CHAPTER 7

EXPERIMENTS ON GASIFICATION-ENGINE-GENERATOR SYSTEM

7.1 INTRODUCTION

The producer gas (PG) generated by the biomass gasifier can be used in a) furnaces, kilns, heaters, etc. for direct heating, b) reciprocating internal combustion engines, rotary gas turbines for mechanical work output, and c) reactors for synthesis of various chemicals like CH$_4$, CH$_3$OH, etc. The use of PG in engines for electrical power generation is the most attractive among all applications and therefore it was investigated.

The PG can be used in both spark ignition (SI) and compression ignition (CI) engines. If it is used in SI engines, 100 % replacement of petrol by PG is attainable but it results in de-rating of the engine. Muñoz et al., (2000) conducted performance tests on SI engine and found that the power output of the engine with PG operation was approximately half of that obtained with petrol operation throughout the operating range. It must be remembered that the heating value of the PG is approximately one-tenth of that of petrol.

In the present work, a CI engine-electrical generator set was tested for its performance under diesel alone and dual fuel (PG + diesel) modes. The specifications of the set are given in Table 7.1.
Table 7.1 Specifications of engine-electrical generator set

<table>
<thead>
<tr>
<th>Engine</th>
<th>Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Type</td>
</tr>
<tr>
<td>Vertical, 4 stroke, direct injection (DI),</td>
<td>Direct coupled to engine, single phase, A.C.,</td>
</tr>
<tr>
<td>water cooled, diesel</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>Rated output</td>
</tr>
<tr>
<td>18.5 :1</td>
<td>3 kVA</td>
</tr>
<tr>
<td>Efficiency</td>
<td>90 %</td>
</tr>
<tr>
<td>Rated output</td>
<td>Voltage</td>
</tr>
<tr>
<td>3.7 kW @ 1500 rpm</td>
<td>230 V</td>
</tr>
<tr>
<td>Bore diameter</td>
<td>Current</td>
</tr>
<tr>
<td>84.5 mm</td>
<td>13 A</td>
</tr>
<tr>
<td>Stroke length</td>
<td>Speed</td>
</tr>
<tr>
<td>112 mm</td>
<td>1500 rpm</td>
</tr>
</tbody>
</table>

7.2 TESTING OF DIESEL INJECTION PUMP

Since an analysis of diesel injection pump (DIP) performance is relevant, it was first taken up before investigating the actual performance of the engine. Generally, the DIP operates at very low delivery rates during dual fuel operation of the engine. Injection process parameters such as injection timing, injection pressure and therefore the spray characteristics, being delivery rate dependent, undergo significant changes at low delivery rates. These changes call for re-tuning of the DIP, if the engine performance is to be optimum (Parikh et al., 1993). So, testing of DIP becomes significant.

The single cylinder engine has a single barrel, cam-driven plunger type DIP whose sectional view is shown in Figure 7.1 (Heywood 1988). The important operating parameters of DIP are:

a) Diesel injection quantity,

b) Diesel injection timing, and

c) Diesel injection pressure.
7.2.1 Diesel Injection Quantity

The quantity of diesel injected depends upon the position of control rack of the injection pump. During engine operation its position is controlled by a speed governor. For finding out the delivered quantities of diesel at different control rack positions, the injection pump was disengaged from the governor and the control rack position was fixed manually. At each setting, the volume of diesel delivered in hundred cycles was measured. The volume of diesel injected per cycle was then calculated.

7.2.2 Diesel Injection Timing

In any engine, the diesel is injected over a few degrees of crank rotation starting before Top Dead Centre (TDC). In the present research, the diesel injection timing was determined by the following procedure. Initially the TDC position was marked on a paper strip pasted on the flywheel. The diesel injector was mounted exactly at the topmost point facing against the paper strip such that its tip was close to it. The crank shaft was rotated and
the markings due to diesel spray were directly obtained on the paper strip from start to stop of injection. The procedure was repeated for different control rack positions. The diesel injection timing i.e., the start of injection and the duration of injection with respect to TDC were obtained by determining the crank angle over which the injection occurred.

7.2.3 Diesel Injection Pressure

The injection pressure of diesel determines its spray characteristics inside an engine cylinder. To determine the injection pressure, the control rack was set at 16 mm, since that would be its position when engine runs in dual fuel. A pressure gauge of Bourdon tube type was connected in the high pressure pipe line between the DIP and the diesel injector. The pressure gauge can read up to a maximum pressure of 350 kg/cm$^2$. The crankshaft was rotated and the pressure gauge display was videographed using a digital camera to record the rapid deflections of the pointer. The diesel injection pressure was obtained by reading against the maximum deflection of the pointer in the pressure gauge and the same is shown in Figure 7.2.

