CHAPTER 4  RESULTS AND DISCUSSION

4.1 Introduction

The observations of experiments to find the fuel properties and engine performance were processed for analysis and results. The importance of some of the important fuel properties on engine performance and emission characteristics is discussed in this chapter. The engine performance parameters BTE, BSFC and also emission parameters CO, CO$_2$, NO$_x$, HC and smoke were discussed. These parameters were based upon the experimental results obtained with diesel and JSVO test fuel in existing engine as well as modified engine.

The high viscosity of fuel which was one of the important fuel properties affecting the engine performance was reduced by fuel preheating using the exhaust gas as heat source. The effect of preheating the fuel to 90° C resulted in engine performance improvement. The engine output at these suggested operating parameters for JSVO fuel improved the BTE of engine from 30.62% to 34.76% in comparison with 32.96% of diesel test fuel at designed operating parameter as recommended by manufacturer for this engine. The appreciable improvements in emission characteristics were shown. Some of the problems like injector choking, deposits build up, lubricating oil dilution and piston ring sticking reported by researchers as a result of endurance test was not investigated in this work. The investigation of engine performance after incorporating these modifications on these reported problems can be considered as future scope of investigation.

4.2 Effect of temperature on viscosity of Jatropha oil and diesel

The high viscosity was an important factor resulting low brake thermal efficiency
of engine due to poor fuel atomization. To lower the viscosity of JSVO to an extent of the viscosity of diesel at room temperature, the JSVO was to be heated to $90^\circ$ C. The exhaust gas was utilized as a heat source. The counter flow heat exchanger was designed to transfer the heat from exhaust gas to JSVO fuel. After the fabrication of heat exchanger, the heat exchanger was installed with necessary modification to direct the exhaust gas through it. The heated fuel was supplied to the fuel pump and from there it was supplied to combustion chamber. Fuel while traveling from fuel pump to combustion chamber looses the heat and temperature gets reduced. This difficulty was overcome by installing the heat exchanger after fuel pump and utilizing the heat of exhaust gas.

4.3 Engine Performance

4.3.1 Brake Thermal Efficiency

The brake thermal efficiency indicates the net output of the engine available on engine shaft for getting utilized to operate machines. The study of brake thermal efficiency of existing engine fueled with diesel, existing engine fueled with JSVO and modified engine fueled with JSVO was carried out while engine operating under following variable parameters and fuel injection conditions, (1) when the engine was operated with diesel fuel at different fuel injection points, (2) when

![Variation in Kinematic Viscosity Of JSVO & Diesel with Temperature](image)

Figure 4.1: Variation of viscosity with temperature
the engine was operated on different fuel injection pressures, and (3) when the heat exchanger was installed on the engine for preheating the fuel.

It was observed that the brake thermal efficiency (BTE) of engine with diesel fuel was higher than the BTE of engine with JSVO fuel at manufacturer's recommended operating parameter. The calorific value of JSVO as found in laboratory was close to the calorific value of diesel. The experiments were carried out under same environment, so the lower BTE was an indication that the fuel combustion efficiency of JSVO was inferior to the diesel. The combustion efficiency largely depends upon the fuel atomization quality. The fuel atomization efficiency depends upon the viscosity of fuel, fuel injection pressure and the time available for atomization process. The viscosity of JSVO was about 10-12 times the viscosity of diesel. Therefore the JSVO was required to be preheated before injecting into the combustion chamber. The heat exchanger was used for preheating the fuel. The exhaust gas was used as heat source. Apart from preheating two more factors i.e. fuel injection advance angle and the fuel injection pressure governing combustion efficiency were also required to be tested to find the optimum angle and injection pressure which can improve the BTE.

4.3.1.1 Effect of varying fuel injection point at constant fuel injection pressure

The fuel injection point was taken for modification because the time duration between the point of fuel injection and the start of combustion process was felt be one factor which was not sufficient to allow the fuel particles to get atomized properly [1]. This time duration which is known as time delay is in two parts, one is physical delay where the atomization process takes place and the other is the chemical delay where the chemical reaction and temperature rise takes place to bring the air fuel mixture at the point of established combustion process. The increase in time delay period provides more time available for this pre-combustion process. Haldar S K [2] stated that the JSVO demands ignition timing to be more for better combustion and hence improves the engine performance and
emission characteristics. The advancing the fuel injection point by 1° results in increase in delay period of approximately 0.08 second because this engine is self governed operating at 1000 rpm irrespective of engine load. This resulted in better fuel atomization characteristics and enhanced the combustion efficiency. The increase in delay period was achieved by advancing the fuel injection point. In present engine the design point of fuel injection was 20° BTDC for diesel fuel. The fuel injection point used for the experiment was 20° BTDC, 22° BTDC, 24° BTDC and 26° BTDC. Advancing the fuel injection point was limited because increased delay period increases the possibility of engine knocking and also the decreased efficiency [2]. The possible reason for knocking and reduction in engine performance is due to the fact that advanced ignition timing results in an increased peak cylinder pressure and temperature as the combustion occurs earlier in the cycle and more heat is released before and around the top dead centre.

It was also found that the BTE of existing and modified engine fueled with diesel and JSVO increased as the engine load was increased for the entire range of operation. The comparative BTE at different load conditions as obtained from experiments in the cases of diesel, JSVO fueled in existing engine and also in modified engine have been shown in figures from 4.2 to figure 4.5.

The analysis of the results obtained from the experiments revealed that the BTE at a constant fuel injection pressure decreased continuously from 20°BTDC to 26° BTDC in case of diesel fuel (figure 4.6). The same experiment was carried out at injection pressures 175 kgf/cm², 185 kgf/cm², 195 kgf/cm² and 205 kgf/cm². The same trend of performance deterioration was observed at all the fuel injection pressures in the case of diesel engine. Also it was observed from the graph that the angle of fuel injection to give optimum output with diesel fuel was 20° BTDC, this is quite in accordance with the manufacturer recommendation for this engine.

When the existing engine was fueled with JSVO the BTE of engine at 20° BTDC fuel injection point and 175 kgf/ cm² fuel injection pressure was observed 30.5% which was much less than the efficiency with diesel (32.96%). This indicates that
the existing engine when fueled with JSVO did not perform as efficiently as with diesel fuel. In contrary to diesel fuel, it was observed that the BTE of JSVO gradually increased as the fuel injection was advanced to 22° BTDC & 24° BTDC where as the BTE started decreasing as the fuel injection point was advanced further to 26° BTDC. The above findings indicates that the desirable fuel injection advance angle at a constant fuel injection pressure to give better efficiency for JSVO was 24° BTDC (figure 4.6).

The BTE was compared when diesel fuel and JSVO was used in existing engine and in modified engine at 7.35 kW engine load by varying the fuel injection point to 20°, 22°, 24° and 26° at constant fuel injection pressure of 175 kgf/cm², 185 kgf/cm², 195 kgf/cm² and 205 kgf/cm². It was found that the BTE of diesel decreased as the advance angle was increased. The BTE of existing as well as modified engine fueled with JSVO was increased up to 24° BTDC. It was observed that the BTE started decreasing when advance angle was increased beyond 24° BTDC to 26° BTDC. The efficiency of modified engine at all the points was improved in comparison with existing engine fueled with JSVO. This may be because the JSVO was injected in modified engine at elevated temperature which reduced the viscosity of JSVO and therefore improved the combustion characteristics (figure 4.6).

4.3.1.2 Effect of varying fuel injection pressure at constant fuel injection point:

The effect of varying fuel injection pressure at a constant fuel injection point was investigated in the experiment at different pressures 175 kgf/cm², 185 kgf/cm², 195 kgf/cm² and 205 kgf/cm². The investigation was carried out with objective that the fuel atomization characteristics which indirectly depend upon fuel droplets size injected into the combustion chamber gets improved as the fuel droplets size reduces at high fuel injection pressures.

The following expression shows the variation of fuel particle size in terms of SMD at elevated pressure. The sauter mean diameter (SMD) which is the ratio of
mean volume to the mean surface area of the fuel droplet and has an important role in defining the fuel atomization characteristics. Smaller SMD results better fuel atomization and ultimately the fuel combustion efficiency. [10]

\[
\text{SMD} = 3.08 \nu^{0.335} \sigma^{0.737} \rho^{0.06} (\Delta P)^{-0.54}
\]

Where, \( \nu \) is kinematic viscosity in \( m^2/s \), \( \sigma \) surface tension of fuel in \( kg/cm^2 \), \( \rho \) is density in \( kg/m^3 \) and \( \Delta P \) is pressure across the injector in Pa.

