CHAPTER 4

EXPERIMENTAL SETUP AND PROCEDURE

4.1 PRODUCTION OF BIOETHANOL

The known quantities of sugar molasses (300gram) were taken in fermentation flask and 1litre of water was added. The pH in the sample was maintained in between 6 to 7 and temperature was maintained at 30°C. In the fermentation flask, 2 gram of Baker’s Yeast (Saccharomyces cerevisiae strain) was added with the samples and kept for anaerobic condition by covering the flask with a rubber cork. The anaerobic condition was maintained for 3 to 4 days as shown in Figure 4.1. During the anaerobic condition the actual fermentation reaction took place. In this period the strain converted the sugar into bioethanol with the evolution of CO₂. The fermented sample of 5ml to 10ml was taken up and pinch of potassium dichromate and few drops of sulphuric acid were added. The colour of the fermented sample changed from pink to green which indicated the presence of bioethanol in the sample. The fermentation samples were collected for every 12 hours interval and transferred to distillation chamber to get bioethanol by using simple distillation method as shown in Figure 4.2.

After the distillation process, the concentration of bioethanol was measured by using UV-VIS Spectrophotometer (Hitachi-Japan) as shown in Figure 4.3. The spectrophotometer is based on Beer-Lambert law which relates the amount of light transmitted through a colored solution to be a function of the length of light path and the concentration of the absorbing
media. It is made up basically of a light source which can be the visible or ultraviolet region, a monochromator, the sample cell and the detectors or photocells.

Figure 4.1 Setup for fermentation of sugar molasses

Figure 4.2 Simple distillation method
The light source is usually a hydrogen or deuterium lamp for capable of operating within the UV spectrum. The monochromator are made of grating or prisms to produce light with a slit width wavelength range of 5mm. The incident light of particular wavelength selected with the monochromator is absorbed by the test solution resulting in lowered intensity of transmitted light. The photomultiplier sends signal to the photometer to display the result. The obtained bioethanol was distilled four times to get maximum concentration of bioethanol.

![Figure 4.3 UV-VIS Spectrophotometer](image)

4.1.1 Optimization of Bioethanol Concentration

During the production of bioethanol, the production process was investigated step by step. The optimal value of each parameter involved in the process was determined while the rest of the parameters were kept constant. After each optimal value was attained, this value was adopted in the optimization of the next parameters (Eevera et al. 2009). In this process, four variables namely pH, fermentation temperature, sugar molasses concentration and yeast concentration were individually considered. The value of each
variable at which maximum yield of bioethanol obtained was noted. The effects of these variables on the maximum yield of production of bioethanol are discussed in the chapter 5.

4.1.2 Estimation of Bioethanol Concentration

Different concentration of bioethanol, from 1% to 99%, was prepared with double distilled water. One ml of the solution was made up with 24ml of distilled water in a distillation flask and distilled completely. The condensate was collected (10 ml to 15ml) in a volumetric flask containing 25ml of 3.4% chromic acid. This was made up to 50ml with double distilled water and mixed thoroughly. This condensate was heated at $80^\circ$C for 15 minutes and cooled. Absorbance was read at 580nm with chromic acid and distilled (1:1) as blank by using an UV-VIS Spectrophotometer (Hitachi-Japan). A standard graph with concentration of ethanol on X-axis and optical density at 580nm on Y-axis was plotted as shown in the Figure 4.4. The bioethanol concentration was calculated from the following graph by plotting the optical density (OD) values (Sadasivam and Manickam, 2007).

![Figure 4.4 Standard graph for measurement of bioethanol concentration](image-url)
4.2 PRODUCTION OF METHYL AND ETHYL ESTERS

4.2.1 Transesterification Process and Unit

Transesterification is an effective way to reduce the viscosity of the vegetable oils. During the process of transesterification, triglyceride of vegetable oil react with alcohol (methanol/ethanol) in the presence of catalyst say NaOH or KOH and form glycerol and vegetable oil ester. A specified quantity of vegetable oil was taken in a reaction unit. A required quantity of any one alcohol (methanol/ethanol) and a few grams of a catalyst commonly NaOH or KOH were thoroughly mixed until it was properly dissolved. This solution was mixed with vegetable oil in the reaction unit. The contents were heated up to 60°-70°C and stirred vigorously till the ester was formed. Then the solution was allowed to settle for 8 hours to 10 hours in the separating funnel and two different layers were formed. The bottom layer was glycerol and water and the top was the ester. The bottom layer was separated by pouring out through a separator valve fitted below. Then the contents were washed with distilled water and allowed to settle overnight in a separator vessel. The product was heated for sufficient time at temperature over 110°C for expelling any remaining water. The final resulting methyl or ethyl ester was collected and cooled down to room temperature. The photographic view of the transesterification unit with accessories and dismantled view of unit used in the investigation are shown in Figures 4.5 and 4.6 respectively.

