Major Dissertation

entitled

EXPERIMENTAL STUDIES ON NO_X REDUCTION IN A DIESEL ENGINE WITH COLD EGR

submitted to the faculty of technology, university of Delhi
in fulfillment of requirements for the award of the degree of

Master of Engineering

In
Thermal Engineering
Department of Mechanical Engineering
Delhi College of Engineering
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2009

CERTIFICATE

It is to certify that the dissertation entitled "**EXPERIMENTAL STUDIES ON NO_X REDUCTION IN A DIESEL ENGINE WITH COLD EGR**" submitted by Mr. Vipin Kumar Sharma, 19/THR/07 in partial fulfillment for the award of the Degree of Master of Engineering in Thermal Engineering, is an authentic record of student's own work carried out by him under my guidance and supervision.

It is also certified that this dissertation has not been submitted to any other Institute/University for the award of any degree or diploma.

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ACKNOWLEDGEMENT

It gives me immense pleasure to acknowledge my indebtedness and great sense of gratitude to Dr. Naveen Kumar, Professor, Mechanical Engineering Department, Delhi College of Engineering, Delhi for his able guidance, sympathetic and encouraging attitude throughout the project work. In spite of his busy schedule, he could find time to provide me precious guidance. I also take this opportunity to thank Prof. S. Maji, Head, Mechanical Engineering Department and other faculty members of the department for encouragement and guidance.

I am thankful to Sh. Kamal Nain, Sh. Bhupender Singh, Sh. Virender Singh, Sh. vikram Singh and other project staff of Center for Advanced Studies and Research in Automotive Engineering for all assistance during execution of this project work. I am thankful to Shri Ashish Karnwal, PhD scholar for his time and help available to me. My sincere thanks are also due to my fellow friends and colleagues who were always there to lend a helping hand in the hour of need.

September, 2009 **Vipin Kumar Sharma**

ABSTRACT

Environmental degradation and depleting oil reserves are matters of great concern round the globe. Developing countries like India depend heavily on oil import for meeting its growing energy need. India is a diesel driven economy and consumption of diesel is four to five times of gasoline consumption. However, un-certainties about supply, escalating prices and environmental degradation caused by indiscriminate burning of diesel have mandated exploration of renewable alternative fuels for diesel engines and biodiesel a fuel consisting of the alkyl esters of fatty acids derived from variety of vegetable oils or animal fats is becoming relevant for substitution of diesel. Various studies have shown that biodiesel fuelled engines produce less carbon monoxide (CO), unburned hydrocarbon (HC), and particulate emissions compared to diesel fuel but higher NO_x emissions. Exhaust gas recirculation (EGR) is an effective method to reduce NO_x from biodiesel fuelled engines because it lowers the flame temperature and the oxygen concentration in the combustion chamber. However, EGR results in higher smoke opacity. Cold EGR, a low cost technique of exhaust gas recirculation, is effectively used in this work to overcome, higher NO_x emissions while using biodiesel. The objective of current research work is to investigate the usage of biodiesel and EGR simultaneously in order to reduce the emissions of all regulated pollutants from diesel engine. A single cylinder, air-cooled, constant speed direct injection diesel engine was used for the experimental work and a cold EGR system was developed and fitted in the engine. Various emissions such as HCs, NO_x, CO and smoke opacity were measured. Engine performance parameters such as brake thermal efficiency (BTE) and brake specific energy consumption (BSEC) were also calculated from the measured data. The results from the exhaustive experiment suggest that up to 40% engine load, 25-30% EGR rate gave excellent NO_x reduction without any significant penalty on smoke opacity or BSEC. At full load 15% EGR rate was found to be optimum, with higher EGR rate of 20% resulting in inferior performance and heavy smoke.

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NOMENCLATURE

ATDC	After Top Dead Center
AVL-437	AVL-437 Smoke Meter
BMEP	Break Mean Effective Pressure
BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
BTDC	Before Top Dead Center
^{o}C	Degree Celsius
Cc	Cubic centimetre
CI	Compression Ignition
cm^{-1}	Per Centimeter
CN	Cetane Number
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPCB	Central Pollution Control Board
cSt	Centi Stoke
CV	Calorific Value
DI	Direct Injection

EGR	Exhaust Gas Recirculation
g/cc	Gram per cubic centimeter
HC	Hydrocarbon
H_2O	Water
HP	Horse Power
Hz	Hertz
IC	Internal Combustion
IDI	Indirect Injection
IS	Indian standard
JO	Jatropha oil
KOH	Potassium Hydroxide
KVA	Kilo Volt Ampere
kW	Kilo Watt
kW-hr	Kilo Watt Hour
JCL	Jatropha Curcas linn
Min.	Minute
Mt	Million Tonnes
Mtoe	Million Tonne of Oil Equivalent
NO	Nitric Oxide
Nos.	Numbers

NO_2	Nitrogen Di-oxide
NO_x	Oxides of Nitrogen
PM	Particulate Matter
Ppm	Parts per million
Rpm	Revolutions Per Minute
Sfc	Specific Fuel Consumption
TDC	Top Dead Center
ULSD	Ultra Low Sulphur Diesel
UBHC	Unburnt Hydrocarbon
Vs	Versus
ρ	Density
%	Percentage

CHAPTER 1

INTRODUCTION

Energy is an underlying driver of economic growth and social development. Human consumption of energy in the form of fossil fuels, primarily in developed countries, is altering the Earth's climate and has been a matter of great concern. While evidence suggests a need for both demand reduction and alternative energy sources in the developed countries, in the developing countries, there is a need to increase energy supplies to meet basic needs-and to do it in a way that promotes sustainable development. Future economic growth shall crucially depend on the long-term availability of energy in increasing quantities from sources that are dependable, safe and environment friendly.

1.1 Energy Scenario

As mentioned above energy has always played an important role in development of a country. It is considered as an index of economic growth and social development. Per capita energy consumption is considered as measure of prosperity of a country besides GDP and per capita income. The world has witnessed industrial revolution in the past century, and it has also faced serious problems of indiscriminate utilization of the energy resources. The ideology was related to more energy consumption for higher industrial development and never considered better and efficient use of energy.

1.1.1 Global Primary Energy Reserves

1.1.1.1 Coal

The proven global coal reserve was estimated to be 8,26,001 million tonnes by end of 2008. The USA had the largest share of the global reserve (28.9%) followed by Russia (19.0%), China (13.9%). India was 4th in the list with 7.1%.

1.1.1.2 Oil

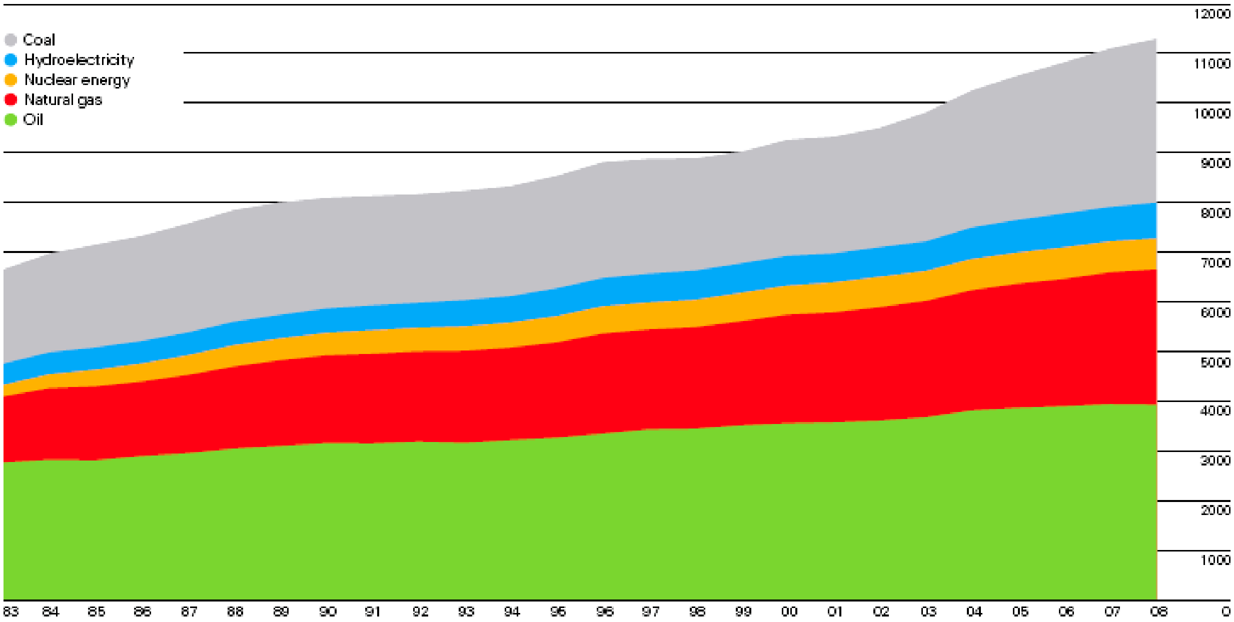
The global proven oil reserve was estimated to be 1258.0 billion barrels by the end of 2008. Saudi Arabia had the largest share of the reserve with almost 21.0% and India had only 0.5% share of the world reserve.

1.1.1.3 Gas

The global proven gas reserve was estimated to be 185.02 trillion cubic metres by the end of 2008. The Russian Federation had the largest share of the reserve with almost 23.4% and India had only 0.6% share of the world reserve.

World oil and gas reserves are estimated at just 42 years and 60.4 years respectively. Coal is likely to last a little over 122 years. However, India's oil and gas reserves are estimated at just 20.7 years and 35.6 years respectively and Coal is likely to last a little over 114 years [1].

The global primary energy consumption at the end of 2008 was equivalent to 11294.9 million tonnes of oil equivalent (MTOE). The Figure 1.1 represents the primary energy consumption fuel wise which clearly dominated by fossils fuels.



World primary energy consumption grew by 1.4% in 2008, below the 10-year average. It was the weakest year since 2001. Oil remains the world's dominant fuel, though it has steadily lost market share to coal and natural gas in recent years. Oil's share of the world total has fallen from 38.7% to 34.8% over the past decade. Oil consumption and nuclear power generation declined last year, while natural gas and coal consumption, as well as hydroelectric generation, increased.

Figure 1.1:- Energy share graph [1]

The primary energy consumption for few of the developed and developing countries is shown in Table 1. It may be seen that India's absolute primary energy consumption is only 1/26th of the world, 1/5.31th of USA, 1/1.17th time of Japan but 1.3, 1.68, 2.05 times that of Canada, France and U.K. respectively.

Table 1:- Primary Energy Consumption by Fuel, 2008 [1]

In Million tonnes oil equivalent						
Country	Oil	Natural Gas	Coal	Nuclear Energy	Hydro electric	**Total**
USA	884.6	600.7	665.0	192.0	56.7	**2299.0**
Canada	102.0	90.0	33.0	21.1	83.8	**329.8**
France	92.2	39.8	11.9	99.6	14.3	**257.9**
Russian Federation	130.4	378.2	101.3	36.9	37.8	**684.6**
United Kingdom	78.7	84.5	35.4	11.9	1.1	**211.6**
China	375.7	72.6	1406.3	15.5	132.4	**2002.5**
India	**135.0**	**37.2**	**231.4**	**3.5**	**26.2**	**433.3**
Japan	221.8	84.4	128.7	57.0	15.7	**507.5**
Malaysia	21.8	27.6	5.0	-	1.5	**56.0**
Pakistan	19.3	33.8	6.7	0.4	6.3	**66.5**
Singapore	49.9	8.3	-	-	-	**58.2**
TOTAL WORLD	**3927.9**	**2726.1**	**3303.7**	**619.7**	**717.5**	**11294.9**

1.1.2 Energy Distribution between Developed and Developing Countries

India is rich in coal and abundantly endowed with renewable energy in the form of solar, wind, hydro and bio-energy, its hydrocarbon reserve is 0.8 billion tones(at the end 2008) which are really very small (0.5 per cent of world's reserve). India accounted for 10.88 % of total primary energy consumption in Asia-Pacific region and 3.83 % of world primary consumption in 2008[**1**]. Per capita energy consumption remains low as 510.0 KGOE (Kilogram of oil equivalent) compared with a world average of 1820.0 KGOE in 2006 [2].

India is one of the fastest growing economy of world and has to extensively use energy to sustain its growth Since India does not have huge reserves of petroleum products, it is heavily dependent upon the import of petroleum products to cater its need for automobiles and other applications. Escalating prices, insufficient supply and limited reserves of petroleum have imposed an enormous burden on country's foreign exchange. In year 2007-08, the indigenous production of crude oil was 34.11 million tones where as consumption were 155.78 million tones forcing to import 121.67 million tones of crude petroleum [3]. The country is spending a great amount of valuable foreign exchange towards import of petroleum oil which could otherwise be utilized for various other development work, which might ultimately prove to be more beneficial to Indian people.

1.2 DIESEL ENGINE AND INDIAN ECONOMY

The diesel engine is typically more efficient than the gasoline engine due to higher compression ratio. Diesel engines also do not suffer from size and power limitations, which the SI engine is prone to. Hence, keeping these factors into account, they are the invariable choice for industrial, heavy duty and truck/trailer engines. Buses and certain locomotives also use diesel engines. Diesel engines also find use as small captive power plant engines, tractor engines and irrigation pump sets. India, which is at a developing stage in its history, has a huge demand for diesel driven machines and unlike countries like USA, is a diesel driven economy. Large proportion of fuel used is diesel, especially in transportation sector. India consumed 10.327 million tones of gasoline (petrol), as compared to 42.847 million tons of diesel in 2007-08 [3]. India is an agriculture based economy and agriculture is an energy transformation process as energy is produced and consumed in it. The production of energy is carried through process of photosynthesis in which solar energy is converted into biomass. Agriculture in India is heavily based upon petroleum and its derived products such as fertilizers and pesticides. Energy sources used in agriculture are oil and electricity whereas indirect energy sources are chemical fertilizers and pesticides. Thus, keeping the above discussion in mind it is imperative for the Indian economy to find a substitute to fuel variety of diesel engines that it is so much dependent upon so as to fulfill its journey to becoming a developed nation.

1.3 Environment degradation

The indiscriminate and inefficient energy utilization has also resulted in environmental degradation which needs to be adequately studied. The process of energy generation, transport and utilization leads to air pollutants. In-efficient use of energy has stretched the global environment to its limits as can be seen from the unprecedented and unpleasant responses of the nature in the past few years. Green house effect, global warming, acid rain, smog, deforestation, shift in climatic conditions etc. are some of the indications.

1.3.1 Climate Change

Climate is referred to as the prevalent long-term weather conditions in a particular area. Climatic elements include precipitation, temperature, humidity, sunshine and wind velocity phenomena such as fog, frost, and hail storms. Climate change is any long-term significant change in the expected patterns of average weather of a specific region (or, more relevantly to contemporary socio-political concerns, of the Earth as a whole) over an appropriately significant period of time. The Reports by the United Nations Framework Convention on Climate Change (UNFCCC) define it as “a change of climate as attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods”. Climate change is caused by increases in the atmospheric concentration of so-called greenhouse gases (GHGs). The build-up of GHGs is rapidly changing how the atmosphere absorbs and retains energy. These GHGs include: carbon dioxide (CO2) (from burning fossil fuels), methane (CH_4), nitrous oxides (NO_x) (created by agriculture, land use and changes in land use where these gases are emitted), ozone (O_3) (generated mostly by fumes from car exhausts) and chlorofluorocarbons (CFCs). The increase of these GHGs in the atmosphere further prevents infrared radiation escaping from the earth’s atmosphere into space, causing what is called ‘global warming’. This acceleration of global warming by humans is referred to as the enhanced greenhouse effect or anthropogenic climate change.

1.3.2 NO_x – Most Concerned Pollutant

Increased environmental concerns and tougher emission norms have led to the development of advanced engine technologies to reduce NO_x and particulate matter (PM) emissions. Among the GHG emissions, NO_x causes a wide variety of health and environmental impacts because of various compounds and derivatives in the family of nitrogen oxides, including nitrogen dioxide, nitric acid, nitrous oxide, nitrates, and nitric oxide. The Health and Environmental Impacts of NOx are summarized as under.

1.3.2.1 Ground-level Ozone (Smog)

Smog is formed when NOx and volatile organic compounds (VOCs) react in the presence of heat and sunlight. Children, people with lung diseases such as asthma, and people who work or exercise outside, are susceptible to adverse effects such as damage to lung tissue and reduction in lung function. Ozone can be transported by wind currents, and can cause health impacts far from original sources. Millions of Americans live in areas that do not meet the health standards for ozone. Other impacts from ozone include damaged vegetation and reduced crop yields [4].

