CHAPTER 5

5.1 INTRODUCTION

The produced mahua oil methyl ester (MOME) is blended with diesel fuel in various percentages (M10, M20, M100). The experiments were carried out to determine the performance, combustion, and emission characteristics of MOME-diesel fuel blends on CI engine. Tests are carried out at various loads (0%, 25%, 50%, and 75%) and speeds (2000 rpm, 3000 rpm, and 4000 rpm). The important parameters such as specific fuel consumption (SFC), brake thermal efficiency (BTE), carbon monoxide (CO) emission, carbon dioxide (CO₂) emission, un-burnt hydrocarbon (HC) emission, nitric oxide (NO) emission, smoke emission, exhaust gas temperature (EGT), in-cylinder pressure, net heat release rate (NHRR), and rate of in-cylinder pressure rise (RPR) are determined and compared these parameters with that of diesel fuel.

5.2 PERFORMANCE, COMBUSTION AND EMISSION CHARACTERISTICS OF MAHUA OIL METHYL ESTER - DIESEL FUEL BLENDS ON MULTI-CYLINDER CI ENGINE

5.2.1 Introduction to engine tests

The results pertaining to performance, combustion, and emission characteristics of mahua oil methyl ester-diesel fuel blends at various engine load and speed are discussed in this section.

5.2.2 Results and discussion pertaining to performance, combustion, and emission characteristics of MOME-diesel fuel blends on CI engine at 2000 rpm

The obtained test results of the performance, combustion, and emission, parameters with the use of M10, M20, MOME, and diesel as fuels at various engine loads are discussed in this section. The engine speed is maintained constant at 2000 rpm during the tests.

5.2.2.1 Specific fuel consumption

SFC trends for the blends M10, M20, MOME, and diesel fuel at a constant speed of 2000 rpm is presented in Fig.5.1. Figure shows the SFC only at 25%, 50%, and
75% of the rated load except no load condition to highlight the SFC values at higher engine load condition. The fuel consumption of CI engine mainly depends on some important fuel properties such as density, lower heating value, and viscosity [103]. It can be seen from the figure that, at all the load condition, the SFC of MOME is found to be higher when compared with that of diesel fuel. Further, the decrease in SFC is observed with decrease in the concentration of the MOME in the blend. This may be due to the increase in the heating value, and decrease in density and kinematic viscosity of the blend. By analyzing the obtained results, the minimum SFC is exhibited at 75% of the full load. At 75% of the full load condition, the SFC of diesel fuel, M10, M20, and MOME are found to be respectively, 0.282 kg/kW-h, 0.295 kg/kW-h, 0.281 kg/kW-h, and 0.360 kg/kW-h. Among these blends, the lowest SFC is found to 0.281 kg/kW-h for the blend M20.

![Graph showing variation of SFC with engine load for MOME and diesel blends at 2000 rpm.](image)

**Fig.5.1: Variation of SFC with engine load for MOME and diesel blends at 2000 rpm**

### 5.2.2.2 Brake thermal efficiency

Fig.5.2 presents the relationship between engine load and BTE at 2000 rpm. It can be seen from the figure that the BTE is increased with the engine load for all the fuels tested. This was due to reduction in heat loss and increase in power with increase in load. At the same time, the blend M20 exhibited the slightly higher BTE at all the
loads. However, MOME has a lesser BTE when compared with other fuels tested. This lower thermal efficiency obtained could be due to the reduction of calorific value and increase in fuel consumption as compared to M20. This blend of 20% also gave minimum specific energy consumption. By analyzing the obtained results, the maximum BTE is exhibited at 75% of the full load. The BTE at 75% of the rated load for MOME, M20, M10 and diesel fuel is found to be respectively, 25.8%, 30.62%, 28.95%, and 30.07%.

![Graph showing BTE vs load for MOME and diesel blends at 2000 rpm](image)

**Fig.5.2: Variation of BTE with engine load for MOME and diesel blends at 2000 rpm**

### 5.2.2.3 In-cylinder pressure-crank angle diagram

The in-cylinder pressure measurement is considered to be a very valuable source of information during the development and calibration stages of the engine. The in-cylinder pressure signal can provide vital information such as peak pressure, indicated mean effective pressure (IMEP), pressure-volume diagram, fuel supply effective pressure, combustion duration, ignition delay, heat release rate and so on [110].

In diesel engine, cylinder pressure depends on the burned 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 burn. High peak pressure and maximum rate of pressure rise correspond to larger amount of fuel burned in premixed combustion stage [102].
The cylinder pressure crank angle history is obtained at different loads for diesel, MOME and its blends are presented in Fig.5.3. From these figures it is clear that peak pressure increases as the load increases and for methyl ester (MOME), fuel combustion starts earlier in comparison to diesel fuel. At 25% of the rated load and constant engine speed of 2000 rpm, the maximum rate of pressure rise for MOME, M20, M10, and diesel fuel is found to respectively, 80.42 bar, 77.15 bar, 76.22 bar, and 75.09 bar. However, at 75% of the rated load, it is found to be 82.73 bar, 79.63 bar, 77.81 bar, and 76.99 bar, respectively. Further, the change in pressure is not significant.

The crank angle where the peak pressure occurs is shown in Fig.5.4. It shows that maximum pressure occurs within the range of 3-7 crank angle degrees after top dead center (TDC) for all the fuels at various loads tested. Pressure reaches its maximum somewhat earlier for pure MOME when compared to the other blends tested at all the loads. The higher in-cylinder pressure of CI engine running with biodiesel and its blends may be attributed to the advanced combustion process initiated by the physical properties such as higher cetane number, density, viscosity, and bulk modulus. The same phenomena were reported by Qi et al.[111] and Muralidharan et al.[112]. However, Jaichander et al.[113] reported that the peak pressure is slightly lower for B20 when compared to that of diesel and they explained this might be due to improper mixing of B20 with air due to higher viscosity and lower calorific value.

The cumulative effects of these properties result a short ignition delay and advanced injection timing for biodiesel. Furthermore, due to the presence of oxygen content in the biodiesel, the hydrocarbons achieve complete combustion resulting in a higher in-cylinder pressure [114]. Gumus [115] however reported that the engine running with diesel resulted in higher in-cylinder pressure that of biodiesel blends due to low volatility and high viscosity of the biodiesel which leads to poor atomisation during the ignition delay period. Qi et al. [111] have argued that the higher viscosity and lower volatility can be compensated by the complex and rapid pre-flame chemical reactions at higher temperatures which results in cracking and creation of lighter biodiesel compounds. These compounds can result in earlier ignition.

