CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter discusses the results obtained from the extensive experimental investigations on the single cylinder four stroke diesel engine. The experimental data generated are analyzed and presented as graphs and tables. An attempt has been made to interpret the graphs and the reasons for variation in trends for specific parameters was also discussed. Performance, combustion and exhaust emission characteristics of diesel engine operated using various proportions of fuel combinations such as diesel, ethanol and water with TMAB additive without coating and with coating conditions of engine components are evaluated and examined.

In the first stage of the research work, the base line data was generated by evaluating the performance, exhaust emission and combustion characteristics of diesel engine operated with 100% diesel fuel. In the second phase of the study, performance, emission behavior and combustion characteristics of engine under 2-phase operation under normal operating conditions without coating engine (WOC operation) was conducted with varying proportions of ethanol and diesel blends with 2% TMAB additives. The experiments were repeated for various loads such as 20, 40, 60, 80 and 100%. Similarly the same experiments were repeated when the engine piston head and cylinder walls were coated with ceramic coating (WC operation) following the same procedures and working conditions.

In the final phase of study, performance, emission behavior and combustion characteristics of engine under 3-phase operation without coating (WOC operation) were conducted using varying proportions of ethanol, water and
diesel blends with 2% TMAB additives. The experiments were again used for various load such as 20, 40, 60, 80 and 100%. Similarly the same experiments were repeated with coated engine (WC operation) following the same procedures and working conditions. The short forms used in the results and discussion are given below:

- **WOC**: Without Coating Operation
- **WC**: With Coating Operation
- **2P**: 2-Phase Operation
- **3P**: 3-Phase Operation
- **D100**: 100% Diesel Fuel
- **2PE10**: 88% Diesel + 10% Ethanol + 2% TMAB
- **2PE15**: 83% Diesel + 15% Ethanol + 2% TMAB
- **2PE20**: 78% Diesel + 20% Ethanol + 2% TMAB
- **2PE25**: 73% Diesel + 25% Ethanol + 2% TMAB

### 4.2 TAGUCHI METHOD OF OPTIMIZATION

Taguchi method of optimization was used to determine the optimum level of parameters simultaneously within few numbers of experiments. Taguchi Method generally uses an orthogonal array to study the entire parameter space with only a small number of experiments (George et al 2004). The total degrees of freedom has to be computed in order to select an appropriate orthogonal array for designing the experiments. The degrees of freedom determines the number of comparisons between design parameters (Yang and Tarng 1998). In the present study, two factors were considered and each factor was analyzed at five levels and thus each one has four degrees of freedom. The factors were load and fuel blend
ratio. For 2 phase operation, the blend ratio considered was D100, 2PE10, 2PE15, 2PE20, and 2PE25.

The L$_{25}$ orthogonal array with 2 columns and 25 rows were used to study the entire parameters levels and to design orthogonal experiment. The parameters such as load, blend ratio are arranged in column 1 and 2. The other columns are used to store the response values of factors like Brake Specific Fuel Consumption (BSFC), Brake Thermal Efficiency (BTE), Exhaust Gas Temperature (EGT), Smoke Density, NOx, Heat release rate, Cylinder Pressure and Max. Cylinder Pressure. Using this layout, twenty five experiments have been conducted and the value of all the response parameters were observed. These observed response parameters are then fed into the software for the post processing of optimization. The statistical software ‘Minitab Release 15’ was used for designing Taguchi method of optimization. The results of the software were obtained in the form of tables and response graphs. The values of the responses are presented in Appendix 7.

The optimum parameters were selected which is based on parameter called Signal to Noise ratio (S/N). Signal represents the desired value while Noise represents the undesired value in the response characteristics. There are three kinds of S/N ratios used to select output characteristics. They are the-higher the-better, the-lower-the better and the-nominal-the-better. For example, for choosing the better BTE, the-higher the-better kind of S/N ratio is used for optimization.

