CHAPTER 7

EXPERIMENTS WITH POME AND ITS BLENDS

7.1 INTRODUCTION

Growing concern regarding energy resources and the environment has increased interest in the study of alternative sources of energy. To meet increasing energy requirements, there has been growing interest in alternative fuels like biodiesel to provide a suitable diesel oil substitute for IC engines. Biodiesel present a very promising alternative to PBDF, since they are renewable and have similar properties. The advantages of biodiesels are that they have higher cetane number, higher lubricity, minimal sulfur content and less pollutant for the environment compared to PBDF.

In the first phase of the present work, the scope of utilizing biodiesel obtained from Pongamia oil as an alternative diesel fuel was investigated. The biodiesel obtained from Pongamia oil i.e. Pongamia Oil Methyl Ester (POME) and four of its blends with PBDF were tried on the test engine with an objective to examine their suitability as alternate fuels for diesel engine. The performance, emissions and combustion characteristics of POME and its blends were compared with PBDF. Six different types of fuels were used for the experimental investigation. Their names and notations are given below in Table 7.1. The main objective is to establish evidence pertaining to the best suitable fuel among the POME and its blends in terms of performance and emission characteristics.
### Table 7.1 Fuels used and their notations

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petroleum Based Diesel Fuel</td>
<td>PBDF</td>
</tr>
<tr>
<td>Pongamia Oil Methyl Ester</td>
<td>POME100</td>
</tr>
<tr>
<td>10 vol% POME + 90 vol% PBDF</td>
<td>POME10</td>
</tr>
<tr>
<td>20 vol% POME + 80 vol% PBDF</td>
<td>POME20</td>
</tr>
<tr>
<td>30 vol% POME + 70 vol% PBDF</td>
<td>POME30</td>
</tr>
<tr>
<td>40 vol% POME + 60 vol% PBDF</td>
<td>POME40</td>
</tr>
</tbody>
</table>

### 7.2 AIM AND OBJECTIVES

The aim of this experimental phase was to investigate the performance, emission and combustion characteristics of POME and its blends and to compare the results with baseline PBDF operation to shortlist the best biodiesel fuel in terms of performance, combustion and emission characteristics. To achieve this aim, the following objectives were set:

- To investigate the impact of POME and its blends on the performance, emission and combustion characteristics at different loads of operation.
- To compare the engine performance, emission and combustion characteristics between POME and its blends with the baseline PBDF.

### 7.3 EXPERIMENTAL PROCEDURE

A single cylinder, four stroke, direct injection, water cooled computerized Kirloskar TV1 diesel engine shown in Figure 4.2 was used to investigate the impact of POME and its blends on engine performance, emission and combustion characteristics. Two fuel tanks were used for
fuelling the engine. The first fuel tank supplied by the manufacturer was used for baseline PBDF and the second fuel tank was used for filling the test fuel which has got the flexibility of frequent removal and fixing. Necessary fuel valves were provided to change over from baseline PBDF to the desired test fuel while the engine was in running condition.

After completion of initial checkup like fuel, lubricating oil, water level in the water sump (a separate water pump was provided to supply cooling water to the engine, exhaust gas calorimeter and to the eddy current dynamometer), the systems like computer, engine control unit, exhaust gas analyzer, smoke meter etc, were switched on. Ambient temperature, atmospheric pressure and the water temperature were recorded. After ensuring no load on the eddy current dynamometer the engine was started on baseline PBDF and performance, emission and combustion tests were conducted using PBDF as fuel, at manufacturers recommended fuel injection pressure of 200 bar and fuel injection timing of 23° bTDC. Readings like, load on the engine dynamometer, fuel consumption time, inlet manifold manometer reading, exhaust gas temperature, engine cooling water temperature, exhaust gas calorimeter temperature, smoke meter reading and exhaust gas analyzer readings were recorded by varying load in steps of 0, 25, 50, 75 and 100% of full load. The performance parameters such as Brake thermal efficiency (BTE), Brake Specific Fuel Consumption (BSFC), Brake Specific Energy Consumption (BSEC), the emission parameters such as Carbon Monoxide (CO), Carbon Dioxide (CO₂), Unburnt Hydrocarbons (UBHC), Oxides of Nitrogen (NOₓ) and Smoke Opacity (Smoke) and the combustion characteristics such as Ignition delay (ID), in-cylinder Peak Pressure (P), Pressure variation with crank angle, Heat Release Rate (HRR), Exhaust Gas Temperature (EGT), were evaluated and analyzed. The performance, emission and combustion characteristics were plotted for the PBDF operation after conducting several trial runs and selected the best performance values and
these values were represented as baseline PBDF values in all the graphs which were supposed to be the best operational values for this particular engine. These test values were compared with the experimental results using various test fuels selected for the experimental program at the same operating conditions.

