Performance analysis of biomass downdraft gasification for different biomass feedstocks

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Abstract

Presently, various forms of biomass are available and exist in large quantities with low-cost availability in many areas of Gujarat. Biomass gasification is a thermochemical process of converting waste biomass into synthesis gas, a mixture of CO and H2. The most common worldwide downdraft gasifier is used for thermal applications and power generation, wherein the air is used as a gasifying medium. The paper describes the experimentation with a newly designed and developed downdraft gasifier. The waste material like cotton stalk, ground nutshell, sugarcane bagasse, and coconut shell waste are used as biomass for the generation of synthetic gas. The major objective of this study is to have a better understanding of the effect of different biomass feedstock on the synthetic gas composition from a downdraft gasifier. The Proximity analysis has been done for four different biomass feedstocks used in the research work. Investigation results are utilized in studying the fuel properties of different biomass feedstocks and its gasification feasibility for downdraft biomass gasifier. The calorific value of four biomass found for the Cotton stalk, groundnut shell, Sugarcane bagasse & Coconut shells were 4700 Kcal/kg, 4100 Kcal/kg, 3500 Kcal/kg and 4400 Kcal/kg respectively. Results comparison for all the four biomass waste has been expressed in terms of synthetic gas composition. Derived results show the composition by volume of CO and H2 for cotton stalk as 17.62% and 22.16%, for groundnut shell as 13.5% and 10.3%, for Sugarcane bagasse as 11.31% and 9.81% and coconut shell as 21.22% and 21.2%.

Keywords: Waste energy, Biomass analysis, Calorific value, Gas analysis

Introduction

Consumption of fossil fuels is the source of environmental issues to a large extent. Due to the reduction of Conventional sources and the increasing demand for fuels, it is important to develop renewable resources for the production of energy security fuels and chemicals. Bio-based materials, including wood pellets and biomass, are among the most promising sustainable sources of energy to replace expensive fossil fuels that disrupt our environment and global climate. As one of the energy resources for the development of advanced biofuels, bio-based materials were introduced. Advanced biofuels from biomass feedstock such as agriculture, industrial and urban waste, each of which has a biological basis for the production of bio energy [1]. Biomass gasification, the complete conversion of biomass into a synthetic fuel by heating it with a gasification medium such as air, oxygen or steam, rapidly becomes the most promising method for generating electricity [2]. Gasification is a partial oxidation method for converting carbonaceous materials into a mixture of primarily H2 and CO (synthetic gas) with small amounts of CH4, CO2, N2, char, ash, tar, oils in a temperature range 973 and 1773 K [3]. In this test, a downdraft gasifier is preferred as it is known to produce high-quality synthetic gas with low tar content (0.015–3 g/Nm3) in the gas stream compared to an updraft gasifier (30–150 g/Nm3) [4]. Designed and manufactured a throat less downdraft gasifier and tested the effect of the equivalence ratio on the gasifier output fed by rice husk and rice husk-sawdust mixture. The gasifier's peak gross heating value was 3.21 MJ/Nm3 and 76.90 % for rice husk pyrolysis at an equivalence ratio of 0.20. The values were 2.18 MJ/Nm3 and 58.09% for blend gasification at an equivalence ratio of 0.15. Only limited works on wood sawdust gasification have been published due to the difficulty in processing producer gas using downdraft gasifiers. The pine sawdust was developed with an open-top throat less downdraft
gasifier. Channeling and bridging during the gasification of the sawdust were considered as major problems. To solve the channeling and bridging issues, the sawdust was pelletized before being used as a feedstock for the downdraft gasifiers. However, the use of a pelletized feedstock, such as rice husk and sawdust, required additional processing costs for pelletizing biomass of low density [5]. The operation of a 30 cm diameter and 140 cm height downdraft gasifier using rice hulls as a source. Used feeding rates of 1.3-5.1 kg h\(^{-1}\) and rates of airflow 2.0-4.44 m\(^3\) h\(^{-1}\), corresponding to 26-55% of the stoichiometric amount needed for the complete process of combustion. It was found that the maximum temperature reached is between 570ºC and 820ºC. The peak yield of fuel constituents in the producer gas was reached at an AF ratio of 55% of that of the stoichiometric event. The gas obtained had a composition of 13.67% CO, 5.13% H\(_2\) and 2.42% CH\(_4\) [6].

Materials and Methods
Proximate analysis was performed and Materials including locally available Cotton stalk, groundnut shell, Sugarcane bagasse & Coconut shells were manually collected from the Gujarat region. Selected biomass i.e. Cotton stalk, groundnut shell, Sugarcane bagasse & Coconut shells were converted into powder form. Pass this powder from 210 microns (70 meshes) sieve and collect this powder for further process. Take a 1-1.5gm sample of different samples of biomass for proximate analysis.

