Gasification characteristics of sugarcane bagasse

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Abstract. Sugarcane bagasse is a residue that results from the crushing of sugarcane in the sugar industry. Among the various agricultural crop residues, sugarcane bagasse is the most abundant lignocellulosic material in tropical and sub-tropical countries including South Africa. Bagasse is a renewable feedstock that can be used for power generation and manufacturing cellulosic ethanol. In the sugarcane industries the bagasse is mainly burnt inefficiently in boilers that provide the heating for the industry. This project seeks to investigate the possibility of gasifying sugarcane bagasse as an efficient conversion technology. Proximate and ultimate analysis of sugarcane bagasse was conducted after which the results were used to conduct computer simulation of the mass and energy balance during gasification. This paper presents the proximate and ultimate analysis as well as the computer simulation results.

1 Introduction

The development of sustainable renewable energy technologies for their use in current and new power plants is of utmost importance now, more than ever before due to several reasons. Some of these reasons include energy security and availability, independence from foreign oils and reduction of greenhouse gas emissions to provide a cleaner environment for better health, plant and animal life. These reasons are precepts for the development of alternative and sustainable energy technologies. Among the various agricultural crop residues, sugarcane bagasse is the most abundant lignocellulosic material in tropical and sub-tropical countries including South Africa. Sugarcane bagasse is a residue produced in large quantities by sugar and alcohol industries. In general, 1 ton of sugarcane generates 280 kg of bagasse, and about 54 million dry tons of bagasse is produced annually throughout the world [1].

In South Africa approximately 6 million tons of bagasse is produced annually [2]. Most large and medium sized mills can use up to 75% of this bagasse onsite to generate heat and electricity [3]. Epithelial cells, vessels, and parenchyma as well as fiber bundles are part of the structural elements contained in sugarcane bagasse [4]. Bagasse holds promise as a fuel source since it can produce more than enough heat energy to supply the needs of a common sugar mill. It is a renewable feedstock that can be used for power generation and manufacturing cellulosic ethanol, and if efficiently utilized, it could generate excess electricity that could be sold to the utility company or any other third party or even be exported [5].

Gasification of sugarcane bagasse provides part of the solution towards sustainable renewable energy sources. Gasification is a process that converts organic or fossil based carbonaceous materials into carbon monoxide, hydrogen, methane and carbon dioxide. This is achieved by reacting the material at high temperatures, usually above 1000°C, in the presence of a limited amount of oxygen and/or steam. The resulting syngas or producer gas has a heating value in the range of 4-6 MJ/kg. The clean syngas from bagasse can be used in stationary gas turbines. The advantage of gasification is that using the syngas is potentially more efficient than direct combustion of the original fuel because it can be combusted at higher temperatures or even in fuel cells, so that the thermodynamic upper limit to the efficiency defined by Carnot's rule is higher or not applicable [5]. Gasification of sugarcane bagasse produces the same amount of CO_2 as it consumes during its growth rendering it carbon neutral [6]. However limited data is available on the efficient conversion of bagasse to clean syngas. The aim of this study is to investigate the possibility of gasifying sugarcane bagasse as an efficient conversion technology.

2 Research Methodology

Samples of sugarcane bagasse (SB) were obtained from TSB sugar, South Africa and were preserved to prevent contamination. The bagasse was dried at 105°C in a furnace for 4 hours. The dried sugarcane bagasse was ground using a cryogenic grinder to size range of 100 μm as required by the analytical instruments used to characterize bagasse. The bagasse, after grinding was preserved in a sample container for further analysis. The characterization methods involved proximate analysis, which gave the amount of fixed carbon, volatile and ash contents as well as moisture content of bagasse. These were determined from the thermo gravimetric curves in Figure 1, and were undertaken at two different heating rates (15°C/min and 20°C/min). Apart from providing information about proximate analysis, the essence of analysis using the thermo gravimetric analyzer (TGA) was to establish the thermal stability and the gasification temperature of sugarcane bagasse since the study is dealing with gasification which is a high temperature process.

