

Major Project -II

UTILIZATION OF n-HEXANOL AND DIESEL BLENDS IN AN UNMODIFIED DIESEL ENGINE-PERFORMANCE, EMISSION AND COMBUSTION STUDIES.

Submitted to **Delhi Technological University**
in partial fulfilment of the requirement for the award of the Degree of

Master of Technology

In

Thermal Engineering

By

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DECLARATION

I, hereby declare that the work embodied in the dissertation entitled “**UTILIZATION OF n-HEXANOL AND DIESEL BLENDS IN AN UNMODIFIED DIESEL ENGINE-PERFORMANCE, EMISSION AND COMBUSTION STUDIES**” in partial fulfilment for the award of degree of MASTER of TECHNOLOGY in “THERMAL ENGINEERING”, is an original piece of work carried out by me under the supervision of Prof. Naveen Kumar, Mechanical Engineering Department, Delhi Technological University. The matter of this work either full or in part have not been submitted to any other institution or University for the award of any other Diploma or Degree or any other purpose what so ever.

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CERTIFICATE

This is to certify that the work embodied in the dissertation entitled “**UTILIZATION OF n-HEXANOL AND DIESEL BLENDS IN AN UNMODIFIED DIESEL ENGINE-PERFORMANCE, EMISSION AND COMBUSTION STUDIES**” by **ANUBHAV KHANDELWAL**, (Roll No.-**2K12/THR/07**) in partial fulfilment of requirements for the award of **Degree of Master of Technology in Thermal Engineering**, is an authentic record of student’s own work carried by him under my supervision.

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

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ACKNOWLEDGEMENT

It is a pleasure to acknowledge our gratitude to all the people involved, directly or indirectly in the completion of this project. I would like to thank our project guide **Dr. Naveen Kumar** who devoted valuable hours for this assignment and providing the motivational guidance during the entire preparation of this project, answering the number of technical queries despite his busy schedule. His valuable suggestions, constructive criticism and timely help proved extremely fruitful.

I am thankful to Sh. Kamal Nain, Sh. Manoj Kumar and other project staff of Centre for Advanced Studies and Research in Automotive Engineering for all assistance during execution of this project work. I am also thankful to my fellow friends and colleagues at CASRAE who were always there to lend a helping hand in the hour of need.

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ABSTRACT

Today, the world is in precarious position due to the ever increasing indiscriminate extraction and lavish consumption rate of fossil fuels which in turn are responsible for a filthy environment. This exploitation forced to look for alternate ways to run engines without compensating with the environment and performance, also at the same time they ought to be renewable and sustainable. Among the various developments to combat the problem of swelling emission, the application of oxygenated fuel is an effective way to moderate pollution without any prior modification of the engine. Alcohol which is bio-based renewable and oxygenated fuel provides a suitable alternate fuel for internal combustion engines. Alcohols can be blended with both the petroleum based and bio origin based fuels such as vegetable oil and biodiesel. Addition of alcohols reduces dependence of diesel fuel with attractive emission levels. Also alcohol has characteristics that make it a natural engine fuel as it prevents engine detonation under load. In this regard exhaustive research has been carried on alcoholic fuels like methanol and ethanol but little work has been done on exploring the potential of higher alcohols for automotive application Long chain alcohols such as pentanol, hexanol despite their analogous properties have rarely been inspected. Hexanol is a promising long chain compound, as it less hydrophilic and possessing high heating value. High cetane number, low vapour pressure and improved miscibility than ethanol make n-hexanol a preferable component to blend with conventional diesel fuel. The effect of 5% n-hexanol blended fuel by volume reported that many properties like density, flash point, viscosity of the blends are well above the requirement than those of ASTM norms of the diesel engine which further increases efficiency with significant improvements in emissions as well.

In the present investigation, four blends of hexanol and diesel were prepared i.e. Hx05D95, Hx10D90, Hx15D85, and Hx20D80. All the blends were found to be homogenous and stable. The calorific value of all the blends was found to be slightly lesser as compared to neat diesel fuel. The brake thermal efficiency for all the blends was found

to be slightly higher in comparison to neat diesel. The maximum brake thermal efficiency was obtained with Hx20D80 blend. Similarly minimum brake specific fuel consumption was obtained for Hx20D80 blend while rest of the blends showed a reduction in brake specific fuel consumption. The CO emissions were lower for all the blends. While increasing the hexanol percentage in the blend, CO emission level decreased. However, after 60% load or higher-load conditions, a steep hike in CO emission was observed irrespective of test fuels. Also smoke and HC emissions were low, but higher NO_x emissions were recorded. Increased concentration of oxygen within the combustion chamber helps to achieve high in-cylinder peak pressure for all the HxD blends with respect to diesel. The crank angle corresponding to maximum heat release rate shifted rightwards for the hexanol diesel blends as compared to baseline data. It can be concluded from the exhaustive study that a diesel engine, without any modifications, can run successfully on hexanol-diesel blend fuel without externally apparent damage to the engine parts. Nevertheless, to recommend its use as a substitute of straight diesel fuel, long-term durability tests are required.

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NOMENCLATURE

A/F	Air to Fuel
ATDC	After Top Dead Center
AVL-437	AVL-437 Smoke Meter
BMEP	Break Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
BTDC	Before Top Dead Center
°C	Degree Celsius
CA	Crank Angle
Cc	Cubic centimeter
CI	Compression Ignition
CN	Cetane Number
CO	Carbon monoxide
CO ₂	Carbon Dioxide
cSt	Centi Stoke
CV	Calorific Value
DI	Direct Injection
DF	Diesel fuel
D100	Neat diesel
$dQ/d\theta$	Apparent Net Heat transfer Rate
$dQ_{ch}/d\theta$	Gross Heat Release Rate
$dQ_{ht}/d\theta$	Heat Transfer across the cylinder walls, J/°CA
g	Gram

g/cc	Gram per cubic centimeter
HxD	Hexanol-diesel
Hx05D95	Hexanol 5% + Diesel 95%
Hx10D90	Hexanol 10% + Diesel 90%
Hx15D85	Hexanol 15% + Diesel 85%
Hx20D80	Hexanol 20% + Diesel 80%
HC	Hydrocarbon
HP	Horse Power
IC	Internal Combustion
IS	Indian standard
mm	Millimeter
Mtoe	Million Tonne of Oil Equivalent
Mboe	Million Barrels of Oil Equivalent
NO	Nitric Oxide
No.	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
UBHC	Unburnt Hydrocarbon
v/v	Volume / Volume
%	Percent

1.1 ENERGY SECURITY

Energy is critical, directly or obliquely, in the entire process of development, growth and survival of all living beings. Also it plays a vital role in the socio-economic development and human welfare of a country. Today's global energy system sits at the nexus of some of the deepest dilemma of growth versus the environment. There have always been tensions in the energy system, but it is becoming more and more apparent that the strains are becoming more acute. Population growth and economic development are intensifying the stresses on energy supply, energy demand and the environment.

Now, energy has come to be known as a 'strategic commodity' and any uncertainty about its supply can threaten the functioning of the economy, particularly in developing economies such as that of India. Achieving energy security in this strategic sense is of fundamental importance not only to India's economic growth but also for the human development objectives. India's rapid economic growth has made it one of the fastest growing markets in the world, which has translated to exponential increase in its total energy consumption for past five decades. However, resource augmentation and growth in energy supply has not kept pace with increasing demand and therefore, India continues to face serious energy shortages.

Unstable price of petroleum fuel in world market and recent environmental concerns on gas emissions during combustion have led to intensive search for alternative energy sources that are not only renewable but sustainable. This also resulted in efficient utilization of energy. The renewable sources of energy are very important and relevant to today's world.

They cause lesser emissions and are available locally and hence they stand out as a source of clean and limitless energy.

1.2 ENERGY SCENARIO: WORLD

Energy has undergone a major transition from a general field of study of technologies to an important issue in economic planning and international relations. Energy is the building block for socio-economic development of any country.

Population and income growth are the key drivers behind growing demand for energy. By 2030 world population is projected to reach 8.3 billion, which means an additional 1.3 billion people will need energy; and world income in 2030 is expected to be roughly double the 2011 level in real terms. World primary energy consumption is projected to grow by 1.6% p.a. from 2011 to 2030, adding 36% to global consumption by 2030. The growth rate declines, from 2.5% p.a. for 2000-10, to 2.1% p.a. for 2010-20, and 1.3% p.a. from 2020 to 2030 [1].

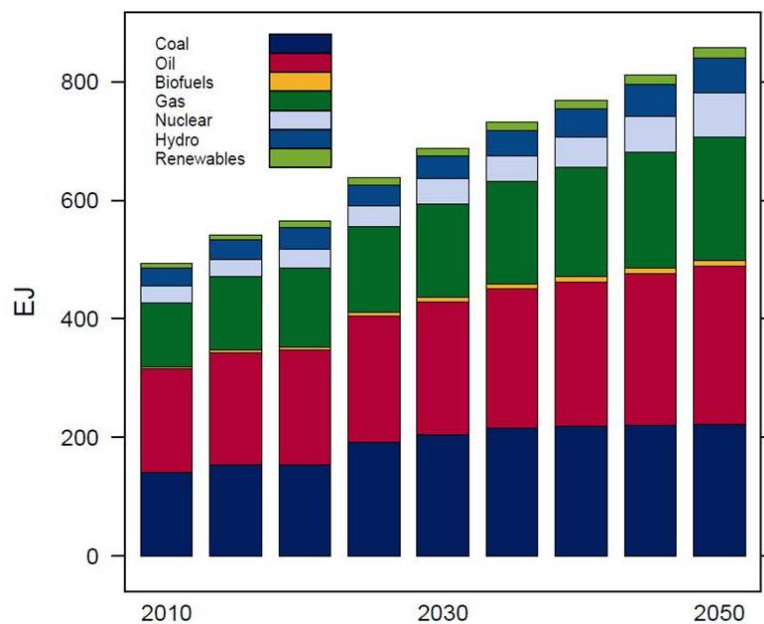


Fig 1.1: Global Energy Use [2]

As global population increases, energy needs will likewise increase. Additionally, with higher incomes, more people can afford to expand their needs and further satisfy their material desires such as buying a car. Global energy use almost doubles by 2050 (Figure 1.1). This growth occurs despite assumptions of substantial improvements in energy efficiency and conservation spurred by higher energy prices [2]. Energy use in developed countries stabilizes, partly due to the assumption that these countries will meet their Copenhagen pledges. The most substantial growth is projected in the other G20 nations (Figure 1.2). These countries currently use slightly less energy than the developed world, but by 2050 their energy use exceeds the amount presently consumed by the entire world (nearly 500 exajoules). Growth in the rest of the world is also projected, with energy use in 2050 approaching the amount presently used in the developed world [2].

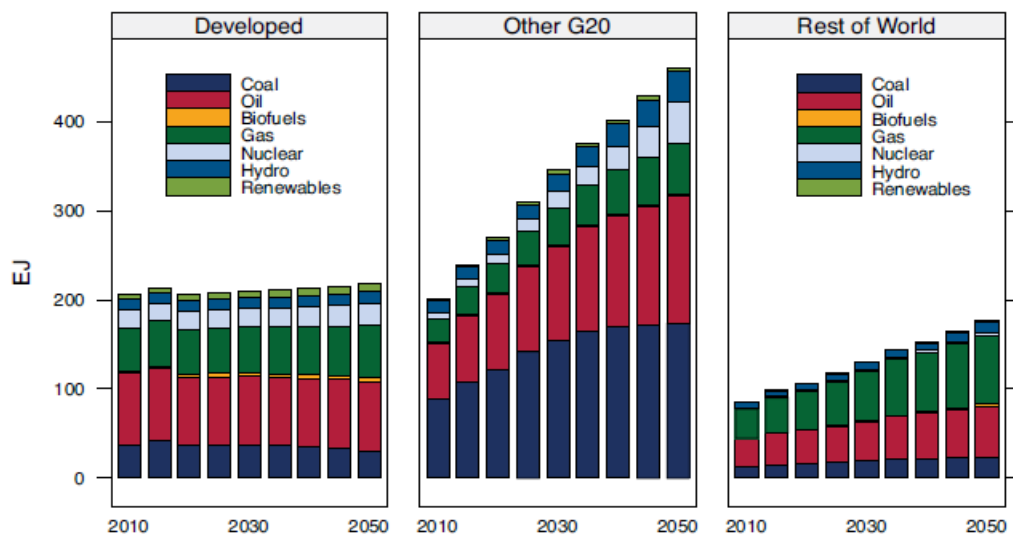


Fig 1.2: Energy Use by Major Group [2]

Over the next 50 years, even with the Copenhagen pledges, the majority of the world's energy is projected to continue to come from the same sources currently utilized: coal, oil and natural gas. Coal use levels off with time, and oil and natural gas use increases

(see Figure 1.1). Meanwhile, nuclear and hydropower use increases mostly in developing nations; however, without substantial mandates (or more widespread and tighter climate policies), those potential sources are not projected to significantly increase [2].

1.3 ENERGY SCENARIO: INDIA

Due to rapid economic expansion, India has one of the world's fastest growing energy markets and is expected to be the second-largest contributor to the increase in global energy demand by 2035, accounting for 18% of the rise in global energy consumption [3]. Given India's growing energy demands and limited domestic fossil fuel reserves, the country has ambitious plans to expand its renewable and nuclear power industries. India has the world's fifth largest wind power market and plans to add about 20GW of solar power capacity by 2022 [3]. India also envisages increasing the contribution of nuclear power to overall electricity generation capacity from 4.2% to 9% within 25 years [3]. The country has five nuclear reactors under construction (third highest in the world) and plans to construct 18 additional nuclear reactors (second highest in the world) by 2025 [3].

It is a known fact that India is second largest country in the world in terms of population inhabiting 17% of world's population. However, in a stark contrast it has just 0.6% of known oil and natural gas resources in the world. As India mainly depends on import of crude petroleum to meet its requirement, any disruption in supply would greatly impact its economy [4].