Following values of fuel properties were taken for SMD analysis.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Diesel at room temp</th>
<th>JSVO at room temp</th>
<th>JSVO at 90° C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic viscosity ((m^2/s) \times 10^{-6})</td>
<td>4.3</td>
<td>48.7</td>
<td>3.68</td>
</tr>
<tr>
<td>Surface tension ((kg/s^2))</td>
<td>0.28</td>
<td>0.42</td>
<td>0.32</td>
</tr>
<tr>
<td>Density of fuel ((kg/m^3))</td>
<td>817</td>
<td>910</td>
<td>910</td>
</tr>
</tbody>
</table>

The expression for SMD was programmed in MATLAB version February 2011, to find the effect of injection pressure, viscosity and surface tension on sauter mean diameter of fuel particle. The three sets of data i.e. first for diesel fuel at room temperature, second for JSVO at room temperature and third for JSVO at 90° C was used in program and the results have been calculated. The density of air is taken as 1.22kg/m³. The graph was plotted for SMD against fuel injection pressure. The numerical values of results obtained have been shown in table 4.2. The SMD of diesel at room temperature and injection pressure 175 kgf/cm² was found 3.82 x 10⁵ m. The SMD of diesel was reduced continuously from 3.82 x 10⁵ m to 3.50 x 10⁵ m as the pressure was increased from 175 kgf/cm² to 205 kgf/cm².
Table 4.2: Estimated values obtained from SMD program

<table>
<thead>
<tr>
<th>Fuel injection pressure (kgf/cm²)</th>
<th>SMD (m) x10⁻⁵</th>
<th>SMD (m) x10⁻⁵</th>
<th>SMD (m) x10⁻⁵</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diesel at room temperature</td>
<td>JSVO at room temperature</td>
<td>JSVO at 90⁰ C temperature</td>
</tr>
<tr>
<td>175</td>
<td>3.82</td>
<td>12.56</td>
<td>4.33</td>
</tr>
<tr>
<td>185</td>
<td>3.68</td>
<td>12.19</td>
<td>4.20</td>
</tr>
<tr>
<td>195</td>
<td>3.59</td>
<td>11.84</td>
<td>4.08</td>
</tr>
<tr>
<td>205</td>
<td>3.50</td>
<td>11.53</td>
<td>3.97</td>
</tr>
</tbody>
</table>

The SMD of JSVO at room temperature and 175 kgf/cm² was obtained 12.56 x 10⁻⁵ m. The SMD of JSVO was reduced linearly from 12.56 x 10⁻⁵ m to 11.53 x 10⁻⁵ m as the fuel injection pressure was increased from 175 kgf/cm² to 205 kgf/cm². The SMD of JSVO at 90⁰ C and 175 kgf/cm² was obtained to be 4.33 x 10⁻⁵ m, this value was reduced to 3.97 x 10⁻⁵ m as the pressure was increased from 175 kgf/cm² to 205 kgf/cm².

As the JSVO was heated to 90⁰ C the SMD at 175 kgf/cm² was reduced from 12.56 x 10⁻⁵ m to 4.33 x 10⁻⁵ m. This is substantial reduction in SMD by preheating. The preheating the fuel has lowered the viscosity from 48.7 x 10⁻⁶ m²/s to 3.68 x 10⁻⁶ m²/s as obtained in laboratory, also the surface tension was reduced from 0.42 kg/s² to 0.32 kg/s². The comparison of SMD for JSVO and diesel at room temperature showed that the difference between them was very high (8.74 x 10⁻⁵ m). This difference was reduced to a great extent (0.51 x 10⁻⁵ m) as the JSVO was preheated. The appreciable improvement is due to the fact that the viscosity and surface tension were reduced to very high extent. By injecting the JSVO at recommended injection pressure (195 kgf/cm²), the difference was further reduced to 0.26 x 10⁻⁵ m. That above results revealed that SMD of JSVO at
90°C and 195 kgf/cm² injection pressure was almost equal to the SMD of diesel fuel.

The almost equal values of SMDs for preheated JSVO and diesel must have brought the atomization characteristics of these test fuels at same level. This fact is quite in accordance to the BTE of engine obtained from preheated JSVO operating at recommended parameters. The BTE (34.76%) of engine with preheated JSVO was found higher than the BTE of engine with diesel fuel (32.96%), this difference may be due to the fact that the fuel injection timing was also advanced by 40 degrees of crank rotation. Advancing the injection point by 40° results in an additional 0.32 second time available for fuel atomization process; also the increase in efficiency can be attributed to the higher energy supplied to the engine by an equal volume of JSVO than the diesel, this is due to the fact that the density of JSVO is higher than the density of diesel which results higher energy supply even though the calorific value (kJ/kg) of JSVO is slightly lower than the calorific value of diesel fuel.
% Program for SMD (metre) Vs fuel injection pressure (Pa) 

clear all;

nue_Jsvo1 = 48.7*10e-6; % m^2/s 
sigma_Jsvo1 = 0.042; % kg/s^2 
nue_Jsvo2 = 3.68*10e-6 
sigma_Jsvo2 = 0.032 
rho_Jsvo = 910; % Unit Kg/m^3 
rho_air = 1.22; % kg/m^3 

delta_P = input('Value of delta_P in pa is:'); 
%delta_P = 175*10e5:10*10e5:205*10e5; % Pa 
SMD_Jsvo1 = 3.08 * nue_Jsvo1^0.335 .* (sigma_Jsvo1 * rho_Jsvo)^0.737 * rho_air^0.06 .* (delta_P).^(-0.54); 
SMD_Jsvo2 = 3.08 * nue_Jsvo2^0.335 .* (sigma_Jsvo2 * rho_Jsvo)^0.737 * rho_air^0.06 .* (delta_P).^(-0.54); 

disp('Value of SMD_Jsvo1 in metre is:') 
format long 
SMD_Jsvo1 


disp('Value of SMD_Jsvo2 in metre is:') 
format long 
SMD_Jsvo2

%plot (delta_P, SMD_Jsvo)

nue_diesel = 4.3*10e-6; % m^2/s 
sigma_diesel = 0.028; % kg/s^2 
rho_diesel = 817; % Unit Kg/m^3 

delta_P = input('Value of delta_P in pa is:'); 
%delta_P = 175*10e5:10*10e5:205*10e5; % Pa 
SMD_diesel = 3.08 * nue_diesel^0.335 .* (sigma_diesel * rho_diesel)^0.737 * rho_air^0.06 .* (delta_P).^(-0.54); 

disp('Value of SMD_diesel in metre is:') 
format long 
SMD_diesel

%plot (delta_P, SMD_diesel)

figure(2) 
%title('bfPlot for SMD(m) Vs injection pressure (Pa)for Diesel and JSVO') 
%xlabel('Delta P in Pascal') 
%ylabel('SMD m')
Value of delta_P in pa is: $175 \times 10^5$

Value of SMD_{Jsvo1} in metre is:

$SMD_{Jsvo1} = 1.255920632652550 \times 10^{-4}$

$ans = 1.2559207 \times 10^{-4}$

Value of SMD_{Jsvo2} in metre is:

$SMD_{Jsvo2} = 4.326730245171972 \times 10^{-5}$

$ans = 4.3267304 \times 10^{-5}$

Value of SMD_{diesel} in metre is:

$SMD_{diesel} = 3.815634943854152 \times 10^{-5}$

$ans = 3.8156348 \times 10^{-5}$

$nue_{Jsvo2} = 3.680000000000001 \times 10^{-5}$

$sigma_{Jsvo2} = 0.03200000000000$

Value of delta_P in pa is: $185 \times 10^5$

Value of SMD_{Jsvo1} in metre is:

$SMD_{Jsvo1} = 1.218793159788331 \times 10^{-4}$

$1.75 \quad 1.8 \quad 1.85 \quad 1.9 \quad 1.95 \quad 2 \quad 2.05$

Plot for SMD(m) Vs injection pressure (Pa) for Diesel and JSVO

JSVO at room temp.
JSVO at 90°C
Diesel at room temp.
Value of SMD_Jsvo2 in metre is:

\[ \text{SMD}_\text{Jsvo2} = 4.198823627833311 \times 10^{-5} \]

\[ \text{ans} = 4.1988238 \times 10^{-5} \]

Value of SMD_diesel in metre is:

\[ \text{SMD}_\text{diesel} = 3.702837304294310 \times 10^{-5} \]

\[ \text{ans} = 3.7028374 \times 10^{-5} \]

Value of SMD_Jsvo1 in metre is:

\[ \text{SMD}_\text{Jsvo1} = 1.184633613406750 \times 10^{-4} \]

\[ \text{ans} = 1.1846336 \times 10^{-4} \]

Value of SMD_Jsvo2 in metre is:

\[ \text{SMD}_\text{Jsvo2} = 4.081141714941745 \times 10^{-5} \]

\[ \text{ans} = 4.0811417 \times 10^{-5} \]

Value of SMD_diesel in metre is:

\[ \text{SMD}_\text{diesel} = 3.599056575280821 \times 10^{-5} \]

\[ \text{ans} = 3.5990564 \times 10^{-5} \]

