CHAPTER 6

RESULTS AND DISCUSSION

6.1 GENERAL

This chapter discusses the experimental results of various methods used for admitting different proportions of ethanol in modified and unmodified DICI engine. It is known that ethanol has poor self-ignition property, lower calorific value, lower cetane number, higher latent heat of vapourisation and higher volatility. Hence, the addition of ethanol into diesel fuel reduces performance, altering combustion and emission characteristics. However, the various methods adopted in the present work have helped to overcome the hurdles.

In this work, four different methods have been used to apply different fractions of ethanol in DICI engine. All methods have been planned as per the objectives and the observations have been made as per the experimental procedure and conditions. The observed results and calculated results have been presented in a graphical manner to have better understanding of the results. This chapter also discusses the reasons for the obtained results, trends and the mechanisms involved alongside the graphical representation.

The results have been presented under various heads such as BTE, CO, HC, NOx, Smoke opacity, cylinder pressure and HRR to understand the
performance, combustion and emission characteristics of applied ethanol fraction.

### 6.1.1 Methods used

Following are the methods used in this work to apply various proportions of ethanol in DI CI engine.

- Application of 10, 20 and 30 percent of ethanol in CI engine without engine modification
- Application of 40 percent of ethanol in CI engine with modified engine operating parameters
- Application of 50 percent of ethanol in CI engine with modified engine operating parameters, Toroidal bowl piston and Thermal Barrier Coating
- Application of 50, 60 and 70 percent of ethanol in CI engine through dual fuel mode

### 6.2 APPLICATION OF 10, 20 AND 30 PERCENT OF ETHANOL IN CI ENGINE WITHOUT ENGINE MODIFICATION

This method employs 10, 20, 30 and 40 percent of ethanol in the test engine without engine modification. In this method, ethanol has been employed in the form of ethanol-diesel blends (E10, E20, E30 and E40). The blends have been allowed into the engine through diesel fuel admission device. All blends have been tested at all load conditions to study the performance, combustion and emission characteristics.
6.2.1 Brake Thermal Efficiency

Brake thermal efficiency expresses the conversion efficiency of heat into work. It is seen as a performance parameter of the engine. In this present work 10, 20, 30 and 40% ethanol diesel blend have been used in an unmodified engine at various load conditions. Observed BTE of the blends have been shown in Figure 6.1. From the figure, it is understood that E20 offer highest BTE and E40 offers the lowest BTE among the used blend. The results of the blends indicate that the addition of ethanol into diesel fuel improves the fuel performance upto certain extent due to the modification of physical and chemical characteristics of fuel used in the engine.

![Variation of BTE of various ethanol diesel blends in unmodified engine](image)

**Figure 6.1** Variation of BTE of various ethanol diesel blends in unmodified engine

More specifically, the addition of ethanol increases volatility and improves the spray characteristics of the blends. This is a major reason for the increase in heat utilisation and higher BTE. However, the excessive addition of ethanol into diesel fuel decreases the performance. This is primarily due to the decrease in self-ignition property and increase in latent heat of
vapourisation of the blend. The figure shows that E20 offers 6% and 20% higher BTE than that of diesel fuel and E40 respectively.

### 6.2.2 Exhaust Gas Temperature

Exhaust gas temperature of an engine indicates the combustion behavior of the fuel used. Higher exhaust gas temperature indicates incomplete combustion of fuel spray and higher heat release rate of fuel used. Generally, highly viscous fuels have poor volatility and heavier molecular structure. These properties reduce the combustion behavior of the viscous oils. This is one of the important reasons for the higher EGT of the high viscous fuels.

Figure 6.2 shows the variation of EGT of various ethanol-diesel blends (E10, E20, E30 and E40) in unmodified engine at various loads. The results of the experiment express that the lower ethanol blends (E10 and E20) offer higher EGT than that of the higher ethanol blends (E30 and E40). The addition of ethanol improves physical properties such as viscosity, volatility and spray characteristics. Hence, lower ethanol blends offer better combustion behavior and higher BTE.

However, the excessive addition (more than 20% by volume) of ethanol reduces the combustion characteristics of the blend by excessive reduction of physical properties. More specifically, the excessive addition of ethanol decreases the self-ignition property of the blend extremely low and causes misfire. This is the main reason for the poor performance of higher ethanol blends such as E30 and E40. From the figure, it is seen that E20 offer 6% and 13% higher EGT than that of diesel fuel and E40 respectively.
6.2.3 Carbon Monoxide Emission

Carbon monoxide emission indicates the efficiency of combustion, degree of combustion temperature, oxygen availability and self-ignition property of the fuel used. The present work uses E10, E20, E30 and E40 in an unmodified diesel engine. The ratio of ethanol in the blend decides the volatility and self-ignition property of the blend. Hence, higher ethanol blends offer lower combustion temperature and higher CO emission than that of lower ethanol blends.

Figure 6.3 shows the variation of CO emission of E10, E20, E30 and E40 at various load conditions. From the figure, it is seen that the higher ethanol blends offer higher CO emission and the lower ethanol blends offer lower CO emission. This is primarily due to the change in physical and chemical property of diesel fuel by the addition of ethanol. However, lower quantity of ethanol in the blend (lower ethanol blends) improves the
performance of the blend. This is due to the decrease in viscosity, increases in volatility and better spray of diesel fuel in the blend.

Higher quantity of ethanol in the blend decreases self-ignition property, increases latent heat of vapourisation and decreases cetane number of the blend. This is the main reason for the poor performance and higher emission characteristics of the higher ethanol blends (E30 and E40). From the figure, it is seen that E20 offer 4% and 9% lower CO emission than that of diesel fuel and E40 respectively.

![Graph showing the variation of CO emission with load for various ethanol-diesel blends](image)

**Figure 6.3** Variation of Carbon monoxide emission of various ethanol diesel blends in unmodified engine

### 6.2.4 Hydrocarbon Emission

Hydrocarbon emission is a measure of an effective utilisation of fuel during the combustion. Figure 6.4 shows the variation of HC emission of E10, E20, E30 and E40 blends at various loads. From the figure, it is seen that E40 offer the highest HC emission and E10 offers lowest HC emission among the used blends.
The addition of ethanol is the main reason for the change of performance, combustion and emission characteristics of the blends. Lower ethanol blends increase combustion characteristics and higher ethanol blends decrease combustion characteristics. In addition to that higher ethanol blend offers comparatively lower combustion temperature due to the lower reaction rate caused by the decrease in self-ignition property. This is the main reason for the higher HC emission of higher ethanol blends. The flame quenching near the cylinder wall and non-penetration of flame in the crevice volume and cylinder corners are other few reasons for the higher HC emission of higher ethanol blends. From the figure, it is observed that E20 offer 6.5% and 40% lower HC emission than that of diesel fuel and E40 respectively.

![Variation of Hydrocarbon emission of various ethanol diesel blends in unmodified engine](image)

**Figure 6.4** Variation of Hydrocarbon emission of various ethanol diesel blends in unmodified engine

### 6.2.5 Oxides of Nitrogen Emission

Oxides of nitrogen emission are the indicators of combustion temperature and efficiency of combustion. From Figure 6.5 it is seen that the lower ethanol blends emit higher NOx emission than that of higher ethanol
blends. The combustion temperature of higher ethanol blends is less than that of the combustion temperature of lower ethanol blends. This is a major reason for the higher NOx emission of lower ethanol blends.

In addition to that the lower quantity of ethanol in the blend decreases viscosity, increases volatility and improves spray characteristics and thus increases the rate of heat release. This effect enhances the combustion temperature and liberates higher NOx emission.

Higher ethanol blends emit lower NOx due to the suppression of combustion characteristics of diesel fuel due to excessive addition of ethanol. Hence, E40 offers lower NOx emission than that of other blends and diesel fuel. The highest NOx emission offered by E20 is 11g/kW h and it is 4% and 50% higher than that of diesel fuel and E40 operation respectively.

![Graph of Oxides of Nitrogen emission](image)

**Figure 6.5** Variation of Oxides of Nitrogen emission of various ethanol diesel blends in unmodified engine
6.2.6 Smoke Opacity

Smoke emission also indicates the temperature of combustion and oxygen utilisation. Figure 6.6 indicates the variation of smoke opacity of E10, E20, E30 and E40 blends at various load conditions. From the figure, it is seen that E20 emits lesser smoke than that of other blends and diesel fuel. This is primarily due to the improved combustion characteristics by the addition of ethanol. The addition of ethanol increases volatility, reduces viscosity and improves spray characteristics. More specifically, lower quantity of ethanol addition increases the evaporation rate and helps to combust the mixture within a shorter duration and offers higher combustion temperature. This is the primary reason for the lower smoke emission of E20 blend.

