CHAPTER 4

EXPERIMENTAL SETUP AND PROCEDURE

4.1 EXPERIMENTAL SETUP

An experimental setup was made with necessary instruments to evaluate the performance, emission and combustion parameters of the engine. The overall view of the experimental setup is shown in Figure 4.1 and Figure 4.2. This chapter discusses the details of the experimental setup, instruments used and software needed for the work.

![Diagram of experimental setup]

1. Engine (Appendix 1, pp 151)  
2. Eddy current dynamometer  
3. Diesel fuel tank  
4. CSO fuel tank  
5. Cylinder pressure transducer  
6. Charge amplifier  
7. Analog to digital convertor  
8. Computer  
9. TDC pickup  
10. Exhaust gas analyzer  
11. Air surge tank  
12. Fly wheel

Figure 4.1 Schematic diagram of the experimental set up
4.1.1 Test engine

A 661cc, single cylinder, water cooled, four stroke direct injection compression ignition engine with a compression ratio of 17.5: 1, developing 5.2 kW power at 1500 rpm was used for this work. The details of the engine are given in Appendix 1. The engine was always run at its rated speed of 1500 rpm the governor of the engine was used to control the speed of the engine. Cooling of the engine was accomplished by supplying water through the jackets on the engine block and cylinder head. The engine had a hemispherical combustion chamber with overhead valves operated through push rods. The injection system of the engine was periodically cleaned and calibrated as recommended by the manufacturer. This engine was modified to operate in the semi adiabatic mode by coating the piston crown and head with partially stabilized zirconia. Pre heating of the vegetable oil was done by electrical heaters in a vessel. The test engine is shown in Figure 4. 3.
4.1.2 Air and Fuel Flow Measurement

An orifice meter connected to an air surge tank was attached to the inlet manifold of the engine to measure airflow. The fuel flow rate was measured on volume basis using a burette and a stop watch.

4.1.3 Computerized digital data acquisition system

The cylinder pressure and TDC signals were acquired and stored on a high speed computer based digital data acquisition system. Data from multiple cycles were stored continuously at each operating condition. Recorded signals were processed to obtain combustion parameters like peak pressure, maximum rate of pressure rise, heat release rate etc. The heat release rate was obtained based on the method outlined by Hayes et al. [87]. The specification of the data acquisition system is given in Appendix 2.
4.1.4 Optical TDC position sensor

An electro optical sensor was fabricated and used to give a voltage pulse exactly when the TDC position is reached. This sensor consists of a well aligned pair of infra red diode and phototransistor so that infra red rays emitted from the diode fall on the phototransistor when not interrupted. Voltage signals from the optical sensor were fed to an analog to digital converter and then to the data acquisition system along with pressure signals for recording.

4.1.5 Load and speed measurement

The engine was coupled to an eddy current dynamometer. The specifications of the eddy current dynamometer are given in Appendix 3. The dynamometer unit comprises basically a rotor mounted on a shaft running on bearings which rotates within a casing supported in ball bearing trunnions which forms the part of the bed plate of the machine. The Dynamometer load measurement is from a strain gauge load cell and speed measurement is from a shaft mounted with a sixty tooth wheel and with a magnetic pulse pick up. The voltage pulses from the sensor are sent to the digital data rpm meter for pulse conversion and it displays the engine speed with an accuracy of 1 rpm.

4.1.6 Exhaust temperature measurement

The temperature of the exhaust gas was measured with a Cr-Al (Chromel-Alumel) thermocouple. The digital indicator with automatic room temperature compensation facility was used. The temperature indicator was calibrated periodically.
4.1.7 Cylinder pressure measurement

In-cylinder pressure was measured with the help of a differential pressure transmitter. A Yokogawa make Dpharp pressure transmitter was used for the purpose. The technical specification of the pressure transmitter is given in Appendix 4. A piezoelectric transducer produces a charge output which is proportional to the in-cylinder pressure. The charge output was supplied to a charge amplifier where it was amplified for an equivalent voltage.