Value of SMD_Jsvo1 in metre is:

\[ \text{SMD}_\text{Jsvo1} = 1.15306956226953e-004 \]

\[ \text{ans} = 1.1530700e-004 \]
Value of $SMD_{Jsvo2}$ in metre is:

$$SMD_{Jsvo2} = 3.972402813280712e^{-005}$$

ans = 3.9724029e-005

Value of $SMD_{diesel}$ in metre is:

$$SMD_{diesel} = 3.503162463694563e^{-005}$$

ans = 3.5031626e-005

4.3.1.3 Effect of fuel preheating at constant fuel injection point & constant fuel injection pressure

The BTE of JSVO when fueled in existing engine and in other case when fueled in modified engine were compared at all the operating points. At initial point where optimum BTE of diesel fuel was obtained 32.96%, the efficiency of existing engine fueled with JSVO was observed to be 30.62%. After preheating the JSVO by installing the heat exchanger, the efficiency of modified engine increased to 31.04%. This shows that the fuel preheating improved the efficiency by 0.42%, which is about 1.37% of 30.62%. The similar improvements were obtained at all the operating points. (Figure 4.2 to figure 4.5)

4.3.1.4 Combined effect of fuel preheating, fuel injection pressure and fuel injection point

It was observed from figure 4.6 that the BTE of existing engine when fueled with JSVO increased as the fuel injection angle increased from $20^\circ$ BTDC to $22^\circ$ BTDC and $24^\circ$ BTDC but it started decreasing when the angle was advanced further to $26^\circ$ BTDC. The same trend was observed with JSVO when fueled in modified engine with fuel preheating with an improvement of BTE at corresponding operating point in modified engine. This improvement can be attributed to the preheating done in modified engine which reduced the viscosity of JSVO and thereby improved the combustion efficiency. It was also seen that
the maximum improvement took place at 24° BTDC, a downward trend was observed at 26° BTDC. Therefore an important inference can be drawn that the maximum BTE in the modified engine fueled with JSVO is at 24° BTDC.

The BTE at all pressures but fixed fuel injection points was compared. The increase in fuel injection pressure resulted that the BTE at corresponding points were improved up to 195 kgf/cm² which started reducing on increasing the pressure to 205 kgf/cm². This ultimately shows that the BTE was improved up to 24° BTDC with increasing the injection pressure and also by preheating the fuel.

It can be concluded that the BTE of engine with JSVO fuel at recommended operating point i.e. 24° BTDC and the 195kgf/cm² with fuel preheating was 34.76% in comparison with 32.96% when diesel fuel was used at 20° BTDC fuel injection point and 175 kgf/cm² fuel injection pressure. It shows that the modifications not only made the engine compatible with JSVO but also the efficiency was improved from 32.96% to 34.76% which is about 5.5 % of present diesel efficiency.
Figure 4.2: BTE vs. Engine load
Figure 4.3: BTE vs. Engine Load
Figure 4.4: BTE vs. Engine Load

(a) 20° BTDC Fuel Injection & 195 kg/cm² Injection Pressure
(b) 22° BTDC Fuel Injection & 195 kg/cm² Injection Pressure
(c) 24° BTDC Fuel Injection & 195 kg/cm² Injection Pressure
(d) 26° BTDC Fuel Injection & 195 kg/cm² Injection Pressure

Legend:
- Blue: Existing engine, Diesel
- Red: Existing engine, JSVO
- Green: Modified engine, JSVO
Figure 4.5: BTE vs. Engine Load
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Figure 4.6: BTE vs. Advance angle of fuel injection
Figure 4.7: BTE vs. Injection pressure
4.3.2 Brake specific fuel consumption

The amount of fuel consumed for generating unit brake power also called as brake specific fuel consumption is directly connected to the economy of engine utilization, and therefore it was one of the most important parameter to be evaluated under different operating conditions. The observations were made about fuel consumption by monitoring the time duration of 50 cc fuel under previously defined engine operating conditions considered during BTE evaluation. Based upon the results obtained, it was observed that the BSFC of the engine with diesel fuel when used in existing engine at 20° BTDC was 0.260 kg/kWh which is optimum at 20° BTDC and 175 kgf/cm². These values of fuel injection timing and injection pressures were the recommended operating parameter by the manufacturer for his engine for rated power output. The small variation in BSFC was owing to the fact that the engine was run under different geographical location and climatic condition (temperature and pressure) however the engine was tested for repeatability of data. The precision of the instrument has been validated before carrying out any further experiments on the engine. After the engine was validated for the results the BSFC of the engine when fueled with JSVO was found to be 0.301 kg/kWh, which was higher than the BSFC of diesel engine. This was quite obvious due to low calorific value, viscosity, low cetane index, higher surface tension resulting in an all together different combustion characteristics. The trend of variation of BSFC was plotted against the varying (increasing from 0 kW to 7.35 kW, which was rated load for best performance of existing engine for the diesel fuel) load, varying fuel injection point and fuel injection pressure. The trends of variation of BSFC at all possible operating points with increasing load is shown in figure 4.8 to fig. 4.11. The graph shows that the BSFC increased as the engine load was increased from 0 kW i.e. no load condition to maximum rated load of 7.35 kW. These graphs show the comparison of BSFC of engine with diesel fuel, existing engine fueled with JSVO and modified engine (incorporating a heat exchanger) fueled with JSVO.
The specific fuel consumption was observed to be high in case of engine run with JSVO. This indicated that the heat released by fuel combustion was lower in this case which subsequently reduced the brake power output. Because of low power output the BSFC became high. To improve the BSFC, the efficiency of fuel combustion phenomena was required to be enhanced. There are many possible methods of improvement such as design improvement in combustion chamber, design change of piston crown, the design change of inlet and exhaust valve, fuel injection system design improvements etc. Among these possible methods most favorable changes were fuel injection system design changes. The parameters taken in consideration for design change were fuel injection advance angle, fuel injection pressure and method to reduce the viscosity of JSVO to improve the fuel atomization characteristics.

4.3.2.1 Effect of varying fuel injection point at constant fuel injection pressure

As mentioned above, the BSFC of existing engine run with JSVO was higher in comparison with engine fueled with diesel at 20° BTDC and 175 kgf /cm². From figure 4.12, it was seen that the BSFC of engine with diesel fuel started increasing whenever the operating point was changed from the manufacturer recommended operating point for this engine, the same fact was also reported by Basinger et al in their findings [1]. The BSFC decreased in both modified engine and existing engine when fueled with JSVO as the fuel injection angle was advanced from 20° BTDC to 22° BTDC and 24° BTDC but the BSFC started rising on further increases in advance angle of fuel injection to 26° BTDC. This was in correlation with the BTE trends with change in fuel injection point (figure 4.6). It was observed very clearly that the optimum performance of the engine corresponds to 24° BTDC with evident decrease in BTE with increasing and decreasing the advance angle of fuel injection point i.e. for 22° BTDC and 26° BTDC. This was convincing also because the brake thermal efficiency deteriorated at 26° BTDC in comparison with 24° BTDC which ultimately
increased the fuel consumption. These results gave information that the engine efficiency was improved on increasing the advance angle up to 24° BTDC. The BSFC of modified engine on comparison with BSFC of existing engine indicated that the trend of change was similar at all the operating points but the BSFC of modified engine was less than the BSFC of existing engine at same combination of advance angle of fuel injection and fuel injection pressure. This shows that the effect of preheating the fuel improved the BSFC substantially.

4.3.2.2 Effect of varying fuel injection pressure at constant fuel injection point

The effect of fuel injection pressure keeping the angle constant has been plotted in figure 4.13. The engine was tested at fuel injection pressures of 175 kgf/cm², 185 kgf/cm², 195 kgf/cm² and 205 kgf/cm² at all considered fuel injection points (20° BTDC, 22° BTDC, 24° BTDC and 26° BTDC). In the previous section the effect of preheating was discussed and it showed an improvement in BTE and BSFC due to fuel preheating. This was quite understandable as the preheating the fuel ultimately results in better atomization of fuel in the cylinder when it is injected through the injector due to lower viscosity at higher temperature. The similar atomization characteristics could also be achieved by higher injection pressures and therefore an improvement in BTE and BSFC. The engine BSFC with diesel fuel got increased when the fuel injection pressure was increased from 175 kgf/cm² which was the rated fuel injection pressure for this engine. The changes in BSFC at different fuel injection pressure while keeping the advance angle of fuel injection point unchanged indicated that the BSFC reduced at elevated fuel injection pressure for the engine with JSVO. This was also indicated that the trend of changes in BSFC was same both in existing engine as well modified engine when they were fueled with JSVO. However increase in pressure beyond 195 kgf/cm² was not advisable because the BTE reduced and BSFC increased beyond this pressure (Figure 4.13). This increase in pressure beyond above said pressure was not advisable because of other associated problem of
poor combustion efficiency due to low momentum of smaller fuel particles released in combustion chamber as mentioned in the case of BTE discussion.