Biodiesel production unit consisted of stainless steel container, with a capacity of six litres and a variable speed D.C motor was fixed on to the top of the container. The mechanical stirrer was attached with D.C. motor through the shaft. The speed of the stirrer was easily varied with the help of an electronic speed regulator. The stirrer consisted of eight stainless steel blades at an angle of 45° and oriented at 45° to the base. A heater having a capacity of 1.5 kW was fixed at the bottom of the container for heating the oil. A
temperature control unit was used to vary the temperature of oil. The temperature of the oil was measured by using Chromel Alumel (k-type) thermocouple along with digital temperature indicator. An electronic microprocessor unit was used to control the motor speed and the temperature. The cooling fan was provided inside the electronic kit to absorb the heat from the transformer and integrated circuits. The inlet valve at the top of the reactor was used to feed the vegetable oil, reactant and catalyst. The drain valve located at the bottom of the reactor was used to collect transesterified product.

Figure 4.5 Photographic view of Transesterification unit

Figure 4.6 View of dismantled Transesterification unit
This unit was used for production of two different esters namely (i) Methyl ester of cotton seed oil (MECSO) (ii) Ethyl ester of Pongamia oil (EEPO) considered in this investigation. The production method of these two fuels is explained in the subsequent sections.

4.2.2 Optimization of Yield of MECSO and EEPO

The increasing biodiesel consumption requires optimized production processes that are compactable with high production capacity, feature simplified operations, high yield, quantity of catalyst, solvent requirements and waste streams reaction are investigated systematically. The production process was investigated step by step. The optimal value of each parameter involved in the process was determined while the rest of the parameters were kept constant. After each optimal value was attained, this value was adopted in the optimization of the next parameters. (Eevera et al 2009).

4.2.3 Methyl Ester of Cottonseed Oil

A specified quantity of Cottonseed oil (2400 ml) was taken in the reactor. 400 ml of Methanol and 14 g of potassium hydroxide (KOH) were thoroughly mixed until the mixture was properly dissolved. Then, this mixture was mixed with cottonseed oil in the reactor. The methoxide solution with cottonseed oil was heated to 60ºC with a different stirred speed of 350 rpm to 550 rpm for the period of 60 minutes. Then the solution was allowed to settle for 8 hours in the separating funnel and two distinct liquid phases were identified. The crude esters phase was observed at the top and glycerol phase were observed at the bottom. After that, a washing process was carried out to remove some unreacted remainder of methanol and catalyst by using double distillated water for four times. After washing, the methyl ester contained some amount of dissolved water molecules. Methyl ester was again heated to 110ºC to remove the dissolved water molecules for 10 minutes to 15 minutes. The pure methyl ester was collected and stored in separating funnel as shown
in Figure 4.7. Finally, the purified methyl ester of cottonseed oil was cooled down to room temperature.

In this investigation three variables, stirrer speed, reaction time and types of catalyst and its quantity were sequentially varied to find out the maximum yield of MECSO. The effect of these three variables on maximum yield of MECSO is explained in the chapter 5.

![Figure 4.7 Photographic view of pure MECSO](image)

4.2.4 Ethyl Ester of Pongamia Oil (EEPO)

A specified quantity of Pongamia oil (2400ml) was taken in the reactor. 400 ml of ethanol and 14g of potassium hydroxide (KOH) were mixed together to form a mixture until it was properly dissolved. This solution was mixed with Pongamia oil and stirred properly. The prepared solution with Pongamia was heated to 70°C and continuously stirred with a stirrer speed of 550 rpm for the period of 90 minutes. The solution was poured down to the separating funnel and was allowed to settle for 10 hours. The glycerin settled at the bottom and the ethyl ester floated at the top. Ethyl ester was separated from the glycerin. After that, a washing process was carried out to remove some unreacted remainder of ethanol and catalyst by using double distillated water for four times. After washing, the ethyl ester contains some amount of dissolved water molecules. Ethyl ester was heated
up to 110°C and maintained for 10 minutes to 15 minutes to remove the dissolved water molecules. Finally, the purified ethyl ester was cooled down to obtain the ethyl ester of pongamia oil.