Subsequently the performance, emission and combustion tests were carried out using the POME and its blends with PBDF following the above procedure to evaluate the performance, emission and combustion analysis at the same injection pressure of 200bar and fuel injection timing at 23° bTDC. Before introducing the test fuel, the engine was run on PBDF for 10 to 15 minutes and after stabilizing the engine parameters, the test fuel was introduced. After running the engine for 10-15 minutes on the test fuel and stabilizing the parameters with the test fuel the readings were recorded. The performance, emission and combustion parameters were computed, evaluated and the fuel, which yields better performance and emission parameters, was identified. After completion of the tests with POME and its blends the engine was switched over to PBDF and run for 5 to 10 minutes on PBDF before stopping the engine to avoid cold starting and fuel injector and fuel pump plunger sticking problems.

The impact of POME and its blends on the DI diesel engine’s performance, combustion and emissions at different loads of operation was investigated and presented in this chapter.

7.4 RESULTS AND DISCUSSION

7.4.1 Combustion Characteristics

Ignition delay of fuel is a significant parameter in determining the knocking characteristics of CI engines. The cetane number of a fuel, which indicates the self-igniting capability, has a direct impact on ignition delay.
The higher the cetane number, the shorter will be the ignition delay and vice versa. Figure 7.1 shows the ignition delay of PBDF, POME and its blends. It was observed that the ignition delay periods of POME and its blends were significantly lower than that of PBDF and were decreasing with an increase in percentage of POME in the blend. This was due to the fact that POME and its blends have a higher cetane number compared to PBDF. The ignition delay for POME10, POME20, POME30, POME40 and POME100 were 1° CA, 1.8° CA, 3.2° CA, 3.8° CA and 5.4° CA, shorter respectively than that of PBDF at full load. It was noticed that for all test fuels the reduction in ignition delay increased with the increase in load. This was due to higher combustion chamber wall temperature and reduced exhaust gas dilution at higher loads.

Heat release calculations are useful to get some information regarding the combustion process in an engine. A thorough knowledge of the heat release pattern of a fuel is essential to analyse the performance and emitant formation inside the combustion chamber and the cooling system requirements of an engine. The comparison of heat release rate variation for PBDF, POME and its blends is shown in Figure 7.2. It can be seen from the figure that the heat release curves of the POME and its blends were retarded compared to that of PBDF at full load operation. POME and its blends did not display the pronounced first heat release peak compared to PBDF. However diffusion burning indicated by the area under the second peak was higher for POME and its blends. whereas, the first heat release peak was lower than that of PBDF mainly due to shorter ignition delay and poor spray formation. Other reasons responsible for this were, lower calorific value and, poor air-fuel mixing and evaporation as a result of higher viscosity and lower volatility. It was also observed that the maximum heat release rate of 84.25 J/°CA was recorded for PBDF at 6° bTDC, while POME20 recorded its maximum heat release rate of 67.6 J/°CA at 7°bTDC. As the percentage of POME in the blend was increased, the maximum heat release rate decreased and the crank angle at which it took place was advanced.
Figure 7.1 Variation of ignition delay for POME and its blends