To obtain more in-depth information, it is necessary to study the rate of pressure rise with crank angle for the selected fuels at different loads.
Fig. 5.3: Variation of cylinder pressure with crank angle for MOME and diesel blends at 2000 rpm
5.2.2.4 Exhaust gas temperature

Fig. 5.5: Variation of EGT with load for MOME and diesel blends at 2000 rpm

Fig. 5.5 presents the EGT for the tested fuels. The EGT is increased with the engine load for all the fuels tested. Owing to the fact that as load the on the engine increases, more fuel is injected into the engine cylinder. Hence, the heat release rate and EGT
rise with the increase in engine load at constant engine speed. The EGT from the pure MOME is found to higher than that of diesel fuel within the entire range of loading. The shorter ignition delay, earlier SOI, inherent oxygen content, and the increased amount of methyl ester undergoing premixed combustion results in higher cylinder pressure and hence temperature [38,91,118,119]. It is observed that EGT increases with increase in the content of the MOME in the blend. The EGT at 75% of the rated engine load from MOME, M20, M10, and diesel fuel is found to be respectively, 357.6°C, 342.4°C, 334.52°C, and 333.57°C. Thus, the highest EGT is obtained from pure MOME.

5.2.2.5 Rate of pressure rise

Fig.5.6 presents the RPR at different load conditions. It can be seen from the figure that the rate of pressure rise increases as the load increases. At 25% of the rated load, the maximum RPR for MOME, M20, M10, and diesel fuel is found to respectively, 7.65 bar/deg, 7.51 bar/deg, 6.43 bar/deg, and 5.9 bar/deg. However, at 75% of the rated load, it is found to be 9.25 bar/deg, 7.68 bar/deg, 6.9 bar/deg, and 6.3 bar/deg, respectively. Thus, the maximum RPR is higher for methyl ester (MOME) relative to diesel fuel. This is due to higher rate of heat release during premixed combustion phase.

In diesel engine, cylinder pressure depends on the burned 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 burn. High peak pressure and maximum rate of pressure rise correspond to larger amount of fuel burned in premixed combustion stage [102].
Fig. 5.6: Variation of RPR with crank angle for MOME and diesel blends at 2000 rpm
5.2.2.6 Net heat release rate

NHRR one of the important parameters to characterise the combustion process in CI engine. Using NHRR diagram, it is possible to determine ignition delay time and peak heat release. Fig.5.7 depicts the NHRR for diesel fuel and different biodiesel blends at a speed of 2000 rpm and at 25%, 50%, and 75% of full load condition. It can be seen from the figure that all the tested blends experience rapid premixed burning followed by diffusion combustion. After the ignition delay period, the premixed fuel burns rapidly releasing heat at a very rapid rate, after which the re-association of the charge may cause the negative values of NHRR (and hence RPR) at certain crank angle and then they become positive due diffusion combustion, where the burning rate is controlled by the availability of the air-fuel mixture. By analyzing the figures, it can be observed that when engine is fueled with pure biodiesel, the combustion starts earlier under all operating conditions and also biodiesel shows shorter ignition delay compared to the other fuels tested. Further, the NHRR is increased with the engine load. The maximum NHRR is found for biodiesel compared to the pure diesel fuel and is decreases with the dilution of the biodiesel concentration in the blend. This phenomenon is attributed to the presence for additional oxygen molecules in biodiesel [120-122]. It can also be observed from the figure that the ignition of biodiesel starts earlier than the diesel fuel by 1, 2, 2 degrees for 25%, 50%, and 75% of the rated load conditions respectively. The advanced start of ignition occurred due to the physical properties of the biodiesel such as higher bulk modulus [92,123], higher viscosity [124,125], and higher cetane number [118,120]. It is well documented from previous reports that biodiesel cetane number is higher than that of diesel fuel which mainly causes for start of early ignition for engine running with biodiesel [126-129].

At 25% of the rated load and constant engine speed of 2000 rpm, the maximum NHRR for MOME, M20, M10, and diesel fuel is found to respectively, 88.81 kJ/m$^3$ deg, 81.71 kJ/m$^3$ deg, 78.73 kJ/m$^3$ deg, and 76.21 kJ/m$^3$ deg. However, at 75% of the rated load, it is found to be 103.17 kJ/m$^3$ deg, 93.05 kJ/m$^3$ deg, 92.19 kJ/m$^3$ deg, and 85.68 kJ/m$^3$ deg, respectively. Thus, the maximum NHRR is higher for methyl ester (MOME) relative to diesel fuel.
Fig. 5.7: Variation of NHRR with crank angle for MOME and diesel blends at 2000 rpm
5.2.2.7 Carbon monoxide emission

Fig. 5.8 shows the variation of CO emission of MOME and its blends at various load conditions. The speed of the engine is maintained constant at 2000 rpm. It can be seen from the figure that the CO emission is decreased with increase in the concentration of the MOME in the blend over the whole experimental range. This may be due to the inherent oxygen content in the methyl ester helps for the complete combustion. Thus, more oxygen percentage leads low CO [118,133]. Further, CO emission is found to be increasing with increasing in the load on the engine. This may be due to decrease in air-fuel ratio. At higher load condition, the CO emissions are found to be higher for all the fuels tested due to low oxidants concentration [134]. Generally, CO emission is affected by fuel type, atomization rate, combustion chamber design, engine load, air-fuel ratio, SOI timing and engine speed. The most important thing among these parameters is air-fuel ratio [79,135]. The CO emissions at 75% of the rated load from MOME, M20, M10, and diesel fuel is found to be respectively, 0.04%, 0.05%, 0.07%, and 0.09%. Thus, MOME produced lowest CO emissions over the whole experimental range compared to other three blends tested.

![Graph showing CO emission vs load for MOME and diesel blends at 2000 rpm](image)

Fig. 5.8: Variation of CO emission with load for MOME and diesel blends at 2000 rpm
5.2.2.8 Carbon dioxide emission

The CO$_2$ emission data for the test engine with the four different fuels is presented in Fig.5.9. It is obtained by complete combustion of fuel. The CO$_2$ emission is increased with the increase of load for all the blends tested. However, it increases with increase in the content of MOME in the blend. This may be due to increase in the percentage of inherent oxygen content in combustion region helps in more complete combustion. Therefore, more CO$_2$ emission is obtained when the engine is fueled with MOME. The CO$_2$ emission at 75% rated engine load from MOME, M20, M10, and diesel fuel is found to be respectively, 10.43%, 9.86%, 9.72%, and 9.52%.