In the production of EEPO also, stirrer speed, reaction time and the quantity of catalyst were sequentially varied to find out the maximum yield of EEPO. The effect of these three variables on maximum yield of EEPO is also explained in the chapter 5.

4.3 FUEL STABILITY TEST

The fixed percentage of bioethanol, diesel and any one selected additive were mixed into a homogenous blend in a container by stirring it. The blends were kept in a glass tube with sealed rubber cork at room temperature to prevent leakage. All the blends were observed for phase separation at an interval of half an hour for observing the stability and solubility. The mixtures were weighed and verified with the initial weight for weight loss due to evaporation. Moreover, all the samples were kept for three to four months to observe the long term stability (Huang et al 2009). The Figure 4.8 shows the arrangement for stability test.

Figure 4.8 Stability test
4.4 MEASUREMENT OF FUEL PROPERTIES

4.4.1 Measurement of Relative Density

A hydrometer is an instrument used to measure the relative density of the blends as shown in Figure 4.9. A hydrometer is usually made of glass and consists of a cylindrical stem and a bulb weighted with mercury or lead shot to make it float upright. The liquid to be tested is poured into a tall container and the hydrometer is gently lowered into the liquid until it floats freely. The point at which the surface of the liquid touches the stem of the hydrometer was noted. Hydrometers usually contain a scale inside the stem, so that the relative density can be read directly (Xing-cai et al 2004).

![Figure 4.9 Photographic view of hydrometer](image)

4.4.2 Measurement of Viscosity

Redwood viscometer is shown in Figure 4.10, and it was used to measure the viscosity of the blends. A 50ml small flask was used to receive the oil from the jet outlet. The leveled oil cup was cleaned and the ball and the ball valve were placed on the agate to close it. The test oil (any one blends) was filled in the cup up to the pointer level. The empty flash was placed just
below the jar. Water was filled in the bath. The heater was switched on, to obtain the required temperature. When the blended fuel reached the desired temperature, the ball valve was lifted and suspended from the thermometer bracket. The time required for 50ml of the blended fuel to collect in the flask was noted and the valve was immediately closed to prevent any overflow of oil (Xing-cai et al 2004). The dynamic viscosity was calculated from the following equations (2.1) and (2.2) by using the time variations.

\[
\mu = 0.0026 \frac{t}{t-1.79} \text{ for } t \text{ up to 100 second} \tag{4.1}
\]

\[
\mu = 0.00247 \frac{t}{t-0.5} \text{ for } t > 100 \text{ second} \tag{4.2}
\]

where \( \mu \) = dynamic viscosity in centistokes

\( t \) = flow time in second

**Figure 4.10 Photographic view of red wood viscometer**

Initially, the experiment was conducted at 35ºC for the blended fuels. Similarly, the same procedure was repeated for all blended fuels at
different temperatures such as 40°C, 45°C, 50°C, 55°C and 60°C and the viscosity was found out.

4.4.3 Measurement of Flash Point

Pensky Martens flash point closed apparatus was used for the measurement of the flash point of the blends as shown in the Figure 4.11. The required level of blended fuel was filled in the removable test cup. The temperature of the cup was raised with the help of the heater arrangement. In this case, the blends were filled in the cup as required and cup was placed in the collection of ice cubes for measurement of flash point. The temperature of the blend started to decrease and at the same time ignition source could be introduced. The temperature at which the blend ignited was measured by thermocouple attached with the arrangement (Xing-cai et al 2004).

Figure 4.11 Photographic view of pensky martens apparatus

4.4.4 Measurement of Calorific Value

The bomb calorimeter was used to measure the calorific value of the blends. The heating values of the different bioethanol - diesel blends with
different additives were measured in an “Advance (ARICO) bomb calorimeter” as shown in Figure 4.12. According to ASTM D2015 standard method, an oxygen-bomb was pressurized to 25kg/cm² with oxygen. The bomb was fired automatically after the jacket and bucket temperatures equilibrated within acceptable accuracy of each other. The calibration of the bomb calorimeter was carried out by using the standard benzoic acid samples which were obtained from Advance Research Instrument Company (ARICO) New Delhi (Xing-cai et al 2004).