4.3.2.3 Effect of fuel preheating at constant fuel injection point & fuel injection pressure

The change in BSFC at 7.35 kW engine load at different IVOP (injector valve opening pressure) and fuel injection point was compared for diesel engine, existing engine and modified engine run on JSVO. The BSFC of JSVO without preheating the fuel was higher than the BSFC of JSVO when it was fueled after preheating. It was found with operating point 20\(^{0}\) BTDC and 175kgf/cm\(^2\), the BSFC in both the cases were 0.301 kg/kWh and 0.297 kg/kWh respectively. This shows that the BSFC improved by preheating the fuel which is about 1.33% in this particular case.

The comparison of existing and modified engine at a particular operating point has shown that the BSFC of modified engine was less than the existing engine with JSVO, which was only because of fuel preheating. This indicated that the contribution of heat exchanger to preheat the JSVO improved the efficiency of engine.

4.3.2.4 Combined effect of fuel preheating, fuel injection pressure and fuel injection point

It was observed from figure 5.13 that the BSFC of existing engine when fueled with JSVO decreased as the fuel injection angle was increased from 20\(^{0}\) BTDC to 22\(^{0}\) BTDC and 24\(^{0}\) BTDC but it started increasing when the angle was advanced further. The same trend was observed with JSVO when fueled in modified engine but there was improvement in BSFC at corresponding operating point in modified and existing engines. It was also seen that the maximum improvement had taken place at 24\(^{0}\) BTDC, when angle was increased to 26\(^{0}\) BTDC the values of BSFC at all the corresponding points were increased.
The comparison of the values of BSFC at all but fixed fuel injection point when the fuel injection pressure was increased show that the BSFC at corresponding points was reduced. This ultimately shows that the BSFC was improved up to $24^0$ BTDC by increasing the injection pressure and also by preheating of the fuel.

Therefore it can be concluded that the performance of JSVO at recommended operating point i.e. $24^0$ BTDC and the $195\text{kgf/cm}^2$ with preheating the fuel by installing the heat exchanger gave BSFC $0.266 \text{kg/kWh}$ in comparison with $0.260 \text{kg/kWh}$ of diesel at design operating point $20^0$ BTDC fuel injection point and $175 \text{kgf/cm}^2$ fuel injection pressure. It shows that the modifications made the engine compatible with JSVO with significant improvement in BSFC of JSVO from $0.301 \text{kg/kWh}$ (at $20^0$ BTDC, $175 \text{kgf/cm}^2$ and without preheating) to $0.266 \text{kg/kWh}$ (at $24^0$ BTDC, $195 \text{kgf/cm}^2$ and pre heating the fuel) which was an improvement of about $1.2\%$ with respect to $0.301 \text{kg/kWh}$. 

Figure 4.8: BSFC vs. Engine Load
Figure 4.9: BSFC vs. Engine Load
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Figure 4.10: BSFC vs. Engine Load
Figure 4.11: BSFC vs. Engine Load
Figure 4.12: BSFC vs. Advance angle of fuel injection
Figure 4.13: BSFC vs. Fuel Injection Pressure
Chapter 4

4.4 Emission Characteristics

4.4.1 CO Emission

The engine emissions were measured with AVL-5 gas analyzer (for CO, CO₂, NOₓ, HC) and smoke-meter. The measured emissions have been shown graphically. The engine requires rich fuel-air mixture during cold starting engine, warm up and transient like acceleration. The engine operation during those modes contributes significantly to CO emission. The CO emission increases sharply beyond equivalence ratio 1.0 so higher BSFC resulted in higher CO emission.

The CO emission was observed to be high for JSVO fuel which is indication of incomplete combustion. All the measures taken for improving the fuel combustion efficiency ultimately reduced the CO emission. In this work testing the engine at different fuel injection pressure, different fuel injection advance angle and preheating the fuel ascertain the improved in CO emission characteristics.

4.4.1.1 Effect of varying fuel injection point at constant fuel injection pressure

The graph was plotted between CO emission (% Vol) and fuel injection point for the fuel injection pressure of 175 kgf/cm², 185 kgf/cm², 195 kgf/cm² and 205 kgf/cm². The CO emission continuously increased for diesel as the angle of fuel injection was increased from 20⁰ BTDC to 26⁰ BTDC in step of 2⁰ for all the load conditions (figure 4.14 to figure 4.17). The CO emission of existing engine with JSVO fuel was observed to be very high at 20⁰ BTDC in comparison with CO emission of engine with diesel test fuel at same point. This may be due to high BSFC of JSVO. The high BSFC required more air for complete combustion, so under a constant operating conditions CO formation might have taken place due to incomplete combustion. The CO emission was decreased in the case of JSVO with increase in advance angle of fuel injection up to the angle of 24⁰ BTDC at
rated (7.35 kW) engine load conditions and at all the fuel injection pressures (175kgf/cm², 185kgf/cm², 195kgf/cm² and 205 kgf/cm²) but the CO emission started increasing as the angle was further increased to 26° BTDC (figure 4.18). This indicated that the combustion efficiency was improved in case of JSVO as the fuel injection angle was increased up to 24° BTDC but the combustion efficiency started deteriorating as the angle was further increased. It was observed that the CO emission of engine running with diesel fuel at rated load was least (0.05 % vol) at 20° BTDC and 175 kgf/cm² which increased on advancing the fuel injection point. The increased CO emission which was an indication of reduced combustion efficiency was in correlation to the change in BTE under similar changes in fuel injection points. The CO emission of the modified engine run with JSVO was also obtained to be decreasing as the angle of fuel injection was increased from 20° BTDC to 22° BTDC and 24° BTDC for all the fuel injection pressures (175kgf/cm², 185kgf/cm², 195kgf/cm² and 205 kgf/cm²) but the CO emission started increasing as the angle was further increased to 26° BTDC (figure 5.19). It was remarkable that the CO emissions of modified engine with JSVO fuel at 24° BTDC and 26 ° BTDC measured at all the fuel injection pressures were lower than the CO emission of engine with diesel fuel and also with JSVO.

4.4.1.2 Effect of varying fuel injection pressure at constant fuel injection point

The data observed during the experiment for CO emission was plotted against varying load ( 0 kW, 1.84 kW, 3.68kW, 5.52kW & 7.35 kW), varying advance angle of fuel injection point ( 20° BTDC, 22° BTDC, 24° BTDC & 26° BTDC) and varying fuel injection pressures (175kgf/cm², 185kgf/cm², 195kgf/cm² & 205 kgf/cm²). It was observed that the CO emission in case of diesel fuel was increased as the fuel injection pressure was increased from the rated value of 175kgf/cm² to 185kgf/cm², 195kgf/cm² and subsequently 205kgf/cm² (figure 4.19). The increase in CO emission on increasing the injection pressure was an
indication that the thermal efficiency of engine deteriorated at elevated fuel injection pressure from the manufacturer’s recommended value (175 kgf/cm²). So the optimum efficiency was obtained at 175 kgf/cm² with diesel fuel. From the graph it was seen that the CO emission of the existing as well as modified engine reduced as the fuel injection pressure was increased from 175 kgf/cm² to 185 kgf/cm² and subsequently to 195 kgf/cm² but the CO emission started reducing as the injection pressure was further increased to 205 kgf/cm². The increase in CO emission at higher pressure may be due to the fact that the spray of smaller fuel particle at higher velocity penetrates more and gets exposed more to air available. These factors lead to better air utilization and combustion characteristics, so the optimum CO emission was obtained at 195 kgf/cm². The difference of CO emission values between existing and modified engine was due to preheating the fuel. Upon comparison, it was also observed that the CO emission of diesel at all the load conditions was less than the CO emission of JSVO. The CO emission of JSVO, when fueled in modified engine was observed to be less than the CO emission of JSVO when fueled in existing engine.

### 4.4.1.3 Effect of Fuel preheating at constant fuel injection point and fuel injection pressure

From figure 4.14 to 4.17, it was observed that the CO emission was less at all the operating point in the case of JSVO fuel in modified engine than the CO emission of JSVO fueled in existing engine. The difference in CO emission of these two engines was due to preheating of fuel because all other operating parameters were the same. It can be concluded that fuel pre-heating reduced the CO emission; the improvement in CO emission at higher temperature of inlet fuel was due to the less heat requirement for getting the fuel atomized. Another effect of fuel preheating was to lower the viscosity which resulted in free flow of fuel and ease of mist formation in the combustion chamber. These phenomena on one side reduce the friction horse power (FHP) and on the other side enhance fuel combustion efficiency. The heat available in the vicinity of fuel particle might
be sufficient to vaporize and atomize the fuel; the low emission of CO was obtained which may be due to improved combustion efficiency.

