Abstract: In today’s scenario of depleting conventional fossil fuels, biomass provides an alternate source of energy. Gasification is a chemical process that converts carbonaceous materials like biomass into useful convenient gaseous fuels or chemical feedstock. The product gas of gasification has a calorific value unlike that of complete combustion process. The present study is going to be focused on parametric analysis and study of the mathematical model to predict the effect of usage of various types of fuels in gasification process and also the usage of oxygen as a gasifying agent. Due to lack of authentic kinetic data to design gasifier, the gasification process will be simulated using thermodynamic model using MATLAB and Engineering Equation Solver. A number of fuels will be used in the study namely coal, rice husk and wood pallets. Their proximate and ultimate analysis will be studied. The analysis of syngas produced can be done by gas chromatography and Orsat apparatus. The simulation will be focused on the effect of pressure, air to fuel ratio and steam to fuel ratio on produced syngas composition. An experimental model has been fabricated to take trial and study the process of gasification. The model has been fabricated so that it can hold a batch of 30kg fuel. An arrangement has been made so as to control the air flow. Sensors have been mounted to record the core temperature, gas temperature and steam temperature. A centrifugal blower of 0.5 HP with 12 cfm (cubic feet per minute) discharge capacity is used. Steam is generated within the setup in the water jacket and supplied to gasification process. This helps in utilising the heat that may have been lost to environment in form of heat from outer side of the experimental gasifier model.

General Terms
Renewable energy, cogeneration, biomass conversion technology.

Keywords: gasification; Syngas; parametric analysis; mathematical modelling; pyrolysis.

1. Introduction
Today industrialization has lead to an increasing need of fuels. It is estimated that almost 80% of the worldwide energy needs are satisfied by fossil fuel¹. Due to their limited nature it is the foremost need today to exploit other environmentally cleans inexhaustible sources of energy. Biomass provides such other alternative. Gasification is one of the technologies to harness the biomass energy and the equipment used is known as gasifier. Prabir Basu²
has studied various types of gasifiers along with their advantages and disadvantages. C Higman and Marteen\textsuperscript{3} have extensively studied the gasification’s reactions and their kinetics. Reed and Das\textsuperscript{4} have discussed the gas composition for various fuels and for various operating conditions. T Shrinivisan\textsuperscript{5} has extensively discussed the effect of various operating parameters on the composition of syngas. The present work makes a practical working of an Updraft Biomass Gasifier apparatus, produces syngas in significant quantities and analyses its composition and heating value. Also a parametric analysis of the input parameters of the gasifier is done to inspect its effects on the composition and heating value of syngas produced. The detailed study of the methods of proximate and ultimate analysis for fuels viz. coal, wood pellets, rice husk and biomass is to be done. Parametric analysis of syngas on basis of variation of air-fuel ratio, pressure, oxygen content and temperature is also analysed.

1.1 Gasification Theory

Gasification is the conversion of solid or liquid feedstock into useful and convenient gaseous fuel or chemical feedstock that can be burned to release energy or used for production of value-added chemicals. A typical biomass gasification process may include the following steps:

- Drying
- Thermal decomposition or pyrolysis
- Partial combustion of some gases, vapours, and char
- Gasification of decomposition products.

The gaseous product is commonly known as “SYNGAS” or “PRODUCER GAS” mainly containing hydrogen, carbon monoxide, carbon dioxide, water vapour, methane and some amount of unburnt carbon. Main gasifying agents are air, oxygen and steam.

1.2 Updraft gasifier

1.2.1 General features:

Updraft gasifier is the oldest and the simplest design of all gasifier. Here the gasifying agents (air, steam or oxygen) flow from the bottom and the biomass flows from the top in a concurrent stream as shown in figure 1. The gasifying medium enters through a grate and comes in contact with the hot ash. The grate is provided to facilitate removal of ash. Sometimes a vibratory or an oscillating grate is provided when high ash removal rate is required.

1.2.2 Advantages of Updraft Gasifier:

Updraft gasifier are suitable for high-ash (up to 25%), high-moisture (upto 60%) biomass. They are also suitable for low-volatile fuels such as charcoal. As a counter current unit, an updraft gasifier utilizes combustion heat very effectively and achieves high cold-gas efficiency. Therefore, it is more suitable for direct firing, where the gas produced is burnt in a furnace or boiler with no cleaning or cooling required.