![Figure 4.12 Photographic view of bomb calorimeter](image)

### 4.4.5 Quantitative and Qualitative Analysis

Apart from physical properties, chemical properties are also very important factors for determining the quantity and quality of raw oil and bio diesel because, bio diesel can be significantly contaminated with both free and bound glycerol, triglycerides and alcohol due to transesterification. It influences the performance, combustion and emission of the engine. Chromatography is a separation technique used for separating a mixture into its components. It consists of a stationary phase through which a mobile phase
percolates. When a sample is introduced in this system due to inter-molecular force of attraction, the stationary phase tries to retain the sample components whereas the mobile phase tries to carry away as it percolates. As a result, the components move down the column with a speed depending upon their relative affinity towards stationary phase and mobile phase components in a mixture. Hence each component in the mixture moves down the column with different speed and come out of the column successively.

The components coming out of the column can be collected using a fraction collector for preparative work or it can be fed into a detector for quantitative and qualitative analysis. The quantitative analysis is very much useful for knowing the percentage of fatty acids and its esters in the raw oil, purified oil and bio diesel. The qualitative analysis is also very useful to determine the quality of raw oil, purified oil and bio diesel that is conversion of triglycerides into fatty acid alkyl esters (bio diesel). The capillary gas chromatography (GC) can provide quantitative and qualitative information about the concentrations of contaminants in bio diesel. This method is appropriate for measuring minor and major components in samples. It gives a high reliability of results and has simple instrumentation. It requires a small amount of sample preparation and has a short analysis time (Adam Karl Khan 2002).

4.4.5.1 Quantitative analysis

The quantitative analysis is useful for identifying the amount of fatty acids present in the oil and bio diesel in the various stages of bio diesel production. Because, the quality of bio diesel depends on the quantity of unwanted glycerol and free fatty acids are removed from the oil. These factors are mainly responsible for the quantity of bio diesel yield and quality of the fuel property.
To identify the composition of fatty acids present in the oil and biodiesel, an Agilent 6890N model gas chromatography is used which is shown in Figure 4.13. The instrument was equipped with auto sampler and hydrogen used as a carrier gas fused with silicon capillary column 25 m long 0.2 mm inner diameter and film thicknesses of 0.33 µm. GC injector was in a split mode 100:1 ratio. Injector temperature was 250ºC, detector temperature was 300ºC and oven temperature was 170 - 300ºC with a ramp (rise in temperature) of 5ºC per minute. The MIDI-SHERLOCK software version 4.5 was used for analyzing quantity of compounds.

![Figure 4.13 Photographic view of gas chromatography (AGILENT 6890N model)](image)

**4.4.5.2 Qualitative analysis**

Gas Chromatography-Mass Spectrometry (GC-MS) is a method that combines the features of gas-liquid chromatography and mass spectrometry to identify different substances within a test sample and identification of unknown samples. Additionally, it can identify trace elements in materials that were previously thought to have disintegrated beyond identification. The gas chromatograph utilizes a capillary column which depends on the column's dimensions (length, diameter, film thickness)
as well as the phase properties (example 5% phenyl) polysiloxane. The
difference in the chemical properties between different molecules in a mixture
will separate the molecules as the sample travels through the length of the
column. The molecules take different period of time (called the retention
time) to come out of (elute from) the gas chromatograph and this allows the
mass spectrometer downstream to capture, ionize, accelerate, deflect and
detect the ionized molecules separately. The mass spectrometer does this by
breaking each molecule into ionized fragments and detecting these fragments
using their mass to charge ratio.

The qualitative analysis of GC-MS is performed for the observed
compounds present in every step and also the nature of compounds change
during the various processes during bio diesel formation. It also identifies the
components in the compounds, molecular weight and purity of compounds by
this analysis it come to know that conversion or interchange in the compounds
by transesterification process. Transesterification process is the conversion of
triglycerides into fatty acid alkyl esters (bio diesel) that needs to be separated
from several impurities and compounds. The conversion of triglyceride to
fatty acid methyl ester takes place in different phases and is determined by
knowing the compound and its quality, Hence it is required to perform the
GC-MS to identify unknown compounds in the samples at each phase. The
compounds were identified mainly by comparing their mass spectra with
those of the standard compounds in the NIST and Wiley library, together with
the comparison of their GC retention times with those of standard compounds
and were confirmed by the standard addition technique. Tentatively the
components are identified based only on comparison of the mass spectra with
the reference spectra of the NIST and WILEY library that yielded more than
90% matches (Plonjarean et al 2007).
The GC-MS analysis was performed on a FISON (GC) 8000 series/MD 800 which is shown in Figure 4.14. Separation was achieved using helium as the carrier gas (1 ml / min) with a fused silica capillary column 30m long, inner diameter 5 micron and 0.5 micron film thickness. The GC injector was in a split less mode. Injector and detector temperature were 250°C and 260°C respectively. The oven temperature was ranges from 100°C to 250°C. The effluent from the capillary column went directly into mass spectrometer. This instrument was operated is the full scan and electron impact ionization mode with an ionizationation voltage 70eV and an acceleration voltage of 70V the iron source temperature was 200°C and the GC-MS transfer line was set to 250 °C. The sample was diluted with petroleum ether; the data is compared with NIST and WILEY library to know the peak compounds.