4.4.1.4 Combined effect of fuel preheating, fuel injection pressure and fuel injection point

The variations in CO emission with change in fuel injection point and fuel injection pressure in both the cases i.e. in modified engine and existing engine exhibited the results that the CO emission characteristics of fuel JSVO was improved by implementing higher degree (24°) of fuel injection and 195 kgf/cm² pressure with a system of fuel pre-heating incorporated in the engine fuel supply system. The present trend of research has accounted the effect of these parameters individually. In this work the effect of these parameters was integrated by testing the engine at all the combinations of operating parameters (fuel injection advance angle, fuel injection pressure and fuel preheating). The result obtained shows that the CO emission at recommended value of injection pressure (195 kgf/cm²) and fuel injection point (24° BTDC) with fuel preheating improved the CO emission of engine with JSVO fuel from 0.10 % vol. to 0.05 % vol. at 7.35 kW engine load. The base line CO emission of engine running at 7.35 kW with diesel fuel is 0.05 % vol. at 20° BTDC and 175 kgf/cm². This shows that the modifications in fuel injection system improved the CO emission to an extent of base line CO emission (0.05%) at rated engine load condition.
Figure 4.14: CO emission vs. Engine Load
Figure 4.15: CO emission vs. Engine Load
Figure 4.16: CO emission vs. Engine Load
Figure 4.17: CO emission vs. Engine Load
Figure 4.18: CO emission vs. Advance angle of Fuel injection
Figure 4.19: CO emission vs. Fuel injection pressure
4.4.2 CO₂ Emission:

The effect of advanced injection timing was evident for the production of carbon dioxide. The highest CO₂ concentrations in the exhaust were recorded when the engine was run on diesel fuel. The rated fuel injection timing (20° BTDC) and 175kgf/cm² fuel injection pressure offered highest (1.24% Vol.) CO₂ emissions in comparison with CO₂ emission (0.76% Vol.) of engine fueled with JSVO at same injection point and injection pressure. The effect of air fuel mixture on CO₂ emission was that the CO₂ emission increased as the A/F ratio was decreased. The emission of CO₂ was therefore, a measure of combustion efficiency of the system. It is desirable to have high CO₂ and less HC emissions under any operating condition [30].

In the range of the whole engine load, the CO₂ emissions of diesel fuel were higher than that of the JSVO because the vegetable oil contains oxygen element. The carbon content was relatively lower in the same volume of fuel consumed at the same engine load and consequently, the CO₂ emissions from the vegetable oil were higher.

4.4.2.1 Effect of varying fuel injection point at constant fuel injection pressure

The data of CO₂ emission obtained during the experiments were plotted against varying engine load (0 kW, 1.84 kW, 3.68kW, 5.52 kW, 7.35kW), varying fuel injection point (20° BTDC, 22° BTDC, 24° BTDC, 26° BTDC) and fuel injection pressure (175 kgf/cm², 185 kgf/cm², 195 kgf/cm², 205 kgf/cm²) in figure 4.20 to figure 4.24. The increase in CO₂ emission was obtained on increasing the engine load (figure 4.20 to figure 4.23). The increase in CO₂ at increased engine load indicated that the brake engine output in relation to fuel consumption was increased. This may be due to the fact that the engine efficiency increases as the engine approaches to rated engine load due to higher temperature of burnt gases at higher engine load. The higher temperature available in combustion chamber
helps in fuel atomization process and also the oxidation of CO available in burnt gases after the combustion process is finished. This results in efficient combustion process and conversion of CO in to CO₂ thereby giving increased CO₂ emission. Decrease in CO₂ emission of engine with diesel fuel was observed at all but fixed fuel injection pressure as the fuel injection advance angle was increased from 20° BTDC to 26° BTDC in steps of 2°. This showed that the optimum engine performance was at 20° BTDC. The performance deteriorated as the advance angle of fuel injection was increased from its rated fuel injection point. The CO₂ emissions of existing as well as modified engine with JSVO fuel increased gradually as the advance angle of fuel injection was increased up to 24° BTDC but the CO₂ emission started decreasing beyond 24° of fuel injection which indicated that the fuel combustion efficiency started deteriorating (figure 4.24).

The increased CO₂ emission on advancing the fuel injection point may be due to the fact that increase delay period offers more time for pre combustion process. This has also been reported by the researchers that advancing the fuel injection point too far can have negative consequence, resulting in engine knocking and erratic engine behavior [1, 30], these effects reduces the engine performance and hence CO₂ emission.

4.4.2.2 Effect of varying fuel injection pressure at constant fuel injection point

It was observed that the CO₂ emission in case of diesel fuel was decreased as the fuel injection pressure was increased from the rated value of 175kgf/cm² to 185kgf/cm², 195 kgf/cm² and subsequently to 205kgf/cm². The graph also indicates that the CO₂ emission was increased as the load was increased from 0 kW to 7.35 kW. In the case of JSVO as test fuel of existing as well as modified engine it was found that the CO₂ emission was increased on increasing the fuel injection pressure up to 195 kgf/cm² where as the CO₂ emission started decreasing on further increase in fuel injection pressure to 205 kgf/cm². That means the higher fuel injection pressure provides better fuel combustion efficiency due to
improved fuel atomization characteristics (figure 4.25). On comparison this was also observed that the CO₂ emission of diesel at all the combinations of operating points were more than the CO₂ emission of JSVO (figure 4.20 to 4.25). However in some of the cases (at 205 kgf/cm² fuel injection pressure ) this was also observed that CO₂ emission of modified engine was lower than the CO₂ emission of existing engine, it indicated that the effect of reducing the CO₂ emission by increasing the fuel injection pressure from optimum value ( 195 kgf/cm²) was more than the effect of preheating the fuel to increase the CO₂ emission. In general the CO₂ emission of JSVO when fueled in modified engine was observed to be more than the CO₂ emission of JSVO when fueled in existing engine.

4.4.2.3 Effect of fuel preheating at constant fuel injection point and fuel injection pressure

It was observed that the CO₂ emission was more at all the operating point in the case of JSVO fuel in modified engine than the CO₂ emission of JSVO fueled in existing engine. The difference in CO₂ emission between these two cases were only because of fuel preheating, as all the other operating parameters were same at any one observation point. This revealed that the fuel pre-heating increases the CO₂ emission. This may be because of improved fuel combustion quality as the viscosity of fuel decreases by pre-heating.

4.4.2.4 Combined effect of fuel preheating, fuel injection pressure and fuel injection point

The data plotted in figures from figure 4.20 to figure 4.25 for CO₂ emission shows that the change in fuel injection point and fuel injection pressure in both the cases i.e. in modified engine and in existing engine exhibited the result that the CO₂ emission characteristics of fuel JSVO was improved by implementing higher degree (24⁰) of fuel injection and 195 kgf/cm² fuel injection pressure with a system of fuel pre-heating incorporated in the engine fuel supply system. The CO₂ emission of modified engine at recommended fuel injection point (24⁰ BTDC) and fuel injection pressure (195 kgf/cm²) was observed to be 1.24 % vol. which was
an improvement of CO\textsubscript{2} emission of existing engine with JSVO fuel from 0.76\% Vol. (at 20\(^{0}\) BTDC and 175kgf/cm\(^{2}\)) to 1.24 \% Vol. (at 24\(^{0}\) BTDC and 195 kgf/cm\(^{2}\) with fuel preheating). The existing engine with diesel fuel at rated operating point (at 20\(^{0}\) BTDC and 175kgf/cm\(^{2}\)) had CO\textsubscript{2} emission 1.24 \% vol. This shows that the modified engine emits equal amount of CO\textsubscript{2} with the modifications incorporated to it. The decrease in CO\textsubscript{2} indicated the incomplete combustion, therefore it was concluded that the emission performance of the engine with diesel fuel got deteriorated as the advance angle of fuel injection was increased from the rated design value of 20\(^{0}\) BTDC and also as the fuel injection pressure was increased from the rated value of 175kgf/cm\(^{2}\). The improvement in CO\textsubscript{2} emission was observed as the load on engine approached to rated load.
Figure 4.20: CO₂ emission vs. Engine Load
Figure 4.21: CO₂ emission vs. Engine Load
Figure 4.22: \( \text{CO}_2 \) emission vs. Engine Load

(a) 20° BTDC Fuel Injection & 195 kgf/cm\(^2\) Injection Pressure

(b) 22° BTDC Fuel Injection & 195 kgf/cm\(^2\) Injection Pressure

(c) 24° BTDC Fuel Injection & 195 kgf/cm\(^2\) Injection Pressure

(d) 26° BTDC Fuel Injection & 195 kgf/cm\(^2\) Injection Pressure
Figure 4.23: CO₂ emission vs. Engine Load
Figure 4.24: CO₂ emission vs. advance angle of fuel injection
Figure 4.25: CO$_2$ emission vs. Fuel injection pressure
4.4.3 NO\textsubscript{x} Emission:

It is important to consider Nitrogen oxides as it is one of the major pollutant and emission concerns. When combustion temperature is decreased the emission of nitrogen oxides are reduced but the smoke and particulate emission increases [30]. By retarding the injection timing the temperature inside the combustion chamber decreases, and therefore a reduction in the NO\textsubscript{x} emission was obtained. To meet the above stated requirements advanced fuel injection technologies that employ very high injection pressure and electronic control of injection timing and rate are being used now a days. The use of electronic fuel injection (EFI) system results into very high injection pressure up to 2000 bar to atomize fuel into very fine droplets for fast vaporization. It has been reported in literatures that increase in fuel injection pressure beyond a point results no further improvement in air – fuel mixing. The retarded fuel injection improves the NO\textsubscript{x} emission characteristics. It is also suggested that the significant reduction in NO\textsubscript{x} and particulate takes place when 75\% fuel is injected in the first pulse and the 25\% in the second pulse after a dwell period of 10\(^0\) crank angle [30].

