibly accredited to lower combustion temperature, lesser density and temperature of the air in the cylinder. The lower combustion temperature, lesser temperature and density of the air may influence the mixing of fuel-air consequently the combustion. The brake thermal efficiency of diesel fuel is 26.84% at the rated load. The brake thermal efficiency of B60M6 blend is 27.3% at the rated load. The higher BTE for the blend B60M6 may well be accredited to inherent oxygen and higher CN of biodiesel in the blend. The natural oxygen and higher

CN may contribute towards complete combustion of blends hence higher BTE. The BTE of the blends is almost comparable with diesel fuel at the rated load.





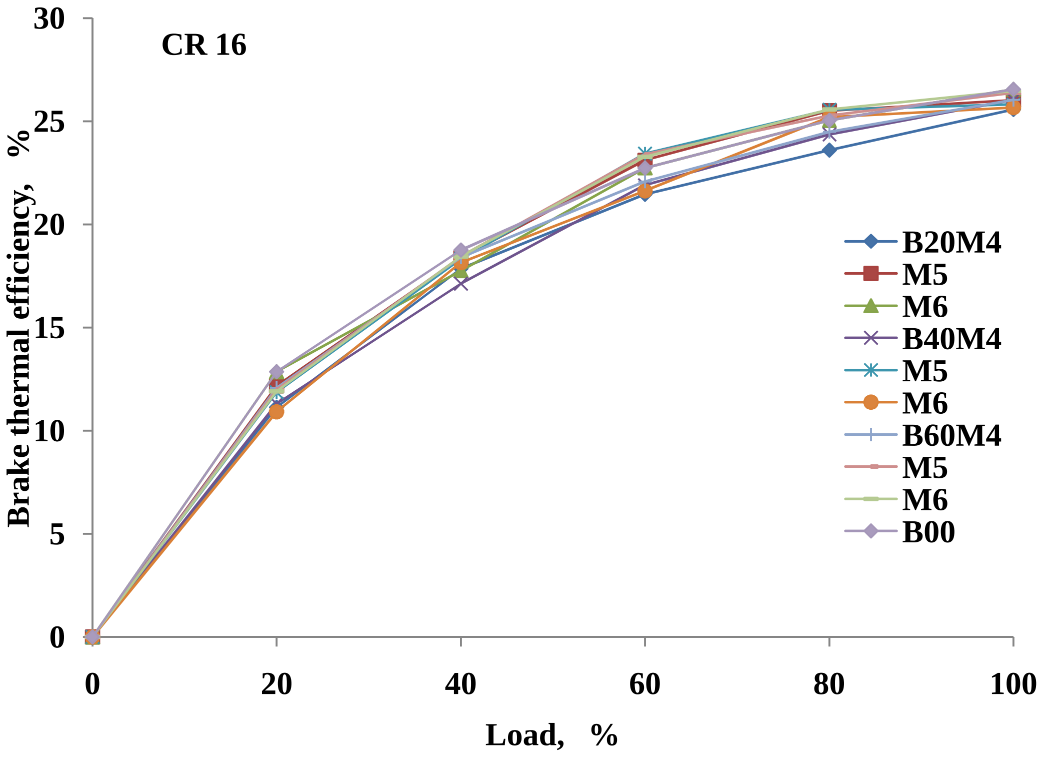


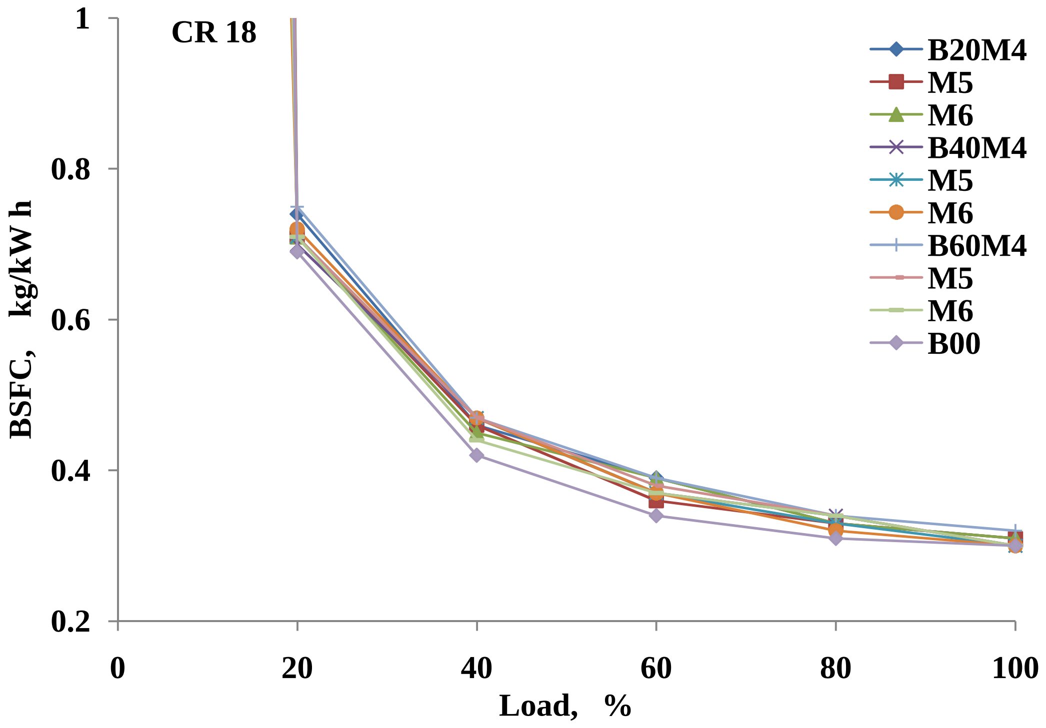
Fig. 5.5.2.1 Variation of BTE with load

The BTE at CR16 are lesser compared to the CR17 and CR18 for the fuels used. The lower BTE at CR16 are lesser which may be because of decreased combustion temperature, lower temperature and density of the air in the cylinder may affect mixture formation and the combustion process. The BTE for the diesel fuel at CR16 is 26.55% at the rated load. BTE for the blend B40M6 is 25.66% which is the lower among the blends. The lower BTE for the blends may perhaps be accredited to higher viscosity and lower volatility of the blends may influence the mixture formation of fuel-air, contributes into the incomplete combustion of blends and hence decreases the brake thermal efficiency.

5.5.2.2 Brake specific fuel consumption with load

The BSFC of diesel fuel and for the various blends for different load at compression ratio 16, 17 and 18 are illustrated in the Fig. 5.5.2.2. The BSFC decreases with increase in load for fuels used. The reduction in BSFC for diesel fuel and for the various blends may perhaps be accredited to increased combustion temperature, higher temperature and density of the air inside the cylinder. The increased combustion temperature, higher pressure and temperature of the air which may improve the atomization and mixing of fuel-air which contributes in improved fuel efficiency. The BSFC of the diesel fuel and biodiesel blends decreases with increase in CR. The lesser BSFC of diesel fuel in comparison to the blends may possibly be accredited to high heating value and better combustible properties. The BSFC of diesel fuel at CR18 is 0.3 kg/kW hr at the rated load. The BSFC of some of the blends are same as that of diesel fuel at the rated load which may perhaps be accredited to increased combustion temperature contributes in the complete combustion of blends. The better combustion of the blends may be accredited to natural oxygen content and higher CN of the biodiesel in the blends. The natural oxygen and higher CN of biodiesel in the blends may improve the mixture formation which results into complete combustion. The BSFC of blend B60M4 is higher and it is 0.32 kg/kW hr. The increases in BSFC for the blends may possibly be accredited to lesser heat value and higher viscosity of biodiesel in the blend. The fuel consumption for the blend B60M4 is increased by about 6.25% compared to diesel fuel at the rated load.

The BSFC is increased at CR17 compared to CR18 for diesel fuel as well as for the various blends used for all the loads. The higher BSFC at CR17 may possibly be accredited to lesser combustion temperature, lower temperature and density of the air inside the cylinder. The above factors may have an effect on the mixing of fuel-air subsequently the incomplete combustion which increases BSFC. The BSFC for diesel fuel at CR17 is 0.31 kg/kW hr at the rated load. The BSFC for the blend B40M6 is 0.32 kg/kW hr for the full load. The higher BSFC for the blend B40M6 may well be accredited



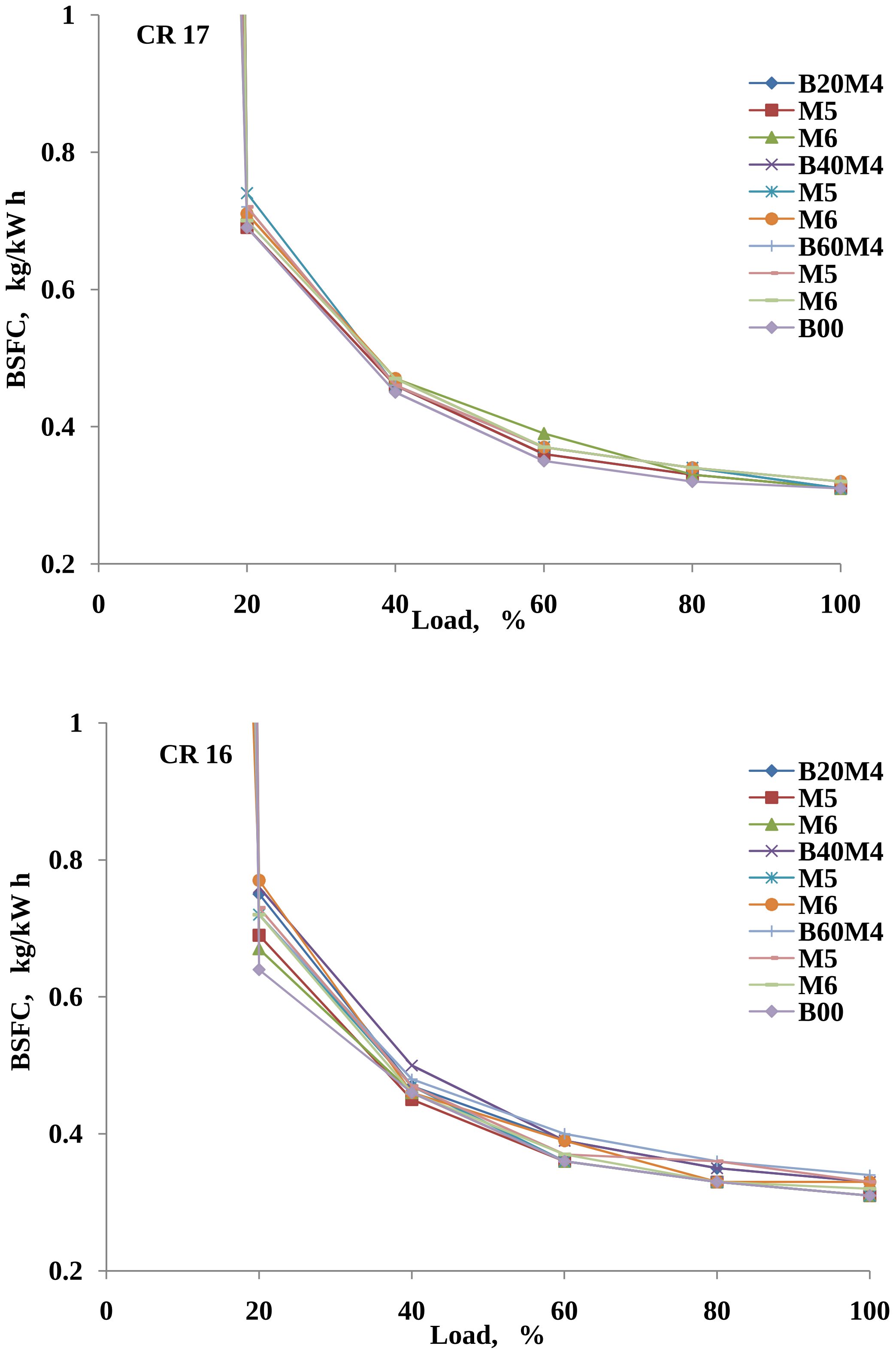


Fig. 5.5.2.1 Variation of brake specific fuel consumption with load

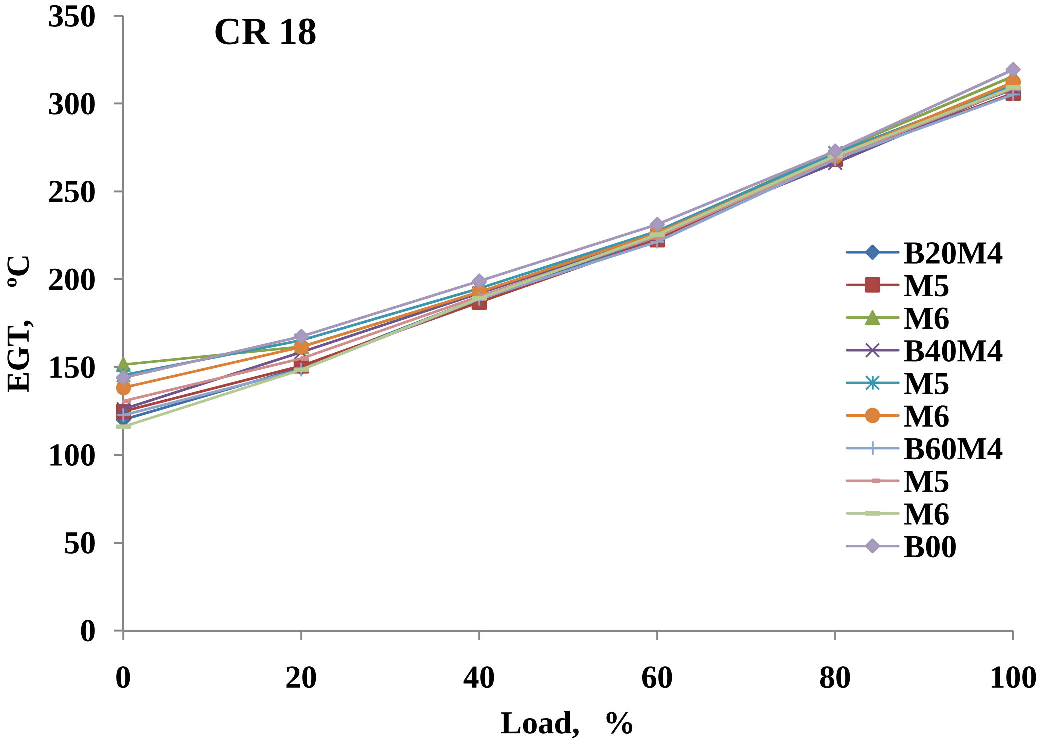
to lower heat value and inferior volatility, higher viscosity of biodiesel in the blend. These factors may influence the mixture formation and the combustion. The BSFC of the blend B40M6 is increased by about 3.12% compared to diesel fuel for the full load.

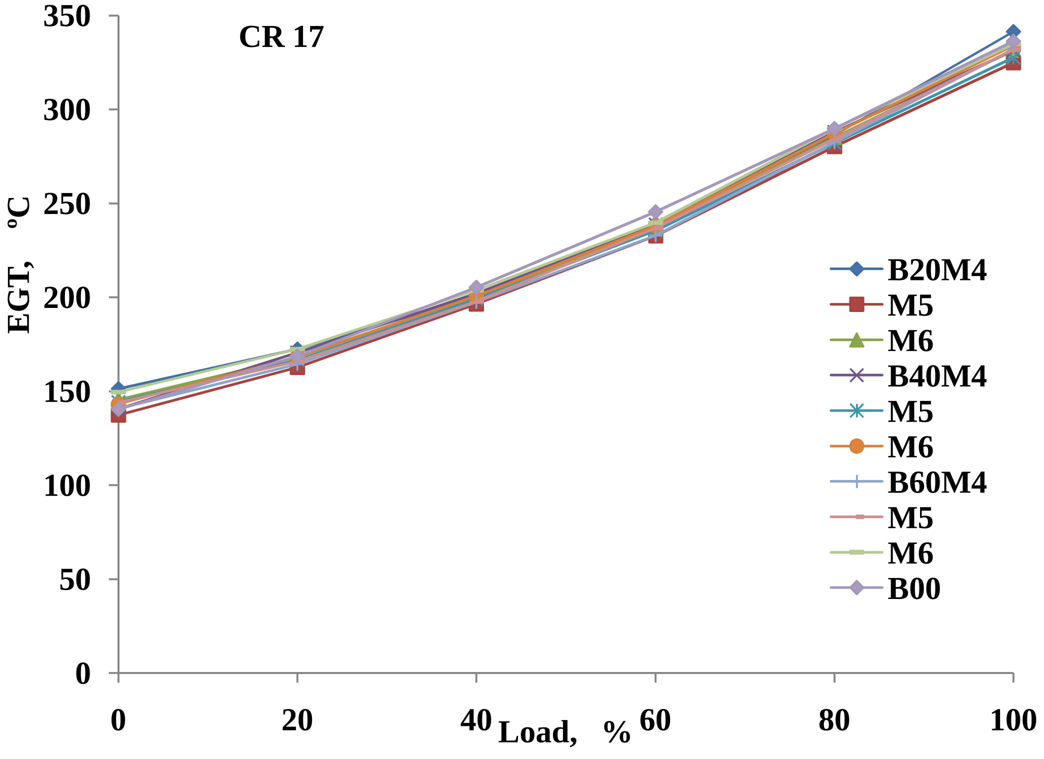
The BSFC is increased at CR16 compared to CR17 and CR18 for the diesel fuel as well as for the various blends. The increased BSFC at CR16 may perhaps be accredited to lower combustion temperature, lesser temperature and density of the air in the cylinder at CR16. The lower combustion temperature, lesser density and temperature of the air may affect the mixing of fuel-air subsequently the incomplete combustion which increases BSFC for the fuels used. The BSFC for diesel fuel at CR16 is 0.31 kg/kW hr at the rated load. The BSFC for the blend B60M4 is 0.34 for the full load. The higher BSFC for the blend B60M4 may perhaps be accredited to lower heating value and higher viscosity of the biodiesel in the blend. The fuel consumption for the blend B60M4 is increased by about 6.25% compared to diesel fuel.

5.5.2.3 Exhaust gas temperature with load

The EGT for diesel fuel and various blends for different load at compression ratio of 16, 17 and 18 are illustrated in the Fig.5.5.2.3. The lower EGT indicates more of the chemical energy of the fuel is converted to heat energy which results in to increase in power output. The EGT increases with increase in load for the fuels used. The increase in EGT with increase in load may well be accredited to more amount of fuel is supplied and burnt to meet the requirement of increased load on engine. The EGT decreases with increase in CR which may perhaps be accredited to increased burning velocity. The increased burning rate reduces the time required for the complete combustion. It is seen from the figure that EGT for the various blends are lesser in comparison with diesel fuel. The EGT for the blend B40M6 and B60M6 are found to be lower by about 3.13% and 4.4% respectively in comparison with diesel fuel at the rated load. The decrease in EGT for the blends may perhaps be to the fact that the air intake at higher compression ratio is compressed to the higher compression which results into the increases in the air temperature. The increased temperature of the air at higher CR may contribute in better atomization and improved combustion of fuel which results in decrease of EGT.

The exhaust gas temperature at CR17 are higher compared to CR18 for diesel fuel as well as for the various blends used. The higher EGT at CR17 may perhaps be attributed to lower temperature and density of the air which affect the mixing of fuel-air subsequently the combustion process. The EGT for the diesel fuel at CR17 is 336º C at the rated load whereas the EGT for the blend B20M4 is 341º C is marginally higher in comparison with diesel fuel. The higher EGT for the blend B20M4 may perhaps be accredited to higher viscosity and lower volatility of biodiesel in the blends contributes into the incomplete combustion. The maximum reduction of EGT for the blend is by about 3.6% compared to diesel fuel at the rated load which indicates the better transformation of chemical energy of fuel into heat energy which results into the higher power output.





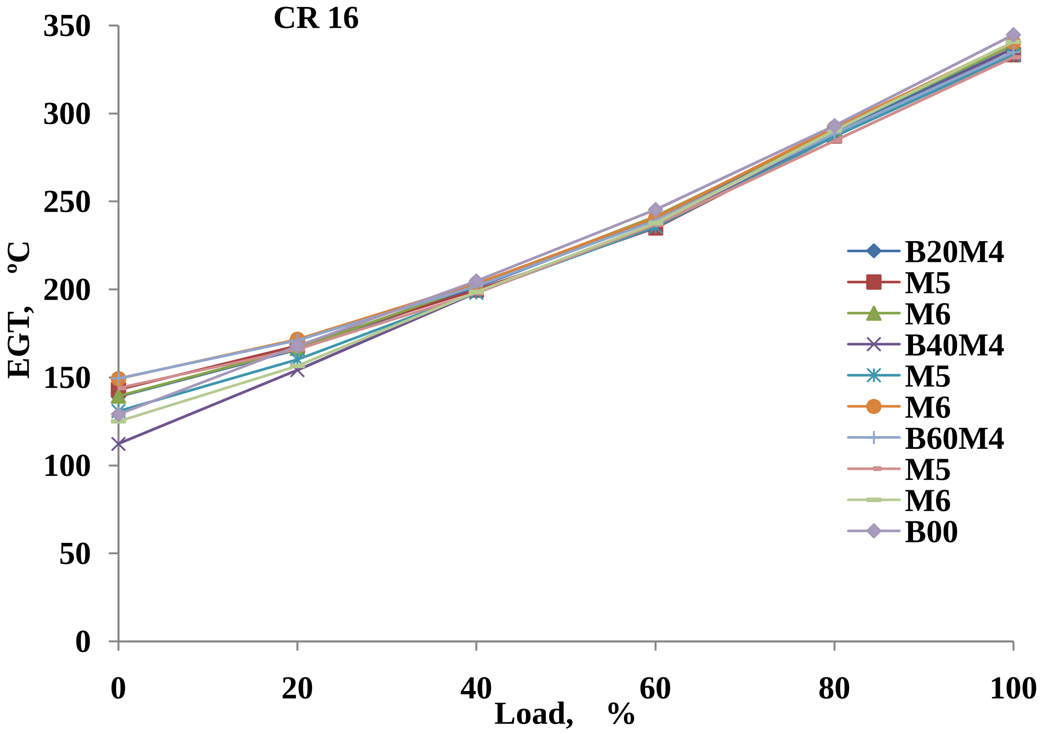


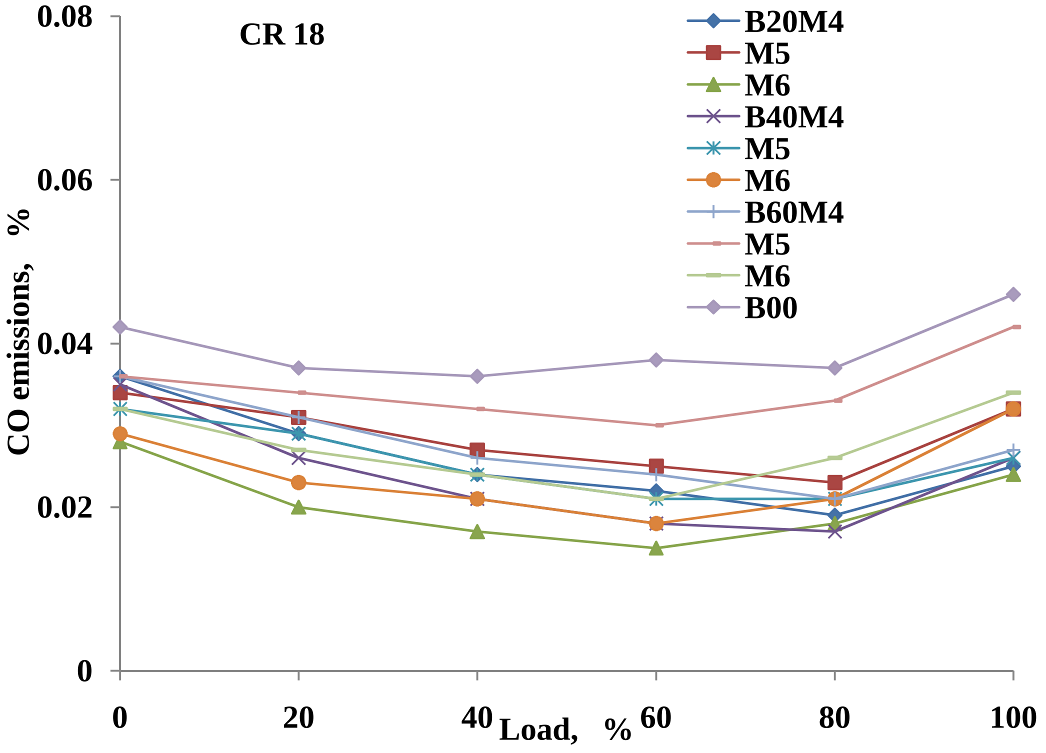
Fig. 5.5.2.1 Variation of EGT with load

The exhaust gas temperatures are higher at CR16 compared to CR17 and CR18 for diesel fuel as well for the various blends used. The EGT are higher for diesel fuel in comparison with blends for the entire load. The higher EGT at CR16 may possibly be accredited to lesser density and temperature of the air in the cylinder. The lesser temperature and density of the air may affect the mixture formation subsequently delay the combustion process which increases EGT. The EGT for diesel fuel at CR16 is 344° C at the rated load. The lower EGT for the blend B20M5 is 331° C at rated load. The reduced EGT for all the blends at CR of 16, 17 and 18 may perhaps be accredited to inherent oxygen and higher cetane number of biodiesel in the blends may contribute in better combustion of blends results into reduced exhaust gas temperature.

5.5.3 Emission analysis

5.5.3.1 CO emissions with load

The CO emission for diesel fuel as well as for the various blends for different load at compression ratio of 16, 17 and 18 are illustrated in the Fig.5.5.3.1. The CO emission increases with the increase in load for fuels used. The CO emission decreases with increase in CR for diesel fuel and various blends. The decreases in CO emissions with increase in CR may perhaps be accredited to increased combustion temperature, higher density and temperature of the air. The higher temperature and density of the air may improve the mixture formation and contributes for the complete combustion. It is seen that the CO emissions are lower at CR18 compared to CR16 and CR17 for almost all the load. The decreases in CO emission at CR18 may perhaps be attributed to higher density and temperatures of the air in the cylinder and increased combustion temperature. The increased combustion temperature which may enhance the mixture formation of fuel-air, contributes in the complete combustion fuels used. The improved combustion at CR18 reduces the CO emissions for diesel fuel as well as for the blends. The CO emissions are higher for diesel fuel and it is 0.046% at the rated load which may perhaps be accredited to lack of oxygen for the complete combustion. The CO emissions for all the blends are lesser in comparison with diesel fuel which may perhaps be accredited to inherent oxygen and higher cetane number of biodiesel in the blends. The inherent oxygen and higher CN which may perhaps enhance the mixture formation subsequently improve the combustion. The maximum higher CO emission for the blend B60M5 is 0.042% which may be because of higher viscosity of the blends results into the poor combustion. The least CO emission for the blend B40M6 is 0.024% at the rated load. The reduction in CO emission for the blend for B60M5 is 20.75% and for the blend B20M4 is 47.8% compared to diesel fuel at the rated load.



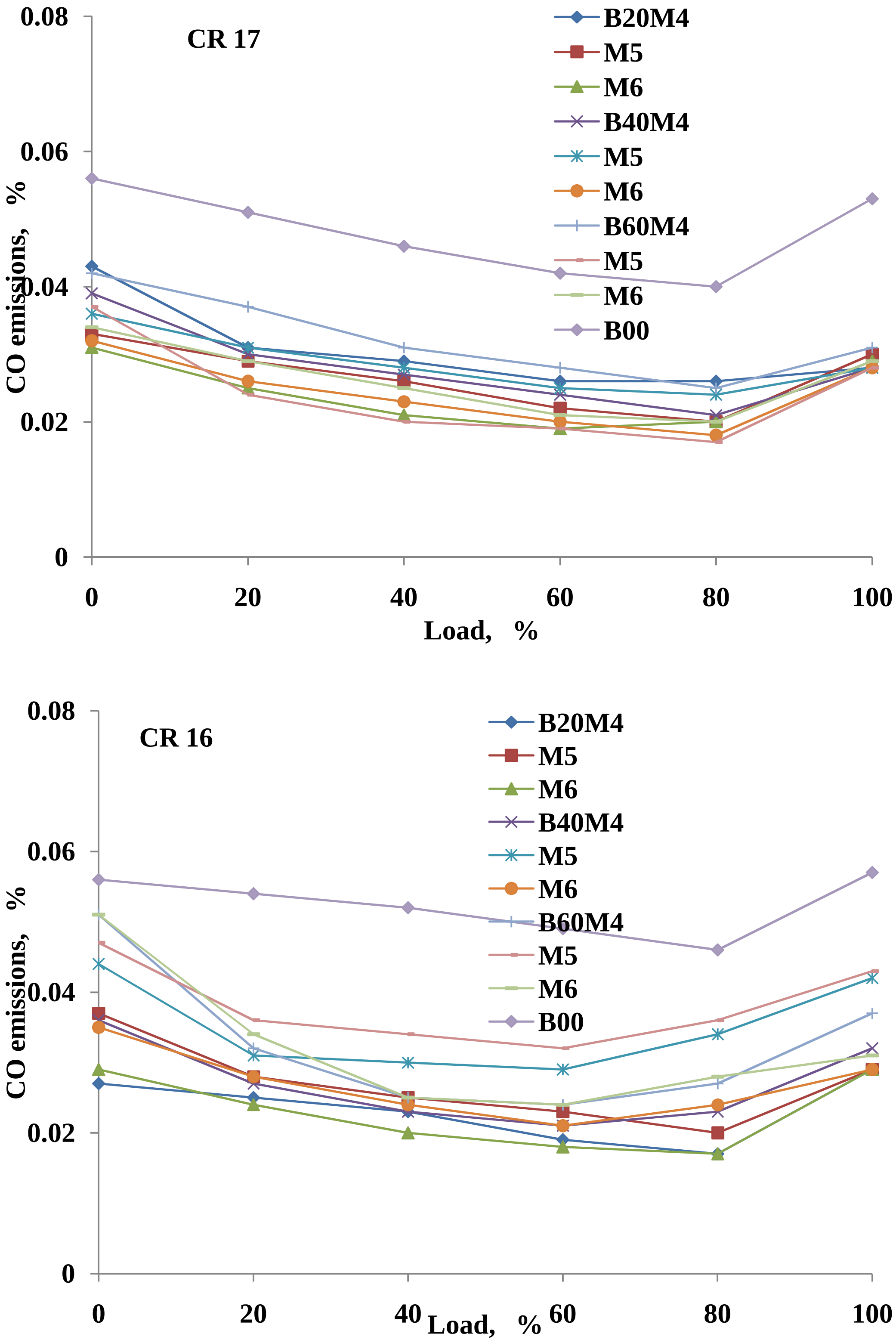


Fig. 5.5.3.1 Variation of CO emissions with load

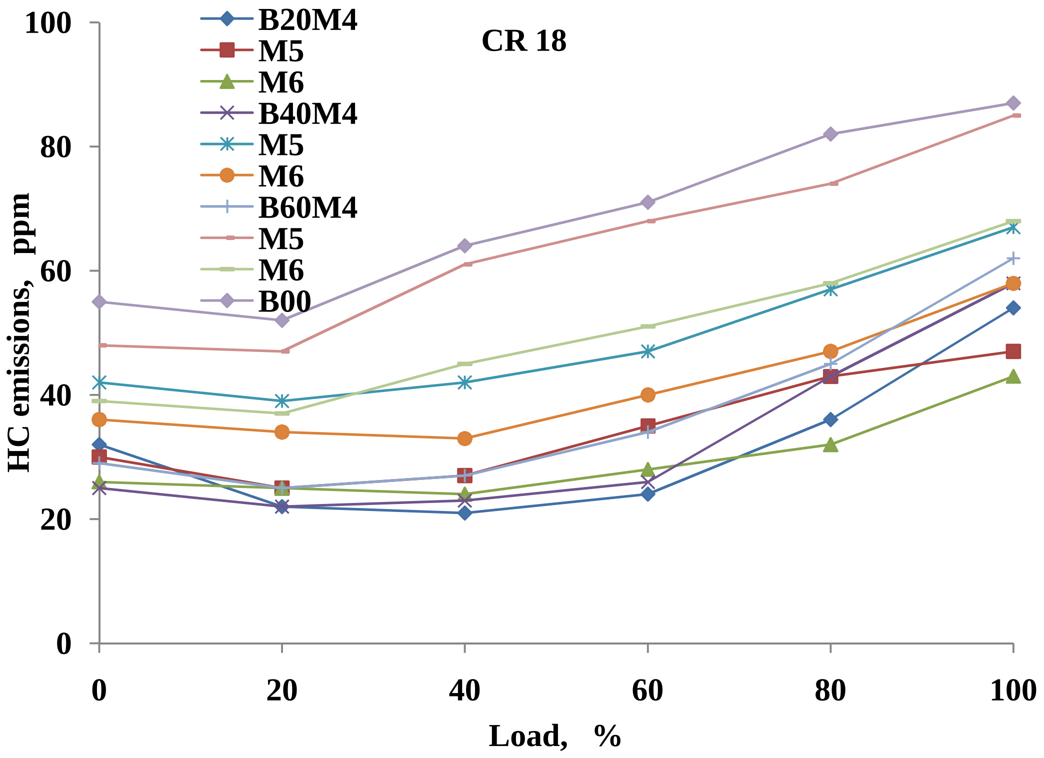
The CO emissions at CR17 are higher compared to CR18 for the diesel fuel and for the various blends used. The CO emissions are higher at CR17 which may perhaps be accredited to decreased combustion temperature, lesser density and temperature of the air inside the cylinder. The lower density and temperature of the air which may affect the mixing of fuel-air consequently incomplete combustion results in to the increase in CO emissions. The CO emission for the diesel fuel at CR17 is 0.053% at rated the load. The minimum CO emissions for the blend B20M6 are 0.028% and maximum CO emission for the blend B60M4 is 0.031% at the full load. The reduction in CO emission for the blend B60M4 is 41.5% and for the blend B20M5 is 47.1% compared to diesel fuel.

