Emission characteristics of an electricity generation system in diesel alone and dual fuel modes

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Abstract

Emission characteristics of a diesel engine in diesel alone and dual mode (with producer gas) at different load conditions are presented in this paper. Concentration of pollutants such as carbon monoxide (CO), oxides of nitrogen (NO\textsubscript{x}), sulphur dioxide (SO\textsubscript{2}), hydrocarbons (HC) and particulates in the flue gas were monitored and emission factors have been derived. In addition to the emission characteristics, diesel replacement rate at different loads has been estimated. It was observed that the emissions increase at low-load conditions. It has been found that CO content in the flue gas increase in dual fuel operation, more so at part loads. NO\textsubscript{x} and SO\textsubscript{2} concentration decrease in dual fuel mode.

Keywords: Biomass gasifier; Diesel engine; Dual fuel mode; Emission characteristics; Producer gas

1. Introduction

In India more than 80,000 villages remain unelectricd by the end of 2000, out of which about 18,000 villages are not feasible to be connected through grid supply as they are located in remote areas including hilly, tribal, forest and desert areas [1]. Even in the electrified villages the supply is erratic. Hence, it would be advantageous to consider non-conventional means of electrification such as solar, wind, biomass and mini-hydroelectric systems for rural electrification depending on their suitability for specific locations and end uses.

In India a large variety of biomass feedstocks are available in huge amounts. As these are available locally, biomass gasifier-based power generation may be an appropriate option for decentralized power generation in many areas of the country. Biomass gasification is one such process where producer gas could be obtained from biomass feed stocks and in turn use the producer gas for power generation purposes. The cumulative installed capacity of biomass based power generation in the country as of December 2001 was only 358 MW (including cogeneration and biomass gasifiers) as against an estimated potential of 19500 MW [1].

Biomass gasifier-based systems capable of producing power from a few kilowatts up to several hundred kilowatts have been successfully developed indigenously. Producer gas from a biomass gasifier can be used either as a partial substitute for diesel in
diesel engines or can be used alone in a gas engine. The utilization of producer gas in the diesel engine in dual fuel mode of operation is an established technique for conservation of diesel. Diesel replacements up to 70-90% have been achieved in the dual fuel mode [2-5].

Earlier studies on dual fuel system reported the feasibility of technology, thermal performance and fuel efficiency [2,3,5]. Performance studies with reference to engine exhaust emission are limited. Parikh et al. [4] reported the emission performance of diesel engine in diesel alone and dual fuel mode with data on carbon monoxide (CO) and hydrocarbon (HC) emissions. Baozhao and Yicheng [6] have studied emission performance of engine in dual fuel mode operated with diesel and producer gas obtained from a rice husk gasifier. Researchers at the Indian Institute of Science, Bangalore and a Swiss team studied the environmental aspects of 100% producer gas engine installed at the Indian Institute of Science [7,8]. In view of the large potential of biomass gasifier-based power generation in the country, it is necessary that the emission characteristics of diesel engines in dual fuel mode (with producer gas) are studied in detail. Such studies should take into account of all major pollutants such as carbon monoxide (CO), particulates, hydrocarbons (HC), sulphur dioxide (SO2) and oxides of nitrogen (NOx). Moreover, in view of the fact that the systems meeting electricity requirements of the villages would often operate at part loads, the performance of such systems at different loads should also be studied. An attempt in this direction has been made in this study.

2. Methodology

The emission monitoring was carried out in a diesel engine (Kirloskar, India) in diesel alone and dual fuel mode. The dual fuel system was operated with producer gas obtained from a down draft gasifier installed by Tata Energy Research Institute (TERI) at Gual Pahari, Haryana. The system description and methodology adopted is presented below.

2.1. System description

The down draft gasifier used in this study is a throat less, closed top system designed by TERI. Biomass such as wood and briquettes made from saw dust or crop residues can be used as feed stock. Tar and dust contents in raw producer gas obtained from this gasifier ranged from 730 to 1440 mg/Nm$^3$. The gas is further cleaned using a cooling and cleaning system consisting of gravity filter, cyclone filter, venturi scrubber, mist separator and paper filter. Cleaned gas is used to drive the diesel engine in dual fuel mode along with diesel. Fig. 1 shows a schematic diagram of the biomass gasifier system used in this study.