1.2.3 Disadvantages of Updraft Gasifier:

The biggest disadvantage of updraft gasifier is that the gas has to be cleaned of tar. Amongst the various types of gasifiers available tar production is maximum in updraft gasifiers. \textsuperscript{2}Tar production varies from 30-150 kg/nm\textsuperscript{3} . This makes it difficult to use volatile fuels in updraft gasifier. Also the available gas cannot be directly used in an IC engine or for storage.

2. Process and Reactions in Updraft Gasifier

As the fuel moves down in the gasifier it passes through various reaction zones namely drying, pyrolysis and gasification.

2.1 Drying Zone:

Here the biomass gets dried due to heat and moisture present in the fuel converts to steam.

2.2 Pyrolysis Zone:

Pyrolysis is a thermo chemical decomposition of biomass into a range of useful products, either in the total absence of oxidizing agents or with a limited supply that does not permit gasification to an appreciable extent. It is one of several reaction steps or zones observed in a gasifier. During pyrolysis, large complex hydrocarbon molecules of biomass...
break down into relatively smaller and simpler molecules of gas, liquid, and char. It takes place at a temperature greater than 2500°C².

2.3 Oxidation or Combustion Zone:
An oxidation or burning zone is formed in the section where air/oxygen is supplied. These combustion reactions are highly exothermic and cause a rapid temperature increase up to 1100-1500°C. The reactions are as follows²,³:

\[ C + O_2 \rightarrow CO_2 \left( +393 \text{ MJ/kg mole} \right) \]  
\[ 2H_2 + O_2 \rightarrow 2H_2O \left( +242 \text{ MJ/kg mole} \right) \]

2.4 Reaction Zone:
This is the main zone of gasifier where we get the product or Syngas. The reactions are as follows:

\[ C + O_2 \rightarrow 2CO \left( -164.9 \text{ MJ/kg mole} \right) \]  
\[ C + H_2O \rightarrow CO + H_2 \left( -122.6 \text{ MJ/kg mole} \right) \]  
\[ CO + H_2 \rightarrow CO_2 + H_2 \left( +42.3 \text{ MJ/kg mole} \right) \]  
\[ C + 2H_2 \rightarrow CH_4 \left( +75 \text{ MJ/kg mole} \right) \]  
\[ CO + 2H_2 \rightarrow CH_4 + H_2O \left( -203.9 \text{ MJ/kg mole} \right) \]

The mixture of gases produced in this zone is called Syngas or producer gas.

3. Mathematical Modeling Of Gasifier
The equations for mathematical modeling were obtained from mass balance of combined biomass gasification equation².

\[ n_1 + n_2 + n_3 + n_4 + n_5 + n_6 + n_7 + n_8 + \frac{3}{2} n_9 = 1 \]  
\[ n_1 + 2n_2 + n_3 + 2n_4 + n_5 + 2n_6 = 2n_7 + 2n_8 + n_9 \]  
\[ n_1 + n_2 + n_3 + n_4 = 1 \]  
\[ n_1 + n_2 + n_3 + n_4 = 1 \]  
\[ n_1 + n_2 + n_3 = 1 \]

where,
\[ a_1 = 1 \]  
\[ a_2 = H/C \text{ molar ratio} \]  
\[ a_3 = O/C \text{ molar ratio} \]  
\[ a_4 = N/C \text{ molar ratio} \]  
\[ n_1 \text{ to } n_6 \text{ are the respective mole of the respective species} \]  
\[ \text{Taking atom balances on carbon, hydrogen, oxygen, and nitrogen we get,} \]  
\[ \text{As we can see there are 6 unknown from } n_1 \text{ to } n_6 \text{ but we have only 4 equations. So we need two more equations and we get them from equilibrium reactions. They are} \]

\[ Boudard \text{ Reaction} \]
\[ C + CO_2 \rightarrow 2CO \left( +172 \text{ MJ/kg mole} \right) \]  
\[ \text{Water Gas Reaction} \]
\[ C + H_2O \rightarrow CO + H_2 \left( +131 \text{ MJ/kg mole} \right) \]

The required two equations results from the equilibrium constants \( K_p \text{ of reactions.} \) \( K_{ph} \text{ and } K_{py} \text{ are the equilibrium constant of the Boudard reaction and Water-Gas reaction respectively.} \)

Equation (14) can be written as:
\[ K_p \cdot V_{CO} = (V_{CO_2})^2 \cdot F_{F_2} \]  
\[ K_{ph} \cdot V_{H_2O} \cdot V_{CO} \cdot (F_{F_2}) \]

We can use volume fraction in place of mole fraction since mole fraction is equal to volume fraction⁴.