![Figure 6.6 Variation of Smoke opacity of various ethanol diesel blends in unmodified engine](image)

Figure 6.6 Variation of Smoke opacity of various ethanol diesel blends in unmodified engine

However, the excessive addition of ethanol decreases combustion temperature and increases smoke emission. This is mainly due to the suppression of combustion characteristics of diesel fuel by the excessive
addition of ethanol. More specifically, higher quantity of ethanol in the blend reduces self-ignition property, increases volatility and reduces calorific value of the blend. Hence, higher ethanol blends emit more smoke than that of lower ethanol blends. Figure shows lower smoke emission for E20 and it is 16\% and 40 \% lower than that of diesel fuel and E40 respectively.

6.2.7 Cylinder Pressure

Cylinder pressure diagram indicates the effect of combustion of fuel inside the engine cylinder. The cylinder pressure of the engine changes with respect to volatility of the fuel, the duration of combustion, heat release rate and calorific value of the fuel used. From Figure 6.7, it is seen that the lower ethanol blends offer higher cylinder pressure and higher ethanol blends offer lower cylinder pressure. Lower ethanol blends improve combustion characteristics and higher ethanol blends suppress combustion characteristics of the blend. This is the main reason for the higher and lower cylinder pressure of E20 and E40 respectively. The peak pressure of E20 is greater than of all other blends and it is 7\% and 20 \% higher than that of diesel fuel and E40 respectively.

In addition to peak pressure, the ignition delay of the blend changes with respect to change in ethanol fraction of the blend. Higher ethanol blends offer lower peak pressure and the longer ignition delay compared to that of lower ethanol blends. This is primarily due to the suppression of combustion characteristics of the blend by ethanol. The peak pressure of the blends retards with respect to increase in ethanol fraction of the blend. The maximum retard of peak pressure has been observed with E40 and it is 6 degrees longer than that of diesel fuel operation. Similarly, the addition of ethanol also changes ignition delay of the blend. Higher ethanol blends offer longer ignition delay and lower ethanol blends offer shorter ignition delay.
6.2.8 Heat Release Rate

Heat release rate is an important indicator of combustion efficiency. This particular parameter helps to explain the change in BTE, EGT, rate of pressure rise, emission parameters and cylinder pressure. Figure 6.8 shows the variation of HRR of various ethanol diesel blends at various loads. From the figure, it is seen that E20 offer higher HRR than that of other blends and diesel fuel. This is primarily due to the improved combustion behaviour of the blend by ethanol. However, excessive addition of ethanol suppresses the combustion characteristics of the blend. Hence, higher ethanol blends offer poor heat release rate.

From the figure, it is further seen that the two phases of combustion changes with respect to change in ethanol proportion in the blend. More specifically, the HRR of the first phase of combustion decreases with respect to increase in ethanol fraction of the blend. Lower ethanol blends offer higher HRR and higher ethanol blends offer lower HRR in the first phase of combustion. This trend reverses in the second phase of combustion. That is
less ethanol blends offer lower HRR and higher ethanol blends offer higher HRR in the second phase of combustion.

Also, the occurrence of peak HRR retards with respect to increase in ethanol fraction of the blend. The figure also shows the duration of combustion changes with respect to ethanol content of the blends. Lower ethanol blends offer shorter duration of combustion and higher ethanol blends offer longer duration of combustion. From the figure, it is observed that E20 offer the highest HRR and it is 13% and 35% higher than that of diesel fuel and E40 respectively.

![Variation of HRR of various ethanol diesel blends in unmodified engine at full load](image)

**Figure 6.8** Variation of HRR of various ethanol diesel blends in unmodified engine at full load

### 6.3 APPLICATION OF 40 PERCENT OF ETHANOL IN CI ENGINE WITH MODIFIED ENGINE OPERATING PARAMETERS

The previous experiment has shown that E40 has failed to perform well in an unmodified engine and has offered poor cold starting ability. Hence, it is decided to use E40 in a modified engine. The present work has
used a modified engine with operating parameters specially modified to use E40 effectively. The suitable level of operating parameters that provided the best performance for E40 have been determined by Taguchi and Gray relational analysis. This part of the work has used Taguchi method for designing experimental layout and Gray relational analysis for optimisation of parametric level. Gray relation analysis has an ability to optimise parameters considering multiple responses. The steps involved in the optimisation process have been listed below.

- Selection of operating parameters and their levels
- Selection of orthogonal array by Taguchi method
- Preparation of experimental layout
- Conducting the experiments using the experimental layout
- Observation of response parameters
- Gray relational analysis
- Normalisation of response parameters
- Generation of Gray coefficients
- Determination of Gray Grades
- Determination of mean Gray Grades
- Depiction of response graph
- Selection of optimum levels
- ANOVA for involved parameters
- Detailed engine experiment using optimum level of operating parameters
- Formation of regression equations
Present investigation has considered four operating parameters namely, compression ratio, intake air temperature, injection pressure and injection timing for optimisation. These parameters are known as control factors and are believed to be controlling the desired response. All operating parameters (control factors) have been allowed to vary in three levels. The range and level of parameters have been selected based on literature support and preliminary engine experiments. The list of operating parameters and their levels are shown in Table 6.1.

Table 6.1 Engine operating parameters and their levels

<table>
<thead>
<tr>
<th>S.No</th>
<th>Symbol</th>
<th>Parameters</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
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<td>Inlet air temperature (IAT) (° C)</td>
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</table>

Using these parameters and levels, the suitable orthogonal array, experimental layout and number of trials required for optimisation process are fixed by Taguchi method of optimisation.

6.3.1 Taguchi Method

Taguchi design of experiment offers a systematic approach for optimising various performance parameters involved in the production of response parameters. The Taguchi method uses an orthogonal array (OA) for the design of experimental layout. The selection of orthogonal array depends upon degrees of freedom of involved parameters (Palani et al 2006). The minimum number of experiments (trials) required for selection of optimum level can be determined using the following relation.
\[ N = (L-1) \times P + 1 \]

Where,  
\[ N = \text{Total number of test runs} \]
\[ L = \text{Number of levels of parameters} \]
\[ P = \text{Number of control parameters} \]

The present study uses 4 parameters and 3 levels and hence, the total degrees of freedom of control parameters are 8. Therefore, \( L_9 \) and \( L_{18} \) are the suitable OA for the total degrees of freedom of involved parameters. However, \( L_{18} \) has been chosen as suitable OA for the current experiment as it has 18 trials (Palani et al 2006). Larger number of experimental trials will provide larger number of response data. This helps to generate regression equations with higher value of regression coefficients. The selected orthogonal array, experimental layout and the response parameters are shown in Table 6.2, 6.3 and 6.4 respectively.

**Table 6.2 Layout of \( L_{18} \) Orthogonal Array**

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Table 6.3 Experimental Layout of $L_{18}$ Orthogonal Array

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Table 6.4 Response parameters and results of L₁₈ orthogonal experiment

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<th>BTE (%)</th>
<th>NO (g/kW h)</th>
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The obtained response parameters of the optimisation experiment (shown in Table 6.4) have been then used by Gray relational analysis to identify the optimum level of operating parameters.

6.3.2 Gray Relational Analysis

Gray relational analysis is one of the useful statistical data processing tools. It helps to identify the optimum level of control parameters
involved in the production of multiple responses (Palani et al. 2006). Unlike Taguchi method, it helps to provide a simple analysis to determine the optimum level of control parameters. The steps involved in the gray relational analysis are given below (Palani et al. 2006).

1. Normalization of data or generation of gray relations.
2. Formation of gray coefficients.
3. Determination of gray grades.
4. Tabulation of mean gray grades
5. Determination of optimum levels from the response graph.

The normalized values of response parameters, Gray relational coefficients and Gray grades of $L_{18}$ orthogonal experiments are shown in Table 6.5. The mean Gray grades of various levels of operating parameters are shown in Table 6.6 and the response graph of operating parameters is shown in Figure 6.9. The optimised level of operating parameters is shown in Table 6.7.