The diesel engine system (Kirloskar, India) tested in this study consists of a turbo charged, four stroke IC engine coupled with an alternator. The engine-alternator specifications are given in Table 1.

2.2. Experimental details

Experimental investigations in diesel alone and dual fuel mode were carried out at different loads (10, 20, 30 and 40 kW). Three experiments were conducted at each load. In each experiment, emission parameters such as carbon monoxide (CO), oxides of nitrogen (NOx) and sulphur dioxide (SO2), hydrocarbon (HC), and particulates were measured. In addition to emission data, parameters related to thermal performance of engine such as fuel consumption, composition of producer gas, 5ue gas temperature, and velocity of the 5ue gas were also measured and recorded. The calorific value of the producer gas was calculated from the composition of producer gas and its corresponding heating value given in the text [9]. A sampling port was provided in the exhaust pipe for measuring temperature, velocity and to collect 5ue gas samples.

A pilot experiment was rst conducted to nalize parameters such as duration of experiment, 5ow rate of sampling. During the pilot test the engine was started and 5ue gas temperature was recorded for every ve-minute interval. It was observed that the 5ue gas temperature was increasing during the initial 15 minutes and then stabilized. Therefore it was decided to start the experiments after 15 minutes of engine start up. This allows the engine to stabilize. Experiments in dual fuel mode were started after an hour of the gasifier start up. During this period the producer gas was 5ared in a 5are port. Small pieces of Keekar wood (Acacia nilotica) with approximate size of 6 cm in length and 4 cm in


Table 1

<table>
<thead>
<tr>
<th>Type</th>
<th>Direct injected six cylinder, vertical, four stroke engine with mechanical injector</th>
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<tbody>
<tr>
<td>Speed</td>
<td>1500 rpm (xed)</td>
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<tr>
<td>Engine rating</td>
<td>77.2 kW</td>
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<tr>
<td>Bore (mm)</td>
<td>110</td>
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<tr>
<td>Stroke</td>
<td>116</td>
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<tr>
<td>Cubic capacity (l)</td>
<td>6.614</td>
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<tr>
<td>Compression ratio</td>
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<td>Specific diesel rated consumption (g/kWh)</td>
<td>230 ± 5%</td>
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<tr>
<td>Alternator rating (kVA)</td>
<td>62.5</td>
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</table>

thickness were used as feedstock for gasification in this study.

2.3. Measurement techniques

Flue gas sampling and measurements were carried out as per the standard methods for source emission monitoring evolved by the Central Pollution Control Board, New Delhi, India [10]. A stack monitoring kit (APM 620, Envirotech, India) was used for 5ue gas sampling and measurement of temperature and velocity. The stack monitoring kit consists of a thermocouple, s-type pitot, and a sampler for particulate and gaseous pollutants. Flue gas temperature was measured with the thermocouple sensor and the velocity was determined from the static and dynamic pressure measured with s-type pitot. Isokinetic sampling conditions were maintained to obtain representative particulate sampling. Glassibre thimbles (Whatman, UK) were used for particulate collection. Prior to sampling the glassibre thimbles were kept in a desiccator for at least 24 h and nal weights were recorded. Weight of the particulate collected in the thimble was determined from the difference in the thimble weights, duration of sampling and sampling flow rate. Flue gas samples were collected in impinger tubes provided in the stack sampler and further analysed for NOx and SO2. Colorimetric technique was followed to determine NOx (US EPA method 7-1) and barium-thorin titration method was adopted for the determination of SO2 concentration in the 5ue gas [10]. Flue gas samples were also collected in tedlar bags and analysed for CO and HC using gas chromatography. A gas chromatograph (GC) with flame ionization detector (FID) was used to analyse CO and HC. In this system, a carbosphere packed column was used to separate CO, a blank column was used to separate hydrocarbon from the 5ue gas and the separated CO and HC were determined by FID. The GC was calibrated with the standard calibration gas mixture supplied by Scott Speciality Gases, Inc., USA. The techniques used for measurement of pollutants are listed in Table 2.
Table 2  
Measurement techniques for particulate and gaseous pollutants  

