Chapter 3

Experimental programme and data collection

Experimental investigations have been carried out to study and fulfill the objectives as mentioned in the earlier chapter. The design of the pilot-scale (10 kWe) downdraft gasifier for lignite fuel is presented in this chapter. In addition, the methods and equipment used in the experiments are also discussed.

3.1. Design of downdraft gasifier

A pilot-scale downdraft type fixed bed gasifier is designed for lignite fuel to produce electrical power 10 kW. The various elements of downdraft gasifiers are designed on the basis of empirical co-relations and previous experimental information available in the literature. The main design parameters are specific gasification rate, gas generation rate and area of air nozzles.
The derived parameters are air velocity, diameter of hearth and throat, height of reduction zone, size of the hopper, diameter of nozzles, number of nozzles, etc.

3.1.1. Calculation of performance parameters

**Power consumption of the gasifier**

The present design is carried out for lignite fuel to produce enough gas to drive an engine which can produce electrical output of 10 kW. Producer gas engines work at a low efficiency in comparison with the engines working on diesel or natural gas [Raman et al., 2013]. The efficiency of producer gas engine (\( \eta_{\text{en}} \)) is taken as 28%. Therefore, the input power required for I.C. Engine or thermal power available at gasifier outlet may be estimated as:

\[
P_e = \frac{P_m}{\eta_{\text{en}}} \]

\[
P_e = \frac{10}{0.28} = 35.71 \text{ kW} \tag{3.1}
\]

Thermal efficiency of gasifier (\( \eta_g \)) is considered as 70% [Rajvanshi, 1986], the thermal input at gasifier inlet (\( P_t \)) at full load may be estimated by using following relation [Basu, 2010]:

\[
P_t = \frac{P_e}{\eta_g} = \frac{35.71}{0.7} = 51 \text{ kW} \tag{3.2}
\]

**Gas generation rate (Q\(_{\text{gen}}\))**

Gas generation rate (\( Q_{\text{gen}} \)) or the volume flow rate of the product gas from its desired lower heating value (LHV\(_g\)) may be calculated from following equation [Basu, 2010, Channiwala, 1992]:

\[
Q_{\text{gen}} = \frac{P_e}{\text{LHV}_g} \tag{3.4}
\]

For downdraft gasifier, the lower heating value of gas is in the range of 4.5 MJ/Nm\(^3\) to 5 MJ/Nm\(^3\) [Basu, 2010]. Considering the producer gas calorific value (LHV\(_g\)) as 4.5 MJ/Nm\(^3\), above equation reduced to:
\[ Q_{\text{gen}} = \frac{35.71}{4500} = 28.56 \text{ Nm}^3/\text{hr.} \quad (3.5) \]

**Lignite consumption rate (\(L_c\))/Lignite feed rate**

The higher heating value of lignite was measured by digital bomb calorimeter. The measured value is 16370 kJ/kg. The lower heating value of lignite (LHV\(_l\)) may be calculated using the following expression [Jarunghammachote and Dutta, 2007]:

\[ \text{LHV}_l = \text{HHV}_l - \left( \frac{9 \times H_v \times hfg}{100} \right) \quad (3.6) \]

\[ \text{LHV}_l = 16370 - \left( \frac{9 	imes 4.93 \times 2256}{100} \right) \quad (3.7) \]

\[ \text{LHV}_l = 15369 \text{ kJ/kg} \quad (3.8) \]

The lignite consumption rate of the gasifier (\(L_c\)) was estimated using following formula [Basu, 2010]:

\[ L_c = \frac{P_t}{\text{LHV}_l} \quad (3.9) \]

\[ L_c = \frac{51}{15369} = 0.00318 \text{ kg/s} = 11.94 \text{ kg/hr.} \quad (3.10) \]

Alternatively, lignite consumption rate can be determined by following expression [Channiwala, 1992]:

\[ L_c = \frac{Q_{\text{gen}}}{\text{Gas yield per kg fuel}} \quad (3.11) \]