Analysis of Variance (ANOVA) was used to select the design parameter which significantly affects the output characteristics. The statistical value called F value determines the significant effect of a parameter on the output characteristic (Yang and Tarng, 1998).
As an outcome of Taguchi method of optimization, the optimum range of operational characteristics of the parameters were determined. In addition, actual experiments were conducted under various load conditions and the results are discussed in the following sections. The details of test run and the optimization results are shown in Appendix 8.
4.3 PERFORMANCE, EMISSIONS AND COMBUSTION STUDY OF A 2– PHASE DIESEL ENGINE USING DIESEL, ETHANOL AND TMAB BLENDS WITHOUT COATED ENGINE

4.3.1 Brake Specific Fuel Consumption (BSFC)

The Brake Specific Fuel Consumption (BSFC) can be calculated from the brake power output of the engine and the mass flow rate of the fuel. It is an important parameter to analyze the performance of the engine and fuel efficiency. The comparison of brake specific fuel consumption with varying brake power ranges from 20% to 100% of load (1 to 5.3 kW) is presented in Figure 4.1 at 1500 rev/min. The Brake Specific Fuel Consumption is observed to be least for the fuel blend of 2PE10 and maximum for the fuel blend 2PE25. Increase in BSFC at higher blends indicates that there is no cavitation due to ethanol additions.

![Graph showing Brake Power vs. Brake Specific Fuel Consumption at different fuel ratios of 2-phase WOC Diesel engine](image)

Figure 4.1 Brake Power vs. Brake Specific Fuel Consumption at different fuel ratios of 2-phase WOC Diesel engine
4.3.2 Brake thermal efficiency

Brake thermal efficiency is an important parameter that measures the net power developed by the engine, which is readily available for using the engine output shaft, as it provides. It is a very important parameter to measure engine performance. Figure 4.2 shows the variation of brake thermal efficiency with load for different proportions of fuel blends with normal engine operation without coating. The thermal efficiency increases with the increase in load. Thermal efficiency of 30% at maximum brake power for neat diesel fuel (D100) can be observed.

It can be observed that the engine fuelled with 2PE10, 2PE15, 2PE20 and 2PE25 for without coating (WOC) operation gives brake thermal efficiency of 29%, 28%, 26%, and 25% respectively at maximum brake power. The maximum brake thermal efficiency is obtained for fuel blend 2PE10. Improvement in combustion, especially diffusion combustion as the oxygen concentration increases by surfactant in the fuel may be the reason for the increase in efficiency. The brake thermal efficiency generally increases up to 10% ethanol addition but slightly decrease for further additions as the combustion temperature drops due to the increased amount of ethanol.

![Figure 4.2 Brake Power vs. Brake Thermal Efficiency at different fuel ratios of 2-phase WOC Diesel engine](image)

"Figure 4.2 Brake Power vs. Brake Thermal Efficiency at different fuel ratios of 2-phase WOC Diesel engine"
4.3.3 Exhaust Gas Temperature

Exhaust gas temperatures are found to be increasing with the increase in load because more fuel is burnt to meet the power requirement. Figure 4.3 depicts the variation of exhaust gas temperature with brake power at various load conditions. The highest exhaust gas temperature was observed for the fuel blend of 2PE25 (243 °C).

![Figure 4.3 Brake Power vs. Exhaust Gas Temperature at different fuel ratios of 2-phase WOC Diesel engine](image)

Figure 4.3 Brake Power vs. Exhaust Gas Temperature at different fuel ratios of 2-phase WOC Diesel engine
4.3.4 Smoke Density

Smoke consists of solid soot particles suspended in the exhaust gas (Avinash Kumar 2007). In the case of a diesel engine, the major concern is the emission of black smoke. The smoke emission of the different fuel blends at various brake power is portrayed in Figure 4.4. Smoke density increases with the increase in brake power. It is evident from the figure 4.4 that, D100 produces the maximum smoke when compared to other fuel proportions. Smoke density was found to be the lowest for 2PE25 fuel blend (49.8 HSU).

Addition of ethanol decreases the smoke density slightly at maximum load. Ethanol has less carbon than diesel fuel and also having oxygen content and thereby increasing the oxygen fuel ratio at rich fuel region. Therefore ethanol addition to diesel fuel is more effective for reduction of smoke density in diesel engine. But the presence of surfactant acted in the opposite way and hence the smoke is maintained.

![Figure 4.4 Brake Power Load vs. Smoke Density at different fuel ratios of 2-phase WOC Diesel engine](image-url)
4.3.5 Hydrocarbon Emission

The term hydrocarbon means the organic compounds in the gaseous state. The solid hydrocarbons form the particulate matter. Hydrocarbon is the most helpful measure of combustion inefficiency (CenkSayin et al 2008). Normally, Hydrocarbon emissions present in diesel exhaust as either decomposed fuel molecules or recombined intermediate compounds.