<table>
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<tr>
<th>Pollutant</th>
<th>Measurement technique</th>
<th>Detection range</th>
<th>Reference</th>
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<tr>
<td>Particulate</td>
<td>Sampling by stack gas sampler and analysis by gravimetric technique</td>
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<td>[3]</td>
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<tr>
<td>CO, HCx</td>
<td>Gas chromatograph with same ionization detector (GC/FID)</td>
<td>1-1000 ppm</td>
<td>2</td>
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<tr>
<td>SO2</td>
<td>Sampling followed by bariumthorin titration method</td>
<td>2-8000 mg/m³</td>
<td>[3]</td>
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<tr>
<td>NOx</td>
<td>Sampling followed by colorimetric technique</td>
<td>2-400 mg/m³</td>
<td>[3]</td>
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</tbody>
</table>

2.4. Wood and producer gas consumption

Wood consumption was measured by an electronic weighing balance. Initially the gasifier was loaded full with wood pieces. After every 2 h the gasifier was loaded up to the top (full) with a weighed quantity of wood. Fuel consumption rate (kg of wood/h) was estimated from the mass of wood consumption and duration of operation.

Amount of producer gas supplied to the engine is estimated from the pressure drop measured by the venturi metre. Producer gas composition was determined using chromatography technique (GC with thermal conductivity detector—GC/TCD). Calorific value of producer gas has been computed from the volume fraction of gas components and its corresponding heating value [7].

2.5. Diesel replacement rate

A graduated cylinder connected to the diesel tank through which the diesel is supplied to the engine was used to measure the diesel consumption. Initially the engine was operated in diesel alone mode and the diesel consumption was recorded. The diesel consumption rate \((\text{DCR})_{\text{diesel}}\) was determined from the diesel consumption and corresponding duration. Then the engine was operated in dual fuel mode and the \((\text{DCR})_{\text{dual fuel}}\) was determined. The diesel replacement rate (% DR) has been calculated as follows.

\[
\text{DR}(\%) = \frac{(\text{DCR})_{\text{diesel}} - (\text{DCR})_{\text{dual fuel}}}{(\text{DCR})_{\text{diesel}}} \times 100,
\]

where \((\text{DCR})_{\text{diesel}}\) is the diesel consumption rate (kg/h) under diesel operation and \((\text{DCR})_{\text{dual fuel}}\) the diesel consumption rate (kg/h) under dual fuel operation.

2.6. Methods for estimation of emission load

Pollutant emission depends on fuel quality, fuel consumption rate and type of engine tested. At different load conditions, fuel consumption rate varies, even at the same load in different operating modes i.e. diesel alone and dual fuel specific energy consumption varies. So for comparing the emissions across different load conditions or different operating modes, it should be normalized either to unit of energy generated or to unit mass of fuel consumed. And moreover the emission norms stipulated by the central pollution control board, India are according to the pollutant emission per unit of electricity generated (g/kWh). So the concentration of pollutants determined in the study are used to estimate mass emission load (g of pollutant/kg of fuel input) and emission load per energy input (g of pollutant/MJ of energy input) were estimated from the concentration, velocity of the 5ue gases, stack dimensions [3]. Emission per unit of electricity produced is derived from the emission load per energy input and specific energy consumption.

The first step in estimating the emission load is to estimate the emission rate.

Emission rate can be calculated as follows.

Emission rate of pollutant (kg/h) = \(S \times QS\),

where, \(Q_s\) is the 5ue gas 5ow rate (25°C, 760 Hg mm), Nm³/h. Flow rate of 5ue gas \(Q_s = \text{Velocity of 5ue}\)
gas x Area of exhaust duct. $S$ is the concentration of pollutant (mg=Nm$^3$).