Proximate Analysis
The proximate analysis was performed using the following standard procedure:

**Moisture Content**
The biomass moisture content was measured using a dry oven process. The specimen with the known weight was initially held at +108ºC in the oven until the constant weight was reached. The dry test of the oven was then calculated (ASTM D-3173). The sample’s moisture content was measured using the following formula.

\[
\text{Moisture content (}% wb) = \frac{X_2 - X_1}{X_2 - X_1} \times 100
\]

**Volatile Matter**
The dried specimen left in the crucible was covered with a lid and put in a muffle furnace that was held for 7 minutes at 900 ± 10 ºC (ASTM D-3175). The crucible was first cooled in the air, then inside the desiccators, and again measured. Percentage-based weight loss was reported as a volatile matter.

\[
\text{Volatile Matter (}% wb) = \frac{Y_2 - Y_1}{Y_2 - Y_1} \times 100
\]

**Ash Content**
The residual sample in the crucible was heated for a half hour (ASTM D-3174) without a lid in a muffle furnace at 800ºC+10ºC. The crucible was then removed, then cooled in the air, then desiccated and measured. There was repeated heating, cooling and weighing until a constant weight was obtained. The ash was recorded as a percentage of the residue.

\[
\text{Ash Content (}% wb) = \frac{Z_3 - Z_1}{Z_2 - Z_1} \times 100
\]

**Fixed Carbon**
Using the mass balance for the biomass test, the fixed carbon content was measured.

\[
\text{Fixed Carbon (}%) = 100 - \% \text{ of (MC + VM +AC)}
\]

Where,

FC= Fixed carbon, (%)
MC= Moisture content, (%)
VM= Volatile matter, (%)
AC= Ash content, (%)

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Calorific Value of Biomass

It's determined by a bomb calorimeter. A sample of air-dried biomass with a known mass is burnt in an atmosphere of oxygen in a stainless steel high-pressure vessel, known as a bomb. The bomb is then placed in a calorimeter outer vessel containing a known amount of water with a known temperature. The resulting heat of combustion is measured from the accurate measurement of the rise in the temperature of water in the calorimeter.

\[
\text{Calorific Value} = \frac{(2600 \cdot \text{Increasetemperature}) - 30}{\text{sample weight}}
\]

Table 1 Calculated proximate analysis of selected biomass

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Biomass sample</th>
<th>Average Moisture Content (%)</th>
<th>Average Volatile Matter (%)</th>
<th>Average Ash Content (%)</th>
<th>Average Fixed Carbon (%)</th>
<th>Average Calorific Value Kcal/Kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cotton stalk</td>
<td>11.41</td>
<td>70.56</td>
<td>0.10</td>
<td>17.93</td>
<td>3800</td>
</tr>
<tr>
<td>2</td>
<td>Groundnut shell</td>
<td>6.37</td>
<td>67.94</td>
<td>5.8</td>
<td>19.88</td>
<td>4100</td>
</tr>
<tr>
<td>3</td>
<td>Sugarcane bagasse</td>
<td>30.97</td>
<td>47.26</td>
<td>7.51</td>
<td>14.26</td>
<td>3500</td>
</tr>
<tr>
<td>4</td>
<td>Coconut shells</td>
<td>8.49</td>
<td>69.36</td>
<td>0.52</td>
<td>21.63</td>
<td>4400</td>
</tr>
</tbody>
</table>

The moisture content of these selected non-woody biomass products, volatile matter, ash content, and fixed carbon are measured as shown in table 1. The moisture content of Cotton stalk, groundnut shell, Sugarcane bagasse & Coconut shells were found to be 11.41%, 6.37%, 30.97%, and 8.49% respectively. Moisture content was found more in Sugarcane bagasse. The presence of moisture in the biomass affects product gas calorific value, heat input, gasifier performance and CO, H₂ and CO₂ concentration. The volatile matter of Cotton stalk, groundnut shell, Sugarcane bagasse & Coconut shells were found to be 70.56%, 67.94%, 47.26%, and 69.36%. The volatile matter is found more in Cotton stalk. The ash content in dry of a Cotton stalk, groundnut shell, Sugarcane bagasse & Coconut shells were found 0.10%, 5.8%, 7.51%, and 0.52% respectively. It was observed that fixed carbon was found highest in Sugarcane bagasse. The calorific value of Cotton stalk, groundnut shell, Sugarcane bagasse & Coconut shells were found to be 3800 Kcal/Kg, 4100 Kcal/Kg, 3500 Kcal/Kg and 4400 Kcal/Kg respectively. The cotton stalk calorific value was found to be 4400 Kcal/Kg indicating good gasification characteristics since higher heat produced during combustion results in high temperatures in the reaction zone [7].