1.3.2.2 Acid Rain

NOx and sulfur dioxide react with other substances in the air to form acids, which fall to earth as rain, fog, snow or dry particles. Some may be carried by wind for hundreds of miles. Acid rain damages; causes deterioration of cars, buildings and historical monuments; and causes lakes and streams to become acidic and unsuitable for many fish [4].

1.3.2.3 Particles

NOx reacts with ammonia, moisture, and other compounds to form nitric acid and related particles. Human health concerns include effects on breathing and the respiratory system, damage to lung tissue, and premature death. Small particles penetrate deeply into sensitive parts of the lungs and can cause or worsen respiratory disease such as emphysema and bronchitis, and aggravate existing heart disease [4].

1.3.2.4 Water Quality Deterioration

Increased nitrogen loading in water bodies, particularly coastal estuaries, upsets the chemical balance of nutrients used by aquatic plants and animals. Additional nitrogen accelerates “eutrophication,” which leads to oxygen depletion and reduces fish and shellfish populations [4].

1.3.2.5 Global Warming

One member of the NOx, nitrous oxide, is a greenhouse gas. It accumulates in the atmosphere with other greenhouse gasses causing a gradual rise in the earth's temperature. This will lead to increased risks to human health, a rise in the sea level, and other adverse changes to plant and animal habitat [4].

1.3.2.6 Toxic Chemicals

In the air, NOx reacts readily with common organic chemicals and even ozone, to form a wide variety of toxic products, some of which may cause biological mutations. Examples of these chemicals include the nitrate radical, nitroarenes, and nitrosamines [4].

1.3.3 Steps towards Environment Protection

Being the one of the fastest growing economy, there had been a rapid increase in urbanization and industrialization in India. Further there had been a significant escalation in number of vehicles in India. All these factors along with mechanized farming are among the major sources of environmental degradation of India and have resulted in a profound deterioration of India's air quality and water resources.

Degradation and low accessibility of water recourses, industrial pollution, and urban congestion are the major environmental issue that deserves high priority for India, besides land and soil resources and deforestation. Awareness of the environment effects of energy production and its use in the transport industrial and domestic sectors on the rise. The concern about over environment degradation brought about by increased consumption of fossil fuels has been growing. Air toxics originate from human-made sources, including mobile sources (e.g., cars, trucks, buses) and stationary sources (e.g., factories, refineries, power plants), as well as indoor sources (e.g., some building materials and cleaning solvents).

Indian government is dedicated to regulate the increasing menace of environmental degradation and numbers of laws have been enforced to protect our environment. Various legislation and standards are formulated to ensure that ambient air quality, water quality and noise levels remain below the safe limit for human being.

The Air (Prevention and Control of Pollution) Act, 1981, and the umbrella legislation brought out in 1986, namely the environment act, covered a gamut of pollution problems, laying down the standards for pollution levels, etc.

The first stage emission norms came into force for petrol vehicles in 1991 and for diesel vehicles in 1992. From April 1995 mandatory fitment of catalytic converters in new petrol passenger cars sold in the four metros of Delhi, Calcutta, Mumbai and Chennai along with supply of Unleaded Petrol (ULP) was affected. Availability of ULP was further extended to 42 major cities and now it is available throughout the country. The emission reduction achieved from pre-89 levels is over 85% for petrol driven and 61% for diesel vehicles from 1991 levels.

In the year 2000, India 2000 norms equivalent to Euro-I was implemented for passenger cars and commercial vehicles. In year 2001, Euro II equivalent Bharat Stage II norms and in year 2005, Euro III equivalent to Bharat Stage III were enforced in 4 metros of Delhi, Mumbai, Chennai and Calcutta. For the whole country Bharat Stage II were implemented in year 2005 and Bharat Stage III will be implemented. Since India embarked on a formal emission control regime only in 1991, there is a gap in comparison with technologies available in the USA or Europe. Currently, we are behind Euro norms by few years, however, a beginning has been made, and emission norms are being aligned with Euro standards and vehicular technology is being accordingly upgraded. Vehicle manufactures are also working towards bridging the gap between Euro standards and Indian emission norms [5].

Table 2:- Indian & European vehicle emission norms for Diesel Cars [5]

Emissions	EURO-I (1993) India (2000)	EURO-II (1996) India (2000*)	EURO-III (2000) India (2005*)	EURO-IV
CO (g/Km)	2.72	1.0	0.64	0.50
HC + NO_x(g/Km)	0.97	0.7 (IDI) 0.9(DI)	0.56	0.30
PM (g/Km)	0.14	0.08	0.05	0.025

Table 3:- Indian & European vehicle emission norms for Diesel Heavy Duty Vehicles [5]

Emissions	EURO-I (1993) India (2000)	EURO-II (1996) India (2000*)	EURO-III (2000) INDIa (2005*)	EURO-IV
CO (g/KWh)	4.5	4	2.1	1.50
HC (g/KWh)	1.1	1.1	.66	0.02
NOx (g/KWh)	8.0	7.0	5.0	3.5
PM (g/KWh)	0.36	0.15	0.10	0.0025

*Implemented only in Metros, For whole of country Euro-II will be implemented in 2005 and Euro III in 2010.

1.4 Bio Fuel- Historical Aspects

World at present is confronted with the twin crisis of fossil fuel depletion and environmental degradation. Energy demand is increasing due to life style change, more use of energy for industrial applications and ever increasing number of vehicles employing internal combustion engines. Search for renewable alternative fuels is becoming very essential for ensuring much needed energy security and environmental protection. Thus, it is highly desired in present context to direct the research towards renewable fuels of bio-origin, which are environment friendly, provide improved performance, while being used as diesel substitute and are not harmful to human health. Bio-fuels have the potential to help the developing countries like India to meet their growing energy demands in sustainable manner. Using bio-fuels in diesel engines is not a new idea. Rudolf Diesel, the inventor of diesel engine demonstrated the principle of compression ignition engine in year 1910 by employing peanut oil as a fuel and suggested that vegetable oils would be the future fuel for diesel engines. However, with the advent of cheap petroleum derived fuels, the vegetable oil based fuels were forced to take the back seat and for nearly next 80 years, the engines were fuelled with petroleum derived fuels. However, with the gulf crisis and subsequent Iraq war, the interest in vegetable oil derived fuels was regenerated and since than it has been the focus of intensive research both in developed and developing countries. Since, straight vegetable oils are not considered as an ideal fuel for diesel engine, the chemically modified vegetable oils commonly called as biodiesel has the potential to directly substitute petroleum diesel with minimum engine modifications. Many countries have brought mandate for compulsorily blending biodiesel in mineral diesel. A large number of diesel engine and vehicle manufacturer are also giving the engine warranty for biodiesel/diesel blends till 20% diesel substitution. More recently, Renault and Peugeot have approved the use of biodiesel in some of their truck engines.

1.5 Biodiesel

Vegetable oils have almost similar energy density, cetane number, heat of vaporization, and stoichiometric air/fuel ratio compared to mineral diesel fuel. However, straight vegetable oils cannot be used directly in engines. Straight vegetable oils or their blends with diesel pose various long-term operational and durability problems in compression ignition engines, e.g. poor fuel atomization, piston ring-sticking, fuel injector coking and deposits, fuel pump failure, and lubricating oil dilution etc. The properties of vegetable oils responsible for these problems are high viscosity, low volatility, and polyunsaturated character. Several techniques are proposed to reduce the viscosity of vegetable oils such as blending, pyrolysis, micro-emulsion and transesterification etc. Heating and blending of vegetable oils reduce the viscosity but its molecular structure remains unchanged hence polyunsaturated character and low volatility problems exist. It has been reported that transesterification is an effective process to overcome all these problems associated with vegetable oils.

Biodiesel is a clean burning mono-alkyl ester-based oxygenated fuel made from natural, renewable sources such as vegetable oils and animal fats. Biodiesel has similar physical and thermal properties compared to conventional diesel fuel. Biodiesel is compatible with conventional diesel and can be blended in any proportion with petroleum diesel to produce a stable blend. Vegetable oil esters have superior fuel properties compared to straight vegetable oils. They have lower viscosity, higher volatility, and lower un-saturation. Glycerin is a valuable by-product of transesterification process, which is used in pharmaceutical and cosmetic industries. Transesterification is a reversible reaction of fat or oil (triglyceride) with a primary alcohol to form esters and glycerol. Alcohol combines with the triglycerides to form glycerol and esters. The reaction is shown below:-

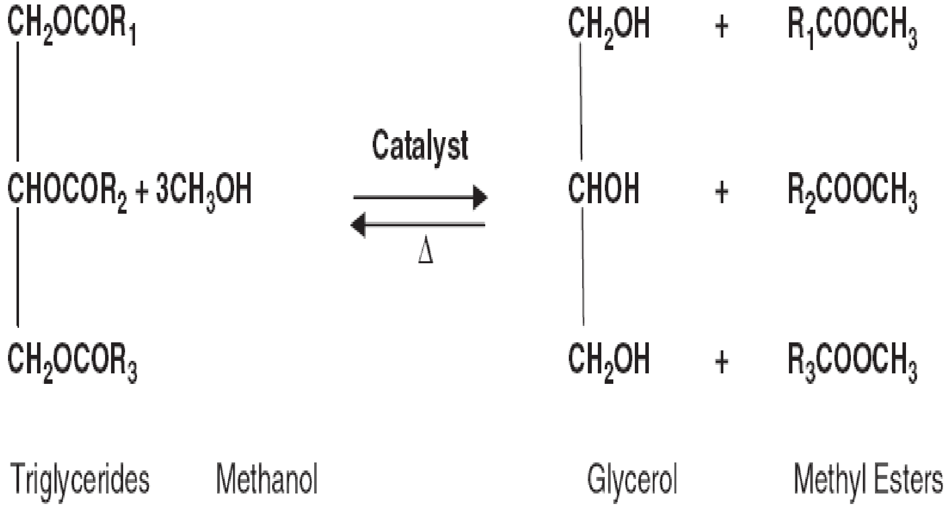


Figure 1.2 Typical Transesterification reaction.

A catalyst is usually used to improve the reaction rate and yield. Alkalies, acids, and enzymes can catalyze this reaction. Alkali-catalyzed transesterification is much faster than acid-catalyzed transesterification and is most often used commercially. Effect of different parameters like temperature, molar ratio of alcohol to oil, catalyst, reaction time have been investigated by several researchers and it was found that for base catalyzed transesterification at atmospheric pressure, 55–60^{0}C temperature, 45 min to 1 h reaction time and 6:1 molar ratio of alcohol to oil the yield is optimum. Figure 1.2 represents the typical base catalyzed biodiesel production process [6].

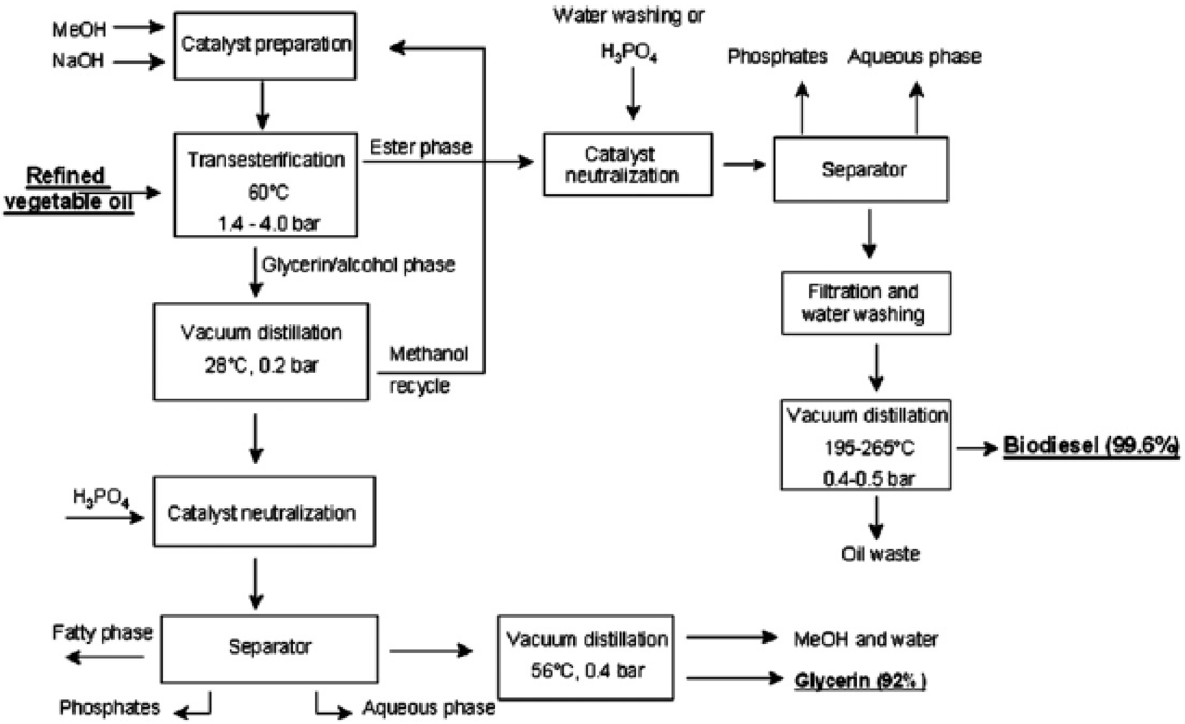


Figure 1.3 : A simplified block diagram for a typical base-catalyzed process for the production of bio-diesel

1.6 Emissions of Biodiesel

Biodiesel gives considerably lower emissions of PM, carbon monoxide (CO) and hydrocarbon (HC) without any fuel consumption or engine performance penalties. Biodiesel's particulate reducing effect could be attributed to its lower aromatic and short-chain paraffin HC and higher oxygen content. It has been observed that carbon deposits on the cylinder head, piston top, piston ring grooves, and injector of biodiesel-fuelled engine are substantially lower compared to the diesel-fuelled engine. Also, the wear of vital moving parts of biodiesel-operated engine is substantially lower compared to the diesel-operated engine due to its inherent lubricity properties. However, researchers found increased NO_x emissions with biodiesel compared to diesel [7].

Salvatore et al carried out experiments on a direct injection turbocharged diesel engine using methyl esters of rapeseed oil. It has been reported by them that, at the same injection timing, methyl ester promoted a rise in NOx emissions and decrease of HC and CO together with a strong reduction of smoke [8].

Chio et al conducted tests on biodiesel blended with diesel fuel in the concentration of 20 and 40% by volume on a single cylinder caterpillar engine, using both single and multiple injection strategies. At high loads using single injection, particle and CO emission were decreased. A slight increase in NOx was observed as the biodiesel concentration is increased. But in the case of multiple injection, decrease in particulate emission was observed with little or no effect on NO_x. At low loads, addition of biodiesel and multiple injection schemes were found to be detrimental to particulate matter and CO emission [9].

Ramesh et al have reported that for jatropha biodiesel and its blended fuels, the exhaust gas temperature increased with increase in load and amount of biodiesel. The CO_2 emission from the biodiesel fuelled engine was slightly higher than diesel fuel as compared with diesel. The carbon monoxide reduction by biodiesel was 16, 14 and 14 per cent at 2, 2.5 and 3.5 kW load conditions. The NO_x emissions from biodiesel was increased by 15, 18 and 19 per cent higher than that of the diesel at 2, 2.5 and 3.5 kW load conditions respectively [10].

Dorado et al have revealed that the use of biodiesel resulted in lower emissions of CO (up to 58.9%), CO_2 (up to 8.6%, excepting a case which presented a 7.4% increase), NO (up to 37.95%), and SO_2 (up to 57.7%), with increase in emissions of NO_2 (up to 81%, excepting a case which presented a slight reduction). Biodiesel also presented a slight increase in brake-specific fuel consumption (lower than 8.5%) that may be tolerated due to the exhaust emission benefits. Combustion efficiency remained constant using either biodiesel or Diesel fuel [11].

CHAPTER 2

LITERATURE REVIEW

The diesel engines dominate the field of commercial transportation and agricultural machinery due to its ease of operation and higher fuel efficiency. The consumption of diesel is 4-5 times higher than petrol in India. Due to the shortage of petroleum products and its increasing cost, efforts are on to develop alternative fuels especially, to the diesel oil for fully or partial replacement. It has been found that the vegetable oils are promising fuels because their properties are similar to that of diesel and are produced easily and renewably from the crops. Vegetable oils have comparable energy density, cetane number, heat of vaporization and stoichiometric air–fuel ratio with that of the diesel fuel. None other than Rudolph Diesel, the father of diesel engine, demonstrated the first use of vegetable oil in compression ignition engine in 1910. He used peanut oil as fuel for his experimental engine [12]. So the use of vegetable oils as alternative fuels has been around for one hundred years when the inventor of the diesel engine Rudolph Diesel first tested peanut oil, in his compression-ignition engine. In the 1930s and 1940s vegetable oils were used as diesel fuels from time to time, but usually only in emergency situations. In 1940 first trials with vegetable oil methyl and ethyl esters were carried out in France and, at the same time, scientists in Belgium were using palm oil ethyl ester as a fuel for buses. Not much was done until the late 1970s and early 1980s, when concerns about high petroleum prices motivated extensive experimentation with fats and oils as alternative fuels. Bio-diesel (mono alkyl esters) started to be widely produced in the early 1990s and since then production has been increasing steadily. In the European Union (EU), bio-diesel began to be promoted in the 1980s as a means to prevent the decline of rural areas while responding to increasing levels of energy demand. However, it only began to be widely developed in the second half of the 1990s [6].