Generally, hydrocarbon emissions are formed mainly due to the stagnation of gaseous hydrocarbons in the low temperature boundary layer along the cylinder wall and in crevices. Hence hydrocarbons remain unburnt in these low temperature areas because the flame does not spread into these areas completely. Generally, CI engines produce lower HC emission as they are operated with overall lean fuel air equivalence ratios. However, at light loads due to the presence of large amounts of excess air and low exhaust temperature, lean fuel-air mixture regions may sometimes survive to escape into the exhaust. The emission levels of un-burnt hydrocarbon at various ratios of fuel mixture are shown in Figure 4.5. It is seen from graph that the hydrocarbon emission is found to be maximum for 2PE20.

![Figure 4.5 Load vs. HC Emission at different fuel ratios of 2-phase WOC Diesel engine](image)

Figure 4.5 Load vs. HC Emission at different fuel ratios of 2-phase WOC Diesel engine
4.3.6 NOx Emission

It is well known that the mechanism of NOx formation from atmospheric nitrogen is highly dependent upon peak cycle temperature and time, for which this temperature is being maintained in the combustion chamber, due to the high activation energy needed for the reactions involved. The variation of NOx emission for different brake power is indicated in Figure 4.6. It can be verified from the graph that 2PE15 blend produces highest NOx emission and D100 produces lower NOx emissions for all the values of brake power.

Nitrogen oxideoxidation reactions are predominately temperature phenomena, depending on the local counteraction of oxygen and the duration of combustion. It is found that initially all the emulsions showed lower NOx emission, however after the part load, the NOx emission has increased gradually. It can be seen that NOx emissions of all blends increase more rapidly than those of sole fuel as the ethanol proportion and load increase at medium and high loads. The maximum increase in NO emissions occur at 80~100% full load conditions because of long ignition delay and rich oxygen circumstance from ethanol in the mixture.

Figure 4.6 Load vs. NOX Emission at different fuel ratios of 2- phase WOC Diesel engine
4.3.7 Cylinder Pressure - Crank Angle Diagram

In a compression ignition engine the cylinder pressure mainly depends upon the fuel-burning rate during the premixed burning phase, which in turn leads to the overall combustion and heat release rate in the phases of combustion to follow. Figure 4.7 shows the variation of in-cylinder pressure with crank angle for different fuel blends at full load. It is observed that the peak pressure of 77 bars was obtained at 45 deg. for 2PE25 fuel blend.

It can be noted that the oxygenated fuel shows higher pressure with sharp regions of change in comparison with pure diesel operation. However, the duration of the higher pressure period is shorter than that of diesel engine. The oxygenated fuel engine are having longer delay period compared to sole fuel.

![Figure 4.7 Pressure vs. Crank Angle at different fuel ratios of 2-phase WOC Diesel engine at Full Load](image-url)
4.3.8 Cylinder Peak Pressure

Figure 4.8 determines the variation of maximum cylinder pressure with brake power at full load. It can be seen that the maximum cylinder pressure for all the fuel blends is high, compared to D100 due to longer ignition delay. The heat release rate of the fuel blends was also higher due to higher values of maximum cylinder pressure. The results from the graph clearly indicate that as the diesel concentration in the fuel mixture decreases the maximum cylinder increases. 2PE25 has the highest peak cylinder pressure compared to other fuel blends.

Figure 4.8 Maximum Pressure vs. Brake Power for different fuel ratios of 2-phase WOC Diesel engine at Full Load
4.3.9 Heat Release Rate

For the investigation of diesel engine combustion, calculation of heat release rate is a very useful technique. Figure 4.9 gives the heat release rate for different fuel blends with crank angle at peak load. D100 shows a lower heat release rate during the initial stage and longer combustion duration. It can be seen from the graph that the maximum value of heat release rate of 133 kJ/m³ deg was obtained for 2PE25 blend.

The reason could be that the rate of diffusion combustion of the oxygenated fuel increases with increase in the heat release rate, consequently oxygenated fuel has controlled rate of pre-mixed combustion. The rate of heat release rate of oxygenated fuel is slightly shifted to the top dead center due to increased pre-mixed combustion.

![Figure 4.9 Heat Release Rate vs. Crank Angle at different fuel ratios of 2-phase WOC Diesel engine at Full Load](image)
4.4 PERFORMANCE, EMISSIONS AND COMBUSTION STUDY OF A 2 – PHASE DIESEL ENGINE USING DIESEL, ETHANOL AND TMAB BLENDS WITH COATED ENGINE

The same set of experiments as discussed in the section 4.2 were repeated for the modified diesel engine in which the cylinder walls and piston head were coated with ceramic materials.