Normally one kg of dry fuel approximately gives about 2.5 m\(^3\) of gas [FAO, 1986].

\[ L_c = \frac{28.56}{2.5} = 11.42 \text{ kg/hr.} \quad (3.12) \]

In the present study, lignite consumption rate is considered as 11.42 kg/hr.
3.1.2. Sizing of gasifier

**Hearth load**

The hearth load \( (B_g) \) is defined as the amount of producer gas to be obtained at normal \((p,T)\) conditions per unit cross sectional area of the throat, which is the smallest area of cross-section in the reactor [FAO, 1986]. It is usually expressed in \(\text{Nm}^3/\text{h-cm}^2\). This may also be referred to specific gasification rate \((\text{SGR})\), which is the volumetric flow rate of gas per unit area based on throat diameter. Alternatively, the hearth load may also be expressed as amount of dry fuel consumed divided by the surface area of the narrowest constriction \((B_s)\), and is expressed in terms of \(\text{kg/h-cm}^2\) [FAO, 1986]. This may also be referred to as specific solid flow rate \((\text{SSR})\), which is the mass flow of fuel measured at throat [FAO, 1986]. As one kg of dry fuel approximately gives about 2.5 \(m^3\) of gas under normal circumstances [FAO, 1986], the relation between \(B_g\) and \(B_s\) is as below [FAO, 1986]:

\[
B_g = 2.5B_s
\]  

(3.13)

The modern gasifier can operate tar-free at \(B_g\) value of as low as 0.15 [FAO, 1986]. Considering \(B_g\) as 0.2

\[
B_s = \frac{L_c}{\text{Throat area } (A_{th})}
\]  

(3.14)

\[
0.2 = 2.5 \times \frac{L_c}{\text{Throat area } (A_{th})}
\]  

(3.15)

Throat area \((A_{th}) = 2.5 \times \frac{11.42}{0.2}
\]

(3.16)

Throat area \((A_{th}) = 142.75 \approx 143 \text{ cm}^2
\]

(3.17)

**Throat Diameter \((D_{th})\)**

\[
A_{th} = \frac{\pi}{4} \times (D_{th})^2
\]  

(3.18)

\[
143 = \frac{\pi}{4} \times (D_{th})^2
\]  

(3.19)

\[
D_{th} = 13.5 \text{ cm}
\]  

(3.20)
The recommended value for throat angle falls in the range of 45° to 60° [Venselaar, 1982]. Throat angle of 45° is selected which is higher than the angle of repose of lignite (38°).

**Particle size (d_p)**

Cold flow studies suggest that ratio of throat diameter (D_th) to particle size (d_p) should be greater than 5 [Channiwala, 1992].

In the present study, ratio of throat diameter (D_th) to particle size (d_p) is selected as 6.

\[
\frac{D_{th}}{d_p} = 6 \quad (3.21)
\]

\[
d_p = \frac{135}{6} = 22.5 \text{ mm} \quad (3.22)
\]

**Sizing of hopper**

The hopper design consist of hopper height (H_shell) and diameter (D_shell). The main factors governing the dimension of hopper height and diameter are storage requirements, size of fuel particle, operation time, etc.

Hopper diameter (D_shell) to particle size (d_p) ratio is normally taken between 15 to 20 [Channiwala, 1992].

Experimental work is planned for various particle sizes. Considering the average particle size and hopper diameter to particle ratio as 20, the hopper diameter (D_shell) is selected as 525 mm.

On the basis of cold flow studies, the height of the shell should be 1.4 times the shell diameter [Channiwala, 1992]. However, bulk density of fuel is also important while determining hopper volume. The bulk density of fuel is a mere function of fuel particle size. In the present study, the height of the hopper shell is taken as 1.1 m.