The CO emissions at CR16 are higher compared to CR17 and CR18 for diesel fuel as well as for various blend used. The higher CO emission for the fuels used at CR16 may well be accredited to lower density and temperature of the air affect the mixture formation of fuel-air subsequently the sluggish combustion. The lower density and temperature of the air may affect the atomization; mixture formation which causes the incomplete combustion. The incomplete combustion increases the CO emission. The CO emission for diesel at CR16 is 0.057% at the rated load. The maximum CO emission for the blend B60M5 is 0.043% and minimum CO emission for the blend B40M6 is 0.029% for the full load. The CO emissions are reduced by about 31.7% and 49% for the blends B60M5 and B40M6 respectively in comparison with diesel fuel for the full load.

5.5.3.2 HC emissions with load

The unburnt hydrocarbon emission for diesel fuel and for the blends for various load at compression ratio 16, 17 and 18 are illustrated in the Fig.5.5.3.2. The HC emission increases for the increased load for the fuels used. The increase in HC emissions with increase in load may perhaps be accredited to increased fuel supply to generate additional power to carry the increased load on the engine. The HC emissions decrease for higher CR for fuels used. The HC emissions for diesel fuel at CR18 are higher which may perhaps be accredited to incomplete combustion because of lack of oxygen. The HC emission of blends follows the similar trend as the diesel fuel which may perhaps be because of comparable properties of biodiesel with diesel. The HC emission for the blends is lesser in comparison with diesel fuel which may perhaps be attributed to inherent oxygen and higher CN number of biodiesel in the blends. The inherent oxygen and higher CN of the blends enhance the mixing of fuel-air and accelerate the chemical reactions subsequently decreases the HC emissions. The emissions of HC for diesel fuel at CR18 are 87ppm at the rated load which is higher for the entire range of blends used. The HC emissions for the blend B60M5 are 85ppm which is higher among all the blends. The higher HC emission for the blend B60M5 may perhaps be attributed to higher viscosity and inferior volatility of biodiesel in the blends. The inferior properties of the blends may have an effect on the atomization, vaporization, and mixing of fuel-air consequently the sluggish combustion which increases the HC emission compared to other blends. The lowest value of HC emission for the blends B20M6 is 40ppm at the rated load. The least HC emission for the said blend may perhaps be accredited to complete combustion of blends at the rated load. The maximum and minimum percentage decrease in HC emissions are by about 5.9% and 55.5% for B60M5 and B20M6 blends respectively in comparison to diesel fuel.

The HC emissions are higher at CR17 compared to CR18 for diesel fuel and for various blends. The HC emissions are increased at CR17 may perhaps be accredited to lesser temperature and density of the air inside the cylinder. The lesser density and temperature of the air may perhaps be distressing the mixture formation of fuel-air subsequently the combustion which contributes for increases in HC emissions. The HC emission for diesel fuel at CR17 is 90 ppm at the rated load. The minimum HC emission for the blend B20M4 is 34 ppm at the rated load. The HC emission for the blend B60M6 is 89 ppm, is higher among all the blends used. The higher HC emissions for the blend B60M6 may perhaps be accredited to higher viscosity and inferior volatility of biodiesel in the blends. The minimum HC emission for the blend B20M4 may perhaps be accredited to better mixture formation and complete combustion of blends. The HC emissions are reduced by about 7.3% and 64.6% for B60M6 and B20M4 respectively compared to diesel fuel.



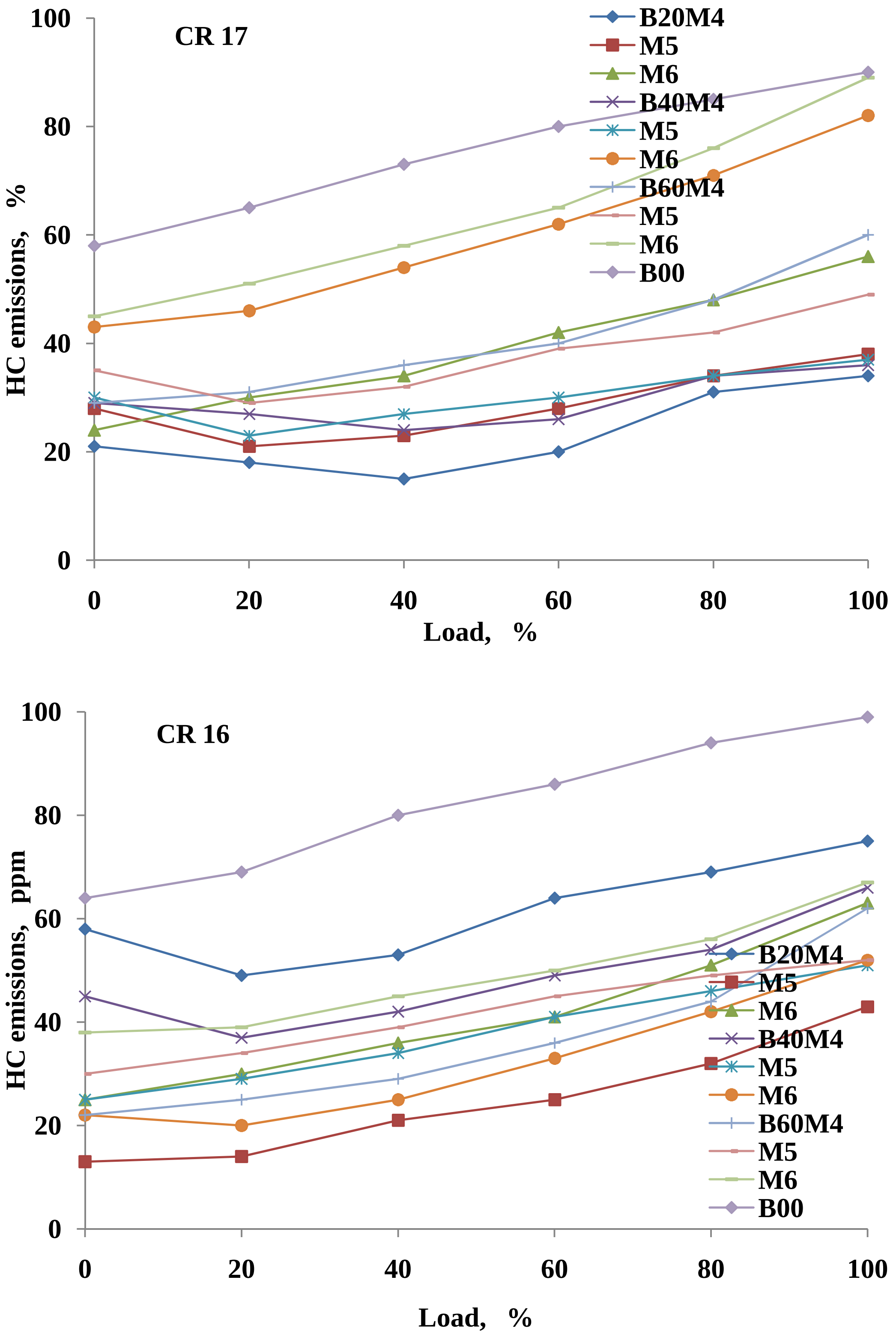


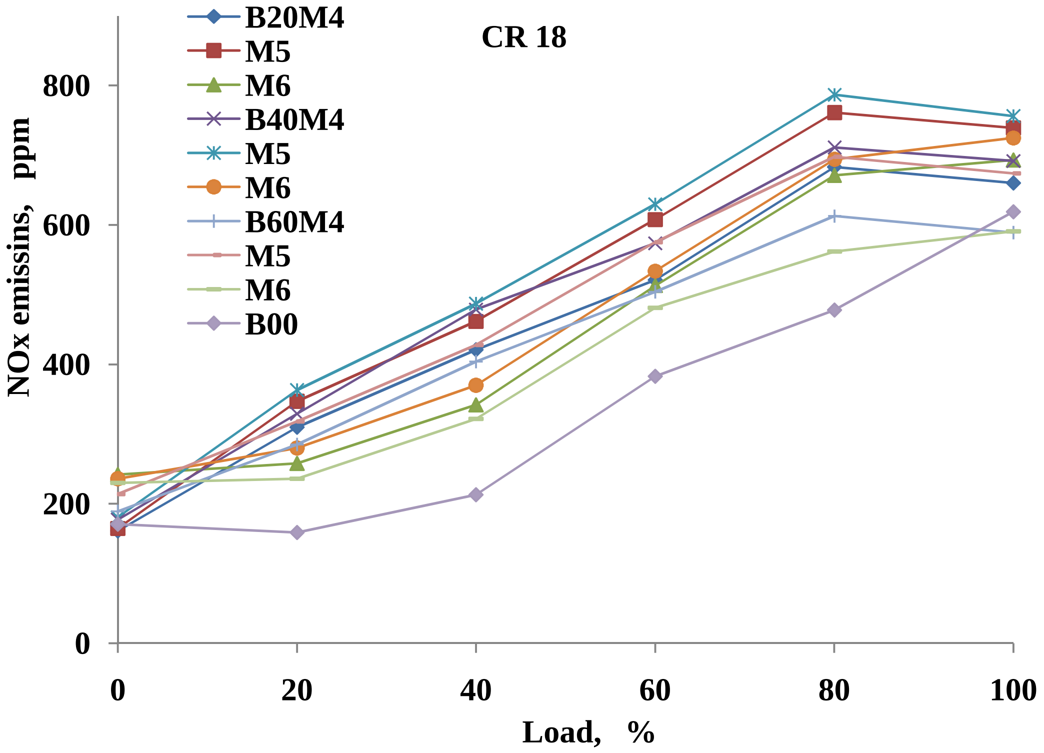
Fig. 5.5.3.2 Variation of HC emission with load

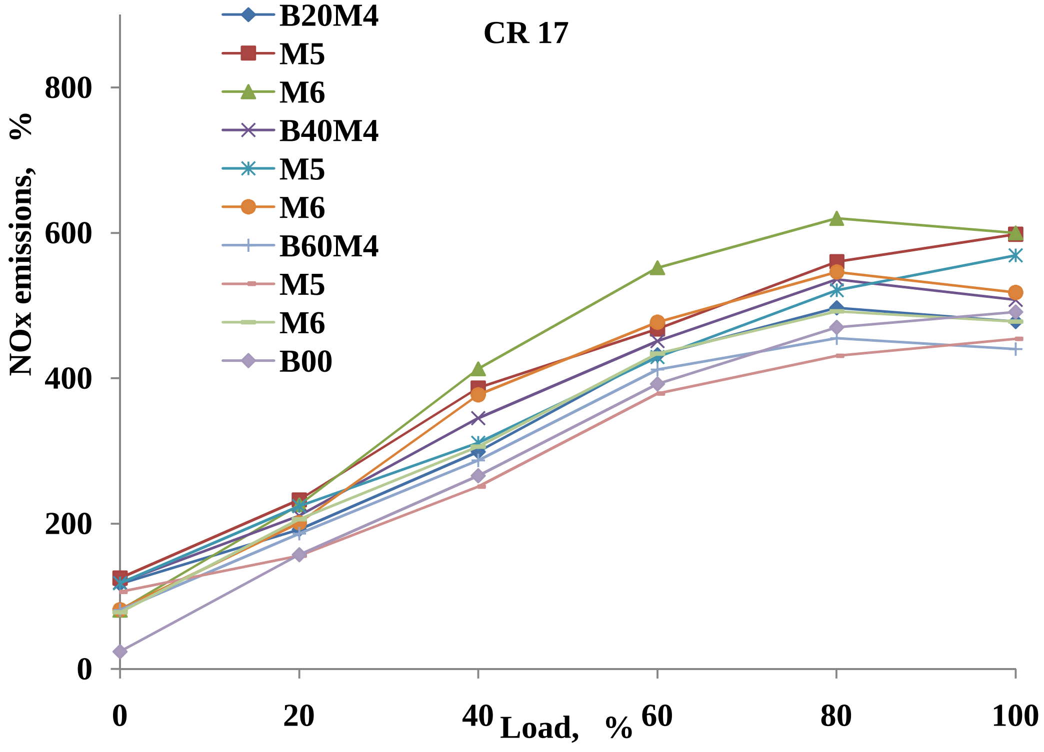
The emissions of HC at CR16 are higher compared to CR17 and CR18 for diesel fuel as well as for the various blends. The HC emission for diesel fuel is 99ppm which may be because of incomplete combustion. The incomplete combustion of diesel fuel may be due to lesser temperature and density of the air at CR16. The minimum and maximum HC emissions for the blends are 43ppm and 75ppm for the blends B20M5 and B20M4 respectively. The higher HC emission at CR16 may perhaps be accredited to lesser temperature and density of the air which may influence the mixing of fuel-air subsequently the combustion. The sluggish mixing of fuel-air affect the combustion hence increases the HC emission at CR16.

5.5.3.3 NOx emissions with load

The NOx emission for diesel fuel as well as for the various blends for different load at the CR 16, 17 and 18 are illustrated in the Fig.5.5.3.3. The NOx emission increases for the increase in load for the fuels used. The NOx increases with increase in compression ratio which may possibly be accredited to increased combustion temperature and availability of oxygen. The NOx emissions for the blends are higher at CR18 in compared to diesel fuel. The higher NOx emission for the blends may perhaps be accredited to oxygen content and higher CN of biodiesel in the blends. The natural oxygen content and higher CN may enhance the mixture formation of fuel-air and accelerate the combustion results into increased combustion temperature hence higher NOx emissions. For the lower load the NOx emissions are less for the blends which may perhaps be attributed to a smaller amount of fuel is burnt hence lower combustion temperature. As the load on engine increases the quantity of fuel supplied and burned increase which may perhaps increases the combustion temperature consequently the NOx emissions. The NOx emission for diesel fuel at CR18 is 619 ppm at the rated load. The higher NOx emission for the blend B40M5 is 787 ppm at 80% of the rated load. The minimum NOx emission for the blend B60M6 is 591 at the rated load. The lesser NOx emission for the blend B60M6 may perhaps be attributed to higher viscosity and lower volatility of the biodiesel in the blend affect the mixing of fuel-air consequently the combustion. The combustion temperatures of the blend B60M6 may be lower because of incomplete combustion hence lesser NOx emissions. The NOx emission for the blend B40M5 is 756ppm at the rated load and is lesser which may perhaps be because increased turbulence at the rated load increases the speed of combustion. The NOx emissions are increased for the blend B40M5 by about 22.1% and decrease for the blend B60M6 is 13.8% compared to diesel fuel at rated load.

The NOx emission at CR17 is lesser compared to CR18 for diesel fuel as well as for the various blends used. The NOx emission at CR17 are lesser for the entire range of fuels used compared to CR18 which may possibly be accredited to decreased combustion temperature, lesser temperature and density of the air. The lesser density and temperature of the air may have an effect on the mixing of fuel-air subsequently the combustion which results in lower temperature hence lesser NOx emissions. The NOx emission for diesel fuel is 491 ppm which is lower compared to almost all the blends at CR17 at rated load. The maximum higher NOx emission for the blend B20M6 is 620 ppm at 80% of the rated load. The lower NOx emission for the blend B60M5 is 554 ppm at the rated load. The





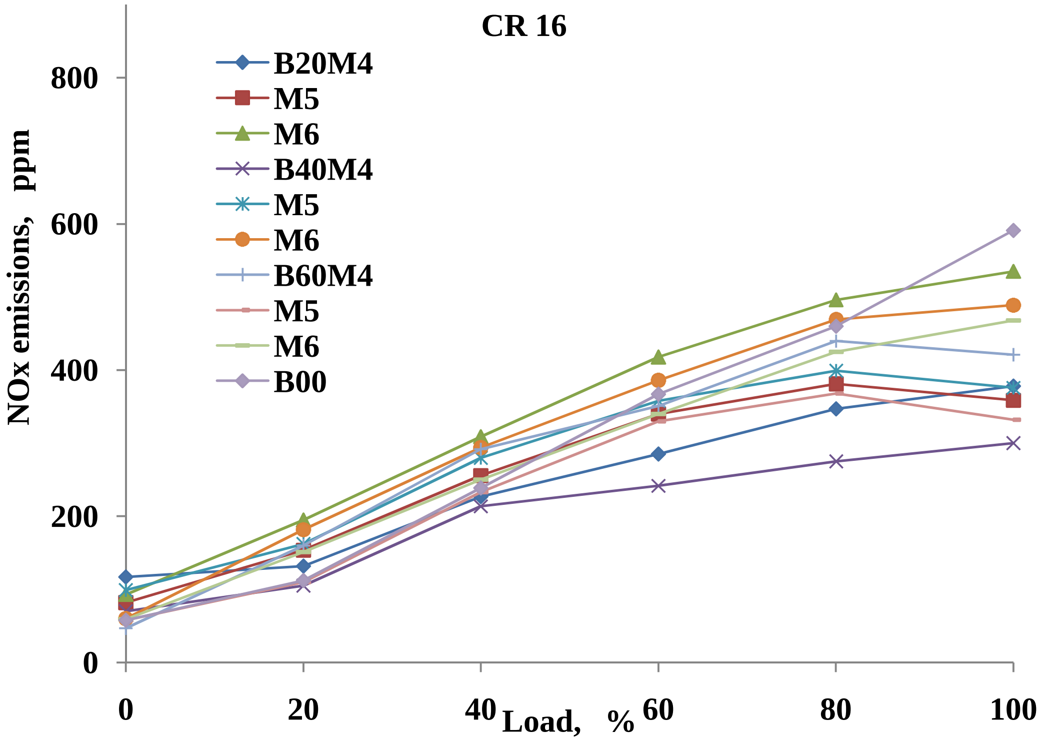


Fig. 5.5.3.3 Variation of NOx emission with load

maximum increase in NOx emission for the blend B20M6 is about 26.3% and decrease in NOx emission for the blend B60M5 is about 7.5% compared to diesel.

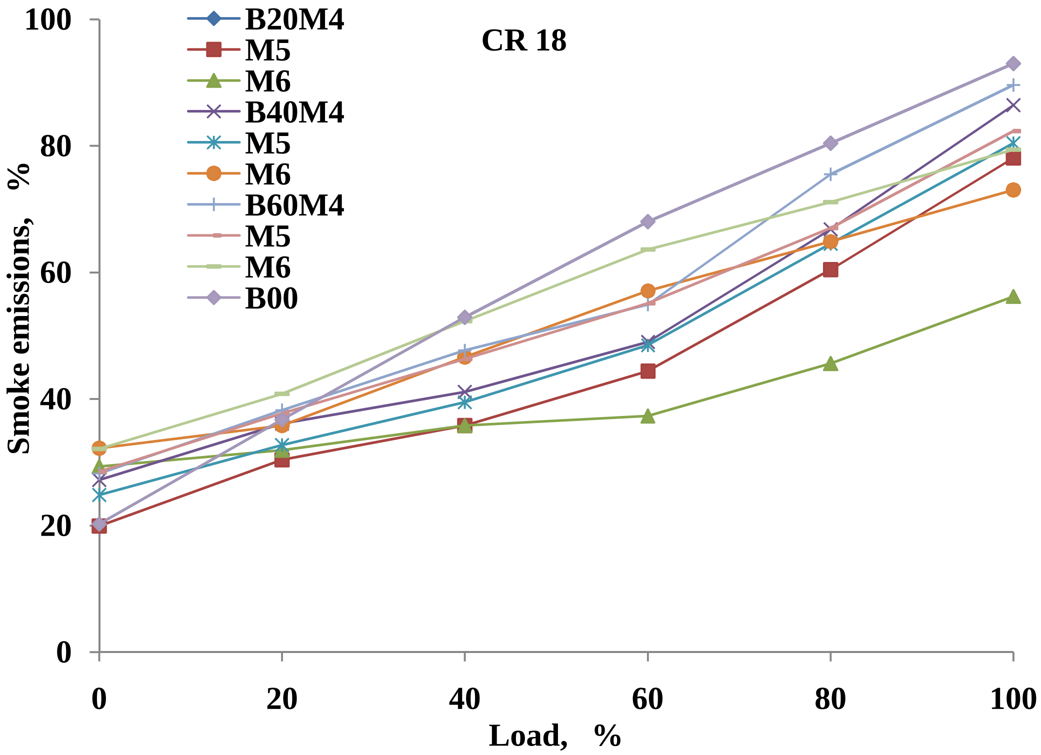
The NOx emissions at CR16 are lesser compared to CR17 and CR18 for the diesel fuel as well as for the various blends. The lesser NOx emissions at CR16 may perhaps be attributed to decreased combustion temperature, lesser temperature and density of the air which may influence the mixture formation consequently the combustion. The slow combustion of fuels may perhaps affect the fuel burning rate results into lower combustion temperatures. The lower combustion temperature may results into lesser NOx at CR16 for all the fuels used compared to CR17 and CR18. The NOx emission at CR16 for diesel fuel is 591 ppm at the rated load. The NOx emission for the blends is lesser compared to diesel fuel at the rated load. The higher NOx emission for diesel fuel may perhaps be attributed to higher combustion temperature at CR16.

5.5.3.4 Smoke emissions with load

The smoke emissions for diesel fuel and for the various blends for different loads at compression ratio 16, 17 and 18 are illustrated in the Fig.5.5.3.4. The smoke emissions increases with increase in load which may well be accredited to increase in fuel supply to compensate for increased load on the engine. The smoke emission decreases for higher

CR which may possibly be attributed to increased temperature and density of the air. The increased temperature and density of the air in the cylinder enhance the mixture formation of fuel-air consequently the combustion process hence decreases the smoke emission. The smoke emission for diesel fuel is higher at CR18 compared to the blends which may be because of incomplete combustion of diesel fuel due to lack of oxygen. The smoke emissions are lesser for all the blends used which may possibly be accredited to oxygen content and higher CN of biodiesel in the blends. The oxygen content and higher CN of biodiesel in the blends may enhance the mixing of fuel-air and accelerate the chemical reactions and complete the combustion. The smoke emission for diesel fuel at CR18 is 93% at the rated load. The maximum smoke emission for the blend B60M1 is 89.6% at the rated load. The minimum smoke emission for the blend B20M6 is 56.2% at the rated load. The smoke emissions are decreased for the blends B60M1 and B20M6 by about 3.7% and 39.5% respectively in comparison to diesel fuel for the rated load.

The smoke emissions are higher at CR17 compared to CR18 for diesel fuel as well as for the various blends. The higher smoke emissions at CR17 may perhaps be accredited decreased combustion temperature, lesser temperature and density of the air. The lower density and temperature of the air may influence the mixture formation of fuel-air consequently the combustion which increases the smoke emission. The smoke emission



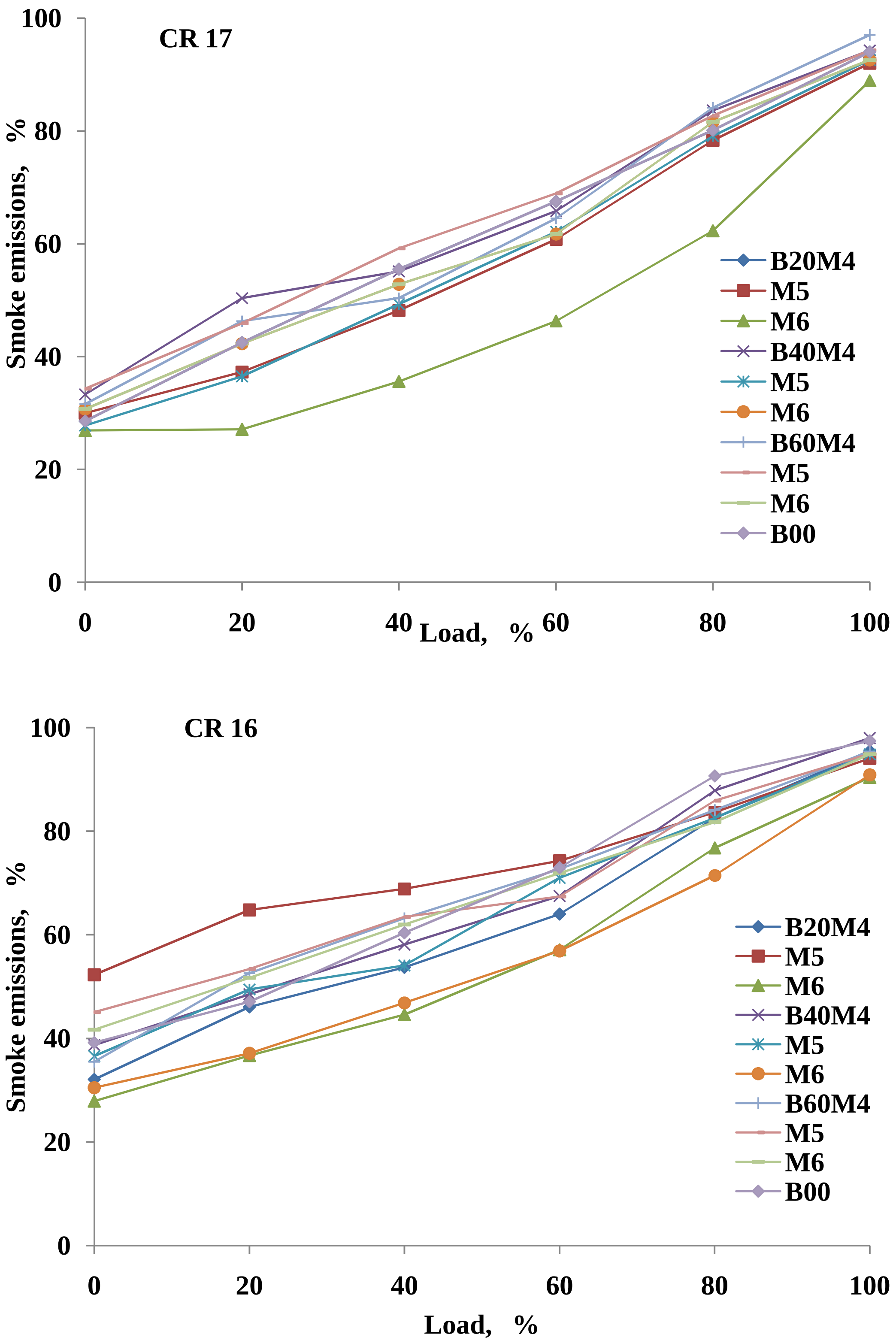


Fig. 5.5.3.4 Variation of smoke emission with load

for diesel at CR17 is 94% at the rated load. The smoke emission for some of the blends are higher compared to diesel fuel which may well be attributed to higher viscosity and lower volatility of the biodiesel in the blends which may slow down slow down the mixing of fuel-air hence sluggish combustion which increases smoke emissions. The maximum smoke emission for the blend B60M4 is 97% and the least smoke emission for the blend B20M6 is 88.9% at the rated load.

The smoke emission at CR16 is higher at lower loads compared to CR17 and CR18 for diesel fuel as well as for the various blends. The higher smoke emission may perhaps be accredited to the incomplete combustion of blends for the lower load at CR16. The higher smoke emissions at lower load may perhaps be attributed to lesser combustion temperature, lower temperature and density of the air. The smoke emission for the diesel fuel is 97.5% at the rated load. The higher smoke emission for the blend B40M4 is 98% at the rated load. The least smoke emission for the blend B20M6 is 90.4% at the rated load. The smoke emissions at CR16 are comparable with CR17 and CR18 at the rated load which may be because of increased combustion temperature contributes in better combustion of fuels for the compression ratio used.

5.5.4 Summary

The summary of combined results for various blends as well as diesel fuel for various compression ratios, loads and for various mixture ratios on combustion characteristics, thermal performance and emission characteristics of DI VCR diesel engine are presented. The results are improved at higher compression ratio for the blends as well as for diesel fuel. The combustion characteristics of blends are comparable with one another and diesel fuel. The thermal performance parameters for the blends are comparable with diesel fuel. The emissions such as CO, HC and smoke are decreases where as NOx emissions increases. The combustion characteristics, thermal performance and emission characteristics are decreases for CR16 and CR17 compared to CR18. The overall improvement in the performance of the engine is observed at CR18, which may be due to higher combustion temperature, higher temperature and the density of the air. The increased temperature and density of the air may perhaps improve the mixing of fuel-air contributing towards complete combustion which increases the thermal performance and decreases the emissions. This shows the overall improvement in the output and decreased emissions of the engine.

Table 5.5.1 Results of engine parameters obtained for diesel and blends of various mixtures for rated load at CR18

Sl.No.		B00	B20M4	B40M4	B60M4	B20M5	B40M5	B60M5	B20M5	B40M5	B60M5
Combustion Parameters											
1	Maximum pressure, bar	71.4	72.38	71.55	72.59	72.33	70.63	71.63	72.12	70.85	70.2
2	Max. heat release, J/ºCA	52.79	40.1	40.69	41.29	43.79	39.56	40.6	44.4	42.75	38.96
3	Max. rate of pressure rise, bar/ºCA	4.79	4.6	4.97	4.78	5.02	4.59	4.42	5.53	4.94	4.72
Performance parameters											
1	Brake thermal efficiency, %	27.66	26.74	28.78	27.58	27.32	28.49	28.73	27.07	28.18	28.73
2	BSFC, kg/kW hr	0.3	0.31	0.3	0.32	0.31	0.3	0.3	0.31	0.3	0.3
3	EGT , ºC	320	308	309	305	306	311	309	316	312	309
Emissions parameters											
1	CO emissions, %	0.046	0.025	0.026	0.027	0.032	0.026	0.042	0.024	0.032	0.034
2	HC emissions, ppm	87	54	58	62	47	67	85	43	58	68
3	NO emissions, ppm	619	660	692	589	739	756	674	693	725	591
4	Smoke emissions, %	93	93	86.4	89.6	78.1	80.4	82.3	56.2	73	79.4

Table 5.5.2 Results of engine parameters obtained for diesel and blends of various mixtures for rated load at CR17

Sl.No.		**B00**	**B20M4**	**B40M4**	**B60M4**	**B20M5**	**B40M5**	**B60M5**	**B20M6**	**B40M6**	**B60M6**
Combustion Parameters											
1	Maximum pressure, bar	63.58	63.2	64.85	64.34	65.86	65.17	62.58	66.37	62.1	63.7
2	Max. heat release, J/ºCA	50.28	42.31	43.56	42.89	46.42	44.34	41.47	46.19	41.79	44.18
3	Max. rate of pressure rise, bar/ºCA	5.09	4.31	4.61	4.47	4.35	4.46	4.29	5.25	4.71	4.72
Performance parameters											
1	Brake thermal efficiency, %	26.54	27.11	27.13	27.23	27.01	27.15	27.21	26.78	27.02	27.3
2	BSFC, kg/kW hr	0.31	0.31	0.31	0.32	0.31	0.31	0.32	0.31	0.32	0.32
3	EGT, ºC	336	311	331	332	325	328	332	331	334	335
Emissions parameters											
1	CO emissions, %	0.053	0.025	0.029	0.031	0.03	0.028	0.028	0.027	0.028	0.029
2	HC emissions, ppm	99	75	66	62	43	51	52	63	52	67
3	NO emissions, ppm	491	478	508	440	598	569	454	600	518	478
4	Smoke emissions, %	94	94	94.3	97	92	92.6	94.3	88.9	90.9	92.6

Table 5.5.3 Results of engine parameters obtained for diesel and blends of various mixtures for rated load at CR16

Sl.No.		B00	B20M4	B40M4	B60M4	B20M5	B40M5	B60M5	B20M6	B40M6	B60M6
Combustion Parameters											
1	Maximum pressure, bar	62.4	62.2	62.13	63.64	62.17	63.19	64.11	61.54	60	60.44
2	Max. heat release, J/°CA	46.16	49.09	45.54	45.16	45.04	46.75	44.44	44.33	44.76	44.8
3	Max. rate of pressure rise, bar/°CA	4.92	4.61	4.32	4.48	4.24	4.43	4.21	5.11	4.47	4.67
Performance parameters											
1	Brake thermal efficiency, %	26.55	25.57	26.03	26.03	26.02	25.82	26.38	26.55	25.66	26.47
2	BSFC, kg/kW hr	0.31	0.33	0.33	0.34	0.31	0.31	0.33	0.32	0.33	0.32
3	EGT, °C	346	337	337	335	333	333	332	339	340	341
Emissions parameters											
1	CO emissions, %	0.057	0.028	0.032	0.037	0.029	0.042	0.043	0.027	0.029	0.031
2	HC emissions, ppm	99	75	66	62	43	51	52	63	52	67
3	NO emissions, ppm	591	378	300	421	359	376	332	535	489	468
4	Smoke emissions, %	95.7	95.5	98	95.4	94.1	94.9	95	90.4	93.5	94.9

5.6 Effect of compression ratio, and blend ratio on combustion, performance and emission characteristics of engine using mixture of J-S (Jatropha + Simarouba) in blend with diesel

The Jatropha and Simaruoba and are mixed in different volume ratio and blended with diesel. The two biodiesel are mixed in the ratio of 75% Jatropha+25% Simarouba, 50% Jatropha+50% Simaruoba and 25% Jatropha+75% Simarouba. These mixtures are designated as M7 for (75% Jatropha +25% Simarouba), M8 for (50% Jatropha + 50% Simarouba) and M9 for (25% of Jatropha +75% of Simarouba). The blends are prepared using the mixture of M7, M8 and M9 in blend with diesel fuel. The blend B20M7 indicates 20% of M7 + 80% diesel; the other blends are prepared using the same procedure and are B40M7 and B60M7. Similarly the other two mixtures i.e. M8 and M9 are used in preparing the blends such as B20M8, B40M8, B60M8 and B20M9, B40M9, B60M9. These blends are used to investigate the combustion, thermal performance and emission characteristics of engine at CR of 16, 17 and 18 varying the load from zero to rated load of the engine with an increment of 20% each time.