4.1.8 Smoke Measurement

Smoke level was measured using a standard BOSCH smoke measuring system specifications of which are given in Appendix 5. The measuring instrument consists of a sampling pump that sucks a definite quantity of exhaust sample through a white filter paper. The reflectivity of the filter paper was then measured using an evaluating unit. The unit is mounted in a steel box which comprises a photoelectric cell pick up. The photoelectric cell pick up has a source of light which throws a beam of light on the soot impregnated filter paper disc held in the filter slide. The unabsorbed portion of light is reflected back on to the annular photoelectric cell which surrounds the light source. The intensity of the reflected light generates a current which is measured by a sensitive ammeter which gives the smoke reading in terms of Bosch smoke units.

4.1.9 HC, CO and NO measurement

Exhaust emissions of HC and CO were measured on dry basis. A CRYPTON 285 OIML mode analyzer was used. The analyzer is a fully microprocessor controlled system employing nondestructive infrared techniques. This analyzer measures carbon monoxide, hydrocarbons, carbon dioxide and oxygen. An automatic auto zero check is performed every 30
minutes when the analyzer is switched on. Appendix 6 give the specifications of the HC/CO analyzer.

A Kane Auto 1 series portable exhaust gas analyzer was used to measure NO. This single gas analyzer measures NO individually using electro-chemical cells. The electrochemical cell correlates NO concentration with changes in impedance by measuring the cell response to an ac signal, which is converted in to a digital output. The electrochemical cell is built into the handset. The gas is sampled via a probe which is inserted into the exhaust pipe. A small pump in the handset draws the flue gas into the analyzer. Specifications of the NO analyzer are given in Appendix 7.

4.1.10 Calculation of Heat Release Rate

A piezo-electric pressure transducer was flush mounted on the cylinder head and the signals are recorded on a data acquisition system. Along with the pressure signal the TDC position signal was also acquired by the A/D converter installed in the personal computer. These voltage signals were stored in two columns in a file at uniform time intervals. Since a piezo-electric transducer provides only relative pressures, it is necessary to know the absolute pressure at some point in the cycle so that the pressure at all other points can be had. For this the cylinder pressure at suction (BDC) was assumed to be equal to mean manifold pressure (Lancaster et al. [82]). Software was used to compute the average pressure crank angle values for 100 consecutive cycles. From this peak pressure, occurrence of peak pressure, maximum rate of pressure rise and heat release were calculated.

The rate at which combustion occurs i.e., the rate of heat release, affects the efficiency, power output and emissions of an engine. The heat release rate curve provides a good insight into the combustion process that
takes place in the engine. A program was used to compute the heat release rate
based on the first law of thermodynamics.

\[
Q_{\text{app}} = \frac{\gamma}{\gamma-1}[PdV] + \frac{1}{\gamma-1}[VdP] + Q_w
\]  \hspace{1cm} (4.1)

where  

- \( Q_{\text{app}} \) - Apparent heat release (J)
- \( \gamma \) - Ratio of specific heats \( \frac{C_p}{C_v - R} \)
- \( \bar{R} \) - Gas constant in (J / kmol-K)
- \( C_p \) - Specific heat at constant pressure (J / kmol-K)
- \( V \) - Instantaneous volume of the cylinder (m³)
- \( P \) - Cylinder pressure (bar)
- \( Q_w \) - Heat transfer to the wall (J)

For this calculation the contents of the cylinder were assumed to
behave as an ideal gas (air) with specific heats dependent on temperature and
the specific heat was calculated using the equation given below (Hayes et al.
[87]);

\[
C_p = \left( 3.6359 - \frac{1.33736T}{1000} + \frac{3.29421T^2}{1 \times 10^6} - \frac{1.91142T^3}{1 \times 10^9} + \frac{0.275462T^4}{1 \times 10^{12}} \right) \bar{R}
\]

for \( T < 1000 \) K \hspace{1cm} (4.2a)

\[
C_p = \left( 3.04473 + \frac{1.338056T}{1000} - \frac{0.488256T^2}{1 \times 10^6} + \frac{0.0855475T^3}{1 \times 10^9} - \frac{0.00570127T^4}{1 \times 10^{12}} \right) \bar{R}
\]

for \( T > 1000 \) K \hspace{1cm} (4.2b)

The heat transfer was calculated based on the Hohenberg [90]
equation given below and the wall temperature was assumed to be 723K
(Hayes et al. [87]). With respect to fuel and load, the wall temperature differs.
As the wall temperature measurement facility is not available, an approximate average value was used for calculations.