4.4.3.1 Effect of varying fuel injection point at constant fuel injection pressure

The graph was plotted between NO\textsubscript{x} emission (ppm) and varying fuel injection point (\(20^0\) BTDC, \(22^0\) BTDC,\(24^0\) BTDC, \(26^0\) BTDC) for the fuel injection pressure of 175 kgf/cm\(^2\), 185 kgf/cm\(^2\), 195 kgf/cm\(^2\) and 205 kgf/cm\(^2\). The NO\textsubscript{x} emission was continuously increasing for existing engine with diesel fuel as the angle of fuel injection was increased from \(20^0\) BTDC to \(26^0\) BTDC in step of \(2^0\) for all the load conditions (figure 4.26 to figure 4.29). The increased NO\textsubscript{x} emission at retarded angle of fuel injection point may be due to the increase in peak cylinder pressure and temperature as the combustion occurs earlier in the cycle and more heat is released before and around the top dead centre. The charge elements which burns early in the cycle are subjected to higher temperature and pressure with advance in peak timing and remain at high temperatures for a longer period.
These early burn elements contribute most to NO formation and hence higher NO formation rates result with advanced ignition timing. The NO\textsubscript{x} emission for JSVO when fueled in existing engine was observed to be high at 20\textdegree BTDC in comparison with NO\textsubscript{x} emission of diesel at same point. The NO\textsubscript{x} emission was decreased in the case of JSVO fuel with increase in advance angle of fuel injection up to the angle of 24\textdegree BTDC at all the load conditions (except at 7.35kW load and 185 kgf/cm\textsuperscript{2} injection pressure) but the NO\textsubscript{x} emission started increasing as the angle was further increased to 26\textdegree BTDC. The reverse behavior of diesel and JSVO in NO\textsubscript{x} emission on varying the advance angle of fuel injection angle may be because the established combustion process in JSVO might be still later than the diesel fuel. This consequence of late combustion could have been due to low temperature even little beyond the TDC point. This indicated that the combustion efficiency was improved in case of JSVO as the fuel injection angle was increased up to 24\textdegree BTDC but the combustion efficiency deteriorated as the angle was further increased (Figure 4.30). The inverse result beyond 24\textdegree BTDC may be due to possibility of engine knocking and erratic behavior. It has also been observed that the NO\textsubscript{x} emission of diesel fuel at all the angles of fuel injection was higher than the NO\textsubscript{x} emission of JSVO except at 175 kgf/cm\textsuperscript{2} fuel injection pressure. The NO\textsubscript{x} emission of the JSVO when fueled in the modified engine was also decreased as the angle of fuel injection was increased from 20\textdegree BTDC to 24\textdegree BTDC in step of 2\textdegree for all the load conditions, but the NO\textsubscript{x} emission started increasing as the angle was further increased to 26\textdegree BTDC (Figure 4.30). It was remarkable that the NO\textsubscript{x} emission at recommended operating point (24\textdegree BTDC, 195 kgf/cm\textsuperscript{2}) for JSVO (330 ppm) was even less than the NO\textsubscript{x} emission of diesel (360 ppm) at rated operating point (20\textdegree BTDC, 175 kgf/cm\textsuperscript{2}).

4.4.3.2 Effect of varying fuel injection pressure at constant fuel injection point

From the graph it was observed that the NO\textsubscript{x} emission in case of diesel fuel was increased as the fuel injection pressure was increased from the rated value of
175 kgf/cm\(^2\) to 185 kgf/cm\(^2\), 195 kgf/cm\(^2\) and 205 kgf/cm\(^2\) (figure 4.31). The graph also indicated that the NO\(_x\) emission kept reducing as the load was increased from 0 kW to 7.35 kW (figure 4.26 to figure 4.29). The NO\(_x\) emission of modified and existing engine was found to be reducing as the fuel injection pressure was increased from 175 kgf/cm\(^2\) to 195 kgf/cm\(^2\) but the trend was reversed when the pressure was further increased (figure 4.32). This may be due to the fact that peak pressure and temperature is very close to TDC or even in some of the cases after the TDC which results in exposing the NO for very small time period to the excess air available for the formation of NO\(_x\). The reverse effect of engine beyond the injection pressure 195 kgf/cm\(^2\) might be due to the possibility of engine knocking and erratic behavior of engine. The NO\(_x\) emission of JSVO when fueled in modified engine was observed to be less than the NO\(_x\) emission of JSVO when fueled in existing engine. This difference was due to the effect of fuel preheating.

### 4.4.3.3 Effect of Fuel preheating at constant fuel injection point and fuel injection pressure

On comparison of figure 4.26 to figure 4.29, it was found that the NO\(_x\) emission was less at all the operating point in the case of JSVO fuel in modified engine than the NO\(_x\) emission of JSVO fueled in existing engine. This shows that the fuel pre-heating reduces the NO\(_x\) emission. This is because of improved fuel combustion quality as the viscosity of fuel was decreased by pre-heating. On comparing the amount of NO\(_x\) emission when the JSVO was used on existing engine and in another case when used in modified engine the amount of emission was observed to be reduced which directly relates to better fuel combustion quality. Though due to better combustion quality the temperature gets increased which should increase the NO\(_x\) emission but this effect might have been dominated by the decrease in temperature due to fuel injection advance angle. That means the preheating of fuel was an advantageous modification which
improved the performance characteristics as discussed earlier and also the emission characteristics.

4.4.3.4 Combined effect of fuel preheating, fuel injection pressure and fuel injection point

The NO\textsubscript{x} emission with change in fuel injection point and fuel injection pressure in both the cases that is in modified engine and in existing engine exhibited that the NO\textsubscript{x} emission characteristics of fuel JSVO was improved by implementing higher degree (24\textdegree) of fuel injection and 195 kgf/cm\textsuperscript{2} pressure with a system of fuel pre-heating incorporated in the engine fuel supply system.

In association with the effect of fuel injection advance angle and the increase in fuel injection pressure the pattern of decrease in NO\textsubscript{x} indicated the improvement in combustion quality of JSVO in combustion chamber. It shows that the emission performance of the JSVO fuel improved as the advance angle of fuel injection was increased from the rated value of 20\textdegree BTDC upto 24\textdegree BTDC but it was deteriorated on further increase to 26\textdegree BTDC. The similar trend was shown on increase in fuel injection pressure from the rated value of 175kgf/cm\textsuperscript{2}.

The NO\textsubscript{x} emission of existing engine with diesel fuel at rated operating point (20\textdegree BTDC and 175 kgf/cm\textsuperscript{2} ) was 360 ppm where as the emission of existing engine with JSVO fuel at same operating point was 430 ppm. After the modifications was incorporated, the NO\textsubscript{x} emission of modified engine at 24\textdegree BTDC and 195 kgf/cm\textsuperscript{2} was obtained to be 330 ppm. This shows that the modification not only made the engine compatible to the existing engine on the basis of NO\textsubscript{x} emission but also the NO\textsubscript{x} emission parameter was further improved.
Figure 4.26: NO\textsubscript{x} emission vs. Engine Load
Figure 4.27: NO\textsubscript{x} emission vs. Engine Load
Figure 4.28: NO\textsubscript{x} emission vs. Engine Load
Figure 4.29: NO\textsubscript{x} emission vs. Engine Load

(a) 20° BTDC Fuel Injection & 205 kgf/cm\textsuperscript{2} injection pressure

(b) 22° BTDC Fuel Injection & 205 kgf/cm\textsuperscript{2} injection pressure

(c) 24° BTDC Fuel Injection & 205 kgf/cm\textsuperscript{2} injection pressure

(d) 26° BTDC Fuel Injection & 205 kgf/cm\textsuperscript{2} injection pressure
Figure 4.30: \( \text{NO}_x \) emission vs. Advance angle of fuel injection
Figure 4.31: NOx vs. Fuel Injection Pressure
4.4.4 Smoke Emission

4.4.4.1 Effect of varying fuel injection point at constant fuel injection pressure

The graph was plotted between smoke emission (opacity) and varying fuel injection point for the fuel injection pressures 175 kgf/cm², 185 kgf/cm², 195 kgf/cm² and 205 kgf/cm². The smoke emission was found to increase continuously for diesel as the angle of fuel injection were increased from 20⁰ BTDC to 26⁰ BTDC in step of 2⁰ for all the load conditions (figure 4.36). The Smoke emission for JSVO when fueled in existing engine was observed to be high at 20⁰ BTDC in comparison with Smoke emission of diesel at same point. The smoke emission was decreased in the case of JSVO with increase in advance angle of fuel injection up to the angle of 24⁰ BTDC at all the load conditions but the Smoke emission started increasing as the angle was further increased to 26⁰ BTDC. This indicated that the combustion efficiency was improved in case of JSVO as the fuel injection angle was increased up to 24⁰ BTDC but the combustion efficiency started deteriorating as the angle was further increased (Figure 4.36). It was also found that the Smoke emission of diesel fuel at all the angles of fuel injection was lower than the smoke emission of JSVO. The smoke emission of the JSVO when fueled in the modified engine was also decreased as the angle of fuel injection was increased from 20⁰ BTDC to 24⁰ BTDC in step of 2⁰ for all the load conditions but the smoke emission started increasing as the angle was further increased to 26⁰ BTDC (figure 4.36). It is remarkable that the Smoke emission at recommended operating point for JSVO (24⁰ BTDC, 195 kgf/cm²) was least.