5.6.1 Combustion analysis

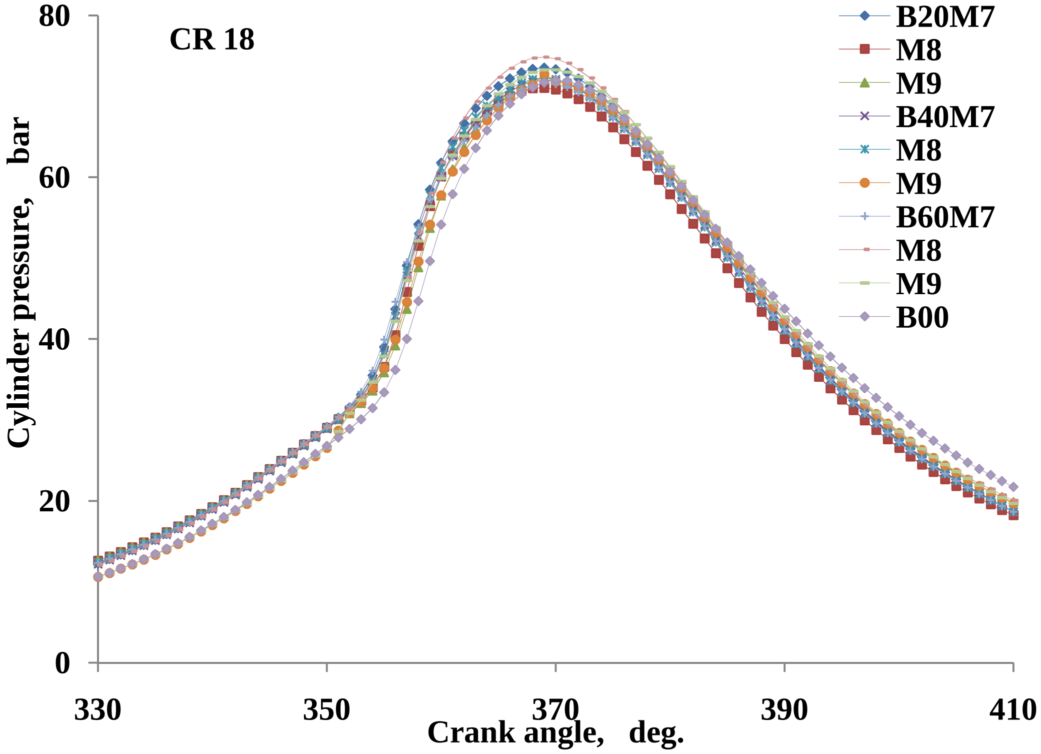
The different combustion characteristics are investigated using DI VCR diesel engine for diesel fuel as well as for the various blends and loads at CR of 16, 17 and 18. The different combustion characteristics investigated are cylinder pressure, net heat release, maximum cylinder pressure, maximum heat release and rate of pressure rise at CR of 16, 17 and 18 for the rated load at constant speed of 1500 rpm.

5.6.1.1 Cylinder pressure with CA

The cylinder pressure variations for diesel fuel as well as for the various blends for different loads for the compression ratio of 16, 17 and 18 are illustrated in the Fig.5.7.1.1. The cylinder pressure increases for increased load on engine for the fuels and the CR used. The maximum cylinder pressure is mainly depends on the amount of fuel burnt during the premixed combustion stage. The higher cylinder pressures at CR 18 which may perhaps be accredited to increased combustion temperature, higher temperature and density of the air. The increased temperatures and density of the air improve the mixing of fuel-air and contributes for complete combustion. The improved combustion at CR18 results into the higher cylinder pressure. The higher cylinder pressure for diesel fuel is

71.94 bars at the rated load. The higher cylinder pressures for diesel fuel which might perhaps be accredited to higher heat value. The higher cylinder pressure for the blend B60M8 is 74.84 bars at the rated load. The higher cylinder pressure for the blend B60M8 may perhaps be attributed to oxygen content and higher CN of biodiesel in the blends. The inherent oxygen and higher CN of biodiesel in the blends may progress the mixing of fuel-air and accelerate the combustion. The blends have the higher cylinder pressure compared for diesel fuel for CR18 for the rated load. The lower maximum cylinder gas pressure for the blend B20M8 is 71.04 bars. The lower cylinder pressure for the blends may be because of lower heat value of biodiesel in the blend. It is seen from the figure that the initiation of combustion of all the blends is earlier in comparison with diesel fuel, which may be accredited to higher CN of biodiesel in the blends. The higher CN may perhaps enhance the chemical reaction and start the ignition earlier for the blends.

The cylinder pressures at CR17 are lower compared to CR18 at the rated load for the diesel fuel and for the various blends. The decrease in combustion temperature, lower temperature and pressure of the air may affect the mixture formation consequently the combustion at CR17 results into lower cylinder pressure. The cylinder pressure at CR17 for diesel is 62.97 bars for the rated load. The higher cylinder pressure for the blend B40M9 is 66.66 bars at the rated load. The higher cylinder pressure for the blend may perhaps be accredited to inherent oxygen and higher cetane number of biodiesel in blends.



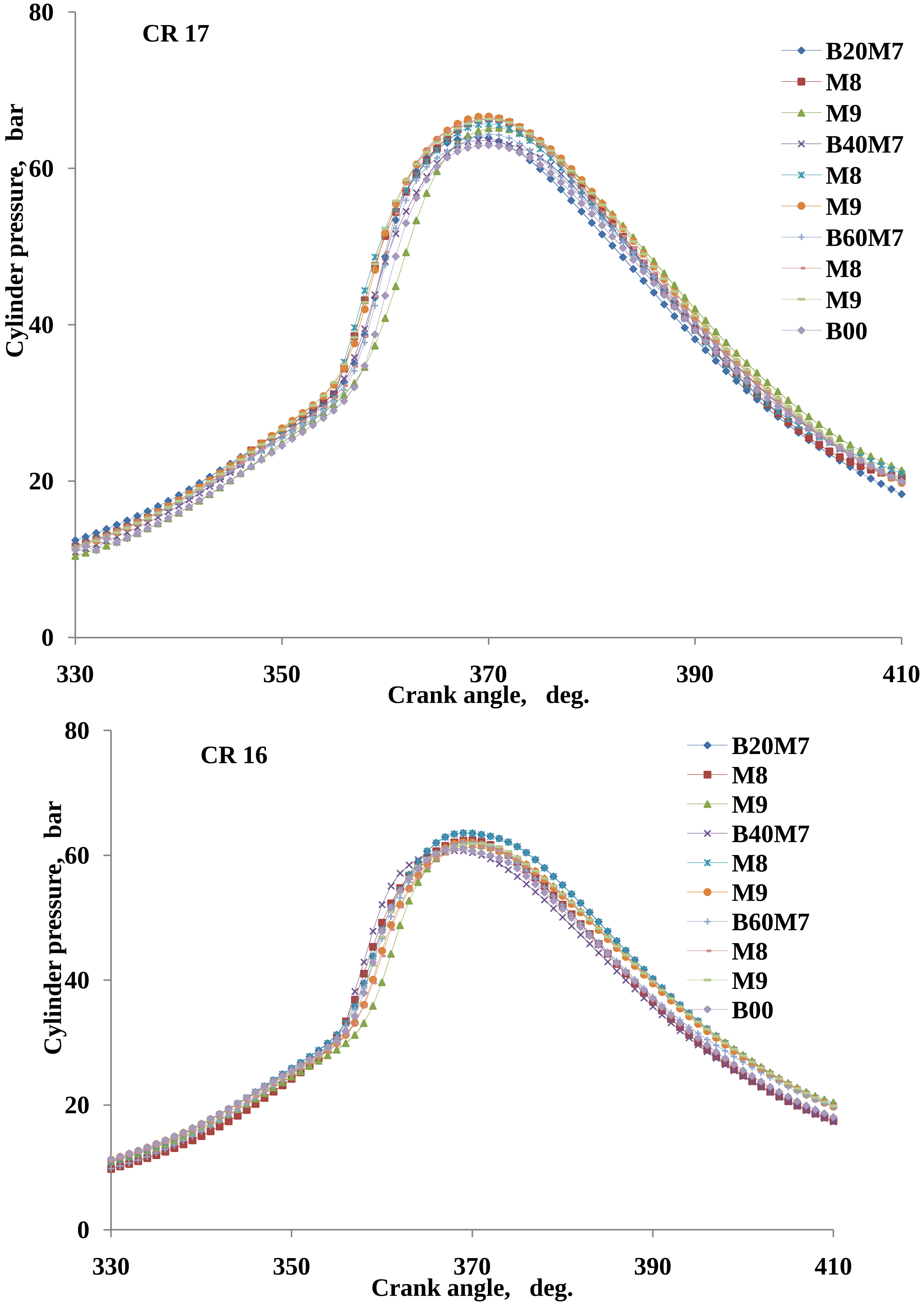


Fig. 5.6.1.1 Variation of cylinder gas pressure with crank angle

The natural oxygen content and higher CN of the blends which may perhaps improve the mixing of fuel-air and contributes for complete combustion. The ignition for the blends are advanced compared to diesel fuel which may be because of higher CN of biodiesel in the blends. The cylinder pressure for the blend B40M9 are higher by about 5.9% compared to diesel fuel.

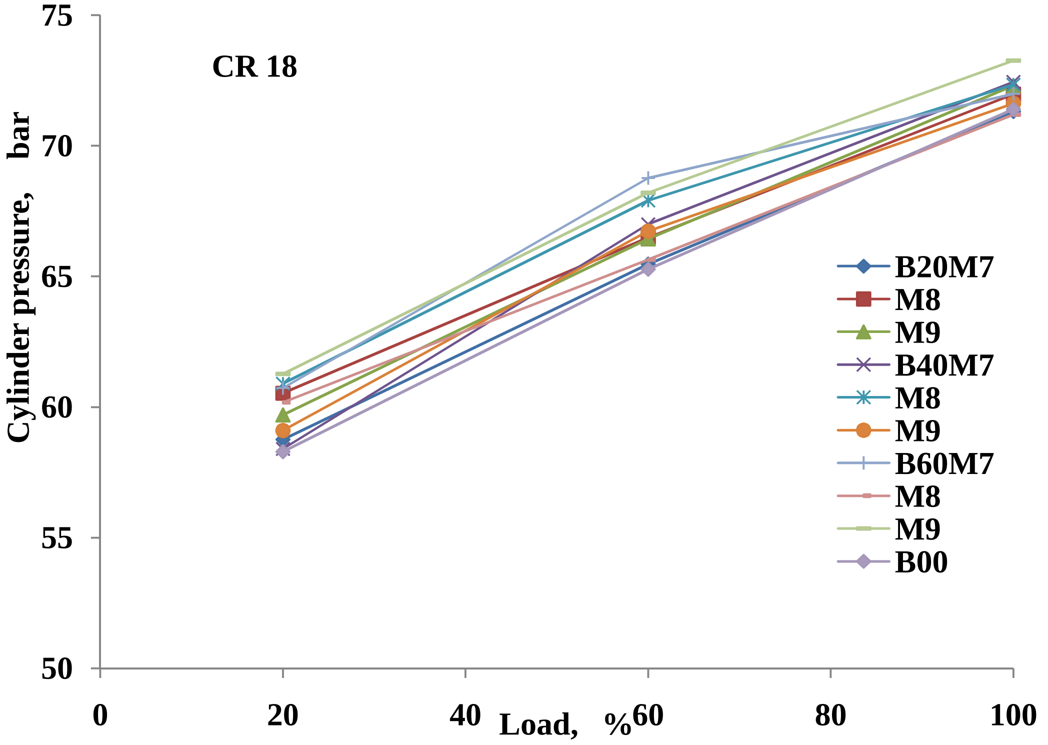
The cylinder gas pressures at CR16 are lesser compared to CR17 and CR18 for diesel fuel as well as for the various blends at the rated load. The lower cylinder gas pressure may perhaps be accredited to decrease in combustion temperature, lesser density and temperature of the air. The lower combustion temperature, lower density and temperature of the air have an effect on the mixture formation of fuel-air subsequently the combustion which results into lower cylinder pressure. The lower cylinder pressure may perhaps be accredited to incomplete combustion at CR16 for the fuels used in the investigation. The cylinder gas pressure at CR16 for diesel fuel is 61.09 bars at the rated load. The cylinder pressure the blend B40M8 is 63.58 bars at the rated load. The higher cylinder pressure for the blends might be accredited to inherent oxygen and higher CN of biodiesel in the blend which may improve the mixture formation of fuel-air which may contribute in the complete combustion of blends. The cylinder pressure for the blend is higher by about 4.1% in comparison with diesel fuel for the rated load.

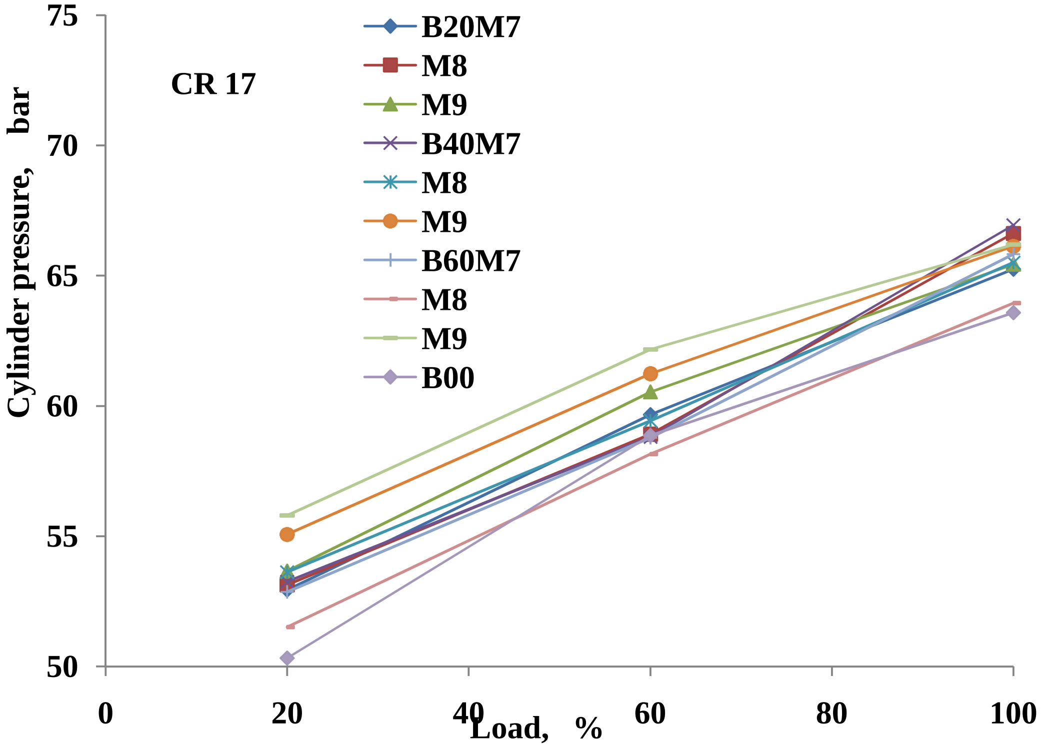
5.6.1.2 Maximum cylinder pressure with load

The maximum cylinder pressures for diesel fuel and for the various blends for different loads at CR 16, 17 and 18 are illustrated in the Fig. 5.6.1.2. The maximum cylinder pressure increases with increase in load for the diesel fuel and for the various blends for the CR used. The maximum cylinder pressure data are extracted from the for P-V plot which are collected from the data acquisition system. The increase in maximum cylinder pressure for the increased load may perhaps be accredited to increased quantity of fuel supply and burnt to generate extra power to sustain the increased load on the engine. The maximum cylinder pressure which may perhaps be depends on the premixed combustion stage. The maximum cylinder pressures at lower loads are less which may perhaps be accredited to less quantity of fuel burnt for the lower load. The higher maximum cylinder pressure for diesel fuel is 71.4 bars for the rated load. The higher maximum cylinder pressures for almost all the blends are higher compared to diesel fuel for the full load. The higher maximum cylinder pressure for the blends may perhaps be accredited to inherent oxygen and higher CN of biodiesel in the blends which may enhance the mixing of fuel-air and increases the velocity of flame results into higher maximum cylinder pressure. The higher maximum cylinder pressure for the blends also may perhaps be attributed to increased combustion temperature, higher density and temperature of the air at CR18, which contributes in complete combustion of blends. The maximum cylinder pressure for the blend B60M6 is 73.26 bars for the rated load. The lowest maximum cylinder pressure for the blend B20M8 is 71.2 bars for the rated load. The increase in maximum cylinder pressure is by about 2.6% for the blend B20M6 and decrease in cylinder pressure for the blend B20M8 by about 0.28% compared to diesel fuel at the rated load. The decrease in cylinder pressure for the blend B20M8 is negligible because of the lesser volume fraction of biodiesel in the blends.

The maximum cylinder pressures at CR17 are less compared to CR18 for diesel fuel as well as for the various blends for the different loads. The lower maximum cylinder pressure at CR17 may possibly be because of lesser combustion temperature, lower temperature and density of the air in the cylinder. Though the premixed combustion increases at CR17, the maximum cylinder pressures are less which may perhaps be accredited to incomplete combustion. The lower combustion temperature, lesser temperature and density of the air at CR17 may affect the mixture formation of fuel-air and consequently the combustion which results into lesser maximum cylinder pressure. The maximum cylinder pressure for diesel fuel is 63.58 bars for the rated load. The maximum cylinder pressure for the blend B40M7 is 66.95 bars at the rated load. The higher maximum cylinder pressure may perhaps be accredited to improved combustion of blends. The minimum higher cylinder pressure for the blend B60M8 is 63.95 bars for the rated load. The increase in cylinder pressure for the blends B40M7 and B60M8 is by about 5.3% and 0.6% at rated load.

The maximum cylinder pressure at CR16 are lesser compared to CR17 and CR18 for diesel as well as for the various blends for all the loads. The diesel fuel has the higher maximum cylinder pressure compared to blends at all the loads which may perhaps be accredited to better burning properties of the diesel fuel. The lesser cylinder pressure at CR16 may possibly because of incomplete combustion of fuels. The incomplete combustion may perhaps be attributed to decreased combustion temperature, lesser temperature and density of the air at CR16. The reduced combustion temperature, lower temperature and density of the air at CR16 may influence the mixture formation subsequently the combustion which results into lower maximum cylinder gas pressure. The maximum cylinder gas pressure for diesel fuel is 62.4 bars for the rated load. The maximum cylinder gas pressure for the blend B60M9 is 62.2 bars for the rated load. The minimum cylinder gas pressure for the blend B20M7 is 59.96 bars at the rated load. The reduction in cylinder gas pressure is by about 0.32% and 3.9% for the blends B60M9 and B20M7 respectively at the rated load compared to diesel fuel.





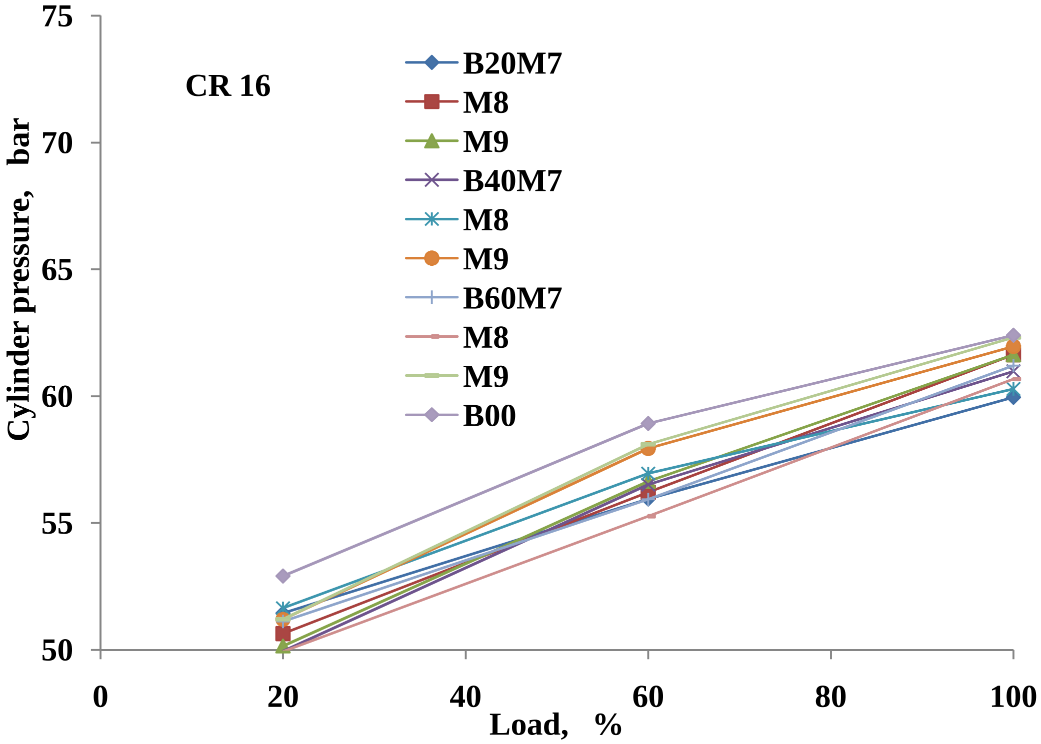


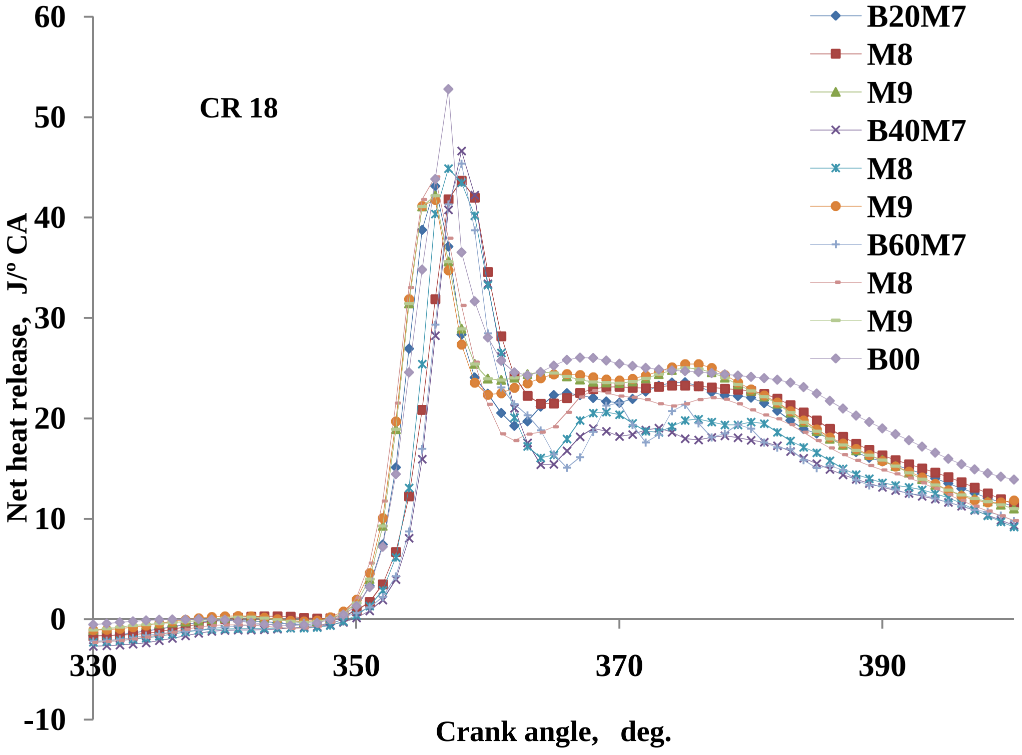
Fig. 5.6.1.2 Variation of cylinder pressure with load

5.6.1.3 Net heat release with crank angle

The net heat release for diesel fuel as well as for the various blends at compression ratio 16, 17 and 18 for rated load are illustrated in Fig.5.7.1.3. The net heat releases are the heat release throughout the uncontrolled combustion stage. The net heat release increases for increased load for the fuels used for different compression ratio. The higher net heat release for the diesel fuel at CR18 at the rated load which might be because of higher heating value and increased ignition delay for diesel fuel. The higher combustion temperature and increased temperature of the air at CR18 may contribute in better mixture formation hence complete combustion for the rated load. The net heat released is 52.79 J/º CA for diesel fuel at the rated load. The net heat release for the biodiesel blends is lesser compared to diesel fuel. The lower net heat release for the blends which may be accredited to lesser premixed combustion and lower heating value of different blends used. The higher maximum net heat release for the blend B40M7 is 46.65 J/ ºCA at the rated load. It may be seen from the figure that the start of combustion for the blends is earlier compared to diesel fuel which may well be accredited to higher CN of biodiesel in the blends. The higher CN may accelerate the chemical reaction of fuel-air and advance the start of ignition. The decrease in net heat release for the blend B40M7 is by about 11% at the rated load. The net heat releases for other blends used are lower compared to diesel fuel.

The net heat release for diesel fuel at CR17 is lesser compared to CR18 at the rated load. The decrease in combustion temperature, lesser temperature and density of the air at CR17 which may perhaps influence the mixture formation consequently the combustion process results into lower heat release. The net heat release for diesel fuel at CR17 is 50.28 J/º CA for the full load. The net heat release for the blend B40M9 is 46.92 J/º CA at the rated load. The lesser net heat release for the blends may perhaps be attributed to decreased premixed combustion and lower heating value. The decrease in net heat release for the blend B40M9 is by about 6.7% in comparison with diesel fuel for the rated load.

The net heat release at CR16 is lesser compared to CR17 and CR18 at the rated load. The lesser net heat release at CR16 may perhaps be attributed to lower combustion temperature, lesser temperature and density of the air. The decreased combustion temperature, lower temperature and density of the air which may affect the mixture formation of fuel-air subsequently the combustion. The net heat release for diesel fuel at CR16 is 46.16 J/ ºCA at the rated load. The lesser net heat release for diesel fuel might be attributed to incomplete combustion. The incomplete combustion may perhaps be because of above said reason which decreases the net heat release. The maximum net heat release for the blend is B20M9 is 50.12 J/º CA at rated load. The higher net heat release for the blends may perhaps be accredited to increased ignition delay for the blends which



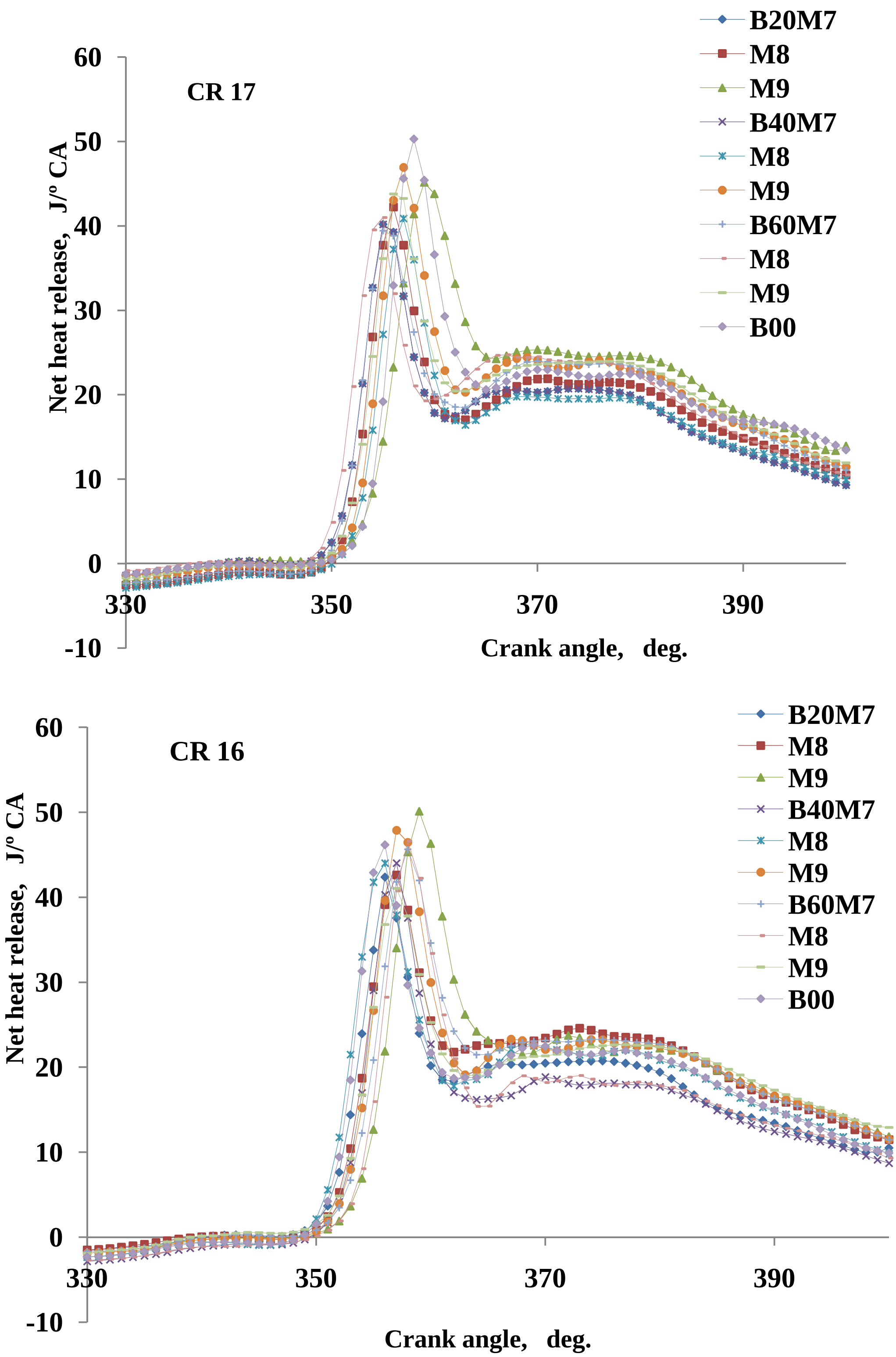


Fig. 5.6.1.3 Variation of net heat release with crank angle

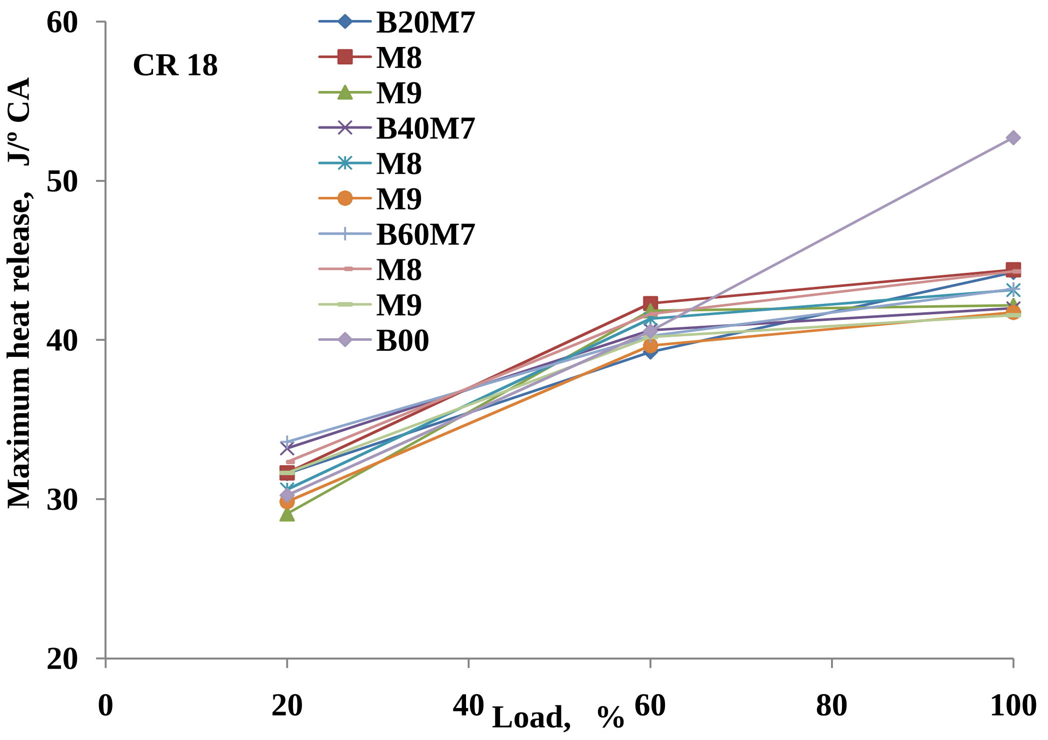
increases the premixed combustion results into increased heat release. The increase in heat release for the blend B20M9 is by about 8.6% compared to diesel fuel at the rated load.