\[ h = C_1 V^{-0.06} P^{0.8} T^{-0.4} (V_p + C_2)^{0.8} \]  \hspace{1cm} (4.3)

Where  
\begin{align*}
  h & \quad \text{Heat transfer coefficient in W/m}^2\text{K} \\
  C_1 & \text{& } C_2 \quad \text{Constants, 130 & 1.4} \\
  V & \quad \text{Cylinder volume in m}^3 \\
  P & \quad \text{Cylinder pressure in bar} \\
  T & \quad \text{Cylinder gas temperature in K} \\
  V_p & \quad \text{Piston mean speed in m/s}
\end{align*}

C\text{\textsubscript{1}} and C\text{\textsubscript{2}} values for vegetable oils is not available. As the properties of vegetable oil is very close to that of diesel, it is assumed to be the same.

Start of combustion was determined from the heat release rate curve. The crank angle at which there is a sudden rise in heat release rate was taken as the start of combustion. End of combustion was determined from the cumulative heat release curve. It was taken as the point where 90\% of heat release had occurred. Ignition delay is the time lag between the start of injection to the start of combustion. The static injection timing was used to calculate the ignition delay.

4.1.11 Fuels Used

Diesel, cotton seed oil (CSO) and ethyl ester of cotton seed oil (EECSO) was used as fuel in the present work. Cotton seed oil is extracted from cotton seed, which carries around 18\% oil content. The properties of the fuels are given in Table 1.1 of Chapter I.

4.1.12 Diethyl ether (DEE)

The important properties of DEE (Brent Bailey \textit{et al.} [91]) compared with CSO and diesel (Ramadhas \textit{et al.} [21]) is shown in Table 4.1.
Table 4.1 Properties of fuels used for present work

<table>
<thead>
<tr>
<th>Property</th>
<th>Diesel</th>
<th>Cotton seed oil (CSO)</th>
<th>EECSO</th>
<th>Diethyl ether (DEE)</th>
<th>Orange oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Formula</td>
<td>C_{10}H_{22}</td>
<td>C_{55}H_{102}O_{6}</td>
<td>C_{54}H_{101}O_{6}</td>
<td>C_{4}H_{10}O</td>
<td>C_{10}H_{20}O</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>0.84</td>
<td>0.87</td>
<td>0.85</td>
<td>0.714</td>
<td>0.845</td>
</tr>
<tr>
<td>Viscosity at 40°C, (cSt)</td>
<td>3.01</td>
<td>50</td>
<td>4.9</td>
<td>0.23</td>
<td>0.95</td>
</tr>
<tr>
<td>Flash point (°C)</td>
<td>45</td>
<td>210</td>
<td>180</td>
<td>-40</td>
<td>46.1</td>
</tr>
<tr>
<td>Calorific value (kJ/kg)</td>
<td>42500</td>
<td>39648</td>
<td>42735</td>
<td>33857</td>
<td>42000</td>
</tr>
<tr>
<td>Cetane number</td>
<td>47</td>
<td>45</td>
<td>45</td>
<td>&gt;125</td>
<td>10</td>
</tr>
</tbody>
</table>

4.1.13 Transesterification of Cotton Seed Oil

The problems attributed to low volatility, high viscosity and poly unsaturated characteristics of neat cotton seed oil were taken care when the oil was subjected to Transesterification process.

Transesterification is the process of using an alcohol in the presence of catalyst such as potassium hydroxide or sodium hydroxide to chemically break the molecule of raw renewable oil sources into methyl or ethyl esters of the renewable oil with the glycerol as byproduct.

\[
\text{RCOOR'} + \text{R"OH} \rightleftharpoons \text{RCOOR}" + \text{R'O\text{OH}}
\]

(Triglyceride) (Alcohol) (Mix of alkyl esters) (Glycerol)

