CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION TO ENERGY SCENARIO

Energy is the major factor for economic growth of any country. The need for the energy is increasing day by day with the growth of population and requirement of modern energy consuming equipment for comfort living. At present energy is supplied from conventional sources (coal, petroleum based fuels, natural gas, etc) and other renewable sources (solar, wind, geothermal, biogas, etc.). The major portion of energy supplied is by petroleum based fuel imported from oil producing countries which forces dependence on them. Table 1.1 shows India’s crude oil production and import details.

Table 1.1 Crude Oil Production and Import Details*

<table>
<thead>
<tr>
<th>Year</th>
<th>Production (MT)</th>
<th>Import (MT)</th>
<th>Total (MT)</th>
<th>Import (%)</th>
<th>Average Crude oil Prices US $/per barrel</th>
<th>Increase in oil Price (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-05</td>
<td>33.981</td>
<td>95.861</td>
<td>129.842</td>
<td>73.82896</td>
<td>39.21</td>
<td>40.14</td>
</tr>
<tr>
<td>2005-06</td>
<td>32.190</td>
<td>99.409</td>
<td>131.599</td>
<td>75.53933</td>
<td>55.72</td>
<td>42.11</td>
</tr>
<tr>
<td>2006-07</td>
<td>33.988</td>
<td>111.502</td>
<td>145.49</td>
<td>76.63894</td>
<td>62.46</td>
<td>12.10</td>
</tr>
<tr>
<td>2007-08</td>
<td>34.118</td>
<td>121.672</td>
<td>155.79</td>
<td>78.10001</td>
<td>79.25</td>
<td>26.88</td>
</tr>
<tr>
<td>2008-09</td>
<td>33.508</td>
<td>132.775</td>
<td>166.283</td>
<td>79.84881</td>
<td>83.57</td>
<td>05.45</td>
</tr>
<tr>
<td>2009-10</td>
<td>33.690</td>
<td>159.259</td>
<td>192.949</td>
<td>82.53943</td>
<td>69.76</td>
<td>-16.53</td>
</tr>
<tr>
<td>2010-11</td>
<td>37.684</td>
<td>163.595</td>
<td>201.279</td>
<td>81.27773</td>
<td>85.09</td>
<td>21.98</td>
</tr>
<tr>
<td>2011-12</td>
<td>38.090</td>
<td>171.729</td>
<td>209.819</td>
<td>81.84626</td>
<td>111.89</td>
<td>31.50</td>
</tr>
</tbody>
</table>

* Source: Ministry of Petroleum and Natural Gas, 2012
The Indian economy is in a critical stage of development where energy requirement is increasing at a phenomenal pace. The petroleum products are being used by various sectors like—transport, agricultural and industrial. To meet these requirements, India has been importing more than 74% of crude oil in the last 8 years. It can be observed that the average crude oil price in the international market had increased every year except in the year 2009-10 (decreased by 16.53 % per barrel).

The invention of internal combustion engine and developments in engine technology resulted in exploitation of the petroleum based reserves which is depleting at a rapid rate. Internal Combustion (IC) engines are mainly classified as Spark Ignition (SI) and Compression Ignition (CI) engines which use petrol and diesel respectively. Combustion of these fuels in engines release substantial amount of pollutants such as Carbon Dioxide (CO₂), Carbon Monoxide (CO), Unburned Hydrocarbon (UBHC), Nitrogen Oxides (NOₓ), and Particulate Matter (PM). Reducing these emissions and increasing the fuel economy of IC engines are the primary concern for all developing nations.

The continuously increasing use of petroleum based fuels in IC engines has given rise to serious consequences. Global warming is the major one among these effects, which resulted in environmental impacts due to emission of increased greenhouse gases. One of the major by-products of combustion is carbon dioxide, a greenhouse gas. Greenhouse gases decrease the rate of infrared radiation to outer space from the earth. This increases the earth’s surface temperature making it warmer. One way to reduce the amount of CO₂ produced by the combustion of fossil fuels from IC engines is to reduce the amount of fuel consumed through improved efficiency or through the use of renewable bio fuels.
Additionally, because of the import of the majority of the fossil fuels, India is dependent on countries that produce fossil fuels. A decrease in the use of fossil fuels also carries important implications. Future economic growth crucially depends on the long-term availability of energy from sources that are affordable and accessible. It is also necessary that the energy source should be environmental friendly.