Speaking of production of all fossil fuels (viz. Oil gas and coal) in the next two decades and gradual extinction of these resources is an accepted scientific fact. With increased demand in future, India, which is highly dependent on crude import, would become more and more import dependent. The implication of large scale imports would ruin country's economy and strategy to move towards energy security or energy dependency is a must for our country [4].

Figure 1.3 shows the domestic production and consumption of crude oil in India for the past years.

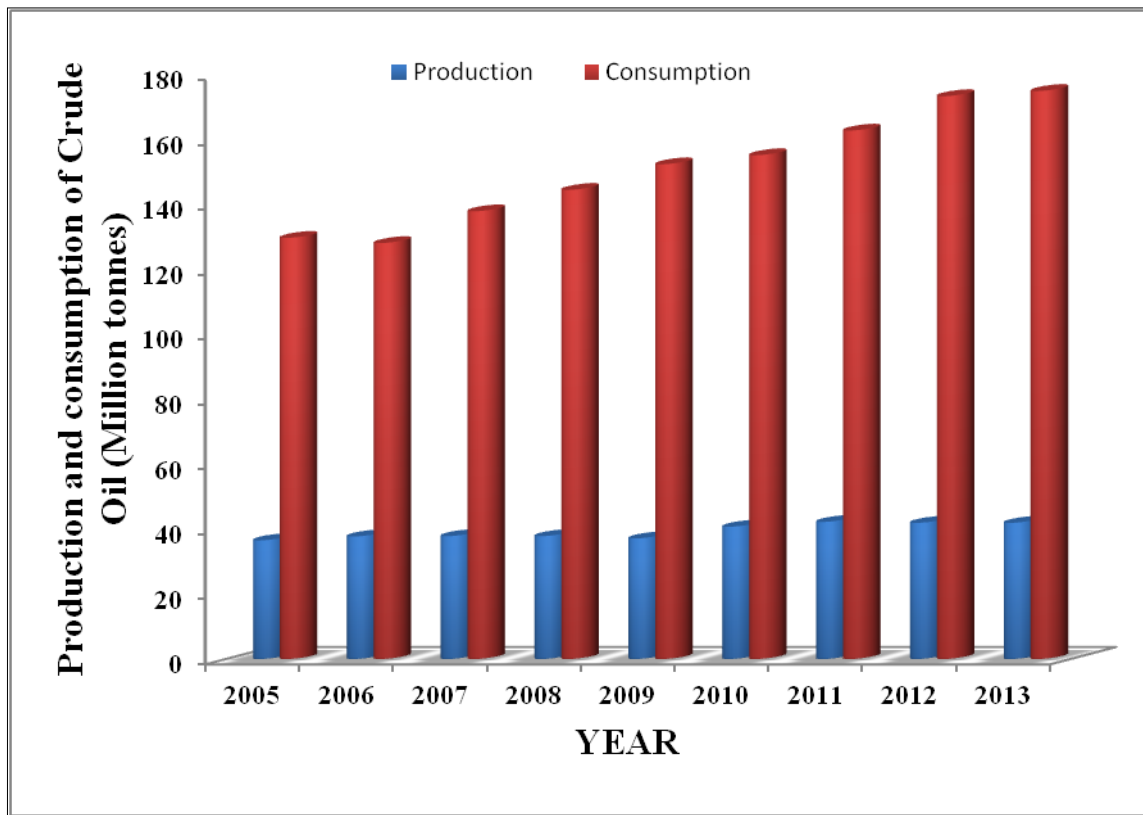


Fig.1 3 Production and Consumption of Crude oil in India over the past years [5].

As seen by the above trends India's dependency on crude imports is increasing every year. There is always a wide gap between domestic production and consumption as evident from figure 1.3. Also considering that India is developing at a really fast pace, the energy requirements in future are going to be significantly higher than the current requirement. According to these trends, India, which is already dependent on their import, would become more and more import dependent. The financial implication of large scale imports would destroy the economy and necessitate strategies to move toward energy autonomy and independency.

Crude oil imports for the past few years has been shown in figure 1.4.

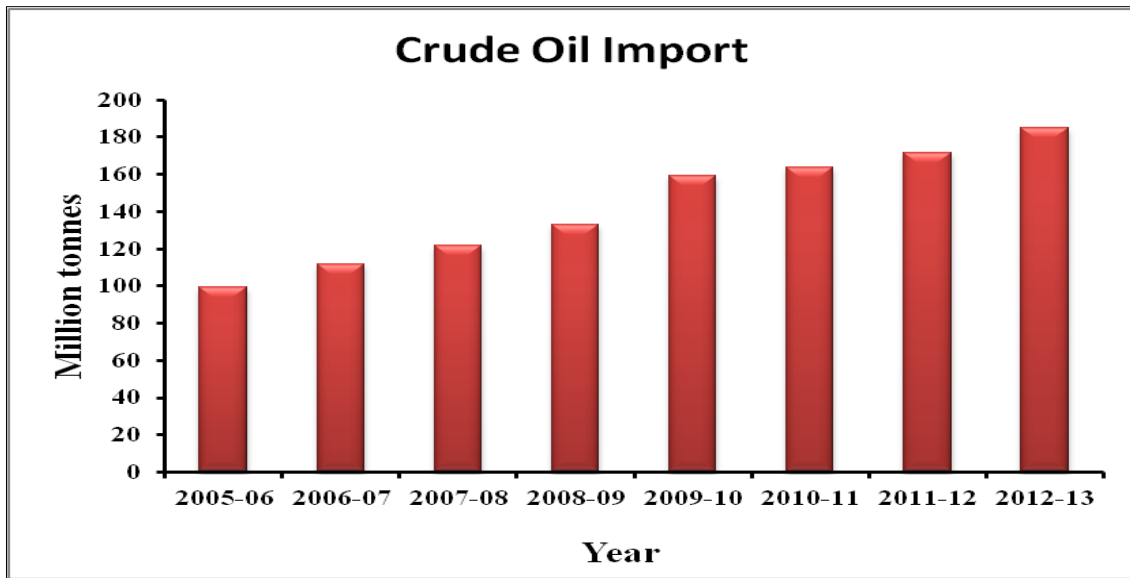


Fig. 1.4 Crude oil imports in the past few years [6].

The past years trends shows that energy requirements of the transport sector of India are increasing at significant pace. This coupled with the fact that it hasn't been able to increase its production to match the increasing demands, has resulted in increased crude imports.

The crude oil imports of the country in terms of Rupees of the past few years are shown in figure 1.5.

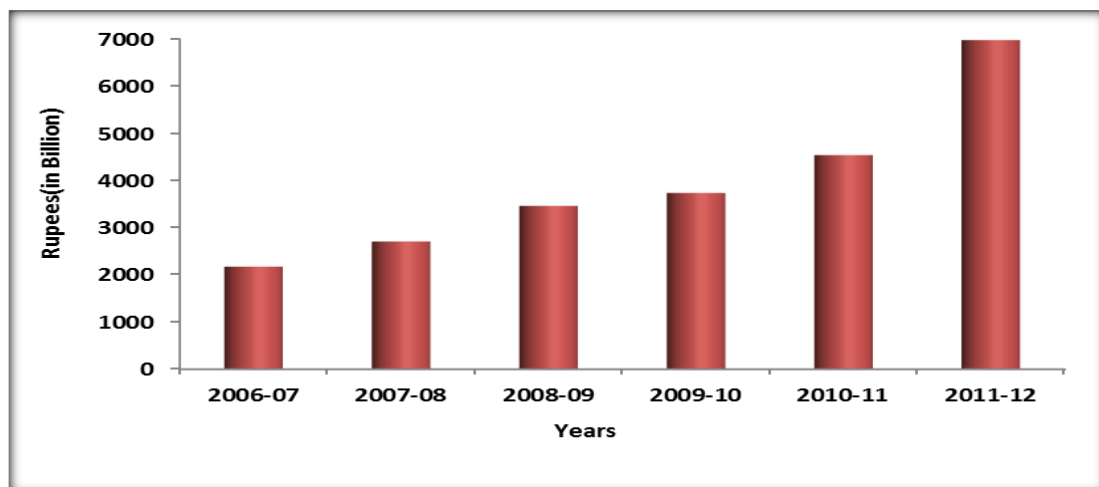


Fig. 1.5 Expenditure incurred in importing Crude oil (in Billion Rupees) [7].

The crude imports when converted rupees equivalent shows how much of the wealth of the country has to be used in imports of petroleum. Imports of Crude Oil during 2012-13, in terms of quantity was 184.795 MMT valued at Rs.7, 84,652 crore. This marked an increase by 7.61% in quantity terms with respect to 171.729 MMT during the year 2011-12, but increased by 16.73% (w.r.t.Rs.6, 72,220 crore) in Rs. value terms over the year of 2011-12. In terms of US\$, the extent of increase in value of crude oil imports was 3.30%. [6] this may have resulted in slower development of the country. According to such trends the future isn't too promising either, with rising demands for petroleum each year.

1.4 FLUCTUATION IN CRUDE OIL PRICES

The world reserves of primary energy and raw materials are very limited. According to an estimate the reserves will last for 218 years for coal, 41 years for oil and 63 years for natural gas, under a business as usual scenario. The enormous growth of world population, increased technical development, and standards of living in the industrial nations has led to this intricate situation in the field of energy supply and demand. The price of crude oil keeps rising and fluctuating on a daily basis [8].

During the year 2012-13, India's total imports value was Rs.2673113 crore out of which imports of crude oil and petroleum products was Rs.881230 crore which is about 33% of the total imports [6]. Such high dependency on crude oil makes the economy very susceptible and sensitive to fluctuations in crude oil prices. This necessitates developing and commercialising fossil fuels alternatives from bio-origin. Development of such alternative fuels would not only reduce dependency of a developing country like India on other developed nations, but also provide employment opportunities within the rural parts of the country which would further help in the development of the country.

Besides, energy independency, the devastating impact of climates change has become an issue of critical importance. Energy production using fossil fuels is the major contributor to greenhouse gas emissions. Hence, transition to a low carbon energy economy is the real

solution for mitigating the impacts of climate change. The single biggest reason for global warming is the burning of fossil fuels. So the solution lies in effecting an accelerated transition to a low carbon energy economy, which means large scale development of renewable energy. Alternative sources of energy need to be found out for various needs, one being transportation.

1.5 ENVIRONMENTAL DEGRADATION

The rapidly growing population and economic development are leading to the environmental degradation throughout the world which is mainly caused by the uncontrolled urbanization and industrialization, expansion and massive intensification of agriculture and the destruction of the forests. Indiscriminate usage of fossil fuels and deforestation have resulted in serious ozone layer depletion and elevated the quantity of harmful emissions in the environment. There is an urgent need to stop releasing more Green House Gases (GHG) into the air. GHGs include Carbon dioxide, methane and some other gases, which trap heat in the atmosphere. This is termed as “green-house effect”. They allow high-energy, small wavelength rays from the sun to reach the earth, but act as barriers to the flow of low-energy, long wavelength radiation that the earth emits, after absorbing sun’s energy. This trapping heats up the atmosphere and keeps the earth warm, even when no sunlight is present.

A certain level of green-house retention of heat is essential, to keep the earth warm during the night. However, if too much excess heat is retained, the temperature of the earth shall rise. This is known as ‘Global Warming’. Greenhouse gas emissions have caused considerable global warming. The average temperature of the earth is poised to increase by about 2-3 °C with a doubling of the CO₂ level, which, at the current rates of CO₂ emissions isn’t too far.

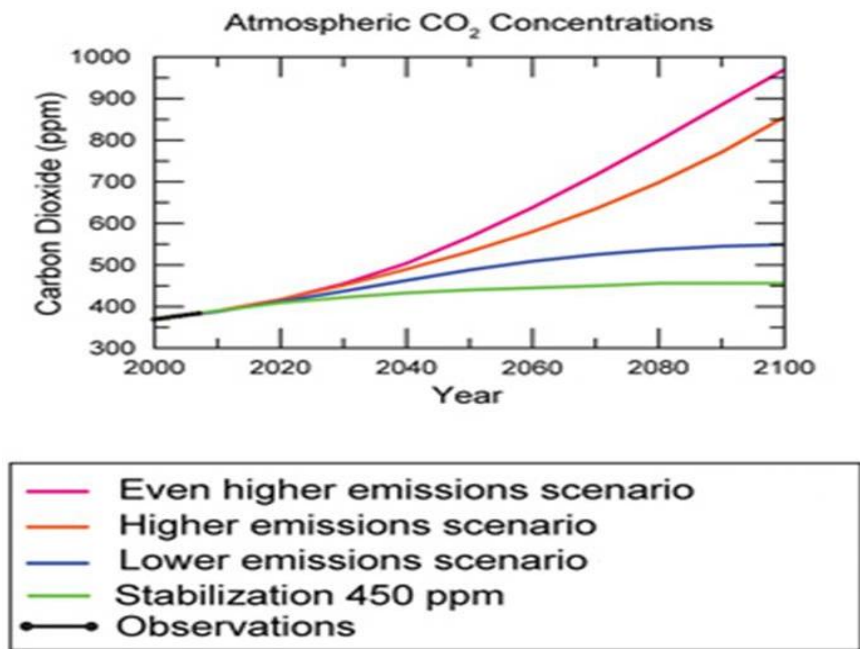


Figure 1.6 Projections of future concentrations of greenhouse gases.

Figure 1.6 shows our projections of future concentrations of greenhouse gases. Based on our current global emissions pathway, the concentration of CO₂ and other greenhouse gases in the atmosphere will rise substantially as emissions rise from a CO₂ concentration of 390 ppm at present to 816 ppm in 2100, and from 474 ppm CO₂-equivalent at present to 1226 ppm CO₂- equivalent in 2100 [9].

Further, with the dramatic growth in the number and the rate of use of road vehicles in recent years, the demand of the conventional energy supplies and the environmental degradations resulting from road transport can no longer be ignored. The trend is same in all the corners of the globe and enforcement of stricter emission norms has become a national priority.