4.4.1 Brake thermal efficiency

The variation of brake thermal efficiency for different load conditions for different proportions of fuel blends is shown in Figure 4.10. The thermal efficiency increases with the increase in load. It can be observed that the thermal efficiency is 34% at maximum brake power for neat diesel fuel (D100).

It can be observed that the engine fuelled with 2PE10, 2PE20, 2PE25 and 2PE30 for with coating (WC) operation gives brake thermal efficiency of 29%, 28%, 26%, and 25% respectively at maximum brake power. The maximum brake thermal efficiency is obtained for fuel blend 2PE10 due to the superior combustion and better intermixing of the fuel.

![Figure 4.10 Load vs. Brake Thermal Efficiency at different fuel ratios of 2-phase WC Diesel engine](image)

Figure 4.10 Load vs. Brake Thermal Efficiency at different fuel ratios of 2-phase WC Diesel engine
4.4.2 Brake Specific Fuel Consumption (BSFC)

The comparison of Brake Specific fuel consumption with various load conditions is presented in Figure 4.11. The brake specific fuel consumption of all the blends was lower than the sole fuel. The specific fuel consumption is observed to be the least for the fuel blend of 2PE10 and maximum for the fuel blend 2PE25. It can be seen from the graph that brake specific fuel consumption decreases with increase in the ethanol percentage in the diesel fuel.

![Figure 4.11 Load vs. Brake Specific Fuel Consumption at different fuel ratios of 2-phase WC Diesel engine](image)

Figure 4.11 Load vs. Brake Specific Fuel Consumption at different fuel ratios of 2-phase WC Diesel engine
4.4.3 Smoke Density

The smoke emission of the different fuel blends at various brake power is described in Figure 4.12. Smoke density increases with the increase in brake power. It is evident from the figure 4.4 that, D100 produces the maximum smoke when compared to other fuel proportions. Smoke density was found to be the lowest for 2PE25 fuel blend (49.8 HSU).

![Figure 4.12 Load vs. Smoke Density at different fuel ratios of 2-phase WC Diesel engine](image-url)
4.4.4 Hydrocarbon Emission

The emission levels of un-burnt hydrocarbon at various ratios of fuel mixture are shown in Figure 4.13. It is seen from the graph that the hydrocarbon emission is the highest for neat fuel operation. On the other hand, the HC emission is less for 2PE25 blend operation.

Figure 4.13 Load vs. HC Emission at different fuel ratios of 2-phase WC Diesel engine
4.4.5 NOx Emission

It is well known that the mechanism of NO$_X$ formation from atmospheric nitrogen is dependent on the peak cycle temperature and time for which this temperature is being maintained in the combustion chamber. The variation of NO$_X$ emission for different values of brake power is accessible in Figure 4.14. It can be verified from the graph that 2PE20 produces highest NOx emission and D100 produces the lower NOx emissions for all the values of brake power.

![Figure 4.14 Load vs. NOx Emission at different fuel ratios of 2- phase WC Diesel engine](image)

Figure 4.14 Load vs. NOx Emission at different fuel ratios of 2- phase WC Diesel engine
4.4.6 Cylinder Pressure -Crank Angle Diagram

Figure 4.15 shows the variation of in-cylinder pressure with crank angle at different compression ratios at full load. It is observed that the peak pressure of 77 bars was obtained at 45 deg. for 2PE15 fuel blend for WOC engine.

Figure 4.15 Pressure vs. Crank Angle at different fuel ratios of 2-phase WC Diesel engine at Full Load
Figure 4.16 shows the maximum pressure developed in test engine for various fuel blends for different crank angle positions. The test engine was run under with coated condition at full Load.

Figure 4.16 Maximum Pressure vs. Crank Angle at different fuel ratios of 2-phase WC Diesel engine at Full Load

Figure 4.17 presents the plot of maximum pressure developed in the test engine for brake power conditions for various fuel blends. The test engine was run under with coated condition at full Load. 2PE10 blend generates maximum power while D100 (Neat Diesel) generates lower cylinder pressure at full load.

Figure 4.17 Maximum Cylinder Pressure vs. Brake Power for different fuel ratios of 2-phase WC Diesel engine at Full Load
4.4.7 Heat Release Rate

For the investigation of diesel engine combustion, calculation of heat release rate is a very useful technique. Figure 4.18 gives the heat release rate at different compression ratios with crank angle at peak load. It is seen from graph that the maximum heat release obtained is 28.70 J/deg. CA at 17 compression ratio on diesel fuel at the engine speed of 1500 rev/min due to longer ignition delay period.