![CO$_2$ emission variation with load for MOME and diesel blends at 2000 rpm](image)

Fig.5.9: Variation of CO$_2$ emission with load for MOME and diesel blends at 2000 rpm

5.2.2.9 Un-burned hydrocarbon emission

Fig.5.10 shows the variation of un-burned HC emissions versus load for MOME, M10, M20, and diesel fuel in the test engine. The un-burned HC emission is found to be decreased with increase in the concentration of MOME in the blend. This may be due to increasing oxygen concentration in the blend, which improves the combustion efficiency significantly. Thus, when the engine is fueled with MOME, the un-burned HC emission is decreased when compared with diesel fuel due increased oxygen content of the methyl ester. Further, methyl ester in the blend improves the cetane
value of the mixture; this situation decreases the ignition delay and promotes reaction timing of the blend and reduces the level of un-burned HC emissions. In addition, the earlier SOI timing represents more air-fuel reaction duration, while later SOI timing represents downward air-fuel reaction. The decrease in the ignition delay effects the premixed combustion phase and gives higher cylinder pressure for methyl ester [96]. It can be seen from the figure that, the un-burned HC emission of MOME at 75% load is 9 ppm whereas that of diesel fuel is 20 ppm. Again, from the blend M10 and M20 it is found to 16 ppm and 15 ppm respectively. Thus, MOME produced lowest un-burned HC emissions when compared to the other three blends tested.

![Graph showing HC emission variation with load for MOME and diesel blends at 2000 rpm](image)

**Fig.5.10: Variation of HC emission with load for MOME and diesel blends at 2000 rpm**

### 5.2.2.10 Nitric oxide emission

The rate of formation of NO emission in CI engines is primarily a function of flame temperature, which is closely related to the peak cylinder pressure and hence temperature. The higher in-cylinder pressure of CI engine running with biodiesel and its blends may be attributed to the advanced combustion process initiated by the physical properties such as higher cetane number, density, and viscosity. The above described trends can explain the higher NO formation associated with the combustion
of methyl ester [38,91,118,119]. The amount of oxygen and nitrogen existing in the combustion region is also important factor for the emissions for nitric oxide [136]. However, it well known that the external oxygen supplied within the air itself is less effective than the fuel borne oxygen in the production of NO emission [79].

The variation of nitric oxide (NO) emission from MOME and its blends with respect to diesel fuel is presented in Fig.5.11. The NO emissions increased with the increasing engine load. This was due to reduction in heat loss and increase in power with increase in load and hence the in-cylinder temperature. The most important factor for the emissions of NO is the combustion temperature in the engine cylinder. It can be seen from the figure that NO emissions from the pure MOME and its diesel blends is found to be high when compared to that of neat diesel fuel. Again, the NO emissions increased with increase in the concentration of MOME in the blend. Thus, more NO emission is obtained when the engine is fueled with MOME. The NO emission at 75% of the rated load from MOME, M20, M10, and diesel fuel is found to be respectively, 1694 ppm, 1485 ppm, 1466 ppm, and 1442 ppm.

![Fig.5.11: Variation of NO emission with load for MOME and diesel blends at 2000 rpm](image-url)
5.2.2.11 Smoke emission

Smoke opacity is a direct measure of smoke and soot. The fuel consumption influences the amount of soot produced in CI engine. Especially, the sulphur and oxygen contents of the fuel affect the soot formation and oxidation respectively [137]. Probably, for these reasons, smoke opacity is generally reduced by the addition of biodiesel to the diesel fuel, due to high oxygen and low sulfur content of biodiesel. Various studies shows that smoke opacity for biodiesel is generally lower [136,138, 139,140]. Another reason is the advance in the injection which allows more time for soot oxidation, so reducing smoke opacity when biodiesel was used [96].

Fig.5.12 shows the variations of smoke opacity of diesel fuel, MOME and its blends at various loads. It can be observed that the smoke density increases for all the fuels tested as load on the engine increases. However, the smoke opacity obtained from the experiment from the MOME and its blends is lower than diesel fuel. This may be due to inbuilt oxygen and higher cetane index of methyl ester which results in better combusting resulting in reduction in smoke opacity. The smoke opacity at 75% of the rated load from MOME, M20, M10, and diesel fuel is found to be respectively, 28%, 35.6%, 38%, and 56%.

![Variation of smoke opacity with load for MOME and diesel blends at 2000 rpm](image)

**Fig.5.12:** Variation of smoke opacity with load for MOME and diesel blends at 2000 rpm
5.2.3 Results and discussion pertaining to performance, combustion, and emission characteristics of MOME-diesel fuel blends on CI engine at 3000 rpm

The obtained test results of the performance, combustion, and emission parameters with the use of M10, M20, MOME, and diesel as fuels at various engine loads are discussed in this section. The engine speed is maintained constant at 3000 rpm during the tests.

5.2.3.1 Specific fuel consumption

Fig.5.13 shows SFC trends for the blends M10, M20, MOME, and diesel fuel. The fuel consumption of CI engine mainly depends on some important fuel properties such as density, lower heating value, and viscosity [103]. It can be seen from the figure that, at all the load condition, the SFC of MOME is found to be higher when compared with that of diesel fuel. Further, the decrease in SFC is observed with decrease in the concentration of the MOME in the blend. This may be due to the increase in the heating value, and decrease in density and kinematic viscosity of the blend.

![Graph showing SFC trends for MOME and diesel blends at 3000 rpm](image)

Fig.5.13: Variation of SFC with engine load for MOME and diesel blends at 3000 rpm
By analyzing the obtained results, the minimum SFC is exhibited at 75% of the full load for all the tested fuels. At 75% of the full load, the SFC of diesel fuel, M10, M20, and MOME are found to be respectively, 0.272 kg/kW-h, 0.287 kg/kW-h, 0.269 kg/kW-h, and 0.353 kg/kW-h. The lowest BSFC is found to 0.269 kg/kW-h for the blend M20.

5.2.3.2 Brake thermal efficiency

The relationship between engine load and BTE at 3000 rpm is shown in Fig. 5.14. It can be seen from the figure that the BTE is increased with the engine load for all the fuels tested. This was due to reduction in heat loss and increase in power with increase in load. At the same time, the blend M20 exhibited the slightly higher BTE at an engine load of 50% and 75% of the rated load. However, MOME has a lesser BTE when compared with other fuels tested. This lower thermal efficiency obtained could be due to the reduction of calorific value and increase in fuel consumption as compared to M20. This blend of 20% also gave minimum specific energy consumption. By analyzing the obtained results, the maximum BTE is exhibited at 75% of the full load. The BTE at 75% of the rated engine load for MOME, M20, M10, and diesel fuel is found to be respectively, 26.16%, 32.02%, 29.79%, and 31.13%.

Fig. 5.14: Variation of BTE with engine load for MOME and diesel blends at 3000 rpm
5.2.3.3 In-cylinder pressure-crank angle diagram

Fig. 5.15: Variation of cylinder pressure with crank angle for MOME and diesel blends at 3000 rpm
In diesel engine, cylinder pressure depends on the burned 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 burn. High peak pressure and maximum rate of pressure rise correspond to larger amount of fuel burned in premixed combustion stage [102].