Figure 7.2 Comparison of HRR at full load for POME and its blends
Figure 7.3 shows the comparison of cumulative heat release rate variation for PBDF, POME and its blends. The experimental investigations revealed that the overall heat release characteristics were quite similar for POME and its blends and PBDF. It can be seen from the figure that the cumulative heat release of the POME and its blends were slightly retarded during the early stage of combustion i.e. pre combustion phase. This can be mainly attributed to shorter ignition delay, lower calorific value and poor spray formation for POME and its blends. However the cumulative heat release of the POME and its blends were slightly advanced during the later stage of combustion i.e. diffusion combustion phase. This trend can be explained on the basis of the presence of the oxygen molecule in POME and its blends that results in the improvement of combustion in the cylinder to burn completely and increase the heat release rate. The cumulative heat release rate for PBDF, POME10, POME20, POME30, POME40 and POME100 were measured as 634 J, 618 J, 599 J, 579 J, 566 J and 551 J at 10°CA aTDC respectively at full load.

The pressure variation in the cycle is important in the analysis of the combustion characteristics of any fuel. The in-cylinder pressure variations for PBDF, POME and its blends at full load are shown in Figure 7.4. POME and its blends followed the similar pattern of pressure rise as that of PBDF at all load conditions. However as seen in the figure, the peak cylinder gas pressures of the POME and its blends were lower than that of the PBDF due to POME’s high viscosity, low calorific value and low volatility. The poor spray atomization characteristics of POME due to higher viscosity and poor evaporation of POME due to lower volatility affect air fuel mixing. This in turn results in poor combustion and lower in-cylinder pressure. The peak cylinder gas pressure for PBDF, POME10, POME20, POME30, POME40 and POME100 were measured as 74.4 bar, 72.4 bar, 67.24 bar, 66.2 bar, 65.3 bar and 62.4 bar at 9°, 8°, 7°, 7°, 6° and 4° CA aTDC respectively at full load.
Figure 7.3  Comparison of CHRR at full load for POME and its blends

Figure 7.4  Comparison of cylinder pressure at full load for POME and its blends
Peak pressure depends mainly on the combustion rate in the initial stages, which is influenced by the fuel taking part in the uncontrolled combustion phase. The variation of peak pressures with respect to brake power for PBDF, POME and its blends is shown Figure 7.5. It can be seen that the peak pressure was slightly lower for POME and its blends when compared to that of PBDF. This was due to the high viscosity, low calorific value and low volatility of POME and its blends. The viscosity and volatility of the fuel have a very important role to improve atomization and to improve air fuel mixing respectively. Because of the high viscosity and low volatility of POME, a slight decrease in the maximum cylinder gas pressure was obtained at all engine loads. From the Figure 7.5 it can be observed that the cylinder peak pressure of all fuels increased from no load to full load. The highest cylinder gas pressure was measured as 74.35 bar with PBDF at full load operation. Similarly peak pressures for POME10 (72.4 bar), POME20 (67.24 bar), POME30 (66.2 bar), POME40 (65.3 bar) and POME100 (62.4 bar) were lower than that of PBDF at full load. The peak pressure decreased by 2.6%, 9.5%, 11%, 12.2% and 16% for POME10, POME20, POME30, POME40 and POME100 compared to that of PBDF at full load operation.

EGT measurement is important because it gives an idea of the temperature within the combustion chamber. These are approximate values because variations occur in the exhaust gases between the combustion chamber and the point at which measurements are made. Figure 7.6 shows the variation of EGT with load for PBDF, POME and its blends. As seen in Figure 7.6 EGT increased for all test fuels as the engine load was increased. This was because the amount of fuel supplied per unit time increased as the engine load was increased, and consequently more heat energy was produced. As a result, EGT was increased. It was also observed that the EGT was higher for POME and its blends. This was attributed to the presence of Oxygen content in POME and its blends. The Oxygen content of the POME had increased the fuel air mixing rate in the cylinder compared to the PBDF, and this caused to extend the combustion duration, which resulted in higher EGT.
Figure 7.5  Variation of peak pressures for different POME blend

Figure 7.6  Comparison of EGT for POME and its blends
The increased EGT for POME and its blends was also attributable to shorter ignition delay, which resulted in reduced premixed combustion, which in-turn increased the diffusion combustion. Improved diffusion combustion resulted in higher EGT.