![Heat Release Rate vs. Crank Angle at different fuel ratios of 2-phase WC Diesel engine at Full Load](image)

**Figure 4.18 Heat Release Rate vs. Crank Angle at different fuel ratios of 2-phase WC Diesel engine at Full Load**
4.4.8 Heat Release Rate in terms of brake power

Figure 4.19 shows the heat release rate of the test engine in terms of brake power. It can be noted that the increase in load and ethanol addition improve the heat release rate. Results show that ethanol emulsions increases the brake thermal efficiency. Higher ethanol percentage reduces the efficiency of heat release rate. It is observed from the graph that the maximum heat release was obtained for D100 operation. E10 operation produces better heat release rate compared to other blends.

![Graph showing heat release rate vs brake power for different fuel ratios](image)

**Figure 4.19** Heat Release Rate vs. Brake Power for different fuel ratios of 2-phase WC Diesel engine at Full Load
4.5 PERFORMANCE, EMISSIONS AND COMBUSTION STUDY OF A 3-PHASE DIESEL ENGINE USING DIESEL, ETHANOL AND TMAB BLENDS WITHOUT COATED ENGINE

This section of the thesis describes the 3 phase operations in which the engine is fuelled by the mixture of diesel, ethanol, water in different proportions along with 2% volumetric concentration of TMAB additive. The test engine was run at maximum load condition and the readings were noted. A large number of figures are presented in this section to show the values produced by the test engine for parameters like Specific Fuel Consumption (SFC) in kg/kW-hr, Brake Thermal Efficiency (BTE) in % at full load, Carbon Monoxide (CO) in ppm, Smoke Density (SD) in HSU, Oxides of Nitrogen (NOx) in ppm, Hydro Carbon emission (HC) in ppm and Maximum Pressure at full load in bar.

The short forms make most in the present study for various fuel ratios operating in 3-phase conditions are given below:

D100,

83D:10E:5W:2T – 3PE10,

78D: 15E:5W:2T - 3PE15,

73D:20E:5W:2T - 3PE20,

68D: 25E:5W:2T - 3PE25
4.5.1 Brake Specific Fuel Consumption (BSFC) at full load for 3 phase WOC Engine

The variations in the value of Brake specific fuel consumption (BSFC) for various fuel blends D100, 83D:10E:5W:2T, 78D:15E:5W:2T, 73D:20E:5W:2T, 68D:25E:5W:2T at full load is shown in Figure 4.20. It can be observed from the figure that D100 and 73D:20E:5W:2T blends produces a higher BSFC when compared to other fuel ratios.

Figure 4.20 BSFC at full load for 3 phase WOC Engine
4.5.2 Brake Thermal Efficiency (BTE) at full load for 3 phase WOC Engine

The variation of BTE at full load for various fuel blends D100, 83D:10E:5W:2T, 78D:15E:5W:2T, 73D:20E:5W:2T, 68D: 25E:5W:2T is shown in Figure 4.21. It can be perceived from the figure that 3PE10 blend offers higher BTE when compared to other fuel blends. Improvement in combustion especially diffusion combustion as the oxygen concentration increases by surfactant in the fuel may be the reason for the increase in efficiency.

![Figure 4.21 BTE at full load for 3 phase WOC Engine](image)
4.5.3 CO Emission at full load for 3 phase WOC Engine

Figure 4.22 exhibits the variation of CO emission of the test engine for the maximum load for various mixture of blends of diesel, ethanol and water along with 2 % TMAB. 3PE2 0 and D100 has the maximum CO emission when compared to other fuel ratios. 3PE15 has the lowest CO emissions.

![Figure 4.22 CO at full load](image)

Figure 4.22 CO at full load
4.5.4 Smoke density at full load for 3 phase WOC Engine

Figure 4.23 reveals the smoke density of the test engine for full load without coating operation for various fuel blends. It can be seen from the graph that 3PE10 blend produces the highest value of smoke density when compared to other blends. Smoke density is lower in neat Diesel operation of the test engine. Ethanol has less carbon than diesel fuel and also having oxygen content and thereby increasing the oxygen fuel ratio at rich fuel region. Therefore ethanol addition to diesel fuel is more effective reduction of smoke density in diesel engine. But the presence of surfactant acted in the opposite way and hence the smoke is maintained.