1.6 DIESEL ENGINE AND INDIAN ECONOMY

Diesel engines are the backbone of Indian economy. In India, the consumption of diesel fuel is nearly five times higher as consumption of gasoline. Diesel Engines due to its higher efficiency and ruggedness play a very significant role in Indian economy as these are used in agriculture, transport and industrial sectors. However, diesel engines also emit harmful emissions and pollute environment [10]. In the financial year 2012-13 the consumption of diesel in India was 69.17 million tones and the consumption of petroleum in India was 15.74 million tonnes [11].

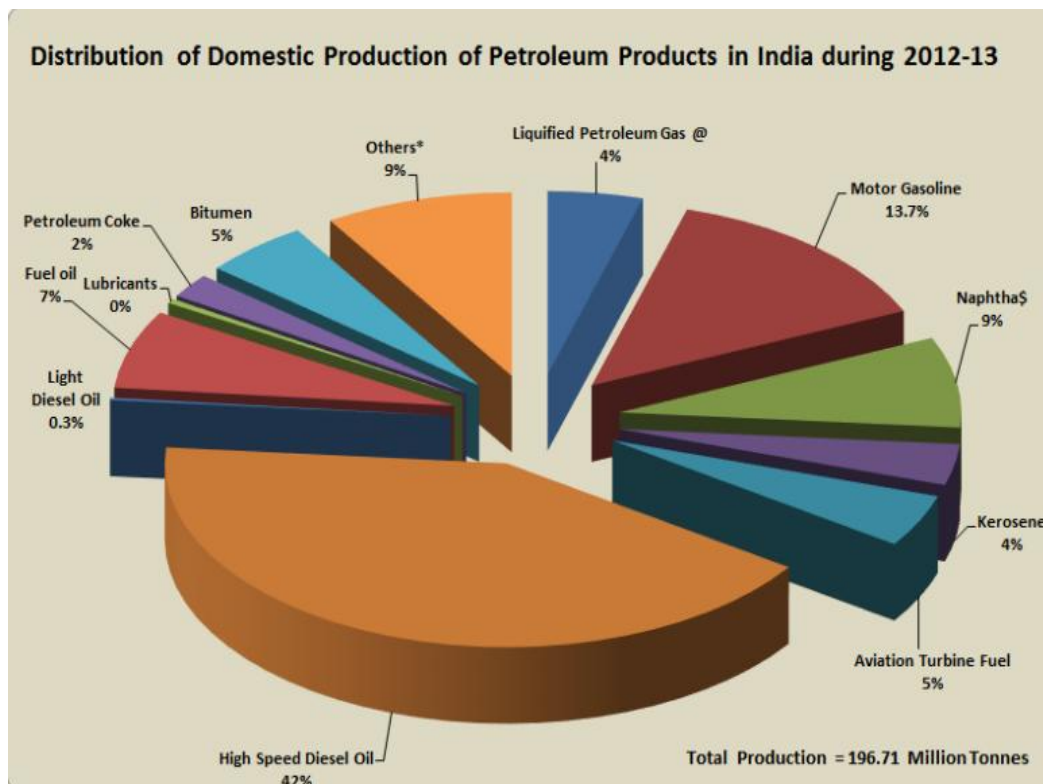


Fig. 1.7 Distribution of Domestic Production of Petroleum Products in India during 2012-13[11].

Diesel (HSD), largely a transport fuel, forms the biggest chunk (42 per cent) of total petroleum product consumption in India. Diesel is mainly used in the road transport, rail transport, and agriculture and power generation sectors. Road transport and agriculture account for 73-75 percent of total diesel consumption. The balance is accounted for by the railways 4-5 per cent, the manufacturing industry (captive power generation) and power utilities 13-14 per cent and other end-users. The transport fuel demand was met with by considerable imports in past six years [12]. From the point of view of protecting the global environment and the concern for long-term supplies of conventional diesel fuel, it becomes necessary to develop alternative fuels that give engine performance at par with diesel [13].

1.7 ALTERNATIVE FUELS

The world is presently confronted with the twin crises of fossil fuel depletion and environmental degradation. Indiscriminate extraction and lavish consumption of fossil fuels have led to reduction of underground based carbon resources. The increasing industrialisation and motorisation of the world has led to a steep rise for the demand of the petroleum based fuels. Petroleum based fuels are obtained from limited reserves. These finite reserves are highly concentrated in certain region of the world. Therefore, those countries not having these resources are facing energy as well as economic crisis, mainly due to import of crude petroleum. Hence it is necessary to look for alternative fuels which can be produced from sources available locally within the country. The search for alternative fuel should be in correlation with sustainable development, energy conservation, efficiency and environmental preservation [14]. Before the introduction of gasoline as an engine fuel, in the late 1800s, the vehicles were often powered by what are now considered as alternative fuels. The first IC engine, designed built and demonstrated by Rudolf Diesel at the Paris World Fair ran on peanut oil.

Alternative fuels look like an attractive prospect due to the following reasons:

- Petroleum based fuels are a fast depleting and getting costlier. Hence a need for a cheaper substitute arises.
- Environmental degradation caused by the petroleum based fuels also encourages experts to look for more environment friendly fuel options.
- Necessity has forced new innovations around the world, to include using garbage, used cooking oil and algae for new fuel sources.

Some of the alternative fuels currently in consideration are

- Hydrogen
- Alcohols
- Propane
- Natural Gas
- Biodiesel

A comparative assessment of the properties of the above mentioned alternative fuels has been presented in Table 1.1.

Table 1.1 Properties of various Alternative fuels

PROPERTIES/FUELS	DIESEL	ETHANOL	METHANOL	NATURAL GAS	HYDROGEN
Calorific Value (MJ/kg)	42-45	26.8	19.9	50	120
Cetane Number	42	11	2	-	-
Octane Number (Research)	90-98	111	112	120	106
Octane Number (Motor)	80-90	92	91	120	120
Molecular Weight	192.21	46.07	32.4	18.7	2.015
Auto-ignition Temperature (°C)	220	363	280	650	580
Specific Gravity	0.837	0.789	0.791	0.667	0.07
Boiling Point (°C)	282-338	78	65	(-)160	(-)253
Stoichiometric A/F ratio (mass)	14.6	8.94	6.43	17.2	34.13

These alternative energy resources are largely environment friendly but they need to be evaluated on case to case basis for their advantages, disadvantages and specific application. Some of these fuels can be used directly while others need to be formulated to bring the relevant properties closure to conventional fuels. The fuels of bio-origin provide a feasible solution to this world wide petroleum crisis. Various bio-fuel energy resources explores includes biomass, biogas, primary alcohols vegetable oils and biodiesel. Adoption of bio-origin alternative fuels which are essentially non-petroleum can result in energy security and environmental benefits.

One such renewable fuel that has shown great prospect to be a substitute of present gasoline based fuels is ALCOHOLS.

1.8 ALCOHOLS AS IC ENGINE FUELS

Alcohols are made from renewable resources like biomass from locally grown crops and even waste products such as waste paper, grass and tree trimmings etc. Alcohols is an alternative transportation fuel since it has properties which would allow its use in existing engines with minor modifications. Indeed alcohols like ethanol and their blends with gasoline have shown that they can be burned in conventional unmodified gasoline engines with performance equivalent to that of premium unleaded petrol. As the experience with Brazil has shown, it is also technically and commercially feasible to manufacture vehicles capable of running on pure alcohols.

Alcohols fuels are relatively benign environmentally, when compared to alternative liquid synthetic fuels. Because the production technologies are well understood, the pollution control technologies are also known, and the emissions and effluents are controllable. Alcohols burns cleaner in comparison to fossil based fuels and produces lesser carbon monoxides, HC and oxides of nitrogen. The most significant advantage of these fuels compared to conventional ones is reduction of emission because of non-sulphur content and oxygen enrichment enhancement of premixed combustion phase and improvement of the diffusive combustion phase [12, 13, 14, 15]. Lower viscosity, high evaporative cooling and high laminar flame propagation speed [16, 17] also add to their advantage. Alcohol has higher heat of vaporization, therefore, it reduces peak temperature inside the combustion chamber leading to lower NO_x emissions and increased engine power. However, the aldehyde emissions go up significantly. Aldehyde plays an important role in formation of photochemical smog.

Alcohols have been attracting attention worldwide. Consumer wants a cleaner fuel that can lower the risk of harm to environment and health. Government aim to reduce reliance on imported energy and promote domestic renewable energy programs, which could utilise domestic resources and create new economic activities. Though bio-fuels remain relatively small in use compared to more traditional energy forms, the scenario is changing rapidly

when factors are coupled with vast agri-resources, new technologies that reduce cost. Emphasis on environment and pollution abatement and a strong will from both government and private entrepreneurs will provide an immense boost to the market of bio-fuels which is slowly but surely gaining momentum.

While increases in oil prices are impossible to predict accurately under prudent assumptions about long term real oil price increases, search for an effective alternative fuel that can be cost competitive is gaining momentum.

1.9 ALTERNATIVE FUEL IMPUTES

There are some very important parameters which should be considered before adaptation of an alternative fuel in an existing engine. These includes: no or minimum modification required in design of engine, use of same storage and transportation infrastructure, biodegradable and non-toxic assuring safe handling and transportation, capability of being produced locally and low investment cost [21,22].

Public policies need to be revised to encourage the development of these resources. Land for production need to be explored, an extraction and transesterification plant would be required, distribution and storage facilities constructed and monitoring of major users for detection of problems in large scale use are all needed before the technology can be recommended for general use. The magnitude of our energy needs provides an inexhaustible market of our total agriculture production capacity at the highest possible level.

1.10 RATIONALE OF ALCOHOL BLENDED FUELS IN INDIA

The rationale of taking up a major Programme for the production of alcohol fuels for utilization in I.C. Engines in our country lies in the context of :-

- Alcohols and biodiesel being superior fuels from the environmental point of view,
- Use of alcohol blended fuel becomes imperative in view of the stringent emission norms and court interventions,
- Need to provide energy security, especially for the rural areas.
- Need to create employment, especially for the rural poor living in areas having a high incidence of land degradation,
- Providing nutrients to soil, checking soil erosion and thus preventing land degradation, addressing global concern relating to containing Carbon emissions,
- Reducing dependence on oil imports,
- Usability of alcohol blended fuel in the present engines without any major modification,
- Use of alcohol blended fuel not requiring major or time consuming studies or research.

Table 2.1 Physico-chemical properties of some alcohols

Property	Diesel	Ethanol	Isobutanol	Hexanol
Density (kg/m³)	822.87	796.2	802.05	822.39
Calorific value (MJ/kg)	42-45	29.30	35.26	39.03
Kinematic viscosity at 40⁰C (cSt)	2.98	1.1878	2.69	3.8273
Flash point (⁰C)	65-88	13	28	63
Cetane Number	45-50	8	24	42
Oxygen (%) (wt)	0	34.73	22	15.7
Latent heat of vaporization (KJ/kg)	250	846	579	486

Higher alcohols as shown in Table 2.1 have physico-chemical properties far better than the lower alcohols and thus needs to be analyzed exhaustively. Among the higher alcohols, hexanol (n-hexanol) is less exploited but has significant properties very similar to diesel and it seems to be the most attractive alternative to partly substitute diesel fuel. Hence, a better performance is expected in comparison to alcohols like methanol or ethanol.

2.2 HEXANOL AS A FUEL FOR CI ENGINES

Hexanol is an attractive alternative fuel because it is renewable bio based resource and it is oxygenated, thereby providing the potential to reduce particulate emissions in compression ignition engines. Hexanol as a fuel reduces emissions of carbon monoxides, particulate matter, oxides of nitrogen and other ozone depleting pollutants.

Hexanol is an organic alcohol with a six-carbon chain and a condensed structural formula of $\text{CH}_3(\text{CH}_2)_5\text{OH}$. This colourless liquid is slightly soluble in water, but miscible with ether and ethanol. It is produced industrially by the oligomerization of ethylalcohol which can be

produced from crops, corns, vegetables, and other feedstock such as wastes from agricultural food and beverage processing [29].

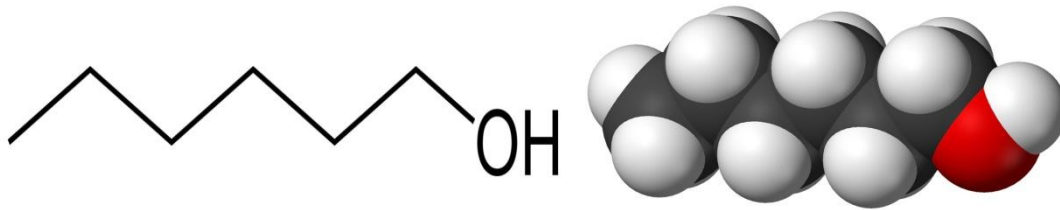


Fig 2.1: Structure of Hexanol.

One of the important properties of hexanol is its production capability from petroleum or nonpetroleum resources. Because it can be produced from agricultural crops, it is classified as a renewable and biomass fuel. Furthermore, it is well known that if the alcohol contains some water, phase separation may occur as an important problem when alcohol and diesel fuel are mixed. In comparison to ethanol and methanol, water affinity characteristic of hexanol is very low, which allows it to easily mix with gasoline and diesel fuel. Moreover, the blends of hexanol with diesel fuel maintain their stability for a long period with no phase separation.