4.4.4.2 Effect of varying fuel injection pressure at constant fuel injection point

It was observed that the Smoke emission in case of diesel fuel was increased as the fuel injection pressure was increased from the rated value of 175kgf/cm² to 185kgf/cm², 195kgf/cm² and 205 kgf/cm² (figure 4.37) The graph also indicates
that the Smoke emission kept reducing as the load was increased from 0 kW to 7.35 kW (figure 4.32 to figure 4.35). The decrease in smoke emission with increase in advance angle of fuel injection was obtained at all load conditions up to 24° BTDC. On comparison, this was also observed that the smoke emissions of diesel at all the load conditions were less than the smoke emission of JSVO. The smoke emission of JSVO when fueled in modified engine was observed to be less than the smoke emission of JSVO when fueled in existing engine.

4.4.4.3 Effect of Constant Fuel Injection point and fuel injection pressure

From the graphs it was found that the smoke emission was less at all the operating point in the case of JSVO fueled in modified engine than the smoke emission of JSVO fueled in existing engine. This shows that the fuel pre-heating reduced the Smoke emission. This may be because of improved fuel combustion quality as the viscosity of fuel decreased by pre-heating. On comparison the amount of smoke emission when the JSVO was fueled in existing engine and modified engine the amount of emission was observed to be reduced which directly related to better fuel combustion quality. Though the better combustion quality increases the temperature which should increase the smoke emission but this effect might have been dominated by the decrease in temperature due to fuel injection advance angle. That means the preheating of fuel was an advantageous modification which improved the performance characteristics as discussed earlier and also the emission characteristics.

4.4.4.4 Combined effect of fuel preheating, fuel injection pressure and fuel injection point

The variations of smoke emission with change in fuel injection point and fuel injection pressure in both the cases i.e. in modified engine and existing engine was compared. The comparison exhibited the result that the smoke emission characteristics of JSVO fuel was improved by implementing higher degree (24°)
of fuel injection and 195 kgf/cm² pressure with a system of fuel pre-heating incorporated in the engine fuel supply system.

In association with the effect of fuel injection advance angle and the increase in fuel injection pressure the pattern of decrease in smoke indicated improvement in combustion quality of JSVO in combustion chamber. It was found that the emission performance of the JSVO fuel improved as the advance angle of fuel injection was increased from the rated value of 20° BTDC upto 24° BTDC but deteriorated on further increase to 26° BTDC. The similar trend was shown on increasing the fuel injection pressure from the rated value of 175 kgf/cm².
Figure 4.32: Smoke emission vs. Engine Load
Figure 4.33: Smoke emission vs. Engine Load
Figure 4.34: Smoke emission vs. Engine Load
Figure 4.35: Smoke Emission vs. Engine Load
Figure 4.36: Smoke emission vs. Advance angle of fuel injection
Figure 4.37: Smoke Emission vs. Fuel injection pressure
4.4.5 HC Emission:

4.4.5.1 Effect of varying fuel injection point on HC emission at constant fuel injection pressure

The viscosity directly affects the HC emission quality of fuel. Because of higher viscosity the injector releases the fuel droplets of larger diameter, which needs more heat as well as more time for proper vaporization. If the advance angle of fuel injection is increased the fuel atomization quality increases and the combustion efficiency increases. The increased combustion efficiency results to low HC emission.

It was observed that at 200 BTDC the HC emission was lowest for diesel fuel, whereas the modified engine fueled with JSVO was emitting the HC more than the engine fueled with diesel but less than the JSVO fueled in existing engine. The HC emission for modified as well as existing engine fueled with JSVO was reduced up to 240 BTDC but it started increasing when the angle was further increased. The gap between them was continuously reducing as the advance angle of fuel injection was increased because the combustion efficiency of diesel might have started decreasing at higher advance angle but the combustion efficiency of JSVO started increasing resulting low HC emission (figure 4.42).

4.4.5.2 Effect of varying fuel injection pressure on HC emission at constant fuel injection point

The HC emission of diesel increased as the fuel injection pressure was increased from 175 kgf/cm² to 185 kgf/cm², 195 kgf/cm² and 205 kgf/cm² (figure 4.43). It shows that the combustion quality deteriorated by using the diesel in existing engine at higher pressure than the design value of this engine. The HC emission of JSVO was decreased as the fuel injection pressure was increased this may be due to the fact that the fuel particle size at higher injection pressure gets reduced and the combustion efficiency gets increased. It was found that the HC emission even at higher value of fuel injection pressure of 195 kgf/cm² increased at 26°
BTDC advance angle. It shows that the effect of increasing the HC emission at high advance angle pre dominated the effect of decreases of HC emission at high injection pressure.

4.4.5.3 Effect of fuel preheating at constant fuel injection point and fuel injection pressure

The HC emission of the JSVO when fueled in existing engine was observed to be higher than the HC emission of JSVO when fueled in modified engine (figure 4.38 to figure 4.43). In modified engine the fuel was preheated so the viscosity was reduced, the reduced viscosity enhanced the fuel injection efficiency so the HC emission was reduced. At all the point of engine running it was found that the HC emission was better in the case of preheating the fuel.

4.4.5.4 Combined effect of fuel preheating, fuel injection pressure and fuel injection point on HC emission

The study of variations in HC emission with change in fuel injection point and fuel injection pressure in both the cases i.e. modified engine and existing engine exhibited the result that the HC emission characteristics of fuel JSVO was improved by implementing higher degree (24$^\circ$) of fuel injection and 195 kgf/cm$^2$ pressure with a system of fuel pre-heating incorporated in the engine fuel supply system. But it was observed that the HC emission increased as the advance angle was increases further.

In association with the effect of fuel injection advance angle and the increase in fuel injection pressure the pattern of decrease in HC indicated the improvement in combustion quality of JSVO in combustion chamber. It was found that the emission performance of the JSVO fuel was improved as the advance angle of fuel injection was increased from the rated value of 20$^\circ$ BTDC upto 24$^\circ$ BTDC but it started deteriorating on further increase to 26$^\circ$ BTDC. The similar trend was shown on increase in fuel injection pressure from the rated value of 175kgf/cm$^2$. 
Figure 4.38: HC emission vs. Engine Load
Figure 4.39: HC emission vs. Engine Load
Figure 4.40: HC emission vs. Engine Load
Figure 4.41: HC emission vs. Engine Load:
Figure 4.42: HC emission vs. Advance angle of fuel injection
Figure 4.43: HC emission vs. Fuel injection pressure
4.5 Performance evaluation of existing and modified engine

The existing engine was operated to record the base line data required for comparison with engine performance with JSVO fuel. There were many sets of operating parameter used for testing the engine. Different fuel injection points, fuel injection pressures were used to test the engine with and without pre heating the fuel. After the analysis of data it was found that the engine incorporated with fuel preheating operating at 195 kgf/cm² fuel injection pressures and 24° BTDC advance angle of fuel injection point gives good results in comparison with existing engine running with diesel fuel. In this chapter the results obtained from the tests of modified engine running with JSVO at recommended operating parameter is compared with base line test results of engine.