Biodiesel is a renewable fuel which is free from sulfur and aromatic compounds. Biodiesel does not overburden the environment with CO_2 emission as CO_2 from the atmosphere is absorbed by the vegetable oil crop during the photosynthesis process, while the plant is growing. Hence biodiesel offers net CO_2 advantage over conventional fuels. The use of biodiesel in diesel engines does not require any hardware modification.

However, the long term impact in modern common-rail injection systems still needs to be identified. Additionally biodiesel is known to degrade up to four times faster than diesel fuel. The products of biodegrading could have detrimental effects on the injection components especially the high pressure fuel pump [7].

2.1 Mechanism of NO_x formation

The increase in NOx emission serves as biodiesel's major impediment to widespread use. A major hurdle in understanding the mechanism of formation and controlling NO_x emission is that combustion is highly heterogeneous and transient in diesel engines. While NO and NO_2 are lumped together as NO_x, there are some distinctive differences between these two pollutants. NO is a colourless and odourless gas, while NO_2 is a reddish- brown gas with pungent odour. Both gases are considered toxic, but NO_2 has a level of toxicity 5 times greater than that of NO. Although NO_2 is largely formed from oxidation of NO, attention has been given on how NO can be controlled before and after combustion [13].

NO is formed during the post flame combustion process in a high temperature region. The most widely accepted mechanism was suggested by Zeldovich [14]. The principal source of NO formation is the oxidation of the nitrogen present in atmospheric air. The nitric oxide formation chain reactions are initiated by atomic oxygen, which forms from the dissociation of oxygen molecules at the high temperatures reached during the combustion process. The principal reactions governing the formation of NO from molecular nitrogen are,

$$N_2 + O \rightarrow NO + N$$

$$N + O_2 \rightarrow NO + O$$

$$N + OH \rightarrow NO + H$$

Chemical equilibrium consideration indicates that for burnt gases at typical flame temperatures, NO_2/NO ratios should be negligibly small. While experimental data show that this is true for spark ignition engines, in diesels, NO_2 can be 10 to 30% of total exhaust emissions of oxides of nitrogen. A plausible mechanism for the persistence of NO_2 is as follows. NO formed in the flame zone can be rapidly converted to NO_2 via reactions such as

$$NO + HO_2 \rightarrow NO_2 + OH$$

Subsequently, conversion of this NO2 to NO occurs via

$$NO_2 + O \rightarrow NO + O_2$$

unless the NO_2 formed in the flame is quenched by mixing with cooler fluid. This explanation is consistent with the highest NO_2/NO ratio occurring at high load in diesels, when cooler regions which could quench the conversion back to NO are widespread [14].

The local atomic oxygen concentration depends on molecular oxygen concentration as well as local temperatures. Formation of NO_x is almost absent at temperatures below 2000 K. Hence any technique, that can keep the instantaneous local temperature in the combustion chamber below 2000 K, will be able to reduce NO_x formation [13].

Canakci has also suggested that the NOx increase is not driven by the Zeldovich mechanism, but instead by the fact that during combustion the double bonded molecules cause higher levels of certain hydrocarbon radicals in the fuel-rich zone of the diesel spray [15].

2.2 NO_x Reduction Strategies

Biodiesel is an oxygenated fuel and after combustion gives higher NO_x emissions. The reason behind this is higher boiling point, higher bulk modulus, and inherent oxygen content. However this presence of oxygen reduces CO and HC emission. Bulk modulus is another important property, which results in a dynamic advance of injection timing in bio-diesel fuelled engine. Bulk modulus of biodiesel is higher than the diesel fuel, which leads to a more rapid transfer of the pressure waves from fuel pump to lift the needle of the injector much earlier. This advance results in more fuel accumulation before the start of combustion leading to higher peak temperature and pressure in premixed phase and subsequently higher NO_x [16]. The following NO_x reduction techniques can be used in a biodiesel fuelled diesel engine.

- Fuel additives
- Selective catalytic reduction (SCR)
- Retarded injection
- Exhaust gas recirculation(EGR)

2.2.1 Fuel additives

Environment and health concerns have resulted in stringent emission standards which require diesel engines to meet a 5.0 g/ kWh NO_x standard in EURO-III. There is a critical need for cost effective technologies to meet these mandates and to clean the environment. One promising approach towards meeting these standards with minimal changes in the present infrastructure of the transportation industry, is the use of fuel additives that when injected into the cylinder, along with the diesel fuel, can result in substantial NO_x reduction.

The use of micro emulsions containing scab-Engen additives offers potential solution for substantial reduction in NO_x. The addition of water was limited to 10 wt% as microemulsions containing less than 10wt% water were found to be effective in carrying scavenger additives. A typical composition containing 10wt% water, less than 10wt% surfactant/co-surfactant/neutralizing agent and 1wt% scavenger additive reduced NO_x by almost 30% across the load range of the engine. The addition of quantities greater than 1wt% of the scavenger additive did not have a beneficial effect on NO_x reduction. This may be due to the additive being destroyed in the flame and not making it past the flame front for reaction with NO_x. The use of scavenger additives leads to a severe depression in the cetane number of the fuel. Selection of a cetane improver is critical from both cost and NO_x reduction perspectives. Moreover, most of the additives are expensive and can promote auto-oxidation in bio-diesel [17].

3.2.2 Selective catalytic reduction

Selective catalytic reduction technique is most versatile technique for NO_x control in diesel engines. Catalysts used in SCR are manufactured from various ceramic materials used as a carrier, such as titanium oxide, and active catalytic components are usually oxides of base metals (such as vanadium and tungsten), zeolites, and various precious metals.

The two most common designs of SCR catalyst geometry used today are honeycomb and plate. The honeycomb form usually is an extruded ceramic applied homogeneously throughout the ceramic carrier or coated on the substrate. Like the various types of catalysts, their configuration also has advantages and disadvantages. Plate type catalysts have lower pressure drops and are less susceptible to plugging and fouling than the honeycomb types, however plate type configurations are significantly larger and more expensive. Honeycomb configurations are significantly smaller than plate types, but have higher pressure drops and plug much more easily. Technical difficulties with SCR units are:-

- Contamination of catalyst.
- Tuning of SCR system with engine operating cycle.
- Low exhaust gas temperature (below the optimal range of catalyst).[18]

2.2.3 Retarded Injection Timing

Injection timing is another well-studied mechanism for controlling NO_x emissions. Advancing injection timing causes higher NO_x emissions since combustion starts earlier, and thus the residence time of the burning mixture in the cylinder is increased. This allows the NO_x formation reactions to proceed. An advance in injection timing for biodiesel relative to that of petroleum diesel is caused by its higher bulk modulus of compressibility. Since pump–line–nozzle (PLN) injection systems generally start fuel injection upon reaching a certain fuel pressure, a higher bulk modulus leads to this pressure requirement being met more quickly, and thus fuel is injected earlier. Engines equipped with high-pressure common rail fuel injection systems do not rely on the transfer of a pressure wave to initiate injection; bulk modulus is therefore not thought to alter injection timing in these types of diesel engines [19]. Retarded injection leads to increased fuel consumption, reduced power, increased HC and excess smoke [16].

Monyem et al. observed a reduction in NO_x emissions of 35% to 43% for 6-degree retardation in injection timing [20].

2.2.4 Exhaust Gas Recirculation

Exhaust gas recirculation is an effective method for NO_x control. The exhaust gases mainly consist of inert carbon dioxide, nitrogen and possess high specific heat. When recirculated to engine inlet, it can reduce oxygen concentration and act as a heat sink. This process reduces oxygen concentration and peak combustion temperature, which results in reduced NO_x. EGR is one of the most effective techniques currently available for reducing NO_x emissions in internal combustion engines. However, the application of EGR also incurs penalties. It can significantly increase smoke, fuel consumption and reduce thermal efficiency unless suitably optimized. The higher NO_x emission can be effectively controlled by employing EGR [7].

2.3 THE EGR STATEGY

Tsolakis et al have analysed and presented the effects of biodiesel (rapeseed methyl ester, RME) and different diesel/RME blends on the diesel engine NO_x emissions, smoke, fuel consumption, engine efficiency, cylinder pressure and net heat release rate. The combustion of RME as pure fuel or blended with diesel in an unmodified engine results in advanced combustion, reduced ignition delay and increased heat release rate in the initial uncontrolled premixed combustion phase. The increased in-cylinder pressure and temperature lead to increased NO_x emissions while the more advanced combustion assists in the reduction of smoke compared to pure diesel combustion. When similar percentages (% by volume) of exhaust gas recirculation (EGR) are used in the cases of diesel and RME, NO_x emissions are reduced to similar values, but the smoke emissions are significantly lower in the case of RME. The retardation of the injection timing in the case of pure RME and 50/50 (by volume) blend with diesel results in further reduction of NO_x at a cost of small increases of smoke and fuel consumption. The use of EGR seems to suit better the B20, B50 and RME combustion, as apart from resulting in the higher NO_x reduction, it maintained the smoke (soot, particulate matter) at relatively low levels. One reason for the higher NO_x reduction is probably the different composition of the engine exhaust gas obtained from the combustion of RME and ULSD. The increased fuel consumption with biodiesel resulted in increased H_2O and CO_2 in the engine exhaust gas. The main reasons for the higher NO_x reduction with the use of EGR in the case of biodiesel fuelling are: (i) the increased CO_2 dilution as more CO_2 enters the combustion as part of the EGR compared to ULSD, (ii) the lower relative air/fuel ratio λ with biodiesel compared to operation with diesel (for the same EGR level), and (iii) the retardation of the already advanced combustion from the use of biodiesel [21].

Szybist et at have explored the efficacy of (1) reducing the iodine value of soy-derived biodiesel fuels through increasing the methyl oleate (methyl ester of oleic acid) content and (2) addition of cetane improvers, as strategies to combat the biodiesel NO_x effect: the increase in NO_x emissions observed in most studies of biodiesel and biodiesel blends. This is accomplished by spiking a conventional soy-derived biodiesel fuel with methyl oleate or with cetane improver. The impact on bulk modulus of compressibility, fuel injection timing, cetane number, combustion, and emissions were examined. The conventional B20 blend produced a NO_x increase of 3–5% relative to petroleum diesel, depending on injection timing. However, by using a B20 blend where the biodiesel portion contained 76% methyl oleate, the biodiesel NO_x effect was eliminated and a NO_x neutral blend was produced. The bulk modulus of petroleum diesel was measured to be 2% lower than B20, yielding a shift in fuel injection timing of 0.1–0.3 crank angle. The bulk modulus of the high methyl oleate B20 blend was measured to be 0.5% lower than B20, not enough to have a measurable impact on fuel injection timing. Increasing the methyl oleate portion of the biodiesel to 76% also had the effect of increasing the cetane number from 48.2 for conventional B20 to 50.4, but this effect is small compared to the increase to 53.5 achieved by adding 1000 ppm of 2-ethylhexyl nitrate (EHN) to B20. For the particular engine tested, NO_x emissions were found to be insensitive to ignition delay, maximum cylinder temperature, and maximum rate of heat release. The dominant effect on NO_x emissions was the timing of the combustion process, initiated by the start of injection, and propagated through the timing of maximum heat release rate and maximum temperature [22].

Agarwal et al investigated that biodiesel-fueled engines produce less carbon monoxide (CO), unburned hydrocarbon (HC), and particulate emissions compared to mineral diesel fuel but higher NO_x emissions. Exhaust gas recirculation (EGR) is effective to reduce NO_x from diesel engines because it lowers the flame temperature and the oxygen concentration in the combustion chamber. However, EGR results in higher particulate matter (PM) emissions. Application of EGR with biodiesel blends resulted in reductions in NO_x emissions without any significant penalty in PM emissions or BSEC. When EGR is applied, NO_x is decreased with increasing EGR rates. The degree of reduction in NO_x at higher loads is higher. The reasons for reduction in NO_x emissions using EGR in diesel engines are reduced oxygen concentration and decreased flame temperatures [7].

Zheng et al compare engine performance and emission between the use of soy, Canola and yellow grease derived B100 biodiesel fuels and an ultra-low sulphur diesel fuel in the high load engine operating conditions. Compared to the diesel fuel engine-out emissions of nitrogen oxides (NO_x), a high-cetane number (CN) biodiesel fuel produced comparable NO_x while the biodiesel with a CN similar to the diesel fuel produced relatively higher NO_x at a fixed start of injection. The soot, carbon monoxide and unburnt hydrocarbon emissions were generally lower for the biodiesel-fuelled engine. Exhaust gas recirculation (EGR) was then extensively applied to initiate low temperature combustion (LTC) mode at medium and low load conditions. An intake throttling valve was implemented to increase the differential pressure between the intake and exhaust in order to increase and enhance the EGR. Simultaneous reduction of NO_x and soot was achieved when the ignition delay was prolonged by more than 50% from the case with 0% EGR at low load conditions. The research intends to achieve simultaneous reductions of NO_x and soot emissions in modern production diesel engines when biodiesel is applied [23].

Hountalas et al investigate the performance and emissions of diesel engine with EGR system. The method is based on the reduction of gas temperature level and O_2 availability inside the combustion chamber, but unfortunately it has usually an adverse effect on soot emissions and brake specific fuel consumption (bsfc). The use of high EGR rates creates the need for EGR gas cooling in order to minimize its negative impact on soot emissions especially at high engine load were the EGR flow rate and exhaust temperature are high. it is examined, using a multi-zone combustion model, the effect of cooled EGR gas temperature level for various EGR percentages on performance and emissions of a turbocharged DI heavy duty diesel engine operating at full load. Results reveal that the decrease of EGR gas temperature has a positive effect on BSFC, soot (lower values) while it has only a small positive effect on NO. As revealed, the effect of low EGR temperature is stronger at high EGR rates [24].

Spring et al addressed the problem of exhaust gas recirculation occurring when pressure-wave superchargers are used as boosting devices for IC engines. During hard accelerations, critical situations arise whenever large amounts of exhaust gas are recirculated over the charger from the exhaust to the intake manifolds of the engine. Such recirculations cause the engine torque to drop sharply and thus severely affect the drive ability of the vehicle. In order to prevent such situations, the actuators such as throttles, valves, etc., have to be controlled in a coordinated way [25].

Agarwal et al conducted an experiment to investigate the effect of exhaust gas re-circulation on the exhaust gas temperatures and exhaust opacity. It is seen that the exhaust gas temperatures reduce drastically by employing EGR. This indirectly shows the potential for reduction of NO_x emission. Thermal efficiency and brake specific fuel consumption are not affected significantly by EGR. However particulate matter emission in the exhaust increases, as evident from smoke opacity observations [13].

Wang et al described an innovative air fraction estimation method for diesel engines with dual-loop exhaust gas recirculation (EGR) systems to conduct multiple and alternative combustion modes for engine-out emission reduction. An observer is designed to estimate the air fractions in all the engine intake/exhaust sections using standard sensors equipped on the engine. The observer can provide indispensable information for the engine controller to exercise closed-loop control on in-cylinder conditions as well as control the in-cylinder high-pressure EGR gas and low-pressure EGR gas amounts, respectively, which are crucial for engines running alternative combustion modes with dual-loop EGR systems. The convergence stability of the observer is proved based on a Lyapunov analysis assisted by physical insights into the engine/combustion systems [26].

Maiboom et al investigated performance of cooled exhaust gas recirculation to control NO_x in diesel engine. Cooled exhaust gas recirculation (EGR) is a common way to control in-cylinder NO_x production and is used on most modern high speed direct injection (HSDI) diesel engines. However EGR has different effects on combustion and emissions production that are difficult to distinguish (increase of intake temperature, delay of rate of heat release (ROHR), decrease of peak heat release, decrease in O2 concentration (and thus of global air/fuel ratio (AFR)) and flame temperature, increase of lift-off length, etc.), and thus the influence of EGR on NO_x and particulate matter (PM) emissions is not perfectly understood, especially under high EGR rates. The increase of inlet temperature with EGR has contrary effects on combustion and emissions, thus sometimes giving opposite tendencies as traditionally observed, as, for example, the reduction of NO_x emissions with increased inlet temperature. For a purely diffusion combustion the ROHR is unchanged when the AFR is maintained when changing in-cylinder ambient gas properties (temperature or EGR rate). At low-load conditions, use of high EGR rates at constant boost pressure is a way to drastically reduce NO_x and PM emissions but with an increase of brake-specific fuel consumption (BSFC) and other emissions (CO and hydrocarbon), whereas EGR at constant AFR may drastically reduce NO_x emissions without important penalty on BSFC and soot emissions but is limited by the turbo-charging system [27].