**Height of the nozzle plane above throat (H_n)**

The height of the nozzle plane above the throat cross-section is a function of throat diameter and can be determined with the help of Figure 3.1 [FAO, 1986].

From the graph, the H_n/D_th = 0.9 (for throat diameter D_th = 135 mm)

\[
H_n = 0.9 \times 135 = 121.5 \text{ mm} \quad (3.23)
\]
Nozzle diameter

The ratio of the nozzle flow area ($A_n$) and the throat area ($A_{th}$) are the function of the throat diameter ($D_{th}$) and may be obtained from Figure 3.2 [FAO, 1986].

\[
\frac{A_n}{A_{th}} = 0.051 \tag{3.24}
\]

\[
A_n = 0.051 \times A_{th} \tag{3.25}
\]

\[
A_n = 0.051 \times 143 = 7.2 \text{ cm}^2 \tag{3.26}
\]

However, \( A_n = \frac{\pi}{4} (d_n)^2 \times (N_n) \) \tag{3.27}

Where, \( N_n \) is number of nozzles which is considered as 2 [Sivakumar, 2013]

\[
\frac{\pi}{4} \times (d_n)^2 \times (2) = 7.2 \tag{3.28}
\]
\( d_n = 20 \text{ mm} \) \hspace{1cm} (3.29)

Diameter of nozzle \((d_n) = 20 \text{ mm}.\)

\[\text{Figure 3.2. Nozzle flow area and air blast velocity for various size of throat diameter [FAO, 1986].}\]

**Air blast velocity \((V_{ab})\)**

Air blast velocity \((V_{ab})\) is the linear velocity of the air in the nozzle under standard condition. The recommended air blast velocity is in the range of 22 to 33 m/s [FAO, 1986]. Higher air blast velocity is preferred because it helps in higher penetration of air in to the bed and prevents formation of hot spots. For the throat diameter of 135 mm, the air blast velocity 29 m/s is obtained from Figure 3.2.

**Nozzle tip ring diameter \((d_{nt})\)**

The nozzle tip ring diameter is a function of throat diameter and may be obtained from Figure 3.3. The ratio of nozzle tip ring diameter and throat diameter is obtained as 2 for throat diameter of 135 mm.
\[
d_{nt} / D_{th} = 2 \quad \text{(3.30)}
\]
\[
d_{nt} = 2 \times 135 = 270 \text{ mm} \quad \text{(3.31)}
\]

Figure 3.3. Nozzle tip ring diameter as a function of throat diameter [FAO, 1986].

**Air flow rate (Q\text{\textsubscript{air}})**

Air requirement for the producer gas generator may be calculated using following relation [Channiwala, 1992]:

\[
Q_{\text{\textsubscript{air}}} = N_n \times \frac{\pi}{4} (d_n)^2 \times V_a \quad \text{(3.32)}
\]

The recommended value of \(V_a\) (Air velocity) is between 6 to 8 m/s [Channiwala, 1992]. In present study, the value is considered as 6.

\[
Q_{\text{\textsubscript{air}}} = 2 \times \frac{\pi}{4} (0.02)^2 \times 6 \quad \text{(3.33)}
\]

\[
Q_{\text{\textsubscript{air}}} = 3.76 \times 10^{-3} \text{ m}^3/\text{s} \quad \text{(3.34)}
\]
\[ Q_{\text{air}} = 13.56 \, \text{m}^3/\text{hr}. \]  

**Optimal equivalence ratio**  

Equivalence ratio is defined as actual air fuel to stoichiometric air fuel ratio. The optimal equivalence ratio may be calculated using following expression [Channiwala, 1992]:

\[
\text{Optimal ER} = \frac{Q_{\text{air}}}{L \times A/F_{\text{st}} \times (1 / \text{air density at NTP})} \tag{3.36}
\]

Where \( A/F_{\text{st}} \) is stoichiometric air fuel ratio and may be obtained by following equation [Basu, 2010]:

\[
A/F_{\text{st}} = \left(0.1153 \times C\%\right) + \left(0.3434 \times H\% - \left(\frac{O\%}{8}\right)\right) + (0.0434 \times S\%) \tag{3.37}
\]

Optimal ER = \frac{13.56}{11.42 \times 3.64 \times 0.81} = 0.4 \tag{3.38}

**Height of reduction zone**  

Total bed height from the point of air entry is in the range of 250 mm to 400 mm for effective conversion [Channiwala, 1992]. Accordingly in present case the total bed height is selected as 300 mm.