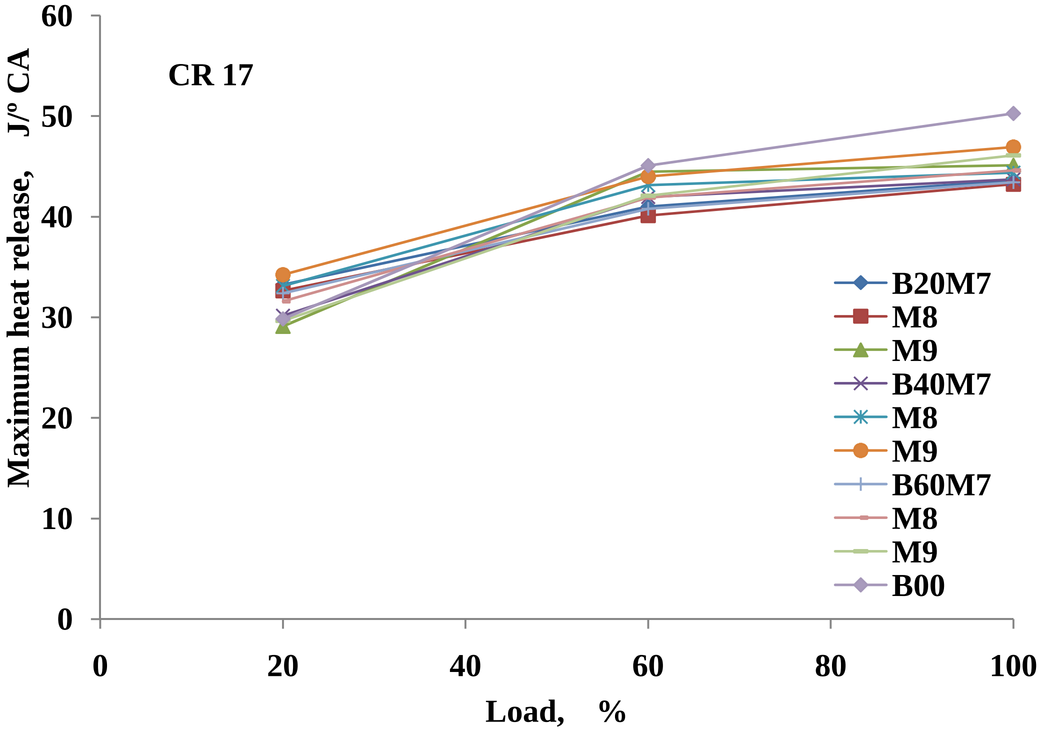
5.6.1.4 Maximum heat release with load

The maximum heat release for diesel fuel as well as for the various blends for different loads at compression ratio of 16, 17 and 18 are illustrated in the Fig.5.7.1.4. The maximum heat release are depends on the type of fuel used, compression ratio and load on the engine. The maximum heat release depends on the quantity of fuel burned all through the premixed combustion stage. The maximum heat release increases with increase in load for fuels and the CR used. The increase in heat release with increase in load may possibly be accredited to increased fuel supply. The maximum heat release at CR18 are lesser compared to CR16 and CR17 which may be accredited to increased combustion temperature, higher temperature and density of the air. The higher combustion temperature, temperature and density of the air which may perhaps decreases the ignition delay consequently premixed combustion which results in reduced net heat release at CR18. The heat release for diesel fuel at CR18 is 52.72 J/º CA at the rated load. The maximum heat release for the blends is lesser compared to diesel fuel at CR18 which may be accredited to lower heating value and higher viscosity of biodiesel in the blends. The higher viscosity of the blends may affect the atomization and mixture formation of fuel-air consequently the incomplete combustion results in to reduced heat release. The higher maximum heat release for the blend B20M8 44.41 J/º CA for the full load. The minimum heat release for the blend B60M9 is 41.57 J/ºCA at the rated load. The decrease in the maximum heat release for the blends are by about 15.8% and 21.2% for the blend B20M8 and B60M9 respectively at the rated load. The higher reduction in maximum heat release for B60M9 may perhaps be accredited to lower heating value and higher viscosity of biodiesel in the blends.

The maximum heat released for diesel fuel and for the various blends at CR17 for different loads increases with the increase in load. The maximum heat release for diesel fuel is higher at the rated load which may perhaps be accredited higher heating value and better combustible properties. The maximum heat release for the blends is lesser compared to diesel fuel at the rated load which may possibly accredited to lower heating value and higher viscosity, lower volatility of biodiesel in the blends which may affects the mixture formation of fuel-air which contribute in the incomplete combustion. The incomplete combustion of blends reduces the maximum heat release for the blends. The maximum heat release for diesel fuel at CR17 is 50.28 J/º CA at the rated load. The maximum net heat release for the blends B40M9 is 46.92 J/º CA for the rated load. The minimum heat release for the blend B60M7 is 43.45 J/º CA at the rated load. The decreases in heat release for the blends are by about 6.7% and 13.6% respectively for B40M9 and B60M7 at the rated load.

The maximum heat release at CR16 for diesel fuel as well as various blends are lesser compared to CR17 and CR18 for all the loads. The lesser heat release at CR16 may





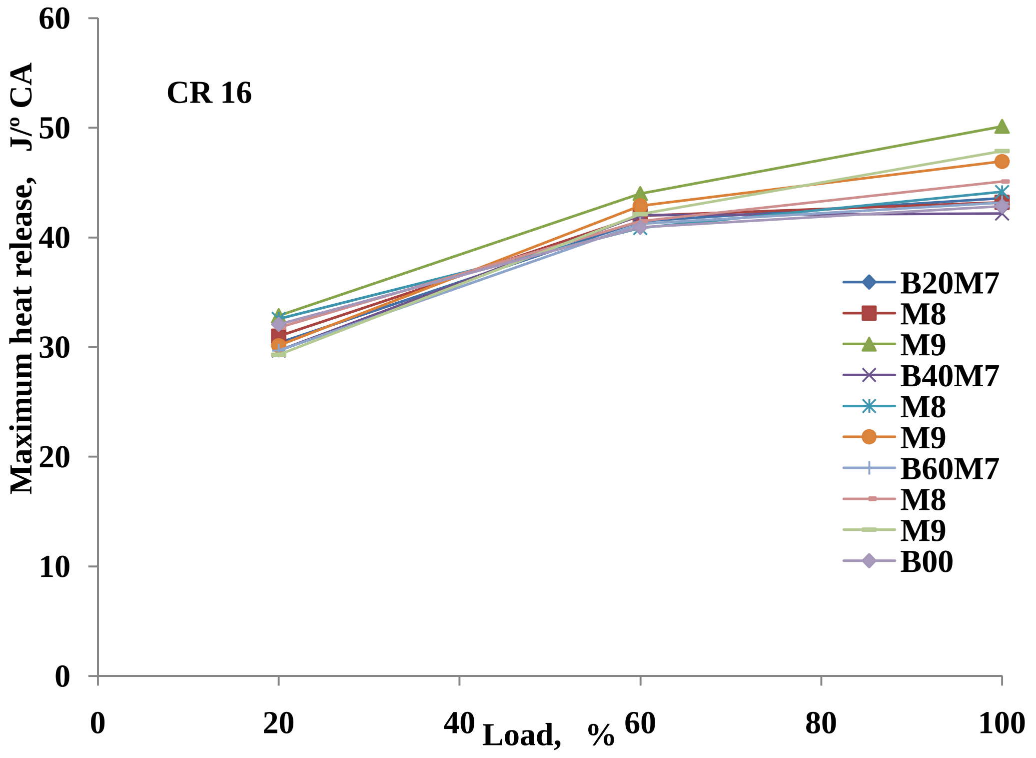


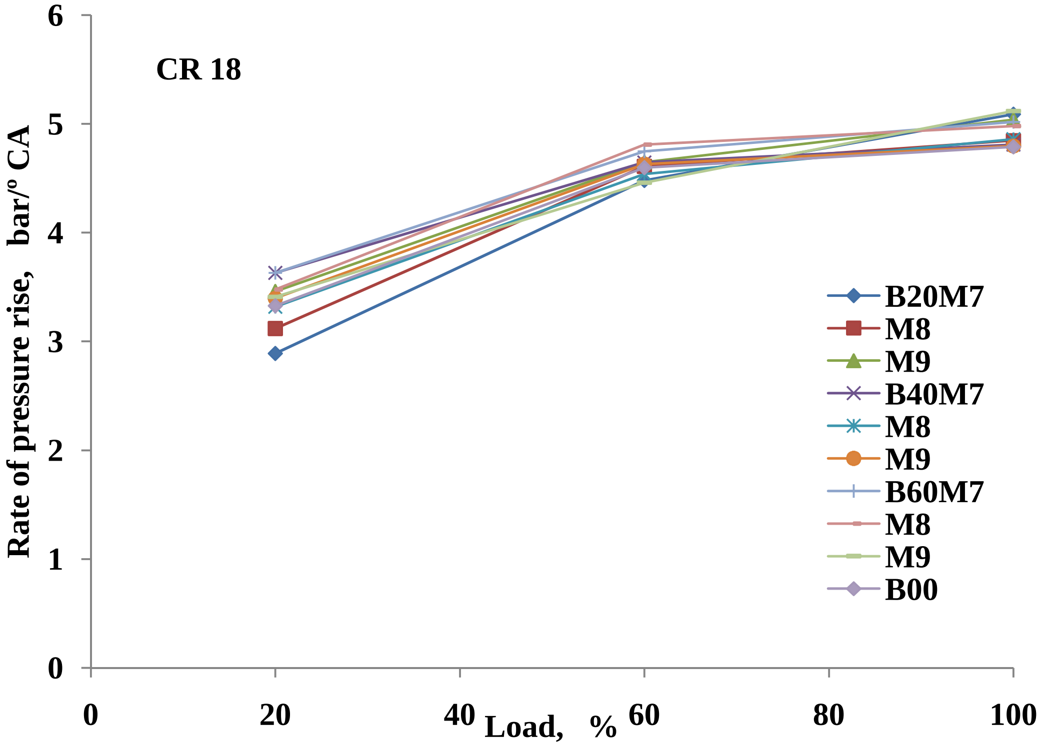
Fig. 5.6.1.4 variation of maximum heat release with load

perhaps be accredited to decreased combustion temperature, lower temperature and density of the air. The decreased combustion temperature and lower air temperature may have an effect on the mixing of fuel-air all through the premixed combustion as well as diffusion combustion which results into lower maximum heat release. The maximum heat release for diesel fuel at CR16 is 42.84 J/º CA at the rated load. The maximum heat release for the blend B20M9 is 50.12 J/ºCA at the rated load. The higher maximum heat release for the blends may perhaps be accredited to inherent oxygen and higher cetane number of biodiesel in blends completes the combustion and contribute in higher heat release.

5.6.1.5 Rate of pressure rise (RPR) with load

The change in RPR for diesel fuel and for the various blends for different loads at CR 16, 17 and 18 are illustrated in the Fig.5.7.1.5. The RPR is mainly depends on the amount of fuel burnt throughout the premixed combustion stage. The RPR increases for the increase in load for different compression ratio. The RPR is lesser at lower load which may perhaps be accredited to lesser amount of fuel burnt. When the load increases the quantity of fuel burnt increases which results in higher RPR. For the rated load the RPR increases but not to the expected level which may perhaps be accredited to incomplete combustion of fuels at the rated load. The incomplete combustion of fuel at the rated load may perhaps be attributed to increased turbulence and speed of combustion. The amount of fuel supplied at the rated load increases though quantity of air remains the same for each load hence the mixture becomes rich hence the lower rate of pressure rise. The RPR for diesel fuel at CR18 is 4.79 bar/ ºCA at the rated load. The maximum RPR for the blend B60M9 is 5.12 bar/ ºCA at the rated load. The higher RPR for the blend B60M9 at the rated load may perhaps be accredited to complete combustion of blends. The complete combustion of blends may perhaps be accredited to increase in combustion temperature, higher temperature and density of the air at CR18. The higher temperatures and density of the air improve the mixture formation and higher combustion temperatures contribute in the complete combustion of blends. The maximum increase in RPR for blends is by about 6.9% compared to diesel fuel at the rated load. The lesser RPR for diesel fuel at the rated load might be accredited to incomplete combustion. The incomplete combustion of diesel fuel at the rated load may be due to lack of oxygen.

The RPR at CR17 is lesser compared to CR18 for the fuels used. Although the premixed combustion increases for CR17, the rate of pressure rise decreases because of incomplete combustion of fuels. The lower RPR at CR17 may possibly be because of lower temperature and density of the air, decreased combustion temperature. The lower air temperature and combustion temperature may affect the mixture formation of fuel-air and contributes towards incomplete combustion results into lower RPR.



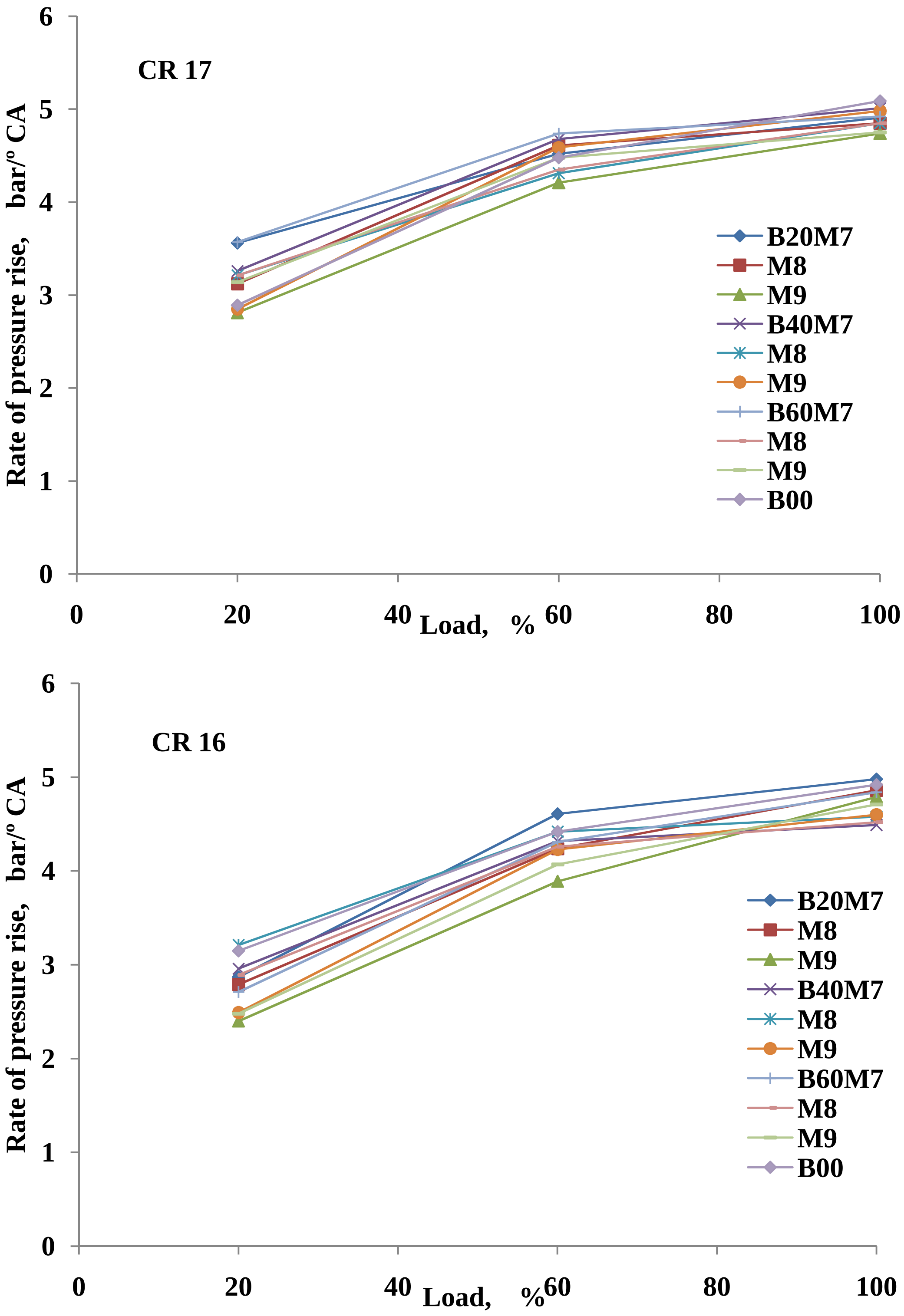


Fig. 5.6.1.4 Variation of maximum net heat release with load

The RPR at CR17 for diesel fuel is 5.09 bars/ ºCA at the rated load which is higher compared to the blends used. The higher RPR for the blend B20M9 is 4.98 bar/ ºCA at the rated load. The lower RPR for the blend B20M9 is 4.74 bar/ ºCA at the rated load. The lower RPR for the blends may well be accredited to lower heating value and higher viscosity of the blends. The inferior properties of the biodiesel in the blends influence the mixture formation of fuel-air hence the incomplete combustion hence lower RPR.

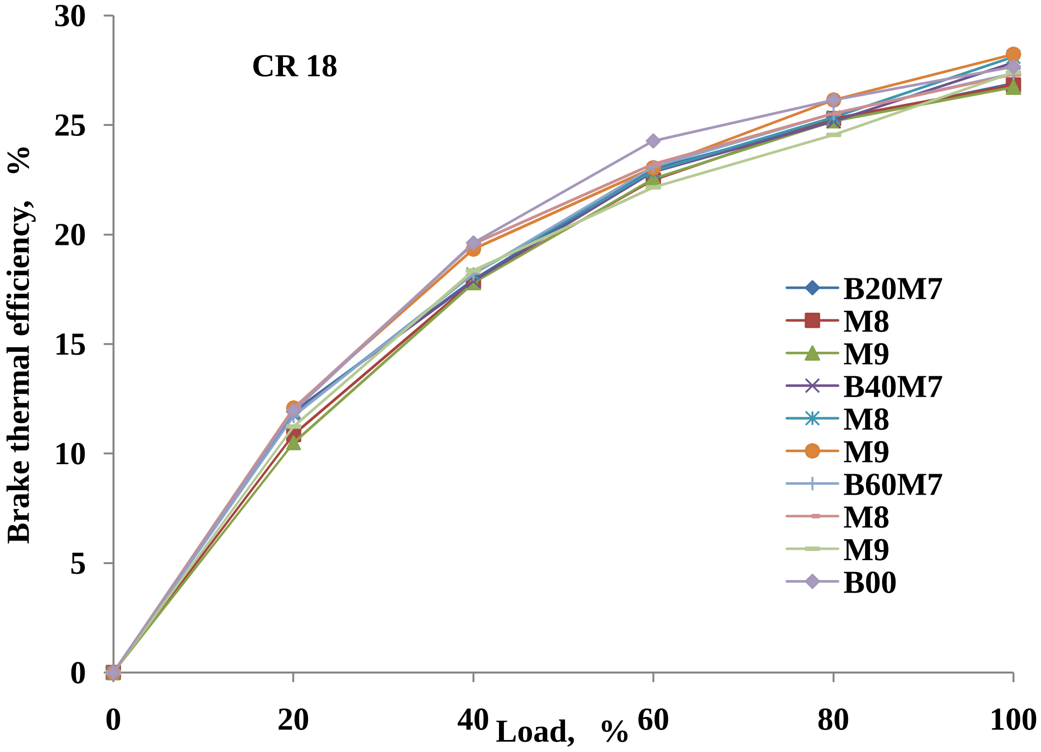
The RPR at CR16 are lesser compared to CR17 and CR18 for the fuels used. The lower RPR at CR16 may perhaps be accredited to the incomplete combustion. The incomplete combustion of fuels used may perhaps be because of lower density and temperature of the air and decrease in combustion temperature at CR16. The lower temperature of the air increases the premixed combustion which may perhaps increases the ignition delay for the fuels used. The increased ignition delay may affect mixture formation at CR16 which results into incomplete combustion hence lesser RPR.

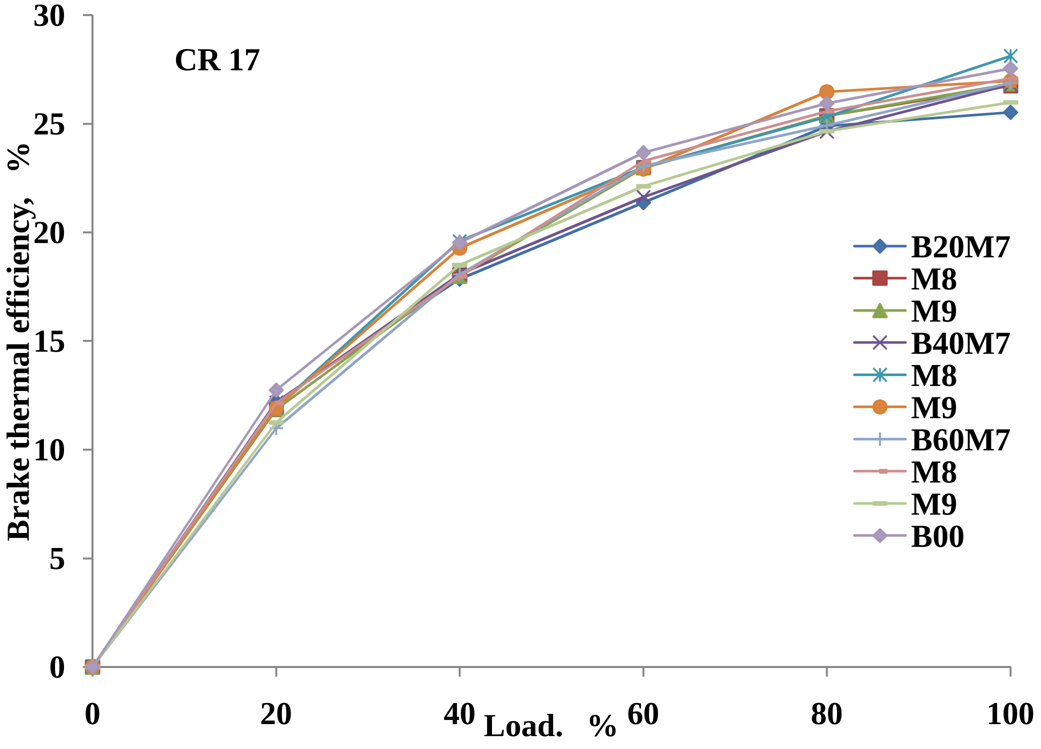
5.6.2 Performance analysis

5.6.2.1. Brake thermal efficiency (BTE) with load

The change in BTE for diesel as well as for the various blends for different load at compression ratio 16, 17 and 18 are illustrated in the Fig.5.6.2.1. The BTE increases for the increase in load for diesel fuel as well as for the various blends used in the investigation. The BTE of diesel fuel is higher at CR18 for the full load. The higher BTE of diesel fuel may perhaps be accredited to higher heating value and better combustible properties. The BTE of diesel fuel is 27.66% for the rated load. The BTE for blends is lesser compared to diesel fuel for almost up to 80% load, which may perhaps be accredited to lesser heating value and higher viscosity, inferior volatility of biodiesel in the blends. The higher viscosity and inferior volatility may influence the mixing of fuel-air consequently the combustion process. The BTE are higher for the blends B20M7 it is 28.35%, B40M9 it is 28.31%, B40M9 28.22%, and B40M8 it is 28.11% at the rated load. The higher BTE for the above mentioned blends at the rated load may perhaps be attributed to higher combustion temperature, higher temperature and density of the air. The higher combustion temperature and temperature of the air may perhaps improve the thermal efficiency of fuel used. For the rated load the combustion temperature are higher which enhance the atomization of blends and improve the mixing of fuel-air subsequently the combustion which increases the brake thermal efficiency of the blends. The BTE is least for the blend B20M7 its value is 26.72%.

The BTE at CR17 are lesser compared to CR18 for the diesel fuel as well as for the various blends used. The lesser brake thermal efficiency at CR17 may possibly attributed to lower density, temperature of the air and the decreased combustion temperature. The lower combustion temperature and lesser temperature, density of the air may perhaps influence the mixture formation of fuel-air consequently the combustion. The BTE of diesel fuel is 27.54% at the rated load. The brake thermal efficiency of B40M8 blend is 28.12% at the rated load. The higher BTE of blend may well be accredited to inherent





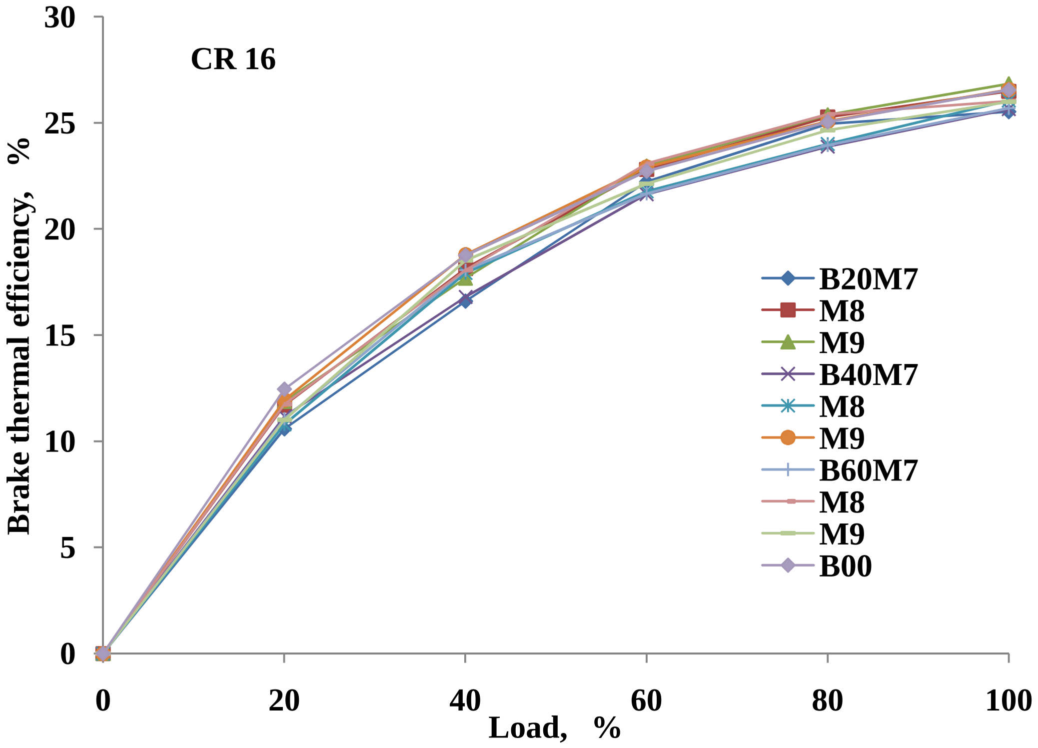


Fig. 5.6.2.1 Variation of BTE with load

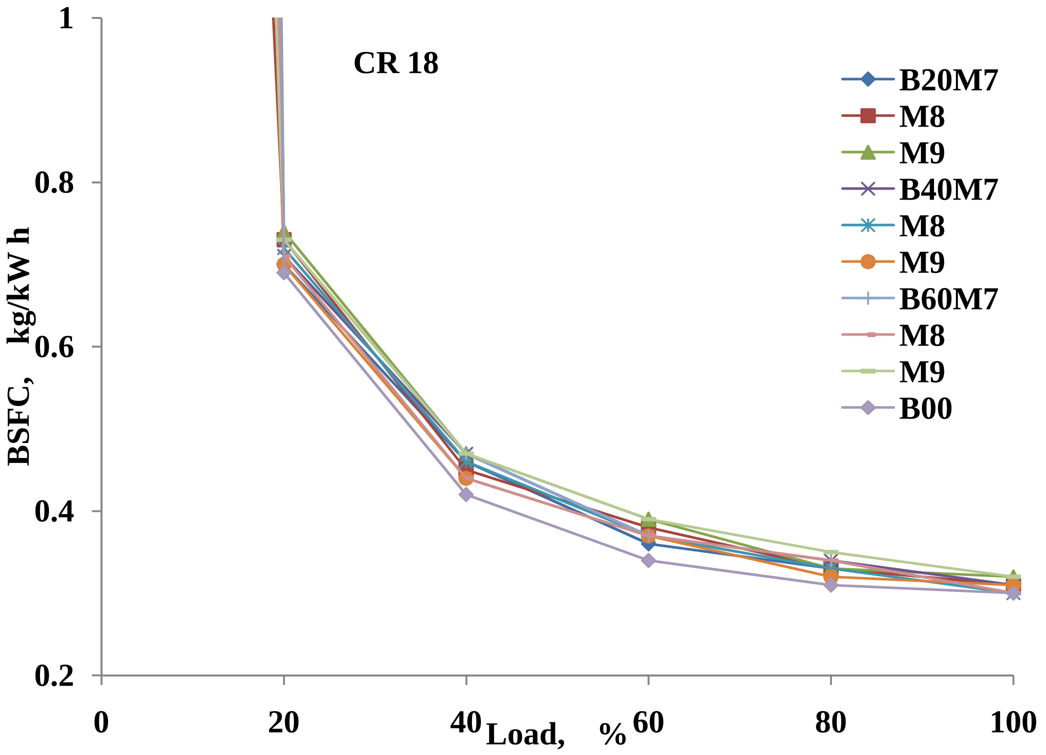
oxygen and higher CN of biodiesel in the blends contributes in better combustion hence higher BTE at the rated load.

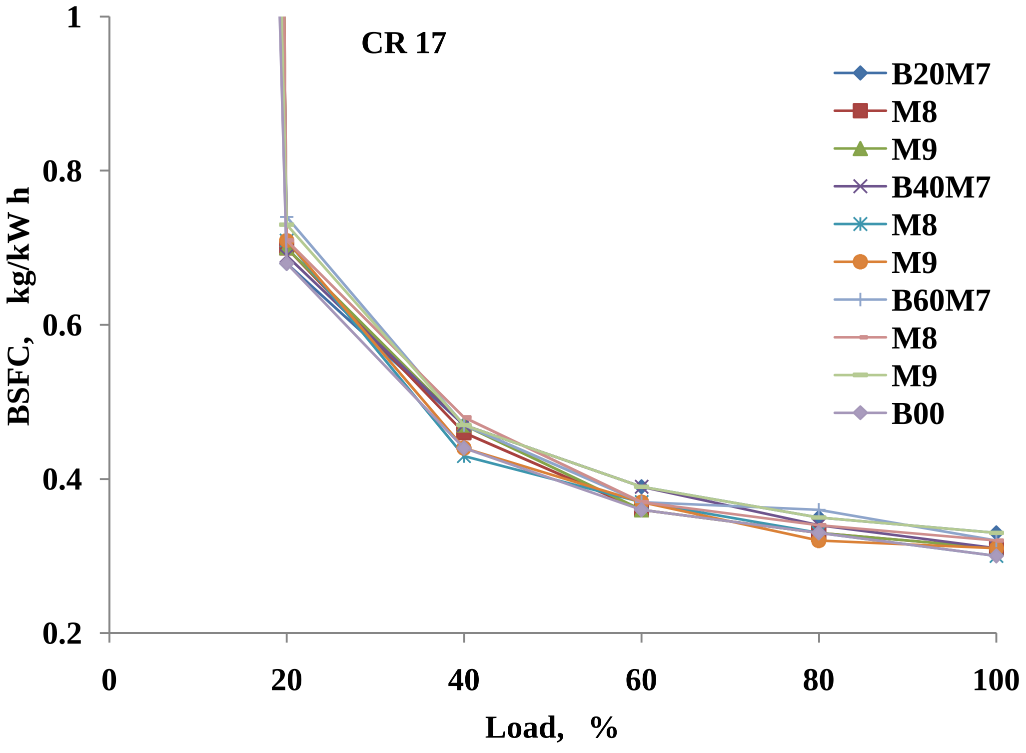
The BTE at CR16 are lesser compared to the CR17 and CR18 for the fuels used. The decreased combustion temperature, lower temperature and density of the air at CR16 may affect the mixture formation and the incomplete combustion hence lesser BTE. The BTE for the diesel fuel at CR16 is 26.55% at the rated load. The brake thermal efficiency for the blends B60M9 is 25.66% which is lowest among all the blends. The higher brake thermal efficiency for the blend B60M9 is 26.84% which is marginally higher compared to diesel. The higher brake thermal efficiency for the blends may be attributed to better and complete combustion of blends.

5.6.2.2 Brake specific fuel consumption (BSFC) with load

The BSFC of diesel fuel and the various blends for different load at compression ratio 16, 17 and 18 are illustrated in the Fig. 5.6.2.2. The BSFC decreases with increase in load for the fuels used. The decrease in BSFC for the diesel fuel as well as for the various blends used may perhaps be accredited to increased combustion temperature improves the fuel efficiency. The BSFC of diesel fuel is lesser compared to the blends which may possibly be accredited to higher heating value and better combustible properties. The BSFC of diesel fuel at CR18 is 0.3 kg/kW hr at the rated load. The BSFC of some of the blends are similar as that of diesel fuel at the rated load which may perhaps be accredited to enhanced combustion. The better combustion of the blends may be attributed to inherent oxygen and higher CN of the biodiesel in the blends which may improve the mixture formations and accelerate the combustion. The BSFC of blend B60M9 is higher and it is 0.32 kg/kW hr. The increases in BSFC for the blends may possibly be accredited to lower heating value and higher viscosity, inferior volatility of biodiesel in the blends. The fuel consumption for the blend B60M9 is increased by about 6.25% compared to diesel fuel at the rated load.