**Table 6.5 Gray relational Coefficients and Gray grades of $L_{18}$ experimental results**

<table>
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<th>Normalised Values</th>
<th>Grey Relation Coefficient</th>
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<td>0.80</td>
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<tr>
<td>0.36</td>
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<td>0.64</td>
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Table 6.5 (Continued)

<table>
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<tr>
<th>Normalised Values</th>
<th>Grey Relation Coefficient</th>
<th>GRG</th>
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<tr>
<td>BTE</td>
<td>NO</td>
<td>Smoke</td>
</tr>
<tr>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>0.28</td>
<td>0.73</td>
<td>0.72</td>
</tr>
<tr>
<td>0.72</td>
<td>0.29</td>
<td>0.28</td>
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<td>0.64</td>
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<td>0.36</td>
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<td>0.48</td>
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<td>0.84</td>
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<td>0.16</td>
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<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>0.36</td>
<td>0.65</td>
<td>0.64</td>
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<tr>
<td>0.44</td>
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Table 6.6 Mean Grey relational Grade for operating parameters

<table>
<thead>
<tr>
<th>S.No</th>
<th>Symbol</th>
<th>Parameters</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>Injection Pressure (bar)</td>
<td>0.494</td>
<td>0.569</td>
<td>0.528</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>Injection timing (°b TDC)</td>
<td>0.504</td>
<td>0.572</td>
<td>0.516</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>Compression Ratio</td>
<td>0.456</td>
<td>0.498</td>
<td>0.637</td>
</tr>
<tr>
<td>4</td>
<td>D</td>
<td>Inlet Air Temperature (IAT) (°C)</td>
<td>0.489</td>
<td>0.595</td>
<td>0.508</td>
</tr>
</tbody>
</table>
6.3.3 Analysis of Variance

Analysis of variance (ANOVA) is also used as a statistical tool for determining the effect of control factors on the production of desired response. It is well proved that the control factors are not equally contributing to the production of desired response (Palani et al 2006). Hence, this particular analysis has been used to determine the percentage contribution of control factors over the desired response. This analysis has used a parameter called F-test to shows the significance of involved control factors. The parameter that offers lowest F-test value (lower than 4) is considered as insignificant parameter and the effect caused by this parameter over the desired response is lower. Similarly, the parameter that offers highest F-test value is considered as a most significant parameter and the effect caused by
the parameters over the desired response is higher. The results of ANOVA for the involved parameters are shown in Table 6.8.

Table 6.8 ANOVA results for parameters used for optimisation

<table>
<thead>
<tr>
<th>S.No</th>
<th>Symbol</th>
<th>Factors</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>DOF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>% P</th>
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<tr>
<td>1</td>
<td>A</td>
<td>IP</td>
<td>0.494</td>
<td>0.569</td>
<td>0.528</td>
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<td>0.009</td>
<td>0.004</td>
<td>53.53</td>
<td>9.6</td>
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<tr>
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<td>B</td>
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<td>0.572</td>
<td>0.516</td>
<td>0.504</td>
<td>2</td>
<td>0.008</td>
<td>0.004</td>
<td>49.81</td>
<td>9.0</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>CR</td>
<td>0.456</td>
<td>0.498</td>
<td>0.637</td>
<td>2</td>
<td>0.054</td>
<td>0.027</td>
<td>336.10</td>
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</tr>
<tr>
<td>4</td>
<td>D</td>
<td>IAT</td>
<td>0.489</td>
<td>0.595</td>
<td>0.508</td>
<td>2</td>
<td>0.019</td>
<td>0.010</td>
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<td></td>
<td>Total</td>
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<td></td>
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<td></td>
<td></td>
<td>0.089</td>
<td>0.045</td>
<td>100.4</td>
<td></td>
</tr>
</tbody>
</table>

6.3.4 Regression Equations

The regression equations are correlation equations that help to determine the response parameters (desired results) for the newer levels that are not visited during the experiments. Present study has used a software called DATAFIT 9.0, a statistical software specially meant for generating the regression equations. This software has several models such as linear, exponential and power series to generate regression equations. The model that gives highest correlation coefficient ($R^2$) was considered as the best regression equation (Palani & Murugan 2006). The adequacy of the model and the significance of the coefficients are tested by analysis of variance (Palani & Murugan 2006). The variables used in the equations and its coefficients are given in Table 6.9.

\[
\text{BTE} = \exp (a*x_1+b*x_2+c*x_3+d*x_4+e) \quad (6.1)
\]

\[
\text{CO} = \exp (a*x_1+b*x_2+c*x_3+d*x_4+e) \quad (6.2)
\]

\[
\text{Smoke} = \exp (a*x_1+b*x_2+c*x_3+d*x_4+e) \quad (6.3)
\]
Table 6.9 Variables and Coefficients of various response parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>BTE</th>
<th>CO</th>
<th>Smoke</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1.11E-03</td>
<td>1.11E-03</td>
<td>1.07E-03</td>
</tr>
<tr>
<td>b</td>
<td>8.14E-03</td>
<td>8.32E-03</td>
<td>9.09E-03</td>
</tr>
<tr>
<td>c</td>
<td>8.88E-02</td>
<td>8.91E-02</td>
<td>8.94E-02</td>
</tr>
<tr>
<td>d</td>
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<td>-1.90E-03</td>
<td>-1.83E-03</td>
</tr>
<tr>
<td>e</td>
<td>1.23E+00</td>
<td>2.16E+00</td>
<td>-4.32E-01</td>
</tr>
</tbody>
</table>

6.3.5 Detailed Engine Experiment using Modified Operating Parameters

The optimised level of engine operating parameters, as shown in Table 6.7 has been used in the test engine to determine the performance and emission characteristics of E40 at all load conditions. Other blends such as E30 and E50 have also been used in the same engine setup to compare the performance and emission characteristics of lower and higher blends (E30 and E50) with E40. The same engine has been used to test diesel fuel operation to establish diesel baseline readings. The results of the experiments have been presented in the following sections as a graphical form and compared with diesel fuel operation.

6.3.5.1 Brake thermal efficiency

Figure 6.10 shows the variation of brake thermal efficiency (BTE) of various ethanol blends and diesel fuel. From the figure, it is seen that E30 offers higher BTE than E40 and E50. The improved combustion ambience provided by the modified engine operating parameters is the main reason for the higher BTE of E30. The modified operating parameters of the test engine
improve the heat content of the combustion chamber and increase the combustion temperature causing the acceptance of higher ethanol blends in the modified engine. The target blend E40 also performs well in the modified engine setup and offers higher BTE than the same blend applied in the unmodified engine. The quantity of ethanol in the blend determines the performance and emission characteristics. Higher ethanol blends offers higher latent heat of vapourisation, poor self-ignition property and lower combustion temperature (Senthil Kumar et al 2001a). The higher latent heat of vapourisation of the blend reduces BTE due to the excessive absorption of heat from the combustion chamber. Similarly, poor self-ignition property of the blend decreases the reaction rate and the combustion temperature. Hence, E50 offers lower BTE than all other blends. The maximum BTE of E30 is 2% lower and 3.1% higher than diesel fuel and E50 respectively.

Figure 6.10 Variation of brake thermal efficiency of ethanol diesel blends in engine with modified operating parameters
6.3.5.2 Exhaust gas temperature

Figure 6.11 shows the variation of Exhaust Gas Temperature (EGT) of various ethanol blends and diesel fuel. From the figure, it is seen that E30 offers higher EGT than other blends. This is mainly due to the improved combustion behaviour of E30 by the modified operating parameters. The modified operating parameters such as higher compression ratio and preheated intake air increases the heat content of compressed air. This helps to evaporate ethanol blends at a rapid rate without offering longer ignition delay. However, higher ethanol blends suffer from poor combustion characteristics resulted by the excessive reduction of cylinder heat (Senthil Kumar et al 2001b). Generally, loss of cylinder heat reduces the charge preparation rate, reaction rate and heat release rate. Hence, E50 offers lower EGT than that of other blends. The maximum EGT of E30 is 4% higher and 3% lower than E50 and diesel fuel respectively.