Pradeep et al Investigated that higher nitric oxide (NO) emissions when a single cylinder diesel engine was fuelled with JBD, without EGR. NO emissions were reduced when the engine was operated under HOT EGR levels of 5–25%. However, EGR level was optimized as 15% based on adequate reduction in NO emissions, minimum possible smoke, CO, HC emissions and reasonable brake thermal efficiency. Smoke emissions of JBD in the higher load region were lower than diesel, irrespective of the EGR levels. However, smoke emission was higher in the lower load region. CO and HC emissions were found to be lower for JBD irrespective of EGR levels. Combustion parameters were found to be comparable for both fuels [16].

Sik Kim et al investigated that with diesel premixed fuel, a simultaneous decrease of NO_x and soot can be obtained by increasing the premixed ratio, with cooled EGR to suppress auto ignition of premixed fuel. However, when the inlet charge is heated for the improved vaporization of diesel fuel, higher inlet temperature limits the operational range of HCCI combustion due to severe knocking and high NO_x emission at high premixed ratios. Gasoline premixing shows the most significant effects in the reductions of NO_x and soot emissions, compared to other kinds of premixed fuels [28].

Abd-Alla et al reviewed the potential of exhaust gas recirculation (EGR) to reduce the exhaust emissions, particularly NO_x emissions, and to delimit the application range of this technique. From the analysis, it was found that adding EGR to the air flow rate to the Diesel engine, rather than displacing some of the inlet air, appears to be a more beneficial way of utilizing EGR in Diesel engines. This way may allow exhaust NO_x emissions to be reduced substantially. In spark ignition engines, substantial reductions in NO_x concentrations are achieved with 10% to 25% EGR. However, EGR also reduces the combustion rate, which makes stable combustion more difficult to achieve. At constant burn duration and brake mean effective pressure, the brake specific fuel consumption decreases with increasing EGR. The improvement in fuel consumption with increasing EGR is due to three factors: firstly, reduced pumping work; secondly, reduced heat loss to the cylinder walls; and thirdly, a reduction in the degree of dissociation in the high temperature burned gases [29].

Saleh et al have studied to quantify the efficiency of exhaust gas recirculation (EGR) when using Jojoba methyl ester (JME) fuel in a fully instrumented, two-cylinder, naturally aspirated, four-stroke direct injection diesel engine. The tests were carried out in three sections. Firstly, the measured performance and exhaust emissions of the diesel engine operating with diesel fuel and JME at various speeds under full load are determined and compared. Secondly, tests were performed at constant speed with two loads to investigate the EGR effect on engine performance and exhaust emissions including nitrogenous oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (HC) and exhaust gas temperatures. Thirdly, the effect of cooled EGR with high ratio at full load on engine performance and emissions was examined. The results showed that EGR is an effective technique for reducing NO_x emissions with JME fuel especially in light-duty diesel engines. With the application of the EGR method, the CO and HC concentration in the engine-out emissions increased. For all operating conditions, a better trade-off between HC, CO and NO_x emissions can be attained within a limited EGR rate of 5–15% with very little economy penalty [30].

George et al investigated the contamination of lubricating oil by diesel soot is one of the major causes of increased engine wear, especially with most engine manufacturers opting for Exhaust Gas Recirculation (EGR) technology to curb oxides of nitrogen (NO_x) emissions. The diesel soot interacts with engine oil and ultimately leads to wear of engine parts. Factors which can change or modify the characteristics of the soot surface are expected to play an important role in controlling the interactions with soot. The results showed that the sulfur oxide concentration in the oil layer is related strongly to the EGR rate, inversely with engine speed and decreases under light load conditions [31].

2.4 Statement of the problem

On the strength of the exhaustive review of work done by previous researchers, it can be found that a good amount of work has been done on assessing the potential suitability of hot and cooled exhaust gas recirculation. However, it is evident that most of the work has been done on hot exhaust gas recirculation. As recycled exhaust gas lowers the oxygen concentration in the combustion chamber and increases the specific heat of intake charge which results in lower flame temperature. Reduced oxygen and flame temperature leads to lower NO_x formation. However, application of EGR also resulted in some penalties. EGR increases smoke opacity, HC and CO emissions. In particular, EGR aggravates the trade-off between NO_x and smoke opacity (which is the direct method to measure the particulate emissions), especially at high loads.

It has been observed that, at the same injection timing, Biodiesel promote a rise in NO_x emissions and decrease of HC and CO together with a strong reduction of smoke compared with diesel. So EGR can be used in a biodiesel fuelled diesel engine to reduce NO_x emissions without significant increase in smoke opacity. Country like India, where major dependency of agriculture sector on diesel engine, need fuel replacement as well as emissions within limits. So EGR with biodiesel can solve both problems. The literature suggests that better NO_x reduction could be achieved without much sacrifice in engine performance with cooled EGR.

Therefore, the following objectives were envisaged for the present research work.

1. Comprehensive literature survey.
2. Development of experimental diesel engine test rig
3. Development of EXHAUST GAS RECIRCULATION system for cooled EGR.
4. Determination of EGR rates.
5. Conducting exhaustive experiments on the test rig to evaluate performance and emission characteristics of biodiesel and diesel with and without EGR and compare with base line data of diesel.
6. Analysis of Results

CHAPTER 3

EXPERIMENTAL SETUP AND METHODOLOGY

World at present is confronted with the twin crisis of fossil fuel depletion and environmental degradation. Energy demand is increasing due to life style changes, more use of energy for industrial applications and ever increasing number of vehicles employing internal combustion engines. Search for renewable alternative fuels is becoming very essential for ensuring much needed energy security and environmental protection. Thus, it is highly desired in present context to direct the research towards renewable fuels of bio-origin, which are environment friendly, provide improved performance, while being used as diesel substitute and must not be harmful to human health.

Biodiesel is a renewable fuel which is free from sulfur and aromatic compounds. Biodiesel does not overburden the environment with CO_2 emission as CO_2 from the atmosphere is absorbed by the vegetable oil crop during the photosynthesis process, while the plant is growing. Hence biodiesel offers net CO_2 advantage over conventional fuels [21, 22]. The use of biodiesel in diesel engines does not require any hardware modification. Biodiesel gives considerably lower emissions of PM, carbon monoxide (CO) and hydrocarbon (HC) without any fuel consumption or engine performance penalties. Biodiesel's particulate reducing effect could be attributed to its lower aromatic and short-chain paraffin HC and higher oxygen content [32]. It has been observed that carbon deposits on the cylinder head, piston top, piston ring grooves, and injector of biodiesel-fuelled engine are substantially lower compared to the diesel-fuelled engine. Also, the wear of vital moving parts of biodiesel-operated engine is substantially lower compared to the diesel-operated engine due to its inherent lubricity properties [7]. However, researchers found increased NO_x emissions with biodiesel compared to diesel [6, 23].

Increased environmental concerns and tougher emission norms have led to the development of advanced engine technologies to reduce NO_x and particulate matter (PM) emissions. One of the most difficult problems that engineers and manufacturers face during diesel engine development is the control and reduction of pollutant emissions to ‘‘acceptable’’ levels as determined by the relevant legislation. During the past decades significant progress has been accomplished in reducing emissions of NO_x and soot, but at the same time permissible emission limits from diesel engines are becoming stricter i.e. EURO-IV. Diesel engines are widely used in transport applications and reduction of emissions from these engines is necessary for their future acceptance as primary power sources. Emission control can be achieved using advanced combustion technologies and/or after-treatment systems. As recognized the only possibility to achieve future limits using internal measures is to combine available technologies exhaust gas recirculation (EGR).

3.1 Selection of engine

The diesel engines dominate the field of commercial transportation and agricultural machinery due to its ease of operation and higher fuel efficiency. The consumption of diesel oil is several times higher than that of petrol. Diesel Engine plays an important role in agriculture sector for mobile or stationary application like tractor, combine or irrigation pump sets. The diesel engine continues to dominate the agriculture sector in our country in comparison to spark ignition engine and have always been preferred widely because of power developed, specific fuel consumption and durability.

In India, almost all irrigation pump sets, tractors, mechanized farm machinery and heavy transportation vehicle are powered by direct injection diesel engines. Considering the wide application of a small capacity diesel engine which has got great dominance in Indian agriculture sector, this engine has been selected for the present study.

3.1.1 Development of an experimental test rig

A Kirloskar make, single cylinder, air cooled, direct injection, DAF 10 model diesel engine was selected for the present research work, which is primarily used for agricultural activities and household electricity generations.

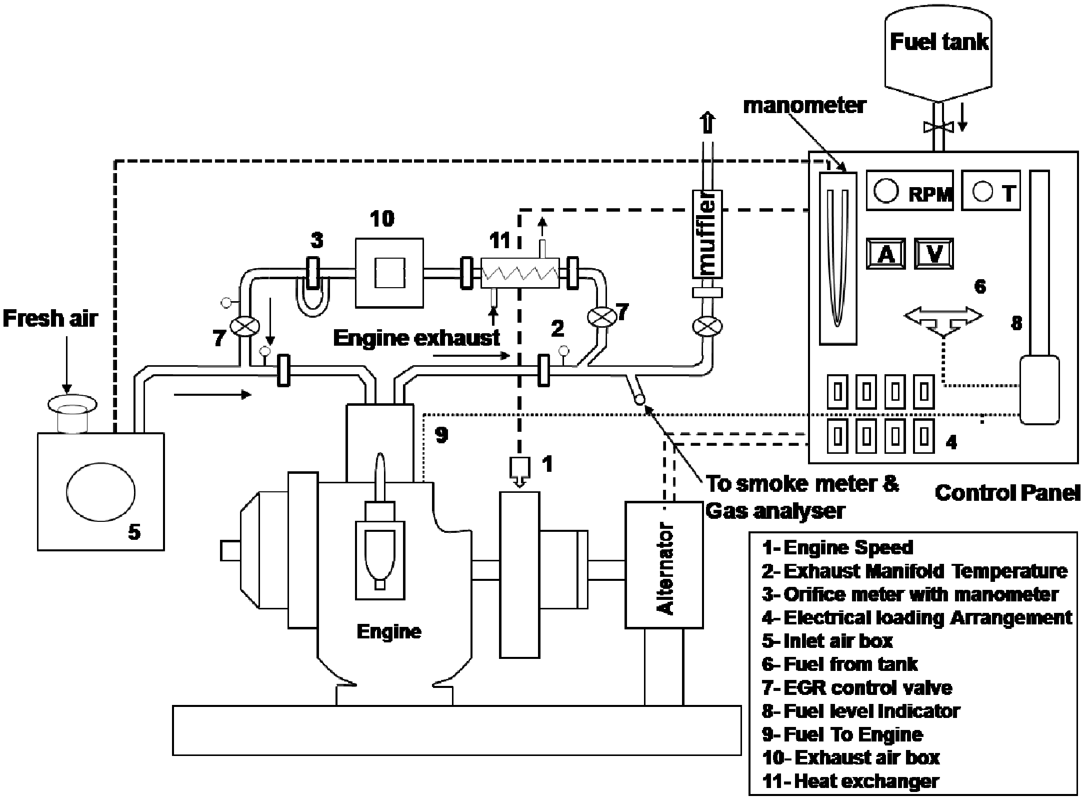


Figure 3.1: Schematic Line Diagram of Test Rig

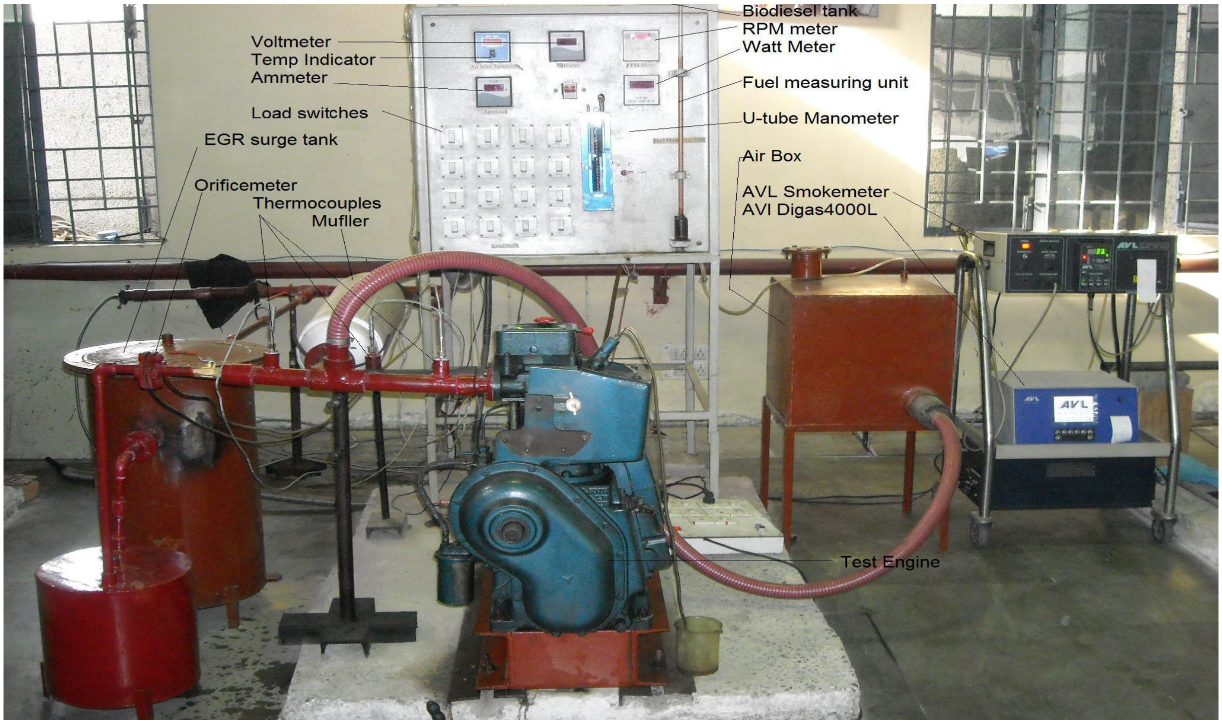


Plate 1: Photograph of Experimental Setup

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

The detailed technical specifications of the engine are given in Table 4.

Table 4:- Specifications of the Diesel Engine

Make	**Kirloskar**
Model	DAF 10
Rated Brake Power (bhp/kW)	9.6 / 7
Rated Speed (rpm)	1500
Number of Cylinder	One
Bore X Stroke (mm)	102 x 110
Compression Ratio	17.5:1
Cooling System	Air Cooled (Radial cooled)
Lubrication System	Forced Feed
Cubic Capacity	0.948 Lit
SFC at rated hp/1500rpm	251 g/kwh (185 g/bhp-hr)
Starting	Hand start with cranking handle
Inlet Valve Open (Degree)	4.5 BTDC
Inlet Valve Closed (Degree)	35.5 ABDC
Exhaust Valve Open (Degree)	35.5 BBDC
Exhaust Valve Closed (Degree)	4.5 ATDC
Fuel Injection Timing (Degree)	26 BTDC

For conducting the desired set of experiments and required data together from the engine, it is essential to get the various instruments mounted at the appropriate location on the experimental setup. Apart from this, a exhaust gas recirculation system has been developed for recirculation of part of exhaust to the inlet of engine. A two fuel tank system is used to easy switch from diesel to biodiesel or vice versa.

3.1.2 Installation of the Instrument Control Panel

After finalizing the procedures for data collection and procurement of the desired instruments, they were put on a panel. A MS Control panel was fabricated and Instruments such as voltmeter, ammeter, watt meter, speed counter, six channels digital temperature display was mounted on the front side of the control panel (Plate 2). Electrical load bank, i.e. 12 bulbs each of 500 watts and 2 bulbs each of 300 watts, were mounted on the rear side of the control panel which is shown in Plate 3 and their switches provided on the front side of the control panel.