The brake BSFC is higher at CR17 compared to CR18 for diesel fuel and various blends used for the various loads. The higher BSFC at CR17 may possibly be accredited to decreased combustion temperature, lower temperature and density of the air in the cylinder which may have an effect on the mixture formation of fuel-air subsequently the combustion process. The BSFC for diesel at CR17 is 0.3 kg/kW hr whereas for the blend B20M7 is 0.33 kg/kW hr at the rated load. The higher BSFC for the blend B20M7 may well be accredited to lower heating value and higher viscosity of the blend. The BSFC of the blend B20M9 is increased by about 10% compared to diesel fuel at the rated load.





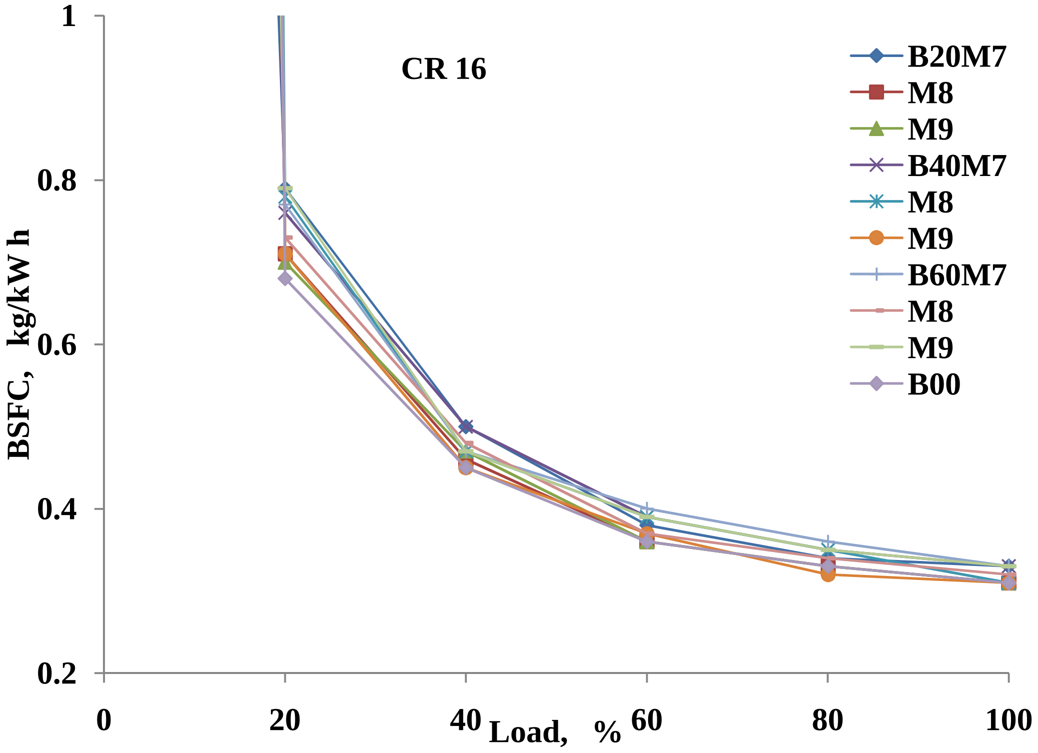


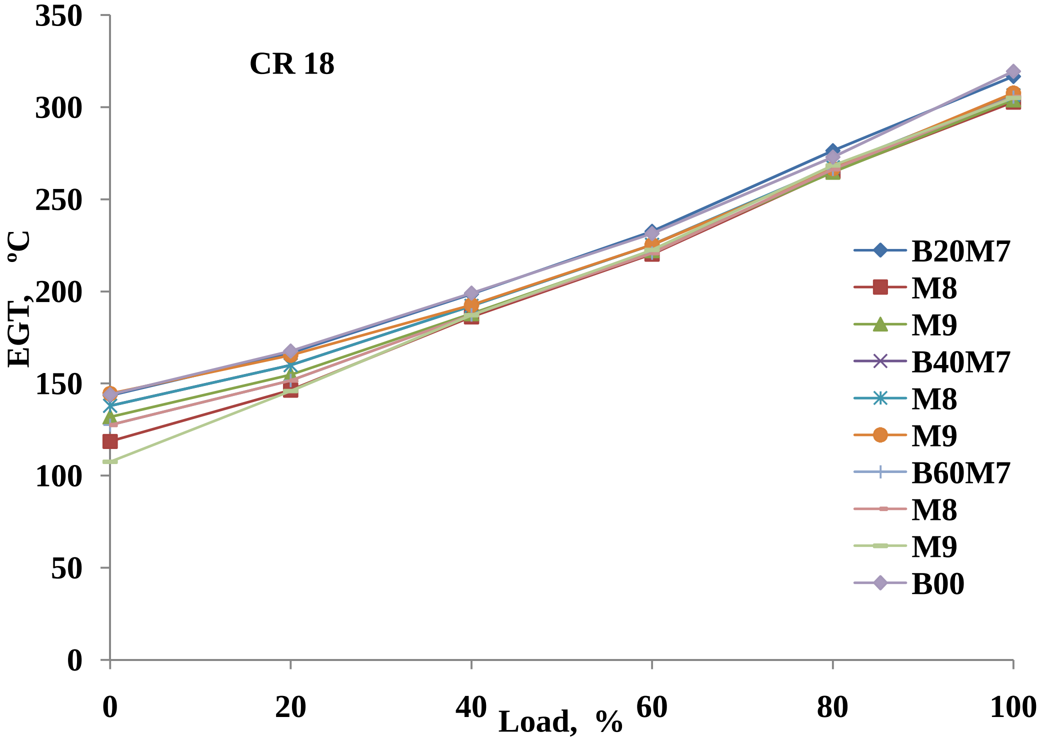
Fig. 5.6.2.2 Variation of BSFC with load

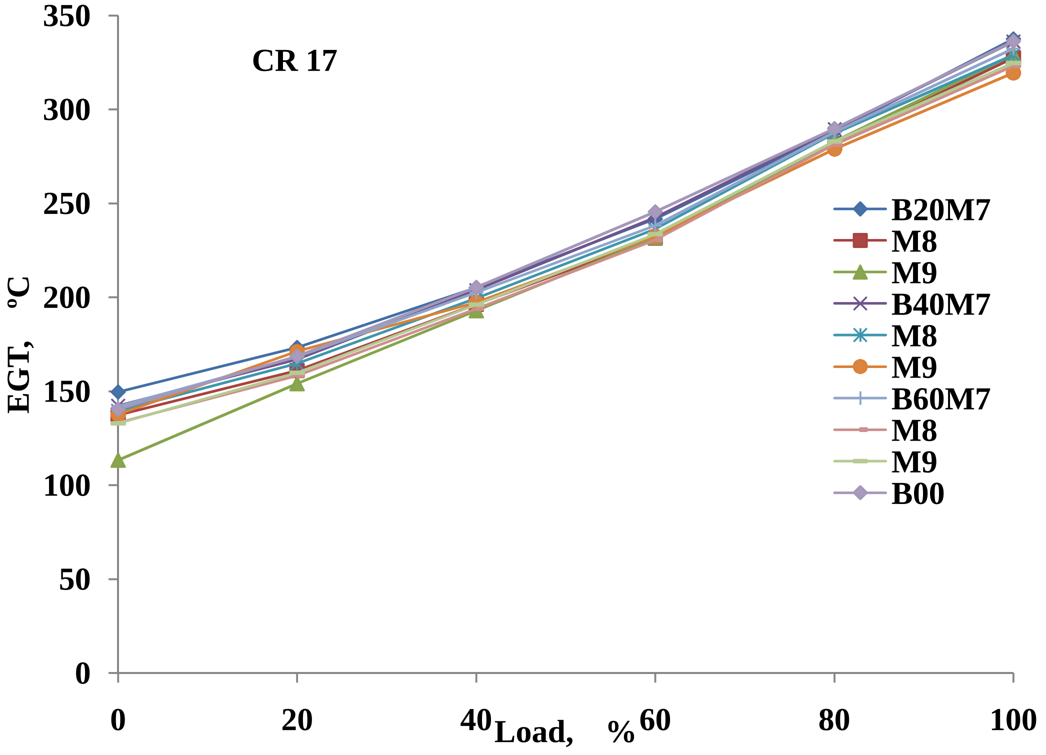
The BSFC are higher at CR16 for the diesel fuel as well as for various blends compared to CR17 and CR18. The BSFC increased at CR16 which may be attributed to decreased combustion temperature, lower temperature and density of the air inside the cylinder. The lower density and temperature of the air may affect the mixture formation of fuel-air subsequently the combustion process which increases BSFC for the fuels used at CR16. The BSFC for diesel fuel at CR16 is 0.31 kg/kW hr whereas for the blend B60M9 is 0.33 kg/kW hr at the rated load. The higher BSFC for the blends may perhaps be accredited to lower heating value and higher viscosity of the blend B60M9. The fuel consumption for the blend B60M9 is increased by about 9.7% compared to diesel fuel.

5.6.2.3 Exhaust gas temperature (EGT) with load

The EGT for diesel fuel as well as for the various blends for different load at compression ratio 16, 17 and 18 are illustrated in the Fig.5.2.2.3. The lower exhaust gas temperature indicates more of the energy of the fuel is converted to heat energy results into power output. The EGT increases with increase in load for diesel fuel as well as for the various blends. The exhaust gas temperature increases for the increased load which may perhaps be accredited to more quantity of fuel is burnt to meet the requirement of additional load on the engine. The EGT decreases with increase in CR which may perhaps be accredited to increased burning velocity and lesser time required for complete combustion. It is seen from the figures that EGT for all the biodiesel blends are lesser compared to diesel fuel. The EGT for the blends is lower for entire range of loads in comparison with diesel fuel. The EGT of diesel fuel at CR18 is 320º C for the rated load. The lower EGT for the blend B20M8 is found to be 303º C and higher EGT for the blend B20M7 is 316º C. The reduced EGT for the blend B20M8 is found to be lower by about 5.3% and for the blend B20M7 is by about 1.3% in comparison with diesel fuel at the rated load. The lower EGT for the blends may perhaps be accredited to the fact that air intake at higher compression ratio is compressed to the higher compression ratio which in turn increases the temperature and density of the air at CR18. The increased temperature and density of the air at CR18 may help in better atomization and improved combustion of fuel which results into decrease in EGT.

The exhaust gas temperatures at CR17 are higher compared to CR18 for diesel fuel as well as for the various blends. The higher EGT at CR17 may perhaps be accredited to decreased combustion temperature; lesser temperature and density of the air affect the mixing of fuel-air subsequently the combustion. The EGT of diesel fuel at CR17 is 336º C at the rated load whereas the EGT for the blend B40M9 is 319º C, which is less compared to diesel fuel which may perhaps be accredited to improved combustion of blends. The maximum reduction of EGT for the blend is about 5.1% compared to diesel fuel at the rated load. The EGT is higher at CR16 compared to CR17 and CR18 for diesel fuel as well as for the various blends. The EGT for diesel fuel is higher compared to the most of the blends for the entire range of loads. The higher EGT at CR16 may possibly be accredited to decreased combustion temperature and lesser density, temperature of the air.





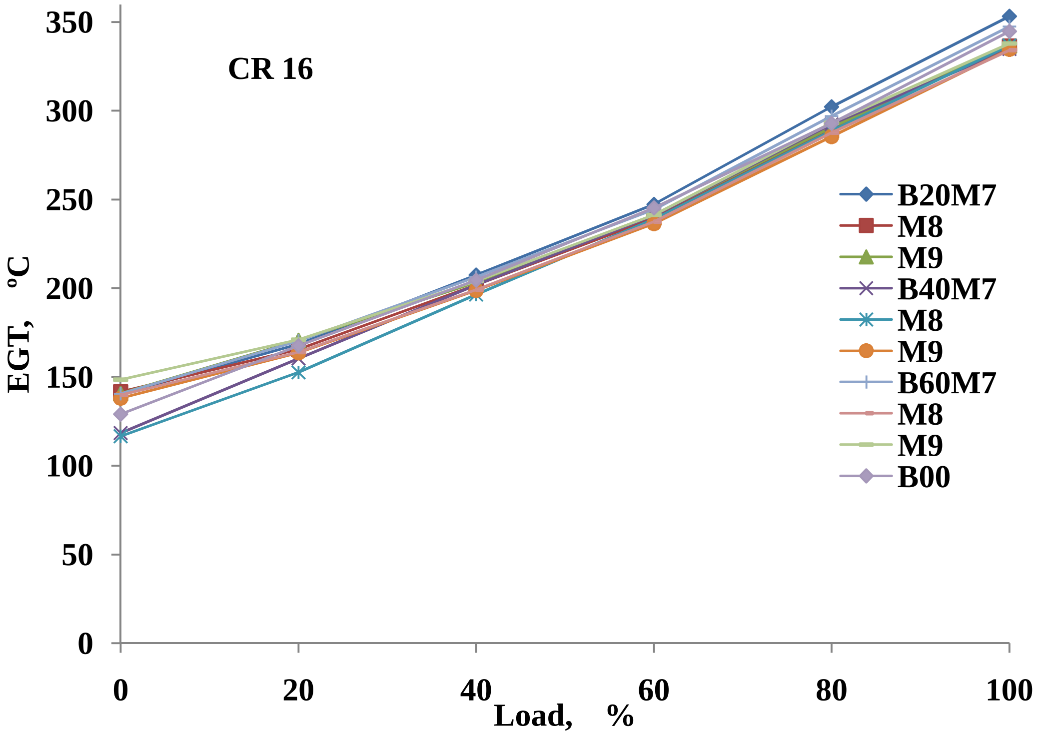


Fig. 5.6.2.3 Variation of exhaust gas temperature with load

The decreased combustion temperature and lower density, temperature of the air may affect the mixture formation subsequently the combustion. The EGT for diesel fuel at CR16 is 345º C at the rated load. The reduced EGT for all the blends at CR of 16, 17 and 18 may well be attributed to inherent oxygen and higher cetane number of biodiesel in the blends may help in complete of combustion of blends. Complete combustion converts the fuel energy of the into heat energy.

5.6.3 Emission analysis

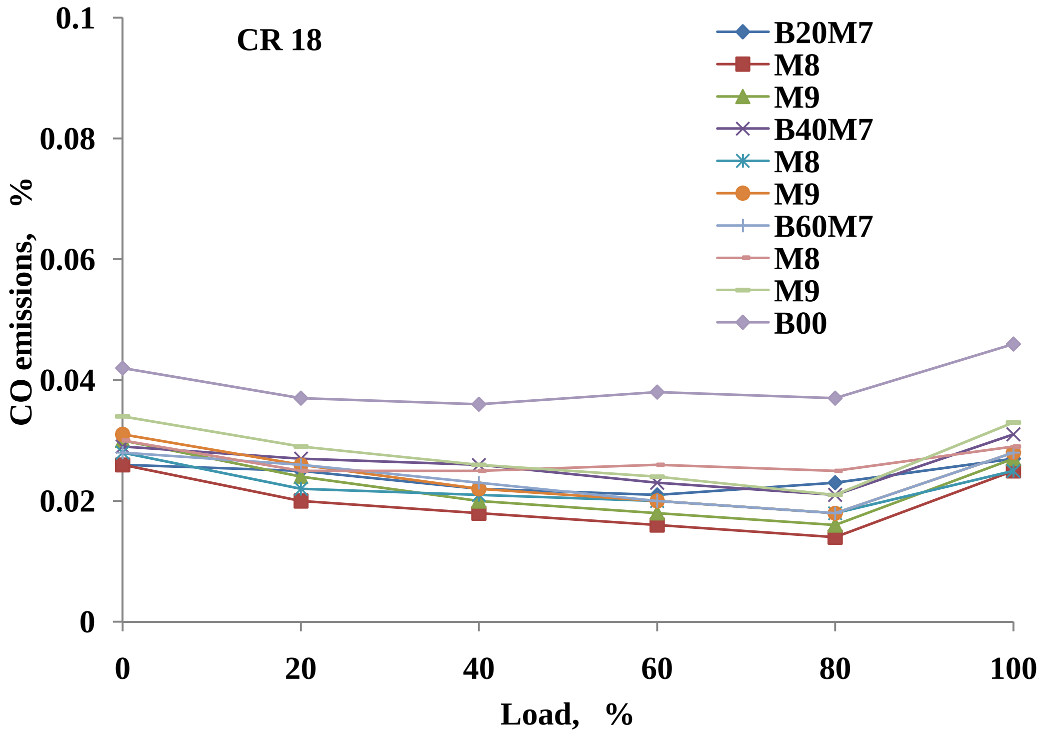
5.6.3.1 CO emissions with load

The emissions of CO for diesel fuel as well as for the various blends for different load at CR of 16, 17 and 18 are illustrated in the Fig.5.6.3.1. The CO emission increases for the increase in load for the CR and the fuels used. The emissions of CO decrease with increase in CR for diesel fuel and for the different blends. The enhanced state of combustion process at higher CR may reduce the emissions of CO. It can be observed from the figures that the emission of CO are lesser at CR18 compared to CR17 and CR16 at the rated load for diesel fuel as well as for the various blends. The increased CR increases the combustion temperature, higher temperature and density of the air which may perhaps improve the mixture formation of fuel-air which contributes for the complete combustion of the fuels.

The emissions of CO at CR18 for diesel fuel are found to be 0.046% for the rated load which is higher in comparison to the blends used. The higher maximum CO emission for blend B60M9 is 0.033% and least CO emission for the blend B20M8 is 0.025% at the rated load. The CO emission for the blends B60M9 and B20M8 are reduced by about 28.3% and 45.7% respectively compared to diesel fuel. The higher CO emission for the blend B60M9 may well be accredited to higher viscosity and inferior volatility of biodiesel in the blends. This may cause the incomplete combustion which increases CO emissions.

The CO emissions at CR17 are higher compared to CR18 which may be attributed to decrease in combustion temperature, lesser temperature and density of the air inside the cylinder which may affect the mixture formation of fuel-air and causes the incomplete combustion. The CO emissions for diesel fuel at CR17 are 0.053% at the rated load. The maximum and minimum CO emission are 0.043% and 0.03% for the blends B20M8 and B20M7 respectively at the rated load. The reduction in CO emissions by about 18.9% and 43.4% compared to diesel fuel at the rated load which are lesser compared to CR18.

The CO emissions at CR16 are higher compared to CR17 and CR18 for the different fuels used. The higher CO emission at CR16 may possibly be accredited to decreased combustion temperature, lower temperature and density of the air. The lesser combustion



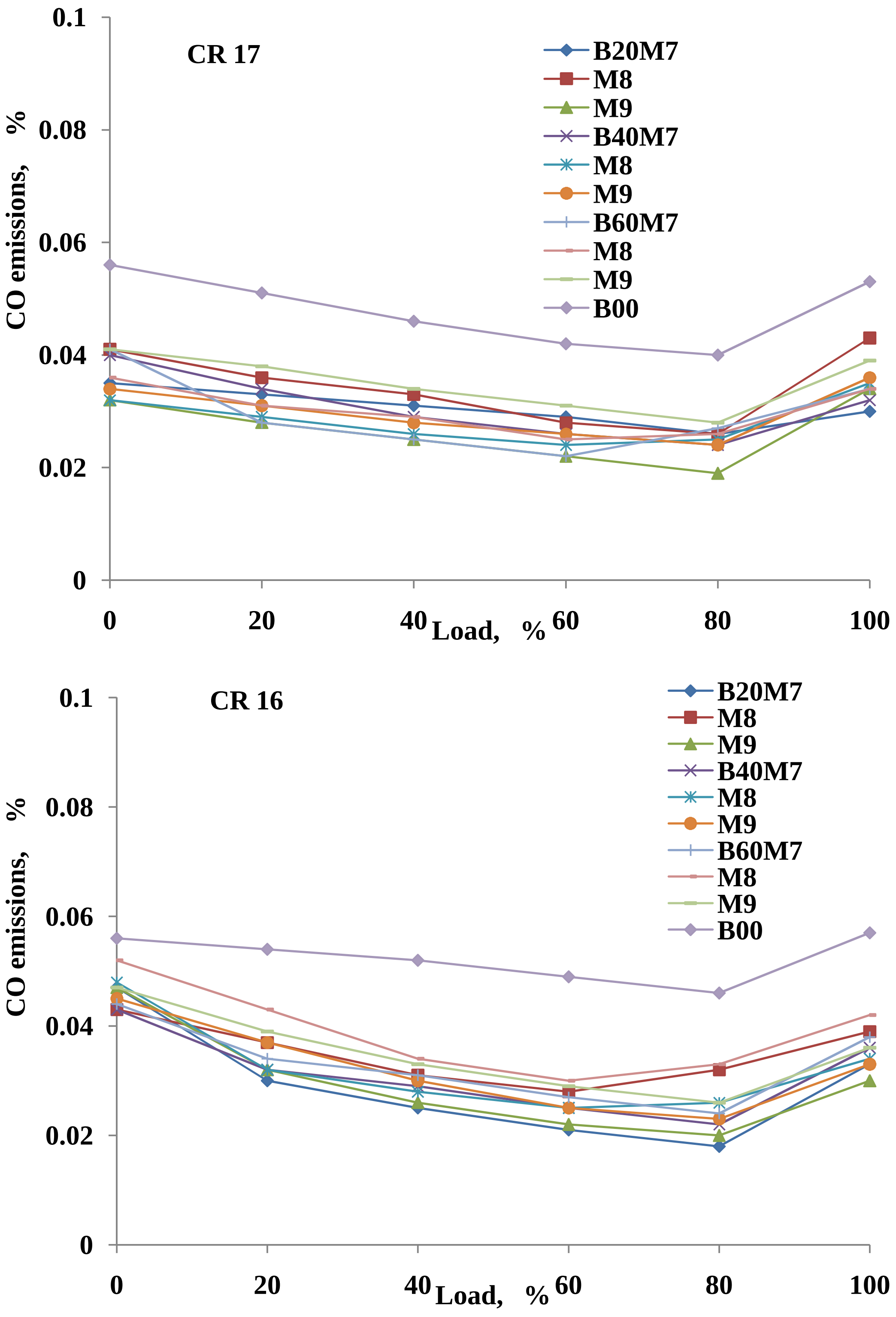


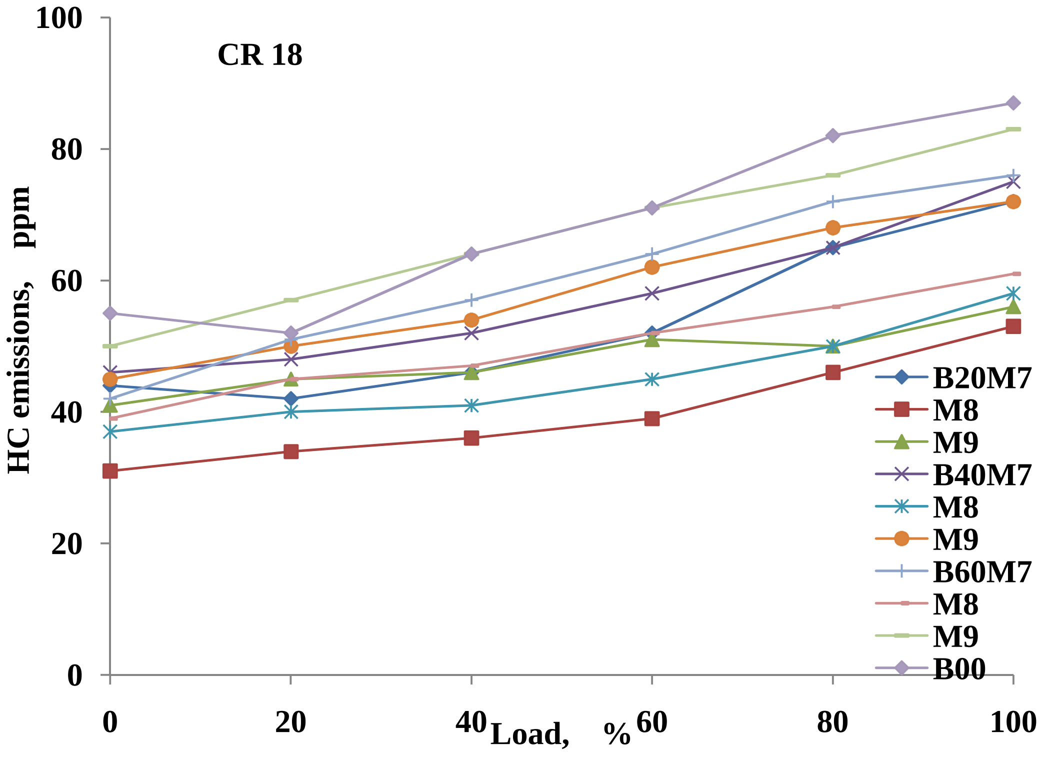
Fig. 5.6.3.1 Variation of CO emissions with load

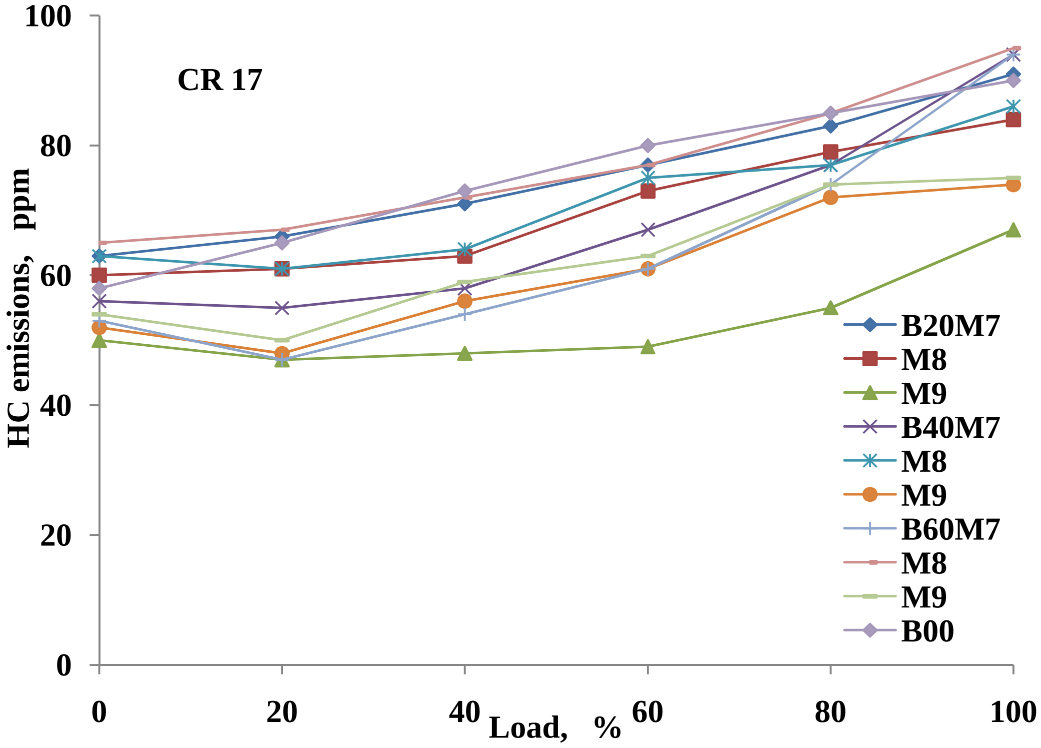
temperature, lesser temperature of the air in the cylinder at the time of fuel injection may influence the mixing of fuel-air which results into incomplete combustion. The incomplete combustion of the fuel at CR16 increases the CO emissions compared to CR17 and CR18

5.6.3.2 HC emissions with load

The emissions of HC for diesel fuel and for the various blends for different load at compression ratio of 16, 17 and 18 are illustrated in the Fig.5.6.3.2. The HC emission increases with increase in load for diesel fuel and for various blends, for the CR used. The HC emissions decrease at higher CR which may be because of higher combustion temperature, increased density and temperature of the air at higher CR. The decrease in HC emission at CR18 may possibly be accredited to increased temperature and density of the air which improves the mixture formation and contributes in complete combustion of fuels. This may also be due to increased combustion temperature, increased diffusion combustion and after burning phenomenon.

The HC emissions are lesser at CR18 compared to CR16 and CR17 which may perhaps be attributed to better combustion of the fuels used. The HC emissions of diesel fuel at CR18 are 87 ppm at the rated load which is higher in comparison with the blends. The higher HC emissions for diesel fuel may be because of incomplete combustion. The incomplete combustion of diesel fuel may perhaps be accredited to lack of oxygen. The maximum and minimum emissions of HC for the blends are 83 ppm and 53 ppm for the blends B60M9 and B20M8 respectively at the rated load. The reductions in HC emissions for the blends are by about 4.8% and 39.1% respectively in comparison with diesel fuel for the rated load.





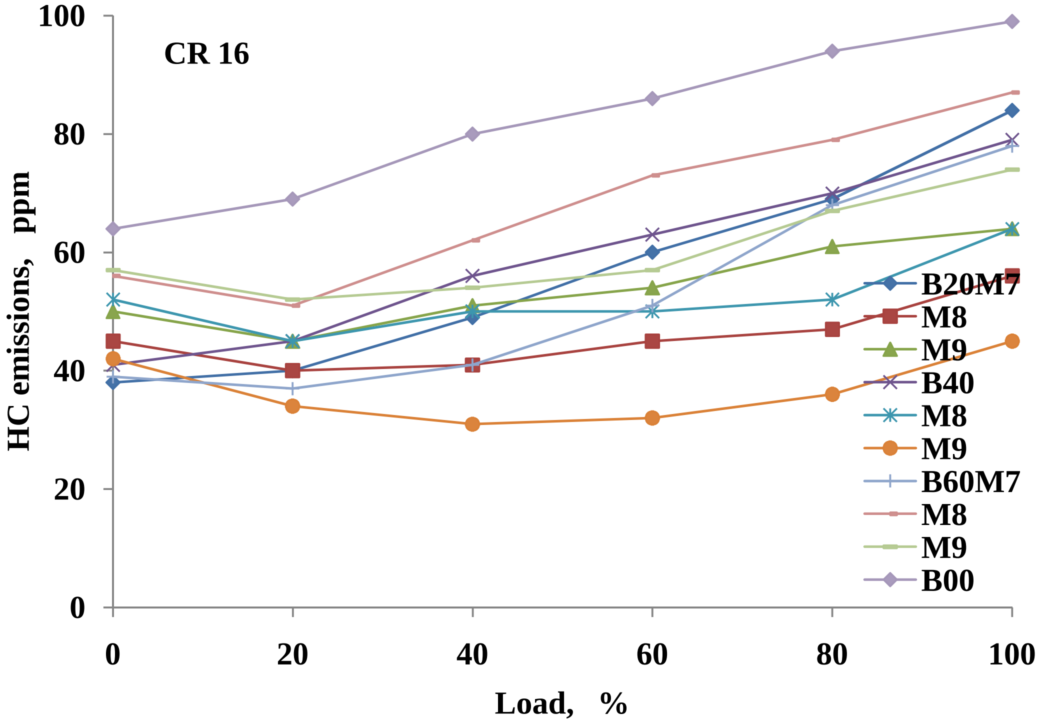


Fig. 5.6.3.2 Variation of HC emissions with load

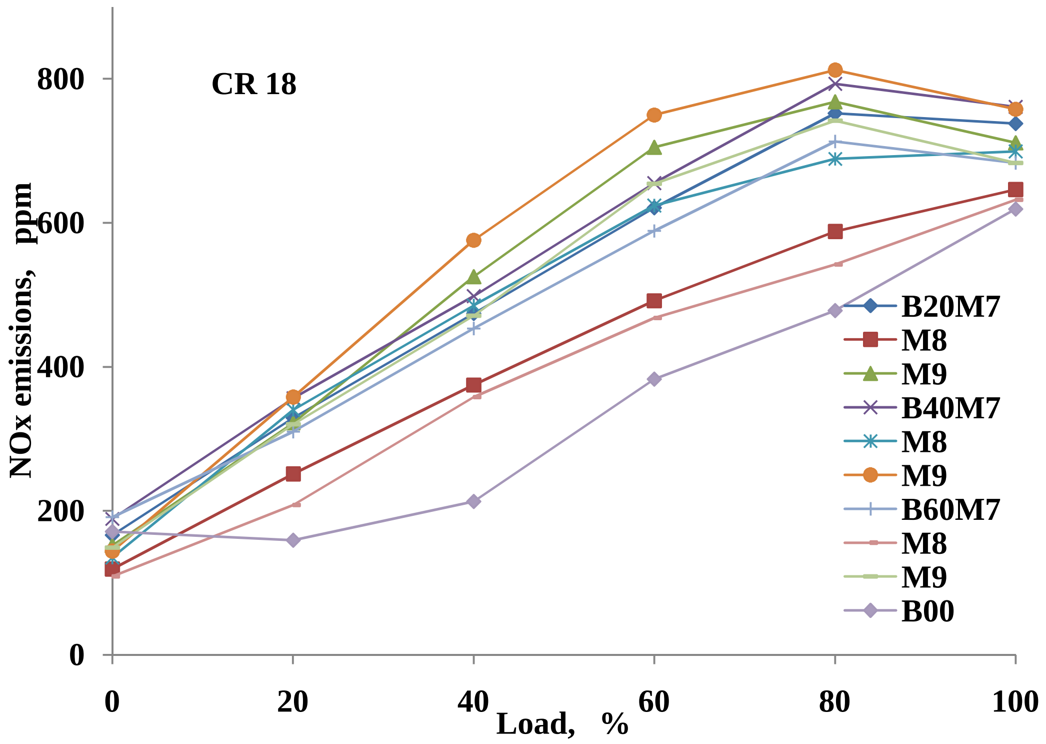
The HC emissions are higher at CR17 compared to CR18 for the fuels used. The higher HC emission at CR17 may perhaps be accredited to decrease in combustion temperature, lesser temperature and density of the air. The decreased combustion temperature, lower temperature and density of the air at CR17 affects the mixture formation of fuel-air and combustion which results into increase in HC emissions. The HC emissions for diesel fuel at CR17 are 90 ppm at the rated load. The higher maximum and minimum HC emissions are 95 ppm and 67 ppm for the blends B60M8 and B20M9 respectively and are lower compared to diesel fuel. The HC emissions for the blends are reduced by about 25.6 % for B20M9 and are increased by about 5.6% for the B60M8 compared to diesel fuel at rated load. The increased HC emissions for B60M8 blend which may be accredited to higher viscosity and inferior volatility of biodiesel in the blends.