Transesterification of vegetable oils with simple alcohol has long been the preferred method for producing esters. There are two methods of transesterification. One method uses a catalyst and the other is without a catalyst. The general equation of transesterification is given above and the schematic transesterification process layout is shown in Figure 4.4.
<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Power supply</td>
</tr>
<tr>
<td>2</td>
<td>Heater</td>
</tr>
<tr>
<td>3</td>
<td>Thermostat</td>
</tr>
<tr>
<td>4</td>
<td>Flask</td>
</tr>
<tr>
<td>5</td>
<td>Stirrer</td>
</tr>
<tr>
<td>6</td>
<td>Connector</td>
</tr>
<tr>
<td>7</td>
<td>Thermometer</td>
</tr>
<tr>
<td>8</td>
<td>Stirrer motor</td>
</tr>
<tr>
<td>9</td>
<td>Slider</td>
</tr>
<tr>
<td>10</td>
<td>Speed control</td>
</tr>
<tr>
<td>11</td>
<td>Cap</td>
</tr>
<tr>
<td>12</td>
<td>Stirrer stand</td>
</tr>
</tbody>
</table>

**Figure 4.4 Transesterification Setup**

The catalyst is dissolved into ethanol by vigorous stirring in a small reactor. The oil is transferred into the bio-diesel reactor, and then, the catalyst/alcohol mixture is pumped into the oil. The final mixture is stirred vigorously for 2 hrs at 60°C in ambient pressure. A transesterification reaction produces two liquid phases: ester and crude glycerin. Crude glycerin, the heavier liquid, is collected at the bottom after several hours of settling. Phase separation is observed within 10 min and completed within 2 hrs of settling. Complete settling will take nearly 20 hours.
After settling is complete, water is added at the rate of 5.5% by volume of the ethyl ester of oil and then stirred for 5 min and the glycerin is allowed to settle again. Washing the ester is a two-step process, which is accomplished with extreme care.

A water wash solution at the rate of 28% by volume of oil and 1gm of tannic acid per litre of water is added to the ester and gently agitated. Air is carefully introduced into aqueous solution for agitation. Water alone is added at 28% by volume of oil for the final washing.

4.1.14 Fuel tank pre-heater

The tank is made up of stainless steel and a stainless steel heating element is used for heating the cotton seed oil. Power supply to the heating element is varied by a voltage controller. A thermocouple is fitted to the tank to monitor the temperature of the oil. Figure 4.5 shows the schematic view of the fuel pre-heater.

![Schematic view of the fuel pre-heater](image)

Figure 4.5 Schematic view of the fuel pre-heater
4.1.15  Conversion of diesel engine to semi-adiabatic engine

After detailed study of material properties and the relevance of application to this project, partially stabilized Zirconia (PSZ) was chosen as the best ceramic for this purpose. The 8%Y$_2$O$_3$-PSZ coating was given to the piston crown and head by plasma spray technique. Pre-treatment (shot-blasting) and post-treatment (grinding & honing) of components were performed to ensure high surface finish and dimensional accuracy. Coating thickness given was 100 microns. The coated components then replaced those that of the conventional diesel engine. Operating conditions were maintained identical to that of the base diesel engine. Figure 4.6 and Figure 4.7 show the coated engine head and piston crown respectively.

Figure 4.6 PSZ Coated head assembly
4.2 EXPERIMENTAL PROCEDURE

All the tests were conducted at the rated speed of 1500 rpm. All the readings were taken only after the engine attained stable operation. All the instruments were periodically calibrated. The injector opening pressure was kept at the rated value throughout the experiments.

The engine output was varied in steps from no load to full load in steps of 20%, 40%, 60% and 80%. At each load, fuel flow rate, airflow rate, exhaust gas temperature, emissions of carbon monoxide, hydrocarbons, oxides of nitrogen and smoke readings were recorded. The pressure crank angle history of 100 consecutive cycles was also recorded by using the data acquisition system and the personal computer. This data was processed to get the average pressure crank angle variation.
4.2.1 Experiments conducted

Initially, experiments were conducted using diesel, cotton seed oil and ethyl ester of cotton seed oil with different injection timings at the rated speed of 1500 rpm under variable load conditions. Load, speed, air flow rate, fuel flow rate, exhaust gas temperature, exhaust emissions of hydrocarbon, carbon monoxide, nitric oxide and smoke and were observed. Cylinder pressure and top dead center (TDC) position signals were recorded for processing to obtain combustion parameters.

In the second phase of the work, cotton seed oil was blended with orange oil and diesel in different proportions. Performance, emissions and combustion parameters were analyzed and compared with neat diesel and neat cotton seed oil operation.

