Chapter 4

Influence of particle size of lignite on performance of downdraft gasifier

4.1. Introduction

Coal has been used as a fuel since long. The reservoir of the coal in the world is large as compared to oil and gas. Lignite is a kind of coal and its depositions are widely distributed. Lignite is found all across the world, and recoverable reserve in world is 201 billion tonnes. So, lignite represents 22.54% of world coal reserves. However, the application of lignite coal has been limited due to their high moisture content. Lignite has not been exploited to any great extent and its utilization is not properly focused, as it is inferior to higher-rank coals. However, lignite seems to be promising material for gasification, as it is highly reactive than other types of coal and high volatile matter content. Lignite proven and total reserves in the India are approximately 6.18 and 41.96 billion tonnes respectively. So, an ample source of lignite is available in India and use of lignite as a primary energy source is a subject of interest.
The objective of this work is to investigate the feasibility of lignite as a fuel for downdraft gasifier. The physical and chemical properties of lignite greatly influence the performance of a gasifier. As stated in Chapter 2, important properties of fuel that influence the gasification are moisture content, volatile matter, ash content and particle size. A literature shows that the fuel particle size is one of the important parameters affecting the composition, quality and final applications of the producer gas. So, the main objective of the study is to investigate the feasibility of the lignite as a fuel for downdraft gasifier and to evaluate the effect of the particle size on gasifier performance. The influence of the particle size on fuel consumption rate, temperature profile in various zone, gas yield, gas composition and cold gas efficiency is studied. Six different particle sizes viz. 13-16 mm, 16-19 mm, 19-22 mm, 22-25 mm, 25-28 mm, 28-31 mm are selected for experimental work.

4.2. Mechanism of gasification of lignite in downdraft gasifier

Lignite is a chemical rock and its composition is very complex. During gasification of lignite, the material is heated to a high temperature, which causes a series of physical and chemical changes through series of reactions in downdraft gasifier.

Gasification is a process for converting carbonaceous materials to a combustible or fuel gas. The gasification of lignite particle in the downdraft gasifier can be explained by following stages: Following four distinct processes take place in a gasifier.

1. Drying
2. Pyrolysis
3. Partial combustion of some gases, vapors and char/combustion
4. Gasification of decomposition of products/reduction

Though, processes of gasification normally overlap [Basu, 2010], each can be assumed to occupy a separate zone where fundamentally different chemical and thermal reactions take place.

In the drying zone, the lignite particle enters a gasifier and moisture is removed by heat of combustion zone. The moisture/water particles present in the lignite gets vaporized. This water
vapor subsequently will flow downwards and add to the water vapor formed in the oxidation zone. This phase can be written as.

Moist feedstock + Heat → Dry feedstock + \( \text{H}_2\text{O} \)

The factors which affect the drying rates are the temperature difference between the hot gases and feed, surface area of the fuel, relative humidity and re-circulation velocity of hot gases [Dogru et al., 2002]. Moisture content of lignite is higher, and it can influence the overall gasification thermodynamics. Figure 4.1 shows temperature profile and zones in gasifier. The height of the drying zone is approximately 46 cm and temperature of this zone is in the range of 60-140 °C.

![Temperature profile and zones in gasifier.](image)

In the pyrolysis zone, temperature of the lignite particle increases. When it reaches above 200 °C, pyrolysis or thermal decomposition takes place without any external agent. The rate of thermal decomposition of lignite depends on rate of heating, particle size, rate of gasification by the water gas reaction, reaction temperature and the partial pressure of steam. Lignite
pyrolysis is extremely complex process and details of these pyrolysis reactions are not well reported. However, same can be explained as follows: The large hydrocarbon molecules break down into medium/small size gas molecules (condensable and non-condensable) and carbon (char) during pyrolysis process. Ultimately, the products of pyrolysis are solid (char or carbon), liquid (tars, heavier hydrocarbons, and water) and gas (CO$_2$, H$_2$O, CO, C$_2$H$_2$, C$_2$H$_4$, C$_2$H$_6$, C$_6$H$_6$, etc.).

Dry feedstock + Heat → Char + Volatiles

The temperature of pyrolysis zone is in the range of 200-400 °C and height is about 33 cm.