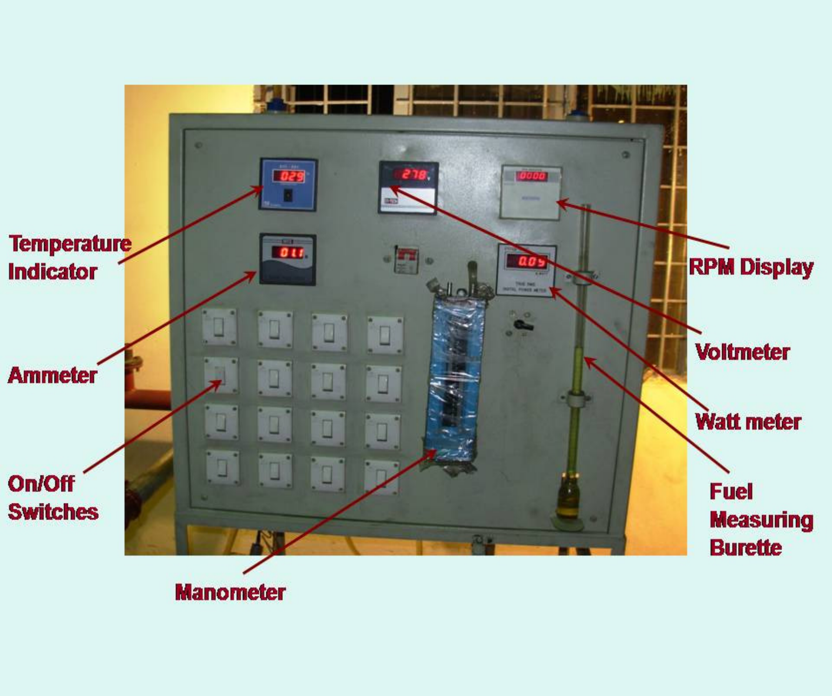


Plate 2: Control Panel

Plate 3: Load Bank

One 50ml burette with stop cocks was also mounted on the front side of the panel for fuel flow measurements of either diesel or neat biodiesel fuel. The two fuel tanks were mounted on the rear side of the panel at highest position with stop cocks as shown in plate 4.

Plate 4: Two Tanks System

A voltmeter, ammeter and wattmeter were connected between alternator and load bank. A nut was welded on the flywheel and the photo reflective sensor was mounted on a bracket attached to engine body. The thermocouples were mounted in the exhaust manifold to measure the exhaust temperature. The AVL 437 smoke meter and AVL Di

Gas Analyzer were also kept in proximity for the measurements of various exhaust gas parameters.

3.2 Parameter Selection

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

1. Power produced by the engines
2. Engine speed (Rev/min)
3. Fuel consumption
4. Temperature
5. Speed of the engine
6. Emission of the engine

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

1. Voltage generated by the alternator
2. Current generated by the alternator
3. RPM of the engine
4. Fresh air flow rate
5. Recirculated exhaust gas flow rate
6. Exhaust gas temperature
7. Fuel consumption rate
8. AVL 437 smoke meter
9. AVL Di Gas analyzer

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

3.3 Measurement Methods

The performance and emission characteristics of an engine can be measured with the help of the fuel consumption measuring unit, electrical loading arrangement, voltmeter, ammeter, RPM meter, temperature indicator and emissions measurement equipments.

3.3.1 Brake Power

The brake power is among the most important parameter in testing of an engine. The power developed by the engine was measured with the help of an electric alternator type of dynamometer. The dynamometer was coupled to the engine with the help of a flexible coupling. The output lead of this mechanically coupled alternator was connected to the control panel along with an ammeter and voltmeter of required range in series and thus by measuring voltage and current, the power developed by the electric generator was known as Brake Power. The lamp load was connected in series with the generator to act as a resistive load bank. Carbon brushes were checked and replaced when worn out. Lamp load consisted of 4 rows in parallel with 4 bulbs in series. The ratings of each incandescent lamp were 250 volts, 300 watts and 250 volts, 500 watts. The dynamometer used in this study was a “Ankur” make, 220 volts, 7.5KVA, single phase alternator. A voltmeter, 0-415 volts AC and an ammeter, 0-30 ampere, were selected for the measurements.

3.3.2 Fuel Flow Measuring System

The fuel consumption of an engine is measured by determining the time required for consumption of a given volume of fuel. The mass of fuel consumed can be determined by multiplication of the volumetric fuel consumption to its density. In the present set up volumetric fuel consumption was measured using a glass burette. The time taken by the engine to consume a fixed volume was measured using a stopwatch. The volume divided by the time taken for fuel consumption gives the volumetric flow rate. The test facilities were built up for measuring both diesel and neat biodiesel consumption rates. For this, two separate tanks, one burette, and a number of valves were provided on the panel as shown in the Plate 5.

Plate 5: Fuel Flow Measuring System

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

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

$$\text{bsfc} = (\text{Vcc} \times \ell \times 3600) / (\text{hp} \times \text{t}) \qquad (3.3)$$

Where,
bsfc = Brake specific fuel consumption, g/kW-h
Vcc = Volume of fuel consumed, cc
ℓ = Density of fuel, g/cc
hp = Brake horsepower, kW
t = Time taken to consume, cc of fuel, sec.

The brake thermal efficiency of the engine on different fuel blends at different operating conditions was determined using the equation as given below:

$$\eta_{th} = \text{Ks} / (\text{HV} \times \text{bsfc}) \qquad (3.4)$$

Where,
η_{th} = Brake thermal efficiency, %
Ks = Unit constant, 3600
HV = Gross heat of combustion, kJ/kg
bsfc = Brake specific fuel consumption, g/kW-h

3.3.3 Rpm of the Engine

An 'MTC' make digital panel tachometer with proximity/photo reflective sensor was used for measurement of RPM. The instrument is capable of functioning in the range of 1 to 9,999 rpm with a sampling time of 1 second. For measurement, a nut was welded (plate 6) on the flywheel face and sensor was mounted on a bracket near the flywheel in such a way that the distance was less than 5 mm. The display unit is digital and mounted on the panel board.

Plate 6: Engine Speed Measurement

3.3.4 Temperature Measurement

Chromel-Alumel K-type thermocouples (plate 7) were connected to a 6 channel digital panel meter to measure temperatures of exhaust gas and inlet air of engine. The meter was calibrated by a millivolt source up to 800^{o} C.

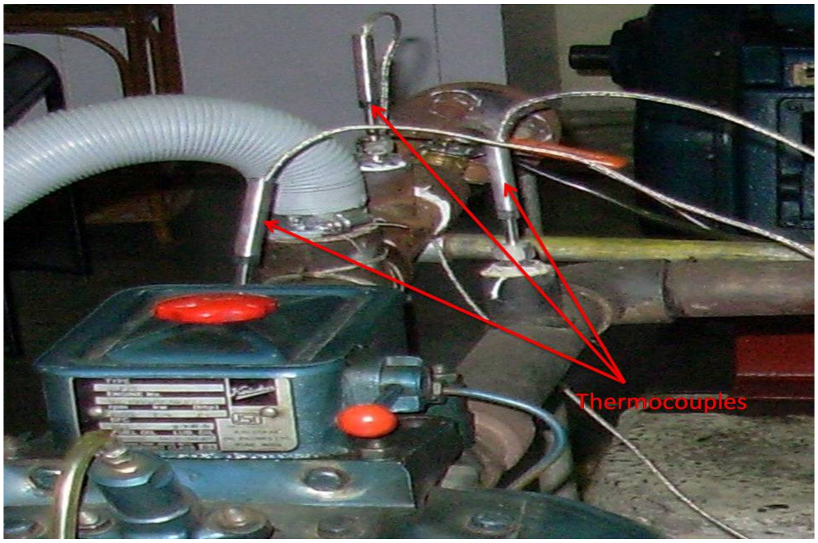


Plate 7: Thermocouples

3.3.5 Intake Air Flow Rate Measurement

An air box is designed to measure the volumetric flow rate of intake air to the engine. It is mounted on the inlet pipe between the air filter and the inlet manifold of the engine. The air box dampens out the fluctuations of the intake air. A diaphragm is provided on the side of the air box for dampening out the local undulations effectively. The air box (plate8) is fitted with an orifice for volumetric flow rate measurement of air. A U-tube manometer is mounted across the orifice, to measure the pressure difference inside the air box and the atmosphere.

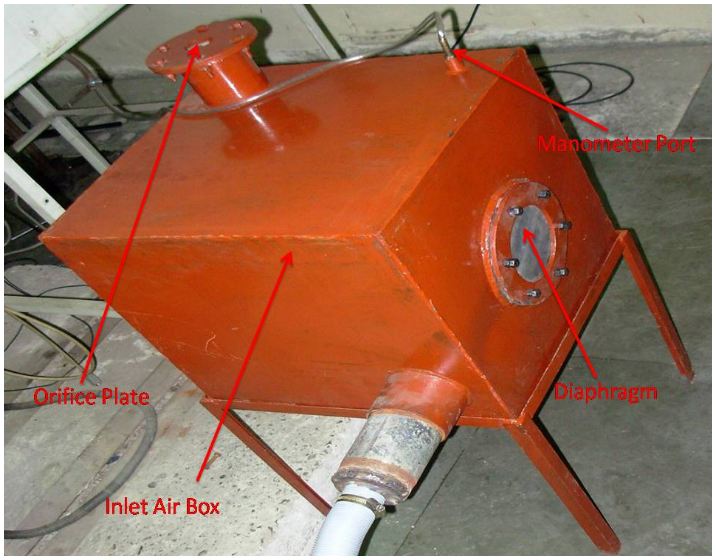


Plate 8 Inlet Air Box

3.3.6 Exhaust Emission Analysis

The major pollutants appearing in the exhaust of a diesel engine are the oxides of nitrogen. Exhaust gas analysis was done for exhaust smoke opacity, UBHC, CO, CO_2 and NO_x. For measuring the smoke opacity, AVL 437 smoke analyzer was utilized. This instrument gave reading in terms of percentage opacity. Of the light beam projected across a flowing stream of exhaust gases, a certain portion of light is absorbed or scattered by the suspended soot particles in the exhaust.

Plate 9: Smoke and Emissions Measuring System

The remaining portion of the light falls on a photocell, generating a photoelectric current, which is a measure of smoke density. For measurement of UBHC, CO, CO_2 and NO_x, AVL4000 Di-Gas Analyzer was used. Both the AVL 437 Smoke meter and AVL Di Gas Analyzer are shown in Plate 9.

3.4 DEVELOPMENT OF EGR SYSTEM

Increased demands are being placed on engine manufacturers to design and build engines that provide better engine performance, improved reliability and greater durability while meeting more stringent emission and noise requirements. One important object for internal combustion engine designers is to reduce NO_x emissions, while minimizing any negative impact on engine fuel economy and durability. An internal combustion engine having an exhaust gas recirculation (EGR) system reduces NO_x emissions while substantially maintaining fuel economy and durability. In many systems, for example, EGR is cooled to reduce NO_x emission levels at high engine loads. Systems in which EGR is not cooled may experience relatively high NO_x emissions during heavy engine throttle or loads. On the other hand, at low engine loads, systems in which EGR is cooled experience fuel droplets vaporization which is not enhanced. Large fuel droplets affect emission by producing soot.

3.4.1 Measurement of Exhaust Gas Re-circulated Air

Part of the exhaust gas is to be recirculated and put back to the combustion chamber along with the intake air. The quantity of this EGR is to be measured and controlled accurately; hence a by-pass for the exhaust gas is provided along with the manually controlled EGR valve. The exhaust gas comes out of the engine during the exhaust stroke at high pressure. It is pulsating in nature. It is desirable to remove these pulses in order to make the volumetric flow rate measurements of the recirculating gas possible. For this purpose, another smaller air box is installed in the EGR route. An orifice meter is designed and installed to measure the volumetric flow rate of the EGR. A U-tube manometer is mounted across the orifice in order to measure the EGR flow rate. Components of exhaust gas recirculation system are shown in plate no.10.

EGR ratio is calculated as:-

$$\mathrm{EGR}\ (\%) = \frac{M_{\mathrm{EGR}}}{M_{\mathrm{i}}} \times 100.$$

Where

M_{EGR} = mass of recirculated gas

M_i = mass of total intake air of the cylinder

Alternatively the formula can also be written as:-

$$\%\mathrm{EGR} = \frac{\text{volume of EGR}}{\text{total intake charge into the cyclinder}} \times 100.$$

EGR (%) is defined as the mass percent of the re-circulated exhaust (M_{EGR}) in Total intake mixture (M_i) [12].

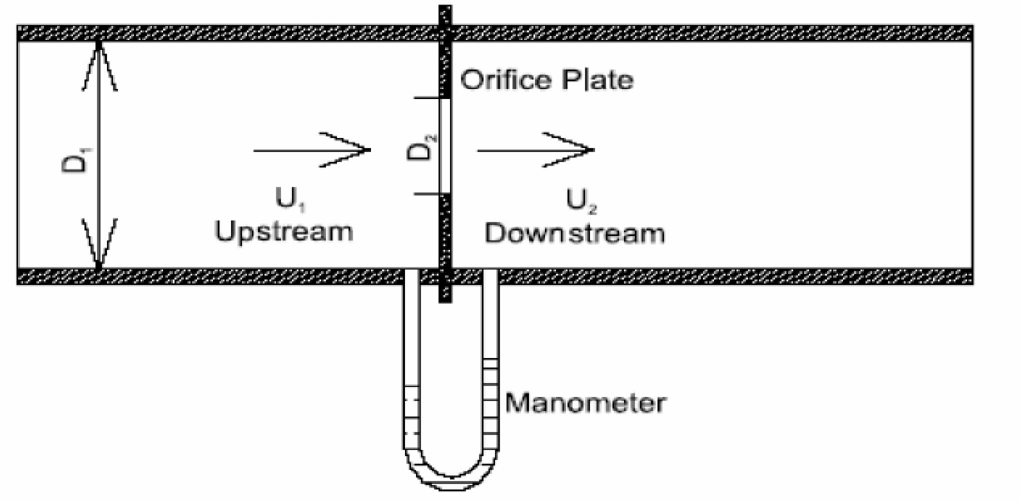


Figure 3.2 EGR flow Orifice Meter

Hence using the above formula under various loads of stabilised condition, first calculating the mass flow rate if intake air for each load the rate of air flow of EGR air can be calculated using the Orifice-meter manometer reading using the following formula:

Egr Air $= a \times \sqrt{2\rho_w gh/\rho_a}$

Inlet Air $= A \times \sqrt{2\rho_w gH/\rho_a}$

Where,

A - Area of Inlet Manifold
H – Height difference on Primary Manometer
A - Area of Orifice-meter orifice.
h – Height on EGR U-tube Manometer.
ρ_w – Density of water
ρ_a – Density of air

$$\boxed{\%EGR = \frac{a \times \sqrt{2\rho_w gh/\rho_a}}{\{(a \times \sqrt{2\rho_w gh/\rho_a}) + (A \times \sqrt{2\rho_w gH/\rho_a})\}}}$$

It should be noted carefully that the rate of air flow is not fixed and is subjected to changes in load thus care has to be taken to record the readings only after allowing time for the alternator to adjust to the new load and thus come to a constant air intake.

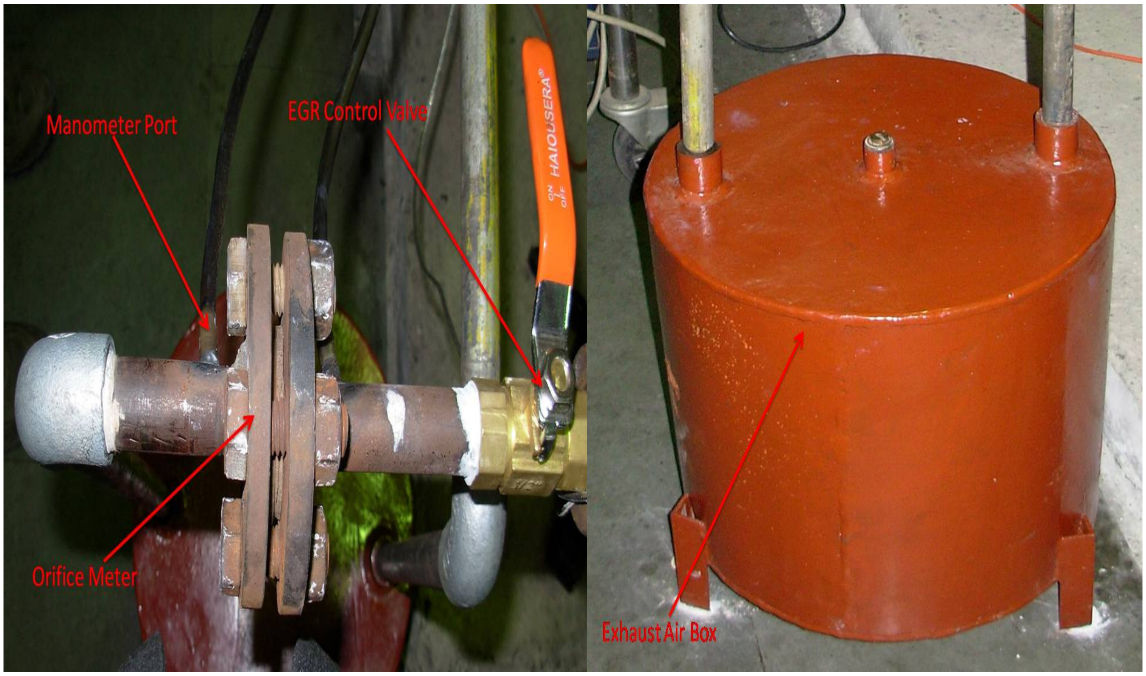


Plate 10: Components of Exhaust Gas recirculation system

CHAPTER 4

RESULTS AND DISCUSSION

Initially with diesel, a series of engine tests were carried out on medium capacity diesel engine at 1500 rpm and different EGR rates in order to show the effect of EGR on the smoke opacity and NO_x concentration in the exhaust. The smoke opacity of the exhaust gas is measured to quantify the PM present in the exhaust gas. Fig. 4.1 shows the smoke opacity at different EGR rates.