As shown in Table 2.1, the cetane number and density of hexanol are very close to the properties of diesel fuel. Although the net heating value of hexanol is higher than that of ethanol and methanol, it is about 16.5% lower than that of diesel fuel. Higher net heating value of hexanol is an important advantage for the engine performance and fuel consumption. Hexanol is an oxygenated fuel like other alcohols and has an oxygen content of about 15.7%, which may significantly promote the combustion process. Excellent cold flow properties of hexanol also add to its advantages and make it applicable as a fuel in various regions where the temperature drops below 0°C. The main obstacle of hexanol for a direct replacement of diesel fuel is its high viscosity, which may deteriorate amount of the fuel injected. However, the use of hexanol as blends with diesel fuel up to 20% may be regarded as a possible solution when

earlier studies performed with ethanol and methanol are taken into consideration. Thus the objective of this study is to investigate the effects hexanol-diesel fuel blend on the performance, combustion characteristics and exhaust emissions of a diesel engine

2.3 REVIEW OF AVAILABLE LITERATURE

The methanol diesel fuel blends are unstable and phase separation takes place immediately when mixed. **Liu et al** [30] prepared emulsion of methanol and diesel using a rotating packed bed. The method was suitable to overcome the homogeneity concerns while making diesel methanol blend. The viscosity of the emulsified fuel appeared similar to Newton fluids. A reduction in surface tension was noticed with increase in surfactant concentration in the emulsion where as the stability of the fuel was found to be high with higher rate of agitation, additive amount and higher liquid flow rate.

Cenk et. al [31] tested methanol-diesel blend and ethanol-diesel blend on single cylinder, four stroke, direct injection, naturally aspirated diesel engine. He observed a decrease in smoke opacity, CO, HC and THC. However, NO_x emissions increased with the use of blends. BSFC with all the fuel blends was found to increase mainly due to the lower LHV of methanol and ethanol.

Ajav et al. [32] tested different proportions of ethanol–diesel fuel blends in a constant speed diesel engine. They observed that a 9% increase occurred in the brake specific fuel consumption (BSFC) with the blends up to 20% as compared to diesel fuel, while emissions of CO and NO_x were lower with the use of blends.

Jilin Lei et. al [33] investigated the performance and emission characteristics of 3.298 L, direct injection, turbocharged diesel engine using diesel ethanol blends and varying the pressure. It was found that HC and CO emission increase with decrease in speed and load while NO_x and smoke opacity decreased at 81 kPa pressure. Increase in pressure had insignificant effect on engine performance.

Dattatray et. al.[34] studied the feasibility of using higher percentage of ethanol in ethanol-diesel blends with biodiesel as co solvent on multi-cylinder direct injection diesel engine using diesel–ethanol–biodiesel blends of high ethanol content. It was found that brake specific fuel consumption increased considerably as thermal efficiency improved slightly. The remarkable reduction in smoke opacity was found at higher loads. NO_x variation depends on operating conditions while CO emissions drastically increased at low loads. Blend which replaced 50% diesel gave satisfactory performance.

Dulari Hansdah et al [35] explored the possibility of utilizing bio ethanol obtained from *Madhuca Indica* flower as an alternative fuel in a direct injection (DI) diesel engine. Bio ethanol (5%, 10%, and 15%) on volume basis was emulsified with diesel proportionality with the help of a surfactant. In a single cylinder, four stroke, and air cooled DI diesel engine developing a power of 4.4 kW at 1500 rpm the bio ethanol–diesel emulsions exhibited a longer ignition delay by about 2.2 CA than that of diesel operation at full load. Overall, the nitric oxide (NO) and smoke emissions were found to be lesser compared to that of diesel operation at full load. The BMDE5 emulsion gave a better performance and lower emissions compared to that of BMDE10 and BMDE15. It was suggested that the bio ethanol produced from *Madhuca Indica* flower can be used as a potential alternative fuel replacing 5% of petroleum diesel.

Singh A et al [36] investigated, 5%, 10%, 15%, 20% (v/v) blends of isopropyl alcohol and diesel on a single cylinder unmodified diesel engine. The various blends were found to be homogenous and stable. The results suggest significant reduction in emission of oxides of nitrogen (NO_x) for various blends as compared to baseline data of diesel. At no load condition, NO_x emissions are nearly same for all the test fuels while at full load the NO_x emissions increased. The brake thermal efficiency increased slightly for 15% and 20% blend. At lower loads, an increase in BSFC was observed. However, at peak loads, variation in BSFC was insignificant. The UBHC emissions were higher and CO₂ was found to decrease with increased percentage of isopropyl alcohol. At peak load, CO emission increased for all the blends and 20 % blend showed lower smoke opacity at peak load.

Murat et al. [37] prepared four different isobutanol–diesel fuel blends containing 5, 10, 15 and 20% isobutanol in volume basis and tested the blends in a naturally aspirated four stroke direct injection diesel engine at full-load conditions at the speeds between 1200 and 2800 rpm with intervals of 200 rpm. Compared to the diesel fuel, all blends yielded an increase in BSFC. Among the blends tested, the highest BTE was obtained with ISB10. The use of isobutanol– diesel fuel blends caused a decrease in CO and NO_x emissions. However, HC emissions increased with the use blends. The formation of exhaust emissions was heavily affected by the isobutanol content of the blend. 10% isobutanol-diesel blend was found to be an optimum in terms of performance and exhaust emissions.

FengXuan et. al. [38] performed a series of steady state engine tests on a common rail direct injection diesel engine equipped with an EGR system. The butanol- diesels blending ratios was varied from 0 vol% to 40 vol% with a step of 10 vol%, and for each blended fuel the influence of EGR and injection timing were studied. He found that butanol-diesel blends with low blending ratios serve to decrease NO_x emissions compared to pure diesel fuel under light load operation without EGR. Not much difference in NO_x production levels was observed from medium load tests across different blending ratios. Soot emission detected from exhaust gas was substantially reduced with the addition of butanol to the engine fuel, especially with high butanol-diesel blending ratios.

Altun et al. [39] studied the effects of n-butanol addition to blends of diesel and biodiesel on the performance and exhaust emissions on a constant speed, single cylinder direct injection CI engine. The addition of n-butanol to the test fuel blend (B20) caused a slight increase in the BSFC and BTE in comparison to the diesel–biodiesel (B20) fuel blend. The CO and HC emissions were decreased, and the NO_x emissions remained almost

unchanged at low engine loads, while they were decreased at high engine loads. The fuel blends also caused a sharp decline in smoke opacity over the entire range of engine tests.

The studies by **Rakopoulos** et al. [40, 41] and **Karabektas** et al. [42] showed that compared to diesel fuel, HC emissions increased, NO_x, CO, and smoke emissions decreased with the use of n-butanol and isobutanol fuel blends. **Dogan** [43] also suggested the similar emission results.

Yao et al. [44] indicated that n-butanol addition can significantly reduce soot and CO emissions without a serious impact on BSFC and NO_x emissions. According to some studies **Al-Hasan** [45], isobutanol/diesel fuel blends showed a trend to reduce the engine power, brake thermal efficiency (BTE), and exhaust gas temperature, as increased the brake specific fuel consumption (BSFC) with increasing isobutanol content in the fuel blends. However, it was reported that n-butanol/diesel fuel blends increased BTE and BSFC, and decreased exhaust gas temperature [40, 43]. The test results of butanol/diesel fuel blends and their effects on engine performance and exhaust emissions in the above literatures are different from each other due to the properties and technologies of the test engines.

Miers [46] did analysis in a light-duty turbo-diesel vehicle with two blends of n-butanol (20% and 40%, by vol.) and compared them with diesel fuel. The results showed that both HC and CO emissions increased for the urban drive cycle, when larger quantities of n-butanol were added to the diesel fuel. NO_x emissions were not significantly affected by the 20% isobutanol blend and decreased with the 40% n-butanol blend. In the same study, HC and CO emissions were not significantly impacted, but NO_x emissions showed a slight increase for the highway drive cycle, when n-butanol percentage increased in the fuel blends.

Rakopoulos et al [47] studied the effects of using blends of diesel fuel with n-butanol in 8% and 16% (by vol.) in six-cylinder, turbocharged and after-cooled, heavy duty, and direct injection (DI) engine. In heat release analysis he found fuel injection pressure diagrams were very slightly displaced (delayed), ignition delay increased, maximum cylinder

pressures slightly reduced and cylinder temperatures were reduced during the first part of combustion.

Zhang et al [48] performed tests on two different volume fractions (20% and 40%) of n-butanol blended into diesel fuel on a modified single cylinder heavy duty diesel engine. He found that with the increase of n-butanol fraction, ignition delay prolonged while the indicated thermal efficiency (ITE) had a slight increase. NO_x emissions were slightly influenced by fuel properties, but NO₂ proportion increased and NO proportion decreased with higher n-butanol fraction.

Siwale et al [49] carried out their study in a high load, light duty, turbo- charged diesel engine. They tested 5%, 10%, and 20% shared volume of n- butanol and diesel fuel which showed great improvement in the reduction of the emissions. The premixed phase combustion was amplified and distinguishable with increase of shared volume of n-butanol in diesel fuel. The combustion cycles of the blends were also found to be more stable than those of diesel fuel.

Sayin et al [50] on the other hand observed lesser heat release rate with the blends as compared to neat diesel. The contradictory result was justified by the varying injection timing of the fuel in the combustion chamber.

Fernández et. al [51]investigated the utilization of ethanol butanol and pentanol diesel blends in three-cylinder, four-stroke, water-cooled, 18.5:1 compression ratio, direct injection diesel engine. They found that 30% Butanol/diesel fuel blend and 25% pentanol/diesel fuel blend could be replaced the use of 100% diesel fuel on unmodified diesel engines without much compromise with the performance .

Aloko et al.[52] characterized the effect of hexanol-diesel blends and reported that many properties like density, flash point, viscosity of the blends are well above the requirement than that of the standard ASTM norms for a Diesel engine. He also indicates that

5% hexanol with diesel by volume is having the required diesel properties and increases anniline point (responsible for particle emission), hence the fuel can perform well with less emission.

Sathiyagnanam et. al[53] evaluated the performance and emission characteristics of hexanol, ethanol blends with neat diesel on DI Kirloskar TV1 diesel engine. It was found that hexanol can be used to increase the stability of ethanol in diesel fuel. The brake thermal efficiency of 20% blend of ethanol with neat diesel was reported to exceed by 1.89 % at full load than the other blends and mineral diesel fuel.

2.4 GAP IN THE LITERATURE REVIEW

In the light of the exhaustive literature review it may be stated that there existed some gaps with employing higher alcohols in diesel engine.

1. The available literature to study the effect of substitution of hexanol in diesel fuel on a diesel engine is not adequate.
2. It was observed that lower alcohols which has issues of low cetane number was not given priority rather many of the work was concentrated to improve the low miscibility of ethanol and methanol.
3. Major physico-chemical properties of hexanol such as calorific value, density cetane number and flash point are very much comparable to diesel.

2.5 STATEMENT OF THE PROBLEM

It is clear from the above literature that alcohol is gaining importance as an alternate fuel in diesel engine. Also it was observed that major emphasis has been given to the lower alcohols. Even though higher alcohols such as pentanol and hexanol have properties very similar to diesel, they have not yet been tested in initial research level. In order to fill this gap, the present work reports the results of complete experimental investigation conducted on a single cylinder direct injected diesel engine for agricultural application. The investigation evaluates the effects of using various blends of diesel fuel with 5%, 10%, 15% and 20% (by vol.) of n-hexanol on the performance and the regulated emissions, i.e. smoke, NO_x, HC and CO at various loads. On the basis of literature review and some initial experimental work, it was found that hexanol can be blended with diesel without any difficulties of phase separation. Throughout the study n-hexanol is referred as hexanol.

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

1. Comprehensive literature survey and identification of suitable of alcohol to be blended with diesel.
2. Prepare and study the solubility and homogeneity of hexanol diesel blends.
3. Determination of important physico-chemical properties of hexanol diesel blends and compare with the properties of neat diesel.
4. Conduct exhaustive experiments on diesel engine test rig to evaluate the combustion, performance and emission characteristics of various hexanol diesel blends prepared and compare them with the baseline data of neat diesel.
5. Analysis of Result.

SYSTEM DEVELOPMENT & EXPERIMENTAL PROCEDURE

3.1 EQUIPMENTS

The following equipments were used in the laboratory for determination of physicochemical properties of the fuel for the specified project. Various tests on these equipments were performed in Centre for Advanced Studies and Research in Automotive Engineering CASRAE at Delhi Technological University, Delhi.

3.1.1 Kinematic Viscometer

The viscosity of the fuel affects atomization and fuel-air mixing as discussed comprehensively in the earlier sections. Viscosity is also an important property associated with the lubricity. As many researchers indicated that biodiesel have superior lubricating properties than diesel, hence determination of viscosity can provide a better understanding of isobutanol-diesel blends as a fuel cum lubricant. Viscosity measurements were conducted for different test fuels under consideration. Kinematic viscosity of liquid fuel samples were measured at 40⁰C as per ASTM D-445. The equipment used was “Petro test Viscometer. A suitable capillary tube was selected, and a measured quantity of sample was allowed to free flow through the capillary tube. Time was noted in passing of the fluid from the capillary tube having an upper level and lower level mark. Subsequently, kinematic viscosity was calculated by multiplying the capillary constant with the time measured in seconds (Equation 3.1). The final value was obtained in mm²/s or centistokes abbreviated as cSt.

$$v = k * t \quad (3.1)$$

Where,

v = Kinematic viscosity, mm²/sec

$k = \text{Constant; mm}^2/\text{sec}^2$ ($k= 0.005675 \text{ mm}^2/\text{sec}^2$)

$t = \text{Time, in second}$



PLATE 3.1: Kinematic Viscometer

3.1.2 Bomb Calorimeter

A bomb calorimeter is a type of constant-volume calorimeter used in measuring the heat of combustion of a particular reaction. Bomb calorimeters have to withstand the large pressure within the calorimeter as the reaction is being measured. Electrical energy is used to ignite the fuel; as the fuel is burning, it will heat up the surrounding air, which expands and escapes through a tube that leads the air out of the calorimeter. When the air is escaping through the copper tube it will also heat up the water outside the tube. The temperature of the water allows for calculating calorie content of the fuel. Parr Model 6100EF was used in laboratory for measuring calorific value of blends.