The equilibrium constants are given by⁵:
\[ \ln K_p = -\frac{G_0}{RT} \]  
\[ \ln K_{ph} = \frac{h_f}{} \]

Where,
\[ G_0 \text{ = the Gibb’s free energy in kJ/kg mol,} \]  
\[ T = \text{ the temperature of gasifier in K, assumed initially,} \]  
\[ R = \text{ the universal gas constant in consistent units.} \]  
\[ h_f = \text{ the enthalpy of formation in kJ/kg mol and} \]  
\[ s = \text{ the entropy measured from 0 K, kJ/kg mol K.} \]

Equations (10) to (13) and (16), (17) are used for stimulation in MATLAB.

4. Simulation And Result Analysis
Thus the solutions of the gasification equations for coal simulated using MATLAB are CO (5.75%), CO₂ (30.55%), H₂ (10.97%), H₂O (14.53%), CH₄ (4.62%), N₂ (33.57%). Also it can be seen that the percentage of CH₄ is less which is the basis objective of gasification. The gasification was carried out for unit weight of steam per kg of fuel required.

The variation of air supply on the gas composition is shown in graph 1. It can be seen that with an increase in supplied air there is a decrease in percentage of H₂, CO and CO₂ while that of N₂ increases.
Variation of pressure also causes a change in gas composition. As seen from the graph with an increasing pressure, there is increased percentages of CO₂ and N₂ while the percentage of H₂ and CO decreases. The same can be seen from graph 2.

Steam feed rate variation causes change in gas composition as well. Increased steam rate from zero causes an increase in hydrogen produced. Graph 4 shows the effect of increased steam rate on syngas.

Increased air supply causes increased CO₂ production which decreases the lower calorific value of the syngas. The same variation can be seen from graph 3.

The stimulation results comply with the ASPEN stimulation and other literature data⁵.

5. Graphs From Simulation

Fig 2: Product gas mole fractions versus Air to fuel ratio

Fig 3: Product gas mole fractions versus Air to fuel ratio

Fig 4: Low Calorific Value versus Air to fuel ratio

Fig 5: Product gas mole fractions versus Pressure
6. Matlab Program Code

Fig 6: MATLAB Code for creation of function

Fig 7: MATLAB Code for main Gasification Program

7. Analysis Of Fuels

7.1 Analysis of Coal

7.1.1 Proximate Analysis

The proximate analysis of coal was developed as a simple means of determining the distribution of products obtained when the coal sample is heated under specified conditions. As defined by ASTM D 121, proximate analysis separates the products into four groups: (1) moisture, (2) volatile matter, consisting of gases and vapors driven off during pyrolysis, (3) fixed carbon, the nonvolatile fraction of coal, and (4) ash, the inorganic residue remaining after combustion. Proximate analysis is the most often used analysis for characterizing coals in connection with their utilization. The actual method of analysis is described below:
7.1.1.1 Moisture
Known weight of coal heated in silica crucible at 105-110°C for 1 hour.

\[ M = \left( \frac{\text{Loss in wt}}{\text{Original wt}} \right) \times 100 \]

7.1.1.2 Volatile Matter
Dry coal is heated at 950°C for 7 minutes in furnace.

7.1.1.3 Ash
Dry coal heated in platinum crucible at 400-700°C then ignite for \( \frac{1}{2} \) hour at 700°C, weigh the burnt material and repeat process until weight of burnt material remains constant.

7.1.1.4 Fixed Carbon

\[ \%FC = 100 - (\%M + \%V + \%A) \]

Table 1. Typical Proximate Analysis of various Coals (percentage)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Indian Coal</th>
<th>Indonesian Coal</th>
<th>South African Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>5.98</td>
<td>9.43</td>
<td>8.5</td>
</tr>
<tr>
<td>Ash</td>
<td>38.63</td>
<td>13.99</td>
<td>17</td>
</tr>
<tr>
<td>Volatile Matter</td>
<td>20.70</td>
<td>29.79</td>
<td>23.28</td>
</tr>
<tr>
<td>Fixed Carbon</td>
<td>34.69</td>
<td>46.79</td>
<td>51.22</td>
</tr>
</tbody>
</table>

7.1.1.5 Significance of Various Parameters in Proximate Analysis

7.1.1.5.1 Fixed Carbon
Fixed carbon is the solid fuel left in the furnace after volatile matter is distilled off. It consists mostly of carbon but also contains some hydrogen, oxygen, sulphur and nitrogen not driven off with the gases. Fixed carbon gives a rough estimate of heating value of coal.