![Figure 4.23 Smoke density at full load](image-url)
4.5.5 NOx emission at full load for 3 phase WOC Engine

Figure 4.24 shows the NOx emission of the test engine for at full load operation for various fuel blends. The graph indicates that the 3PE15 blend produces maximum NOx emissions. D100 operation of the engine produces very less NOx emissions. It is found that initially all the emulsions NOx emission was reduced after the part load the NOx emission was increased gradually. It can be seen that NOx emissions of all blends increase more rapidly than those of sole fuel as ethanol proportion and load increase at medium and high loads. The maximum increase in NOx emissions occur at 80~100% full load conditions because of long ignition delay and rich oxygen circumstance from ethanol in the mixture.

Figure 4.24 NOx emission at full load
4.5.6 Heat release rate at full load for 3 phase WOC Engine

Figure 4.25 depicts the heat release rate of the test engine for full load operation under without coated condition. It is observed that 3PE20 has maximum heat release rate when compared to other ratios of blends. 3PE15 blend has the lowest heat release rate. The reason is the rate of diffusion combustion of the oxygenated fuel increasing the heat release rate – consequently oxygenated fuel has controlled rate of pre-mixed combustion. The rate of heat release rate of oxygenated fuel is slightly shifted to the top dead center due to increased pre-mixed combustion.

![Figure 4.25 HRR at full load](image)

<table>
<thead>
<tr>
<th>Blend</th>
<th>HRR (kJ/m²·deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D100</td>
<td>114.94</td>
</tr>
<tr>
<td>83D:10E:5W:2T</td>
<td>117.08</td>
</tr>
<tr>
<td>78D:15E:5W:2T</td>
<td>112.13</td>
</tr>
<tr>
<td>73D:20E:5W:2T</td>
<td>165.86</td>
</tr>
<tr>
<td>68D:25E:5W:2T</td>
<td>145.07</td>
</tr>
</tbody>
</table>
4.5.7 HC emission at full load for 3 phase WOC Engine

Figure 4.26 portrays the HC emissions of the test engine at full load operation for various duel blend ratios under without coated engine condition. It is observed that D100 produces maximum HC emissions when compared to other ratios of blends. 3PE15 blend has the lowest HC heat release rate. This is due to the presence of oxygen in ethanol and water which enhances complete combustion.

![Figure 4.26 HC at full load](image)
4.5.8 Max. Pressure at full load for 3 phase WOC Engine

Figure 4.27 shows the maximum pressure developed in the test engine for full load operation under without coated condition for various fuel blends. It is observed that 3PE20 produces maximum pressure at full load when compared to other ratios of blends. On the other hand, 3PE15 blend shows the lowest heat release rate. It can also be seen that the pressure variations of oxygenated fuel engine higher pressure region will change sharply as with diesel engine, but the durations of the higher pressure period is shorter than that of diesel engine. The oxygenated fuel engine are having longer delay period compared to sole fuel.

![Graph showing maximum pressure at full load](image)

**Figure 4.27 Maximum Pressure at full load**
4.6 PERFORMANCE, EMISSIONS AND COMBUSTION STUDY OF A 3-PHASE DIESEL ENGINE USING DIESEL, ETHANOL AND TMAB BLENDS WITH COATED ENGINE

This section of the thesis describes the 3-phase operation of the test engine when the piston walls and piston head of the engine are coated with ceramic coating. A number of experiments were conducted and the results are presented here.

4.6.1 BSFC at Full Load for 3-Phase Coated Engine

Figure 4.28 demonstrates the comparison of BSFC of the test engine for various fuel ratios at constant speed operation for maximum load condition. It is seen from the plot that the blend 3PE20 has produced maximum BSFC while D100 has least BSFC.

![Figure 4.28 BSFC at full load](image)
4.6.2 BTE at Full Load for 3-Phase Coated Engine

In general, Brake Thermal Efficiency (BTE) decreases as the ethanol concentration in the fuel mixture is increased. Figure 4.29 predicates the Brake Thermal Efficiency (BTE) of the test engine for full load operation under with coated condition for various fuel blends. It is observed that D100 produces maximum BTE at full load when compared to other ratios of blends. On the other hand, 3PE10 blend produces highest BTE with other blends.

Figure 4.29 BTE at full load
4.6.3 CO Emission at Full Load for 3-Phase Coated Engine

The values of CO emission at full load for various ratios of fuel blends are presented in Figure 4.30. The values of CO emission for most of the fuel blends was minimum at around 0.06 ppm. 3PE20 recorded maximum value of CO emission (0.11 ppm). On the other hand, the blend 3PE10 recorded very low value for CO emission at full load.