1.2 USE OF BIO-DIESEL IN CI ENGINES

There has been a world-wide interest in the search of alternatives to petroleum derived fuels due to their depletion and concern for the environment. Bio-diesel derived from edible, non-edible oils and animal fats can be used in diesel engines with little or no modifications (EL-Kasaby & Nemit-allah, 2013). The advantages of using bio-diesels are as follows:

- Bio-diesels are cleaner sources of energy than conventional petroleum based diesel.
- Emission of greenhouse gases is reduced significantly.
- Reduced imports of petroleum based fuel providing energy security for the country.
- Reduced carbon emissions.
- Employment opportunities in the rural sector which will help rural development.
- Reduction in fossil fuel use.
- Bio-diesel is biodegradable, non-toxic and renewable.
- High flash point of bio-diesel makes it safer as chances of burning after accidents are less.
- Reduced smoke, UBHC and CO emissions, as bio-diesels are oxygenated fuels.
The search for suitable oil source is necessary for the development of bio-diesel industry especially in heavily populated and food-deficient countries.

Some of the plant-based oils suitable for generation of biodiesel are rapeseed/mustard, peanut, coconut, soybean, sunflower, palm, corn, rice bran, neem, mahua, jatropha, cotton seed, linseed and karanja/pungam oil. For developing countries like India with a large population, there is an increasing demand for edible oil for human consumption. Therefore, production of biodiesel from edible oil is not an affordable solution for India. Instead, non-edible oil and animal fat can be considered as good options. Jatropha oil methyl esters and fish oil methyl esters (FOMEs) are one of the best options in non-edible category and animal fat category respectively.

Jatropha oil methyl esters are well proven alternatives to petroleum diesel. But jatropha cultivation requires huge land area as well as good quality jatropha plant seed to generate sufficient oil. India promotes the cultivation of jatropha seeds by utilising wastelands, which is available abundantly in all parts of the country. Renewable raw material at low cost is a very important requirement for economic and sustainable production of biodiesel.

Fish processing industry generates large quantities of tissue waste and byproducts which are either discarded or retailed at low price for fertiliser and animal feed. These discarded tissue wastes and byproducts may be converted to bio-diesel at a low cost. Biodiesel produced from fish oil is a very good and low cost alternative to petroleum diesel. India is one of the countries in Asia having a long coastline with excellent potential for marine fishing. Biodiesel based on fish oil is easy to produce and provides cleaner-burning fuel. Biodiesel and blended diesel, (Petroleum-based diesel mixed with biodiesel), could potentially replace or reduce petroleum-based diesel fuel requirement of the country.
Even though biodiesel offers reduction in Smoke, UBHC and CO emissions due to the molecular oxygen present in it, NO\textsubscript{x} emissions are higher which can be reduced by using exhaust gas recirculation (EGR). The main factors that help in reducing the NO\textsubscript{x} emissions by using EGR are: the burnt gases replace air partially from the intake port and decrease the O\textsubscript{2} concentration which results in slowing down the combustion reaction rate and extending the combustion duration. The peak combustion temperature is reduced as the specific heat capacity of H\textsubscript{2}O and CO\textsubscript{2} is higher.

1.3 HOMOGENEOUS CHARGE COMPRESSION IGNITION (HCCI) TECHNOLOGY

Homogeneous Charge Compression Ignition (HCCI) is a promising alternative combustion technology for diesel engines with high efficiency and lower NO\textsubscript{x} and particulate matter emissions. It is a novel engine combustion mode in which fuel and air are mixed before combustion starts and the mixture auto-ignites at multiple sites within the combustion chamber as a result of the temperature increase during the compression stroke as shown in Figure 1.1.

![Image of Fuel Injector and Spark Plug]

**Figure 1.1 Comparison of Diesel, Gasoline and HCCI Combustion**
This is an engine combustion process that is essentially a cross-breed of the spark ignition (SI) and compression ignition (CI) processes. Table 1.2 shows the comparison of key features between SI, CI and HCCI engines.