Figure 6.11 Variation of exhaust gas temperature of ethanol diesel blends in engine with modified operating parameters
6.3.5.3 Carbon monoxide Emission

Figure 6.12 shows the variation of carbon monoxide emission of ethanol diesel blends in engine with modified operating parameters. From the figure, it is observed that lower ethanol blends offers lower CO emission and higher ethanol blends offers higher CO emission. The modified operating parameters enhance combustion and reduce CO emission. However, higher ethanol blends emits more CO due to the poor combustion caused by the higher fraction of ethanol in the blend. Higher ethanol blends also affects the self-ignition property and hence it reduces the reaction rate, heat release rate and combustion temperature (Cenk Sayın 2010). This is another important reason for the higher CO emission of E50. From the figure, it is observed that E30 offers 4% higher and 12% lower CO emission than diesel fuel and E50 operation respectively.
6.3.5.4 Hydrocarbon Emission

Figure 6.13 Variation of hydrocarbon emission of ethanol diesel blends in engine with modified operating parameters

Figure 6.13 shows the variation of Hydrocarbon emission (HC) of various ethanol blends and diesel fuel. From the figure, it is seen that E30 offers lower HC emission than other blends. The increased heat content of the combustion chamber and compressed air by the modified operating parameter is the main reason for the better performance of E30. However, higher ethanol blends emits higher HC due to the poor combustion characteristics. Generally, higher quantity of ethanol in the blend increases volatility and reduces self-ignition property. The combined effect of these two properties decreases mixture preparation rate, reaction rate and heat release rate (Kim & Choi 2008). Hence, higher ethanol blends offer higher HC than lower ethanol blends. Maximum HC emission of E30 is 4% higher and 45% lower than that of diesel fuel and E50 operation respectively.
Oxides of Nitrogen Emission

![Graph showing variation of oxides of nitrogen emission of ethanol diesel blends in engine with modified operating parameters]

Figure 6.14  Variation of oxides of nitrogen emission of ethanol diesel blends in engine with modified operating parameters

Oxides of nitrogen emission is a significant emission parameter that shows the effectiveness of combustion. The present work uses E30, E40 and E50 blends in CI engine using modified operating parameters. The modified operating parameters of the engine increase the heat content of the combustion chamber and compressed air. This helps to combust ethanol blends without much longer ignition delay. This is the main reason for the higher NOx emission of E30. However, E50 offers lower NOx emission due to the poor combustion characteristics resulted by the higher quantity of ethanol in the blend.

The addition of ethanol increases volatility, reduces calorific value, reduces self-ignition property, reduces heat release rate and reduces combustion temperature. This is the important reason for the change in combustion behavior of the ethanol diesel blend.
Though the modified operating parameter enhances the combustion, no increase in NOx emission has been observed with E40 operation. This is due to the higher latent heat of vapourisation of ethanol in the blend. Figure 6.14 shows the variation of NOx emission of various ethanol diesel blends at all loads. From the figure, it is seen that E30 offers 7% lower and 45% higher NOx emission than diesel fuel and E50 operation respectively.

### 6.3.5.6 Smoke Opacity

![Figure 6.15](image)

**Figure 6.15 Variation of smoke emission of ethanol diesel blends in engine with modified operating parameters**

Figure 6.15 shows the variation of smoke opacity of various ethanol blends and diesel fuel at all loads. From the figure, it is seen that higher ethanol blends offers lower smoke emission and lower ethanol blends offers higher smoke emission. Generally smoke emission is produced by an instant pyrolysis of fuel spray at the high temperature combustion regions.

The temperature of combustion is inversely proportional to ethanol content of the blend (Chong Lin et al 2007). In other words, higher ethanol
content of the blend lowers combustion temperature and lower ethanol content of the blend increases combustion temperature. Therefore, E30 offers higher smoke than higher ethanol blends such as E40 and E50.

Higher ethanol content of the blend prepares particle less fuel vapour after consuming higher portion of heat from the combustion chamber. This reduces the reaction rate, heat release rate and temperature of combustion. Hence, E50 (higher ethanol blend) offers lower smoke emission than E30. The smoke value of E30 at full load is 12% lower and 13% higher than diesel fuel and E50 operation respectively.

6.3.5.7 Cylinder Pressure

Figure 6.16 Variation of cylinder pressure of ethanol diesel blends in engine with modified operating parameters at full load

Figure 6.16 shows the variation of cylinder pressure of various ethanol diesel blends at full load. From the figure, it is seen that the peak pressure of the blends decreases with respect to increase in ethanol fraction of the blend. Higher ethanol blends offers lower combustion temperature and lower ethanol blends offers higher combustion temperature. This is the main
reason for the higher and lower cylinder pressure of lower and higher ethanol blends respectively. The addition of ethanol increases volatility, reduces self-ignition property, decreases calorific value and reduces heat releases rate. This is another important reason for the decrease in combustion characteristics with respect to increase in ethanol fraction of the blend. From the figure, it is also observed that E30 offer 5% lower and 16% higher cylinder pressure than that of diesel fuel and E50 operation respectively.

6.3.5.8 Heat Release Rate

![Heat Release Rate Diagram](image)

**Figure 6.17** Variation of heat release rate of ethanol diesel blends in engine with modified operating parameters at full load

Figure 6.17 shows the variation of HRR of ethanol diesel blends and diesel fuel at full load. From the figure, it is found that E30 offers higher HRR than all other blends. This is mainly due to the enhanced combustion ambience provided by the modified operating parameters (Bari et al 2002). However, higher ethanol blends perform inferior than lower ethanol blends. Hence, E50 offers lower HRR than that of all other blends.
All blends show the two phases of combustion and it is seen that the first phase of combustion reduces with respect to increase in ethanol fraction of the blend. This indicates that the rate of reaction decreases with respect to increase in ethanol fraction of the blend. The figure also demonstrates that the second phase of combustion and the duration of combustion increases with respect to increase in ethanol fraction of the blend. Higher ethanol blends offers longer duration of combustion and lower ethanol blends offers shorter duration of combustion. The figure also shows that the peak HRR of the blends retards with respect to increase in ethanol fraction of the blend.

6.4 APPLICATION OF 50 PERCENT OF ETHANOL IN CI ENGINE WITH MODIFIED ENGINE OPERATING PARAMETERS, TOROIDAL BOWL PISTON AND THERMAL BARRIER COATING

The previous experiment has shown that E50 is unable to perform well in the modified engine and has offered inferior performance and emission characteristics. The modified operating parameters are ineffective and insufficient for combusting E50. Hence, the present work has included additional engine modifications that have an ability to increase the heat content of the combustion chamber and compressed air. This work has used two new modifications such as Thermal Barrier Coating (TBC) and toroidal bowl piston in the same engine setup that had used the modified operating parameters. The combined effect of above said all three modifications increase the heat content of the combustion chamber and compressed air comparatively higher than the previous method. Hence, E50 performs well in the present method and offers better performance and lower emission.
6.4.1 Brake Thermal Efficiency

Figure 6.18 shows the variation of BTE of E50 operation in a modified engine using TBC and toroidal bowl piston. From the figure, it is found that E50 offers higher BTE than BTE of E50 used in the previous method. This is mainly due to the improved combustion characteristics of the blend of the modified combustion ambience. The modification such as TBC and toroidal bowl piston increases the heat content of the combustion chamber and compressed air. More specifically, TBC increases heat content of the combustion chamber by minimizing heat loss from the cylinder (Chen et al 2008). Similarly, toroidal bowl piston increases the hot surface area of the piston bowl. The hot surface area of the bowl increases the rate of evaporation and rate of mixture preparation. These are important reasons for the better performance of E50 in the modified engine using TBC and toroidal bowl piston.

![Graph showing variation of brake thermal efficiency](image)

**Figure 6.18 Variation of brake thermal efficiency of ethanol diesel blends in engine with TBC and toroidal bowl piston**
Since, ethanol has higher latent heat of vaporization it requires comparatively higher amount of heat for evaporation. This effect reduces the heat available for auto-ignition and hence the blend fails to perform well. Therefore the heat content inside the engine cylinder is insufficient to provide heat for evaporation and auto-ignition of the mixture. The present method has overcome this by suitable engine modification such as TBC and toroidal bowl piston. Hence, E50 performs well in the present method and offers 2% higher and 3.2% lower BTE than E50 (MOP) and diesel fuel respectively.

### 6.4.2 Exhaust Gas Temperature

EGT is an indicator of effectiveness of combustion. Generally, higher EGT indicates poor combustion and lower EGT indicate better combustion. In addition to that EGT also indicates the rate of heat release, caloric value and the temperature of combustion. Figure 6.19 shows the variation of EGT of E50 in modified engine using TBC and toroidal piston. From the figure, it is seen that E50 (TBC) offers lower EGT than that of EGT of E50 used in the previous method. This is due to improved combustion behaviour of E50 caused by the higher heat content of the combustion chamber and compressed air. The modifications provided in the method such as TBC and toroidal bowl piston increase the heat content of the combustion chamber (Chen et al 2008). More specifically, TBC minimizes the heat loss and retains more amount of heat in the combustion chamber. This helps to increase the evaporation rate, reaction rate and heat release rate.