PLATE 3.2: Bomb Calorimeter

3.1.3 Density meter

Density meter used in laboratory is DMA 4500 Anton Parr model. This density meter works on the principle of oscillating U-tube. The oscillating U-tube is a technique to determine the density of liquids and gases based on an electronic measurement of the frequency of oscillation, from which the density value is calculated. This measuring principle is based on the Mass-Spring Model.

The sample is filled into a container with oscillation capacity. The Eigen frequency of this container is influenced by the sample's mass. This container with oscillation capacity is a hollow, U-shaped glass tube (oscillating U-tube) which is electronically excited into un-damped oscillation (at the lowest possible amplitude). The two branches of the U-shaped oscillator function as its spring elements. The direction of oscillation is normal to the level of the two branches. The oscillator's Eigen frequency is only influenced by the part of the sample that is actually involved in the oscillation. The volume involved in the oscillation is limited by the stationary oscillation knots at the bearing points of the oscillator. If the oscillator is at least filled up to its bearing points, the same precisely defined volume always participates in the oscillation, thus the measured value of the sample's mass can be used to calculate its density.



PLATE 3.3: Density Meter

3.1.4 Cold Filter Plugging Point (CFPP)

Cold Filter Plugging Point (CFPP) is defined as the minimum temperature at the fuel filter does not allow the fuel to pass through it. At low operating temperature fuel may thicken and does not flow properly affecting the performance of fuel lines, fuel pumps and injectors. Cold filter plugging point of vegetable oils reflects its cold weather performance. It defines the fuels limit of filterability. The apparatus for CFPP measurement is shown in plate 3.4.



Plate 3.4: Cold Filter Plugging Point Apparatus

3.1.5 Flash Point

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

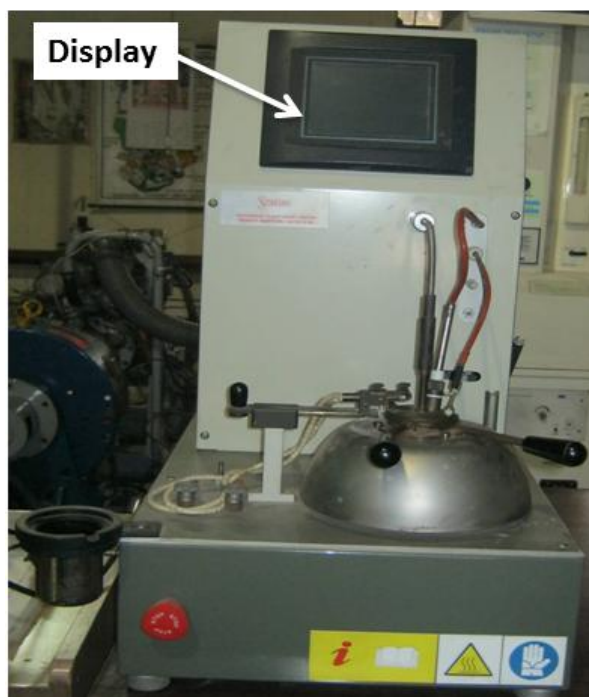


Plate 3.5 Flash point apparatus

3.2 PREPARATION OF FUEL BLENDS FOR ENGINE TRIAL

The commercial diesel fuel employed in the tests was obtained locally. The Hexanol (99.7% purity) was supplied from Merck India private Limited. Four test fuel samples were prepared by volume wise substitution of diesel with hexanol by directly mixing. The samples were 5% hexanol in 95% Diesel (Hx05D95), 10% hexanol in 90% Diesel (Hx10D90), 15% hexanol in 85% Diesel (Hx15D85) and 20% hexanol in 80% Diesel (Hx20D80) respectively. It was found that hexanol had no solubility or stability problems when blended with diesel fuel. As there was not phase separation in the blends, no additive was added. The test samples that were prepared are as shown in plate 3.6.



Plate 3.6: Hexanol-diesel blend samples prepared

3.3 ENGINE TEST RIG

3.3.1 Test Engine

Diesel Engine plays indispensable role in agriculture sector either for mobile or stationary applications, such as tractor, harvester or irrigation pump sets etc. It is preferred over spark ignition engine because of higher power developed, lower specific fuel consumption and better durability. Almost all irrigation pump sets, tractors, mechanized farm machinery and heavy transportation vehicle are powered by direct injection diesel engines in India.

Considering the wide application of a small capacity diesel engine in Indian agriculture sector, a medium capacity, direct injection diesel engine was selected for the present study. The direct injection diesel engine used for the present study is manufactured by Kirloskar.

3.3.2 Development of Engine Test Rig

A single cylinder, four stroke, vertical, light duty, water cooled, diesel engine of Kirloskar make was chosen for the present engine trials. Such types of engines are generally used for agricultural activities or decentralized power generation purposes in India. Plate 3.7 shows the engine.

The engine can be hand started using decompression lever and was provided with centrifugal speed governor. The cylinder was made of cast iron and fitted with a hardened high-phosphorus cast iron liner. The lubrication system used in this engine was of wet sump type, and oil was 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 were operated by an overhead camshaft driven from the crankshaft through two pairs of bevel gears. The fuel pump was driven from the end of camshaft.

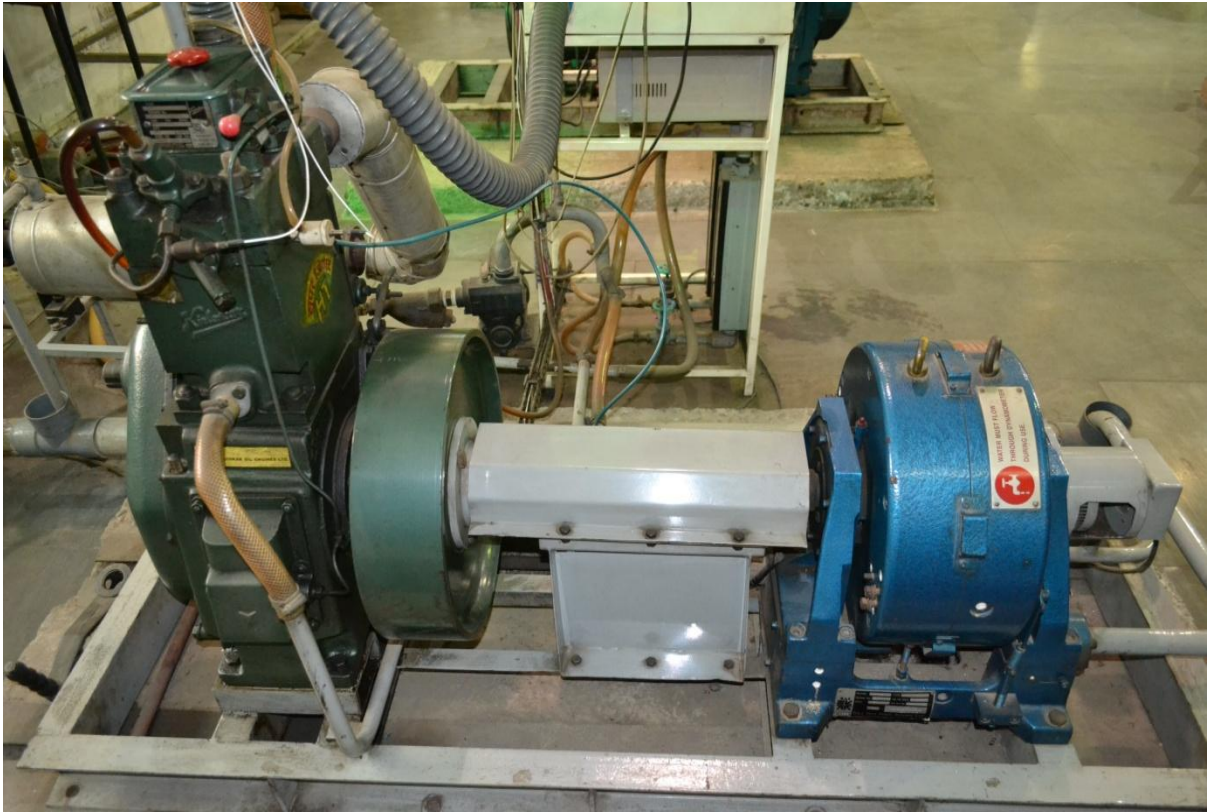


Plate 3.7: The Test Engine

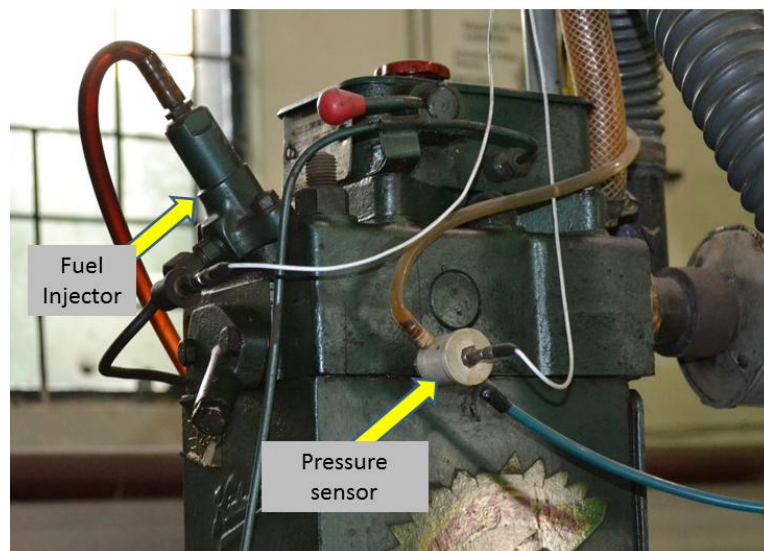


Plate 3.8: Fuel injector and pressure sensor

The detailed specification of the engine is provided in table 3.1 and the specification of the fuel injector is shown in table 3.2.

Table 3.1: Test Engine Specification

Make	Kirloskar
No. of cylinder	1
Strokes	4
Rated Power	5.2 kW @ 1500rpm
Cylinder diameter	87.5mm
Stroke length	110mm
Compression ratio	17.5:1
Dynamometer arm length	185mm
Orifice diameter	20mm
Connecting rod length	234mm
Inlet valve opening	4.5°BTDC
Inlet valve closing	35.5°ABDC
Exhaust valve opening	35.5°BBDC
Exhaust valve closing	4.5°ATDC
Fuel injection timing	23°BTDC

Table 3.2: Injector specification

Type	Bosch
No. of injector holes	3
Nozzle diameter	0.148 mm
Spray orientation angle	55°CA
Injection duration	18°CA
Full load diesel injection per cycle	32.8 mg

Two sets of fuel tanks were provided for the engine set up. One tank was used for diesel and the other tank was meant for the blends of Hexanol and diesel. The control panel of the engine test rig comprised of the data acquisition system, burette for manual fuel measurement, orifice and “U” tube manometer for air measurement, sensor indicator for manual data access, load variation switch etc. The control panel was used for loading and unloading the engine. Besides, the air and fuel consumption data of the sensor was verified from the manual measurements. The data acquisition system inside the control panel received the signals and transmitted them to the computer. Plate 3.9 shows the control panel, rotameters for water flow, and fuel and air flow sensors.



Plate 3.9: (a) Control Panel

(b) Rotameters

(c) Fuel flow meters

3.3.3. 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, CO₂ 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. 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, CO₂ and NO_x, AVL 4000 Light Di-Gas Analyzer was used. Both the AVL 437 Smoke meter and AVL Di Gas Analyzer are shown in Plate 3.10. The details of and AVL Di Gas Analyzer and AVL 437 Smoke meter are shown in Appendix II and III respectively. The engine trial was conducted as specified in IS: 10,000.

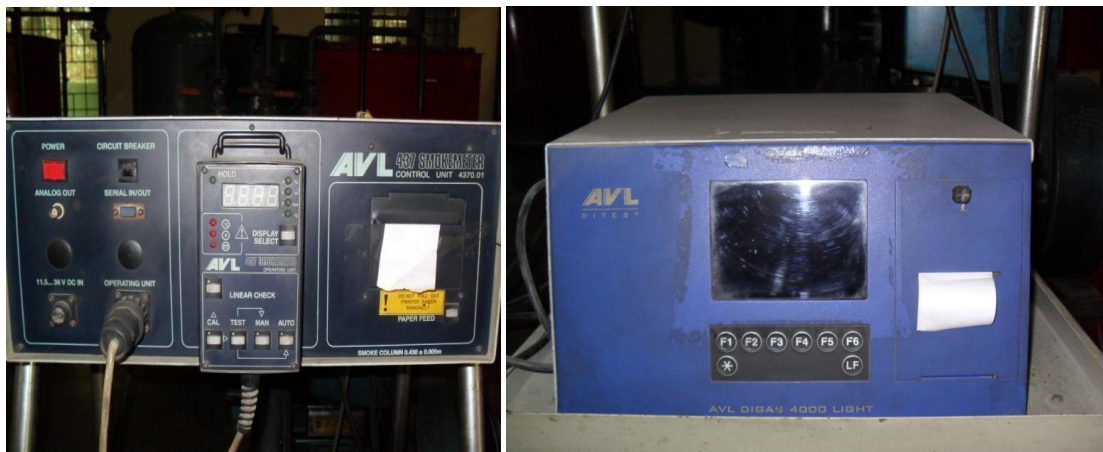


Plate 3.10: AVL Smoke analyzer and AVL Di-Gas Analyzer

The final experimental test setup consisted of the CI engine, engine cooling water system, the fuel supply and measurement system, air supply and measurement system, load variation and measurement system, rpm measurement system, in-cylinder pressure measurement system, emission measurement system, digital data acquisition system and computer. Fig. 3.1 shows the engine test rig lay out comprising of individual components and their inter-connectivity.