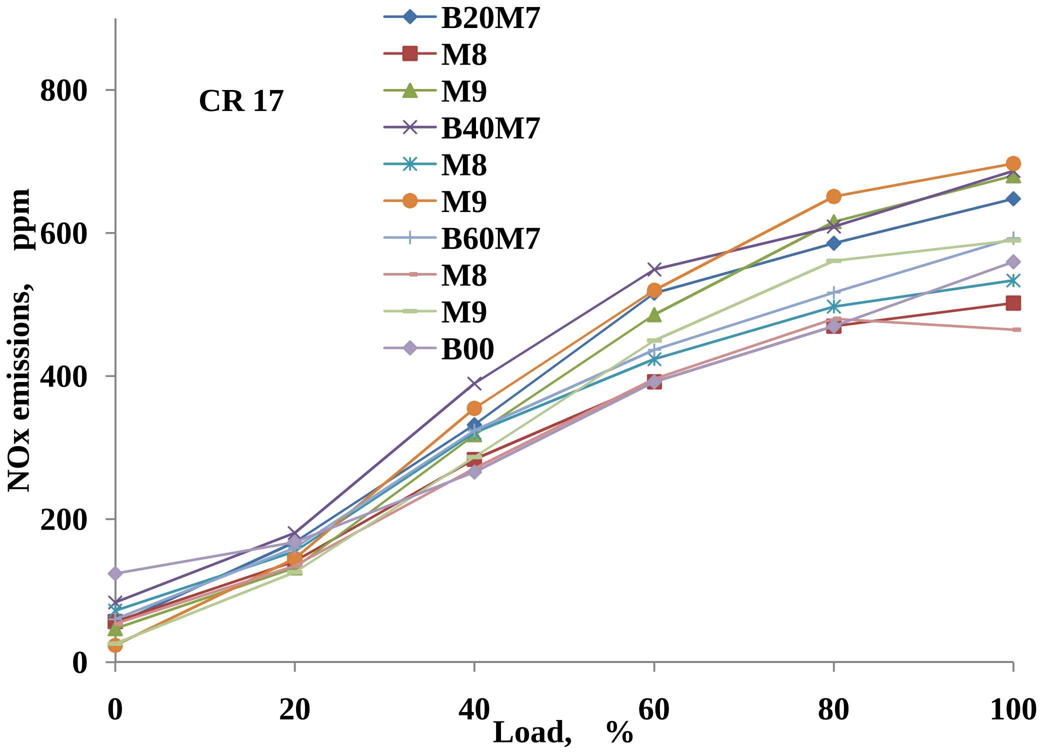
The emissions of HC are higher at CR16 compared to CR17 and CR18 for diesel as well as for the various blends used. The increase in HC emissions at CR16 may perhaps be accredited to decreased combustion temperature, lower temperature and density of the air at CR16 which may affect the mixture formation consequently the sluggish incomplete combustion. The incomplete combustion increases the HC emissions. The HC emissions for diesel fuel are 99ppm at the rated load. The least HC emissions for the blend B40M9 are 45ppm whereas the maximum HC emissions for the blend B60M8 are 87ppm at the rated load. The higher HC emissions for the blend B60M9 may be because of higher viscosity and inferior volatility of biodiesel in the blends which causes the incomplete combustion hence increases the HC emissions.

5.6.3.3 NOx emissions with load

The emissions of NOx for diesel fuel and for the various blends for different loads at compression ratio of 16, 17 and 18 are illustrated in the Fig.5.6.3.3. It is seen that for the CR used the NOx emissions increases with increase in load for the various fuels used. The NOx emissions are increased at CR18 in comparison to CR16 and CR17 for diesel fuel as well as for the blends. The increased combustion temperature at higher compression ratio may increase the NOx emissions all through the diffusion combustion. The NOx emissions for diesel fuel at CR18 are 619 ppm at the rated load. The higher maximum and minimum NOx emissions for the blends are B40M7 and B60M8 are 761 ppm and 638 ppm respectively at the rated load. The NOx emissions are higher by about 23% and 3.1% for the blends B40M7 and B60M8 respectively in comparison with diesel fuel at the rated load. The NOx emissions for the other blends are in between the of the two blends.

The NOx emissions at CR17 are lesser compared to CR18 for diesel fuel as well as the various blends used. The lesser NOx emission at CR17 may possibly be accredited to reduced combustion temperature, lesser temperature and density of the air. The lower combustion temperature, lesser temperature and density of the air in the cylinder affect the mixture formation of fuel-air consequently the burning. The sluggish combustion at CR17 may have lower combustion temperature which forms the lesser NOx emission.





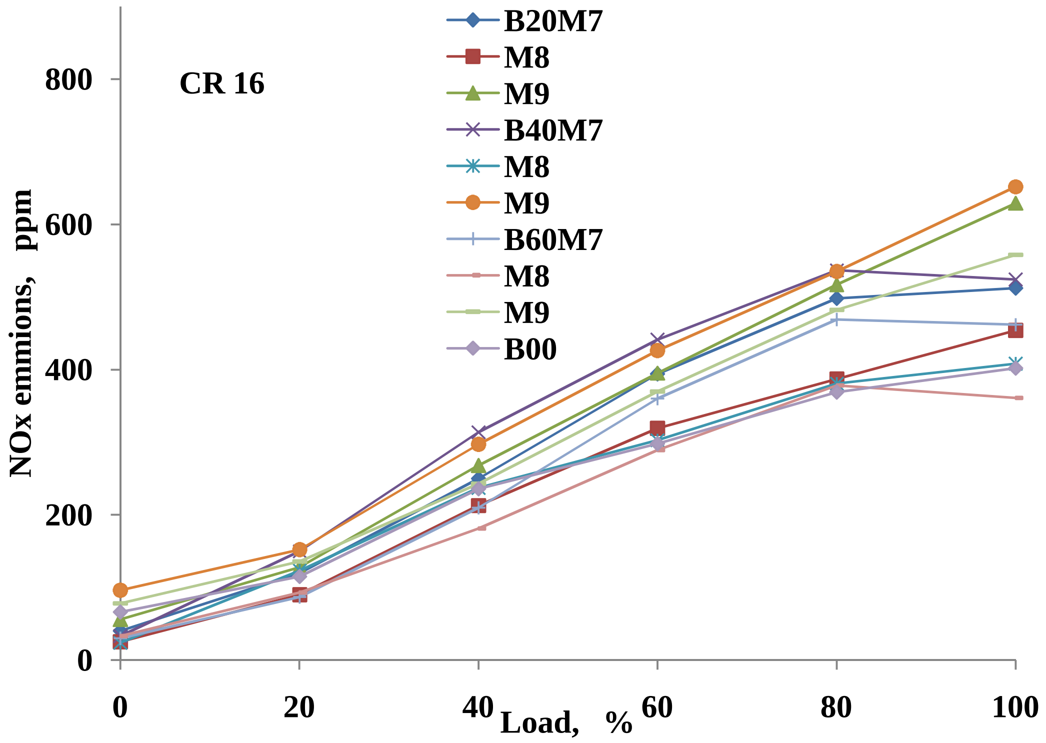


Fig. 5.6.3.3 Variation of NOx emission with load

The lesser NOx emission for diesel fuel is 560 ppm at the rated load. The higher NOx emission for the blend B40M9 is 697 ppm which is higher in comparison to diesel fuel. The higher NOx emissions for the blends may possibly accredited to inherent oxygen and higher CN of biodiesel in the blends which may perhaps improve the combustion of blends. The NOx emission for the blend B60M8 is 465 ppm at the rated load. The lesser NOx emission for the blend B60M8 may be well be attributed to higher viscosity and inferior volatility of the blends which may affect the mixture formation subsequently the combustion temperature.

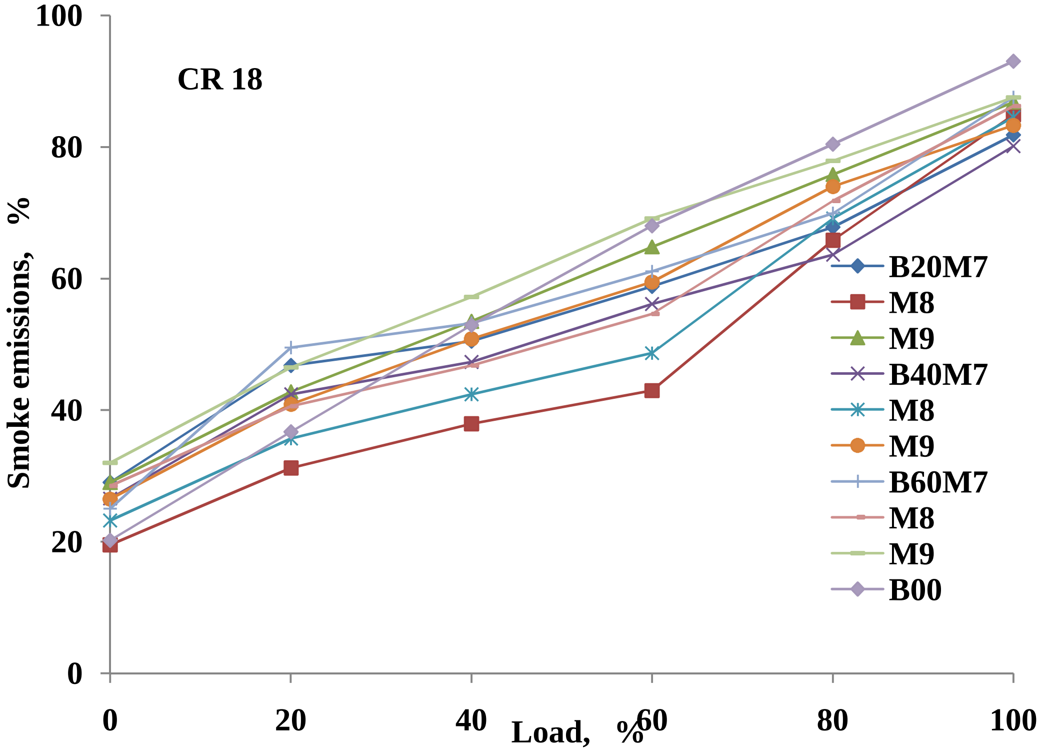
The NOx emissions at CR16 are lesser compared to CR17 and CR18 for diesel fuel as well as for various blends used. The lower NOx emissions at CR16 may be because of lower combustion temperature for different fuels used. The lower combustion temperature may perhaps be accredited to lesser temperature and density of the air at lower compression ratio. The lower combustion temperature forms lesser amount of NOx though the oxygen is available with the blends. The NOx emission for diesel fuel is 402 ppm at the rated load. The higher maximum NOx emission for the blend B40M9 is 652 ppm and the minimum for the blend B60M8 is 361 ppm at the rated load.

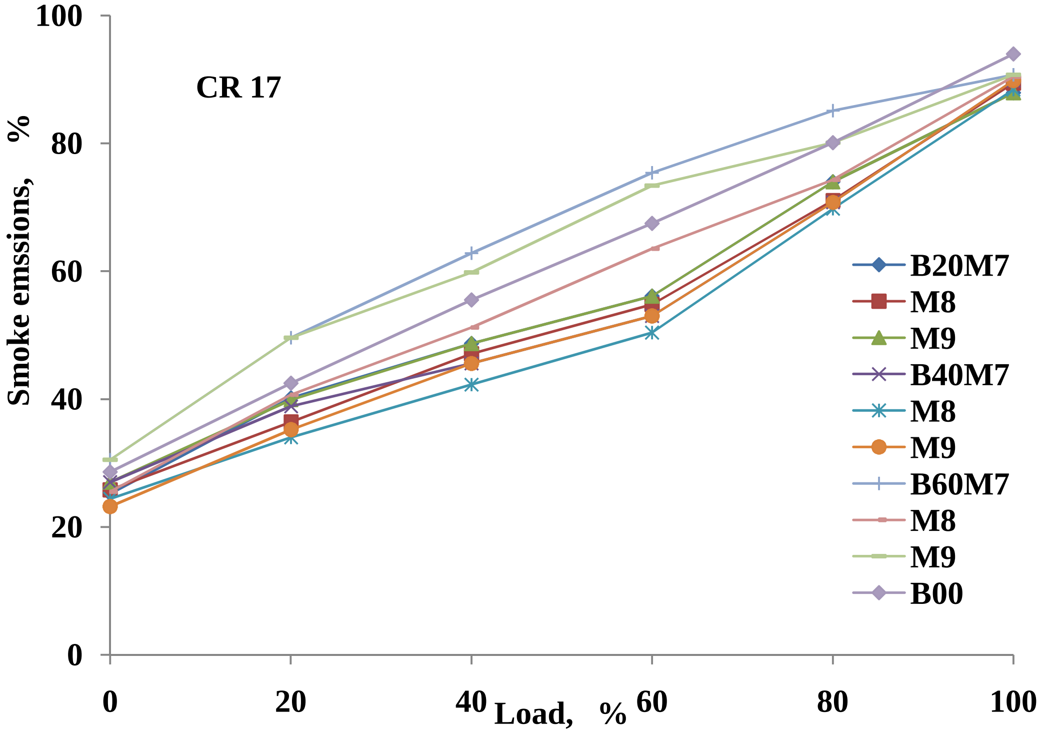
5.6.3.4 Smoke emissions with load

The smoke emission for diesel fuel as well as for the various blends for different load at compression ratio 16, 17 and 18 are illustrated in the Fig. 5.6.3.4. The smoke is formed because of incomplete combustion of the fuels. The smoke emission increases for the increased load for diesel fuel as well as for the various blends and the CR used. The smoke emission decreases with increase in CR which may perhaps be because of increased combustion temperature, higher temperature and density of the air inside the cylinder. The increased temperature and density of the air at higher CR improve the mixing of fuel-air subsequently complete combustion which decreases the smoke emissions. The smoke emissions for diesel fuel at CR18 are 93% at the rated load which is higher compared to the blends used. The lesser smoke emission for diesel fuel at lower load may perhaps be accredited to better combustion of diesel fuel. At lower load combustion temperature is lesser which may influence the mixture formation and combustion of the fuel. The smoke emission for the blends is higher at lower load for the blends which may be because of higher viscosity and inferior volatility of biodiesel in the blends. The maximum and minimum smoke emission for the blends B60M8 and B40M7 are 86.2% and 80.1% respectively at the rated load. The decrease in smoke emission for the blend is by about 7.3% and 13.9% for B60M9 and B40M7 respectively compared to diesel fuel for the full load.

The smoke emissions at CR17 are higher compared to CR18 for diesel fuel as well as for the various blends for different loads. Air is compressed to a lesser level at CR17 hence the temperature and density of the air is lower which causes the lesser combustion temperature. The lower combustion temperature may influence the mixture formation and the combustion of fuels. The lower combustion temperature at CR17 forms higher smoke which may be because of incomplete combustion. The smoke emission at CR17 for diesel fuel is 94% at the rated load. The smoke emissions for some of the blends are higher compared to diesel fuel because of incomplete combustion. The incomplete combustion of the blends may possibly be attributed to higher viscosity and inferior volatility of the blends. The lower smoke emission for the blend B20M9 is 87.9% at the rated load. The smoke emissions are reduced by about 6.5% for the blend B20M9 compared to diesel fuel for the rated load.

The smoke emission at CR16 is higher than CR17 and CR18 for diesel fuel as well as for the various blends used. The higher smoke emission at CR16 may well be accredited to reduced combustion temperature, lesser temperature and density of the air. The air is compressed to lesser level at CR16 hence the density and temperature of the air is lesser which results into lower combustion temperature. The lower temperature and density of the air influence the mixing of fuel- air subsequently the incomplete combustion which increases the smoke emission. The smoke emission for diesel at CR16 is 95.7% for the





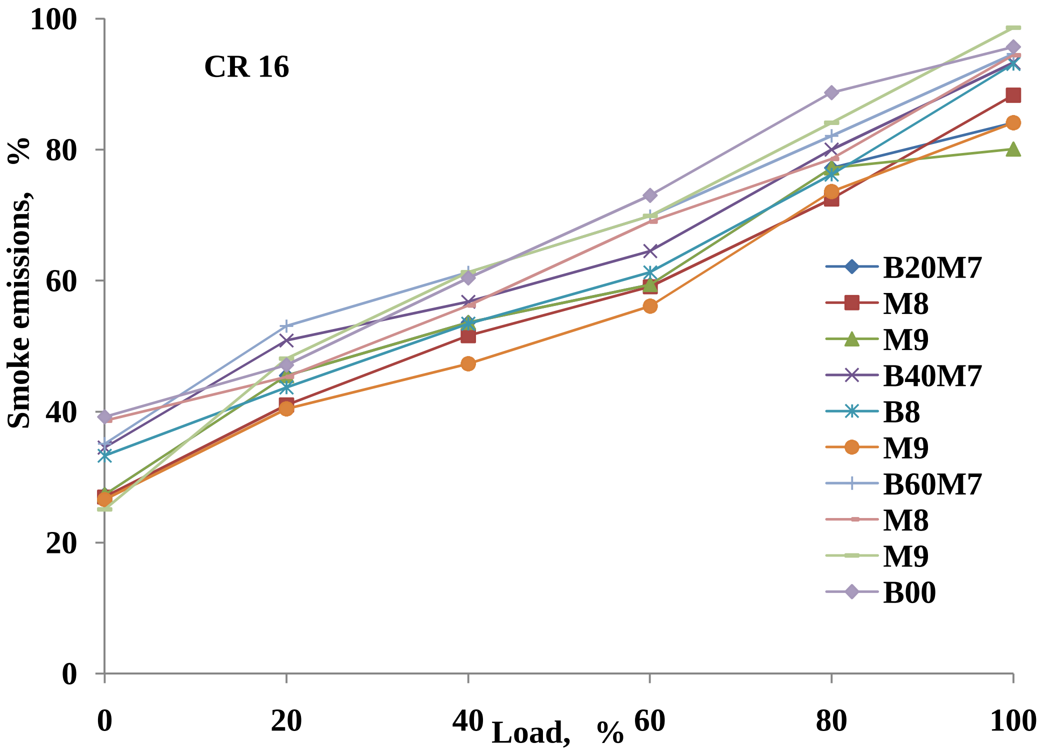


Fig. 5.6.3.4 Variation of smoke emission with load

rated load. The lesser smoke emission for the blend B20M9 is 80.1% at the rated load. The maximum reduction in smoke emission for the blends B20M9 is about 16.3% compared to diesel fuel.

5.6.4 Summary

The summary of combined results of the various blends as well as the diesel fuel for different compression ratio, loads and for the various mixture ratios on combustion characteristics, thermal performance and emission characteristics of DI VCR diesel engine are investigated and analysed. The results are improved at higher compression ratio for the blends as well as for diesel fuel. The combustion characteristics of blend are towards comparable with another. The combustion characteristics at CR18 are for various mixtures and blends used are improved for lower blends. The thermal performance parameters for the blends are comparable with diesel fuel. The emissions such as CO, HC and smoke are decreases where as NOx emissions increases. The combustion characteristics, thermal performance and emission characteristics are decreases for CR16 and CR17 compared to CR18. The overall improvement in the performance of the engine at CR18 may be because of higher combustion temperature, higher temperature and density of the air. The increased temperature, density of the air may perhaps improve the mixing of fuel-air contributes towards complete combustion which results into the increase in the combustion, performance characteristics with reduced emissions. This shows the overall improvement in the output and decreased emissions of the engine at higher compression ratio.

Table 5.6.1 Results of engine parameters obtained for diesel and blends of various blends for the rated load at CR18

Sl.No.		**B00**	**B20M7**	**B40M7**	**B60M7**	**B20M8**	**B40M8**	**B60M8**	**B20M9**	**B40M9**	**B60M9**
Combustion Parameters											
1	Maximum pressure, bar	71.2	71.32	72.44	71.99	71.98	70.85	72.35	71.2	72.31	71.62
2	Max. heat release, J/ºCA	52.79	44.26	42.01	43.21	44.41	43.16	44.31	42.18	41.75	41.57
3	Max. rate of pressure rise, bar/ºCA	4.79	4.89	4.81	5.02	4.89	4.86	4.98	5.04	4.8	5.12
Performance parameters											
1	Brake thermal efficiency, %	27.66	26.9	27.84	27.35	26.82	28.11	27.31	26.72	28.22	27.4
2	BSFC, kg/kW hr	0.3	0.31	0.31	0.32	0.31	0.3	0.31	0.32	0.31	0.32
3	EGT , ºC	320	317	312	316	303	307	306	304	308	305
Emissions parameters											
1	CO emissions, %	0.046	0.027	0.031	0.028	0.025	0.029	0.027	0.027	0.028	0.033
2	HC emissions, ppm	87	72	75	76	53	58	61	56	72	83
3	NO emissions, ppm	619	738	761	683	646	699	632	711	758	683
4	Smoke emissions, %	93	81.8	80.1	87.5	84.9	84.5	86.2	86.8	83.3	87.5

Table 5.6.2 Results of engine parameters obtained for diesel and blends for the various blends for the rated load at CR17

Sl.No.		**B00**	**B20M7**	**B40M7**	**B60M7**	**B20M8**	**B40M8**	**B60M8**	**B20M9**	**B40M9**	**B60M09**
Combustion Parameters											
1	Maximum pressure, bar	63.58	65.25	66.95	65.83	66.63	65.51	63.95	65.44	66.14	66.19
2	Max. heat release, J/ºCA	50.28	43.61	43.71	43.45	43.25	44.38	44.61	45.13.95	46.92.99	46.12
3	Max. rate of pressure rise, bar/ºCA	5.09	4.91	5.01	4.92	4.85	4.85	4.85	4.74	4.98	4.75
Performance parameters											
1	Brake thermal efficiency, %	27.54	25.53	26.81	26.89	26.75	28.12	27.09	26.84	26.97	25.99
2	BSFC, kg/kW hr	0.31	0.33	0.31	0.32	0.31	0.3	0.32	0.31	0.32	0.33
3	EGT, ºC	336	338	336	332	327	329	323	329	319	325
Emissions parameters											
1	CO emissions, %	0.053	0.03	0.032	0.034	0.043	0.035	0.034	0.034	0.036	0.039
2	HC emissions, ppm	90	91	94	94	84	86	95	67	74	75
3	NO emissions, ppm	560	648	617	593	502	534	465	680	697	590
4	Smoke emissions, %	94	87.9	90.7	89.4	91.7	88.4	90.4	87.9	89.8	90.7

Table 5.6.3 Results of engine parameters obtained for diesel and blends of various blends for the rated load at CR16

Sl.No.		B00	B20M1	B40M1	B60M1	B20M2	B40M2	B60M2	B20M3	B40M3	B60M3
Combustion Parameters											
1	Maximum pressure, bar	62.4	59.96	60.98	61.21	61.63	60.28	61.63	61.96	58.93	62.31
2	Max. heat release, J/°CA	42.84	43.56	42.16	43.16	43.18	44.17	45.08	50.12	46.94	47.88
3	Max. rate of pressure rise, bar/°CA	4.92	4.98	4.49	4.84	4.86	4.58	4.52	4.79	4.60	4.71
Performance parameters											
1	Brake thermal efficiency, %	26.55	25.53	26.65	26.69	26.5	26.06	26.02	26.84	26.57	25.99
2	BSFC, kg/kW hr	0.31	0.33	0.33	0.33	0.31	0.31	0.32	0.31	0.31	0.33
3	EGT, °C	345	353	334	347	336	336	334	337	334	338
Emissions parameters											
1	CO emissions, %	0.057	0.033	0.036	0.038	0.039	0.034	0.042	0.03	0.033	0.036
2	HC emissions, ppm	99	84	79	78	56	64	87	64	45	74
3	NO emissions, ppm	402	512	524	462	454	408	361	629	653	558
4	Smoke emissions, %	95.7	84.1	93.3	94.6	88.3	93.1	94.4	80.1	84.1	98.6

Chapter 6

ARTIFICIAL NEURAL NETWORK MODEL

6.1 Introduction

The engines are designed to operate for their optimum performance with minimum emissions using diesel. The fuels used other than diesel with the same engine; it requires changing the engine operational parameters, setting in order to run with optimum efficiency with minimum emissions. The change in engine setting is necessary to operate with different fuel with different physico-chemical properties which were to be used as an alternative fuels. This is meeting through the chain of experiments with each change in operating condition. This was done to attain the optimum operating condition of the engine for the maximum efficiency and minimum emissions. The testing of the engine under all operational circumstances and the fuels, mixtures and blends cases were expensive and time consuming. On the other hand develop a precise model which can simulate the actual engine system behaviour with minimum permissible error. As the alternative, the engine performance and emission constituents were modelled by employing the Artificial Neural Network (ANN). ANN modelling method might be applied to assess the desired outputs for the number of input information which were made available. The ANN models have the competence to re-learn to get better the performance if new information's were readily accessible [145, 146]. The ANN modelling can be used in different applications, manufacturing, robotics, process control systems, optimization, forecasting etc.

The use of ANN modelling in the internal combustion engine operation was an addition to recent progress. The ANN model was used for the prediction of various combustion characteristics, thermal performance and emission constituents from diesel engine [147]. The ANN model suggests the research engine behaviour to the expected thermal performance and exhaust emission constituents with respect to the optimised engine operational parameters.

ANN modelling technique consists of heavily interrelated adaptive, however easy processing elements called artificial neurons or nodes. These artificial neurons were capable of achieving substantial parallel computation to set up the correlation among the input and output parameters. Artificial Neural Network was competent to solve the non linear problem by obtaining the information and make out the connection between the input parameters and the output response and the data was complex, incomplete and noise contaminated. In number of cases, numerical approach employ mean square error and correlation coefficient were made use for finding out the accuracy level of the expected information from the created ANN model. The mean square errors enumerate the inequality among Artificial Neural Network expected values and the accurate values of the parameter of attention, where as the correlation coefficient was the proportionality value among the expected and genuine set of data.

One of the major inconveniences with the ANN training was over fitting, where the created ANN method was capable to construct only the correct predictions for the known set of information and not suitably expert to generate good quality prediction for the new set of data. One method of attending to this was by early stopping technique which is implemented in the analysis.

Islam et al. used overall four combination of transfer functions which were tested against different training functions existing in MATLAB software. Only the Levenberg Marquardt functions were found to predict the significantly correct end results. TRAINLM be able to train every network, make available that its weight, net input, and transfer functions have derived functions, and that of the network have mean square error performance function. Here the weight and bias values were updated for every epoch after every individual arrangement [148].

ANN in general consists of three categories of neuron layers, input, hidden, and output [147]. There were two types of ANN modelling single layer and multilayer, here the multilayer method was employed. ANN based on the multilayer perception was developed for the expected outcome of the performance and emissions using the experimental data [149].

A variety of training functions could be employed to train the network to achieve from particular input to a definite end output. As the each input was applied to the network the output was compared with the actual target and the errors were calculated. The errors were between the network output and the actual outputs were minimized by network weights and biases. The aim was to reduce the average of sum of these errors which were calculated as mean square error of the outputs. The mean square errors were given by, $\text{Mean square error} = \frac{1}{q\sum_{k=1}^{q}(t(k)-t(k))^2}$, Where *t*(k) was the actual value, t(k) was the network value and ‘q’ was the number of epochs. When MSE fall below the predetermined value the maximum numbers of epochs have been achieved, the training method stops. This trained network could be employed to reproduce the system output which were not established earlier [150].

The 2376 sets of data collected from the experiments are employed in the direction to develop an ANN modelling. The 70% of the data are selected arbitrarily for the training of the Network, 15% of the data are selected for the test purpose and left over 15% data are used for the confirmation purpose. Further, the training is done by using Levenberg-Marquardt method.

The experiments are conducted on DI VCR CI engine using mixture of two biodiesel in blend with diesel fuel and with the various blends. The inputs to the engine are Load, CR, blends, and mixtures, are employed to develop the ANN model. The output from the engine are BTE, BSFC, EGT, and the various exhaust emission constituents are CO, HC, NOx and smoke.

6.2 Multilayer Neural Network Model

The inception of artificial neural networks (ANNs) has been forced from the working of the human brain. The brain is a extremely complex, nonlinear and analogous to computer and it works differently from a conventional digital computer [151]. It uses neurons organized in a structured way to carry out certain computations. A developing neuron gathers information from its surrounding and learns to adapt to it. The brain is composed of average 100 billion neurons. A nonlinear sculpt of a neuron is publicized in the Fig. 6.2.1. It have three basic fundamentals, a set of synapses differentiated by a load or strength, an adder for addiing the inputs biased through the relevant synapses of the neuron and the activation purpose of limiting the output of a neuron. In numerical terms, it may describe a neuron by equation (6.2.1) and (6.2.2).

$$\neg_k = \sum_{j=0}^{m} w_{kj} x_j \tag{6.2.1}$$

$$y_k = \text{¤}\left(\neg_k\right) \tag{6.2.2}$$

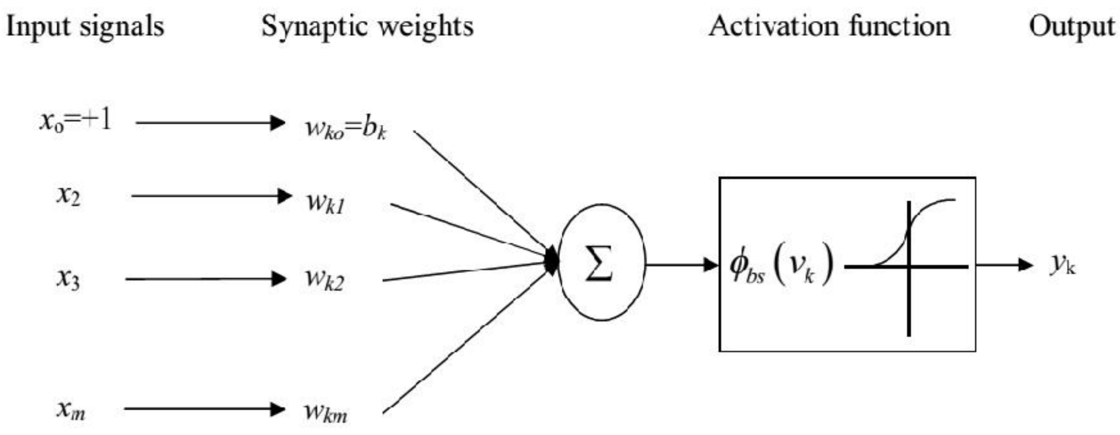


Fig. 6.2.1 Artificial neuron

where $x_1, x_2, ...x_m$ are the input indicators, $w_{k1}, w_{k2}, ...w_{km}$ are the synaptic weights of a neuron k, v_k is the linear combiner output towards the inputs, ¤$(¬_k)$ is the commencement function and y_k is the output gesture of the neuron. The activation function ¤$(¬_k)$, can be of five basic types, a linear activation function, a hard limiter activation function, a

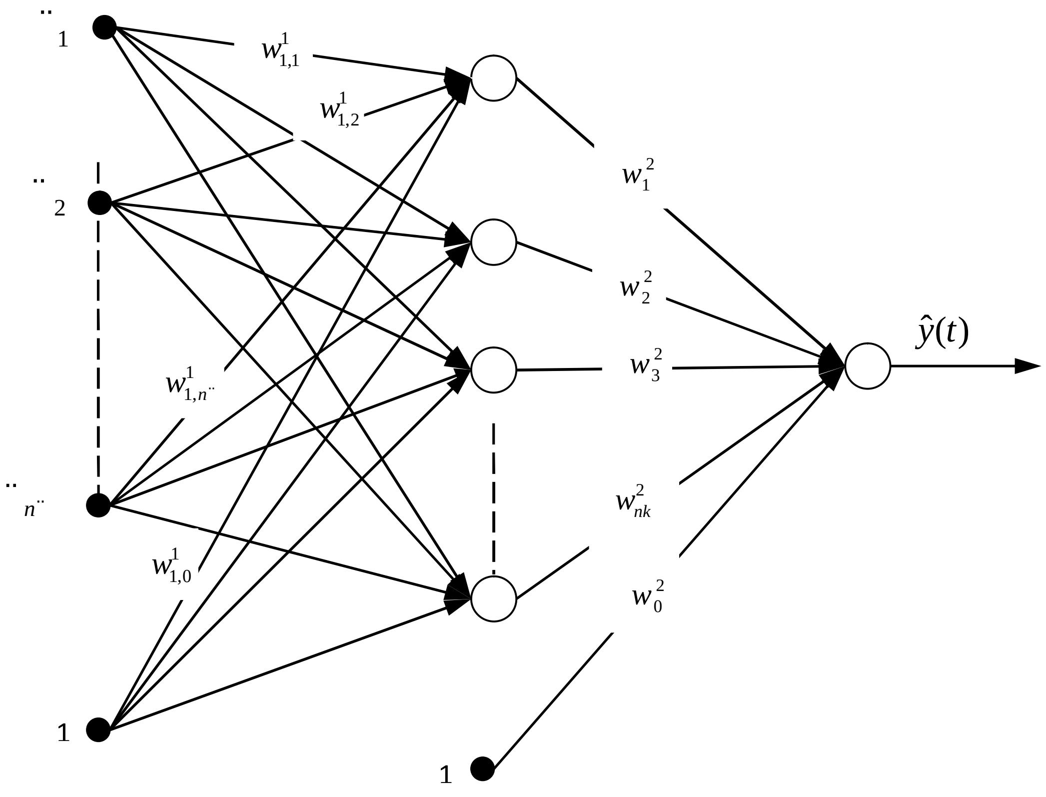


Fig. 6.2.2 Neural network with single hidden layer and one output

saturating linear function, a sigmoid function or a hyperbolic tangent function. The most common kind of neural network used is a lone hidden layer neural network by hyperbolic tangent activation function, used in favour of neurons in the unknown layer and linear activation function used for the neurons within output layer. This network is most often used because of its ability to fairly accurate any continuous function with any desired accuracy.