Figure 4.14  Photographic view of gas chromatography mass spectrum analyzer. (FISON (GC) 8000 SERIES / MD 800)
4.5 RESPONSE SURFACE METHODOLOGY MODEL FOR OPTIMIZATION OF BIOETHANOL, MECSO AND EEPO

Response surface methodology (RSM) is an empirical statistical modeling technique employed for multiple regression analysis using quantitative data obtained from properly designed experiments to solve multivariate equations simultaneously (Rao et al., 2000). A Box Behnken Design (BBD) with three factors at three levels was used to design the experiments. Box–Behnken is a spherical, revolving response surface methodology design that consists of a central point and the middle points of the edges of the cube circumscribed on the sphere. It consists of three interlocking $2^2$ factorial designs with points lying on the surface of a sphere surrounding the center of the design. This design has been applied for several chemical and physical processes to study the effect of process variables and the numbers of experiments are decided accordingly (Kumar et al., 2007).

The process parameters (independent variables) were selected for the optimization was stirring speed, retention time and KOH concentration. The number of experiments (N) required for the development of BBD is defined as $N=2k (k-1) + C_o$ (where k is number of factors and $C_o$ is the number of central point). The design included 17 experiments and with 5 central points. Each independent variable was coded at three levels between +1, 0 and -1, whereas stirring speed: 350-550; retention time: 50-90 min and KOH concentration: 12-16g respectively. Coding of the variables was done according to the following equation:

$$x_i = \frac{X_i - X_{cp}}{\Delta X_i} \quad i = 1, 2, 3, \ldots, k$$ (4.3)

where $x_i$, dimensionless value of an independent variable; $X_i$, real value of an independent variable; $X_{cp}$, real value of an independent variable at the center
point; and $\Delta X_i$, step change of real value of the variable $i$ corresponding to a variation of a unit for the dimensionless value of the variable $i$.

Performance of the process was evaluated by analyzing the responses ($Y$), which depend on the input factors $x_1, x_2, \ldots, x_k$, and the relationship between the response and the input process parameters is described by

$$
Y = f(x_1, x_2, \ldots, x_k) + e
$$

(4.4)

where $f$ is the real response function the format of which is unknown and $e$ is the error which describes the differentiation.

A second-order polynomial equation was used to fit the experimental data to identify the relevant model terms using statistical software (Design Expert 8.0.7.1). A quadratic model, which also includes the linear model, can be described as

$$
Y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{j=1}^{k} \sum_{j\neq j}^{k} \beta_{ij} x_i x_j + e_i
$$

(4.5)

where $Y$ is the response; $x_i$ and $x_j$ are variables ($i$ and $j$ range from 1 to $k$); $\beta_0$ is the model intercept coefficient; $\beta_j$, $\beta_{jj}$ and $\beta_{ij}$ are interaction coefficients of linear, quadratic and the second-order terms, respectively; $k$ is the number of independent parameters ($k=4$ in this study); and $e_i$ is the error (Sridhar et al 2011).

The statistical analysis was performed using Design Expert Statistical Software package 8.0.7.1 (Stat Ease Inc., Minneapolis, USA). The experimental data was analyzed using multiple regressions and the significance of regression coefficients was evaluated by $F$-test. Modeling was
started with a quadratic model including linear, squared and interaction terms and the model adequacies were checked in terms of the values of $R^2$, adjusted $R^2$ and prediction error sum of squares (PRESS). The significant terms in the model were found by Pareto analysis of variance (ANOVA) for each response and ANOVA tables were generated. The regression coefficients were used to make statistical calculations to generate response surface plots from the regression models.

The optimization of the process parameters were performed by numerical optimization technique using Derringer’s desirability function method. This function searches for a combination of factor levels that jointly optimize a set of responses by satisfying the requirements for each response in the design. The optimization is accomplished by converting each response $Y_i$ ($i = 1, 2, \ldots, m$) into a dimensionless desirability scale that defines a partial desirability function ($d_i$), combining the individual desirabilities to obtain the composite or global desirability function ($D$), and finally maximizing the $D$ and identifying the optimal factor settings. The scale of the desirability function ranges between 0 (completely undesirable response) to 1 (fully desired response) (Gonzalez et al 2007).