The products of drying and pyrolysis processes enter into the next section, namely oxidation zone. In the oxidation zone, controlled amount of air is continuously supplied to the reactor. Reactions with oxygen are highly exothermic and results in a rapid rise of the temperature up to 900 °C. The volatile products of pyrolysis zone react with oxygen and same are converted to CO, CO$_2$ and H$_2$O [Rezaiyan and Cheremisinoff, 2005]. The important function of oxidation zone is to generate the heat which is used for the drying of the fuel and to drive the endothermic reactions in the reduction and pyrolysis zones [Ruiz et al., 2013]. The oxidation zone is located above throat. The height of the oxidation zone is approximately 31 cm above throat section and temperature varies from 700 °C to 900°C.

In the reduction or gasification zone, the char react with the hot gases formed in oxidation zone in the absence of oxygen and is converted in to the product gas. The main chemical reactions that take place in reduction zone are endothermic which requires heat during reduction processes. Hence, temperature falls down in the zone. Consequently, the temperature range in the reduction zone is 400-600 °C. The height of the reduction zone is approximately 30 cm below the throat section. The gas produce in the reduction zone made up mainly of H$_2$, CO, CH$_4$, CO$_2$, N$_2$ and a small amount of hydrocarbon compounds, is loaded with tar, dust and water vapor and leaves the gasifier at 250-350 °C.

During the gasification process, complex reactions take place, as shown below [Higman and Burgt, 2003].

Combustion reactions,

\[ C + \frac{1}{2}O_2 = CO \quad -111 \text{ MJ/kmol} \quad (4.1) \]
\[ \text{CO} + \frac{1}{2}\text{O}_2 = \text{CO}_2 \quad -283 \text{ MJ/kmol} \quad (4.2) \]
\[ \text{H}_2 + \frac{1}{2}\text{O}_2 = \text{H}_2\text{O} \quad -242 \text{ MJ/kmol} \quad (4.3) \]

Boudouard reaction,
\[ \text{C} + \text{CO}_2 \leftrightarrow 2\text{CO} \quad +172 \text{ MJ/kmol} \quad (4.4) \]

Water gas reaction,
\[ \text{C} + \text{H}_2\text{O} \leftrightarrow \text{CO} + \text{H}_2 \quad +131 \text{ MJ/kmol} \quad (4.5) \]

Methanation reaction,
\[ \text{C} + 2\text{H}_2 \leftrightarrow \text{CH}_4 \quad -75 \text{ MJ/kmol} \quad (4.6) \]

Water gas shift/CO shift reaction,
\[ \text{CO} + \text{H}_2\text{O} \leftrightarrow \text{CO}_2 + \text{H}_2 \quad -41 \text{ MJ/kmol} \quad (4.7) \]

Steam methane reforming reaction,
\[ \text{CH}_4 + \text{H}_2\text{O} \leftrightarrow \text{CO} + 3\text{H}_2 \quad +206 \text{ MJ/kmol} \quad (4.8) \]

Coal gasification comprises the combustion reactions, Boudouard reaction, water gas reaction and methanation reaction. If the Boudouard reaction (Eq. 4.4) is subtracted from water gas reaction (Eq. 4.5), considering the mole and heat effect, the obtained reaction is the water gas shift (Eq. 4.7), and subtraction of methanation reaction (Eq. 4.6) from water gas reaction (Eq. 4.5) gives the steam methane reforming reaction (Eq. 4.8). So, these two reactions (water gas shift-Eq. 4.7 and steam methane reforming-Eq. 4.8) are actually implicit in Boudouard reaction (Eq. 4.4), water gas reaction (Eq. 4.5) and methanation reaction (Eq. 4.6) [Higman and Burgt, 2003].

Reactions 4.1 to 4.3 are exothermic, almost all the oxygen consumed during these reactions and releases heat which is used to dry the fuel and drive the reactions 4.4 through 4.6. These reactions do not play any key role in determining of an equilibrium syngas composition [Higman and Burgt, 2003]. Reactions 4.4 to 4.6 are principle gasification reactions, they affect the gas composition.

Reaction 4.4, the Boudouard reaction, also known as char-carbon dioxide reaction, is a much slower than char-oxygen reaction (Eq. 4.1) and responsible for production of CO. Reaction 4.5 is water gas reaction, is the main gasification reaction and slightly faster than Boudouard
reaction (Eq. 4.4) [Basu, 2010]. The water gas reaction favors the high temperature and produces CO and H$_2$. The char-hydrogen reaction generates methane and it’s a slowest reaction except for high pressure environment.