The application of toroidal bowl piston increases the hot surface area of the piston crown and increases evaporation rate. This is the main reason for the better combustion and lower EGT of E50 (TBC) than E50 used in the previous method. The maximum EGT of E50 (TBC) is 7% lower and 15% higher than diesel fuel and E50 (MOP) operation respectively.
Figure 6.19 Variation of exhaust gas temperature of ethanol diesel blends in engine with TBC and toroidal bowl piston

6.4.3 Carbon monoxide Emission

Figure 6.20 shows the variation of CO emission of E50 in the modified engine using thermal barrier coating and toroidal piston. It is seen that CO emission of E50 (TBC) is lower and higher than E50 (MOP) and diesel fuel operation respectively. This is due to the higher combustion temperature caused by TBC and toroidal bowl piston. The modifications provided in the present method increases the heat content of the combustion chamber and increase the evaporation rate, reaction rate, heat release rate and combustion temperature. These are the main reason for the better performance of E50 (TBC). Maximum CO emission of E50 (TBC) is 9% lower and 14% higher than E50 (MOP) and diesel fuel operation respectively.
Figure 6.20 Variation of carbon monoxide emission of ethanol diesel blends in engine with TBC and toroidal bowl piston

6.4.4 Hydrocarbon Emission

Figure 6.21 shows the variation of HC emission of E50 in the modified engine using thermal barrier coating and toroidal piston. It is seen that HC emission of E50 (TBC) is lower and higher than E50 (MOP) and diesel fuel operation respectively. This is primarily due to the higher heat content of the combustion chamber caused by the combined effect of TBC and toroidal bowl piston.

The TBC acts as an insulator for the combustion chamber and hence it retains a higher amount of heat inside the chamber. This helps to increase evaporation rate, reaction rate, heat release rate and combustion temperature. These are important reasons for the lower HC emission of E50 (TBC) than E50 used in the previous method. The toroidal bowl piston also helps to improve the combustion characteristics of E50 by offering better evaporation and considerable change in air motion. Maximum HC emission
of E50 (TBC) is 33% lower and 54% higher than E50 (MOP) and diesel fuel operation respectively.

![Graph showing variation of hydrocarbon emission of ethanol diesel blends in engine with TBC and toroidal bowl piston](image)

**Figure 6.21** Variation of hydrocarbon emission of ethanol diesel blends in engine with TBC and toroidal bowl piston

### 6.4.5 Oxides of Nitrogen Emission

An oxide of nitrogen emission is an important parameter to show the quality of combustion. Higher NOx emission indicates better quality of combustion and lower NOx emission indicates poor quality of combustion. Figure 6.22 indicates the variation of NOx emission of E50 in modified engine using TBC and toroidal bowl piston. From the figure, it is observed that E50 (TBC) offer higher and lower NOx emission than E50 (MOP) and diesel fuel operation respectively.

This is due to improved combustion characteristics of E50 by the higher heat content of combustion chamber. The combined effect of TBC and toroidal bowl piston is responsible for the higher heat content of the combustion chamber. From the figure, it is also seen that E50 (TBC) offer
25% higher and 23% lower NOx emission than E50 (MOP) and diesel fuel respectively.

![Graph showing variation of oxides of nitrogen emission of ethanol diesel blends in engine with TBC and toroidal bowl piston.](image)

**Figure 6.22 Variation of oxides of nitrogen emission of ethanol diesel blends in engine with TBC and toroidal bowl piston**

### 6.4.6 Smoke Opacity

Generally, smoke emission is produced by instant pyrolysis of injected spray by the high temperature combustion regions. It is governed by the volatility, charge homogeneity, combustion temperature and air motion inside the cylinder. Figure 6.23 shows the variation of smoke emission of E50 in the modified engine using thermal barrier coating and toroidal bowl piston. From the figure, it is observed that smoke emission of E50 (TBC) is lower than E50 (MOP) and diesel fuel operation. This is due to the increase in evaporation rate, charge preparation rate, reaction rate, rate of heat release and combustion temperature caused by the engine modifications. The engine modifications such as the use of TBC and toroidal bowl piston increase the heat content of the combustion chamber. This is an important reason for the improved combustion behaviour and lower smoke emission of E50 (TBC).
Generally, the heat content of the combustion chamber is used to provide the heat requirement of evaporation and self-ignition of fuel. The quantity of heat required for evaporation and self-ignition varies with respect to the type of fuel used. More specifically, higher volatile fuels require a higher amount of heat for evaporation due to the higher latent heat of vaporisation of the fuel. The present work handles a higher volatile fuel and hence, the engine uses modifications to supply the higher amount of heat before the start of combustion. These modifications such as TBC and toroidal bowl piston help to keep a higher amount of heat in the combustion chamber.

The use of toroidal bowl piston increases the hot surface area and produces particleless vapor immediately after the injection. This helps to establish charge homogeneity throughout the cylinder and assists auto-ignition. Hence, E50 (TBC) emits lower smoke than that of diesel fuel and E50 (MOP). Maximum smoke emitted by E50 (TBC) is 12% and 14% lower than diesel fuel and E50 (MOP) operation respectively.

![Figure 6.23 Variation of smoke emission of ethanol diesel blends in engine with TBC and toroidal bowl piston](image-url)
6.4.7 Cylinder Pressure

Figure 6.24 shows the variation of cylinder pressure of E50 in the modified engine using thermal barrier coating and toroidal bowl piston. It is seen that E50 (TBC) offers higher peak pressure than E50 used in the previous method. This is due to improved combustion performance of E50 caused by the TBC and toroidal bowl piston. The combined effect of TBC and toroidal bowl piston increases the heat content of the combustion chamber and compressed air. The increase in heat content of the combustion chamber increases the charge preparation rate, reaction rate and heat release rate. This is the main reason for higher cylinder pressure of E50 (TBC) than E50 (MOP).

The figure also shows that the peak pressure of E50 (TBC) occurs earlier than that of E50 (MOP). This is caused by the shorter ignition delay of E50 (TBC) caused by the combined effect of TBC and toroidal bowl piston. The ignition delay offered by E50 (TBC) is shorter than E50 (MOP) and it is 7° degrees shorter than E50 used in the previous method. The maximum peak pressure offered by E50 (TBC) is 16% higher and 13% lower than that of E50 (MOP) and diesel fuel operation respectively.

Figure 6.24 Variation of cylinder pressure of ethanol diesel blends in engine with TBC and toroidal bowl piston at full load
6.4.8 Heat Release Rate

The heat release rate of E50 in the modified engine using TBC and toroidal bowl piston is illustrated in Figure 6.25. From the figure, it is seen that the HRR of E50 (TBC) and E50 (MOP) are higher than diesel fuel operation. This is mainly due to the higher volatility caused by the higher fraction of ethanol in the blend. Since ethanol has higher volatility and lower boiling point, it prepares air fuel mixture in a shorter duration. Hence, it offers higher rate of heat release and shorter duration of combustion. Though it has a shorter duration of combustion, it fails to offer a higher combustion temperature and hence it offers lower cylinder pressure than diesel fuel operation.

In addition to it, the higher volatility of the blend causes longer ignition delay and higher premixed phase of combustion than diesel fuel operation. This is an important reason for the lower BTE of E50 (TBC) and E50 (MOP) than diesel fuel operation.

![Figure 6.25 Variation of heat release rate of ethanol diesel blends in engine with TBC and toroidal bowl piston at full load](image)

Figure 6.25 Variation of heat release rate of ethanol diesel blends in engine with TBC and toroidal bowl piston at full load
6.5 APPLICATION OF 50, 60 AND 70 PERCENT OF ETHANOL IN CI ENGINE THROUGH DUAL FUEL MODE

Based on the objectives, previous methods have tried various techniques for admitting ethanol of different proportions in CI engine. However, the results of the investigations have proven that ethanol of higher proportions has failed to perform well in a CI engine due to the excessive reduction of required fuel properties. This has resulted in poor performance, combustion and emission characteristics. Hence, the maximum percent of ethanol utilisation in direct injection application has limited to 50% by volume.

The present method has been designed to admit ethanol of more than 50% by volume in CI engine. This method has employed dual fuel technique (DF mode) for admitting 50, 60 and 70 percent of ethanol. The dual fuel technique has used ethanol as the primary fuel and diesel as pilot fuel (igniting fuel). The primary fuel has been allowed through induction manifold using electronic fuel injection system and the pilot fuel has been admitted through regular diesel fuel injection system.

The test engine used for this method has a few modifications such as TBC, toroidal bowl piston and modified operating parameters for the effective utilisation of ethanol in CI engine. The results of experiments obtained from the modified engine are given below in graphical form and compared with the diesel fuel operation.

6.5.1 Brake Thermal Efficiency

Brake thermal efficiency is a performance parameter and it depicts the effectiveness of conversion of heat into work. Also, it helps to understand the combustion characteristics of the fuel used. Figure 6.26 shows the
variation of BTE of E50, E60 and E70 in dual fuel mode of operation at various loads. It is seen that E50 offers higher BTE than E60 and E70. This is due to the improved combustion characteristics caused by the high quantity of pilot fuel utilization. The higher quantity of pilot fuel utilization (50% diesel fuel) forms a strong ignition source and combusts the remaining mixture by flame propagation at a rapid rate. This phenomenon increases the heat release rate yielding higher BTE than other blends.