The individual desirabilities ($d$) for each response are obtained by specifying the goals, i.e., minimize, maximize or target the response, and boundaries required for each one. A weight factor, which defines the shape of the desirability function for each response, is then assigned. Weights must be between 0.1 and 10, with larger weights corresponding to more important responses. A weight factor of 1 was chosen for all individual desirabilities in this work. The importance of a goal can be changed in relation to the other goals. It can range from 1 (least importance) to 5 (most important). The default is for all goals to be equally important in a setting of 3.
4.6 ENGINE EXPERIMENTAL SETUP AND PROCEDURE

4.6.1 Description of the Engine

A single cylinder, water cooled, four stroke direct injection compression ignition engine with a displacement volume of 553cc, compression ratio of 16.5:1, developing 3.7 kW at 1500 rpm was used in the present study for the analysis of performance and emissions characteristics. The layout of the experimental setup used in this present study is shown in Figures 4.15. The photographic view of the experimental setup used for performance and emissions analysis is shown in Figure 4.16. The specifications of the engine used for performance and emissions analysis are given in Appendix 1.

The engine is fitted with conventional fuel injection system, which has a three hole nozzle of 0.2mm separated at 120 degrees, inclined at an angle of 60 degrees to the cylinder axis. The injector opening pressure recommended by the manufacturer was 200 bar. The injection system of the engine was periodically cleaned and calibrated as recommended by the manufacturer. The injection timing was 23° bTDC (spill). The governor was used to maintain constant speed under varying load conditions, which controlled the fuel flow as load changes over engine. The engine had an open combustion chamber with overhead valves operated through push rods.

For the present study on combustion analysis, a single cylinder, water cooled, four stroke direct injection compression ignition engine with a displacement volume of 661cc, compression ratio of 17.5:1, developing 5.9 kW at 1800 rpm was used. The photographic view of the experimental setup
used for combustion analysis is shown in Figure 4.17. The specifications of the engine used for combustion analysis are given in Appendix 1(A).

![Diagram of experimental setup](image1)

**Figure 4.15 Layout of experimental setup**

![Photograph of experimental setup](image2)

**Figure 4.16 Photographic view of the experimental setup used for Performance and emissions analysis**
4.6.2 Engine Instrumentation

4.6.2.1 Load and speed measurement

The test engine was directly coupled to an eddy current dynamometer with suitable switching and control facility for loading the engine. The length of torque arm of the dynamometer was 0.24m. The output measurements were made from a microprocessor based load cell. The specifications of the dynamometer are given in Appendix 2. The engine was set to run at a constant speed of 1500rpm. The load of the engine was obtained from load cell reading. The speed of the engine was monitored using photo sensor along with digital speed indicator.

4.6.2.2 Fuel flow rate measurement

Fuel flow rate was measured on the volume basis using a burette and stop watch. The fuel from the tank is sent to the engine through a
graduated burette using a two way valve. When the valve is set at position 1 the fuel is sent to the engine directly and in position 2 the fuel contained in the burette is sent to the engine. For the measurement of fuel flow rate of the engine, the valve is set at position 2 and the time for a definite quantity of the fuel flow is noted. This gives the fuel flow rate for the engine.

4.6.2.3 Air flow rate measurement

The inlet manifold of the engine is connected to the surge tank to avoid pressure fluctuation at the inlet. A calibrated turbine type flow meter is attached to the tank which is directed to the atmosphere. This is done with due care that there is no air leakage. During the engine operation the air to the engine from the atmosphere is through the flow meter. The time required for the intake of a definite quantity of air gives the air flow rate of the engine.

4.6.2.4 Temperature measurement

Temperature of the cooling water inlet, outlet and exhaust gas was measured by using Chromel Alumel (K-Type) thermocouples. A digital indicator with an automatic room temperature compensation facility was used and it was calibrated periodically.

4.6.2.5 Emission measurement

The exhaust emissions namely NO\textsubscript{x}, HC, CO, CO\textsubscript{2} and O\textsubscript{2} were measured with the help of an AVL 444 exhaust gas analyser. The oxides of nitrogen (NO\textsubscript{x}) were measured by chemical reaction method. The carbon monoxide and carbon dioxide emission were measured by using Non-Dispersive Infra Red (NDIR) analyzer and unburned hydrocarbons (UBHC) was measured by Flame Ionization Detector which is a well established and accepted method for measuring unburned hydrocarbons. Oxygen was
measured by using Lamda sensor. The AVL five-gas analyzer is shown in Figure 4.18. The measuring range, accuracy and resolution of AVL 444 exhaust gas analyser is given in Table 4.1. The specification of the gas analyzer is given in Appendix 3.