The ultimate analysis of bagasse was determined using a carbon, hydrogen, nitrogen and sulfur (CHNS) analyzer, which is an instrument used to determine, in weight percentage, the concentration of these elements. The analyzer is restricted only to the analysis of these elements. The weight percentage of oxygen is usually obtained by difference. The higher heating value (HHV) of bagasse was measured using a bomb calorimeter (CAL2K Model). Analyses were undertaken in triplicates using each of the techniques (TGA, CHNS and Calorimeter) and an average value was calculated. A downdraft biomass gasification program developed by Jayah et al, 2003 [7] was used to undertake computer simulation of the gasification process of sugarcane bagasse. Table 1 shows the parameters used during simulations. The moisture content of the material was varied between 2.14%, 7.14% and 15.0% respectively. Gas profiles were obtained after computer simulation of the gasification process and were used to calculate the gas heating value from the percentage composition of the combustible gases in the syngas using the following equation [8]:

$$HV_{gas} = \left(\frac{(CO_{vol} \times HVCO) + (H_{2vol} \times HVH_2) + (CH_{4vol} \times HVCH_4)}{100\%}\right) \qquad [1]$$

where HV_{gas} is the gas heating value in MJ/kg, CO_{vol} is the volume concentration of carbon monoxide gas in percentage, $HVCO$ is the heating value of carbon monoxide gas (usually 12.64 MJ/kg by standard [9], H_{2vol} is the volume concentration of hydrogen gas in percentage, HVH_2 is the heating value of hydrogen gas (10.1 MJ/kg by standard [10], CH_{4vol} is the volume concentration of methane gas in percentage, $HVCH_4$ is the heating value of methane gas (38 MJ/kg by standard measurement [9]. The heating values of the combustible gases were obtained from the standard gas table.

The conversion efficiency of the gasification process was calculated from the heating value of the gas obtained from equation 1.1 and that of the feedstock which was measured and found to be 17.8 MJ/kg. This was calculated from equation 2 [8]:

$$\eta = \left[\left(\frac{HV_{gas} \times 2}{HV_{fuel}}\right) \times 100\right] \qquad [2]$$

where η is the efficiency of the gasifier, and HV_{fuel} is the heating value of the fuel (sugarcane bagasse).

Table 1. Parameters used during gasification simulation

Fuel properties	**Value**	**Gasifier operating conditions**	**Value**
Carbon (%)	44.1	Throat diameter (cm)	25.5
Hydrogen (%)	5.7	Throat angle (°)	30
Oxygen (%)	47.7	Insulation thickness (cm)	17.5
Nitrogen (%)	0.20	Thermal conductivity (W/cm K)	2.8
Fixed carbon (%)	18.19	Temperature of input air (K)	300
Bulk density (g/cm^3)	0.178	Air input (kg/hr)	44.5
Diameter of SB particle (cm)	14.3	Heat loss (%)	12.8
Moisture content	1.14 (%)		

The values for the fuel properties in Table 1 are as measured from the material (bagasse) except for the particle diameter (14.3) which was assumed to be unground based on the maximum/minimum allowable size for a downdraft gasifier system. In terms of thermodynamics and mass transfer in the conversion process, the particle size of the material is of prime importance and severely affects the thermochemical conversion of the material to the desired product; therefore, smaller particle diameter results in increased conversion efficiency due to larger surface area per unit weight of the material and larger pore sizes which facilitates faster rates of heat transfer and gasification [11]. However, the effect of particle diameter (on the conversion efficiency of the gasification process of sugarcane bagasse) was varied in another study and published in a peer reviewed journal.

3 Results and discussion

3.1 Sugarcane bagasse proximate and ultimate analysis

Table 2 presents the proximate analysis of sugarcane bagasse under study at 15°C/min and 20°C/min heating rates. The maximum temperatures reached were approximately 670°C and 488°C for the 15 and 20°C/min heating rates respectively.

Table 2. Proximate analysis of SB at 15°C/min and 20°C/min heating rates

Components	**% Composition @ 15°C/min**	**% Composition @ 20°C/min**
Moisture Content	2.14	3.62
Volatile Matter Content	58.02	68.4
Fixed Carbon	19.25	18.19
Ash	-	0.53

No ash composition was observed for the 15°C/min heating rate due to the fact that the maximum temperature reached was not enough for complete combustion and determination of ash content. At 20°C/min heating rate, an ash content of 0.53% was observed which is typical of biomass materials. The ash content and its composition are important factors for biomass use in thermochemical processing due to its catalytic activity [12]. It is also evident from table 2 that the heating rate influences the rate of volatile evolution from the material as volatile matter content increased from 58.02% at 15°C/min heating rate to 68.4% at 20°C/min heating rate. The ultimate analysis of SB is presented in table 3. It can be observed from the table that sugarcane bagasse contains more oxygen than carbon, which is typical of biomass materials.