4.5.1 Performance of existing engine fueled with JSVO

The existing low speed IDI engine manufactured by field marshal was tested with diesel and JSVO at 20° BTDC fuel injection point and 175 kgf/cm² fuel injection pressure. These parameters were the manufacturer’s recommended operating parameters for this engine with diesel fuel. The engine performance parameters as obtained from the experiments at 7.35 kW load on the engine are listed in table 4.1. The analysis of above listed parameters of the engine shows that the efficiency of the engine 30.62 % with JSVO was quite low in comparison with BTE of engine with diesel fuel which was 32.96% (figure 4.44). The cetane number is the scale for comparing the ignition delay angle of fuel. The higher CN means a lower delay period and smoother engine operation. The cetane number depends upon chemical composition of fuel. If more paraffinic hydrocarbons are contained in the fuel, the cetane number will be higher. The cetane number of JSVO was 38 in comparison with 48 as cetane number of diesel. The fuel with low cetane number requires large time delay and maximum rate of pressure rise. The other important phenomena are fuel atomization which governs the maximum temperature rise in combustion chamber. The larger fuel particle released by the
Table 4.3: Performance parameters of engine at 7.35 kW load

<table>
<thead>
<tr>
<th>Performance parameters</th>
<th>Diesel fuel</th>
<th>JSVO</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTE (%)</td>
<td>32.96</td>
<td>30.62</td>
</tr>
<tr>
<td>BSFC (kg/kWh)</td>
<td>0.260</td>
<td>0.301</td>
</tr>
<tr>
<td>CO emission (% vol)</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>CO2 emission (% vol)</td>
<td>1.24</td>
<td>0.76</td>
</tr>
<tr>
<td>NOx emission (ppm)</td>
<td>360</td>
<td>430</td>
</tr>
<tr>
<td>HC emission (ppm)</td>
<td>18</td>
<td>21.5</td>
</tr>
<tr>
<td>Smoke emission (% opacity)</td>
<td>9.7</td>
<td>17.9</td>
</tr>
</tbody>
</table>

fuel injector due to higher viscosity needs more heat and time to get atomized properly. Since the viscosity of JSVO was 10-12 times the viscosity of diesel so the JSVO also may have required higher heat and delay period. In scarcity of these factors the pre combustion process might be inefficient and would have negative effect on fuel combustion efficiency. The inefficient fuel combustion might have reduced the brake thermal efficiency. The BSFC of engine with JSVO was recorded to be 310 kg/kWh which was much higher in comparison with BSFC (0.260 kg/kWh) for diesel fuel (figure 4.45). The emission parameters of JSVO was poor in comparison with diesel fuel for CO, CO, NOx, HC and smoke (figure 4.46). These results made the JSVO unfit for use in existing engine. The feasibility of JSVO as efficient alternate fuel was only in modified engine. The existing engine can also be run by fuelling it with processed JSVO. The fuel properties of JSVO will improve by chemical processing. In this work the first method was utilized. The existing engine was modified to have advance angle of fuel injection 24° BTDC, fuel injection pressure 195 kgf/cm² and also by preheating of fuel. The engine was tested and the results obtained are discussed in following paragraph.
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Fig. 4.44: BTE vs Engine Load

Fig. 4.45: BSFC vs Engine Load
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Fig. 4.46: Emission vs Engine Load
4.5.2 Comparison of existing engine performance fueled with diesel and modified engine fueled with JSVO

The performance of existing engine fueled with JSVO at 20° BTDC fuel injection point and 175 kgf/cm² fuel injection pressure was poor in comparison with engine performance with diesel fuel at same operating parameters. The modifications on advance angle of fuel injection and fuel injection pressure with preheating the fuel to 90° C improved the engine performance. The recommended advance angle of fuel injection was 24° BTDC and the fuel injection pressure 175 kgf/cm² for JSVO to be used as alternate fuel in engine. The comparative engine performance parameters of modified engine to be fueled with JSVO and existing engine fueled with diesel is shown in figure 4.47. The improvements in engine performance after the modification of advance angle of fuel injection point and the fuel injection pressure with heat exchanger to preheat the JSVO to 90° C can be seen at a glance from the table 4.2. BTE of modified engine was obtained to be 34.76% which is an improvement of 4.14% on BTE of existing engine with JSVO fuel. It can be seen that the BTE of modified engine with JSVO test fuel was improved to such an extent that it was not only equal but higher than the BTE of existing engine with diesel fuel.

The BSFC was reduced in both the cases as the engine load was increased. The BSFC of existing engine with diesel fuel was found 0.260 kg/kWh. The BSFC of modified engine fueled with JSVO was obtained 0.266 kg/kWh. (figure 4.48). It can be concluded that the modification reduced the BSFC substantially but it was still marginally higher than the BSFC of base line engine.

The emission parameters ( CO, CO₂, NOₓ, HC and smoke) of modified engine fueled with JSVO and existing engine fueled with diesel were compared (figure 4.49). It was found that CO emission was improved and it became almost equal to the base line data. The CO₂ emission of existing diesel engine was higher than the modified engine with JSVO fuel but the difference was reduced substantially.
The NO\textsubscript{x} emission of modified engine was found to be reduced to an extent even less than emission of existing engine with diesel fuel. The HC and smoke emission were also improved to very good extent.

<table>
<thead>
<tr>
<th>Performance parameters</th>
<th>Existing engine, Diesel fuel</th>
<th>Existing engine, JSVO fuel</th>
<th>Modified engine, JSVO fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTE (%)</td>
<td>32.96</td>
<td>30.62</td>
<td>34.76</td>
</tr>
<tr>
<td>BSFC (kg/kWh)</td>
<td>0.260</td>
<td>0.301</td>
<td>0.266</td>
</tr>
<tr>
<td>CO (% vol)</td>
<td>0.05</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td>CO\textsubscript{2} (% vol)</td>
<td>1.24</td>
<td>0.76</td>
<td>1.08</td>
</tr>
<tr>
<td>NO\textsubscript{x} (ppm)</td>
<td>360</td>
<td>430</td>
<td>330</td>
</tr>
<tr>
<td>HC (ppm)</td>
<td>18</td>
<td>21.5</td>
<td>16.5</td>
</tr>
<tr>
<td>Smoke (% opacity)</td>
<td>9.7</td>
<td>17.9</td>
<td>10.5</td>
</tr>
</tbody>
</table>

Table 4.4: Comparative performance parameters of engine at 7.35 kW load
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Fig. 4.47: BTE vs Engine Load

Fig. 4.48: BSFC vs Engine Load
Figure 4.49: Emission parameters vs Load

(a) CO emission (%vol.)
(b) CO2 emission (%vol.)
(c) NOx (ppm)
(d) HC (ppm)

Existing engine, 20° BTDC fuel injection point and 175 kgf/cm² fuel injection pressure, diesel test fuel

Modified engine, 24° BTDC fuel injection point, 195 kgf/cm² fuel injection pressure, preheated JSVO test fuel
4.5.3 Techno economic evaluation of modified engine

The technical aspects of engine modifications are not complicated; it can be done locally for the engines already in use and by the manufacturer at the production level. The modification of engine can be done by the users also after short term training. This will retain the possibility of using the engine with petro diesel also as and when it becomes essential. The financial implications involved in modification are almost negligible.

Based upon the market survey the cost of Jatropha seeds at present is about Rs 20 per kg. The oil yield of the seed which was obtained in our laboratory was 28%. The oil yield of the seeds depend upon factors such as Jatropha species, plantation time, expellers efficiency etc. The production cost of 1 litre JSVO including power used by the expeller and the labor involved is about Rs 75 under present market value. The use of JSVO in scenario of scarce availability of seed and high price projects lean feasibility for industrial and agricultural applications. The cost of one liter JSVO is much higher than the cost of diesel. The cost of JSVO can be expected to reduce as the farmers get encouraged to cultivate jatropha at large scale. The production of oil by the farmers at site will not cost to this extent because there will not be any cost of packing, storage, transportation, traders profit and all other financial liabilities of market.

The engine operating cost and other associated maintenance requirements are not included in this study. The researchers have reported the possibilities of injector choking, gum formation, piston sticking and carbon deposit under the endurance test. These symptoms may increase maintenance and engine operating cost. The test conducted by these researchers have either not utilized the modifications, if utilized then the modifications was carried out partially. The engine performance will improve on these reported symptoms if the engine is run with modification operating at recommended operating parameters. The combustion quality, emission quality and ultimately the behavior of engine has improved to large extent by incorporating the modifications. The improvements in efficiency, BSFC
and emission characteristics indicate that the engine will be running trouble free for recommended life span without any change in its maintenance protocol. This shows that there will not be any additional maintenance cost involved by using the JSVO in this engine on regular basis. However the detailed study on these parameters under endurance test is yet needs to be carried out in future research work.

4.5.4 The engine operation on long term basis

The engine after the modification will be functioning efficiently without any starting trouble. Engine starting trouble was not encountered at the time of experiments. Since the experiments were conducted at an ambient temperatures 25\(^0\) C-30\(^0\) C even without any modification of fuel injection system and without preheating the fuel. It can be expected that the staring trouble will not arise even during winter season and also at cold climatic places. However, if it is there then the engine can be started with diesel just for a while and later it can be changed over to neat JSVO.

4.5.5 Socio economic evaluation of modified engine

The use of JSVO as alternate fuel will not only reduce the load on petroleum fuel reserves but also help in global objective of having clean and environmental friendly fuel. The scope of usage of JSVO in engine will encourage the farmers to cultivate the Jatropha. The Jatropha is primarily cultivated at barren land so the land utilization and revenue generation of farmers will increase. The production of JSVO at user end will make them self dependent. The trouble of the farmers to go to market for purchase of diesel will reduces to maximum extent. The self dependence of farmers for the procurement of engine fuel becomes more important for the users residing in remote areas. The barren land utilization by the farmers will enhance their prosperity and generate he employment opportunities to local laborers.