The cylinder pressure crank angle history is obtained at different loads for diesel, MOME and its blends are presented in Fig.5.15. From the figure it is clear that peak pressure increases as the load increases and for methyl ester (MOME), fuel combustion starts earlier in comparison to diesel fuel. At 25% of the rated load and constant engine speed of 3000 rpm, the peak in-cylinder pressure for MOME, M20, M10, and diesel fuel is found to respectively, 90.34 bar, 87.49 bar, 86.64 bar, and 85.81 bar. However, at 75% of the rated load, it is found to be 93.43 bar, 89.4 bar, 88.52 bar, and 87.49 bar, respectively.

![Fig.5.16: Crank angle for peak cylinder pressure for MOME and diesel blends at 3000 rpm](image)

The crank angle where the peak pressure occurs is shown in Fig.5.16. It shows that maximum pressure occurs within the range of 3-9 crank angle degrees after top dead center (TDC) for all the fuels at various loads tested. Pressure reaches its maximum somewhat earlier for pure MOME when compared to the other blends tested at all the
loads. The higher in-cylinder pressure of CI engine running with biodiesel and its blends may be attributed to the advanced combustion process initiated by the physical properties such as higher cetane number, density, viscosity, and bulk modulus. The same phenomena were reported by Qi et al.[111] and Muralidharan et al.[112]. However, Jaichander et al.[113] reported that the peak pressure is slightly lower for B20 when compared to that of diesel and they explained this might be due to improper mixing of B20 with air due to higher viscosity and lower calorific value.

The cumulative effects of these properties result a short ignition delay and advanced injection timing for biodiesel. Furthermore, due to the presence of oxygen content in the biodiesel, the hydrocarbons achieve complete combustion resulting in a higher in-cylinder pressure [114]. Gumus [115] however reported that the engine running with diesel resulted in higher in-cylinder pressure that of biodiesel blends due to low volatility and high viscosity of the biodiesel which leads to poor atomisation during the ignition delay period. Qi et al. [111] have argued that the higher viscosity and lower volatility can be compensated by the complex and rapid pre-flame chemical reactions at higher temperatures which results in cracking and creation of lighter biodiesel compounds. These compounds can result in earlier ignition.

To obtain more in-depth information, it is necessary to study the rate of pressure rise with crank angle for the selected fuels at different loads.

5.2.3.4 Exhaust gas temperature

Fig.5.17 presents the EGT for the tested fuels. The EGT is increased with the engine load for all the fuels tested. The EGT increases as the load on the engine increases for all the fuels tested. Owing to the fact that as load the on the engine increases, more fuel is injected into the engine cylinder. Hence, the heat release rate and EGT rise with the increase in engine load at constant engine speed. It is observed that EGT increases with increase in the content of the MOME in the blend. The EGT from the pure MOME is found to higher than that of diesel fuel within the entire range of loading. The shorter ignition delay, earlier SOI, inherent oxygen content, and the increased amount of methyl ester undergoing premixed combustion results in higher cylinder pressure and hence temperature [38,91,118,119]. It is observed that EGT increases with increase in the content of the MOME in the blend. The EGT at
75% of the rated engine load from pure MOME, M20, M10, and diesel fuel is found to be respectively, 443.21°C, 422.62°C, 416.35°C, and 388.05°C.

5.2.3.5 Rate of pressure rise

Fig.5.18 shows the RPR at different load conditions. It can be seen from the figure that the rate of pressure rise increases as the load increases. At 25% of the rated load, the maximum RPR for MOME, M20, M10, and diesel fuel is found to respectively, 8.23 bar/deg, 8.04 bar/deg, 7.68 bar/deg, and 7.68 bar/deg. However, at 75% of the rated load, it is found to be 9.99 bar/deg, 8.42 bar/deg, 8.21 bar/deg, and 7.79 bar/deg, respectively. Thus, the maximum RPR is higher for methyl ester (MOME) relative to diesel fuel. This is due to higher rate of heat release during premixed combustion phase.

In diesel engine, cylinder pressure depends on the burned 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 burn. High peak pressure and maximum rate of pressure rise correspond to larger amount of fuel burned in premixed combustion stage [102].
Fig. 5.18: Variation of RPR with crank angle for MOME and diesel blends at 3000 rpm.
5.2.3.6 Net heat release rate

Fig.5.19 depicts the NHRR for diesel fuel and different biodiesel blends at 25%, 50%, and 75% of full load condition. It can be seen from the figure that all the tested blends experience rapid premixed burning followed by diffusion combustion. After the ignition delay period, the premixed fuel burns rapidly releasing heat at a very rapid rate, after which the re-association of the charge may cause the negative values of NHRR (and hence RPR) at certain crank angle and then they become positive due diffusion combustion, where the burning rate is controlled by the availability of the air-fuel mixture. However, the combustion starts earlier for neat methyl ester under all operating conditions and also methyl ester shows shorter ignition delay compared to the other blends tested. Further, the NHRR is increased with the engine load. The maximum NHRR is found to for biodiesel compared to the pure diesel fuel and is decreases with the dilution of the biodiesel concentration in the blend. This phenomenon is attributed to the presence for additional oxygen molecules in biodiesel [120-122]. It can be seen from the figure that the ignition of biodiesel starts earlier that the diesel fuel by 1, 2, 2 degrees for 25%, 50%, and 75% of the rated load conditions respectively. The advanced start of ignition occurred due to the physical properties of the biodiesel such as higher bulk modulus [92,123], higher viscosity [124,125], and higher cetane number [118,120]. It is well documented from previous reports that biodiesel cetane number is higher than that of diesel fuel which mainly causes for start of early ignition for engine running with biodiesel [126-129].

At 25% of the rated load and constant engine speed of 3000 rpm, the maximum NHRR for MOME, M20, M10, and diesel fuel is found to respectively, 120.02 kJ/m$^3$ deg, 108.88 kJ/m$^3$ deg, 108.15 kJ/m$^3$ deg, and 103.9 kJ/m$^3$ deg. However, at 75% of the rated load, it is found to be 136.37 kJ/m$^3$ deg, 118.7 kJ/m$^3$ deg, 114.54 kJ/m$^3$ deg, and 111.13 kJ/m$^3$ deg, respectively. Thus, the maximum NHRR is higher for methyl ester (MOME) relative to diesel fuel.
Fig. 5.19: Variation of NHRR with crank angle for MOME and diesel blends at 3000 rpm
5.2.3.7 Carbon monoxide emission

The variation of carbon monoxide emission of MOME and its blends at various load conditions is shown in Fig.5.20. It can be seen from the figure that the CO emission is decreased with increase in the concentration of the MOME in the blend over the whole experimental range. This may be due to the inherent oxygen content in the methyl ester helps for the complete combustion. Thus, more oxygen percentage leads low CO [118,133]. Further, CO emission is found to be increasing with increasing in the load on the engine. This may be due to decrease in air-fuel ratio. At higher load condition, the CO emissions are found to be higher for all the fuels tested due to low oxidants concentration [134]. Generally, CO emission is affected by fuel type, atomization rate, combustion chamber design, engine load, air-fuel ratio, SOI timing and engine speed. The most important thing among these parameters is air-fuel ratio [79.135]. The CO emission at 75% of the rated engine load from MOME, M20, M10, and diesel fuel is found to be respectively, 0.03%, 0.04%, 0.05%, and 0.07%. Thus, MOME produced lowest CO emissions over the whole experimental range compared to other three blends tested.