![Figure 7.2 Diesel injection pressure measurement](image)
7.3 GASIFICATION-ENGINE-GENERATOR SYSTEM

The working of engine in dual fuel mode requires the simultaneous operation of biomass gasification system. The layout of complete gasification-engine-electrical generator system is shown in Figure 7.3. The constructional features of the gasification system have already been described in Chapter 3. Some of the distinct features of the system are: (i) generation of PG in a fully co-current flow gasifier, (ii) dry cleaning of PG using dry cyclone separator, candle type dust filter, and tar adsorber, and (iii) cooling of PG in a shell and tube type heat exchanger. The cleaned and cooled PG from the gasification system is then supplied to the engine through a PG–air mixer.

![Figure 7.3 Layout of gasification-engine-generator system](image-url)
fitted to the inlet manifold of the engine. The detailed diagram of the mixer has been shown in Figure 3.8.

7.4 EXPERIMENTS ON ENGINE-GENERATOR SET

7.4.1 Diesel Alone Mode

In this mode, the engine was run by using diesel only. Performance tests were conducted for two different methods of engine air supply. In the first method, the engine was allowed to draw air directly through an air filter but in the second method it was allowed to draw air only through the gasification system. When air was drawn through the gasification system, the gasifier was packed with biomass but was not fired. In both cases, the engine was operated at a constant speed of 1500 rpm at all electrical loads and for each load the following readings were recorded: (i) diesel consumption rate, (ii) engine air flow rate, (iii) speed, (iv) voltage, (v) current, (vi) electrical power output, (vii) O₂ and CO₂ contents of engine exhaust, (viii) DIP control rack position, (ix) cooling water temperature, and (x) engine exhaust gas temperature. The experiment was conducted from no load to maximum load.

7.4.2 Dual Fuel Mode

In any diesel engine, the actual air/fuel ratio is about 2-4 times the stoichiometric requirement. If it is operated in dual fuel mode, this excess air volume must be suitably replaced by PG. This principle was followed in dual fuel operation of engine. The engine was run with dual fuel (PG+diesel) and a performance test was conducted. For this purpose, the gasifier was started by supplying air from the blower. The generated PG was directly flared at gasifier exit without scrubbing and cooling for about 5 minutes. Afterwards, the PG was passed through scrubbing and cooling train and was flared at the tar adsorber exit for about 30 minutes to bring the gasification system to steady state condition. Jorapur and Rajvanshi (1995) also prescribed the use
of blower to supply air to gasifier, during the engine operation, in order to ensure proper gas flow to the engine at all loads.

The engine was then started in diesel and once its operation became stable, the PG was admitted gradually to the PG-air mixer by opening the PG valve. The valve on air supply line to the PG-air mixer was kept fully open throughout the experiment. This was done to ensure maximum possible air flow to the engine. The PG valve was regulated depending upon the power output and the knocking tendency of the engine. The PG-air mixer was under a slight negative pressure as it had been connected to the inlet manifold of the engine. Till the PG valve, the PG pressure was positive in the gasification system and it got throttled across the PG valve to the pressure which was prevailing in the PG-air mixer. Ramadhas et al., (2006) also analysed the performance of the gasifier-engine system by running the engine for various PG/air flow ratios.

For every electrical load, (i) diesel consumption rate, (ii) engine air flow rate, (iii) PG flow rate, (iv) speed, (v) voltage, (vi) current, (vii) electrical power output, (viii) O$_2$ and CO$_2$ contents of engine exhaust, and (ix) DIP control rack position were measured in the engine system. Simultaneously, (i) air flow rate to gasifier, (ii) wood feed rate, (iii) bed temperatures at eight points along the gasifier height, (iv) PG temperature at gasifier outlet, and (v) PG temperature at gas cooler outlet were measured in the gasification system. The condensate formed in the gas cooler was discharged out at regular intervals of time. After the test, the PG flow to the engine was cut off, followed by diesel. The gasifier was then stopped and its residual contents were weighed.
7.5 RESULTS AND DISCUSSION

7.5.1 Operating Parameters of Diesel Injection Pump

The operating parameters of DIP namely diesel injection quantity, diesel injection timing, and diesel injection pressure were determined by conducting tests as described in Section 7.2.