In the third phase, the engine was operated with preheated cotton seed oil. Experiments were conducted at constant loads of 100%, 80%, 60%, 40% and 20% with various temperatures. The fuel temperature was varied from room temperature to 110°C in steps of 10°C. Performance, emission and combustion parameters for cotton seed oil diesel blends pre-heated to various temperatures were also done.

In the fourth phase experiments were carried out to obtain performance, emission and combustion parameters using the oxygenate diethyl ether (DEE) as an additive.

During the final phase, experiments were conducted with adiabatic engine components with neat cotton seed oil as fuel.
4.2.2 Data processing

The cylinder pressure and TDC position signals obtained from sensors were passed to the analog to digital converter installed in the personal computer. The data acquisition frequency and data length were selected depending on the engine speed, number of cycles of data to be processed, number of signals and resolution required. The signals were taken with a resolution better than one sample per degree of crank angle.

The data of pressure and TDC were stored as voltages in two columns of a file at uniform time intervals for processing. Since the piezoelectric transducer provides only relative pressures, it is necessary to know the absolute pressure at some point in the cycle so that the value can be used to reference the signal. For this the cylinder pressure at suction (BDC) was assumed to be equal to the mean manifold pressure (Lancaster et al. [82]). The mean manifold pressure was separately recorded using a manometer and used as input. Software was developed to compute the average pressure crank angle values for the specified number of consecutive cycles. From this pressure, IMEP, peak pressure, occurrence of peak pressure, maximum rate of pressure rise etc were calculated.

4.2.3 Ignition delay and Combustion duration

The start of combustion was determined from the differentiated cylinder pressure variation time data. This shows a sudden rise in the slope at the point of ignition due to the sudden high premixed heat release. The end of combustion was taken as the point where 90% of the heat release had occurred (calculated from the cumulative heat release curve). The ignition delay is the time lag between the start of injection and the start of ignition. The start of injection was obtained based on the static injection timing.
4.3 **TEST MATRIX**

The test matrix indicating all the experiments conducted is given in Table 4.2.

Table 4.2 Test Matrix

<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>FUELS USED</th>
<th>REQUIREMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Normal operation and esterification</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintained constant load at 20%, 40%, 60%, 80% and 100% at the rated speed of 1500 rpm</td>
<td>1. Diesel 2. CSO (CSO) 3. Ethyl ester of CSO (EECSO)</td>
<td>Compare the performance, emission and combustion characteristics of base fuels</td>
</tr>
<tr>
<td><strong>Operation with blends</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSO + Orange oil</td>
<td>CSO + Orange Oil (5%, 10% and 15% orange oil)</td>
<td>Evaluation of performance, emissions and combustion parameters and selection of an optimum blend</td>
</tr>
<tr>
<td>Maintained constant load at 20%, 40%, 60%, 80% and 100% at the rated speed of 1500 rpm</td>
<td>CSO + diesel (20%, 40%, 60% and 80% diesel)</td>
<td>Evaluation of performance, emissions and combustion parameters and selection of an optimum blend</td>
</tr>
<tr>
<td><strong>Operation with preheating</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintained constant load at 20%, 40%, 60%, 80% and 100% at the rated speed of 1500 rpm</td>
<td>1. CSO preheated 2. CSO and diesel blend Preheated (20%, 40%, 60% and 80% diesel)</td>
<td>Evaluation of performance, emissions and combustion parameters of CSO and its blend with diesel at different temperatures</td>
</tr>
<tr>
<td><strong>Operation with oxygenate (CSO+DEE)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintained constant load at 20%, 40%, 60%, 80% and 100% at the rated speed of 1500 rpm</td>
<td>CSO + DEE (10%, 20% and 30% DEE)</td>
<td>Evaluation of performance, emissions and combustion parameters and selection of an optimum blend</td>
</tr>
<tr>
<td><strong>Operation with adiabatic engine</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintained constant load at 20%, 40%, 60%, 80% and 100% at the rated speed of 1500 rpm</td>
<td>CSO operation in a semi adiabatic diesel engine</td>
<td>Evaluation of performance, emissions and combustion parameters</td>
</tr>
</tbody>
</table>