4.3. **Influence of particle size on fuel consumption**

The feed consumption rate for different lignite particle sizes is shown in Figure 4.2. As can be observed, the lignite consumption rate increases as the particle size of the fuel is reduced. It may be due to the fact that the effective surface area increases for reaction with smaller particle size which in turn increases the reactivity of the fuel. Fuel consumption trend obtained in this work is inline with the same reported in the literature [Tinaut et al., 2008; Pe’rez et al., 2012]. Specific fuel consumptions rate are in the range of 1.81-2.32 kg/kWh of coal for various particle sizes. From Figure 4.2 it can be observed that the fuel consumption for smallest particle size (13-16 mm) was 10.67 kg/hr. and largest particle size (28-31 mm) was 9.58 kg/hr.

![Graph showing influence of particle size on fuel consumption](image)

Figure 4.2. Influence of particle size on fuel consumption.
4.4. Influence of particle size on temperature profile

Temperature profile at different time interval with different particle sizes in combustion, reduction, pyrolysis and drying zone are shown in Figures 4.3-4.5 and 4.7 respectively. It is notable that the particle size of the lignite has a profound effect on temperature distribution in the downdraft fixed bed gasifier.

Temperature profile in combustion zone is shown in Figure 4.3. It was observed that initially temperature was very high. Temperature drop after 30 min for all particle sizes. It may be due to the reason that initially char is burnt resulting in to higher temperature. Lignite burns slowly, so temperature drop after 30 min was observed in all the cases. It is observed that temperature increases as particle size decreases and it remains in the range of 700 °C-900 °C for all particle size.

![Temperature profile at combustion zone for gasification of various size of lignite.](image)

Figure 4.3. Temperature profile at combustion zone for gasification of various size of lignite.
From Figure 4.4 it is observed that the temperature in reduction zone after 90 min are higher with medium particle sizes and lower with smaller and larger particle sizes. Essentially for the smaller fuel particle size, the gasification processes are under kinetic controls and hence temperature inside the particle would be higher. With decrease in particle size, surface area increases. Hence in combustion zone temperature is increased due to increased reactivity with oxygen. The tendency of fusion of ash present in lignite fuel is increased with higher combustion zone temperature and smaller particle size which in turn resulted into clinkers. The clinker formation subsequently reduced the flowability which resulted into reduction of temperature in reduction zone. It was also observed that highest temperature in reduction zone is reported for 22-25 mm lignite particle size.

![Temperature profile at reduction zone for gasification of various size of lignite](image)

Figure 4.4. Temperature profile at reduction zone for gasification of various size of lignite.

Thermochemical decomposition of the lignite occurs in the pyrolysis zone. Pyrolysis process has not been totally understood in gasification because of formation of complex products [García-Bacaicoa et al., 2008]. Figure 4.5 shows the temperature profile at pyrolysis zone for different particle sizes. The temperature in the pyrolysis zone and drying zone increased slowly.
due to limited heat transfer in upward direction and thermal inertia of the gasifier. Pyrolysis process can be understood better by studying thermal decomposition of material by Thermogravimetric analysis. Thermogravimetric analysis gives the good indication of temperature range in which pyrolysis process occurs [Slopiecka et al., 2011]. Figure 4.6 shows the TGA (Thermogravimetric analysis) of the lignite. It indicates the loss of mass with temperature for lignite. As expected different regions indicating water evaporation and pyrolysis are evident. The main pyrolysis process proceeds in the range from approximately 200 °C to 400 °C which is corresponding to major mass loss as shown in Figure 4.6. So, it is observed that the pyrolysis process takes place in the temperature range of 200-400 °C for all particle sizes which is in line with result reported in the literature [García-Bacaicoa et al., 2008]. It is also observed that the temperature remains lower for the larger particle sizes (25-28 mm, 28-31 mm). It can be explained as follows: for the lignite with larger particle size, the particle external surface area/volume ratio is lower resulting in less effective mass and heat transfer. The gasification processes mainly take place on the surface of lignite. So, larger is the particle, the greater is the heat transfer resistance, and therefore lower is the actual temperature.

Figure 4.5. Temperature profile at pyrolysis zone for gasification of various size of lignite.
Figure 4.6. Thermogravimetric analysis of lignite.