7.1.1.5.2 Volatile Matter
Volatile matters are the methane, hydrocarbons, hydrogen and carbon monoxide, and incombustible gases like carbon dioxide and nitrogen found in coal. Thus the volatile matter is an index of the gaseous fuels present. Typical range of volatile matter is 20 to 35%. Volatile Matter

- Proportionate increases flame length, and helps in easier ignition of coal.
- Sets minimum limit on the furnace height and volume.

- Influences secondary air requirement and distribution aspects.
- Influences secondary oil support

7.1.1.5.3 Ash Content
Ash is an impurity that will not burn. Typical range is 5 to 40%. Ash

- Reduces handling and burning capacity.
- Increases handling costs.
- Affects combustion efficiency and boiler efficiency
- Causes clinkering and slagging.

7.1.1.5.4 Moisture Content
Moisture in coal must be transported, handled and stored. Since it replaces combustible matter, it decreases the heat content per kg of coal. Typical range is 0.5 to 10%. Moisture

- Increases heat loss, due to evaporation and superheating of vapour.
- Helps to limit, in a binding fines
- Aids radiation heat transfer

7.1.2 Ultimate Analysis
The ultimate analysis indicates the various elemental chemical constituents such as Carbon, Hydrogen, Oxygen, Sulphur, etc. It is useful in determining the quantity of air required for combustion and the volume and composition of the combustion gases. This information is required for the calculation of flame temperature and the flue duct design etc.

Table 2. Typical Ultimate Analyses of Coals

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Indian Coal, %</th>
<th>Indonesian Coal, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>5.98</td>
<td>9.43</td>
</tr>
<tr>
<td>Carbon</td>
<td>41.11</td>
<td>58.96</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>2.76</td>
<td>4.16</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1.22</td>
<td>1.02</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.41</td>
<td>0.56</td>
</tr>
<tr>
<td>Oxygen</td>
<td>9.89</td>
<td>11.88</td>
</tr>
</tbody>
</table>

7.1.2.1 Carbon and Hydrogen

\[
C + O_2 \rightarrow CO_2 \\
2H_2 + O_2 \rightarrow 2H_2O
\]

Absorbers used are

- Anhydrous magnesium perchlorate or calcium chloride for H₂O
- Soda lime & potassium hydroxide for CO₂

\[ \%ef = \left( \frac{2}{10} \right) \times \left( \frac{H_2O \text{ wt}}{Coal \text{ wt}} \right) \]
7.1.2.2 Nitrogen (Kjeldahl's Method)

\[
2N + 6H \rightarrow (NH_3)_2SO_4 + \text{heat} + \text{alkali} \rightarrow NH_3 + \text{Acidic}
\]

\[
\%N = \frac{[\text{wt. of acid consumed} - \text{normality of } NaOH \times 1.4]}{\text{wt of coal}} 
\]

7.1.2.3 Sulphur

- Burn known weight of coal completely
- 10 ml distill water in bomb pot
- Collect washing of bomb pot
- Add BaCl_2

BaSO_4 is precipitate. Weigh it.

\[
\%S = \frac{[\text{wt. of } BaSO_4 \times 32 \times 100]}{[\text{wt of coal} \times 233]} 
\]

7.2 Analysis of Rice Husk and Wood Pellets

The proximate analysis classifies the fuel in terms of its moisture (M), volatile matter (V), fixed carbon (FC) and ash.