![Figure 5.20: Variation of CO emission with load for MOME and diesel blends at 3000 rpm](image-url)
5.2.3.8 Carbon dioxide emission

Fig. 5.21 shows the CO\textsubscript{2} emission data for the test engine with the four different fuels. It is obtained by complete combustion of fuel. The CO\textsubscript{2} emission is increased with the increase of load for all the fuels tested. However, it increases with increase in the content of MOME in the blend. This may be due to increase in the percentage of inherent oxygen content in combustion region helps in more complete combustion. Therefore, more CO\textsubscript{2} emission is obtained when the engine is fueled with MOME. The CO\textsubscript{2} emission at 75\% of the rated load from pure MOME, M20, M10, and diesel fuel is found to be respectively, 10.6\%, 9.93\%, 9.8\%, and 9.7\%.

![Variation of CO\textsubscript{2} emission with load for MOME and diesel blends at 3000 rpm](image)

**Fig. 5.21: Variation of CO\textsubscript{2} emission with load for MOME and diesel blends at 3000 rpm**

5.2.3.9 Un-burned hydrocarbon emission

Fig. 5.22 shows the variation of un-burned HC emissions versus load for MOME, M10, M20, and diesel fuel in the test engine. The un-burned HC emission is found to be decreased with increase in the concentration of MOME in the blend. This may be due to increasing oxygen concentration in the blend, which improves the combustion efficiency significantly. Thus, when the engine is fueled with MOME, the un-burned HC emission is decreased when compared with diesel fuel due increased oxygen
content of the methyl ester. Further, methyl ester in the blend improves the cetane value of the mixture; this situation decreases the ignition delay and promotes reaction timing of the blend and reduces the level of un-burned HC emissions. In addition, the earlier SOI timing represents more air-fuel reaction duration, while later SOI timing represents downward air-fuel reaction. The decrease in the ignition delay effects the premixed combustion phase and gives higher cylinder pressure for methyl ester [96]. It can be seen from the figure that, the un-burned HC emission of MOME at 75% load is 8 ppm whereas that of diesel fuel is 18 ppm. Again, from the blend M10 and M20 it is found to 15 ppm and 14 ppm respectively. Thus, MOME produced lowest un-burned HC emissions when compared to the other three blends tested.

![Graph of HC emission with load for MOME and diesel blends at 3000 rpm](image)

Fig.5.22: Variation of HC emission with load for MOME and diesel blends at 3000 rpm

### 5.2.3.10 Nitric oxide emission

The rate of formation of NO emission in CI engines is primarily a function of flame temperature, which is closely related to the peak cylinder pressure and hence temperature. The higher in-cylinder pressure of CI engine running with biodiesel and its blends may be attributed to the advanced combustion process initiated by the physical properties such as higher cetane number, density, and viscosity. The above
described trends can explain the higher NO formation associated with the combustion of methyl ester [38,91,118,119]. The amount of oxygen and nitrogen existing in the combustion region is also important factor for the emissions for nitric oxide [136]. However, it well known that the external oxygen supplied within the air itself is less effective than the fuel borne oxygen in the production of NO emission [79].

The variation of nitric oxide (NO) emission from MOME and its blends with respect to diesel fuel is presented in Fig.5.23. The NO emissions increased with the increasing engine load. This was due to reduction in heat loss and increase in power with increase in load and hence the in-cylinder temperature. The most important factor for the emissions of NO is the combustion temperature in the engine cylinder. It can be seen from the figure that NO emissions from the pure MOME and its diesel blends is found to be high when compared to that of neat diesel fuel. Again, the NO emissions increased with increase in the concentration of MOME in the blend. Thus, more NO emission is obtained when the engine is fueled with MOME. The NO emission at 75% of the rated load from MOME, M20, M10, and diesel fuel is found to be respectively, 2485 ppm, 2127 ppm, 2107 ppm, and 2065 ppm.

![Fig.5.23: Variation of NO emission with load for MOME and diesel blends at 3000 rpm](image-url)
5.2.3.11 Smoke emission

Smoke opacity is a direct measure of smoke and soot. The fuel consumption influences the amount of soot produced in CI engine. Especially, the sulphur and oxygen contents of the fuel affect the soot formation and oxidation respectively [137]. Probably, for these reasons, smoke opacity is generally reduced by the addition of biodiesel to the diesel fuel, due to high oxygen and low sulfur content of biodiesel. Various studies shows that smoke opacity for biodiesel is generally lower [136,138, 139,140]. Another reason is the advance in the injection which allows more time for soot oxidation, so reducing smoke opacity when biodiesel was used [96].

Fig.5.24 shows the variations of smoke opacity of diesel fuel, MOME and its blends at various loads. It can be observed that the smoke density increases for all the fuels tested as load on the engine increases. However, the smoke opacity obtained from the experiment from the MOME and its blends is lower than diesel fuel. The smoke opacity at 75% of the rated load from MOME, M20, M10, and diesel fuel is found to be respectively, 32%, 38.5%, 39.3%, and 57%.

![Variation of smoke opacity with load for MOME and diesel blends at 3000 rpm](image-url)
5.2.4 Results and discussion pertaining to performance, combustion, and emission characteristics of MOME-diesel fuel blends on CI engine at 4000 rpm

The obtained test results of the performance, combustion, and emission parameters with the use of M10, M20, MOME, and diesel as fuels at various engine loads are discussed in this section. The engine speed is maintained constant at 4000 rpm during the tests.

5.2.4.1 Specific fuel consumption

Fig.5.25 shows SFC trends for the blends M10, M20, MOME, and diesel fuel. The fuel consumption of CI engine mainly depends on some important fuel properties such as density, lower heating value, and viscosity [103].

![Fig.5.25: Variation of SFC with engine load for MOME and diesel blends at 4000 rpm](image)

It can be seen from the figure that, at all the load condition, the SFC of MOME is found to be higher when compared with that of diesel fuel. Further, the decrease in SFC is observed with decrease in the concentration of the MOME in the blend. This may be due to the increase in the heating value, and decrease in density and kinematic viscosity of the blend. By analyzing the obtained results, the minimum SFC is exhibited at 75% of the full load for all the tested fuels. At 75% of the full load, the SFC of diesel fuel, M10, M20, and MOME are found to be respectively,
0.294 kg/kW-h, 0.300 kg/kW-h, 0.293 kg/kW-h, and 0.373 kg/kW-h. The lowest SFC is found to 0.293 kg/kW-h for the blend M20.