### 3.2. Lignite selection, characterization and sample preparation

The lignite used in this study was collected from Rajpardi village of Gujarat state, India. Lignite is available in lump form in nature as shown in Figure 3.4. It is soft due to presence of high volatile matter. Once the lignite was mined, it was broken down (crushed) to approximately less than 100 mm and then sieved to separate particles with different size. The objective of this work was to study the effect of particle size of lignite on gasifier performance. In order to use lignite as a fuel in gasifier, it was required to break lignite in a predetermined sizes. However, lignite is soft material, it was very difficult to break in exact size. So, it was decided to perform the experiments with selected particle range rather than exact size. In order to so, the experiments were carried out with six different particle sizes, viz. 13-16 mm, 16-19 mm, 19-22
mm, 22-25 mm, 25-28 mm, 28-31 mm as shown in Figure 3.5. Based on selection of particle range for each size, the sieves were prepared. Table 3.1 shows the sieve hole diameter corresponds to selected particle range.

Figure 3.4. Lignite in lump form

Figure 3.5. Various particle size of lignite
Table 3.1. Selection of particle size.

<table>
<thead>
<tr>
<th>Selected particle range (mm)</th>
<th>Sieve hole diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Min.</td>
<td>Max.</td>
</tr>
<tr>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>16</td>
<td>19</td>
</tr>
<tr>
<td>19</td>
<td>22</td>
</tr>
<tr>
<td>22</td>
<td>25</td>
</tr>
<tr>
<td>25</td>
<td>28</td>
</tr>
<tr>
<td>28</td>
<td>31</td>
</tr>
</tbody>
</table>

Since lignite used for entire study was collected once from only single site and all the samples with different size were stored in plastic container for experiments, composition and properties were assumed same for all particle sizes. Table 3.2 shows the characteristics of lignite. The proximate analysis was carried out for determination of volatile matter, moisture, ash content and fixed carbon, while ultimate analysis of lignite was carried out for determination of carbon, hydrogen, nitrogen, sulfur and oxygen. The procedure for proximate analysis is given in Appendix-I. The calorific value of the lignite was measured by digital bomb calorimeter (Rajdhani Scientific Instruments Co., New Delhi, India), according to IS 1350 (Part II)-1970. The properties of lignite which differs considerably from wood are heating value, ash content and volatile matter. High ash content may make operational difficulty of gasifier as it leads to occurrence of clinkering and slagging.

Table 3.2. Characteristic of lignite.

<table>
<thead>
<tr>
<th>Proximate(^a)</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Volatile Matter</td>
<td>42</td>
</tr>
<tr>
<td>Ash</td>
<td>15</td>
</tr>
<tr>
<td>Moisture</td>
<td>12</td>
</tr>
<tr>
<td>Fixed Carbon(^b)</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>HHV(^c) (MJ kg(^{-1}))</td>
<td>16.37</td>
</tr>
</tbody>
</table>

\(^a\) Test method IS 1350 (part I)-1984. \(^b\) By difference. \(^c\) Test method IS 1350 (part II)-1970.
3.3. Bulk density

Density of lignite changes with particle sizes. The bulk density of lignite was measured based on test method IS 7190-1974 and same is given in Appendix-II. The bulk density of lignite is presented in Table 3.3.