7.4.2 Performance Characteristics

BSFC is the ratio between mass of fuel consumption and brake power. Figure 7.7 shows the comparison of BSFC of POME, various blends of POME with PBDF and PBDF. As the load was increased, BSFC decreased for all fuel blends. At full load, POME100 showed the highest BSFC. The BSFC for POME100 and its blends was slightly higher than that of PBDF. The BSFC was found to increase with the increasing proportion of POME in the PBDF. This may be attributed to that, the test engine had a mechanically controlled in-line type fuel injection pump; the engine load was controlled by the fuel injection volume. For the same volume, more POME and its blends, based on the mass was injected into the combustion chamber than that of PBDF due to their higher densities. The BSFC for POME10, POME20, POME30, POME40 and POME100 was higher than that of PBDF by about 7%, 11%, 15%, 19% and 26% respectively at full load operation. Because the calorific value of biodiesel fuel was lower than that of PBDF, the BSFC of POME and its blends was higher than that of PBDF. It is well known that BSFC is inversely proportional to the BTE. From the Figure 7.8 it was learnt that BTE with biodiesel mixtures was little lower than that of PBDF. The slight reduction of BTE with POME and its blends can be attributed to poor spray characteristics, poor air fuel mixing, higher viscosity, lower volatility and lower calorific value of POME and its blends than that of PBDF.

Thermal efficiency is the ratio between the power output and the energy introduced through fuel injection, the latter being the product of the injected fuel mass and the lower heating value. Thus, the inverse of thermal efficiency is often referred as BSFC. Since it is usual to use the brake power
Figure 7.7 Variation of BSFC for POME and its blends

Figure 7.8 Comparison of BTE for POME and its blends
for determining thermal efficiency in experimental engine studies, the efficiency obtained is really a brake-specific efficiency. This parameter is more appropriate than fuel consumption to compare the performance of different fuels, besides their heating value.

Figure 7.8 shows the BTE of POME and its blends. BTE of POME and its blends was lower, compared to that of PBDF. At rated load the BTE of POME100 was lower than that of PBDF by 19.9%. The BTE of blends of POME lie between those of PBDF and POME100 at all loads. The decrease in BTE at full load was 5.26% for POME10, 9.58% for POME20, 11.74% for POME30 and 14.31% for POME40. Apart from the factors stated earlier another reason that was responsible for lower BTE could be that, since the engine was operated under constant injection advance and POME had a smaller ignition delay, combustion was initiated much before TDC was reached. This, increased the compression work and more heat loss for POME and its blends and thereby reduced the BTE of the engine.

BSEC is defined as the amount of energy consumed per kilowatt power developed in one hour. For the comparison of economy of two fuels, BSEC is the best way of judgement as compared to BSFC because the heating value and density of the fuels exhibit slightly different trends. Figure 7.9 illustrates the variation of BSEC of POME and its blends. Among the blends, POME20 gave a comparable result (≤ 10%) as that of PBDF but POME100 had higher BSEC when compared with PBDF. The BSEC in the case of POME100, increased to 24.3% when compared to PBDF. The use of POME10, POME20, POME30 and POME40 caused an increase in BSEC in the range of 5.1%, 10.1%, 12.71% and 16.11% with respect to PBDF at rated load respectively. This was due to lower calorific values and higher viscosity of these blends than that of reference fuel.
7.4.3 Emission Characteristics

Unburnt hydrocarbons (UBHC) are the results of incomplete combustion of fuel and quenching of flame near the combustion chamber walls. There are normally some regions within the combustion chamber of an engine fuelled with PBDF where the mixture is either too lean or too rich fail to ignite and oxidized fuel in the exhaust. These unburnt species are collectively known as UBHC emissions. UBHC emissions generally found to be very less in diesel engine compared to a petrol engine. The UBHC emissions with POME and its blends were compared with PBDF as shown in Figure 7.10. UBHC emissions were reduced over the entire range of loads for POME and its blends. It decreased with increase in the level of POME in the blend. Since the POME is an oxygenated fuel, it promotes combustion and results in reduction in UBHC emissions. The UBHC emissions of POME100 relative to PBDF decreased by 10.6% at the rated load operation. All POME blends i.e. POME10, POME20, POME30 and POME40 produced lesser HC emissions by 6%, 12.12%, 16.16% and 13.63% respectively at full load compared to that of standard PBDF.