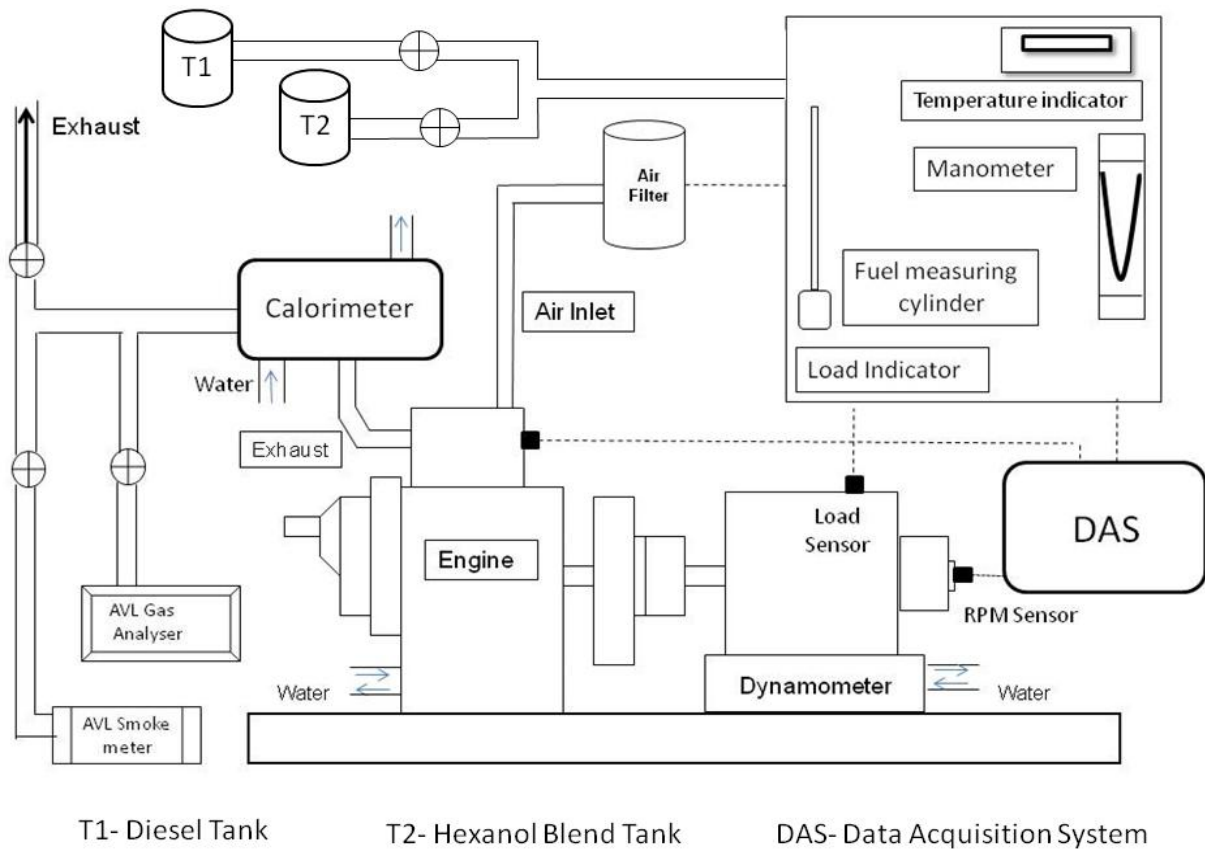


Fig 3.1: Layout of engine test rig

3.4 PARAMETERS SELECTION

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

1. Power produced by the engine
2. Brake Specific Fuel Consumption
3. Brake Mean Effective Pressure
4. Engine speed (Rev/min)
5. Fuel consumption
6. Temperature
7. Exhaust Gas Emissions
8. Exhaust Gas Temperature

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. Fuel consumption rate
5. AVL 437 smoke meter reading
6. AVL Di Gas analyzer reading

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

3.5 EXPERIMENTAL PROCEDURE

The engine was started at no load by pressing the exhaust valve with decompression lever and it was released suddenly when the engine was hand cranked at sufficient speed. After feed control was adjusted so that engine attains rated speed and was allowed to run (about 30 minutes) till the steady state condition was reached. With the fuel measuring unit and stop watch, the time elapsed for the consumption of 10, 20 and 30cc of fuel was measured and average of them was taken. Fuel Consumption, exhaust temperature, smoke density, CO, NO_x, HC, CO₂ and power output were also measured. The engine was loaded gradually keeping the speed within the permissible range and the observations of different parameters were evaluated. The performance and emission characteristics of various blends of hexanol and diesel were evaluated and compared with baseline diesel fuel. All the performance and emission were evaluated at each load thoroughly. Every time the engine was started with diesel and stopped after running at least 20 minutes on diesel.

RESULT AND DISCUSSION

4.1 INTRODUCTION

In the present study an unmodified single cylinder diesel is fuelled with blends of hexanol and diesel. The combustion, performance and emission studies on various blends were evaluated and the results were compared with baseline data that is diesel fuel.

4.2 PHYSICOCHEMICAL PROPERTIES RESULTS

The diesel fuel and the various blends formed were analyzed for several physical, chemical and thermal properties.

Table 4.1 Physico-chemical Properties of the test samples

Blend	Density (Kg/m³)	Viscosity (mm²/sec)	Calorific Value (MJ/kg)	CFPP	Flash Point (°C)
D100	822.31	2.98	44.56	-6°C	59.6
Hx100	813.42	3.82	39.03	-34°C	63.4
Hx05D95	821.56	3.06	44.28	-11°C	59.89
Hx10D90	820.05	3.17	43.8	-11°C	60.36
Hx15D85	819.26	3.26	43.13	-11°C	60.93
Hx20D80	817.74	3.41	42.32	-12°C	61.58

The results from table 4.1 show that the density and heating value decreases while kinematic viscosity and flash point increases with the addition of hexanol in mineral diesel. Greater the amount of hexanol, lesser is the density and heating value and higher is the kinematic viscosity. Presence of oxygen in the blended fuel improves combustion properties

and emissions but reduces the calorific value of the fuel. All the blends have approximately 85-90% calorific value compared to diesel.

4.3 PERFORMANCE CHARACTERISTICS

Various performance characteristics were analyzed for different test fuels and they are summarized in this section. The results obtained for different blends of hexanol and diesel are compared with baseline diesel fuel.

4.3.1 Brake Thermal Efficiency (BTE)

BTE is one of the most important engine performance parameter and is the ratio of mechanical work obtained at the engine shaft and the gross energy of the injected fuel, which is the product of fuel heating value and mass flow rate [54]. The variation of the engine brake thermal efficiency obtained for different fuel blends with respect to brake mean effective pressure is shown in Figure 4.1.

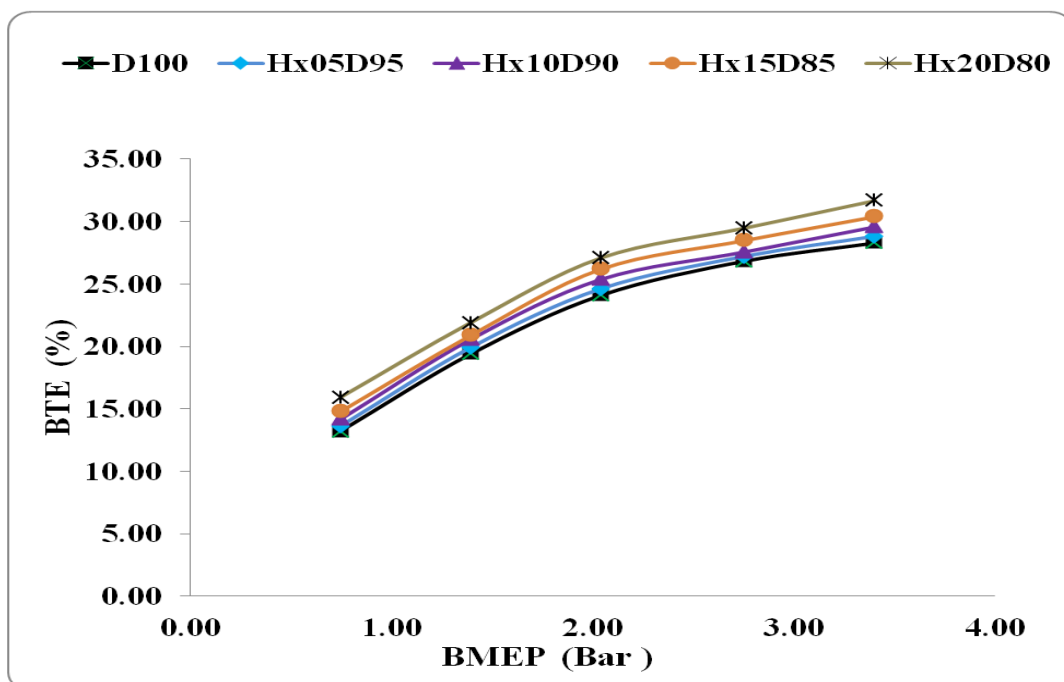


Fig. 4.1 Variation of BTE (%) with respect to engine BMEP (bar)

The result shows that, for a given a fuel blend BTE increases with load for all fuel samples. While comparing for different fuels, it was concluded that BTE of the hexanol diesel blend is slightly higher than that for the corresponding neat diesel case, with the increase in the blend percentage BTE also increases linearly. This may be explained by a better combustion due to the presence of oxygen, which involves combustion efficiency and a reduction of heat losses due to the lower boiling point of hexanol compared to diesel fuel [51]. Also, there is a rapid rate of heat release due to the increased ignition delay of hexanol blended fuels which tends to reduce the heat loss from the engine [55]. Figure 4.1 shows an increment of 1.76%, 4.6%, 7.42% and 12.01% in BTE for 5%, 10%, 15% and 20% hexanol diesel blends respectively from neat diesel at full load.

4.3.2 Brake Specific Fuel Consumption (bsfc)

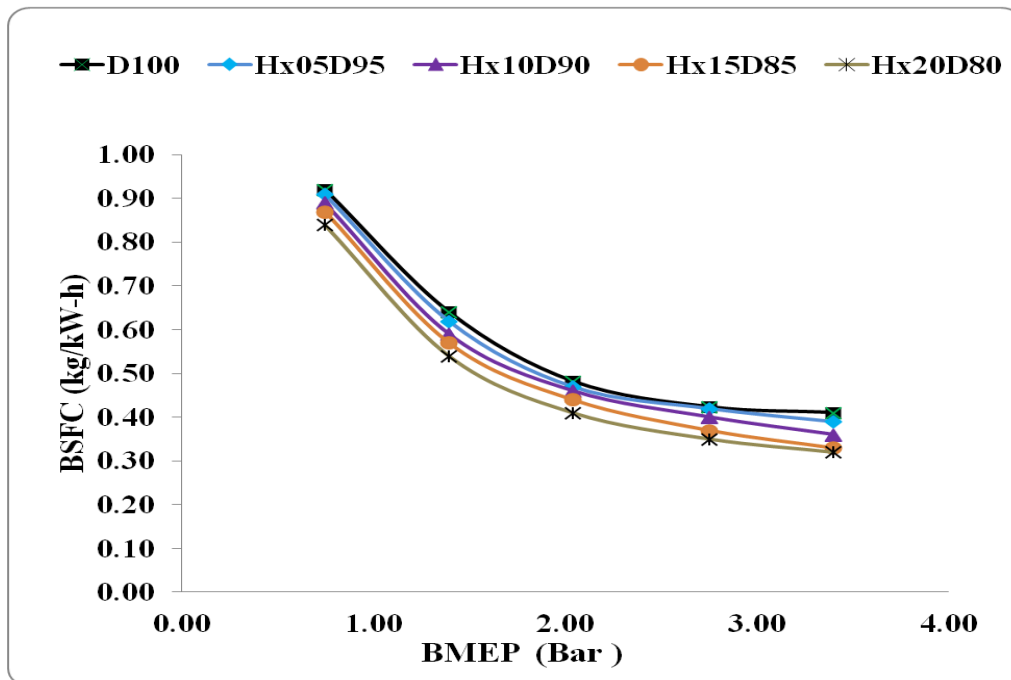


Fig.4.2 Variation of BSFC (kg/KW-hr) with respect to engine BMEP (bar)

Brake specific fuel consumption is also one of the important performance parameters of an engine. Fig. 4.2 shows the test results of the brake specific fuel consumptions (BSFCs) with the engine power outputs, when the engine is fuelled with different blends and diesel. The plot of BSFC is similar to an inverse plot of BTE which is explained by the fact that increase in BTE will invariably decrease energy consumption to meet the same load requirement. The general trend that is observed is that the BSFC decreases as the load is increased.

As shown in Figure 4.2, there were about 4.87%, 12.19%, 19.5%, and 22% lower specific fuel consumption for the blends Hx05D95, Hx10D90, Hx15D85 and Hx20D80 respectively than diesel fuel. The higher reduction in BSFC at higher volume fractions of hexanol may be attributed towards the enhanced combustion as discussed earlier.

4.4 EXHAUST EMISSIONS ANALYSIS

4.4.1 Carbon Monoxides

Carbon monoxide is considered a major diesel engine pollutant. The formation of CO during combustion in diesel engines is primarily attributed to lower fuel-air equivalence ratios of combustible mixtures [56]. Lower fuel-air equivalence ratios results in lack of oxygen, poor air entrainment in the mixture and thus causes incomplete burning during the combustion process [57].