Figure 4.7 shows the temperature profile in drying zone for various particle size of lignite. In drying zone, moisture is removed from the lignite by evaporation. This moisture evaporation take place at constant temperature, which is independent of particle size. So, temperature for different particle sizes in drying zone is almost constant and comparable with literature value [Garci’a-Bacaicoa et al., 2008]. The constant temperature profile in drying zone for various particle size is also reported in the literature [Yin et al., 2012].
4.5. Influence of particle size on gas yield

The dry gas yield, one of the important parameters, usually signifies the gasifier performance. It is defined as the volume of producer gas at standard condition per mass of feedstock supplied to the system. Effect of particle size on dry gas yield during the run for all particle size is calculated by using following equation.

\[
\text{Gas yield (Nm}^3/\text{kg}) = \frac{\text{(Gas flow rate)} \times \text{(Gas production time)}}{\text{Mass input of feedstock}}
\]

Influence of particle size on gas yield is shown in Figure 4.8. From Figure 4.8, it is observed that gas production or gas yield increases with the increase in particle size, which is similar as the result reported in the literature [Yin et al., 2012; Feng et al., 2011]. In the present experimental work, actual mass input of feedstock was taken to evaluate gas yield. A reduction
of particle size involves an increasing density of the fuel and, as a consequence, an increasing mass input. Rate of combustion depends on the particle size. Larger particle sizes have a lower rate of combustion due to slower rate of diffusion within particles, which reduces the feeding rate [Ryu et al., 2006]. Moreover as air was introduced in oxidation zone, oxygen reacts with the feedstock, and resulting reactions were incomplete combustion reactions. Larger particle sizes takes more time for complete oxidation, which leads to prolonged traveling time and larger residence time of producer gas [Yan et al., 2010]. Thus, better cracking reaction obtained for longer residence time increases the gas yield [Chen et al., 2003]. The gas yield obtained for various lignite particle sizes are in the range of 2.43-2.63 Nm$^3$/kg, which is comparable with wood gasification [Martínez et al., 2012] and biomass gasification [Martínez et al., 2011].

![Gas yield of lignite gasification as a function of particle sizes.](image_url)

Figure 4.8. Gas yield of lignite gasification as a function of particle sizes.
4.6. Influence of particle size on gas composition

The reactions of carbon with the oxygen of the air at 700 °C or higher produces a gaseous fuel known as producer gas or syngas. The gas quality and gasifier performance widely depends on the composition of the feedstock, moisture content, ash content, size, density, and reaction temperature profile.

The main components of the produced gas are H₂, CO, CO₂, CH₄, and N₂. The gaseous products mainly H₂, CO, CO₂, CH₄, N₂ were analyzed. The hydrocarbon compounds were not analyzed due to its relatively low concentration (approximately 1%) [Dogru et al., 2002] [Yin et al., 2012]. Four gas samples were collected in each run and analyzed to reduce the experimental error. Gas composition is mainly depends on temperature in reactor. As seen from Figures 4.3-4.5 and 4.7, no much variation in temperature is observed after 45 min during each run. Not much variation in gas composition was observed in the different samples collected at specified intervals. The average of the gas composition and gas calorific value with different particle sizes of lignite obtained experimentally is shown in Figures 4.9 and 4.10 respectively. The temperatures in the reactor and particle size have considerable effect on the producer gas composition [Martinez et al., 2012; Luo et al., 2010; Erlich and Fransson, 2011; Guo et al., 2009]. The temperature in the reactor is directly related to the reactivity of the lignite. Lignite is a less reactive fuel than biomass, hence lower temperature results in a gas with a lower concentration of combustible components [Erlich and Fransson, 2011].

It was found that when the particle size varied from 22-25 mm to 28-31 mm, the content of H₂ and CO decreased from 10.27% to 6.72% and from 18.28% to 15.71%, respectively. In addition, the content of H₂ and CO increased from 8.24% to 10.27% and 14.25% to 18.28% respectively when the particle size varied from 13-16 mm to 22-25 mm.

The content of CO₂ increased from 12.12% to 13.77% as particle size varied from 22-25 mm to 28-31 mm, while same decreases from 15.16% to 12.12% as particle size varied from 13-16 mm to 22-25 mm. The concentration of CH₄ was not affected much by particle size in the range studied. As stated in literature [Luo et al., 2010], the concentration of CH₄ for coal gasification is less than the biomass gasification. The content of CH₄ obtained here varied in the range of 1.41-1.81%.
Figure 4.9. Gas composition of a lignite gasification as a function of particle sizes.