Table 3.3. Bulk density of lignite.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Particle size (mm)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lignite</td>
<td>13-16</td>
<td>1080</td>
</tr>
<tr>
<td></td>
<td>16-19</td>
<td>1020</td>
</tr>
<tr>
<td></td>
<td>19-22</td>
<td>899</td>
</tr>
<tr>
<td></td>
<td>22-25</td>
<td>776</td>
</tr>
<tr>
<td></td>
<td>25-28</td>
<td>716</td>
</tr>
<tr>
<td></td>
<td>28-31</td>
<td>669</td>
</tr>
</tbody>
</table>

3.4. Fuel consumption

The feedstock consumption rate was measured in a similar way as reported by some of the researchers [Dogru et al., 2002; Ouadia et al., 2013]. The level of feedstock was measured precisely by marking the feedstock level at six different places and average of these were taken as level at the start and end of each operation/trial. The total lignite consumed during each ran was calculated by multiplying the average bulk density of the feedstock by the reduction of hopper volume. The feed rate was also determined by dividing total lignite consumed by the total operating time of gasifier.
3.5. Char preparation

It is difficult to burn or gasify the lignite when initial temperature is low. In order to initiate the combustion of lignite, char can be used as an igniter as it burns easily. So, char was used in the gasifier as initial heat source. It was prepared from the wood. As per requirement of char, the wood was taken, and with the help of diesel or kerosene, it was fired and allowed it to burn for 20 min. Subsequently, it was covered with suitable vessel in order to burn wood in the absence of oxygen. After 2 hours, the resulting product was char which was blackish in color and shining in nature.

3.6. Experimental set-up

The throat type, fixed bed, 10 kWe downdraft gasifier, operating on a lignite as shown in Figure 3.6 was designed and fabricated. The experimental set-up consists of downdraft gasifier (reactor), gas conditioning system, flow measuring device and spark ignition producer gas engine.

Figure 3.6. Schematic diagram of the 10 kWe downdraft (lignite) gasifier system.
3.6.1. Reactor

The reactor of the system is cylindrical in shape, made from 3 mm thick mild steel sheet with an internal diameter of 525 mm and total height of 2.165 m. The gasifier consist of four sections namely, fuel hopper, gasifier combustion and reduction cell, air supply system and ash removal chamber. The pilot-scale downdraft type fixed bed gasifier is operated at atmospheric pressure. A vibrating mechanism driven by an electric motor is employed at the top of the reactor to generate mild vibrations which ensure the continuous downward flow of lignite in gasifier to avoid bridging and channeling of fuel. Vibration also reduces the ash sintering on the wall. The cone height is 187 mm and diameter at the top and bottom are 505 mm and 135 mm respectively. The cone angle is 45° which is higher than the angle of repose for lignite (38°). This higher cone angle provides the smooth movement of lignite in the combustion zone. This smooth flow also enables the cracking of tar at throat and reduces the bridging effect in the gasifier. The air is used as gasifying agent and two nozzles of 20 mm diameter are provided for supply of air in the reactor. Due to the fact that lignite is high ash content fuel, very effective and continuous ash removal system is designed to tackle the problem of build-up of ash on the grate. The ash produced during gasification is disposed continuously from bed by rotating the grate which is installed at bottom of a gasifier.

3.6.2. Gas cooling and cleaning unit

The gasifier is connected to gas conditioning and cleaning system as shown in Figure 3.6. Temperature of the gas at the exit of gasifier is relatively high, around 250-350 °C [Parikh et al., 1989] and energy density of gas is low at this high temperature. For Internal Combustion engine application, cooling of gas is necessary to increase the energy density in order to maximize the amount of combustible gas going in to the cylinder on each intake stroke. There are considerable amount of tar, dust and particulates present in the gas at the outlet of the gasifier. If tar and dust laden gas enters in to downstream equipment (Internal Combustion Engine), tar may condense on valves and fittings, hinder the movement of valves, whereas dust, tar and particulates cause erosion and corrosion of different engine components resulting to higher maintenance, affect the lubricating properties of the oil and, overall, are harmful to
engine performance [Bridgwater, 1995]. Hence, an effective gas-conditioning and cooling system is required to remove all undesirable constituents from the gas. This was achieved by employing three-stage gas cooling and cleaning system as shown in Figure 3.6. It consists of a water scrubber, wet filter and dry filter. In the first stage of gas cooling and cleaning, water spray scrubber was used to cool the gas and to remove particulates from flowing gas. Tar was also removed in wet scrubber. The second stage of cooling and cleaning system consist of passive filter, which uses a saw dust as a filtering medium. The moisture present in the gas is reduced as gas flows through the saw dust. The fine dust particles and tar were captured at final cleaning stage which employs fabric filter.