Figure 6.26 Variation of brake thermal efficiency of dual fuel operation with different proportions of ethanol

In DF mode of operation, the heat release occurs by two types of combustion. They are the combustion by auto-ignition and the combustion by flame propagation. Both are governed by the quantity of pilot fuel used for combustion. A higher quantity of pilot fuel combests the major faction of mixture by auto-ignition and the lower quantity of pilot fuel combests the minor fraction of mixture by auto-ignition. The higher quantity of pilot fuel increases the heat release rate and combustion temperature and the lower quantity of pilot fuel decreases the heat release rate and combustion temperature. This is the main reason for the decrease in BTE with a decrease
in pilot fuel quantity. Also, the decrease in pilot fuel quantity decreases the heat content of the total fuel participated in the combustion. This is an important reason for the decrease in BTE with a decrease in pilot fuel quantity. From the figure, it is observed that E50 offers 5% and 6% higher BTE than E60 and E70 respectively.

6.5.2 Exhaust Gas Temperature

Exhaust gas temperature is an indirect indicator of the combustion characteristics of the fuel. It also indicates the effective conversion of heat into work. Higher EGT indicates inefficient combustion and sluggishness in the combustion process. The higher EGT also indicates the temperature of combustion and rate of heat release.

Figure 6.27 shows the variation of EGT of E50, E60 and E70 in dual fuel mode of operation at various loads. It is seen that E50 offer lower EGT than E60 and E70. This is due to the better combustion of E50 caused by higher quantity of pilot fuel utilisation. Generally, a higher quantity of pilot fuel utilisation increases the rate of heat release and combustion temperature. This helps to combust the mixture comparatively in shorter duration and utilise more amount of heat for producing work. This is the main reason for the lower EGT of E50 operation. It is also found that the EGT increases with decrease in pilot fuel quantity. The decrease in pilot fuel quantity decreases the heat release rate and combustion temperature causing a decrease in the heat content of the total fuel due to the increase in ethanol fraction. These are the important reason for the increase in EGT with a decrease in pilot fuel.

The higher quantity of pilot fuel forms a strong ignition source that helps to combust the remaining fuel air mixture by flame propagation. The strength of the ignition source depends upon the quantity of pilot fuel used for ignition. A higher quantity of pilot fuel forms a stronger ignition source than
the lower quantity of pilot fuel. Hence, E50 offers lower EGT than the E60 and E70. From the figure, it is found that E70 offers higher EGT and it is 3% and 5% higher than E50 and E60 respectively.

Figure 6.27 Variation of exhaust gas temperature of dual fuel operation with different proportions of ethanol

6.5.3 Carbon monoxide Emission

Carbon monoxide emission indicates the effectiveness of combustion, oxygen utilisation and combustion temperature. Generally, higher CO emission indicates poor combustion and lower indicates better combustion. The properties of fuel such as latent heat of vapourisation, boiling point, calorific value and self-ignition temperature also play a vital role in the CO emission.

Figure 6.28 shows the variation of CO emission of E50, E60 and E70 in dual fuel mode of operation at various loads. It is seen that E50 emits lower CO than E60 and E70. This is due to the better combustion of E50 caused by the higher quantity of pilot fuel utilisation. The higher quantity of
pilot fuel develops a stronger ignition source that helps to combust the mixture with a higher rate of heat release and combustion temperature. This effect reduces with reduction in pilot quantity and hence, CO emission increases with a decrease in pilot quantity. In addition to it, the decrease in pilot quantity decreases the rate of heat release, combustion temperature and the total heat content of the fuel. This is the major reason for the increase in CO emission with a decrease in pilot fuel quantity. From the observation, it is found that E50 emits 3% and 4% lower CO emission than E60 and E70 respectively.

![Graph showing variation of carbon monoxide emission](image)

**Figure 6.28** Variation of carbon monoxide emission of dual fuel operation with different proportions of ethanol

### 6.5.4 Hydrocarbon Emission

Hydrocarbon emission indicates the effective utilisation of fuel and the combustion temperature prevailing in the cylinder. Higher HC emission indicates poor combustion and lower indicates better combustion. The properties of fuel also play an important role in the production of HC emission. More specifically, poor fuel properties such as higher latent heat of
vaporization, poor self-ignition property, lower boiling point and the lower calorific value increase HC emission.

Figure 6.29 shows the variation of HC emission of E50, E60 and E70 in dual fuel mode of operation at various loads. It is seen that E50 emits lower HC than E60 and E70. This is due to the better combustion performance of E50 caused by higher percent of pilot fuel (diesel fuel). The higher percent of pilot fuel application forms a stronger ignition source that helps to combust the fuel air mixture at a rapid rate with higher combustion temperature. Hence, HC emission decreases with increase in pilot quantity. This is the main reason for the increase in HC emission with an increase in ethanol fraction. From the observed results it is seen that E50 emits 9% and 16% lower HC than E60 and E70 respectively.

![Figure 6.29 Variation of hydrocarbon emission of dual fuel operation with different proportions of ethanol](image)

**Figure 6.29** Variation of hydrocarbon emission of dual fuel operation with different proportions of ethanol

### 6.5.5 Oxides of Nitrogen Emission

An oxide of nitrogen emission is an indicator of combustion temperature that prevails during the combustion. Higher NOx emission
indicates higher combustion temperature and vice versa. Figure 6.30 shows the variation of NOx emission of E50, E60 and E70 in dual fuel mode of operation at various loads. It is seen that E50 emits higher NOx than E60 and E70. This is due to the high combustion temperature of E50 caused by higher quantity of pilot fuel utilisation and rapid rate of heat release. The utilisation of pilot fuel for dual fuel operation plays a vital role in the combustion behavior. A higher quantity of pilot fuel utilization increases the rate of heat release, reduces the duration of combustion and increases the combustion temperature. This is the main reason for the increase in HC emission with a decrease in pilot quantity. From the observed results, it is found that E50 offers 7% and 11% higher NOx emission than E60 and E70 respectively.

![Graph showing variation of oxides of nitrogen emission of dual fuel operation with different proportions of ethanol.](image)

**Figure 6.30** Variation of oxides of nitrogen emission of dual fuel operation with different proportions of ethanol

### 6.5.6 Smoke Opacity

Figure 6.31 shows the variation of smoke emission of E50, E60 and E70 in dual fuel mode of operation at various loads. It is seen that E50 emits lower smoke than E60 and E70. This is due to the high combustion temperature caused by higher percent of pilot fuel utilization. The higher
percent of pilot fuel utilisation form a stronger ignition source and combust the mixture with a rapid rate of heat release and higher combustion temperature. This is an important reason for the decrease in smoke emission with an increase in pilot fuel utilisation. Hence, E60 and E70 emit higher smoke than E50. From the obtained results, it is seen that E50 offers 7% and 15% lower smoke than E60 and E70 respectively.

![Graph showing variation of smoke emission](image)

**Figure 6.31** Variation of smoke emission of dual fuel operation with different proportions of ethanol

### 6.5.7 Cylinder Pressure

Figure 6.32 shows the variation of cylinder pressure of E50, E60 and E70 in dual fuel mode of operation at full load. It is seen that E50 offers higher cylinder pressure than E60 and E70. This is due to better combustion characteristics of E50 caused by higher quantity of pilot fuel utilisation. The higher quantity of pilot fuel combusts the major fraction of mixture by auto-ignition and increases the heat release rate (Chong Lin et al 2007). The higher heat release rate causes higher combustion temperature and higher cylinder pressure. This is an important reason for the higher cylinder pressure for E50.
The quantity of pilot fuel application determines the combustion characteristics of DF mode. A higher quantity of pilot fuel application offers higher cylinder pressure and lower quantity of pilot fuel offers lower cylinder pressure. From the figure it is seen that the maximum cylinder pressure of ethanol operation retards with an increase in ethanol proportion and decrease in pilot quantity. It is also seen that the peak cylinder pressure decreases with an increase in ethanol proportion. From the observed results, it is found that E50 offers 9% and 18% higher cylinder pressure than E60 and E70 respectively.