![Photographic views of AVL 437 standard smokemeter and AVL 444 digas analyzer](image)

**Table 4.1 Measuring range, accuracy and resolution of AVL 444 gas analyser**

<table>
<thead>
<tr>
<th>Exhaust gas</th>
<th>Measuring range</th>
<th>Resolution</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>0 – 10 % vol.</td>
<td>0.01 % vol.</td>
<td>&lt;0.6% vol.: ±0.03% vol.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>≥0.6% vol.: ±5% of ind. val.</td>
</tr>
<tr>
<td>HC</td>
<td>0 – 20000 ppm vol</td>
<td>≤ 2000 ppm: 1 ppm vol.</td>
<td>&lt; 200 ppm vol.: ±10 ppm vol.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;2000 ppm: 10 ppm vol.</td>
<td>≥ 200 ppm vol.: ±5% of ind. val.</td>
</tr>
<tr>
<td>CO_2</td>
<td>0 – 20% vol</td>
<td>0.1% vol.</td>
<td>&lt; 10% vol.: ±0.5% vol.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>≥ 10% vol.: ±5% vol.</td>
</tr>
<tr>
<td>O_2</td>
<td>0 – 22 vol. %</td>
<td>0.01% vol.</td>
<td>&lt; 2% vol.: ±0.1% vol.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>≥ 2% vol.: ±5% vol.</td>
</tr>
<tr>
<td>NOx</td>
<td>0 – 5000 ppm</td>
<td>1 ppm vol.</td>
<td>&lt; 500 ppm vol.: ±50 ppm vol.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>≥ 500 ppm vol.: ±10% of ind. val.</td>
</tr>
</tbody>
</table>
The intensity of smoke was measured by light obscuration method, in which the intensity of a light beam was reduced by smoke, which was a measure of smoke intensity. The AVL 437 smoke meter is shown in Figure 4.18. The specification of the smoke meter is given in Appendix 4.

<table>
<thead>
<tr>
<th>Quality</th>
<th>Measuring range</th>
<th>Accuracy</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smoke Opacity</td>
<td>0 – 100%</td>
<td>± 1% of full scale</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

4.6.2.6 Engine Instrumentation used in Combustion Analysis

4.6.2.6.1 Pressure Measurement

The AVL water cooled flush mounted piezoelectric transducer was used to measure the cylinder pressure. The sensitivity of AVL pressure transducer used in the present study is 36.8 PC/bar. The transducer was flush mounted in the cylinder head to eliminate errors due to the passage restriction. A hole was drilled vertically through the cylinder head to mount the pressure transducer. The pressure transducer is used to measure the dynamic pressure inside the cylinder. The change in value of compression ratio of the engine as a result of the additional volume formed by connecting passage is negligible. It was also estimated that an error of only 0.5 degree crank angle or less could result due to the propagation of pressure wave through the communication passage. A piezoelectric transducer produces a charge output, proportional to the in-cylinder pressure. The charge output was supplied to an AVL charge amplifier and it was amplified as an equivalent voltage which was converted to the actual pressure. The photographic view of AVL pressure transducer is shown in Figure 4.19.
4.6.2.6.2 Crank Angle Marker

For the measurement of cylinder pressure with respect to the crank position, a crank angle marker, an electromagnetic pickup and signal-processing unit were used. The marker was fitted concentrically to the end of the crankshaft. The photographic view of crank angle marker is shown in Figure 4.20.
4.6.2.6.3 Charge Amplifier

In order to obtain sharp, flicker free and stable signal of any desired portion of the cylinder pressure trace, the charge amplifier was used. The pickup was suitably positioned with respect to single pulse generator installed on the extension of the generator shaft and the signal derived from the pickup was fed to a charge amplifier. The output of the amplifier is sent to the computer.