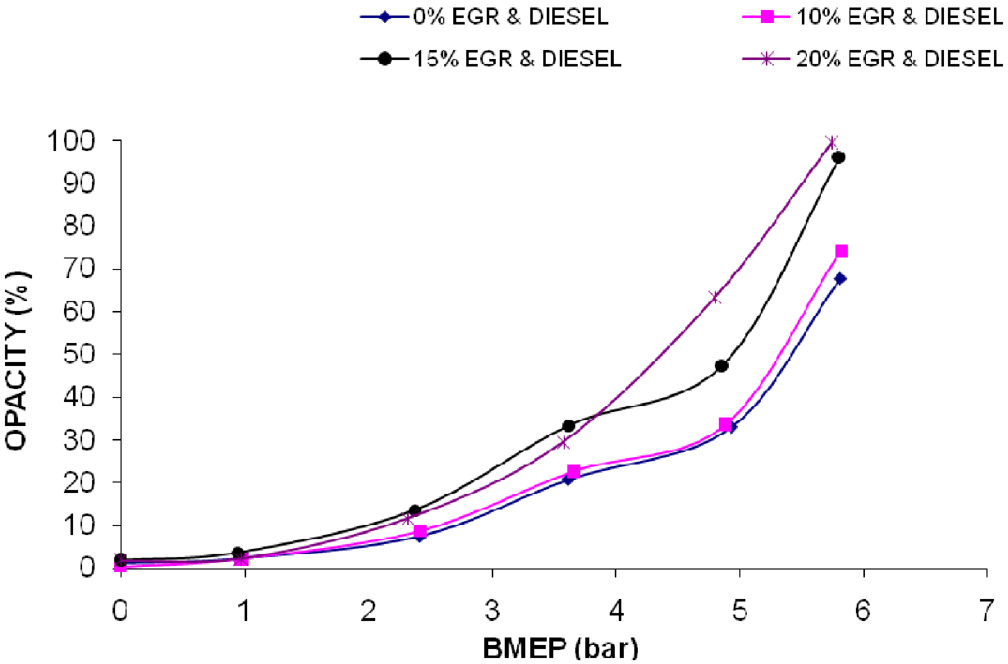


Figure 4.1: variation of Opacity Vs BMEP with different EGR ratios

Higher smoke opacity of the exhaust is observed when the engine is operated with EGR compared to without EGR. Smoke opacity increases with increasing EGR rates and increasing engine load. The variation in smoke opacity level at high loads was higher compared to lower loads. EGR reduces availability of oxygen for combustion of fuel, which results in relatively incomplete combustion and increased formation of PM.

Fig. 4.2 shows the well-established benefit of EGR in reducing NO_x emissions from diesel engine. When EGR is applied, NO_x is decreased with increasing EGR rates. The degree of reduction in NO_x at higher loads is higher. The reasons for reduction in NO_x

emissions using EGR in diesel engines are reduced oxygen concentration and decreased flame temperatures.

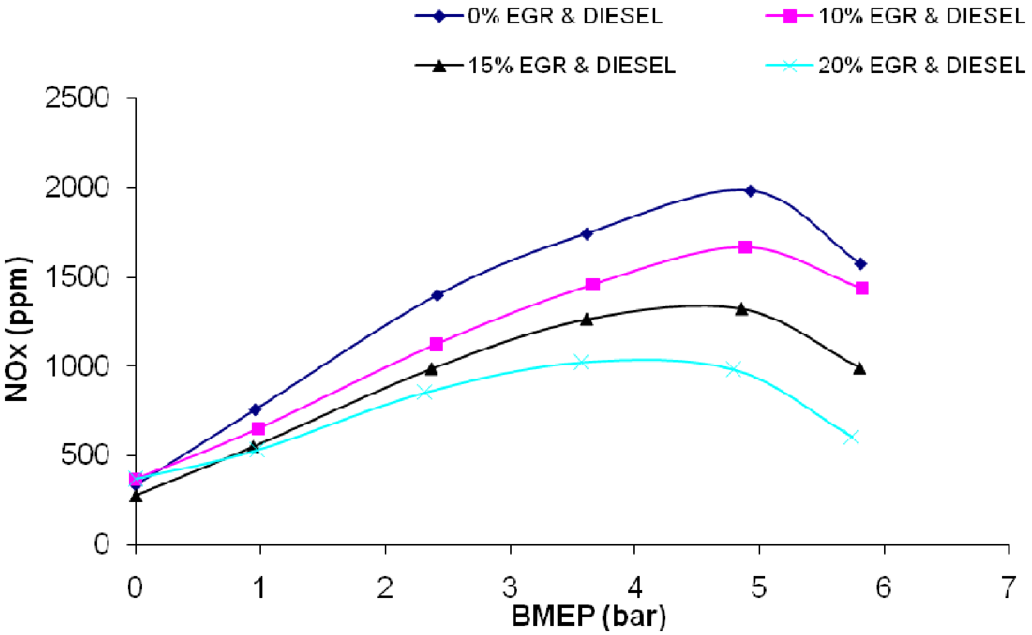


Figure 4.2 Variation of NO_x Vs BMEP with different EGR rates

Therefore, it can be observed that when EGR is applied to diesel engine, NO_x is reduced but smoke opacity is increased. This is a well-known trade-off between NO_x and PM. On the other hand, if biodiesel is used in diesel engine, smoke opacity is decreased but NO_x is increased. Thus, biodiesel with EGR can be used to reduce NO_x and smoke opacity simultaneously. A series of exhaustive engine test were carried out using 0-20% EGR rate and different concentration of jatropha biodiesel i.e. B20, B50, B100 to evaluate the performance and emission pattern of the engine. The performance and emission data were analyzed for thermal efficiency, BSEC, exhaust gas temperature, HC, CO, NO_x emissions, and smoke opacity.

4.1 Performance Characteristics

The performance characteristics of test engine on Diesel, Blends and pure jatropha Biodiesel are summarized below.

4.1.1 Exhaust Gas Temperature

The amount of fuel injected increases with the engine load in order to maintain the power output and hence the heat release and the exhaust gas temperature rise with increase in load. Exhaust gas temperature is an indicative of the quality of combustion in the combustion chamber.

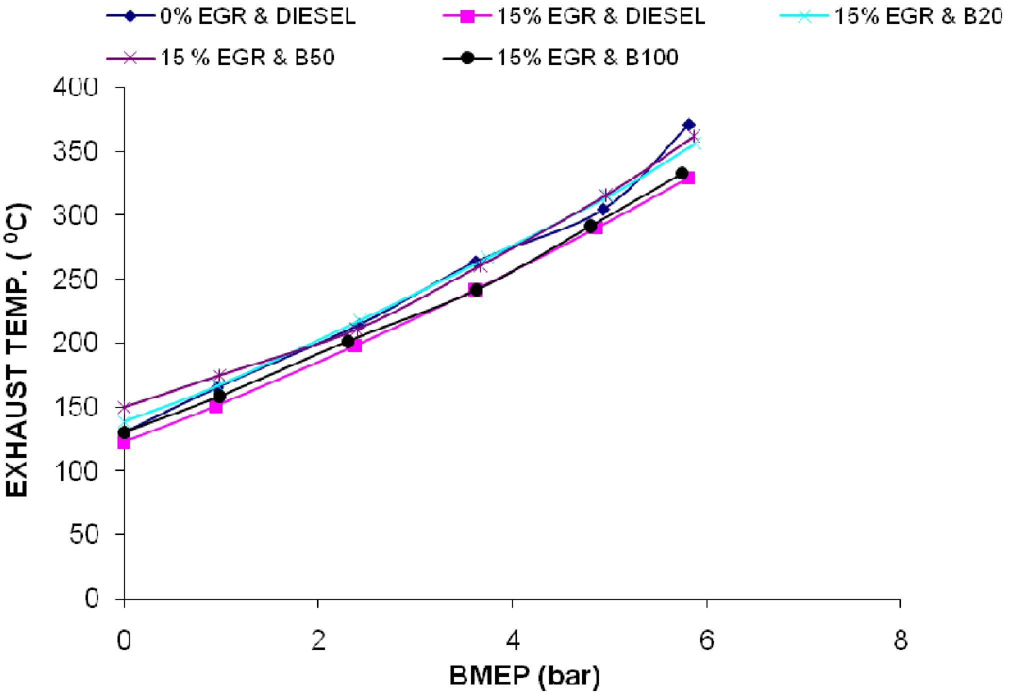


Figure 4.3 Variation of Exhaust gas temp. Vs BMEP for fuel samples with 15% EGR

The exhaust gas temperature profiles are shown in Fig. 4.3 and fig.4.4. It can be observed that with increase in load, exhaust gas temperature also increases. Temperature of the exhaust gas was found to be lower in case of EGR-operated engine. The possible reason for this temperature reduction may be relatively lower availability of oxygen for combustion and higher specific heat of intake air mixture. It is observed from figure 4.3 that with 15%EGR rates diesel have the lowest exhaust gas temperature among all fuel samples. This is possibly due to unavailability of molecular oxygen in the fuel which causes incomplete combustion. However, blends of biodiesel with application of EGR give lower exhaust gas temperature than baseline diesel data without EGR.

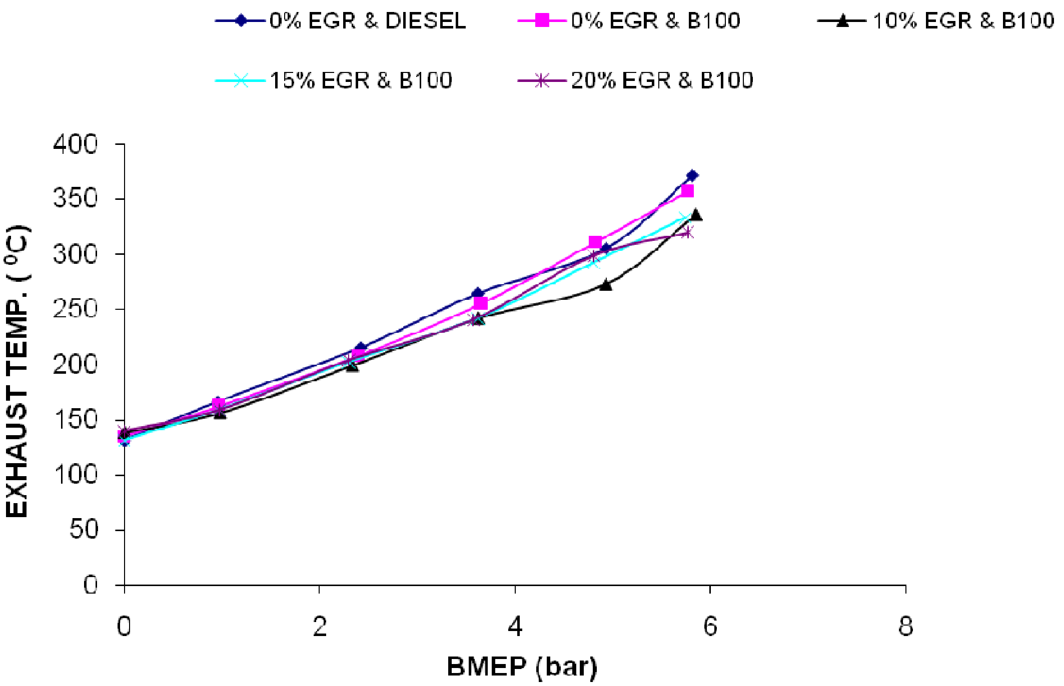


Figure 4.4 Variation of Exhaust gas temp. Vs BMEP for Biodiesel with different EGR rates

The higher exhaust temperature with Diesel without application of EGR is indicative of lower thermal efficiencies of the engine. At lower thermal efficiency, less of the energy input in the fuel is converted to work, thereby increasing exhaust temperature.

4.1.2 Thermal Efficiency

From the test results it was observed that initially with increasing brake power, the brake thermal efficiencies of all the fuels were increased and then tended to decrease with further increase in brake power.

The trends of the thermal efficiency are shown in Fig. 4.5. Thermal efficiency is found to be slightly increased with EGR at lower engine loads. The possible reason may be re-burning of HCs that enter the combustion chamber with the recirculated exhaust gases. At higher engine loads, thermal efficiency remains unaffected by EGR.

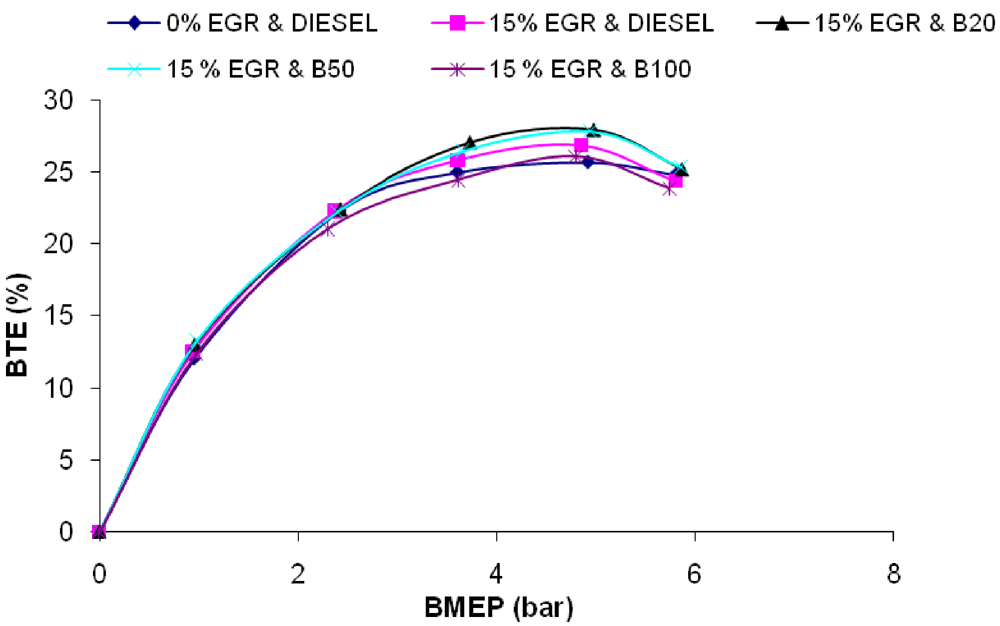


Figure 4.5 Variation of BTE Vs BMEP for different fuels with 15% EGR rate

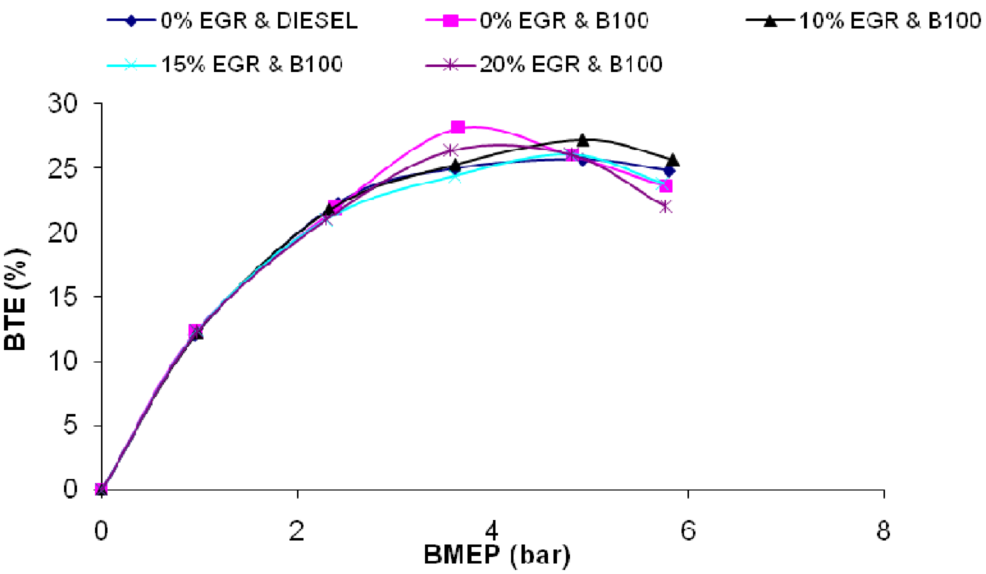


Figure 4.6 Variation of BTE Vs BMEP for Biodiesel with different EGR rates

When engine was operated on biodiesel blends with EGR, thermal efficiency improved with increasing concentration of biodiesel in the blend. This may be possibly due to improved thermal efficiency observed with oxygenated fuels. An important observation is that all biodiesel blends have higher thermal efficiency than the baseline data.