7.5.1.1 Diesel Injection Quantity

The quantities of diesel injected per cycle at different control rack positions are shown in Figure 7.4. The DIP fitted on the engine actually had a wider range of diesel delivery quantities ranging from 0 to 142 mm$^3$/cycle. In the actual operation of engine, the diesel consumption rate was calculated for both diesel alone and dual fuel modes. From that data, the volume per cycle was calculated and it is also plotted in the same Figure 7.4. It shows that only 10 – 25 mm$^3$/cycle was required to be injected to the engine even in diesel alone operation for the entire range of loads. For that value of injection, the mechanical speed governor maintained the control rack position of DIP between 14 mm and 17 mm throughout the load range. In dual fuel mode, the diesel injection quantity was only 8 – 16 mm$^3$/cycle and for that requirement, the governor maintained the control rack position between 14.5 mm and 17 mm. It is evident that the DIP fitted on the engine was over-rated.

7.5.1.2 Diesel Injection Timing

The diesel injection timing can be obtained from Figure 7.5 which shows the angular position of crank during diesel injection into the engine cylinder at different control rack positions. During dual fuel operation, when control rack was positioned by the governor between 14.5 mm and 17 mm, the diesel injection occurred only at one instant i.e., 23° crank angle before
Figure 7.4  Volume of diesel injected per cycle for different control rack positions

TDC. This was due to drastic reduction in the diesel injection quantity in dual fuel mode. But for achieving better combustion, diesel should be injected over an angle. This must be ensured even for dual fuel operation where the quantity of diesel injected is very little. With the available type of DIP, it is not possible to get such a precise control over quantity and angular range of diesel injection. However, this limitation on the part of available DIP does not hamper the engine operation completely but potentially reduces the engine performance. Suitable injector design, ignition advance, combustion chamber design, compression ratio, etc. will have to be optimized to get high thermal efficiency and low CO emission (Uma et al., 2004). The modern electronically controlled DIP which is fitted in automobile engine may be suitably modified for stationary dual fuel engine application.
7.5.1.3  **Diesel Injection Pressure**

Since the pressure variation during diesel injection was rapid, the process of pressure measurement by the pressure gauge was videographed as described in Section 7.2.3. From the image analysis, the diesel injection pressure was determined to be 270 kg/cm².

7.5.2  **Engine Valve Timing**

The valve timing diagram of the engine is shown in Figure 7.6. The actual values determined experimentally were lesser than the values given by Heywood (1988). The valve timings of the engine were kept same in both diesel alone and dual fuel modes.
7.5.3 Performance of Engine-Generator Set

As described in Section 7.4, the engine was tested for its performance in both diesel alone and dual fuel modes.

7.5.3.1 Diesel Alone Mode

In diesel alone mode, the engine’s performance was tested for two different methods of air supply. In the first method, the engine sucked air via the air filter directly, while in the second method it sucked air only through the gasification system.

Engine Drawing Air via Air Filter: As the pressure drop for engine air flow was lesser when the engine sucked air via air filter, all the performance parameters of the engine were superior. The plots of diesel consumption rate, BSDC, mechanical efficiency, indicated thermal efficiency, brake thermal efficiency, and overall electrical conversion efficiency versus electrical power output of the engine-generator set are shown from Figures 7.7 to 7.12.
The plots of volumetric efficiency, air/fuel ratio, oxygen and carbon dioxide contents of exhaust gases, DIP control rack position, cooling water temperature, and exhaust gas temperature versus electrical power output of the engine-generator set are shown from Figure 7.13 to Figure 7.18. When electrical power output was increased, air/fuel ratio decreased from 65:1 to 27:1, the oxygen content of exhaust gases also decreased but the carbon dioxide content of exhaust gases increased.

**Engine Drawing Air via Gasification System:** This test had been conducted because when the engine was run in dual fuel mode later, it actually sucked (a) air through the air filter, and (b) PG through the gasification system. All the performance parameters which were determined in the first method were determined in the second method also. When the engine sucked air through gasification system, many of the performance parameters showed a small change with respect to the first method. The diesel consumption rate, BSDC, mechanical efficiency, indicated thermal efficiency, brake thermal efficiency, and overall electrical conversion efficiency at various electrical power outputs of the engine-generator set were plotted in the same graphs which are shown from Figures 7.7 to 7.12.