4.6.2.6.4 Data Acquisition System

The AVL Indimeter software is easy to operate and it contains menu driven parameter editor for setting up the system, utilized for TDC detection, the numerical monitor for on-line display of calculated results like Indicated Mean Effective Pressure (IMEP) or mass burn fractions as well as monitor program for oscilloscope like graph display. This versatile software designed by AVL, Austria was used for on-line data acquisition from the pressure transducer and crank angle marker. The AVL indiwin software is used to calculate the various heat release parameter. The photographic view of data acquisition system is shown in Figure 4.21.
4.6.3 Scheme of Experimentation

The tests were carried out at steady states with different loads at the constant engine speed of 1500rpm. The original mechanical fuel injection system was used for injecting diesel or different blends. Initially the engine was allowed to run with diesel for nearly 30 minutes to attain the steady state conditions at the lowest possible load before taking readings. For each engine mode, the engine was allowed to run for at least 3 minutes until the exhaust gas temperature and the CO₂ concentrations reached steady state values and data were measured subsequently. The exhaust gas analyzer and smoke meter were switched on quite early so that all its systems would get stabilized before the commencement of the experiment. For taking exhaust emission and smoke readings, the exhaust gas was allowed to flow for 3 minutes before reading were recorded. The probe of the equipment was frequently cleaned for removing the carbon deposits. The load on the engine was controlled by the dynamometer while keeping the engine at constant speed.

After the engine stabilized for a particular operating point, fuel flow, cooling water inlet and outlet temperature and exhaust temperature were recorded. The exhaust gas was made to pass through the probe of exhaust gas analyzer for measurement of CO, CO₂, O₂, HC and NOₓ and then passed through the probe of smoke meter for the measurement of smoke density. The observations were made twice for concordance. Before start of the experiment with new fuel variant, fuel of the previous experiment was completely purged from the fuel line, filter, fuel pump and fuel tank. The engine was left to operate for few minutes to stabilize at its new condition. The experimental work started with a preliminary investigation of the engine running on neat diesel fuel, to determine the engine characteristics and exhaust emission levels constituting the baseline. The same procedure was repeated for each fuel blends by keeping the same operating conditions. The
differences in the measured performance and exhaust emission parameters from the baseline operation of the engine and all fuel blends tested were determined and compared. The temperature of cooling water was maintained in between 60°C to 65°C for throughout the tests. The cylinder pressure traces of 200 cycles and their average were measured and stored in a computer hard disc for the same operating conditions of performance and emission analysis. Sufficient care was taken to label the data for post processing. Each test was repeated for three times and the results of the three repetitions were averaged to ensure the reproducibility of data.

The different category of fuels tested in these investigations is given in Table 3.1. After completing the experiment with the different blended fuels, the engine was allowed to run for about half an hour with diesel to eliminate the interference of the previous blended fuels. The diesel fuel was then retested to check repeatability. The results tended to confirm the result of the first run with diesel fuel. From the measured values, the performance parameters like Brake power (BP), Fuel Consumption (FC), Fuel power (FP) and Brake Thermal Efficiency (BTE) were calculated and sample calculation is given in Appendix A.5(A).

4.6.4 Experimental Uncertainty

Any measurement, irrespective of the type of instrument used, possesses a certain amount of uncertainty or error. Some of these errors are of random nature and needs a device to specify consistently the uncertainty in analytical form. Hence, a brief attempt is made to estimate the magnitude of uncertainty in various measurements by theoretical methods. The uncertainties for the basic measurements such as barometer pressure, length, weight, temperature, time etc., are equal to the least count of respective instruments. While carrying out the error analysis, probable uncertainties
involved in the measurement of various parameters are taken into consideration. The method prescribed by Kline and McClintock (1953), discussed in Holman (1997) has been used to carry out the error analysis. First the method has been described in Appendix A.5 (B). The method of arrival of uncertainties for the derived quantities such as brake power (BP), fuel consumption (FC), fuel power (FP) and brake thermal efficiency (BTE) with sample calculation is given in Appendix A.5(C). The uncertainty of some derived quantities is given in Table 4.3.

Table 4.3 Uncertainty of some derived parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Percentage of Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brake power</td>
<td>1.08</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>0.25</td>
</tr>
<tr>
<td>Fuel power</td>
<td>0.25</td>
</tr>
<tr>
<td>Brake thermal efficiency</td>
<td>1.108</td>
</tr>
<tr>
<td>Airflow</td>
<td>0.6481</td>
</tr>
<tr>
<td>Fuel flow</td>
<td>0.7319</td>
</tr>
<tr>
<td>Viscosity</td>
<td>0.7</td>
</tr>
</tbody>
</table>

The uncertainty of some measured quantities such as HC, CO, CO₂, NOx and smoke are equal to the resolution of the respective quantity which are referred from the Tables 4.1 and 4.2. It can be observed that the uncertainties involved in the various parameters were with in the limited values. Therefore, these uncertainties values may not affect the accuracy of results. The results obtained from the detailed experimental investigations are presented and discussed in the forth coming chapter.