The highest brake thermal efficiency was found in case of diesel with 10% EGR at 80% load. The peak thermal efficiency for B20, B50 and B100 were 27.90%, 27.77% and 26.05% respectively whereas the peak thermal efficiency of diesel was 26.79% with 15% EGR.

4.1.3 Brake Specific Energy Consumption

Since Brake Specific Fuel Consumption is not a very reliable parameters to compare the performance of two different fuels since density and calorific value of both the fuel are significantly different. Therefore, brake specific energy was taken as a parameter to compare the energy requirement for producing unit power in case of different test fuels.

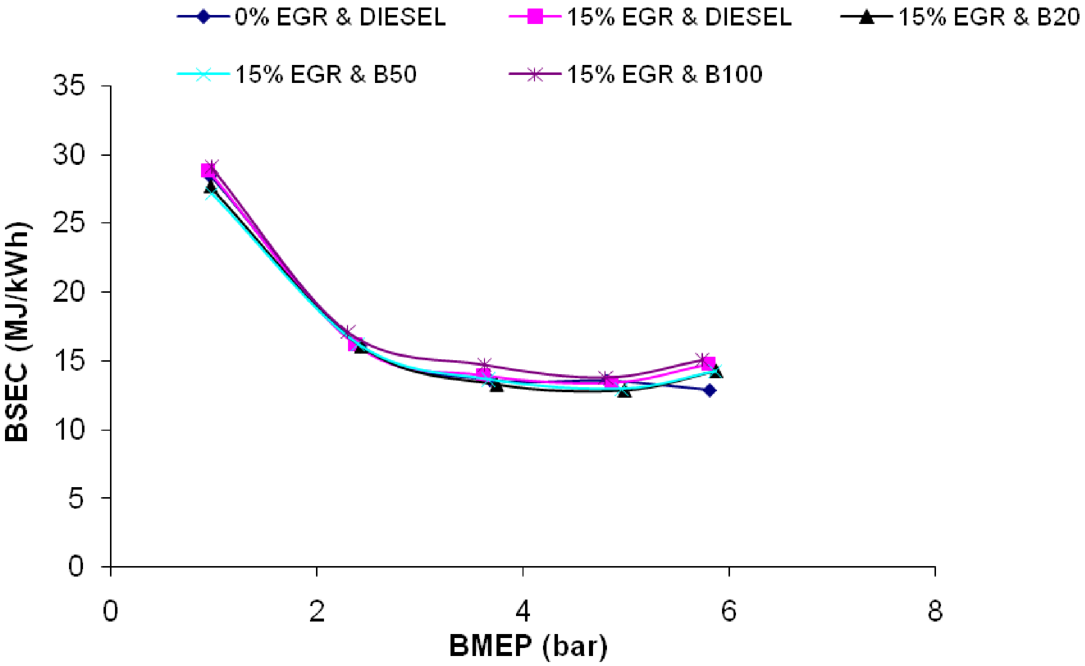


Figure 4.7 Variation of BSEC Vs BMEP for different fuels with 15% EGR rate

Figures 4.7 and 4.8 represent BSEC results with different engine loads for the set of experiments. It can be observed that BSEC was lower for diesel with EGR compared to baseline data at lower loads. But at higher loads BSEC with and without EGR follows the same trend. When engine was operated on biodiesel blends, BSEC reduced with increasing concentration of biodiesel. The possible reason for lower BSEC may be better thermal efficiency. 50% biodiesel blend gave lowest BSEC with EGR.

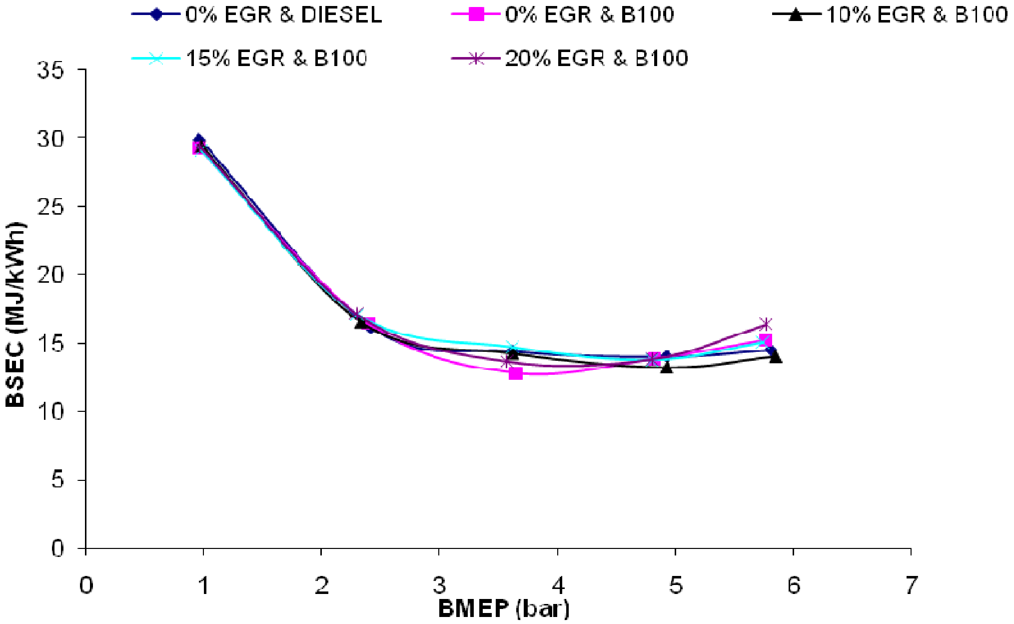


Figure 4.8 Variation of BSEC Vs BMEP for Biodiesel with different EGR rates

For neat Biodiesel with and without EGR, BSEC was higher than baseline data at lower loads. At higher loads, the engine followed almost similar BSEC trend for all data sets and with increasing EGR rates, BSEC keep on increasing.

4.2 EMISSION CHARACTERISTICS

4.2.1 NO_x Emissions

The variations of NO_x emissions for all the test fuels are shown in Figures 4.9, 4.10 and 4.11. The NO_x emissions increased with the increasing engine load, due to higher combustion temperature. This proves that the most important factor for the emissions of NO_x is the combustion temperature in the engine cylinder and the local stoichiometry of the mixture.

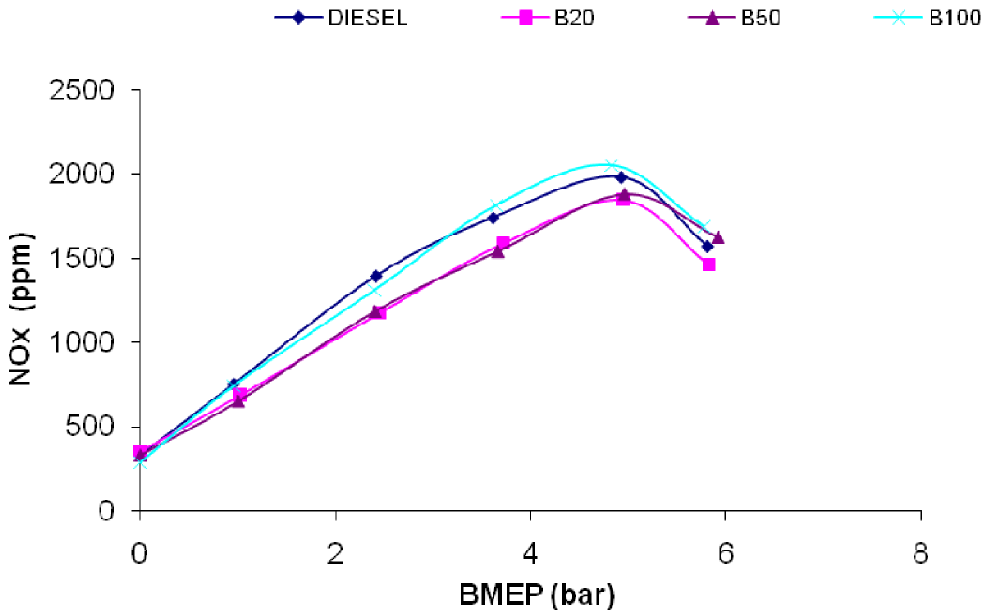


Figure 4.9 Variation of NO_x Vs BMEP for different fuels without EGR

NO_x emissions were found to be 1987 ppm for diesel and 2055 ppm for biodiesel at 80% load and 0% EGR operation. NO_x emissions were higher for bio-diesel fuel compared to Diesel. This is probably due to higher bulk modulus of Biodiesel resulting in a dynamic injection advance apart from static injection advance provided for optimum efficiency. Excess oxygen (10%) present in the Biodiesel would have aggravated the situation. At higher loads, NO_x levels were higher by 5–8% compared to diesel. An important observation is that Biodiesel blend B20 has lower NO_x emissions than the baseline data for diesel without EGR.

Figure 4.10 and 4.11 shows the well-established benefit of EGR in reducing NO_x emissions from diesel engine. The degree of reduction in NO_x at higher loads is higher. The reasons for reduction in NO_x emissions using EGR in diesel engines are reduced oxygen concentration and decreased flame temperatures. However, NO_x emissions in case of biodiesel blends are higher than diesel due to higher temperatures prevalent in the combustion chamber.

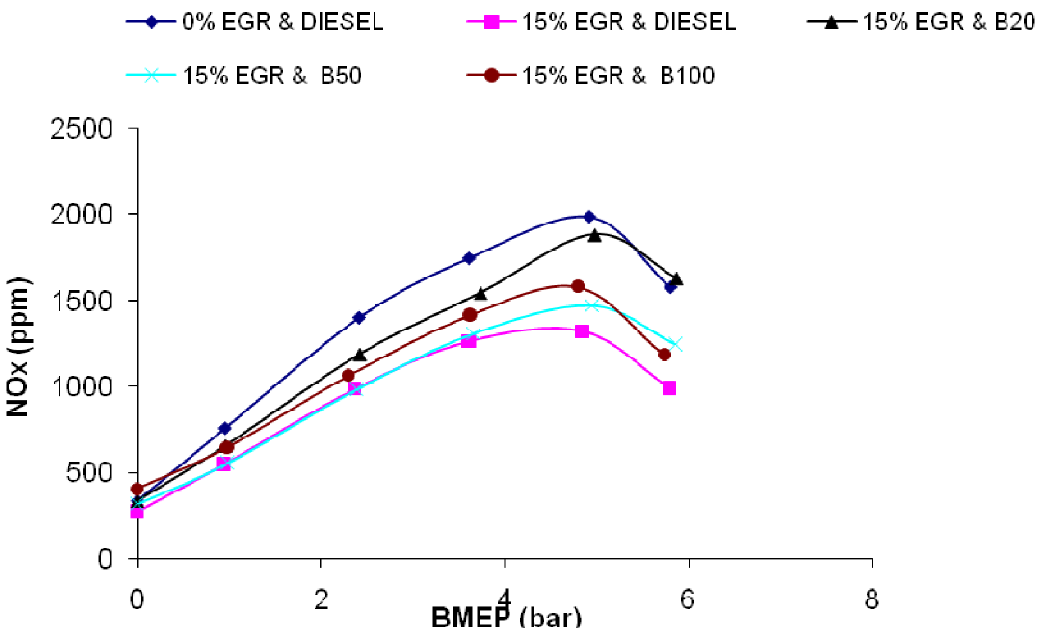


Figure 4.10 Variation of NO_x Vs BMEP for different fuels with 15% EGR rate

Here it was observed that diesel with 15% EGR gave lowest NO_x emission as compared to the other test fuel samples. This is due to presence of inert gases in combustion chamber and unavailability of molecular oxygen.

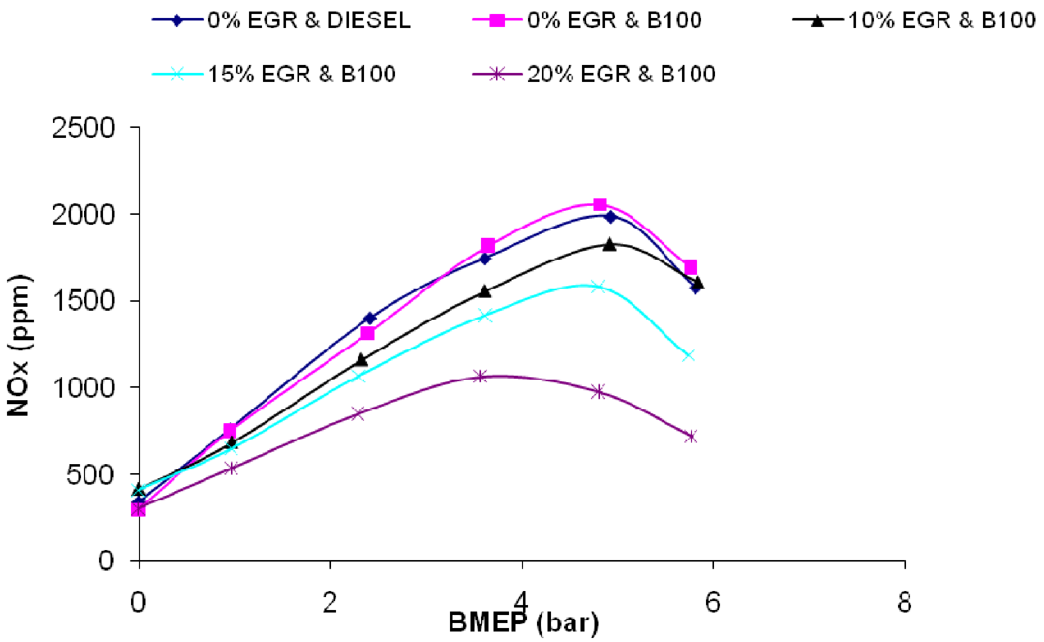


Figure 4.11 Variation of NO_x Vs BMEP for Biodiesel with different EGR rates

Even though 20% and more EGR ratios were able to reduce NO_x by a large amount but reduction in BTE and large increase in smoke, CO and HC emissions were observed.

4.2.2 Carbon Monoxide Emission

In this experiment CO and HC emissions are measured to check the completeness of combustion inside the cylinder. Figure 4.12 compares the CO emission for the set of fuels employing 15% EGR with diesel baseline data. At full load steep rise in CO emission is probably due to dilution effect of exhaust gases and lower air fuel ratio.

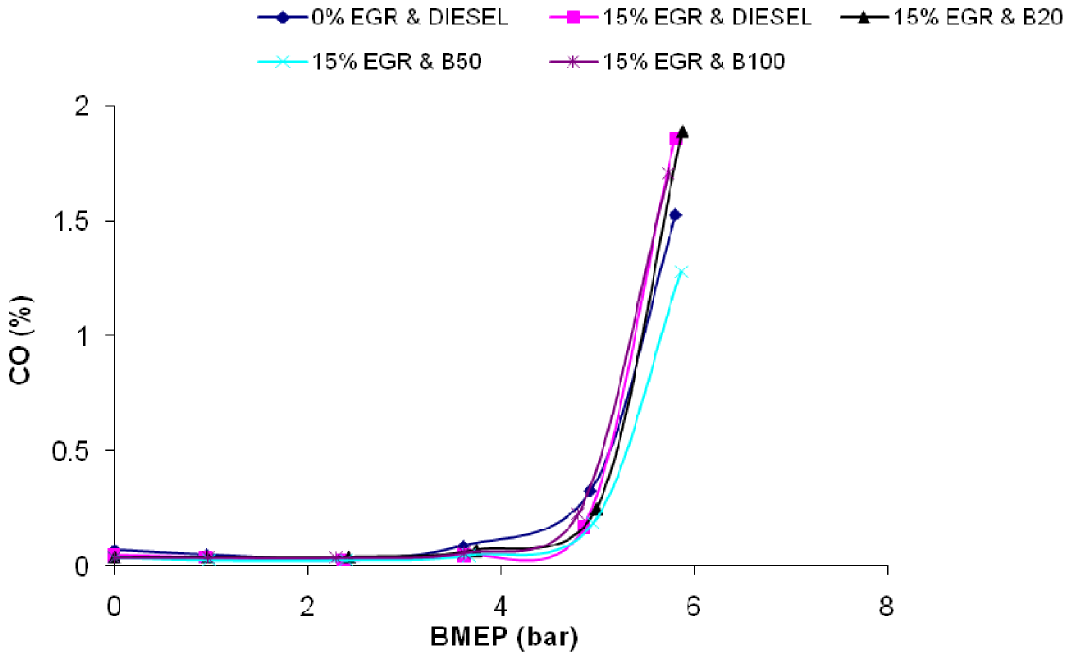


Figure 4.12 Variation of CO Vs BMEP for different fuels at 15% EGR rate

It was observed that diesel and B20 at 15% EGR gave maximum CO emission, which is probably due to oxygen deficient operation. Here it is important to note that with 15% and more EGR rates combustion quality detoriates faster.