5.2.4.2 Brake thermal efficiency

The relationship between engine load and BTE is shown in Fig.5.26. It can be seen from the figure that the BTE is increased with the engine load for all the fuels tested. This was due to reduction in heat loss and increase in power with increase in load. At the same time, the blend M20 exhibited the slightly higher BTE at all the loads. However, MOME has a lesser BTE when compared with other fuels tested. This lower thermal efficiency obtained could be due to the reduction of calorific value and increase in fuel consumption as compared to M20. This blend of 20% also gave minimum specific energy consumption. By analyzing the obtained results, the maximum BTE is exhibited at 75% of the full load. The BTE at 75% of the rated load for pure MOME, M20, M10, and diesel fuel is found to be respectively, 24.74%, 29.42%, 28.48%, and 28.85%.

![Graph showing variation of BTE with engine load for MOME and diesel blends at 4000 rpm](image-url)

**Fig.5.26**: Variation of BTE with engine load for MOME and diesel blends at 4000 rpm
5.2.4.3 In-cylinder pressure-crank angle diagram

Fig. 5.27: Variation of cylinder pressure with crank angle for MOME and diesel blends at 4000 rpm
In diesel engine, cylinder pressure depends on the burned 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 burn. High peak pressure and maximum rate of pressure rise correspond to larger amount of fuel burned in premixed combustion stage [102].

The cylinder pressure crank angle history is obtained at different loads for diesel, MOME and its blends are presented in Fig.5.27. From the figure it is clear that peak pressure increases as the load increases and for methyl ester (MOME), fuel combustion starts earlier in comparison to diesel fuel. At 25% of the rated load, the peak in-cylinder pressure for MOME, M20, M10, and diesel fuel is found to respectively, 85.65 bar, 79.3 bar, 79.17 bar, and 75.55 bar. However, at 75% of the rated load, it is found to be 89.24 bar, 82.33 bar, 80.01 bar, and 79.17 bar, respectively.

The crank angle where the peak pressure occurs is shown in Fig.5.28. It shows that maximum pressure occurs within the range of 2-11 crank angle degrees after top dead center (TDC) for all the fuels at various loads tested. Pressure reaches its maximum somewhat earlier for pure MOME when compared to the other blends tested at all the loads. The higher in-cylinder pressure of CI engine running with biodiesel and its blends may be attributed to the advanced combustion process initiated by the physical properties such as higher cetane number, density, viscosity, and bulk modulus. The same phenomena were reported by Qi et al.[111] and Muralidharan et al.[112]. However, Jaichander et al.[113] reported that the peak pressure is slightly lower for B20 when compared to that of diesel and they explained this might be due to improper mixing of B20 with air due to higher viscosity and lower calorific value.

The cumulative effects of these properties result a short ignition delay and advanced injection timing for biodiesel. Furthermore, due to the presence of oxygen content in the biodiesel, the hydrocarbons achieve complete combustion resulting in a higher in-cylinder pressure [114]. Gumus [115] however reported that the engine running with diesel resulted in higher in-cylinder pressure that of biodiesel blends due to low volatility and high viscosity of the biodiesel which leads to poor atomisation during the ignition delay period. Qi et al. [111] have argued that the higher viscosity and lower volatility can be compensated by the complex and rapid pre-flame chemical
reactions at higher temperatures which results in cracking and creation of lighter biodiesel compounds. These compounds can result in earlier ignition. To obtain more in-depth information, it is necessary to study the rate of pressure rise with crank angle for the selected fuels at different loads.

![Crank angle for peak cylinder pressure for MOME and diesel blends at 4000 rpm](image)

**Fig.5.28: Crank angle for peak cylinder pressure for MOME and diesel blends at 4000 rpm**

### 5.2.4.4 Exhaust gas temperature

Fig.5.29 presents the EGT for the tested fuels. The EGT increases as the load on the engine increases for all the fuels tested. Owing to the fact that as load the on the engine increases, more fuel is injected into the engine cylinder. Hence, the heat release rate and EGT rise with the increase in engine load at constant engine speed. It is observed that EGT increases with increase in the content of the MOME in the blend. The EGT from the pure MOME is found to higher than that of diesel fuel within the entire range of loading. The shorter ignition delay, earlier SOI, inherent oxygen content, and the increased amount of methyl ester undergoing premixed combustion results in higher cylinder pressure and hence temperature [38,91,118,119]. The EGT at 75% rated engine load from pure MOME, M20, M10, and diesel fuel is found to respectively, 425.67°C, 389.05°C, 376.85°C, and 372.1°C.
Fig. 5.29: Variation of EGT with load for MOME and diesel blends at 4000 rpm

5.2.4.5 Rate of pressure rise

Fig. 5.30 shows the RPR at different load conditions. It can be seen from the figure that the RPR increases as the load increases. At 25% of the rated load, the maximum RPR for MOME, M20, M10, and diesel fuel is found to respectively, 5.31 bar/deg, 4.01 bar/deg, 3.9 bar/deg, and 3.81 bar/deg. However, at 75% of the rated load, it is found to be 6.54 bar/deg, 4.57 bar/deg, 4.48 bar/deg, and 3.9 bar/deg, respectively. Thus, the maximum RPR is higher for methyl ester (MOME) relative to diesel fuel. This is due to higher rate of heat release during premixed combustion phase.

In diesel engine, cylinder pressure depends on the burned 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 burn. High peak pressure and maximum rate of pressure rise correspond to larger amount of fuel burned in premixed combustion stage [102].
Fig. 5.30: Variation of RPR with crank angle for MOME and diesel blends at 4000 rpm
5.2.4.6 Net heat release rate

Fig. 5.31 depicts the NHRR for diesel fuel and different biodiesel blends at 25%, 50%, and 75% of full load condition. It can be seen from the figure that all the tested blends experience rapid premixed burning followed by diffusion combustion. After the ignition delay period, the premixed fuel burns rapidly releasing heat at a very rapid rate, after which the re-association of the charge may cause the negative values of NHRR (and hence RPR) at certain crank angle and then they become positive due diffusion combustion, where the burning rate is controlled by the availability of the air-fuel mixture. However, the combustion starts earlier for neat methyl ester under all operating conditions and also methyl ester shows shorter ignition delay compared to the other blends tested. Further, the NHRR is increased with the engine load. The maximum NHRR is found for biodiesel compared to the pure diesel fuel and is decreases with the dilution of the biodiesel concentration in the blend. This phenomenon is attributed to the presence for additional oxygen molecules in biodiesel [120-122]. It can be seen from the figure that the ignition of biodiesel starts earlier that the diesel fuel by 3, 5, 3 degrees for 25%, 50%, and 75% of the rated load conditions respectively. The advanced start of ignition occurred due to the physical properties of the biodiesel such as higher bulk modulus [92,123], higher viscosity [124,125], and higher cetane number [118,120]. It is well documented from previous reports that biodiesel cetane number is higher than that of diesel fuel which mainly causes for start of early ignition for engine running with biodiesel [126-129].