From the emission rate, mass emission (g/kg of fuel input) could be calculated as follows.

\[
\text{Mass emission (g/kg)} = \frac{\text{Emission rate of pollutant (g/h)}}{\text{Fuel consumption rate (kg/h)}}.
\]

Emission load per unit of energy input could be estimated as follows.

\[
\text{Emission per MJ of energy input (g/MJ)} = \frac{\text{Emission rate of pollutant (g/h)}}{\text{Energy input rate (MJ/h)}}.
\]

This emission per unit of energy input could be further used to estimate the emission per unit of electricity produced.

\[
\text{Emission per unit of electricity produced (g/kWh)} = \text{Emission per unit of energy input (g/MJ)} \times \text{Specific energy consumption (MJ/kWh)}.
\]

### 3. Results and discussion

Results of emission measurement and estimated emission load for the engine in diesel alone mode and dual fuel mode are presented and a brief discussion on the results are given in this section. In addition to the emission results, data on fuel consumption and diesel replacement are also presented.

Concentration of pollutants at different load in diesel alone and dual fuel mode are given in Table 3. Concentrations of NO$_x$ in the flue gas from the diesel engine ranges from 172 to 412 ppm. These values fall within the range of reported NO$_x$ emission (80-456 ppm) from diesel engine [8]. NO$_x$ emissions in dual fuel mode are lower than the emissions from diesel engine in diesel alone mode. SO$_2$ levels are low in dual fuel mode. This may be due to low sulphur content in biomass fuel. Sulphur content of Acacia wood species, type of biomass used as feedstock for producer gas is reported as 0.01% [11], which is lower than the 0.05% sulphur in diesel supplied in the National Capital Region.

Carbon monoxide (CO) emission in dual fuel mode is higher than the CO emission in diesel alone mode. High concentration of CO in the dual fuel exhaust is an indication of incomplete combustion. At part load condition concentration of CO increases. This also suggests the need for lower load limit for dual fuel operation. These findings on CO emissions are similar to those reported by Parikh et al. [12]. At part load condition the specific energy consumption also increases. High CO emission in dual fuel mode operation could be due to combination of factors such as low heating value of gas, low adiabatic flame temperatures, and low mean effective pressures. Additionally, the engines are not actually designed for producer gas operation but for diesel, so many issues related to low thermal efficiency can be resolved if efforts are focused on development of new engine designs for producer gas operation. Apart from injector design, other parameters such as compression ratio, ignition advance, combustion chamber design etc will have to be optimized to produce low CO emissions.

Hydrocarbon emissions in dual fuel mode are little lower than HC emissions in diesel alone mode. Currently there is no emission standard for gasifier-based power and thermal system in India. As per the Swiss standards, emission norms for gasifier-based engine are 400 mg=Nm$^3$ for NO$_x$ and 650 mg=m$^3$ for CO [13,14]. The emission levels measured with the dual fuel system were compared with the Swiss standards. When compared to the Swiss emission norms, it is found that CO emissions from the engine in dual fuel mode exceed the standard of 650 |ig/m$^3$ whereas the NO$_x$ concentrations were meeting the standard at 10, 20 and 30 kW loads and exceeded the standard only at 40 kW load.

#### 3.1. Fuel and specific energy consumption

Specific energy consumption in diesel alone and dual fuel mode are calculated from the fuel consumption and calorific value of diesel and producer gas. Calorific value of diesel (43 MJ=kg) reported in the literature [15] is used to estimate the specific energy consumption. Producer gas composition is as follows: 19% CO, 14% H$_2$, 19% CH$_4$, 10% CO$_2$ and the remaining is N$_2$. Calorific value computed from the gas composition is 4.6 MJ=Nm$^3$. Fuel and Specific
Table 3
Concentration of pollutants from diesel engine in diesel alone and dual fuel mode

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Load (kW)</th>
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<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
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<tr>
<td>CO (ppm)</td>
<td>181</td>
</tr>
<tr>
<td>CO₂ (%)</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>3.2</td>
</tr>
<tr>
<td>HC (ppm)</td>
<td>109</td>
</tr>
<tr>
<td></td>
<td>112</td>
</tr>
<tr>
<td></td>
<td>103</td>
</tr>
<tr>
<td>CH₄ (ppm)</td>
<td>7.0</td>
</tr>
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<td></td>
<td>7.2</td>
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<td></td>
<td>7.0</td>
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<tr>
<td>SO₂ (ppm)</td>
<td>4.6</td>
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<tr>
<td></td>
<td>4.2</td>
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<tr>
<td></td>
<td>3.9</td>
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<tr>
<td>NOx (ppm)</td>
<td>172</td>
</tr>
<tr>
<td></td>
<td>181</td>
</tr>
<tr>
<td></td>
<td>188</td>
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<tr>
<td>Particulates (mg/m³)</td>
<td>22</td>
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<tr>
<td></td>
<td>20</td>
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<td></td>
<td>27</td>
</tr>
</tbody>
</table>