![Figure 6.32 Variation of cylinder pressure of dual fuel operation with different proportions of ethanol at full load](image)

### 6.5.8 Heat Release Rate

Figure 6.33 shows the variation of HRR of E50, E60 and E70 in dual fuel mode of operation at full load. It is seen that E50 offers higher HRR than E60 and E70. This is due to the better combustion of E50 caused by the higher percent of pilot fuel utilisation. A higher quantity of pilot fuel utilisation offers higher peak during premixed phase of combustion and hence, E50 offers higher HRR in the first phase of combustion. This is the
main reason for the higher cylinder pressure, higher BTE, higher NOx and low smoke emission of E50 operation (Ekrem et al 2006). This trend reverses when ethanol quantity increases or pilot quantity decreases. A higher quantity of ethanol application reduces the rate of heat release due to the reduction of combustion characteristics. Also, a higher percent of ethanol application uses lower percent of pilot fuel and forms a weaker ignition source.

This weaker source of ignition takes a longer time to complete combustion and offers a lower rate of heat release. This is the main reason for the decrease in heat release rate with decrease in pilot fuel quantity. It is also seen that the first phase of combustion decreases with decrease in pilot quantity. The duration of combustion and ignition delay increases with increase in ethanol quantity (Ekrem et al 2006). From the observed results, it is seen that E50 offers 20% and 32% higher HRR during the premixed phase of combustion than E60 and E70 respectively.

Figure 6.33  Variation of heat release rate of dual fuel operation with different proportions of ethanol at full load
6.6 COMPARISON OF E50 IN DICI MODE AND DUAL FUEL MODE

This part of the work compares the performance, combustion and emission characteristics of E50 in DICI and dual fuel mode. The previous experiments have proved that the application of ethanol more than 50% by volume is difficult in DICI mode. Hence, the application quantity of ethanol in DICI mode has been limited to 50%. However, the dual fuel method has used more than 50% of ethanol in CI engine. The dual fuel mode of operation has a great potential to apply a large quantity of low cetane fuels in CI engines with better performance and emission characteristics.

In DI CI mode of operation, E50 is applied in the form of ethanol diesel blend and in dual fuel mode of operation ethanol and diesel fuel is applied separately using two different fuel admission device. That is, ethanol is applied through manifold injection system and diesel fuel is applied through regular diesel fuel injection system.

6.6.1 Brake Thermal Efficiency

Figure 6.34 compares BTE of DICI mode and Dual fuel (DF) mode of operation. From the figure it is seen that DF mode offers higher BTE than DICI mode of operation. This is due to the progressive combustion of the mixture by flame propagation and shorter duration of combustion. In DF mode two types of combustion occur, such as premixed combustion and diffusive combustion by flame propagation (Can et al 2004). The combined effect shortens the duration of combustion. However, the combustion temperature is not higher than DICI mode of operation. This is due to the combustion of the mixture by flame propagation and the presence of homogeneous mixture.
In all DF mode of operation, the primary fuel has been admitted well before the commencement of combustion. That is the primary fuel has been admitted during the suction stroke. This helps to prepare homogeneous mixture by utilizing the heat from the combustion chamber and the induction manifold without the loss of heat developed by adiabatic compression stroke. Hence, the maximum portion of heat developed by adiabatic compression has been utilised for auto-igniting the mixture of primary and pilot fuel (Bari et al 2002). This is the main reason for the better performance of DF mode compared to DICI mode of operation. The presence of heterogeneous charge due to in-cylinder direct injection and longer duration of diffusive combustion are the important reasons for the lower BTE of DICI mode of operation. From the observed results it is seen that DF mode offers 2 % higher BTE than DICI mode of operation.

![Figure 6.34 Comparison of brake thermal efficiency of E50 in DICI and dual fuel mode of operation](image)

**Figure 6.34** Comparison of brake thermal efficiency of E50 in DICI and dual fuel mode of operation

6.6.2 Carbon monoxide Emission

Figure 6.35 compares CO emission of DICI mode and Dual fuel (DF) mode of operation. From the figure it is seen that DF mode offers higher
CO than DICI mode of operation. This is due to the incomplete combustion of cool layers of charge near the cylinder wall. Generally, DF mode of operation combust the primary fuel air mixture by the flame propagation and offers lower combustion temperature. This is the main reason for the higher CO emission in DF mode.

In addition to it, the DF mode prepares an air fuel mixture in a wider range (beyond the combustible range) due to the inductance of primary fuel well before the commencement of combustion (Bari et al 2002) (during the suction stroke). Out of the prepared range, the lean side mixtures have been combusted partially and released as CO emission during the exhaust stroke. This is another important reason for the high CO emission of DF mode. However, this is inevitable in DF mode of operation. From the observed results it is seen that DF mode offers 3 % higher CO than DICI mode of operation.

![Figure 6.35 Comparison of carbon monoxide emission of E50 in DICI and dual fuel mode of operation](image-url)
6.6.3 Hydrocarbon Emission

Figure 6.36 compares HC emission of DICI mode and Dual fuel (DF) mode of operation. From the figure it is seen that DF mode offers higher HC emission than DICI mode of operation. This is due to the non-penetration of flame in the cylinder corners and crevice volume (Chen et al 2008). The cooled layer of charge near the cylinder wall and the cooler combustion caused by the lower rate of heat release are the other few reasons for the higher HC emission of DF mode.

The DICI mode of operation offers lower HC emission due to the rapid rate of heat release and higher combustion temperature. The charge heterogeneity and the combustion by auto-ignition are the other few reasons for the lower HC emission (Chen et al 2008). More specifically, the HC emission of DICI mode of operation is 0.3 times lower than the DF mode of operation. From the observed results it is seen that DF mode offers 14 % higher HC than DICI mode of operation.

![Figure 6.36 Comparison of hydrocarbon emission of E50 in DICI and dual fuel mode of operation](image)

**Figure 6.36** Comparison of hydrocarbon emission of E50 in DICI and dual fuel mode of operation
6.6.4 Oxides of Nitrogen Emission

Figure 6.37 compares NOx emission of DICI mode and Dual fuel (DF) mode of operation. From the figure it is seen that DF mode offers lower NOx emission than DICI mode of operation. This is due to lower combustion temperature caused by the lower rate of heat release. In DF mode, the primary fuel has been combusted by the flame propagation. The flame propagation combust the mixture progressively and offers a lower combustion temperature (Cenk Sayin 2010). This is the main reason for the lower NOx emission. In addition to it, lower volumetric efficiency and poor oxygen availability are the other few reasons for the lower NOx emission (Cenk Sayin 2010).

On the contrary, the DICI mode of operation emits higher NOx due to the rapid rate of heat release and higher combustion temperature. From the observed results it is seen that DICI mode offers 8% higher NOx emission than the DF mode of operation.

![Figure 6.37 Comparison of oxides of nitrogen emission of E50 in DICI and dual fuel mode of operation](image-url)
6.6.5 Smoke Opacity

Figure 6.38 compares smoke emission of DICI and Dual fuel (DF) mode of operation. From the figure it is seen that the DF mode offers low smoke emission than DICI mode of operation. The lower combustion temperature and charge homogeneity are the two main reasons for the lower smoke emission of DF mode. Basically smoke emission is produced by the instant pyrolysis of fuel spray by higher combustion temperature. The smoke emission of DICI mode of operation is higher than the DF mode of operation as it offers a higher rate of heat release and higher combustion temperature (Senthil Kumar et al 2001a). From the observed results it is seen that the DICI mode offers 7% higher smoke opacity than the DF mode of operation.

![Figure 6.38 Comparison of smoke emission of E50 in DICI and dual fuel mode of operation](image)

6.6.6 Cylinder Pressure

Figure 6.39 compares the cylinder pressure of DICI and Dual fuel (DF) mode of operation. From the figure it is seen that the DF mode offers higher cylinder pressure than DICI mode of operation. This is due to the
combustion of homogeneous mixture by flame propagation and shorter duration of combustion. The higher cylinder pressure of DF mode is the main reason for the higher BTE, lower NOx and low smoke emission of this mode. Though the DICI mode of operation offers a higher rate of heat release and higher combustion temperature, it fails to complete the combustion within shorter duration. This is due to the lower rate of heat release caused by the long duration of diffusive phase of combustion (Senthil Kumar et al 2001b). From the observed results it is seen that the DICI mode offers 6 % lower cylinder pressure than the DF mode of operation.

![Figure 6.39 Comparison of cylinder pressure of E50 in DICI and dual fuel mode of operation at full load](image)

**Figure 6.39** Comparison of cylinder pressure of E50 in DICI and dual fuel mode of operation at full load

### 6.6.7 Heat Release Rate

Figure 6.40 compares HRR of DICI and Dual fuel (DF) mode of operation. From the figure it is seen that the DF mode offers a lower rate of heat release than DICI mode of operation. In DF mode, the combustion occurs by the mixed mode, such as the combustion by auto-ignition and the combustion by flame propagation. The first peak in the heat release curve indicates the premixed combustion by auto-ignition and the second peak
indicates diffusive combustion by flame propagation (Chueung et al 2008). It is also seen that the DF mode offers longer ignition delay and shorter duration of combustion. This is due to the availability of poor oxygen caused by reducing volumetric efficiency and lower temperature of charge (Chueung et al 2008). From the observed results it is seen that the DICI mode offers 32 % higher HRR than the DF mode of operation.