CO is an intermediate combustion product and is predominantly formed due to the lack of Oxygen and incomplete combustion. If combustion is complete, CO will be converted to CO\(_2\) however if the combustion is incomplete due to shortage of air or due to low in-cylinder temperature, CO will be formed. Usually high CO emissions are formed with fuel-rich mixtures, but as diesel combustion is occurring with lean mixture and has an abundant amount of air, CO from diesel engine is low. Figure 7.11 shows that CO emissions were greatly reduced with the addition of POME to PBDF. CO emissions were slightly higher at lower load for all test fuels; it decreased at medium load and then increased again above the medium load. For the POME and its blends, the CO emissions were less compared to PBDF. It decreased
Figure 7.9 Variation of BSEC for POME and its blends

Figure 7.10 Variation of UBHC emissions for POME and its blend
with increase in the percentage of POME in the blend. The least CO emissions were obtained for the POME40. It was noticed that CO varied from 0.08% by volume at low load to 0.22% by volume at full load for PBDF and for POME100 it varied from 0.057% by volume at low load to 0.17% by volume at full load. At full load CO emissions for POME10 (0.19% by volume), POME20 (0.16% by volume), POME30 (0.15% by volume) and POME40 (0.148% by volume) were lower than that of PBDF. Since POME is an oxygenated fuel, it leads to better combustion of fuel resulting in the decrease in CO emissions. This, was a strong advantage in favour of POME.

CO₂ emission is produced by the complete combustion of fuel. CO₂ is an important component in the global warming. Figure 7.12 shows the CO₂ emissions of POME, its blends and PBDF versus brake power. The CO₂ emissions of the POME and its blends were higher than that of PBDF at all test conditions. The results show that the POME did provide an improved complete combustion at all loads of operation as it has Oxygen content. The CO₂ emission of POME10, POME20, POME30 and POME40 compared with those of PBDF increased by 0%, 3%, 5.88% and 7.35% respectively at full load. However the CO₂ emissions of POME100 relative to PBDF decreased by 3% at rated load operation due to deteriorated combustion as a result of poor mixing of POME with air.

Oxides of Nitrogen (NOₓ) are formed by chain reactions involving Nitrogen and Oxygen in the air. These reactions are highly temperature dependent. Since diesel engines always operate with excess air NOₓ emissions are mainly a function of gas temperature and residence time. Figure 7.13 shows the increase in the emission of NOₓ with an increase in percentage of POME in the fuel. An increase of 5.5%, 9.9%, 13.58%, 14.81% and 8.33% in NOₓ emissions for the POME10, POME20, POME30, POME40 blend and POME 100 respectively were observed at full load compared to PBDF.
Figure 7.11 Variation of CO emissions for POME and its blends

Figure 7.12 Variation of CO$_2$ emissions for POME and its blends
The NO\textsubscript{x} increase for POME may be attributed to the Oxygen content of the POME, since the Oxygen present in the fuel may provide additional Oxygen for NO\textsubscript{x} formation. The increase in NO\textsubscript{x} emission may also be due to the effect of physical properties of biodiesel on the injection advance had been widely proved in engines with pump-line-nozzle injection systems. The bulk modulus of biodiesel is 5–10\% higher than that of standard PBDF. This difference in bulk modulus can result in earlier fuel injection into the combustion chamber for biodiesel relative to standard PBDF, even when the physical injection process begins at the same time. Advancing the fuel injection timing is known to yield increased NO\textsubscript{x} by shifting the start of combustion earlier and raising the peak in-cylinder temperatures. Another reason for the increase in NO\textsubscript{x} could be the possibility of higher combustion temperatures arising from improved combustion. It has to be noted that a larger part of the combustion was completed before TDC for POME and its blends compared to PBDF due to their lower ignition delay. So higher peak cycle temperatures were reached for POME and its blends compared to PBDF. However NO\textsubscript{x} can be controlled by adopting proper injection timing, Exhaust Gas Recirculation (EGR) and by employing suitable catalytic converters.