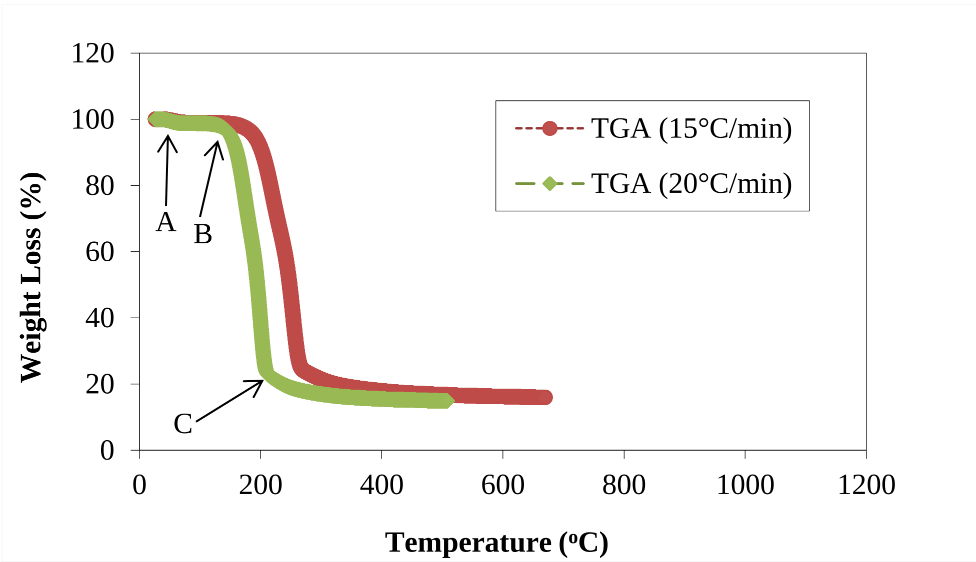
Table 3. Ultimate analysis of sugarcane bagasse

Chemical Components	Composition (%)
N	0.20
C	44.1
H	5.7
S	2.3
O	47.7

The ratio of the products formed during gasification of biomass is influenced by the chemical composition of the biomass feedstock and the operating conditions of the gasifier [13].

3.2 Thermogravimetric analysis

Figure 1 shows the TGA plot for sugarcane bagasse under study at 15°C/min and 20°C/min heating rates under nitrogen atmosphere. This was obtained using a thermo gravimetric analyzer which was used to observe the weight loss of the sample as a function of temperature.



<u>Figure 1</u>. TGA curve of SB at 15°C/min and 20°C/min heating rates

In general, three distinct weight loss stages could be noticed. In the first stage (A), a slight weight loss is noticed from the material at both heating rates, and indicated by an arrow, which reflects the loss of moisture from the material at temperatures approximately 27°C. This slight weight loss in stage A is due to the fact that the material was dried before the TGA analysis. A rapid weight loss is observed in stage B at temperatures slightly above 130°C which reflects the loss of volatiles from the material, resulting from the major components (cellulose, hemicellulose and lignin) of the material [14]. The degradation of hemicellulose typically occurs in the temperature range 100-230°C while cellulose decomposes at a higher temperature range of 200-300°C (B). The weight loss of the material continued up to stage C where there is a much lower rate of weight loss than in stage B, which corresponds partly to the end of cellulose degradation and partly to the starting of degradation of heavier volatiles and formation of char. Lignin degradation also continues in this region [14]. This analysis is based on the heating rate of the sample at 20°C/min. A rapid weight loss of the material occurred also in stage B at a much higher temperature range (approximately 189°C) for the 15°C/min heating rate, which means that the rate of decomposition of the material is dependent on the heating rate. The last weight loss stage at 15°C/min heating rate also occurred at a much higher temperature range (273°C) as compared to the 20°C/min heating rate.