![Heat release rate comparison](image)

**Figure 6.40** Comparison of heat release rate of E50 in DICI and dual fuel mode of operation at full load

### 6.7 COMPARISON OF METHODS

This part of the work compares the methods used for admitting different proportions of ethanol in CI engine. Since ethanol has unsuitable fuel properties for CI engine operation, various engine modifications have been tried in the present research to admit different proportions of ethanol in CI engine. The present work has used four different methods for admitting ethanol range from 10% to 70% by volume. Each method has permitted different proportions of ethanol in CI engine. In addition to it, the present work has used two types of fueling such as blended form of fueling and dual
fueling for admitting different proportions of ethanol in CI engine. The blended form of fueling has been used for admitting ethanol upto 50% and more than 50% has been admitted through dual fuel technique.

The comparison of methods has been made by considering BTE, CO, HC, NOx and Smoke.

6.7.1 Brake Thermal Efficiency

Figure 6.41 Comparison of BTE of different proportions of ethanol used in different methods

Figure 6.41 show that the first method (that uses no engine modification) offers the highest BTE for E20 and the lowest for E40 operation. The highest BTE of E20 is 2% and 5.3% higher than diesel fuel and E40 operation respectively. Second method offers the highest BTE for E30 and the lowest for E50 operation. The highest BTE of E30 is 0.5 and 3.1% higher than E40 and E50 operation respectively. Compared to the previous method, this method offers 3.2 and 4.7% higher BTE for E30 and E40 respectively. Third method has been used for improving E50 operation. In this
method, thermal barrier coating and toroidal bowl piston have been used for improving E50 operation. In addition to it, the E50 has been tested without TBC to study the effect of TBC on ethanol combustion. From the observed results it is seen that E50 offers 1.3% higher BTE than non-TBC operation. It is also seen that this method offered 1.8% higher BTE than the second method. Fourth method offers the highest BTE for E50 and the lowest BTE for E70 operation. The highest BTE of E50 is 1.4 and 1.9% higher than E60 and E70 respectively. It is also seen that the BTE of E50 is 3.1 and 1.3% higher than the second and third method respectively.

### 6.7.2 Carbon monoxide Emission

![Figure 6.42 Comparison of CO emission of different proportions of ethanol used in different methods](image)

Figure 6.42 shows that the first method offers the lowest CO for E20 and the highest CO for E40 operation. The lowest CO of E20 is 5 and 14% lower than diesel fuel and E40 operation respectively. The second method offers the highest CO for E50 and the lowest for E30 operation. The highest CO of E50 is 13 % and 7% higher than E30 and E40 operation.
respectively. Compared to the previous method, this method offers 4 and 3% lower CO for E30 and E40 operation respectively. It is found that the E50 operation of the third method offers 3% lower CO than non-TBC operation and it is 6% lower than the second method. The fourth method offers the highest CO for E70 and the lowest for E50 operation. The highest CO of E70 is 5 and 3% higher than E50 and E60 respectively. It is also seen that the CO emission of E50 operation is 4% lower and 3% higher than second and third method respectively.

6.7.3 Hydrocarbon Emission

![Hydrocarbon Emission Graph](image)

Figure 6.43 Comparison of HC emission of different proportions of ethanol used in different methods

From Figure 6.43 it is found that the first method offers the lowest HC for E10 and the highest HC for E40 operation. The highest HC of E40 is 55% and 65% higher than diesel fuel and E20 operation respectively. The second method offers the highest HC for E50 and the lowest for E30 operation. The highest HC of E50 is 57% and 36% higher than E30 and E40 operation. Compared to the previous method, this method offer 18% and 14%
lower HC for E30 and E40 operation respectively. It is found that the E50 operation of the third method offers 12% lower HC than non-TBC operation and it is 34% lower than the second method. The fourth method offers the highest HC for E70 and the lowest HC for E50 operation. The highest HC of E70 is 11 and 7% higher than E50 and E60 respectively. It is also seen that the HC emission of E50 operation is 25% and 14% higher than second and third method respectively.

6.7.4 Oxides of Nitrogen Emission

From Figure 6.44 it is found that the first method offers the highest NOx for E20 and the lowest NOx for E40 operation. The highest NOx of E20 is 4% and 48% higher than diesel fuel and E40 operation respectively. The second method offers the highest NOx for E30 and the lowest for E50 operation. The highest NOx of E30 is 19% and 44% higher than E40 and E50 operation respectively. Compared to the previous method, this method offers 20% and 17% higher NOx for E40 and E50 operation respectively. It is found
that the E50 operation of third method offers 6% higher NOx than non-TBC operation and it is 22% higher than the second method. The fourth method offers the highest NOx for E50 and the lowest NOx for E70 operation. The highest NOx of E50 is 5% and 10% higher than E60 and E70 respectively. It is also seen that the NOx emission of E50 operation is 4% and 25% lower than second and third method respectively.

6.7.5 Smoke Opacity

![Figure 6.45 Comparison of smoke emission of different proportions of ethanol used in different methods](image)

From Figure 6.45 it is found that the first method offers the lowest smoke for E20 and the highest smoke for E40 operation. The highest smoke of E40 is 30% and 42% higher than diesel fuel and E20 operation respectively. The second method offers the highest smoke for E50 and the lowest for E30 operation. The highest smoke of E50 is 17 and 13% higher than E30 and E40 operation respectively. Compared to the previous method, this method offers 37% and 45% lower smoke for E30 and E40 operation respectively. It is found that the E50 operation of third method offers 9%
lower smoke than non-TBC operation and it is 24% lower than E50 of second method. The fourth method offers the highest smoke for E50 and the lowest smoke for E70 operation. The highest smoke of E50 is 8% and 9% higher than E60 and E70 respectively. It is also seen that the smoke emission of E50 is 29 and 7% lower than second and third method respectively.

### 6.8 COMPARISON OF PRESENT STUDY WITH OTHER KNOWN STUDY

<table>
<thead>
<tr>
<th>S. No</th>
<th>Present study</th>
<th>Other known study</th>
<th>Advantages of present study</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Method 1 used 10, 20 and 30 % ethanol in CI engine in the form of ethanol diesel blend. This method used the engine without any special modification.</td>
<td>Application of ethanol in the form of ethanol diesel blend is a common ethanol admission technique of CI engine. However, this method limits ethanol application upto 15% by volume (Cenk Sayn 2010)</td>
<td>The present study offered 2-2.5% higher BTE and 4-5% lower CO emission. The engine used for this application was optimised for diesel fuel operation.</td>
</tr>
<tr>
<td>2</td>
<td>Method 2 used 30, 40 and 50 % ethanol in CI engine in the form of ethanol diesel blend. This method used modified engine whose operating parameters are specially modified for offering better performance.</td>
<td>Ignition improver method, surface injection method and hot air induction method are the common methods for using ethanol more than 20% by volume (30, 40 and 50 %). Those methods consume additional energy and liberates comparatively higher CO, HC and smoke emissions (Hunter et al 1990).</td>
<td>Consumes comparatively lower additional energy as this method uses lower air-preheat temperature. This method liberates comparatively lower CO, HC and Smoke emission.</td>
</tr>
<tr>
<td>S. No</td>
<td>Present study</td>
<td>Other known study</td>
<td>Advantages of present study</td>
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<td>3</td>
<td>Method 3 used 50% ethanol in CI engine in the form of ethanol diesel blend. This method used engine modifications such as thermal barrier coating, toroidal bowl piston and modified operating parameters</td>
<td>The regular DICI engine with thermal barrier coating is the known method for admitting higher proportion of ethanol in CI engine (George et al 2004, Huseyin Aydin 2013).</td>
<td>The present study offered better performance than regular method as this method used thermal barrier coating, toroidal bowl piston and modified engine operating parameters.</td>
</tr>
</tbody>
</table>
| 4     | Method 4 used thermal barrier coating, toroidal bowl piston and modified operating parameters in dual fuel operation. This new method helps to apply higher fraction of ethanol upto 70% by volume in CI engine. | -regular dual fuel method with hot air induction  
-regular dual fuel method with thermal barrier coating  
are the two common methods for admitting ethanol of more than 50% by volume (Roberto Freitas et al 2014, Srinivas Padala et al 2014). | The present study used all modifications in the engine and hence it offered better performance than regular methods. Also this method offered lower CO, HC and lower smoke emission. |