**Table 1.2 Comparison of Key Features between SI, CI and HCCI Engines**

<table>
<thead>
<tr>
<th>Feature</th>
<th>SI Engine</th>
<th>CI Engine</th>
<th>HCCI Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogeneous Charge</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Ignition</td>
<td>Spark</td>
<td>Compression</td>
<td>Compression</td>
</tr>
<tr>
<td>Ignition timing</td>
<td>Spark</td>
<td>Fuel injection</td>
<td>Chemical kinetics</td>
</tr>
<tr>
<td>High temperature flame</td>
<td>Yes – flame front</td>
<td>Yes – fuel rich regions</td>
<td>No</td>
</tr>
</tbody>
</table>

The advantages of HCCI combustion are shown in Figure 1.2 in comparison with Diesel and Gasoline combustion.

![Figure 1.2 Advantages of HCCI Combustion](image)
The advantages of HCCI are numerous and depend on the combustion system with which it is compared. Relative to SI engines, HCCI engines are more efficient, approaching the efficiency of a Compression Ignition Direct Injection (CIDI) engine. This improved efficiency results from three reasons: the elimination of throttling losses, the use of high compression ratios (similar to a CIDI engine), and a shorter combustion duration (since it is not necessary for a flame to propagate across the cylinder). HCCI engines also have lower engine-out NOx emissions compared to SI engines.

Relative to CIDI engines, HCCI engines have substantially lower emissions of PM and NOx (Christensen et al 1997, Aceves et al 1999, Wontae et al 2007, Ezio et al 2008 and Andreas et al 2008). The low emissions of PM and NOx in HCCI engines are a result of the dilute homogeneous air and fuel mixture in addition to low combustion temperatures. The charge in HCCI engine may be made dilute by being very lean, by stratification, by using exhaust gas recirculation (EGR), or combination of these methods.

Because flame propagation is not required in HCCI engines, dilution levels can be higher than the levels tolerated by either SI or CIDI engines. Combustion is induced throughout the charge volume by compression heating due to the piston motion, and it will occur in almost any fuel-air-exhaust-gas mixture once the ignition temperature is in the range of 800 to 1100K. In CIDI engines combustion temperatures of 1900 to 2100K are high enough to produce high NOx emissions. (Homogeneous Charge Compression Ignition (HCCI) Technology, 2001).
Even though HCCI engines show significant advantages, there are a few challenges faced as given below:

- High CO and UBHC emissions are caused by incomplete oxidation due to rapid combustion and low in-cylinder temperature
- The operating range of automotive engines using HCCI mode is found to be too narrow (Su, 2007). Improper combustion or misfire under fuel-lean conditions limits the minimum power output at which the engine can operate. Near rated power, HCCI engines are often extremely loud and strong acoustic oscillations resembling those of a knocking spark-ignited engine occur.
- High heat release rates and high in-cylinder pressure may cause more wear and damage to the components. Stronger materials are required for engine components to withstand high pressure and temperature at high load operations as a result of which weight power ratios of the engine increase.
- Auto-ignition is difficult to control

1.4 HCCI COMBUSTION

Homogeneous charge compression ignition (HCCI) engines are being considered as an alternative to diesel engines. The objectives of HCCI combustion in diesel engines are to reduce both NOx and Particulate Matter (PM) emissions with better thermal efficiency and engine performance.

In HCCI combustion, homogeneous mixture is prepared in the inlet manifold or in the combustion chamber during the intake process. Hence the pressure and temperature rise during the compression stroke results in a
spontaneous ignition of the charge in the whole volume of combustion chamber and does not occur in a particular region in a fuel spray as in conventional CIDI combustion. No high temperature flame front appears as in the case of SI engines and this leads to negligible formation of NO$_x$. Due to homogeneous lean mixture, there are no fuel rich zones and hence soot formation is also negligible. Hence to achieve efficient diesel HCCI combustion, the following key factors should be considered:

1. Preparation of homogeneous mixture
2. Ignition of the prepared mixture
3. Control of combustion

1.4.1 Preparation of Homogeneous Mixture

Preparation of homogeneous diesel air mixture is difficult compared to spark ignition engines where the gasoline readily evaporates and mixes with air. The following problems are encountered in the formation of homogenous charge using diesel and air:

1. Time required for mixing diesel and air
2. Low volatility of diesel fuel

It is reported in the literature that the above problems are addressed in three different ways as discussed below:

1. **Port Fuel Injection:** Considering the time required for the preparation of homogeneous charge, port fuel injection is the simplest solution which also reduces NO$_x$ and soot emissions. Low volatility of diesel fuel affects evaporation process and its high cetane number will cause problems in the control of auto ignition (Iua Zhao, 2007). Higher UBHC, CO and
limited operating range and efficiency are the disadvantages of this method.