The Fig. 6.2.2 shows the neural network with single hidden layer and one output neuron. Two kinds of signal propagate in the network: Functional signals flowing in the forward direction and the error signal flowing in the backward direction. Functional signals originate from the input layer and propagate forward through the network. Error signal propagates at the output layer and flows in the backward direction.

6.3 Methodology

The Multilayer Neural Network (MLNN) shown in Fig. 6.3.1 is also an artificial neural network based model employed for mapping every parameter since it is supposed to be a universal approximate and is largely appropriate for demonstration of non linear systems. The advantages of ANN over the other modelling techniques are that it can be employed to model the nonlinear system, can provide input-output mapping with nonparametric statistical inference, adaptive and is fault tolerant [152]. The parameters are modelled using single MLNN. The NN output is expressed by equation (6.3.1)

$$P(\mathbf{w}) = f[x_1, x_2, ...x_n, \mathbf{w}] \tag{6.3.1}$$

where $P(\mathbf{w})$ be the expected output of multilayer neural network. The hyperbolic tangent function [152] given by equation (6.3.2) is used as the starting function for the unseen layer whereas linear starting function [153] specified by equation (6.3.3) be employed for the output layer.

$$\text{¤}_{\tanh}(v) = \tanh(v) \tag{6.3.2}$$

$$\text{¤}_{lin}(\neg) = \neg \tag{6.3.3}$$

where, $\neg$ is the net input to the neuron. Further, $\mathbf{w}$ is the weight factor vector to be recognized throughout the training course of action and $x_1, x_2, ...x_n$ characterize the system inputs.

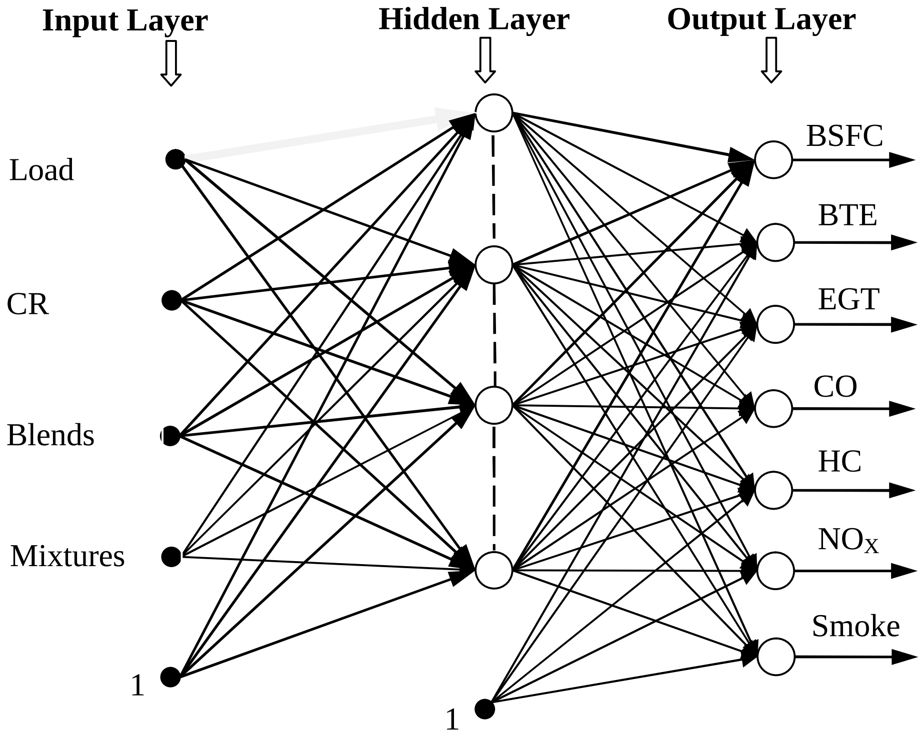


Fig. 6.3.1 Multi layer neural network

The inputs to MLNN considered are load, CR, mixtures and blends. The weights $\mathbf{w}$ are estimated by minimizing the cost function $\P(\mathbf{w})$ given by equation (6.2.4).

$$\P(\mathbf{w}) = \frac{1}{2N}\sum \pounds(\mathbf{w})^2 + \frac{1}{N}\mathbf{w}^T D\mathbf{w} \qquad (6.3.4)$$

where $\pounds(\mathbf{w}) = y - \hat{y}(\mathbf{w})$ and D is the weight decay matrix and is given by equation (6.2.5).

$$D = \quad [I]_{m\times m} \qquad (6.3.5)$$

where, is the weight decay term and I is the identity matrix. To get better of the overview, data on network points are separated arbitrarily into three subsets consists of 70%, 15% and 15% of data. The first subsets are employed for training while the other two subsets are employed for confirmation and cross confirmation, in that order. The early stopping technique is employed to choose most excellent epoch [137], which corresponding to least amount of mean square error on confirmation of the information set shown in the Fig. 6.2.1.

6.4 Results and Discussions

6.4.1 ANN model for M1, M2, M3 mixtures and their blend with diesel fuel

The MLNN model developed for the different CR, load and various mixtures (M1, M2 and M3) and blends of mixture of M1, M2, M3 with diesel fuel prepared and the results of the same are discussed. On training the network using the Levenberg Marqadrt method the network performance is illustrated in the Fig.6.4.1.1. The training, validation and cross validation errors are to decrease at the faster rate near the start of training. The error results and coefficient of determination of MLNN model is given in the table 6.4.1.1.

The thermal performance parameters from the ANN model are illustrated in the Figs.6.4.1.2 to 6.4.1.4. The plots for the experimental values to estimated values from the ANN model are for BTE, BSFC and EGT. The emission constituents of ANN model are illustrated in the Figs. 6.4.1.5 to 6.4.1.8. The plots are for the experimental values and estimated values from the ANN model for the CO, HC, NOx and smoke emission. The mean square errors for validation and cross validation are closer to each other and within the permissible limits.

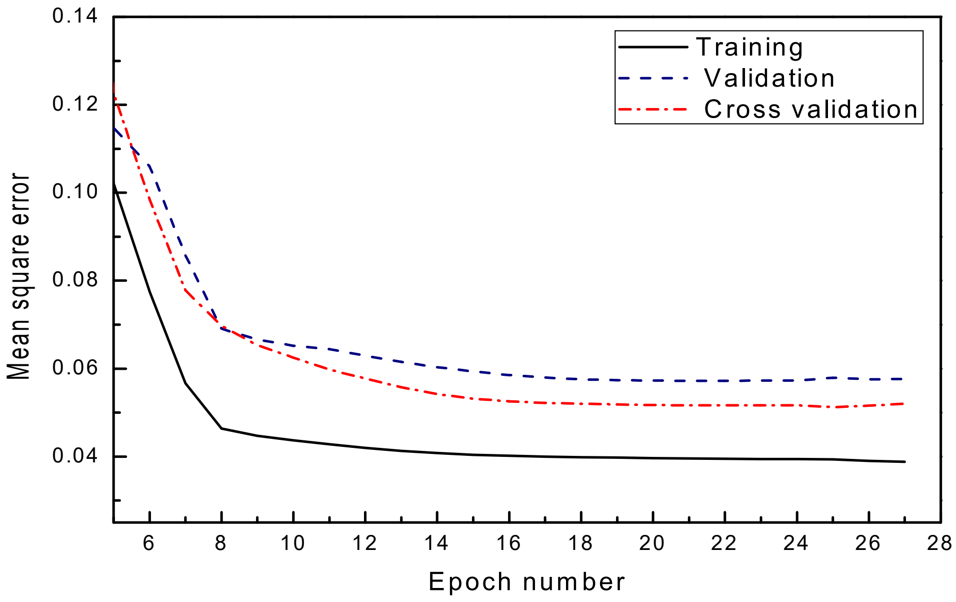
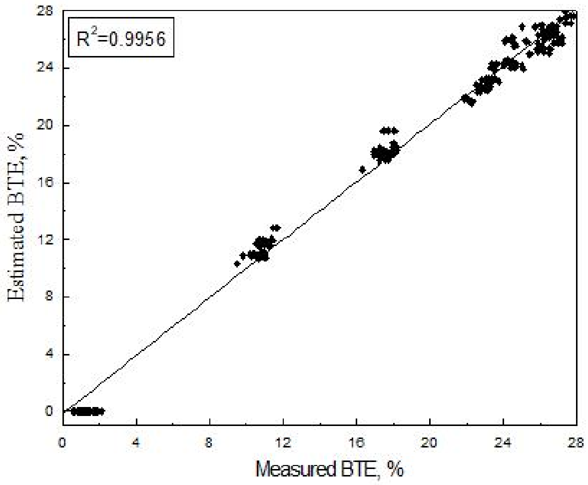


Fig. 6.4.1.1 Network performance

Table 6.4.1.1 Results for MLNN model for the estimated parameters

Sl. No.	Inputs	Architecture	MSE (validation)	MSE(cross-validation)	R^2
1.	Load, Blend, CR, Mixture	4_**2**_7	0.3477	0.3093	0.975
2.	Load, Blend, CR, Mixture	4_4_7	0.0994	0.0867	0.987
3.	Load, Blend, CR, Mixture	4_6_7	0.0694	0.0634	0.992
4.	Load, Blend, CR, Mixture	4_8_7	0.0634	0.0582	0.995
5.	Load, Blend, CR, Mixture	4_10_7	0.0503	0.0623	0.995

The various topologies of multilayer neural network with number of hidden neurons increased from 2 to 10 are trained employing NN toolbox of MATLAB®2014. The topology which provides smallest amount of MSE for confirmation data is chosen as the most excellent topology to predict the parameters. The MSE corresponding to most excellent architecture is used for parameters prediction. Table 6.3.1.1 shows the values of MSE for validation and cross-validation data for the most excellent architecture. It is seen that MSE values for validation and cross-validation data decreases as the number of hidden neurons are increased from 2 to 10. Thereafter, employing inputs at the hidden neurons more than eight does not show any significant improvement in MSE. The finest architectures as established above are employed for predicting the parameters on any specified working points of engine. Further, the accuracy of the developed model is evaluated by regression analysis. The criterion used for measuring the model accuracy in regression analysis is correlation coefficient (R^2). The correlation coefficient measures the strong point of relationship between measured parameter and estimated parameter, respectively. The R^2 ranges between -1 and +1. Further, R^2 value close to +1 point toward a stronger +ve linear relationship, while R^2 value close to -1 point toward a stronger -ve linear correlation. The comparison of measured and estimated parameters is done for all operating points in data set. Further, the coefficient of determination (R^2) for the estimated parameters viz., BSFC, BTE, EGT, and exhaust emissions CO, HC, NO_x and Smoke density is shown in the Figs. 6.4.1.2-6.4.1.8, respectively. It is seen from the Figs. 6.4.1.2-6.4.1.8 that expected values are nearer to the investigated values.



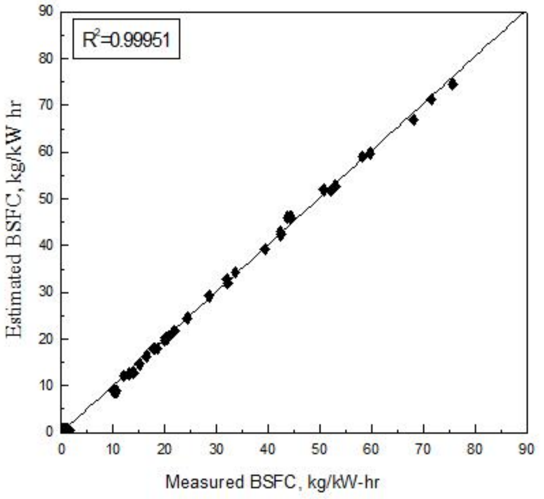
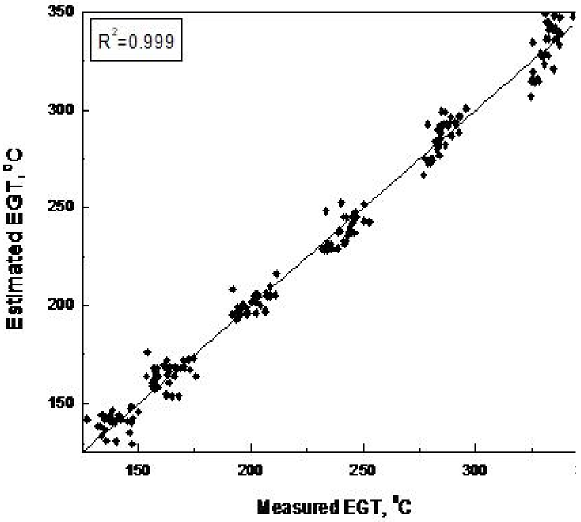


Fig. 6.4.1.2 Measured and estimated BTE **Fig. 6.4.1.3 Measured & estimated BSFC**



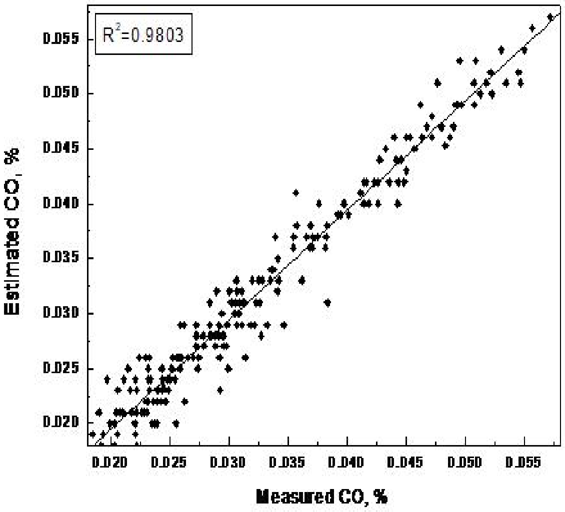
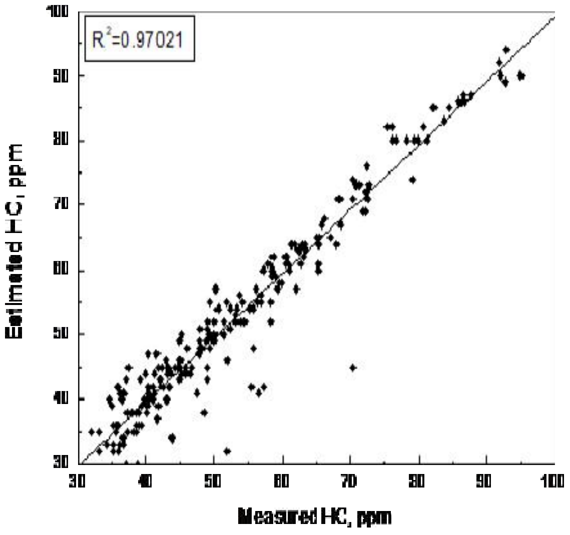


Fig. 6.4.1.4 Measured and estimated EGT **Fig. 6.4.1.5 Measured and estimated CO**



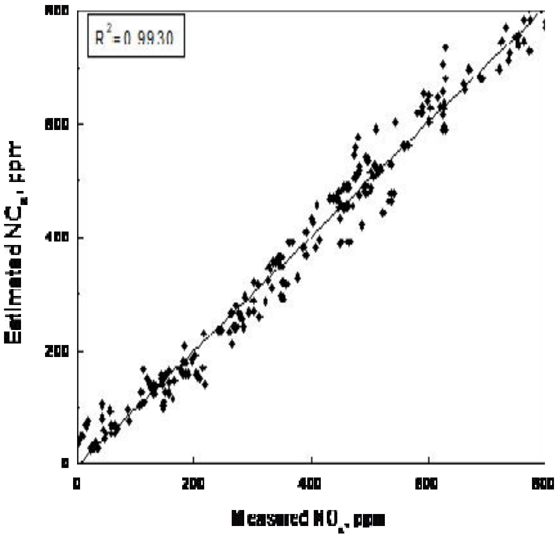


Fig. 6.4.1.6 Measured and estimated HC **Fig. 6.4.1.7 Measured & estimated NOx**

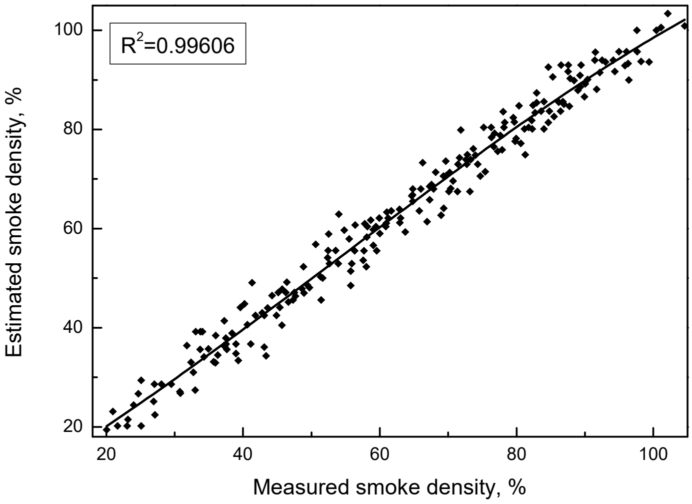


Fig. 6.4.1.8 Measured and estimated smoke density

Table 6.4.1.2 Performance and emission model

Sl. No.	Variable	R^2
1	BSFC	0.99560
2	BTE	0.99915
3	EGT	0.99299
4	CO emissions	0.98033
5	HC emissions	0.97021
6	NOx emissions	0.99300
7	Smoke emissions	0.99606

6.4.2 ANN model results for the mixtures of M4, M5, M6 and their blend with diesel fuel

The MLNN model developed for the different CR, load and various mixtures (M4, M5 and M6) and blends of mixture of M4, M5, M6 with diesel fuel prepared and the results of the same are discussed. On training of the network using the Levenberg Marqadrt method are illustrated in the Fig.6.4.2.1. The training, validation and cross validation errors are to decrease at the faster rate near the start of training period. The error results and coefficient of determination of MLNN model is given in the table 6.4.2.1.

The thermal performance parameters from the ANN model are illustrated in the Figs.6.4.2.2 to 6.4.2.4. The plots from the ANN model for the experimental values to estimated values for BTE, BSFC, and EGT. The emissions constituent models are illustrated in the Figs. 6.4.2.5-6.4.2.8. The plots for the experimental values and estimated values from the ANN model for CO, HC, NOx and smoke emission. The mean square errors for validation and cross validation are closer to each other and within the permissible limits. The standard permissible errors are considered to be less than 8% is taken as standard value.

Table 6.4.2.1 Results for MLNN model for the estimated parameters

Sl. No.	Inputs	Architecture	MSE (validation)	MSE(cross-validation)	R^2
1	Load, blend, CR, mixture	4_2_7	0.3161	0.2091	0.9721
2	Load, blend, CR, mixture	4_4_7	0.0986	0.1064	0.9882
3	Load, blend, CR, mixture	4_6_7	0.0680	0.0753	0.9910
4	Load, blend, CR, mixture	4_8_7	0.0542	0.0499	0.9933
5	Load, blend, CR, mixture	4_10_7	0.0508	0.0465	0.9944
6	Load, blend, CR, mixture	4_12_7	0.0584	0.1033	0.9951

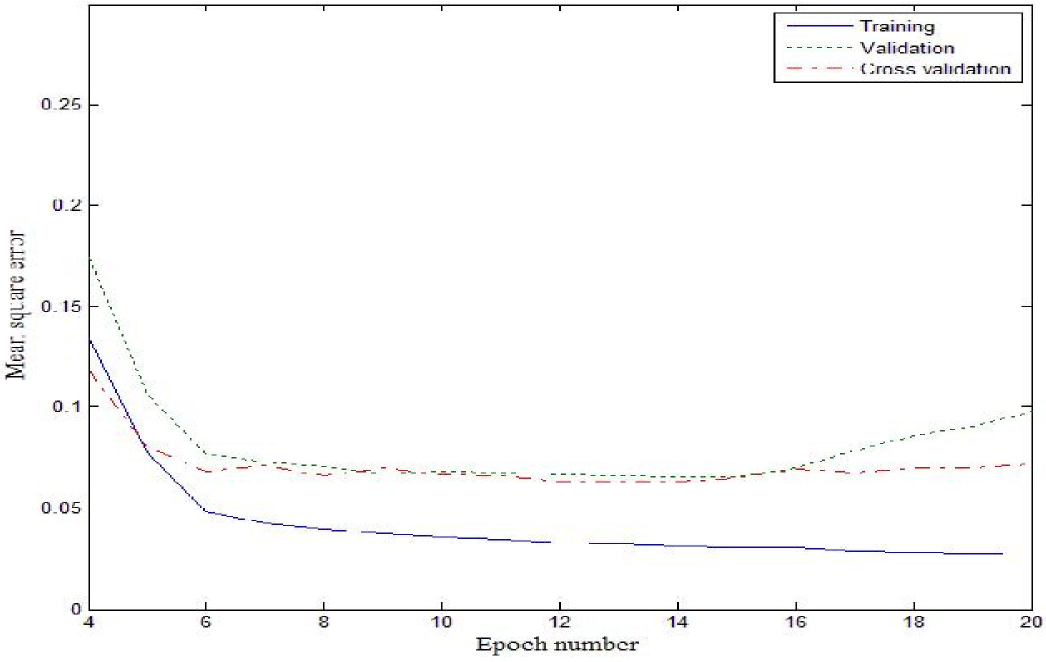


Fig.6.4.2.1 Network performance

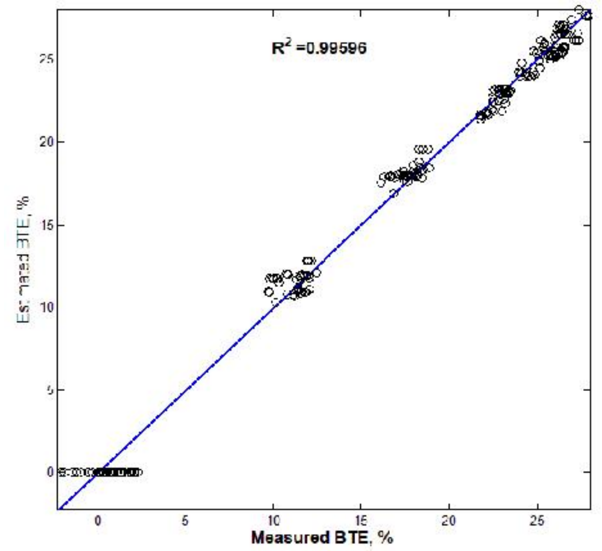


Fig. 6.4.2.2 Measured and estimated BTE

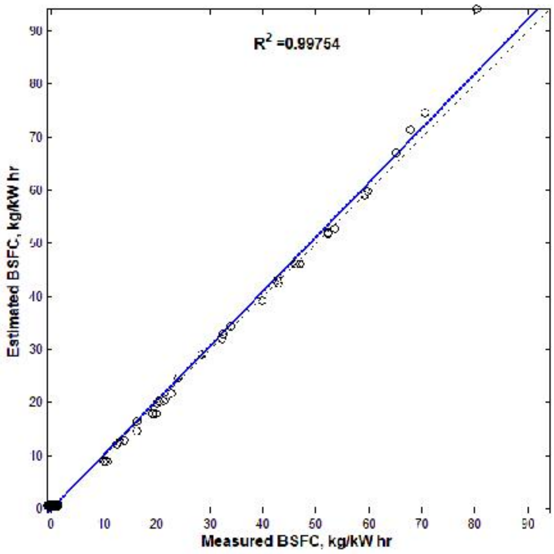


Fig.6.4.2.3 Measured and estimated BSFC

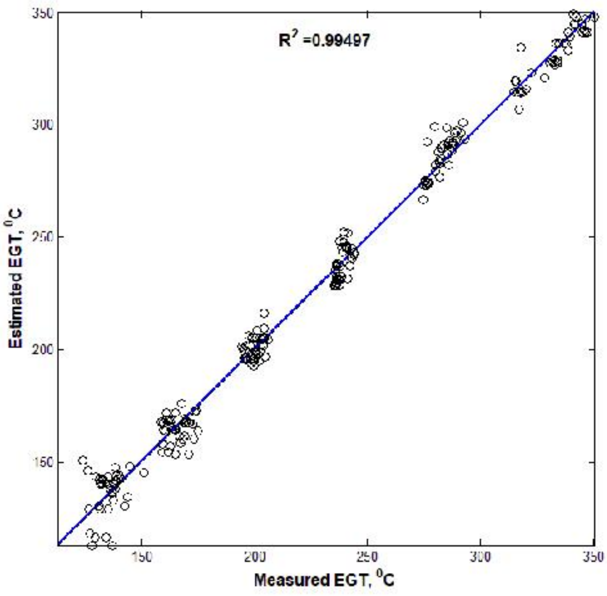


Fig.6.4.2.4 Measured and estimated EGT

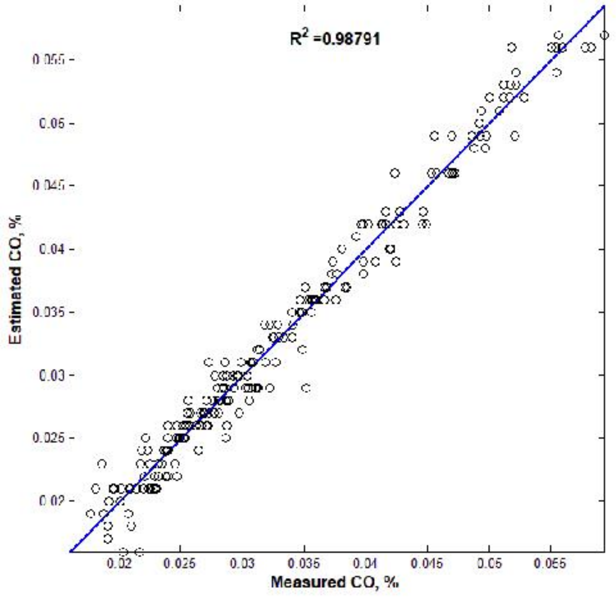
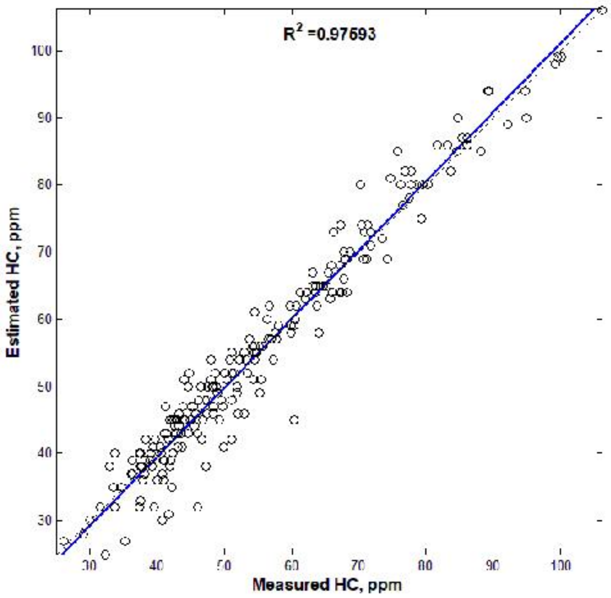


Fig. 6.4.2.5 Measured and estimated CO



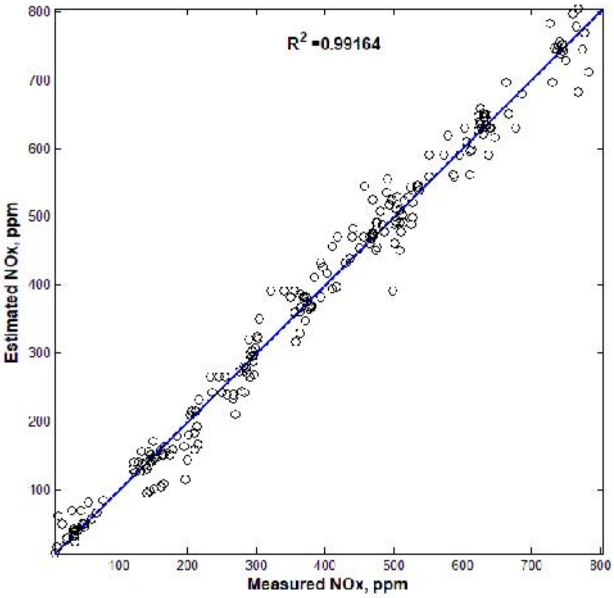


Fig. 6.4.2.6 Measured and estimated HC **Fig.6.4.2.7 Measured and estimated NOx**

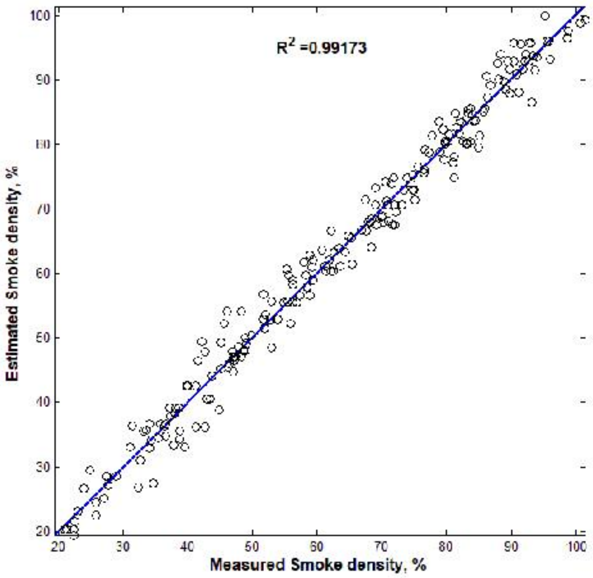


Fig. 6.4.2.8 Measured and estimated smoke density

Table 6.4.2.2 Results of performance and emission model

Sl. No.	Variable	R^2
1	BSFC	0.99596
2	BTE	0.99754
3	EGT	0.99497
4	CO emissions	0.98791
5	HC emissions	0.97593
6	NOx emissions	0.99264
7	Smoke emissions	0.99173

6.4.3 ANN model results for the M7, M8 and M9 mixtures and their blend with diesel

The MLNN model developed for the different CR, load and various mixtures (M7, M8 and M9) and blends of mixture of M7, M8, M9 with diesel fuel prepared and the results of the same are presented below. On training of the network using the Levenberg Marqadrt method are illustrated in the Fig.6.4.3.1. The training, validation and cross validation errors are to decrease at the faster rate near the start of training period. The error results and coefficient of determination of MLNN model is given in the table 6.4.3.1.

The thermal performance parameters from the ANN model are illustrated in the Figs.6.4.3.2 - 6.4.3.4. The plots for the experimental values to estimated values from the ANN model are for BTE, BSFC, and EGT. The emission constituents for the ANN model are illustrated in Figs. 6.4.3.5-6.4.3.8. The plots from the ANN model are for the experimental values and estimated values for CO, HC, NOx and smoke emissions. The mean square errors for validation and cross validation are closer to each other and within the permissible limits. The standard permissible errors are considered to be less than 10% is taken as standard.