3.6.3. Instrumentation

In order to study the temperature profile of various zones in the gasifier, the K type (Chromel-Alumel) thermocouples were fixed along the vertical axis of gasifier at various locations as shown in Figure 3.6. The thermocouple probes were developed using 22 gauge K type thermocouple wire. These wires were electrically separated from each other using ceramics beads and it was housed inside a tube. The tube was made of Inconel material which is ideal for severely corrosive environments and at elevated temperatures. Thermocouples were connected to single channel digital temperature indicator with 8-channel selector switch which was used to read out to the temperature values at different locations. U-tube manometers were used to measure the pressure drop at critical locations in the system. The gas flow rate was measured using pre-calibrated orifice meter within ±3Nm³ h⁻¹. The gaseous products mainly CO, CO₂, H₂, CH₄ and N₂ were analyzed using a gas chromatography GC 2010 (Shimadzu) equipped with a Shin Carbon ST 100/120 micro packed column and operating on μTCD (microthermal conductivity detector). The chromatographs were recorded and peak areas were calculated. The gas calorific value was calculated based on concentration of gaseous products [Reed and Das, 1988]. The gas analysis procedure is included in Appendix-III.
3.7. Experimental procedure

Before any new trial, the entire system was cleaned to remove ash, char and tar fouling. At the commencement of each experiment, measured amount of the fresh charcoal was initially filled up to the level of air suction port in the reactor as recommended in NETPRO renewable energy 20 kWe-operational and maintenance manual (1999). Char bed in gasifier provides the heat source, which enables quick start in the subsequent gasification runs and also assists in reducing tar formation during start-up. Then, predetermined sized, prepared lignite feedstock of known weight was loaded into gasifier. After loading the feedstocks, the top cover was closed and sealed to ensure no air leakage. A 0.5 HP pump placed to circulate water in water scrubber system for suction on gas from gasifier system was then switched on. The fuel was ignited by holding the fire continuously in front of the air nozzles. Initially noncombustible white opaque smoke was generated. After 10-15 min, the colorless and combustible gas was generated, which was burnt using a producer gas burner. A steady state operational condition of gasifier was established after 20-25 min. That instant was marked as the beginning of the experimental run. Pressure drops across the orifice meter were recorded with the help of U-tube manometer using water as the manometric fluid. Temperature distribution in the reactor and gas temperature at the exit of the gasifier were measured every 15 min. The producer gas was collected in gas balloon from one of the sampling port installed at the exit of the filter in the prior stage of burner. In order to collect the gas with stable composition during run, samples were collected after steady state gasifier operation (20-25 min from start of the gasification) and stable flare was obtained. The first sample was collected after 45 min from start of gasification. Second, third and fourth samples were collected at the interval of 30 min. The gas samples were analyzed by gas chromatograph (Shimadzu GC-2010). The flow rate of producer gas was measured using orifice meter located after water scrubber in gas carrying pipe. The feedstock consumption rate was measured in a similar way as reported by some of the researchers [Dogru et al., 2002; Ouadia et al., 2013]. In the present study, each experiment was repeated three times and results are plotted based on average of three readings.

Performance of downdraft gasifier with different particle size of lignite is given in next chapter.