In diesel engine smoke formation generally occurs in the rich zone at high temperature, particularly within the core region of fuel spray. Smoke is due to incomplete combustion. Smoke formation strongly depends on the air entrainment into the cylinder, the Oxygen amount in the fuel and the composition and structure of hydrocarbon in the fuel. Figure 7.14 shows the smoke intensity of PBDF, POME and its blends. For the biodiesel and its blends as shown in Figure 7.14, the smoke emissions were less than that for the PBDF. The use of POME10, POME20, POME30, POME40 and POME100 caused a reduction in smoke in the range of 8.96\%, 15.75\%, 19.88\%, 22.10\% and 14.36\% respectively with respect to PBDF at rated load.
Figure 7.13 Comparison of NO\textsubscript{x} emissions for POME and its blends

Figure 7.14 Comparison of smoke emissions for POME and its blends
A vast reduction in smoke intensity was observed with increase in percentage of POME in the blend. Smoke is mainly produced in the diffusive combustion phase; the oxygenated fuel blends lead to an improvement in diffusive combustion for the POME and its blend. The smoke reduction when using POME and its blends was mainly due to the Oxygen content in the fuel, that contributes to complete fuel oxidation even in locally rich zones. Other reasons for smoke reduction when using biodiesel may be attributed to the lower C/H ratio and absence of aromatic compounds as compared with PBDF.

7.5 SUMMARY

In this experimental phase POME and its blends were prepared. Experimental investigations were carried out on a single cylinder, DI diesel engine and the performance, combustion and emission characteristics of POME and its blends were evaluated and compared with that of PBDF. From this phase of investigation, the following conclusions were drawn.

1. The BSFC and BSEC were increased for POME and its blends due to the lower calorific value and poor mixture formation. The BTE decreased with increase in percentage of POME in the PBDF. Compared to PBDF, for POME10, POME20, POME30, POME40 and POME100, the BSFC was higher by about 7%, 11%, 15%, 19% and 26%, and the BTE was lower by about 5.26%, 9.58%, 11.74%, 14.3% and 19.9% respectively at full load operation.

2. Due to the higher Oxygen content in the POME and its blends, emissions of CO and UBHC decreased with increase in percentage of POME in the blend. It was also observed that there was a significant reduction in smoke intensity for POME and its blends compared to that of PBDF.
3. The higher Oxygen content in the POME and its blends resulted in better combustion and increased the combustion chamber temperature. This increased the NO_x emission of POME and its blends compared to PBDF. Compared to PBDF, for POME10, POME20, POME30, POME40 and POME100, the NO_x was higher by about 5.5%, 9.9%, 13.58%, 14.81% and 8.33% respectively.

4. The ignition delay of POME and its blends was found to be lesser as compared to that of PBDF.

5. The engine developed higher peak pressure and maximum heat release rate for PBDF, compared to POME and its blends. With increase in percentage of POME in the blend, the higher peak pressure and maximum heat release rate decreased.

The present analysis reveals that biodiesel from Pongamia oil is quite suitable as an alternative to PBDF. Keeping in mind the world's energy security as a result of dwindling fossil fuel reserves, considering biodiesel’s disadvantages like the higher viscosity and density, and lower calorific value and volatility and taking into account the results of the present investigation and past research findings, the blend POME20 was shortlisted for further studies to evaluate the effects of combustion chamber geometry and injection parameters to enhance the existing performance and emissions characteristics of a biodiesel fuelled DI diesel engine.