Table 4. Proximate Analysis data of selected biomass materials\(^6\)

<table>
<thead>
<tr>
<th>Dry</th>
<th>Wheat</th>
<th>Rice</th>
<th>Cotton</th>
<th>Wood</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Straw</td>
<td>Bran</td>
<td>Straw</td>
<td>Husk</td>
</tr>
<tr>
<td>Volatile</td>
<td>69</td>
<td>70</td>
<td>59</td>
<td>66</td>
</tr>
<tr>
<td>Fixed Carbon</td>
<td>23</td>
<td>22</td>
<td>19</td>
<td>17</td>
</tr>
<tr>
<td>Ash</td>
<td>8</td>
<td>8</td>
<td>21</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 5. Ultimate Analysis data of selected biomass materials\(^6\)

<table>
<thead>
<tr>
<th>Wheat</th>
<th>Rice</th>
<th>Hay</th>
<th>Cotton Stalks</th>
<th>Wood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straw</td>
<td>Bran</td>
<td>Straw</td>
<td>Bran</td>
<td>Straw</td>
</tr>
<tr>
<td>C</td>
<td>45.7</td>
<td>47.7</td>
<td>39.2</td>
<td>44.5</td>
</tr>
<tr>
<td>H</td>
<td>5.7</td>
<td>6.4</td>
<td>4.8</td>
<td>6.3</td>
</tr>
<tr>
<td>O</td>
<td>43.3</td>
<td>42.0</td>
<td>36.4</td>
<td>36.9</td>
</tr>
<tr>
<td>N</td>
<td>0.5</td>
<td>2.8</td>
<td>0.4</td>
<td>0.9</td>
</tr>
<tr>
<td>S</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Cl</td>
<td>0.7</td>
<td>-</td>
<td>1.9</td>
<td>-</td>
</tr>
</tbody>
</table>

8. Syngas Testing Methods

8.1 Orsat Gas Apparatus\(^7,8\)

An Orsat gas analyser is a piece of laboratory equipment used to analyse a gas sample (typically fossil fuel flue gas) for its oxygen, carbon monoxide and carbon dioxide content. Although largely replaced by instrumental techniques, the Orsat remains a reliable method of measurement and is relatively simple to use. It was patented before 1873 by Mr. H Orsat.

8.1.1 Construction

The apparatus consists essentially of a calibrated water-jacketed gas burette connected by glass capillary tubing to two or three absorption pipettes containing chemical solutions that absorb the gasses it is required to measure. For safety and portability, the apparatus is usually encased in a wooden box.

The absorbents are:

- Potassium Hydroxide (Caustic Potash)
- Alkaline pyrogallol
- Ammoniacal Cuprous chloride

The base of the gas burette is connected to a levelling bottle to enable readings to be taken at constant pressure and to transfer the gas to and from the absorption media. The burette contains slightly acidulated water with a trace of chemical indicator (typically methyl orange) for colouration.

8.1.2 Method of Analysis

By means of a rubber tubing arrangement, the gas to be analyzed is drawn into the burette and flushed through several times. Typically, 100mls is withdrawn for ease of calculation. Using the stopcocks that isolate the absorption burettes, the level of gas in the leveling bottle and the burette is adjusted to the zero point of the burette.

The gas is then passed into the caustic potash burette, left to stand for about two minutes and then withdrawn, isolating the remaining gas via the stopcock arrangements. The process is repeated to ensure full absorption. After leveling the liquid in the bottle and burette, the remaining volume of gas in the burette indicates the percentage of carbon dioxide absorbed.

The same technique is repeated for oxygen, using the pyrogallol, and carbon monoxide using the ammoniacal cuprous chloride.
8.2 Gas Chromatography

Gas chromatography (GC), is a common type of chromatography used in analytical chemistry for separating and analyzing compounds that can be vaporized without decomposition. Typical uses of GC include testing the purity of a particular substance, or separating the different components of a mixture (the relative amounts of such components can also be determined). In some situations, GC may help in identifying a compound. In preparative chromatography, GC can be used to prepare pure compounds from a mixture.9,10

8.2.1 Construction

In gas chromatography, the mobile phase (or "moving phase") is a carrier gas, usually an inert gas such as helium or an unreactive gas such as nitrogen. The stationary phase is a microscopic layer of liquid or polymer on an inert solid support, inside a piece of glass or metal tubing called a column (a homage to the fractionating column used in distillation). The instrument used to perform gas chromatography is called a gas chromatograph (or "aerograph", "gas separator").

8.2.2 Working

The gaseous compounds being analyzed interact with the walls of the column, which is coated with a stationary phase. This causes each compound to elute at a different time, known as the retention time of the compound. The comparison of retention times is what gives GC its analytical usefulness.

9. References

2. Prabir Basu, "Biomass Gasification and Pyrolysis", Practical Design

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