At 25% of the rated load, the maximum NHRR for MOME, M20, M10, and diesel fuel is found to respectively, 105.83 kJ/m$^3$ deg, 95.39 kJ/m$^3$ deg, 93.92 kJ/m$^3$ deg, and 85.13 kJ/m$^3$ deg. However, at 75% of the rated load, it is found to be 113.92 kJ/m$^3$ deg, 105.87 kJ/m$^3$ deg, 103.9 kJ/m$^3$ deg, and 96.17 kJ/m$^3$ deg, respectively. Thus, the maximum NHRR is higher for methyl ester (MOME) relative to diesel fuel.
Fig. 5.31: Variation NHRR with crank angle for MOME and diesel blends at 4000 rpm
5.2.4.7 Carbon monoxide emission

The variation of carbon monoxide emission of MOME and its blends at various load conditions is shown in Fig.5.32. It can be seen from the figure that the CO emission is decreased with increase in the concentration of the MOME in the blend over the whole experimental range. This may be due to the inherent oxygen content in the methyl ester helps for the complete combustion. Thus, more oxygen percentage leads low CO [118,133]. Further, CO emission is found to be increasing with increasing in the load on the engine. This may be due to decrease in air-fuel ratio. At higher load condition, the CO emissions are found to be higher for all the fuels tested due to low oxidants concentration [134]. Generally, CO emission is affected by fuel type, atomization rate, combustion chamber design, engine load, air-fuel ratio, SOI timing and engine speed. The most important thing among these parameters is air-fuel ratio [79.135]. The CO emission at 75% of the rated engine load from MOME, M20, M10, and diesel fuel is found to be respectively, 0.06%, 0.08%, 0.09%, and 0.12%. Thus, MOME produced lowest CO emissions over the whole experimental range compared to other three blends tested.

![Graph showing variation of CO emission with load for MOME and diesel blends at 4000 rpm](https://example.com/graph.png)

**Fig.5.32:** Variation of CO emission with load for MOME and diesel blends at 4000 rpm
5.2.4.8 Carbon dioxide emission

The CO$_2$ emission data for the test engine with the four different fuels is presented in Fig.5.33. It is obtained by complete combustion of fuel. The CO$_2$ emission is increased with the increase of load for all the fuels tested. However, it increases with increase in the content of MOME in the blend. This may be due to increase in the percentage of inherent oxygen content in combustion region helps in more complete combustion. Therefore, more CO$_2$ emission is obtained when the engine is fueled with MOME. The CO$_2$ emission at 75% of the rated engine load from pure MOME, M20, M10, and diesel fuel is found to be respectively, 9.87%, 9.51%, 9.35%, and 9.08%.

![Graph of CO$_2$ emission with load for MOME and diesel blends at 4000 rpm](image)

Fig.5.33: Variation of CO$_2$ emission with load for MOME and diesel blends at 4000 rpm

5.2.4.9 Un-burned hydrocarbon emission

Fig.5.34 shows the variation of un-burned HC emissions versus load for MOME, M10, M20, and diesel fuel in the test engine. The un-burned HC emission is found to be decreased with increase in the concentration of MOME in the blend. This may be due to increasing oxygen concentration in the blend, which improves the combustion efficiency significantly. Thus, when the engine is fueled with MOME, the un-burned
HC emission is decreased when compared with diesel fuel due increased oxygen content of the methyl ester. Further, methyl ester in the blend improves the cetane value of the mixture; this situation decreases the ignition delay and promotes reaction timing of the blend and reduces the level of un-burned HC emissions. In addition, the earlier SOI timing represents more air-fuel reaction duration, while later SOI timing represents downward air-fuel reaction. The decrease in the ignition delay effects the premixed combustion phase and gives higher cylinder pressure for methyl ester [96]. It can be seen from the figure that, the un-burned HC emission of MOME at 75% load is 14 ppm whereas that of diesel fuel is 29 ppm. Again, from the blend M10 and M20 it is found to 24 ppm and 21 ppm respectively. Thus, MOME produced lowest un-burned HC emissions when compared to the other three blends tested.

![Graph showing variation of HC emission with load for MOME and diesel blends at 4000 rpm](image)

**Fig.5.34: Variation of HC emission with load for MOME and diesel blends at 4000 rpm**

### 5.2.4.10 Nitric oxide emission

The rate of formation of NO emission in CI engines is primarily a function of flame temperature, which is closely related to the peak cylinder pressure and hence temperature. The higher in-cylinder pressure of CI engine running with biodiesel and its blends may be attributed to the advanced combustion process initiated by the
physical properties such as higher cetane number, density, and viscosity. The above described trends can explain the higher NO formation associated with the combustion of methyl ester [38,91,118,119]. The amount of oxygen and nitrogen existing in the combustion region is also important factor for the emissions for nitric oxide [136]. However, it well known that the external oxygen supplied within the air itself is less effective than the fuel borne oxygen in the production of NO emission [79].

The variation of nitric oxide (NO) emission from MOME and its blends with respect to diesel fuel is presented in Fig.5.35. The NO emissions increased with the increasing engine load. This was due to reduction in heat loss and increase in power with increase in load and hence the in-cylinder temperature. The most important factor for the emissions of NO is the combustion temperature in the engine cylinder. It can be seen from the figure that NO emissions from the pure MOME and its diesel blends is found to be high when compared to that of neat diesel fuel. Again, the NO emissions increased with increase in the concentration of MOME in the blend. Thus, more NO emission is obtained when the engine is fueled with MOME. The NO emission at 75% of the rated engine load from pure MOME, M20, M10, and diesel fuel is found to be respectively, 2248 ppm, 1955 ppm, 1919 ppm, and 1885 ppm.

![Fig.5.35: Variation of NO emission with load for MOME and diesel blends at 4000 rpm](image-url)
5.2.4.11 Smoke emission

Smoke opacity is a direct measure of smoke and soot. The fuel consumption influences the amount of soot produced in CI engine. Especially, the sulphur and oxygen contents of the fuel affect the soot formation and oxidation respectively [137]. Probably, for these reasons, smoke opacity is generally reduced by the addition of biodiesel to the diesel fuel, due to high oxygen and low sulfur content of biodiesel. Various studies shows that smoke opacity for biodiesel is generally lower [136,138, 139,140]. Another reason is the advance in the injection which allows more time for soot oxidation, so reducing smoke opacity when biodiesel was used [96].