Table 6.4.3.1 Results for MLNN model for the estimated parameters

Sl. No.	Inputs	Architecture	MSE (validation)	MSE(cross-validation)	R^2
1	Load, blend, CR, mixture	4_2_7	0.2010	0.2365	0.9714
2	Load, blend, CR, mixture	4_4_7	0.1011	0.0789	0.9877
3	Load, blend, CR, mixture	4_6_7	0.0462	0.0779	0.9919
4	Load, blend, CR, mixture	4_8_7	0.0544	0.0713	0.9935
5	Load, blend, CR, mixture	4_10_7	0.0542	0.0607	0.9938
6	Load, blend, CR, mixture	4_12_7	0.0651	0.0649	0.9962

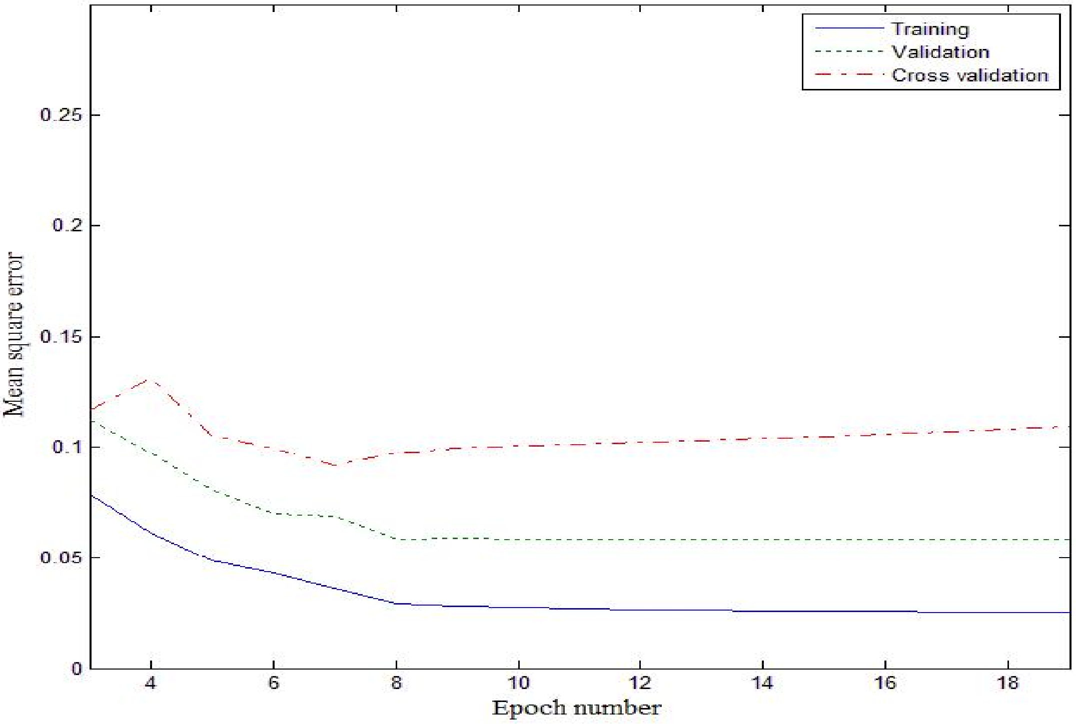


Fig.6.4.3.1 Network performance

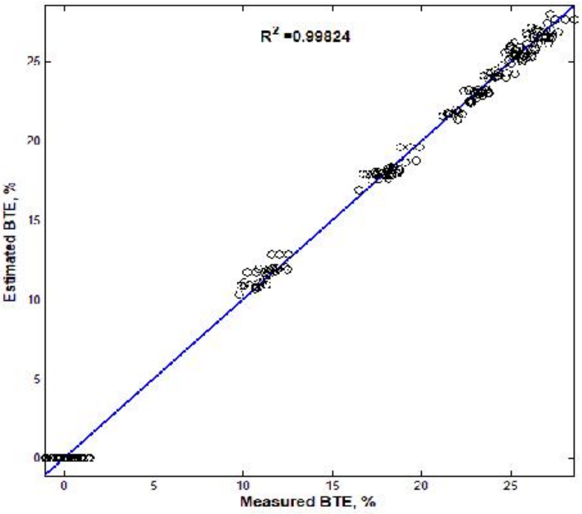


Fig. 6.4.3.2 Measured and estimated BTE

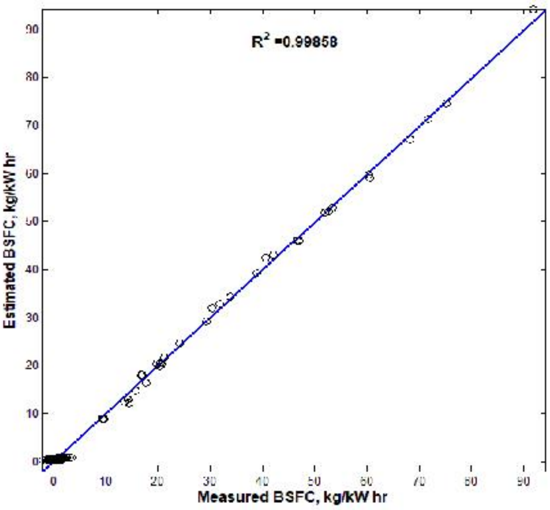
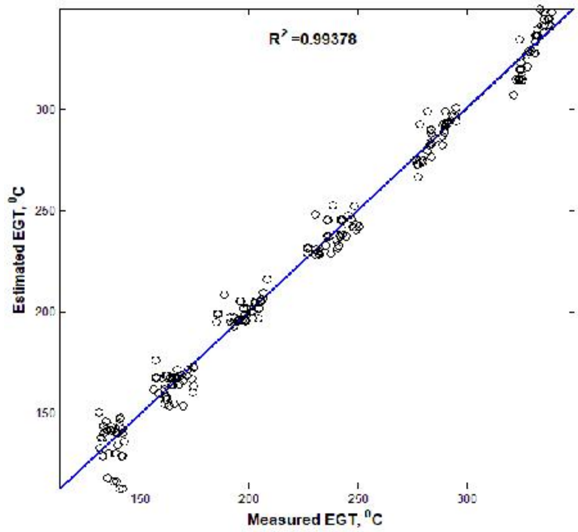


Fig.6.4.3.3 Measured and estimated BSFC



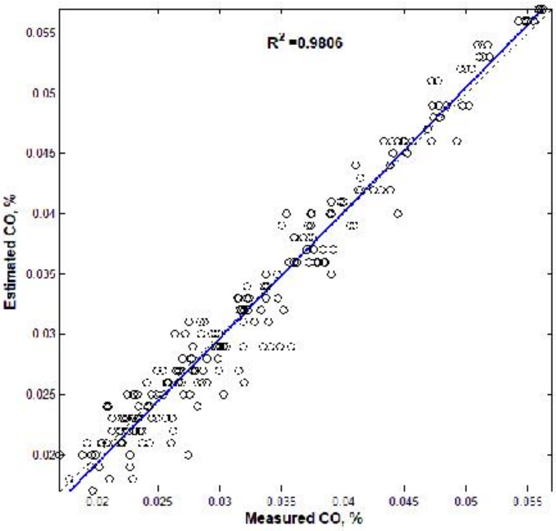
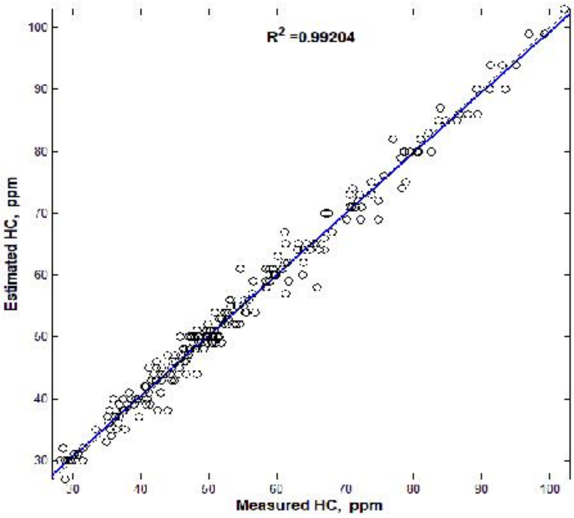


Fig. 6.4.3.4 Measured and estimated EGT

Fig.6.4.3.5 Measured and estimated CO



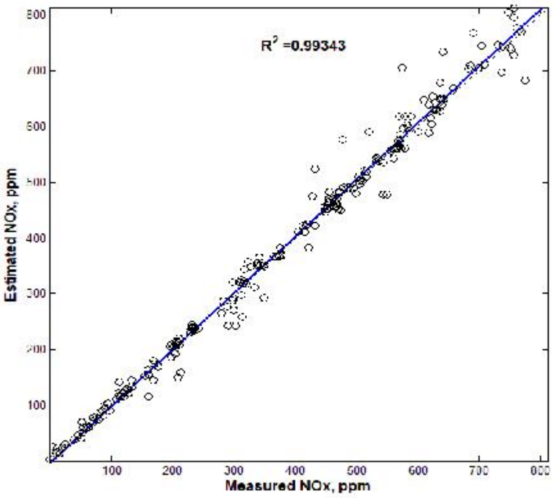


Fig. 6.4.3.6 Measured and estimated HC

Fig. 6.4.3.7 Measured and estimated NOx

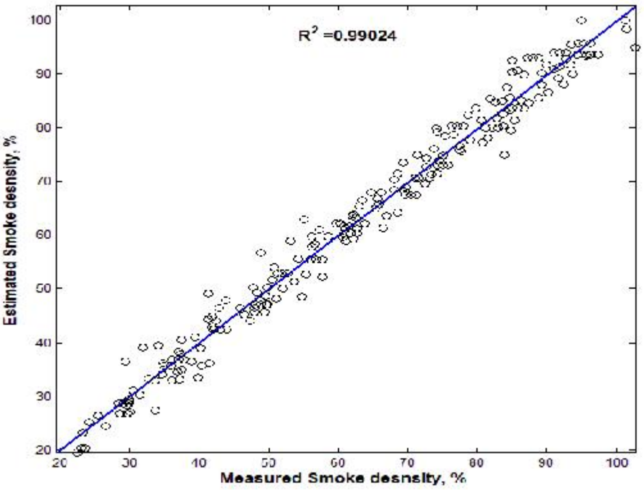


Fig. 6.4.3.8. Measured and estimated Smoke density

Table 6.4.2.2 Results of performance and emission model

Sl. No.	Variable	R^2
1	BSFC	0.99824
2	BTE	0.99858
3	EGT	0.99376
4	CO emissions	0.9806
5	HC emissions	0.99204
6	NOx emissions	0.99343
7	Smoke emissions	0.99024

6.5 Summary

This study develops the MLNN model to estimate BTE, BSFC, EGT, carbon monoxide, unburnt hydrocarbons, nitrogen oxide, and smoke emissions. The training and validation data for developing MLNN are generated at various operating points on an experimental test rig consisting of four stroke, single cylinder, DI VCR diesel engine attached to the eddy current dynamometer. The inputs to Multi Layer Neural Network are compression ratio, load, blends and mixtures. Further, different topologies of Multi Layer Neural Network with number of hidden neurons varying from 2 to 10 are trained employing NN toolbox of MATLAB®2014. The topology which provide smallest amount of MSE for validation data is chosen as the most excellent topology to predict the parameters for the mixture M1, M2 and M3. The different topologies of multilayer neural network with number of hidden neurons varying from 2 to 12 are trained employing the NN tool box of MATLAB®2014. The topology which provides the least MSE for the validation data is chosen for the mixtures M4, M5, M6 and M7, M8, M9. The parameters predicted by MLNN are found to be quite close to experimental values with reasonable accuracy.

Chapter 7

CONCLUSIONS

The core endeavor of this research is to investigate the combustion, performance and emission characteristics of the engine using the mixture of two biodiesel in a blend with diesel fuel. It is also the study of the impact of the various factors like CR, load, blend ratio and mixture ratio on combustion, performance and emission characteristics of engine and analysis of the same.

7.1 Outcome of literature review

Review of the work done by various researchers in the past was carried out with reference to the topic, the use of biodiesel with diesel blends and a mixture of two biodiesel with diesel blends as an alternate fuel in the existing diesel engines without or with little modification. work done on the fuel properties and their impact on combustion, performance, and exhaust emission constituents of the engine is thoroughly reviewed.

Based on the open literature available the following conclusions are drawn:

The fuel properties vary from biodiesel to biodiesel in terms of density, viscosity, heating value, cloud point, filter plugging point. The fuel properties have a specific influence on the combustion, thermal performance and emission characteristics of the engine.

The combustion in the diesel engine largely follows two stages which are premixed combustion and mixing controlled combustion. The inherent oxygen, CN, fuel viscosity and heating value may affect the mixture formation and that may shift the ratio of premixed and mixing controlled combustion stage. The ignition delay which is primarily influenced by combustion temperature and CN, if lengthened allows a large amount of fuel to be mixed with air before the ignition which results in strong uncontrolled combustion that increases heat release rate lead to higher noise and oxides of nitrogen formation.

The particulate matters are formed in mixing controlled combustion stage in the fuel rich and lean fuel-air zone. The nonexistence of aromatics and inherent oxygen with biodiesel fuels will reduce the particulate matters considerably.

The most promising biodiesels are produced by the transesterification method using vegetable oils with methanol or ethanol in presence of catalysts to produce fatty acids of methyl or ethyl esters. The produced biodiesel may be used in existing CI engines without or with little modification.

Biodiesel produced have poor oxidation stability and poor cold start properties than the petroleum diesel fuel. Production price of biodiesel fuels is higher than diesel fuel.

Most of the literature point towards the reduced CO, HC, particulate formation and higher NOx emissions for the biodiesel used engines than diesel fuel may be because of inherent oxygen and lower aromatics.

Based on the different criteria the different fuels are chosen for the investigations are Pongamia, Jatropha, and Simarouba biodiesel, as they are believed to be the potential alternative fuel for diesel engines in the years to come. These can be cultivated on all type of land under any climatic conditions.

7.2 Fuel property analysis

7.2.1 Fuel properties of a mixture of two biodiesels

The various fuel properties are investigated using ASTM standard equipment and procedure. The fuel properties investigated are density and viscosity.

The mathematical correlations are established for density and viscosity of biodiesel blends like Pongamia and Jatropha, Jatropha and Simaruoba, Pongamia and Simarouba, as a function of volume fraction and temperatures. The established correlations are unique in nature.

The correlations for various mixture are as under, for P-J mixture are specified in (Eq. 7.1, 7.2), J-S mixtures (Eq.7.3, 7.4), and P-S mixtures (Eq. 7.5, 7.6)

$$\circ_{P-J} = [0.200(X_{P-J}\%) + 862][-0.00058\ (T) + 1.02324] \qquad \text{kg/m}^3 \qquad (7.1)$$

$$\neg_{P-J} = [0.014(X_{P-J}\%) + 4.540][-0.78\ln(T) + 3.875] \qquad \text{mm}^2\text{/sec} \qquad (7.2)$$

X_{P-J} is the % Pongamia biodiesel in Pongamia-Jatropha blends, T is the temperature in ºC

$$\text{kg/m}^3 \qquad (7.3)$$

$$\circ_{J-S} = [0.029(X_{J-S}\%) + 859.3][-0.00061(T) + 1.02413]$$

$$\text{mm}^2\text{/sec} \qquad (7.4)$$

$$\neg_{J-S} = [-0.009(X_{J-S}\%) + 5.964][-0.76\ln(T) + 3.802]$$

$X_{J\text{-}S}$ is the % Jatropha biodiesel in Jatropha-Simarouba blends, T is the temperature in ºC

$$°_{P-S} = [0.225(X_{P-S}\%) + 859.1][-0.00060(T) + 1.0239] \qquad \text{kg/m}^3 \qquad (7.5)$$

$$\neg_{P-S} = [0.012(X_{P-S}\%) + 4.977][-0.77\ln(T) + 3.862] \qquad \text{mm}^2\text{/sec} \qquad (7.6)$$

$X_{P\text{-}S}$ is the % Pongamia biodiesel in Pongamia-Simarouba blends, T is the temperature in ºC

Density of Pongamia, Jatropha and Simarouba methyl-esters at 40^0 C are 881.8 kg/m^3, 868.6 kg/m^3 and 859.2 kg/m^3 respectively and are reduced to 854.8 kg/m^3, 833.6 kg/m^3 and 833.2 kg/m^3 at 95^0 C.

The kinematic viscosity of Pongamia, Jatropha and Simarouba methyl-esters at 40^0 C is 6.08 mm^2/sec, 5.0 mm^2/sec, and 6.01 mm^2/sec respectively and reduced to 1.91 mm^2/sec, 1.5 mm^2/sec and 2.9 mm^2/sec at 95º C.

The results from the correlations compare well with the experimental results.

These correlations can be set as standards for the said biodiesel fuels.

7.2.2 Properties of Simarouba and diesel blends

Simarouba biodiesel and diesel blends are investigated for the properties like; density, viscosity, flash point, and heating value.

The mathematical correlations are established to find the density and viscosity of the Simarouba and diesel blends at various temperatures.

The correlations are also established for flash point and heating value with the various volume fraction of biodiesel in the blends.

The mathematical correlations are also found for the density, flash point, heating value with the viscosity of the Simarouba and diesel blends.

The results from the various correlations compare well with the experimental results.

It is observed that the properties of various mixtures are comparable with diesel and are close to the ASTM and European standard.

7.3 Combustion, thermal performance and emission characteristics analysis

7.3.1 Combustion thermal performance and emission characteristics of a mixture of two (P-J) biodiesel in a blend with diesel.

The experimental investigation is carried out on a single cylinder, four strokes, DI VCR CI engine using a mixture of two biodiesel in a blend with diesel fuel. The parameters are evaluated at compression ratio 16, 17 and 18, for the various blends ratios and operating loads of the engine(zero to the rated load). The combustion characteristics investigated are cylinder pressure, maximum cylinder pressure, heat release; the rate of pressure rise, mass fraction burned, etc. The thermal performances evaluated are BTE, BSFC and EGT. The various exhaust emissions measured are CO, HC, NOx, and smoke.

Based on the experimental results the following observations are made and the conclusions are drawn

- The biodiesel obtained from different tree born oils can be used as an alternative fuel in a diesel engine without or with little modification to the engine.
- The mixture of two biodiesel in a blend with diesel can be used in a diesel engine with or without changes to the engine hardware.
- The cylinder gas pressures are higher for the blends which may be because of higher cetane number and inherent oxygen of biodiesel in the blends may accelerate and complete the combustion of blends.
- Heat releases for the blends are decreased compared to diesel fuel because of reduced ignition delay and lower heating value of the methyl esters in the blends.
- Maximum cylinder pressures are higher for the blends because of complete combustion of blends.
- The injection and combustion are advanced for the blends because of higher bulk modulus and higher CN of biodiesel in the blends.
- The combustion durations are increased for the blends because of higher viscosity and inferior volatility of biodiesel in the blends.
- The BTE for the blend B40M2 is decreased by about 2.4% and BSFC for the blend B60M2 is increased by about 6.25% compared to diesel fuel. this may be related to the lower heating value and higher viscosity, inferior volatility of

biodiesel in the blends contributes in the complete combustion of blends. Hence, both the fuels result in the performance of similar order.

- The CO, HC, and smoke emissions are reduced by 47.8%, 51.7%, and 13.6% respectively for blend B40M2 compared to the diesel fuel. At the same time, The emissions are increased for the higher blends may be because of increased viscosity and inferior volatility of biodiesel in the blends. The emissions are lower in comparison with neat diesel.
- The NOx emissions are increased for the blend B40M2 by about 25.7% compared to the diesel fuel. This may be because of higher combustion temperature and inherent oxygen of biodiesel in the blends forms higher NOx.
- A mixture of two biodiesel in any volume fraction in a blend with diesel fuel or mixture two biodiesel may be used in the diesel engine without any trouble.

The results reveal that B40M2 is the better blend having higher maximum cylinder pressure, better rate of pressure rise and BTE are comparable with diesel fuel. There is a higher reduction of emissions for B40M2 blends. Hence B40M2 may be substitute fuel for the diesel without any modification to the engine.

7.3.2 Combustion thermal performance and emission characteristics of a mixture of two (P-S) biodiesel (M5) in a blend with diesel.

- The combustion characteristics are of P-S blends follow the comparable trend as that of P-J bends.
- The BTE is increased by 3% for B40M5 blend whereas for the B60M5 blend it decreased by about 1.6% compared to diesel fuel. This may be because of the better burning of blends influenced by the higher CN and natural oxygen available with biodiesel in the blends.
- The BSFC for the blend B40M5 is same as that of diesel fuel, even though the energy content is less, still, it gives similar BSFC because of inherent oxygen and higher CN may contribute in the complete combustion.
- The CO, HC, and smoke emissions are decreased for the blend B40M5 by about 43.5%, 23%, and 13.5% respectively compared to the diesel fuel for the rated load. The reduction of these emissions is because of the complete combustion of blends. The emissions are higher for the higher blends but are low compared to diesel fuel.

- The NOx emissions are increased for the blend B40M5 by about 22.1% compared to diesel fuel for the rated load due to the higher combustion temperature and natural oxygen of biodiesel in the blends.
- The mixture of two said biodiesel in a blend with diesel can be used as an alternative in a diesel engine without any trouble.

The results reveal that the blend B40M5 can be a better alternative fuel having higher maximum cylinder pressure, higher RPR, BTE, and BSFC are comparable with diesel fuel. The emissions for the B40M5 are significantly low compared to diesel fuel.

7.3.3 Combustion, thermal performance and emission characteristics of a mixture of two biodiesel (J-S) in a blend with diesel.

- The combustion characteristics of J-S blends follow the comparable tendency as that of P-J and P-S blends.
- The BTE for the blends B20M8 and B40M8 are increased by about 3.3% and 3.2% respectively at the rated load compared to diesel fuel, may be because of higher CN and inherent oxygen of biodiesel in the blends which contribute in the complete combustion.
- The BSFC of the blend B20M8 it is decreased by about 3.3% because of the lower heating value of the biodiesel in the blend. Whereas, for the blend B40M8, BSFC is comparable with diesel fuel which may be because inherent oxygen contributes in the complete combustion.
- EGT for the blend B20M8 is lower by about 1.6% compared to diesel fuel.
- The CO, HC and smoke emissions for the blend B20M8 are decreased by about 43.5%, 39.1%, and 8.7% compared to the diesel fuel at the rated load.
- The NOx emissions are increased by about 5.7% compared to diesel fuel at the rated load.
- The mixture of Jatropha and Simarouba biodiesel in a blend with diesel can be used as an alternative fuel in a diesel engine without complications.

The results reveal that the blend B20M8 can be an alternative fuel having higher maximum cylinder pressure, the maximum rate of pressure rise, higher BTE and BSFC compared to diesel fuel. The various emissions are decreased for the blend B20M8.

7.3.4 Combustion, thermal performance and emission characteristics and analysis using various mixtures of (P-J) in a blend with diesel

The mixture of two biodiesels in various ratios is blended with the diesel fuel and used in the investigation of combustion characteristics, thermal performance, and emission constituents of the engine at CR of 16, 17 and 18 for different loads.

Based on the experimental results and analysis the following conclusions are drawn.

- The cylinder pressures, maximum cylinder pressures, net heat release and RPR are higher at CR18 compared to CR16 and CR17. The better combustion characteristics at CR18 for the blends and the diesel fuel may be because of increased combustion temperature, higher temperature and density of the air.
- The cylinder pressure for the blends are marginally higher compared to the diesel fuel at CR18 may be because of higher cetane number and inherent oxygen of biodiesel in the blends.
- The heat release for the blends are lower compared to diesel fuel may be because of the lesser heating value of biodiesel in the blends.
- The rates of pressure rise for most of the blends are higher at CR18 compared to the diesel fuel.
- The BTE for the blend B40M2 is decreased by 2.4% in comparison with diesel fuel at CR18 for the rated load which may be because of the lower heating value of the biodiesel in the blends.
- The BSFC for the blend B40M2 is increased by about 6.6% at CR18 for the rated load compared to the diesel fuel. This may be because of the lesser heat content of biodiesel in the blends.
- The EGT for the blends is lesser compared to diesel fuel at CR18. The EGT for the blend B60M3 is decreased by 4% at CR18 compared to diesel fuel at the rated load. This is because of the complete combustion of blends. The lower EGT indicates better thermal efficiency.
- The harmful emissions such as CO, HC, and smoke for the blend B40M2 by about 47.8%, 51.7%, and 13.6% respectively compared to diesel fuel at CR18 for the rated load which may be because of inherent oxygen and higher CN, contribute in the complete combustion of blends. These emissions are less compared to CR16 and CR17 as well.

- The NOx emissions are increased for the blends by 23.2% at CR18 and 15.2% at CR17 compared to diesel fuel.

From the experimental results, it can be asserted that the blend B40M2 can be used as alternative fuel in a diesel engine without any changes to engine hardware. The combustion characteristics, thermal performance and emission characteristics of blends are towards the comparison with diesel fuel. The emissions are reduced significantly for the blends with an increase in NOx hence it is concluded that mixture of two biodiesel in a blend with diesel can be a potential alternative fuel to the diesel engine.

7.3.5 Combustion, thermal performance and emission characteristics analysis using various mixtures of P-S in a blend with diesel

- The cylinder pressures, maximum cylinder pressures, net heat releases, the rate of pressure rise are higher at CR18 compared to CR16 and CR17. The better combustion of fuels used in the investigation is for the reason that of increased combustion temperature and higher temperature, the density of the air at CR18.
- The Cylinder pressure for the various blends are higher in comparison to diesel fuel may be due to inherent oxygen and higher CN of biodiesel in the blends which contributes to the complete combustion of blends.
- The heat releases for the various blends are lesser for the blends in comparison to diesel fuel because of the lower heat value of biodiesel in the blends.
- The rates of pressure rise for the blends are almost comparable with diesel fuel and are higher for some of the lower blends may be because of better combustion.
- The start of injection and ignition are advanced for the blends compared to the diesel fuel because of higher bulk modulus, higher CN and inherent oxygen of biodiesel in the blends.
- Combustion durations are increased for the blends may be because of higher viscosity and inferior volatility of the blends.
- The BTE for the blend B40M4 is increased by 4% and B40M5 is increased by about 2.8% compared to diesel fuel at the rated load.
- The BSFC for the blend B40M4 and B40M5 are comparable with diesel fuel which may be because of inherent oxygen and higher CN of biodiesel in the blends which contribute in the complete combustion that increase the fuel efficiency.

- The EGT for the blends B40M4 and B40M5 are decreased by about 3.4% and 2.8% respectively in comparison to diesel fuel which may be for the reason that of complete combustion of blends.
- The CO, HC, and smoke emissions are decreased for the blend B40M4 by 43.5%, 38%, and 7.1% respectively, the decrease for the blend B40M5 are approximately 43.6%, 23% and 13.6% in comparison to diesel fuel at the rated load.
- The NOx emissions are increased for the blend B40M4 and B40M5 by about 11.8% and 8.9% respectively in comparison to diesel fuel for the rated load.

It is concluded that the mixture of P-S in a blend with diesel fuel at CR18 have better combustion, improved thermal performance for some of the blends and decreased emissions compared to CR16 and CR17. Hence blend B40M4 and B40M5 may perhaps be used in a diesel engine without any change to the engine hardware.

7.3.6 Combustion, thermal performance and emission characteristics analysis using various mixtures of J-S in a blend with diesel

- The combustion of J-S blends follows the comparable trend as that of P-J and P-S blends. Hence, both the fuels result in the performance of similar order.
- The BTE for the blends B40M8 and B40M9 are increased by about 1.6% and 2% respectively compared to diesel fuel at the rated load, which may be because inherent oxygen and higher CN contributes for the complete combustion of blends.
- The BSFC of the blends B40M8 are same as diesel fuel and B40M9 are increased by about 3.3% compared to diesel fuel for the rated load, this may be because of the inherent oxygen of biodiesel in the blends contributes incomplete combustion hence improve the fuel efficiency.
- The EGT of the blends B40M8 and B40M9 are reduced by about 4.1% and 3.8% respectively compared to diesel fuel at the rated load which results into higher BTE for the blends which is observed from the results.
- The emissions of CO for the blends B40M8 and B40M9 are decreased by about 37%, 39.1% respectively in comparison to diesel fuel for the rated load because of inherent oxygen contributes in the complete combustion of the blends.
- The emissions of HC for the blends B60M8 and B40M9 are decreased by about 33.3% and 17.3% respectively compared to diesel fuel for the rated load because of the earlier explained reason.

- The emissions of smoke for the blends B40M8 and B40M9 are decreased by about 9.1% and 10.4% respectively compared to diesel fuel for the rated load because of the complete combustion of the blends. The inherent oxygen is a source for the reduction in smoke emissions.
- The emissions of NOx for the blends B40M8 and B40M9 are increased by about 12.9% and 22.5% respectively compared to diesel fuel for the rated load because of higher combustion temperatures and inherent oxygen of biodiesel in the blends.
- A mixture of two biodiesel in any volume fraction in a blend with diesel fuel or mixture two biodiesel may be used in the diesel engine without any trouble.

The results reveal that B40M8 and B40M9 are the better blends having higher maximum cylinder pressure, better rate of pressure rise and BTE are comparable with diesel fuel. There is a higher reduction in emissions for the B60M8 blends. Hence B60M8 may be an alternative fuel for the diesel without engine modification.

7.3.7 ANN modelling

- ANN model is used to predict the complex interaction between the engine control variables and output response with minimum number of input parameters.
- The combined model is developed for thermal performance and emission constituents using Levenberg Marqadrt method.
- The performance characteristics and emission constituents of the engine are assessed by mean square error (MSE) and coefficient of determination (R) values as the assessment condition.
- The model developed gives the error within the permissible limits. The results indicated that TRAINLM predict the optimum correlation between the input parameters and output response of the engine.
- The designed ANN model is able to predict the high-quality relationship between the four input parameters with the seven response parameters with reasonable accuracy.
- The model developed to predict the results are comparable with the experimental values. The ANN model is a capable as a promising modelling technique with high economical benefit with low simulation run time.

  - When the ANN model is applied during engine testing phase, the number of experimental run can be reduced considerably and by conducting only the minimum number experiments required for the ANN modelling.
  - The developed model can be applied to other engine performance and emission applications.

7.4 Scope for further work

The suggestions for the feature investigation using mixture of biodiesel in blend with diesel fuel are as follows

- Investigations using the mixture of more than two biodiesel in blend with diesel fuel.
- Investigations with the change in volume fraction of biodiesel to 30% and 50% in the blend with diesel.
- Investigations with change in injection pressure and injection timing.
- Investigations with higher CR of 19, 20 and 21
- The endurance test of the engine using the mixture of two or more biodiesel in blend with diesel fuel.
- Use of the mixture of two or more biodiesel in blend with diesel fuel in the automobiles.

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Annexure- I

Properties of diesel and various biodiesels

Properties	Diesel	Pongamia biodiesel	Jatropha biodiesel	Simarouba biodiesel
Density, kg/m^3	830	890	874	880
Heating value, MJ/kg	44	39	41	39.8
Viscosity, at 40° C	2.27	6.08	5.0	6.01
Flash point, ° C	56	156	146	152
Cetane number	48	54	55	54
Oxygen content, %	--	11	11.5	11

Annexure-II

The Detailed Technical Specification of the Engine

Type of Engine	Make Kirlosker TV I , single cylinder for stroke CI engine, water cooled, rated power 3.5 kW, at 1500rpm, stroke 110mm, bore 87.5 mm, CR17.5 Modified to VCR of 12 to 18.
Dynamo meter	Eddy current type, water cooled, with loading unit
Calorimeter	With pipe in pipe type
Piezo sensor	Range 5000 psi, with low noise cable
Crank angle sensor	Resolution 1°, with speed of 5500 RPM with TDC pulse
Data acquisition device	NI USB-6210, 16 bit,250 ks/s
Piezo powering unit	Make-cuarda, moadel AX-409
Temperature sensor	Type RTD, PT100 and thermocouple, type K
Load Indicator	Digital, range 0-50 kg, supply 230 VAC
Load sensor	Load cell, type strain gauge, range 0-50 kg
Fuel flow transmitter	DP transmitter, Range 0-500 mm WC
Air flow transmitter	Pressure transmitter, Range (-) 250 mm WC
Software	“ICEngineSoft version 9” , compute the data of combustion and thermal performace
Rotameter	Engine cooling 40-400 LPH, Calorimeter cooling 25-250 LPH

Annexure III

Technical specification of pressure sensors

Sl.No.	Description	Data
1	Sensor name	Dynamic pressure sensor with built in amplifier
2	Make	PCB Piezotronics, INC
3	Model	HSM111A22
4	Range FS (5V output)	5000psi
5	Resolution	0.1 psi
6	Sensitivity	1mV/psi
7	Linearity	2%
8	Acceleration sensitivity	0.002psi/g
9	Operational temperature range	-100 to + 275° F
10	Excitation	2 to 20 mA
11	Sensing element	Quartz
12	Sensing geometry	Compression

Annexure IV

Technical specification of crank angle encoder

Sl.No.	Description	Data
1	Make	Kubler
2	Model	8.3700.1321.0360
3	Output	Push-pull (AA, BB,OO)
4	PPR	360
5	Encoder diameter	Dia. 37,
6	Shaft size	Dia. 6mm x 12 mm length
7	Weight	120 mg

Annexure-V

Technical specification of AVL 437 smoke meters

Sl. No.	Description	Data
1	Measuring range	0-100 %
2	Accuracy and repeatability	±1% of full scale
3	Linearity check	48.4 to 53.1%/1.43m^{-1} to1.76m^{-1}
4	Alarming signal temperature	Lights up when temperature of measuring temperature is below 70° C
5	Measuring chamber length	430±5 mm
6	Measuring chamber heating	Thermostatically controlled
7	Light source	Halogen lamp 12V
8	Detector	Selenium photocell diameter 45mm
9	Weight	24Kg

Annexure VI

Technical specification MARS gas analyser

Sl.No.	Description	Units
1	Principle	NDIR (Non-dispersive infrared based Technology
2	Gas measured	CO, CO_2, HC, O_2, and NOx
3	Measuring range	CO(0-10%vol), CO_2 (0-20% vol), HC (0-15000ppm vol), O_2 (0-25% vol), NOx (0-5000ppm vol)
4	Resolution	CO(0.001%), CO_2 (0.01%), HC (1ppm), O_2 (0.01%), NOx (1pp)
5	Gas flow rate	1500ml/min
6	Response time	Less than 15 seconds
7	Warm-up time	4 minutes
8	Zero calibration	After every 25 minutes
9	Operating Conditions Pressure Humidity temperature	 860 hpa to 1060 hpa 0 to 90% 5° to 45° C
10	Storage Temperature	0 to 50° C

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