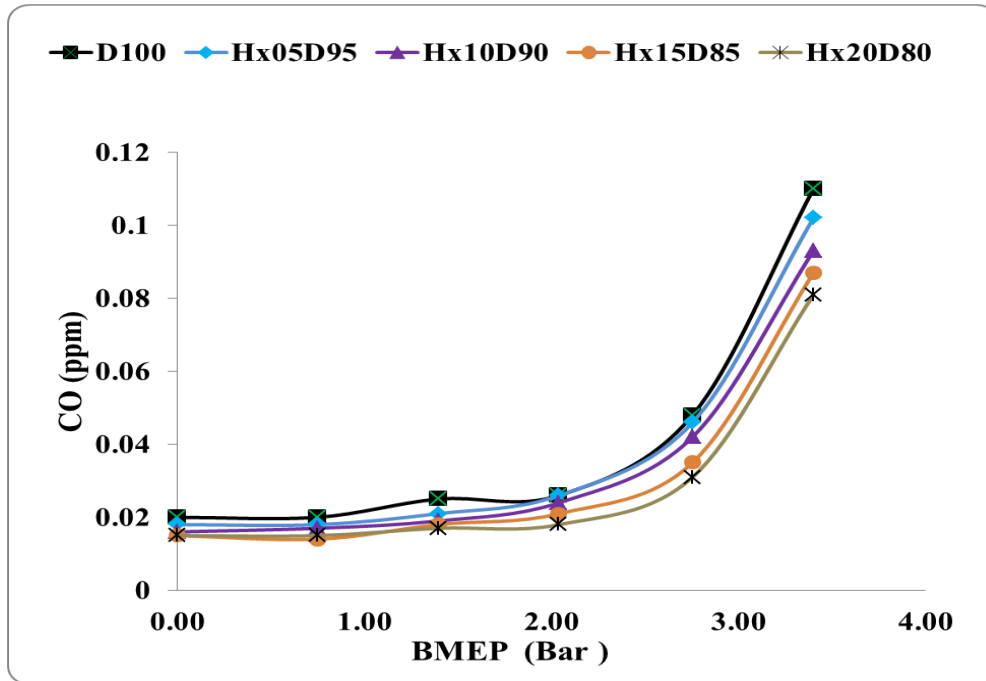


Fig. 4.3: Variation of CO (%) with respect to engine BMEP (bar)

The variations of CO emissions of different blends of fuel are shown in figure 4.3. It has been observed that the CO emission is lower for all the blends of HxD than that of neat diesel. While increasing the hexanol percentage in the blend, CO emission level decreases as the amount of oxygen content in blend increases and also the cetane number improves which subsequently enhances the combustion and hence results in better oxidation. The CO emissions are found to be increasing with increase in load since the air-fuel ratio decrease with increase in load in internal combustion engines [58].

However, after 60% load or higher-load conditions, a steep hike in CO emission was observed irrespective of test fuels. This is because that the thermal condition in-cylinder at low-load is low so that the flame quenching regions, which prevent CO from further oxidation, expand. Furthermore, addition of hexanol may aggravate this phenomenon due to its higher latent heat of evaporation. Under high-load conditions, the in-cylinder gas temperature is high enough to weaken the effect of latent heat of evaporation of hexanol and thus lean flame-out zones are shrunk and CO oxidation is strengthened [59].

At the highest engine loads tested, the reductions of CO emissions of blend fuels from the baseline data of neat diesel were approximately 7.27% (for the blend of Hx05D95) to 15.45% (for the blend of Hx10D90) and 21% (for the blend of Hx15D85) to 26.36% (for the blend of Hx20D80).

4.4.2 Hydrocarbon Emissions

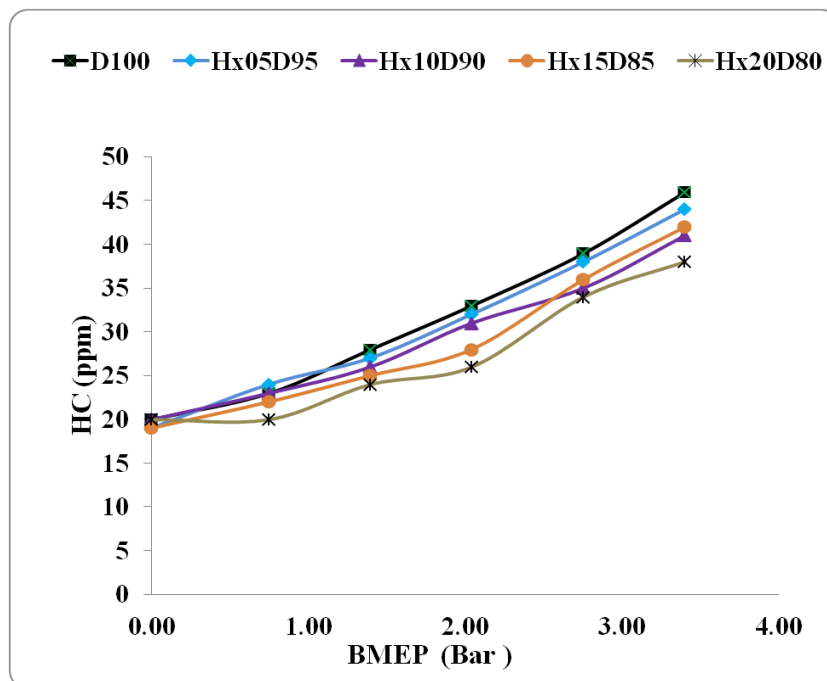
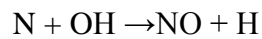
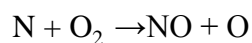
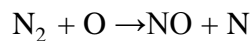


Fig.4.4: Variation of HC (ppm) with respect to engine BMEP (bar).

HC content in exhaust is a parameter to measure the combustion quality of the fuel and it increases with the extent of incomplete combustion. The test results for the unburned HC from the engine are shown in Figure 4.4. Maximum decrease in HC emissions were found with the use of 20% HxD blend. An approximated 4.34 %, 8.69% and 10.86% decrease in HC emissions was observed for 5%, 10% and 15% HxD blends. However for 20% HxD blend the HC emissions decreased by 17%.

4.4.3 Oxides of Nitrogen

The formation of NO_x highly depends on in-cylinder temperatures, oxygen concentration and residence time for the reaction to take place. At a temperature above 2000K, N₂ and O₂ in the combustion chamber disassociate into their atomic states and participate in a series of reactions. The three principal reactions producing thermal NO_x are described in Zeldovich mechanism [60, 61].



In general, the NO_x variation is linear with the load. With increase in load, the overall fuel-air ratio increases which results in increase temperature of combustion chamber and hence results in higher NO_x. Combustion flame temperature, availability of oxygen and time for oxygen-nitrogen reaction are the major factors controlling NO_x formation in diesel engines [62, 63, 64]. Fig.4.5 shows the emissions of NO_x demonstrated by various test fuels under the designated operating loads. It may be observed that NO_x emissions increased with increase in engine load for all test fuels. This may be attributed to the fact that increase in engine loading leads to increase in- cylinder pressure and bulk gas temperature. As NO_x formations are highly temperature dependent phenomena, hence, an almost linear increase in the formation of NO_x was observed with loading for all test fuels [65].

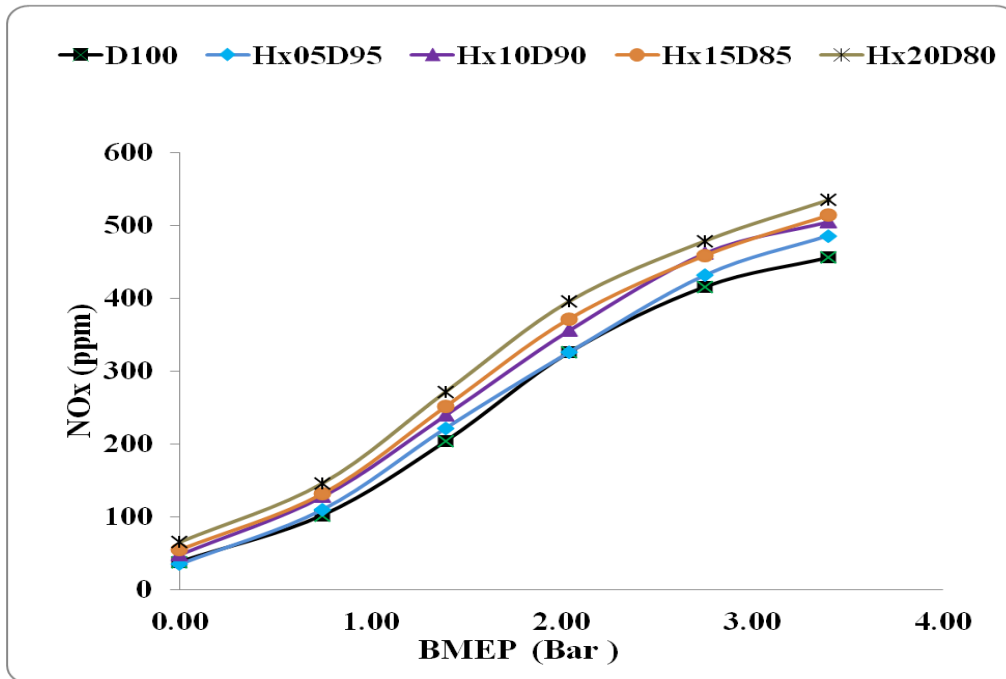


Figure 4.5: Variation of NOx (ppm) with respect to engine BMEP (bar)

The results showed that Hx05D95, Hx10D90, Hx15D85 and Hx20D80 exhibited 486, 505, 514 and 535 ppm volumetric emissions of NOx at full load which was higher than 456 ppm showed by the baseline data of diesel under the maximum load condition.

4.4.4 Smoke Opacity

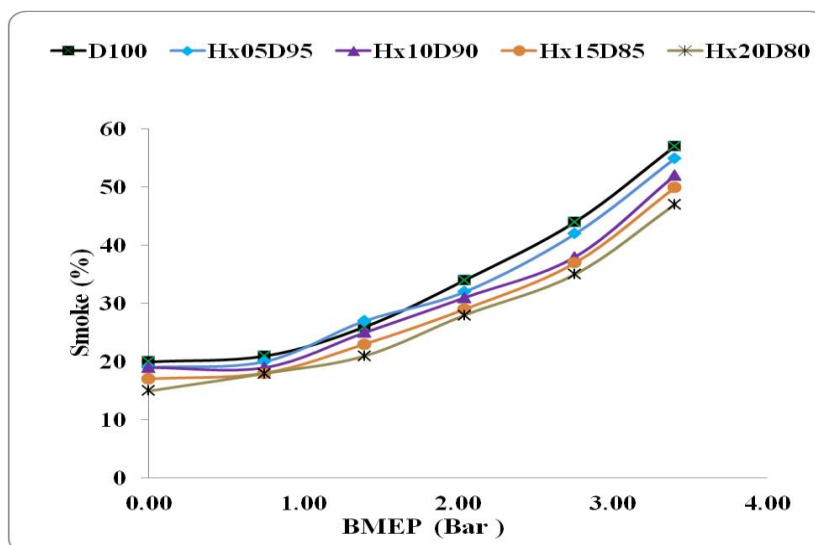


Figure 4.6: Variation of Smoke (%) with respect to engine BMEP (bar)

The highest smoke emissions of all fuels are obtained at high loads (Fig. 4.6), thus the formation of smoke strongly depends upon the engine load. As the load increases, more fuel is injected, causing an increase of diffusion combustion duration. This reduces the oxidation of soot during the expansion stroke because there is less time after the end of diffusion combustion and there is also less oxygen. Thus, higher loads lead to a higher formation of smoke. At almost all engine loads, the smoke decreases with a higher content of hexanol in the blend. This is due to the complete and stable combustion of the blend, which contains more number of oxygen atoms. This occurs due to longer ignition delay period (keeping all parameters constant) because of more fuel injection before ignition, at higher temperature in the cycle and earlier termination of combustion process. The residence time is therefore increased. All these factors have found to reduce smoke opacity in exhaust. As shown in Figure 4.6, the smoke emissions for the blends Hx05D95, Hx10D90, Hx15D85 and Hx20D80 were about 3.5%, 8.77%, 12.28%, and 17.54% respectively lower than D100.

4.5 COMBUSTION ANALYSIS

4.5.1 Estimation of the Experimental Heat Release Rate

For each operating condition, 91 engine pressure cycles were recorded, and the mean cylinder pressure trace was estimated. Evaluation of cyclic heat release is very much significant for combustion study. Various heat release models have been developed by researchers for determining critical combustion parameters like heat release rate, pressure rise rate etc. In the present study Sorenson's [66] zero dimensional heat release model was used for heat release characterization. It is a thermodynamic model based upon energy conservation principle.

Neglecting the heat loss through piston rings [67] the energy balance inside the engine may be written as

$$\frac{dQ_c}{d\theta} - \frac{dQ_w}{d\theta} = \frac{d(mu)}{d\theta} + P \frac{dV}{d\theta} = mC_v \frac{dT}{d\theta} + P \frac{dV}{d\theta} \quad (1)$$

Now the universal gas equation is given by

$$PV = mRT \quad (2)$$

The derivative of universal gas equation with respect to crank angle is given by

$$P \frac{dV}{d\theta} + V \frac{dP}{d\theta} = mR \frac{dT}{d\theta} \quad (3)$$

Putting equation (3) in equation (1), the heat release rate is derived as follows.

$$\frac{dQ_c}{d\theta} = P \frac{C_p}{R} \frac{dV}{d\theta} + V \frac{C_v}{R} \frac{dP}{d\theta} + mT \frac{dC_v}{d\theta} + \frac{dQ_w}{d\theta} \quad (4)$$

Equation (4) is further simplified for actual heat release calculation and is given below.

$$\frac{dQ_c}{d\theta} = \frac{1}{\gamma-1} V \frac{dP}{d\theta} + \frac{\gamma}{\gamma-1} P \frac{dV}{d\theta} + \frac{dQ_w}{d\theta} \quad (5)$$

Where,
$$\frac{dQ_w}{d\theta} = h.A (T_w - T_j) \quad (6)$$

The heat transfer coefficient ‘h’ was evaluated by using the correlation formula given by Huang [69].

$$h_c = 3:26B^{-0.2}P^{0.8}T^{-0.55}W^{0.8} \quad (7)$$

Here w is the average cylinder gas velocity Cp and Cv is specific heat and are temperature dependent parameters. The primary data used for heat release calculation was the pressure crank angle data obtained during experiment. Equation (5) was used for the determination of heat release rate. Pressure rise rate and cumulative heat release was calculated by standard mathematical operations in the HRR spread sheet database.