![Figure 4.30 CO at full load](image)

It can be noted that the CO emitted by the ethanol-diesel fuel blends was lower than that for the corresponding neat diesel fuel case, with the reduction being higher when the percentage of ethanol in the blend is higher. This may be attributed to the engine running overall “leaner”, with the combustion being assisted by the presence of the fuel-bound oxygen of the ethanol even in locally rich zones. TBC reduces the CO emissions due to the in-cylinder heat transfer reduction and increase in combustion duration.
4.6.4 Smoke Density at Full Load for 3-Phase Coated Engine

Figure 4.31 presents the smoke density at full load condition for various fuel blends. The smoke density was maximum for pure diesel engine operation (74.2 HSU). Smoke density was minimum (57.5 HSU) for 3PE15 operation of diesel engine.

![Figure 4.31 Smoke density at full load](image-url)
4.6.5 NOx Emission at Full Load for 3-Phase Coated Engine

Figure 4.32 make known the NOx emission at full load for various fuel blends. NOx emission was maximum for engine operation using clear diesel. NOx emission values gradually decrease for increases in ethanol ratio in the fuel blend. However, it is interesting to note that when the ethanol ratio is increased beyond certain values, say, 25% of volume of the fuel mixture, NOx emission started to increase.

![Figure 4.32 NOx emission at full load](image)

Figure 4.32 NOx emission at full load
4.6.6 HRR at Full Load for 3-Phase Coated Engine

The values of Heat Release Ratio (HRR) for various fuel blends can be seen in Figure 4.33. HRR initially decreases with increase in ethanol ratio in the fuel. It decreases with further increase in the ethanol ratios.

![Figure 4.33 HRR at full load](image)

Figure 4.33 HRR at full load
4.6.7 HC Emission at Full Load for 3-Phase Coated Engine

It is very clear from the Figure 4.34 that when the 3-phase coated engine was operated with clear diesel (100%), maximum hydrocarbon emissions were produced (90 ppm). However, the blend with maximum ethanol (3PE25) produced minimum HC emissions. Thus it is very clear that, as the percentage of ethanol is increased in the fuel blend, the HC emissions reduce significantly.

![Figure 4.34 HC at full load](image)
4.6.8 Maximum Pressure at Full Load for 3-Phase Coated Engine

Figure 4.35 determines the plots for maximum pressure at full load for 3-phase coated engine operation for various fuel ratios. It can be seen from the figure that the fuel blends 3PE10 and 3PE15 generated maximum pressure at full load conditions. On the other hand, fuel blends D100 and 3PE20 recorded minimum value of peak pressure at full load operation.

![Figure 4.35 Maximum Pressure at full load]
4.7 OVERALL SUMMARY

The major findings of the experiments are detailed in the following paragraphs.

4.7.1 Brake Specific Fuel Consumption (BSFC)

Ethanol has lower heat value than diesel fuel. Hence as the quantity of ethanol in the blends increases, the heat value of the blends decreases. Maintenance of the power at the same level needs consumption of additional fuel. As a result, BSFC will increase as the blended fuels with high ethanol concentration are used. For the engine without modifications the increase in BSFC is 4.4% against neat diesel, for 2phase operation it is further increased to 7.3% for the engine with thermal barrier coating. However, for 3 phase operation on a normal engine the BSFC was decreased by 2.9% due to the presence of water molecules but for thermal barrier coating (TBC) engines the BSFC increased by 3.6%. The variation in BSFC is shown in figure 4.36. It is clear from the figure that substantial reduction in combustion chamber heat transfer and reduced friction due to increased wall temperature (Thring, 1986) decreases the BSFC for thermal barrier coating (TBC) engines. The decrease is 7.3% for 2 phase operation and is 3.8% for 3phase operation.

![Figure 4.36 BSFC at full load](image-url)
4.7.2 Brake Thermal Efficiency (BTE) at full load

For sole fuel, TBC engine improves the brake thermal efficiency (BTE) by 3% under 2 phase operation when compared to the standard engine due to in-cylinder heat transfer reduction and increase in combustion duration as indicated by Ramu et al. (2009). However, for 3 phase operation there is an increase of 2% in normal engine when compared with diesel at full load condition and there is no significant change in TBC engine. This is due to the presence of oxygen due to ethanol in the oxygenated fuel, improve the combustion, especially diffusion combustion and hence increase the BTE. In 2 phase operation (without water) BTE is decreased by 2% for normal engine and the change is not significant in TBC engine. Figure 4.37 shows the comparison of BTE of test engine under full load for optimal proportion (10E) of fuel blend under WOC and WC conditions at both 2\textsuperscript{nd} and 3\textsuperscript{rd} phase operations.