Table 4
Fuel consumption and specific energy consumption of diesel engine in diesel alone and dual fuel mode

<table>
<thead>
<tr>
<th>Load (kW)</th>
<th>Fuel consumption</th>
<th>Specific energy consumption (MJ/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diesel alone mode</td>
<td>Dual fuel mode</td>
</tr>
<tr>
<td></td>
<td>Diesel (kg/h)</td>
<td>Diesel (kg/h)</td>
</tr>
<tr>
<td>10</td>
<td>5.3</td>
<td>1.9</td>
</tr>
<tr>
<td>20</td>
<td>7.2</td>
<td>1.3</td>
</tr>
<tr>
<td>30</td>
<td>9.8</td>
<td>1.5</td>
</tr>
<tr>
<td>40</td>
<td>12.2</td>
<td>3.7</td>
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</tbody>
</table>

energy consumption in diesel alone and dual mode are presented in Table 4.

Two significant inferences can be drawn from Table 4. The specific energy consumption increases with decreasing load both in diesel alone and dual fuel mode. This implies the considerable efficiency loss at low-load condition. Specific energy consumption in dual fuel mode is higher than the diesel mode throughout the tested load condition. Increased specific energy consumption indicates the efficiency reduction in the dual fuel mode, which could be due to reduced heating value of the producer gas air mixture, drop in the pressure of the gas entering the air inlet and lower flame velocity. Earlier studies [12,16] also
reported de-rating of diesel engine operated in dual fuel mode.

### 3.2. Diesel replacement rate

Diesel replacement rate under different load conditions have been calculated from the diesel consumption in diesel alone mode and the diesel consumption in dual fuel mode and shown in Fig. 2.

Fig. 2 shows that diesel replacement rate varied between 67% and 86%. Maximum diesel replacement was recorded at 30 kW load. It was observed that both at low- and high-load condition the diesel replacement rate decreases.

### 3.3. Emission load

Estimated NO$_x$ and CO emission loads in diesel alone mode are compared with NO$_x$ and CO emissions in dual fuel mode (Figs. 3 and 4). Fig. 3 illustrates the NO$_x$ emissions per unit of electricity generated in dual fuel mode are lower than NO$_x$ emissions in diesel alone mode at all tested load conditions. Whereas the opposite trend has been observed in the case of CO emissions that are high in dual fuel in all measured loads (Fig. 4). Higher concentration of CO in the dual fuel exhaust is an indication of incomplete combustion. The figure also implies the specific energy consumption for both diesel and dual fuel mode reduces at lower load.

Fig. 5 presents the comparison of hydrocarbon emission from diesel alone and dual fuel operation. Not much change in the hydrocarbon emission when the engine is operated at optimal load with diesel and dual fuel. However at part load the hydrocarbon emissions were slightly higher in dual fuel mode. This may be due to efficiency loss in part load condition, which may increase the product of incomplete combustion. SPM emissions from diesel and dual fuel mode are compared (Fig. 6). There is a marginal decrease in the particulate (SPM) emissions in the dual fuel mode. Reduction in sulphur dioxide emission (Fig. 7) was achieved in dual fuel operation. This is mainly due to the low sulphur content of biomass.

As emission standards are generally applicable for the engines operated at optimal load, the emission values for the engine operated at 40 kW (80% of rated
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emission from dual fuel operation, which exceeds the standard.

(3) Carbon monoxide emissions from dual fuel engines were higher than diesel engines at all operated load condition.

(4) Dual fuel operation reduces NOx and SO2 emission without increasing particulate emission.

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References