The volumetric efficiency, air/fuel ratio, oxygen and carbon dioxide contents of exhaust gases, DIP control rack position, cooling water temperature, and exhaust gas temperature at various electrical power outputs of the engine-generator set were plotted in the same graphs which are shown from Figures 7.13 to 7.18. It may be noticed that volumetric efficiency and air/fuel ratio of the engine were lesser at all electrical power outputs when the engine sucked air through gasification system. This is attributed to the increased pressure drop for engine air flow through the various components of gasification system.
Figure 7.7  Diesel consumption rate vs. electrical power o/p

Figure 7.8  BSFC vs. electrical power o/p

Figure 7.9  Mechanical efficiency vs. Electrical power o/p

Figure 7.10  Indicated thermal efficiency vs. electrical power o/p

Figure 7.11  Brake thermal efficiency vs. electrical power o/p

Figure 7.12  Electrical conversion efficiency vs. electrical power o/p
Figure 7.13  Volumetric efficiency vs. electrical power o/p

Figure 7.14  Air/Fuel ratio vs. electrical power o/p

Figure 7.15  O₂ % and CO₂ % vs. electrical power o/p

Figure 7.16  DIP setting vs. electrical power o/p

Figure 7.17  Cooling water temp. vs. electrical power o/p

Figure 7.18  Exhaust gas temp. vs. electrical power o/p
7.5.3.2 Dual Fuel Mode

All the performance parameters which had been determined when the engine was run in diesel alone mode, were determined in dual fuel mode also. Besides, the extent of diesel conserved also called as ‘diesel replacement’ when the engine was run in dual fuel mode was calculated. As PG had distinct physical and chemical properties with respect to diesel, its usage in diesel engine resulted in variations in the entire engine operating parameters.

**Diesel Consumption Rate:** The Diesel Consumption Rate (DCR), which is the quantity of diesel consumed per unit time, was calculated at different loads for both diesel alone and dual fuel operation of the engine. The DCR varied between 0.46 kg/h and 1.03 kg/h in diesel alone operation. In dual fuel mode, when PG-air mixture was admitted to the engine, the mechanical speed governor automatically reduced the diesel injection to the engine and hence the DCR got reduced and it varied between 0.14 kg/h and 0.47 kg/h. The DCR at different electrical loads are shown in Figure 7.19 for both diesel alone and dual fuel modes.

**Brake Specific Diesel Consumption:** The Brake Specific Diesel Consumption (BSDC) is shown in Figure 7.20 over the entire loading range of the engine. As desired, the diesel consumption got decreased in dual fuel mode. An average value of 0.17 kg/kWh was obtained over a larger loading range i.e., about 4 - 5 units of electricity could be generated from a litre of diesel even in low capacity engines.

**Efficiencies:** The plots of mechanical efficiency, indicated thermal efficiency, brake thermal efficiency, and overall electrical conversion efficiency versus electrical power output of the engine are shown from Figure 7.21 to Figure 7.24 for both diesel alone and dual fuel modes. From Figure
7.24, it is clear that there was substantial decrease in the conversion efficiency when engine was run in dual fuel mode. It can be improved by (i) certain modifications in combustion chamber design, (ii) valve timing and injection timing adjustments in the engine under dual fuel mode, and (iii) increasing the calorific value of PG by removing inert gases present in it. The variation of volumetric efficiency with electrical power output is shown in Figure 7.25 for both diesel alone and dual fuel modes. It may be seen that the volumetric efficiency in dual fuel mode was higher than that in diesel alone mode. This was due to the supply of PG to the engine at positive pressure from the gasification system.

**Air/Fuel Ratio:** For internal combustion engines, the air/fuel ratio is defined as the ratio of the rate of air supply to the rate of fuel supply. In diesel alone mode, the word ‘fuel’ refers to diesel alone, whereas in dual fuel mode, it refers to both PG and diesel. Figure 7.26 shows that the air/fuel ratio was higher in diesel alone mode at all electrical loads when compared to that in dual fuel mode. In diesel alone mode, even at maximum load, an air/fuel ratio of 27:1 was attained. Whereas, in dual fuel mode even at no load an air/fuel ratio of only 2.7:1 was attained. Hence, when PG is contemplated as fuel for high capacity engines, supercharging becomes essential. Consequent to engine air flow reduction, the O\textsubscript{2} content of engine exhaust gases in dual fuel mode was lesser than that in diesel alone mode. The same is shown in Figure 7.27 for the entire loading range. But the CO\textsubscript{2} content of engine exhaust gases in dual fuel mode was higher than that in diesel alone mode and it is shown in Figure 7.28. It was due to the presence of CO\textsubscript{2} in the PG supplied to the engine. The proportion of PG in the PG-air mixture supplied to the engine was important for its smoother operation. If PG quantity was increased beyond a limit, smoother operation of the engine could not be achieved. It also caused fluctuations in the electrical power produced by the generator.
The DIP control rack positions as regulated by the mechanical governor at different electrical power outputs are shown in Figure 7.29. The lesser quantity of diesel injection in dual fuel mode is once again evident by the difference in DIP control rack positions between the two modes.