Experimental Setup and Procedure

The design of the gasifier is based on empirical data and charts based on past experiences. Treatment of wastewater and disposal of the water used are the main challenges commonly faced in the existing downdraft gasification systems designs[8]. Downdraft gasifier having 8.10 kg h⁻¹ biomass consumption capacity. Perforations are made to improve the movement of ash particles on the base plate in the reduction region. Coal was charged below the heart zone during start-up and other biomasses were manually loaded from the hopper having a capacity of 60kg. Initial ignition was performed at the air inlets through the firing ports and within 5-8 minutes a continuous fire was observed. Air suction was created through water circulation through a gas outlet-connected venturi scrubber. Approximately 20-40 min was needed to attain full gas production capacity. Upon drying and pyrolysis at the top of the reactor, the biomass was burned in the oxidation area where the air was drawn in. Gaseous combustion products entered the hot charcoal bed reduction zone. The gases were further reacted to create a gas mixture of the fuel producer. The exiting hot gas at the bottom of the reactor went through the scrubber through which ambient temperature water was circulated. The cool gas-water mixture was then used to separate the char and tar particles together with water into the cyclone separator. The gas was further cleaned by passing through the sawdust filter and two bag filters successively. The samples are collected in the syringes of this producer gas exiting from the downdraft gasifier. A gas chromatograph is used to analyze sampled gas. Each biomass experimental run is carried out for 20 -40 min. Any remaining biomass and charcoal are removed from the gasifier at the end of the experiment.
Fig. 1 Downdraft gasifier

Gas Composition and Calorific Value

Producer gas was found to have calorific value and volumetric percentage of its fuel components, along with gasification efficiency[9]. The calorific value of the biomass feedstock is determined for its gasification and gasification efficiency suitability. The proximate analysis provides the details of the amount of ash in the biomass. If there is less ash content in the biomass, it means the gas quality is good and the performance of the gasifier is also improved. The moisture content of the biomass increases the concentration of CO2 and H2 while the CO decreases and the production of CH4 do not affect. When wood is used as a feedstock in the downdraft gasifier, the total acceptable moisture content limit is 40% [10].

Table 2 Influence of moisture content on product-gas compounds with Downdraft Gasifier[10]

<table>
<thead>
<tr>
<th>Moisture content</th>
<th>CO</th>
<th>CO₂</th>
<th>H₂</th>
<th>CH₄</th>
<th>Max Limit(%w/b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increases</td>
<td>Decreases</td>
<td>Increases</td>
<td>Increases</td>
<td>No change</td>
<td>40</td>
</tr>
</tbody>
</table>

It is known that the temperature of the neck at 850 ° C gives a good composition of the fuel. As the air factor decreases, in most cases the amount of H₂ increases. In the case of lignite, in the 19-22 mm range of particle size, the proportion of H₂ and CO is higher with a slight reduction of CH₄. This may be due to good gasification. As the middle part of the gasifier (Distillation zone) temperature rises from 525 ° C to 890 ° C, the percentage gas composition also rises for most gases except CO₂ and O₂[11].

Results and Discussions

Table 3 Biomass Gas Composition

<table>
<thead>
<tr>
<th>Biomass</th>
<th>H₂ (%)</th>
<th>N₂ (%)</th>
<th>CH₄ (%)</th>
<th>CO (%)</th>
<th>CO₂ (%)</th>
<th>LHV(MJ/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton stalk</td>
<td>22.16</td>
<td>37.03</td>
<td>2.54</td>
<td>17.62</td>
<td>15.83</td>
<td>4.69</td>
</tr>
<tr>
<td>Ground Nut Shell</td>
<td>10.3</td>
<td>52.9</td>
<td>2.1</td>
<td>13.5</td>
<td>11.2</td>
<td>3.55</td>
</tr>
<tr>
<td>coconut shell</td>
<td>21.2</td>
<td>39.4</td>
<td>2.1</td>
<td>21.22</td>
<td>9.77</td>
<td>3.91</td>
</tr>
<tr>
<td>Sugarcane bagasse</td>
<td>9.81</td>
<td>65.91</td>
<td>2.42</td>
<td>11.31</td>
<td>10.6</td>
<td>3.23</td>
</tr>
</tbody>
</table>

- This experiment observed that downdraft gasifier design compatible with the direct use of low-density feedstock such as cotton stalk, groundnut shell, coconut shell, and sugarcane bagasse, without pelletizing.

- In this experiment single downdraft gasifier used for different biomass feeds and found variation in output gas composition (in volume percentage) CO 11-18% percent, CO₂9-15%, H₂9-23%, and N₂37-66% with low methane traces.

- The lower heating values of producer gas from various biomass are found to be 3.2 -4.7 MJ/m³.
The syngas was noticed to be produced after igniting the gases. A yellowish flame was observed indicating the production of these combustible gases.

It was found that the biomass with a lightweight in the gasification process was best for feeding.

It was observed that more value of moisture of biomass produces less parentage of carbon monoxide. Sugarcane bagasse with a moisture content of more than 30% contains poor-quality product gas and therefore low gasification performance.

The above study showed that cotton stalk was an excellent feedstock for gasification compares to other biomass, due to their fuel characteristics, which was comparable to wood. there were no problems during the operation.

References

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