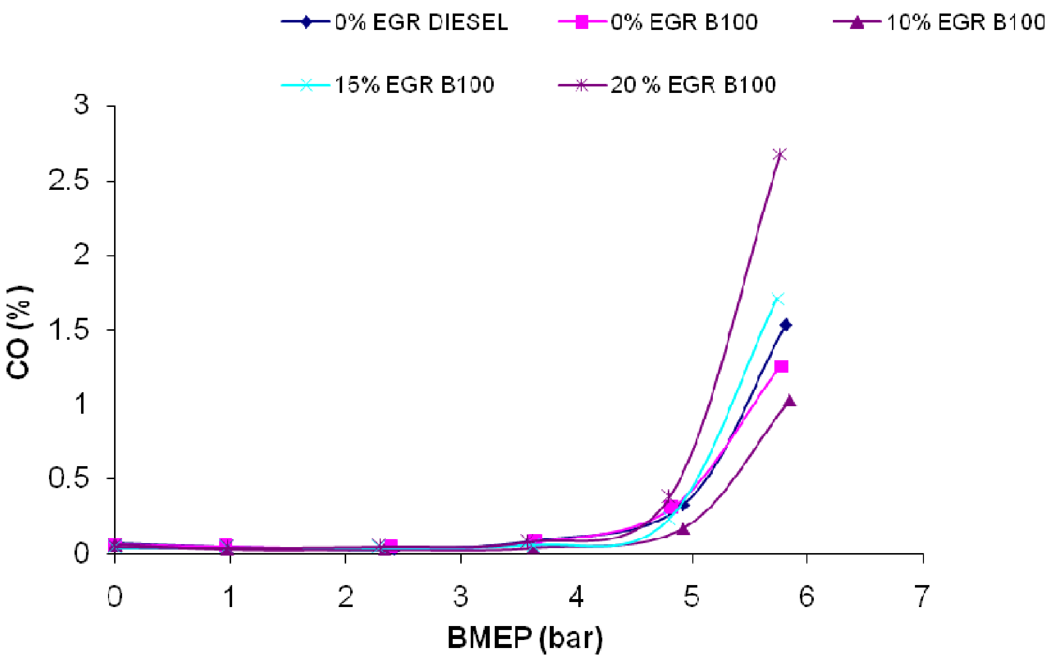


Figure 4.13 Variation of CO Vs BMEP for Biodiesel at different EGR rates

Figure 4.13 compares CO emissions of Jatropha Biodiesel at different EGR rates with baseline Diesel data. Without EGR for whole load range, the CO emission from the pure jatropha biodiesel fuel is lower than that from diesel fuel. This is possible because of the molecular oxygen availability in biodiesel fuel. With increasing EGR percentage, CO emission remains same at lower loads but increases at higher loads due to dilution effect of exhaust gases. In case of biodiesel, 10% EGR gave 1.03% (minimum) CO emission at full load and emissions level rise rapidly with 20% EGR rate.

4.2.3 Un-burnt Hydro Carbon Emissions

Effects of EGR and biodiesel on unburned HCs are shown in Figures 4.14 and 4.15. These graphs show that HC emissions increase with EGR and load. The HC emissions of all the fuels are lower in partial engine load, but increased at higher engine load. The possible reason may be lower excess oxygen available for combustion. Lower excess oxygen concentration results in poor air-fuel mixtures at different locations inside the combustion chamber. This heterogeneous mixture does not combust properly and results in higher HC emissions.

Adding biodiesel to diesel decreases the oxygen required for combustion because of presence of molecular oxygen in fuel. This results in lower HC emission. It can be observed from Figure 4.14 that HC emissions are lower for biodiesel blends than with diesel when the engine was operated employing EGR. However, HC emissions for pure biodiesel with 15% EGR are lowest compared to baseline data of diesel without EGR.

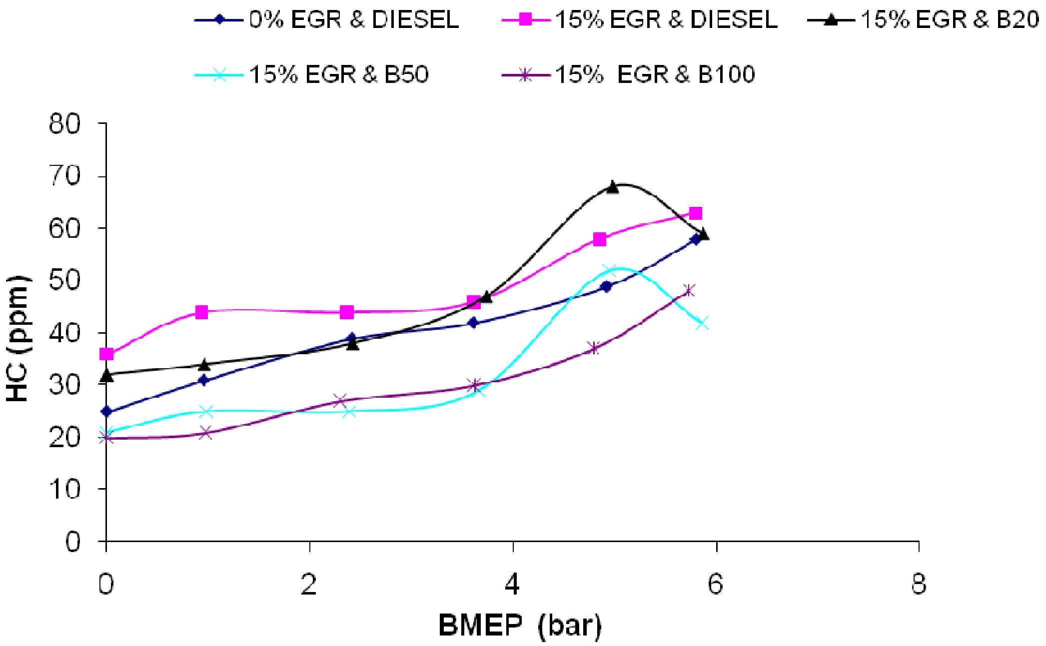


Figure 4.14 Variation of HC Vs BMEP for different fuels at 15% EGR rate

Figure 4.15 shows the variation of HC emission of Biodiesel fuel at different exhaust gas recirculation rates. Graphs indicate that biodiesel, without application of EGR, gave lower HC emission than diesel. The reason behind this trend is inbuilt oxygen content of biodiesel. Application of EGR shows slight reduction in HC emission than without EGR. This trend followed up to 15% EGR rate. This is due to reburning of HCs in combustion chamber.

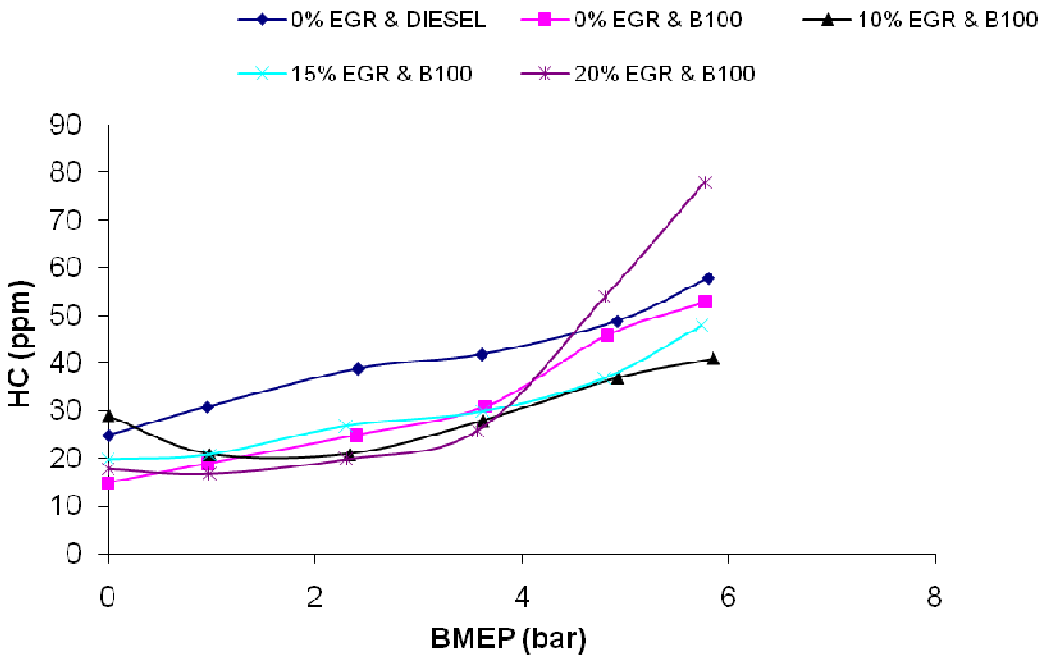


Figure 4.15 Variation of HC Vs BMEP for Biodiesel at different EGR rates

4.2.4 Smoke Opacity

Fig. 4.16 shows the comparison of smoke opacity with baseline diesel data for all set of test fuels at different load conditions with 15% EGR rate. Higher smoke opacity of the exhaust is observed when the engine is operated with EGR compared to without EGR on diesel. EGR reduces availability of oxygen for combustion of fuel, which results in incomplete combustion and increased formation of PM. Smoke opacity for biodiesel blends with EGR is noticed to be generally lower than that of diesel. The molecule of biodiesel contains some oxygen that takes part in combustion and this may be a possible reason for improved combustion and thus lower smoke. It is observed that pure biodiesel gives lowest smoke opacity for all data sets with 15% EGR.

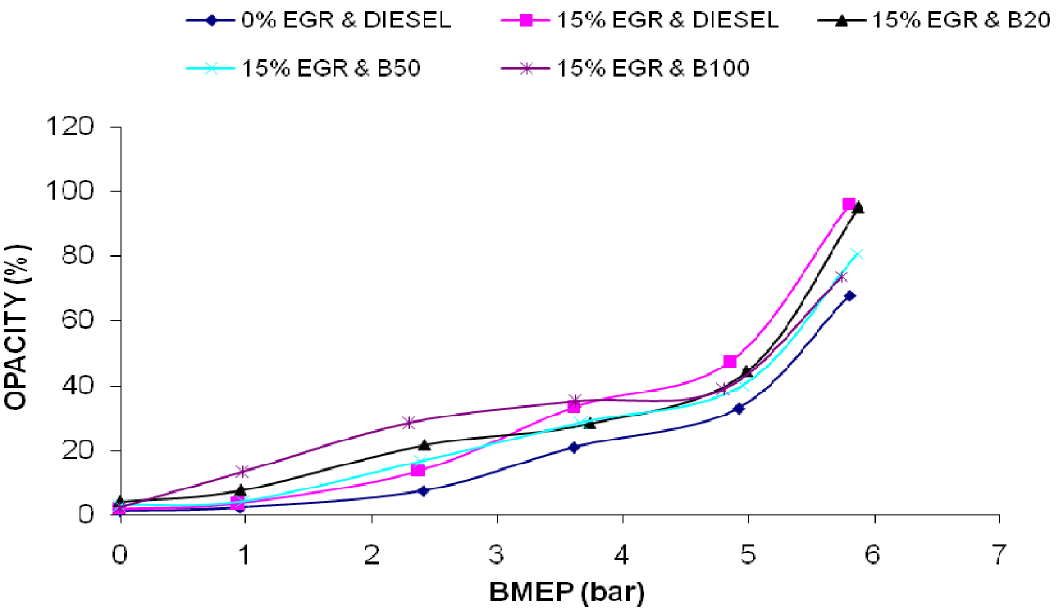


Figure 4.16 Variation of Opacity Vs BMEP for different fuels with 15% EGR rate

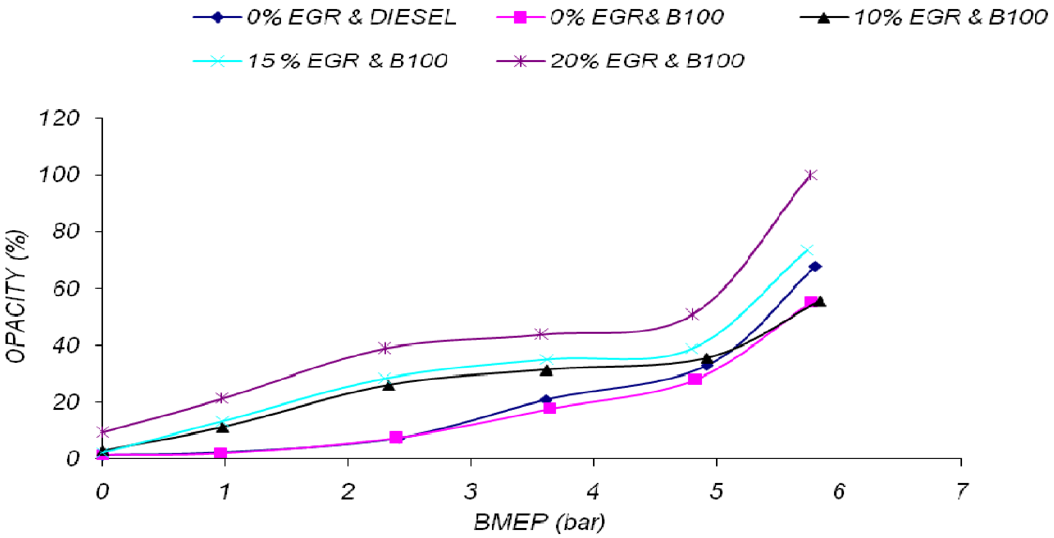


Figure 4.17 Variation of Opacity Vs BMEP for Biodiesel with different EGR rates

Within the experimental range, the smoke opacity for biodiesel is lower than diesel fuel for no load to full load conditions. This may be due to the fact that, molecular oxygen content of biodiesel may be responsible for better combustion and resulting into lower smoke opacity. Opacity increases with increasing EGR rates for no load to full load. In case of biodiesel sudden rise in particulate matter is observed with 20% EGR.

CHAPTER 5

CONCLUSIONS AND SCOPE FOR FUTURE WORK

Increasing concerns about fossils fuel depletion and Environment degradation suggests bio origin fuels as future alternative fuels. But the bio-fuels don't cope up with eminent emission norms. Higher NO_x emission reported in biodiesel fuels in comparison to fossils fuel.

The present study was carried on an unmodified diesel engine which was converted to run on exhaust gas recirculation (EGR) system. The main objective of the present investigation was to evaluate suitability of EGR system for reduction of oxides of nitrogen (NO_x) of biodiesel fueled Diesel engine and to evaluate the performance and emission characteristics of the engine with different EGR rates. The experimental results show that with application of EGR, overall engine performance and emission characteristics with Biodiesel and its blends are slightly better than the diesel fuel. The thermal efficiency of the engine was lower and the brake specific energy consumption of the engine was higher when the engine was fueled with biodiesel and its blends compared to diesel fuel, when no exhaust gas was recirculated. But in case of EGR these parameters were superiors for biodiesel and its blends. Without EGR, NO_x emission of biodiesel was higher than diesel. With increasing EGR rates, the degree of reduction in NO_x at higher loads was higher. With and without application of EGR, the Carbon monoxide (CO), Hydrocarbon (HC) and smoke opacity from the biodiesel and its blends was found lower than diesel fuel during the whole experimental range. Even though 20% and more EGR rates were able to reduce NO_x by a large amount but reduction in BTE and large increase in smoke, CO and HC emissions were observed. The experimental results show that optimum EGR rate is basically trade off between NO_x and smoke opacity. From the experimental study it can be suggested that at low loads more than 15% EGR rates can be employed but at higher loads maximum EGR rate is limited to 15% to obtain better results from Exhaust gas recirculation system.

In future, long term assessment of engine durability and effect on lubricating oil of biodiesel fueled diesel engine with exhaust gas recirculation, need to be examined.

Another field of research is development of the sophisticated EGR valve which could response to dynamic mode of engine operation.

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APPENDIX – I

TECHNICAL SPECIFICATION OF AVL 437 SMOKE METER

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

APPENDIX – II

TECHNICAL SPECIFICATION OF AVL Di-GAS ANALYZER

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