Figure 4.10. Gas calorific value of a lignite gasification as a function of particle sizes.
Typically, raising the temperature increases the concentration of CO and H₂ in the producer gas. The temperature in the oxidation zone was gradually increases as particle size decreases; however this trend was not followed in reduction zone. In the reduction zone highest temperature was observed for 22-25 mm particle size followed by 19-22 mm particle size and smaller particle sizes (13-16 mm, 16-19 mm) had a lower temperature profile. During the experimental work, the clinker formation problem was faced as lignite contains higher ash. Clinkers were primarily due to the temperature in the reactor bed which was exceeding probably ash fusion temperatures for the lignite. Lignite ash has a high level of Ca and Fe elements [Saw and Pang, 2013]. The ash fusion behavior depends on the ash composition, specifically the Ca and Fe content in the lignite [van Dyk et al., 2001]. Fuel containing higher Ca and/or Fe has low ash fusion temperature and Fe can slag at temperature as low as 700 °C [van Dyk et al., 2001]. For small particle sizes, chances were great for clinker formation as higher oxidation zone temperature. Larger clinkers were formed while gasifying the small particle sizes. These ash clinkers disturbed fuel and air flow in the gasifier which caused bridging or channel burning and pressure drop problems resulted in to lower temperature in reduction zone and unstable gasifier operation. So, the obtained results were unusual and contrary to general cases for smaller particle sizes for wood and other biomass. The percentages of CO and H₂ in gas produced in the reactor generally depend upon the rate of reactions occurring in the reduction zone and these reactions are affected by temperature in the reduction zone. So, higher temperature favors/accelerates the conversion of CO₂ in to CO i.e. the Boudouard reaction improves in reduction zone. Water gas reaction, Boudouard reaction and steam reforming reactions, will partly contribute to the increases in H₂ and CO at higher temperatures.

4.7. Influence of particle size on cold gas efficiency

The cold gas efficiency is the percentage energy of lignite converted in to cold producer gas. The cold gas efficiency is the ratio of total energy in producer gas and total energy in supply fuel. So the cold gas efficiency depends upon calorific value of lignite, consumption rate of lignite, calorific value of producer gas and gas flow rate. The following expression was used to compute the gasification efficiency.
\[ \eta_e = \frac{\text{LHV of gas} \times \text{Amount of gas produced}}{\text{LHV of lignite} \times \text{Quantity of lignite used}} \]  

(4.9)

The result of measured gasification efficiency on cold basis is plotted against lignite particle size in Figure 4.11. It is observed that better efficiency obtained with the lignite having size of 22-25 mm. The poor efficiency with smaller size of lignite is attributed to lower calorific value of producer gas and higher fuel consumption. The maximum efficiency 65.78% obtained for 22-25 mm particle size.

![Figure 4.11. Cold gas efficiency for lignite gasification as a function of particle sizes.](image)

4.8. Closure

The effect of various lignite particle sizes on the performance of gasifier is experimentally investigated in a 10 kWe downdraft gasifier. The major conclusions established from the experimental study are as follows:
1. As the particle size varied from smaller (13-16 mm) to larger (28-31 mm), the fuel consumption rate decreased. The specific gas yield is increased as the fuel consumption is decreased. In addition, temperatures in the pyrolysis and oxidation zone were decreased when the particle size varied from 13-16 mm to 28-31 mm.

2. For the smaller particle sizes (13-16 mm, 16-19 mm), larger size of clinkers were formed which caused flow problem in throat of reactor resulted in unstable gasifier operation.

3. The temperature in the reduction zone played a great role on producer gas composition. The LHV (Lower heating value) of gas increased as the reduction zone temperature increased. A gas with higher H\textsubscript{2} and CO was obtained for 22-25 mm particle size among all particle sizes.

4. The 22-25 mm particle size was found most favorable with respect to producer gas properties. The producer gas obtained for 22-25 mm particle size had a more stable composition of 10.27\% [H\textsubscript{2}], 18.28\% [CO], 12.12\% [CO\textsubscript{2}] and 1.71\% [CH\textsubscript{4}] with LHV (Lower heating value) of 4.17 MJ/Nm\textsuperscript{3} and a gasifier efficiency of 65.78\%.