2. **Early Direct Injection:** In this method, the homogeneous premixed fuel air mixture is obtained by the injection of fuel in the combustion chamber approximately 60-40 °CA bTDC in the compression stroke (Iwabuchi et al 1999). But the in-cylinder density is low at the time of injection resulting in cylinder wall impingement which leads to erosion of cylinder liner and absorption of fuel by the lubricating oil.

3. **Late Direct Injection:** In this method, the homogeneous premixed fuel air mixture is obtained by the injection of fuel in the combustion chamber around 40 °CA bTDC in the compression stroke so that a rapid homogenization (Wimmer et al 2006). High injection rates are necessary to obtain optimum results and injection is completed within the auto-ignition delay period. It is observed that late injection is the most successful method of HCCI combustion compared to the other two methods and start of combustion is better controlled with the help of high EGR rates.

1.4.2 **Ignition of the Prepared Mixture**

HCCI combustion of diesel fuel occurs in two stages of heat release (Mingfa Yao et al 2009) as shown in Figure 1.3.
**Figure 1.3**  Rate of Heat Release with Crank Angle from HCCI Combustion of n-heptane fuel (Mingfa Yao et al 2009)

Low Temperature Combustion (LTC) occurs in the first stage followed by much stronger main reaction named High Temperature Combustion (HTC). Crank angle between LTC and HTC is termed as Negative Temperature Co-efficient (NTC).

### 1.4.3 Control of Combustion

In HCCI combustion, control over the start of combustion (SOC) is the main issue. Conventional control techniques are not applicable for this type of combustion mode like CI engines (i.e. fuel injection event to start
combustion). Hence, indirect methods like variable EGR technique, variable compression ratio (VCR), variable valve timing (VVT), increased intake charge temperature, equivalence ratio variation, injection timing, modulating two or more fuels, fuel additives etc (Aceves et al 1999, Christensen et al 1999, Dae & Chang, 2006, Keeler & Shayler 2008) which alter the compression process are necessary.

1.5 EMISSIONS IN HCCI COMBUSTION

Since HCCI engine operates on lean mixtures, the peak temperatures are always lower in comparison to spark ignition and diesel engines. Low peak temperatures prevent the formation of NOx. However, they also lead to incomplete burning of fuel especially near the walls of the combustion chamber. This results in high carbon monoxide and hydrocarbon emissions and an oxidising catalyst would be effective in removing them.

1.6 PARTIALLY PREMIXED CHARGE COMPRESSION IGNITION (PPCCI)

It is proposed to study the effect of Partially Premixed Charge Compression Ignition (PPCCI) combustion mode a variant of HCCI combustion mode in diesel engines. In this method generally two fuels are used. One fuel is injected into the intake air, upstream of the intake valve to obtain a premixed charge. Remaining fuel is injected into the combustion chamber through conventional injection system. The PPCCI technique reduces NOx and PM using partially premixed charge compression ignition (PPCCI) combustion. In this method of combustion, diesel, petrol, methanol, ethanol, Propane, n-Pentane, n-heptane, Dimethyl ether (DME), Diethyl Ether (DEE), Liquefied petroleum gas (LPG), Compressed natural gas (CNG), Methyl tert-butyl ether (MTBE) and acetylene are commonly used as premixed fuel or main fuel (in-cylinder injection). It is observed that not
much work has been done on the usage of bio-diesel in PPCCI combustion mode. Hence an attempt was made to study the effect of biodiesels (JOME and FOME) as main fuels and diesel as premixed fuel.