4.5.2 Combustion Characteristics

Fig. 4.7 and 4.8 shows, the in-cylinder pressure rise and heat release rate against crank angle diagrams, respectively, for neat diesel and all other blends at full loads. For the purpose of clarity, in visualization of firing pressure for different test fuels, the pressure data between -100°CA to +100°CA (from TDC) was taken for in-cylinder pressure.

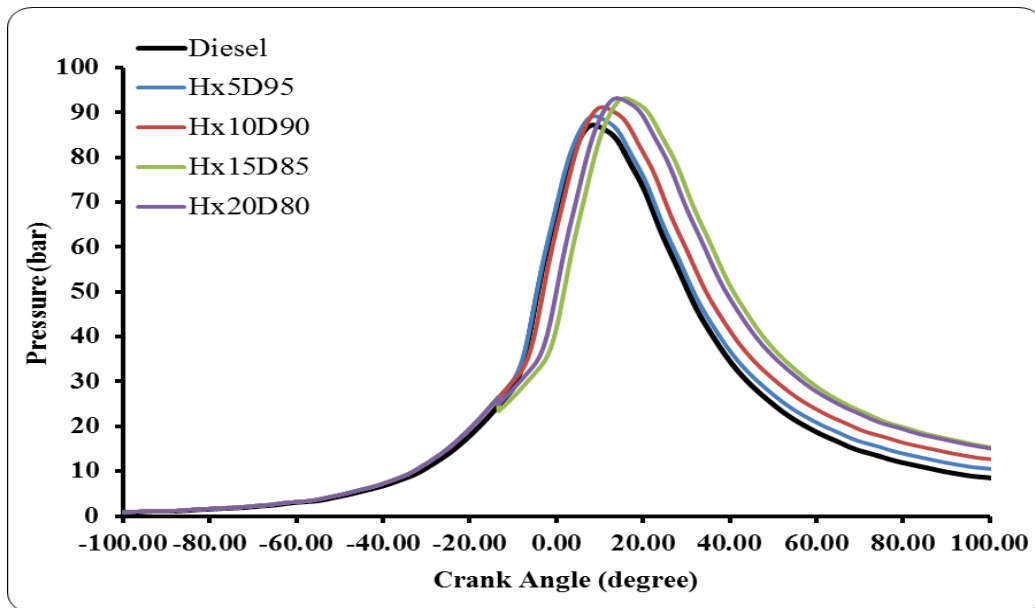


Fig. 4.7: Variation of In-cylinder Pressure (bar) with respect to engine crank angle

From the above figure it is observed that pressure increases with the load along with the increase in ignition delay for all range of blends. At full load, fuel ignition starts later for all the hexanol-diesel blends in comparison to diesel fuel. Maximum cylinder pressure was found to be slightly higher for the blends with respect to diesel. In diesel engine, cylinder pressure depends on the burnt fuel fraction during the premixed burning phase i.e., initial stage of combustion. Cylinder pressure characterizes the ability of the fuel to mix well with air and atomised charge. High peak pressure corresponds to large amount of fuel burnt in premixed combustion stage. The ignition delay in a diesel engine is defined as the time between the start of fuel injection and the onset of combustion. Rapid premixed burning followed by diffusion combustion is typical for naturally aspirated diesel. The slightly high in cylinder pressure exhibited by the hexanol blends can be accounted for better atomization and vaporization of the fuel samples due to the presence of hexanol in the fuel blends.

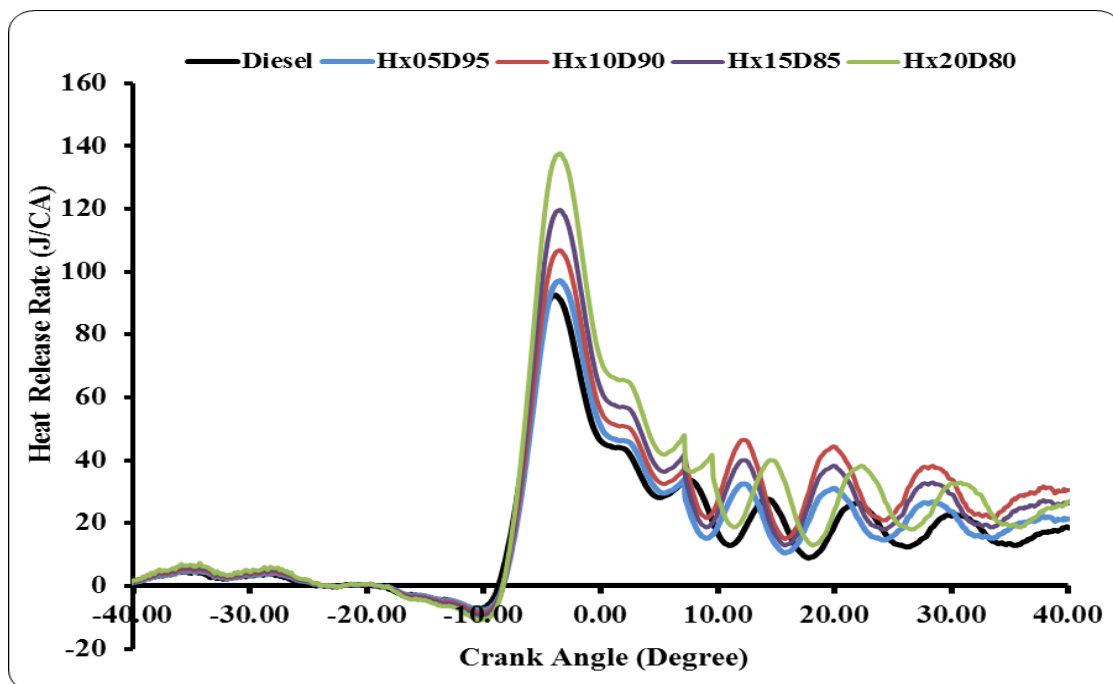


Fig. 4.8: Variation of HRR (J/CA) with respect to engine crank angle

The ignition quality of a fuel is usually characterized by its cetane number or cetane index. Lower cetane index/number generally means higher ignition delay. It is observed from fig. 4.8, that the ignition delay for the oxygenated blend is slightly higher than the corresponding one for the neat diesel fuel case, while its premixed combustion peak is much higher and sharper. It is the cetane number of hexanol which is very much comparable to diesel that causes the above observation in ignition delay. Ignition delay causes higher peak heat release rate due to more accumulation of the fuel before the start of burning. Therefore premixed combustion heat release is higher for HxD blends, which is responsible for higher peak pressure in comparison to diesel. The ignition delay also depends on fuel viscosity with result in poor atomization, slower mixing, increased mixing and reduced cone angle.

CONCLUSION AND SCOPE FOR FUTURE WORK

5.1 CONCLUSION

In the present study, combustion, performance, and emission studies were carried out for blends of hexanol and diesel. Based on the experimental results, the following major conclusions have been drawn:

1. It was observed that full load brake thermal efficiency was found to increase with increase in hexanol percentage in the blend. This may be explained by a better combustion due to the increase in the presence of oxygen within the combustion chamber. Full load BTE of Hx20D80 was found to be the maximum which was approximately 12% higher than the baseline diesel operation.
2. Brake specific fuel consumption followed an inverse pattern with respect to the BTE. As the percentage of hexanol in the test samples increased a steady decrease in the fuel consumption was observed. For the blends Hx05D95, Hx10D90, Hx15D85 and Hx20D80 decrement of about 4.87%, 12.19%, 19.5%, and 22% was observed in comparison to D100.
3. Carbon monoxide was found to get reduced with increase in hexanol percentage in the blends. At part loads, CO emission was found to be low for all the test fuels, however, substantial increase was observed after 60% load. Reduction in carbon monoxide emissions for higher blends may be attributed to improved combustion of oxygenated fuel HxD blends.
4. Hydrocarbon emissions were found to decrease for all the blends HxD compared to neat diesel fuel confirming better combustion characteristics.

5. The NO_x emissions increased with increase in engine load for all test fuels. Under full load conditions higher percentage of hexanol showed an increase in NO_x emissions as compared to the neat diesel. This may be attributed to a rise in in-cylinder mean gas temperature due to proper combustion. NO_x emission of 456ppm was observed for diesel at full load. For 5% HxD blend, NO_x was 486 ppm where as for 20% HxD blend , NO_x was 535ppm. The NO_x for rest of the blends were in between 5% and 20% HxD blend.
6. The highest smoke emissions of all fuels are obtained at high loads thus the formation of smoke strongly depends upon the engine load. At almost all engine loads, the smoke decreases with a higher content of hexanol in the blend. This is due to the complete and stable combustion of the blend, which contains more number of oxygen atoms. Among all the test fuels 20% HxD blend showed the mosr decrement of about 17% with respect to D100.
7. Heat release rate was found higher for blends, which is responsible for higher peak pressure and higher rate of pressure rise in comparison to mineral diesel. This may be due to the lower cetane rating of HxD blends compare to baseline diesel fuel. Lower cetane index hexanol diesel blend results in higher ignition delay from that of diesel.
8. It was observed that addition of hexanol in the fuel blend significantly alters the in-cylinder combustion process due to bulk changes in fuel atomization and fuel- air mixing processes.

From the exhaustive engine trial, it can be fairly concluded that a blending of 20% hexanol in diesel will result in better engine performance and emissions of HC, CO and smoke opacity. However, emission of NO_x was found to get enhanced with addition of hexanol which may be addressed through adequate catalytic converters. Therefore addition of hexanol in diesel does provide an opportunity to decrease the dependency to a certain extent and also at the same time improve performance emission and combustion parameters.

However, long-term run and wear analysis of HxD fueled engine is also necessary along with injection timing and duration for better combustion of HxD blends in diesel engines.

5.2 FUTURE WORK

The knowledge so gained during the present research work may be extended in the following directions for further research.

1. Comparisons of different alcohol and their combustion analysis should be done to get a clear picture about alcohol fuel and their effects.
2. Effect of cetane improvers may be studied.
3. In the present study, the compression ratios were unaltered. Hence, further work can be carried out studying the effect of variable compression ratios and injection angles.
4. To employ various NO_x reduction technologies
5. Some computational and simulation analysis may be carried by further researchers.
6. Quasi-dimensional heat release model may be developed for more accurate heat release characterization.
7. Effect of hexanol on the engine component especially the combustion chamber and their suitability should be carried out exhaustively.

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APPENDIX-I

Formula for calculation of Brake Thermal Efficiency and Brake Energy Fuel Consumption

Brake Thermal Efficiency (η_{th}):

$$\eta_{th} = \frac{\text{brake power}}{\text{fuel power}}$$

$$\eta_{th} = \frac{3600 \times BP}{FC \times Q_{lcv}}$$

Where:

η_{th} = thermal efficiency;

BP = brake power [kW];

FC = fuel consumption [kg/h = (fuel consumption in L/h) x (ρ in kg/L)];

Q_{lcv} = calorific value of kilogram fuel [kJ/kg];

ρ = relative density of fuel [kg/L].

Brake Fuel Energy Consumption:

$$BSEC = \frac{m_f \times Q_{lcv}}{1000 \times BP} \times 3600 [\text{MJ/KWh}]$$

Where:

m_f = mass flow rate [Kg/sec];

Q_{lcv} = calorific value of kilogram fuel [kJ/kg];

BP = brake power [KW].

APPENDIX-II

Technical Specifications of AVL Di-Gas Analyser

Measurement principle	CO, HC, CO ₂	Infrared measurement
	O ₂	Electrochemical measurement
	NO (option)	Electrochemical measurement
Operating temperature	+5 to +45°C	Keeping measurement accuracy
	+1 to +50°C	Ready for measurement
	+5 to +35°C	with integral NO sensor (+40°C)
Storage temperature	-20 to +60°C	
	-20 to +50°C	With integrated O ₂ sensor
	-10 to. +45°C	With integrated NO sensor
	0 to +50°C	With water in filter 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	

Measurement Ranges of AVL Di-Gas Analyser

Parameter	Measurement Range	Resolution
CO	0-10% vol	0.01% vol
CO ₂	0-20% vol	0.1% vol
HC	0-20000 ppm vol	1 ppm
NO _x	0-5000 ppm vol	1 ppm
O ₂	0-25% vol	0.01% vol

APPENDIX-III

Technical Specifications of AVL 437 Smoke Meter

Accuracy and Reproducibility	$\pm 1\%$ full scale reading
Heating Time	Approx. 20 min
Light source	Halogen bulb 12 V / 5W
Colour temperature	3000 K \pm 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	250°C Temperature at entrance

APPENDIX-IV

Accuracies and uncertainties of measurements

S.N.	Measurements	Measurement Principle	Range	Accuracy
1	Engine load	Strain gauge type load cell	0-25 Kg	±0.1Kg
2	Speed	Magnetic pick up type	0-2000 rpm	±20 rpm
3	Time	Stop watch	--	±0.5%
4	Exhaust Temperature	K-type thermocouple	0-1000°C	±1°C
5	Carbon monoxide	Non-dispersive infrared	0-10% vol.	±0.2%
6	Carbon dioxide	Non-dispersive infrared	0-20% vol.	±0.2%
7	Total hydrocarbons	Non-dispersive infrared	0-20,000 ppm	±2 ppm
8	Oxides of nitrogen	Electrochemical	0-4000 ppm	±15ppm
9	Smoke	Photochemical	0-100%	± 2%
10	Crank angle encoder	Optical	0-720 °CA	± 0.2°CA
11	Pressure	Piezoelectric	0-200 bar	± 1 bar
	Calculated results			Uncertainty
12	Engine power	--	0-8 kW	±1.0%
13	Fuel consumption	Level sensor	--	±2.0%
14	Air consumption	Turbine flow type	--	±1.0%
15	BTE	--	--	±1.0%
16	BSEC	--	--	±1.5%
17	Heat release	Sorenson model	--	±5.0%
18	In-cylinder temp.	Ideal gas equation	Up to 3000°K	±5.0%