Fig.5.36 shows the variations of smoke opacity of diesel fuel, MOME and its blends at various loads. It can be observed that the smoke density increases for all the blends tested as load on the engine increases. The maximum smoke emission is obtained at 75% of the rated engine load. The smoke opacity at 75% of the rated load from MOME, M20, M10, and diesel fuel is found to be respectively, 38.4%, 44.5%, 46.3%, and 59%.

Fig.5.36: Variation of smoke opacity with load for MOME and diesel blends at 4000 rpm
5.2.5 Effect of engine speed on performance, combustion, and emission characteristics of MOME-diesel fuel blends on CI engine at 75% engine load

Higher break thermal efficiencies, lower specific fuel consumption, higher peak in-cylinder pressures, higher exhaust gas temperatures, higher rate of pressure rise, and higher net heat release rate are observed for all the tested blends at 75% of the rated engine load. Therefore, 75% of the rated engine load was found to be the optimum engine load giving maximum decrease in specific fuel consumption, highest thermal efficiency, and advantages in terms of fuel economy. Further, the blend M20 was found to be the optimum methyl ester blend giving maximum increase in thermal efficiency, lowest specific fuel consumption, and advantages in terms of reduced emissions. Therefore, the obtained results are analyzed with respect to engine speed to study the performance, combustion, and emission characteristics of the MOME-diesel fuel blends on CI engine by keeping the engine load constant as 75% of the rated load.

5.2.5.1 Results and discussions

Variation of performance, combustion, and emission characteristics of the MOME-diesel fuel blends with different engine speeds are presented in Figs.5.37 to 5.46. It can be seen from the figures that, the BTE, peak cylinder pressure, maximum NHRR, EGT, CO$_2$ emission, and NO emission are increased with the increase in the engine speed from 2000 rpm to 3000 rpm and then decreased by increasing the engine from 3000 rpm to 4000 rpm. However, the other parameters such as SFC, CO, HC are found to be decreased by increasing the engine speed from 2000 rpm to 3000 rpm and then increased by accelerating the engine speed up the level of 4000 rpm.

The emission of NO is determined by oxygen concentration, peak pressure, combustion temperature and reaction time [91]. The availability of oxygen in biodiesel can explain the increase in the NO emission, since additional oxygen for NO formation may be provided by the fuel oxygen [141].

At lower engine speed operating test condition, the droplet size of the injected fuel is slightly higher. Therefore, CO formation for the fuels increased at lower engine speed [96].
When the engine speed is increased from 2000 rpm to 3000 rpm, more fuel is burned in the premixed burning phase, and this causes higher value of peak pressure and NHRR.

When the test engine was accelerated, HC emission dropped. Especially at 3000 rpm, increased air turbulence and atomization rate which increase the cylinder gas temperature and hence the peak in-cylinder pressure. Therefore, SFC, CO and HC dropped for all the tested fuels. On the other hand, at lower engine speed of 2000 rpm, higher SFC, CO, and HC were observed for all the tested blends. This may be due to the reduced atomization rate.

On further increasing the engine speed beyond 3000 rpm, the EGT, peak in-cylinder pressure, NHRR, CO₂, NO, and BTE were found to be decreased. Very high fuel-air ratio at high speed test conditions where the additional fuel might have cooled the charge [90]. This results from the fact that when the engine speed is increases, the friction horse power increases according to the decrease in the mechanical efficiency in order to maintain a fixed torque output, leading to an increase in the fuel consumption rate. This significant of increase of consumption at high speeds results in a lesser evaporation rate which reduces the combustion flame temperature, which consequently leads to the reduction of NO emissions [104]. The insufficient time for chemical reaction and insufficient air due to the richer mixture formed at higher engine speed may leads to the increase in smoke density, and reduction of EGT, peak in-cylinder pressure, NHRR, CO₂, NO, and BTE.

Therefore, higher break thermal efficiencies, lower specific fuel consumption, higher peak in-cylinder pressures, higher exhaust gas temperatures, higher rate of pressure rise, and higher net heat release rate are observed for all the tested fuels at 75% of the rated engine load and 3000 rpm. Therefore, 75% of the rated engine load and 3000 rpm were found to be the optimum engine load, and speed giving maximum decrease in specific fuel consumption, highest thermal efficiency, and advantages in terms of fuel economy.
Fig. 5.37: Comparison of SFC with engine speed for MOME and its diesel blends at 75% of rated load

Fig. 5.38: Comparison of BTE with engine speed for MOME and its diesel blends at 75% of rated load
Fig. 5.39: Comparison of peak cylinder pressure with engine speed for MOME and its diesel blends at 75% of rated load.

Fig. 5.40: Comparison of EGT with engine speed for MOME and its diesel blends at 75% of rated load.
Fig. 5.41: Comparison of maximum NHRR with engine speed for MOME and its diesel blends at 75% of rated load

Fig. 5.42: Comparison of CO emission with engine speed for MOME and its diesel blends at 75% of rated load
Fig. 5.43: Comparison of CO₂ emission with engine speed for MOME and its diesel blends at 75% of rated load.

Fig. 5.44: Comparison of un-burned HC emission with engine speed for MOME and its diesel blends at 75% of rated load.
Fig. 5.45: Comparison of NO emission with engine speed for MOME and its diesel blends at 75% of rated load

Fig. 5.46: Comparison of smoke opacity with engine speed for MOME and its diesel blends at 75% of rated load
5.3 CONCLUSIONS

The following conclusions are drawn from the experimental study with the use of MOME and its diesel blends as alternate fuel.

Brake thermal efficiency for the blend M20 is found to be 32.02\% when compared to 31.13\% of that of neat diesel fuel at 75\% of the rated load when the engine is running at 3000 rpm.

The minimum SFC is found to be 0.269 kg/kW-h with M20 when compared to 0.272 kg/kW-h of diesel fuel at 75\% of the rated load when the engine is running at 3000 rpm.

The highest EGT is found to 443.21°C with neat MOME when compared to 338.05°C of diesel fuel at 75\% of the rated load when the engine is running at 3000 rpm.

The peak in-cylinder pressure is found to be 93.43 bar with neat MOME when compared to 87.49 bar of diesel fuel at 75\% of the rated load when the engine is running at 3000 rpm.

The maximum rate of pressure rise is found to be 9.99 bar/deg with neat MOME when compared to 7.79 bar/deg of diesel fuel at 75\% of the rated load when the engine is running at 3000 rpm.

The maximum NHHR is found to be 136.37 kJ/m³ deg with neat MOME when compared to 111.13 kJ/m³ deg of diesel fuel at 75\% of the rated load when the engine is running at 3000 rpm.

Smoke opacity, CO, and HC emissions are reduced considerably for MOME blended fuels compared to neat diesel fuel.

The diesel fuel exhibited maximum smoke emission of 59\% at 4000 rpm.

A slight increase in NO emission is observed with the use of neat MOME compared to neat diesel fuel and other blends tested. Neat MOME exhibited maximum NO emission of 2485 ppm emission at 3000 rpm.