In PPCCI, combustion takes place predominantly in premixed manner than in diffusive manner due to homogeneous mixture formation by fuel-air premixing. Moreover, premixed mixture combustion is faster than conventional diesel combustion as it occurs at multiple points in the cylinder. This sudden combustion causes a sharp increase in pressure and temperature leading to high maximum values. Therefore, in PPCCI combustion takes place with a highly diluted mixture to maintain the temperature and pressure low in the cylinder and is normally restricted to low loads. In this way, possible engine damage is avoided while NOx emissions are lowered by low temperatures.

Although the low-temperature premixed combustion can simultaneously reduce NOx and soot emissions, the following problems are to be solved before it is applied in practice:

- **Simultaneous control of ignition and combustion phase:**
  Simultaneous control of ignition and combustion phase is required to restrict the maximum pressure to prevent the fall of combustion efficiency.

- **Method of preparation and premixed mixture quality:**
  Formation of a homogeneous or relatively homogeneous premixed mixture is necessary before ignition to achieve better premixed combustion.
• **Load adaptability of Premixed Combustion**: Determining the extent of premixed combustion to high loads without knocking combustion and how to extend it to low loads without a flame out is one of the key issues.

• **UBHC and CO emissions**: The premixed combustion has higher HC and CO emissions compared to conventional combustion due to an early fuel injection in HCCI and a high level of EGR in PCCI combustion

### 1.7 PRESENT RESEARCH WORK

In the present experimental work, the performance, emission and combustion characteristics have been studied using Jatropha oil methyl esters (JOME) and Fish oil methyl esters (FOME) in CIDI and HCCI modes with the following objectives:

• To find the optimum blend ratio of JOME and FOME with diesel in CIDI mode.

• To find the optimum EGR percentages for better tradeoff of soot and NOx emissions for both JOME and FOME.

• To study the effect of PPCCI combustion mode with diesel and Biodiesel blends as given in Table 1.3.
Table 1.3 Test Matrix for PPCCI Combustion Mode

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>PPCCI Mode</th>
<th>Main Injection</th>
<th>Premixed Injection</th>
<th>Performance without EGR for Premixed ratios of</th>
<th>Performance with 0.25 Rp with EGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>D-D</td>
<td>Diesel</td>
<td>Diesel</td>
<td>0.25, 0.50 &amp; 0.75</td>
<td>10%, 20% &amp; 30%</td>
</tr>
<tr>
<td>2</td>
<td>D-20J</td>
<td>20% JOME*</td>
<td>Diesel</td>
<td>0.25, 0.50 &amp; 0.75</td>
<td>10%, 20% &amp; 30%</td>
</tr>
<tr>
<td>3</td>
<td>D-20F</td>
<td>20% FOME*</td>
<td>Diesel</td>
<td>0.25, 0.50 &amp; 0.75</td>
<td>10%, 20% &amp; 30%</td>
</tr>
</tbody>
</table>

*20% JOME and 20% FOME are optimised blends

1.8 ORGANISATION OF THE THESIS

Chapter 1 gives the introduction on energy scenario, bio-diesel for diesel engines, introduction to HCCI engines and PPCCI engine.

Chapter 2 presents the literature survey pertaining to the present work like use of bio-diesel in CIDI diesel engines, HCCI and PCCI combustion and their controls, reduction of emissions, effect of different fuels and effect of EGR. In chapter 3 the properties and preparation of biodiesel are discussed.

Chapter 4 gives the details of the experimental set up, PPCCI setup with Electronic Control Unit, instruments and emission measurement equipments used.

Chapter 5 presents the results and discussion.

The use of alternative fuels like JOME and FOME in conventional diesel combustion, determination of optimum blends of JOME and FOME with conventional diesel fuel for use in CI engines and optimum EGR for reducing the NOx emission with optimum blend of JOME and FOME are discussed in the first part of Chapter 5.
In the second part of the chapter the PPCCI combustion mode with diesel as premixed fuel and main fuel with and without EGR and PPCCI combustion mode with diesel as premixed fuel and 20% JOME / 20% FOME as main fuel with and without EGR are discussed.

The performance characteristics (brake thermal efficiency, exhaust gas temperature), emission characteristics (UBHC, CO, NO\textsubscript{x} and Soot emissions) and combustion parameters (in-cylinder pressure, ignition delay and heat release rate) are presented.

Chapter 6 records the conclusions arrived based on various experiments conducted using different modes of operation.