![Figure 4.37 BTE at full load](image)

Figure 4.37 BTE at full load
4.7.3 Smoke Density at full load

The addition of ethanol results in the decrease of the smoke density of the engine due to the increased heat release rate and more complete combustion of the oxygenated fuel. Figure 4.38 shows the comparison of smoke density produced in the test engine under full load for WOC and WC conditions of operation. For the normal engine, the increase in SD is 25.3% against neat diesel for 2 phase operation and is decreased to 2.9% for the TBC engine. However, for 3 phase operation on a normal engine the SD was increased by 6.4% but for thermal barrier coating (TBC) engines the SD decreased by 18.2% due to the highertemperatures both in the gases and at the combustion chamber walls of the TBC engine assist in permitting the oxidation reactions to proceed close to completion.

Figure 4.38 Smoke Density at full load
It can be observed that reduction in smoke density was observed for the engine with thermal barrier coating because of the decreased quenching distance and the increased lean flammability limit. The higher temperatures both in the gases and at the combustion chamber walls of the TBC engine assist in permitting the oxidation reactions to proceed close to completion. Sathiagnanam et al. 2010 was also observed that, for same engine speed and load, the SD for the TBC coating plus additive was higher than the standard normal engine.

4.7.4 NOx at full load

Figure 4.39 point out the comparison of NOx levels produced in the test engine under full load for 10E with neat diesel under WOC and WC conditions of various operation. When compare to neat diesel, 15.9% decreased in any modification of engine and further decreased to 11.9% in coated engine at 2 phase operation. But in 3 phase operation, 6.5% NOx is increased in normal engine and it is reduced into 6.8% in coated engine this increase is due to the presence of oxygen in water.

![Figure 4.39 NOx at full load](image)

**Figure 4.39 NOx at full load**
Nitrogen oxides emissions are predominately temperature phenomena. The presence of oxygen increases the heat release rate for the oxygenated fuel and hence the NOx emission will be high. Late combustion due to change in the delay period lower the peak pressure in TBC engines for the sole fuel and low oxygenated fuels. Since the peak pressure rise is lower, for the same value of mass, the peak gas temperature may also be lower, resulting reduced NOx emissions for sole fuel and low oxygenated fuels. The same trend was observed by Assanis et al. (1991). Similarly, Ramu and Saravanan (2009) also found lower NOx for Zirconia Alumina coated engine for diesel fuel.
4.7.5 Heat Release Rate at full load

Figure 4.40 shows the comparison of Heat Release Rate of test engine under full load for 25E with neat diesel under WOC and WC conditions of operation. For the normal engine, HRR is increased 15.9% and 0.9% is decreased in TBC engine at 2 phase operation when compare to diesel. For 3 phase operation, 44.3% is increased in normal engine and 3.3% is decreased in TBC engine when compare to neat diesel fuel. It can be noted that the HRR is high [3P25E] for oxygenated fuels due to the longer duration of the combustion. The reason is that the rate of diffusion combustion of the oxygenated fuel increases the heat release rate and consequently oxygenated fuel has controlled rate of pre-mixed combustion. Sathiyagnanam et al. 2010 also found that, the heat release rate was slightly lower in the case of coating engine when compared to standard engine due to the effect of coating and coating plus fuel additives.
4.7.6 Cylinder Pressure at full load

Figure 4.41 indicates the comparison of Cylinder Pressure of test engine under full load for 25E (optimal fuel proportion) under WOC and WC conditions of various operation. It is observed in the figure that, 25E has the decreased value of 1.5% in TBC engine and further decreased to 1.4% in normal engine when compare to diesel at 2 phase operation. But there is no significant changes on both normal and TBC engine when compare to diesel in 3 phase operation.

It is found that at the same engine speed and maximum load, the ignition delay for the oxygenated blend is higher \([3P25E]\) (the pressure rise due to combustion starts later) than the corresponding one for the neat diesel fuel case, while there is a slight increase in the maximum pressure. Rakopoulos et al., (2008) obtained the same result for 25% ethanol but with no appreciable difference in the maximum pressure due to the lower cetane number of ethanol.