**Diesel Replacement:** The diesel replacement percentage in dual fuel operation of the engine is shown in Figure 7.30. There was no smoother variation over the entire load range. This was due to the batch feeding of wood pieces into the gasifier. The quantity of volatiles release was more, just after feeding the wood pieces. Afterwards, it decreased gradually till the next batch of wood pieces is fed. Another phenomenon can also be observed in Figure 7.30. At higher engine loads, the thermal energy released by the combustion of PG was insufficient to take up the increased load. Hence, the additional load was borne by more diesel combustion resulting in reduced diesel replacement percentage at higher loads.

**Air, PG, and Diesel Flows:** In diesel alone mode, the air flow and diesel flow to the engine at different electrical power outputs are shown in Figure 7.31. In dual fuel mode, the air flow, PG flow, and diesel flow to the engine for the entire loading range are shown in Figure 7.32.
Figure 7.19  Diesel consumption rate vs. Electrical power o/p (dual)

Figure 7.20  BSDC vs. electrical power o/p (dual)

Figure 7.21  Mechanical efficiency vs. Electrical power o/p (dual)

Figure 7.22  Indicated thermal eff. vs. Electrical power o/p (dual)

Figure 7.23  Brake thermal efficiency vs. electrical power o/p (dual)

Figure 7.24  Electrical conversion efficiency vs. Electrical power o/p (dual)
Figure 7.25 Volumetric efficiency vs. Electrical power o/p (dual)

Figure 7.26 Air/Fuel ratio vs. Electrical power o/p (dual)

Figure 7.27 O₂ % in exhaust gases vs. Electrical power o/p (dual)

Figure 7.28 CO₂ % in exhaust gases vs. Electrical power o/p (dual)

Figure 7.29 DIP setting vs. Electrical power o/p (dual)

Figure 7.30 Diesel replacement vs. Electrical power o/p (dual)
In diesel alone operation, the range of actual air/fuel ratios was 65:1 – 27:1. These values were very much higher than stoichiometric value of 15:1 for diesel. As the volumetric capacity of the engine was constant, the air volume was partially displaced by PG volume in dual fuel mode resulting in reduced air intake. Consequently, the range of actual air/fuel ratios got decreased to 2.7:1 – 2:1, which was only marginally higher than stoichiometric range of values 1.3:1 – 1.6:1. The same observation was made by Bhattacharya et al., (2001) also. In their case, the air/fuel ratio became lesser than the stoichiometric value. For a 100 kVA engine-generator set, Baliga et al., (1993) reported that the diesel replacement decreased to about 50 % at 80 % load in dual fuel mode. This was attributed to the low excess air factor of the engine.

**Figure 7.31** Reactant flows in diesel engine vs. Electrical power o/p  
**Figure 7.32** Reactant flows in dual fuel engine vs. Electrical power o/p

### 7.6 CONCLUDING REMARKS

From the various tests conducted upon the DIP and gasification-engine-generator system, the following major conclusions are drawn:

- The DIP was required to inject only a maximum of 25 mm³/cycle to the engine at maximum load even in diesel alone
mode. But it can inject a maximum of 142 mm$^3$/cycle on the basis of its design capacity. So, the DIP fitted on the engine was over-rated. It must be replaced by a smaller DIP but it is not available in the market.

- The DIP injected diesel into the engine as a single pulse at about 23° crank angle before TDC in dual fuel mode. But for better combustion, it should be injected over an angle.

- If electronically controlled diesel injection system is used in dual fuel mode, still higher diesel conservation and engine efficiency may be realized due to precise control on the quantity and timing of diesel injection.

- In diesel alone mode, when engine sucked air entirely through gasification system instead of air filter, its volumetric efficiency and air/fuel ratio got decreased.

- In dual fuel mode at all electrical loads, (a) DCR was lower than that in diesel alone mode, (b) BSDC was lower than that in diesel alone mode, (c) electrical conversion efficiency was lesser than that in diesel alone mode, and (d) air/fuel ratio was very low and it decreased drastically with increasing electrical power output. The low air/fuel ratio resulted in meagre O$_2$ content of engine exhaust gases.

- In dual fuel mode, it was possible to conserve diesel by replacing it with PG to an extent of 75 – 80 %. The diesel replacement at lower loads was higher than that at higher loads.

- Engine suction alone was insufficient to draw the required quantity of PG into the engine. For this purpose, blower
became a necessity in the gasification system to aid better flow of PG to the engine. The water-free dry cleaning of PG in cyclone separator, dust filter and tar adsorber and the indirect cooling of PG in gas cooler were sufficient for the low capacity engine-generator set tested. But, PG cleaning and cooling using water is very effective and is indispensable for large capacity diesel engine-gensets.