3.2 Gasification simulation results

The higher heating value of the material was measured and found to be 17.8 MJ/kg, which was used during calculation of the conversion efficiency of the gasification process. Moisture content was varied between 2.14, 7.14 and 15% respectively in order to establish its effect on the volume of the syngas produced after computer simulation. Figure 2 shows the gas volumes and percentage difference obtained during gasification simulation using the gasifier operating parameters presented in Table 1.

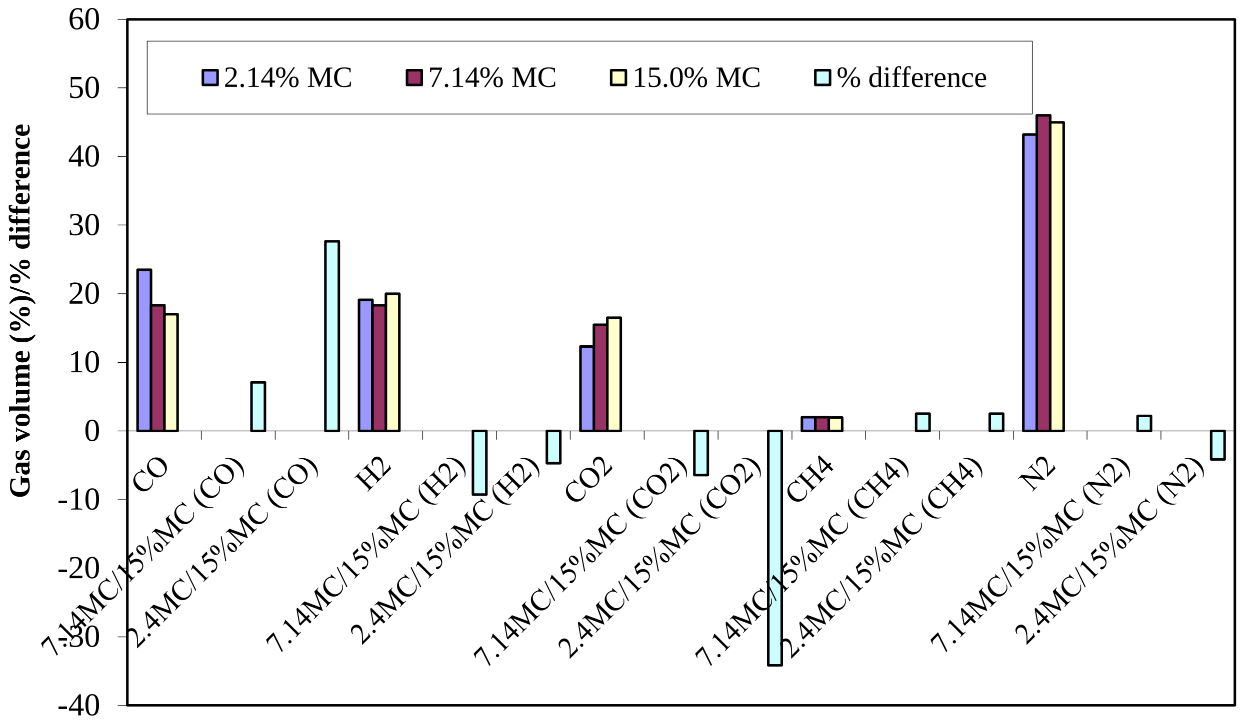


Figure 2. Gas volumes obtained through computer simulation

The major part of the syngas is formed through reduction reactions in the reduction zone of the biomass gasifier, most of which are endothermic reactions. The reactions are as follows [15]:

Boudouard reaction

$$CO_2 + C \rightleftharpoons 2CO \qquad -164.9 \text{ kJ/mol} \tag{3}$$

Water-gas reaction

$$C + H_2O \rightleftharpoons C + H_2 \qquad +122.6 \text{ kJ/mol} \tag{4}$$

Water shift reaction

$$C + H_2 \rightleftharpoons CO + H_2O \qquad +42.3 \text{ kJ/mol} \tag{5}$$

Methane production reaction

$$C + 2H_2 \rightleftharpoons CH_4 \qquad +75 \text{ kJ/mol} \tag{6}$$

The volume of carbon monoxide was found to be higher (27% by difference) when the moisture content of bagasse was low (2.14%) compared to when it was higher (7.14% and 15% respectively). This can be attributed to the fact that heat is not consumed during the drying of the feedstock; it is rather available for the reduction reactions to take place. The hydrogen content was found to be higher when the moisture content of the bagasse was assumed to be higher (15%). This is because of the availability of moisture for the water-gas reaction to take place. However the reduction in carbon monoxide implied a reduction in conversion efficiency and the gain in hydrogen could not compensate for the loss in CO content. The volume of the combustible gases in the syngas largely influences the gas heating value. This in turn influences the conversion efficiency of the gasification process because the gas heating value is directly proportional to the conversion efficiency of the gasifier. Figure 3 shows the simulated gasifier conversion efficiency. The Boudouard reaction in equation 3 is a reaction named after a French chemist, and involve the disproportionation of carbon monoxide to carbon dioxide and carbon. The reaction is exothermic because energy is released in the process [16, 17, 18].

The effect of moisture content on the conversion efficiency of the gasification process of sugarcane bagasse was also determined by varying the moisture content from 2.14, 7.14 and 15% respectively. This was established after computer simulation of the gasification process. Figure 3 presents a plot of the impact of moisture content on the conversion efficiency of the gasification process of bagasse.

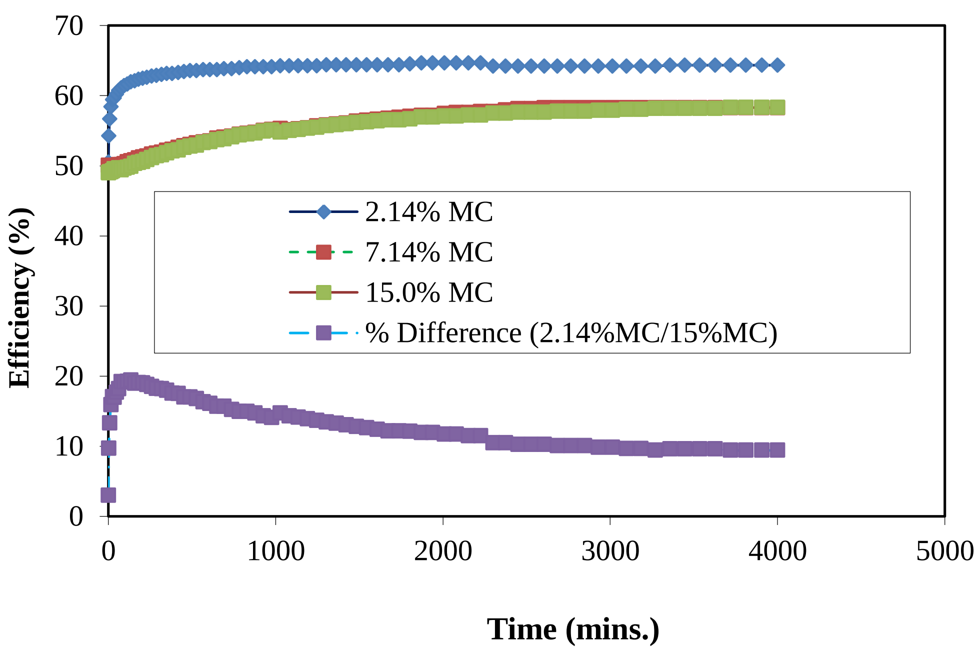


Figure 3. Computer simulation of the conversion efficiency of the sugarcane bagasse

The impact of moisture content on the conversion efficiency of the gasification process of bagasse is evident in Figure 3. As moisture content increases, conversion efficiency decreases considerably as evident. Optimum conversion efficiency (61%) was achieved at low moisture content of 2.14%. The implication for this is that the chemical reactions that favour the production of carbon monoxide during gasification of sugarcane bagasse should be optimized. This observation could also be explained by the reaction kinetics. A high quantity of energy is consumed during the drying process of the material and the energy is no longer available for reduction reactions to take place (equations 3-6). However, at higher moisture contents (7.14% and 15% respectively), the low oxidation temperature inhibiting the rate of reaction is compensated by a high water (H_2O) concentration which accelerates the water – gas shift reaction (equations 4 and 5). The percentage difference between 2.14% and 15% moisture contents is approximately 20% in terms of efficiency. This value is significantly higher when compared to that of 7.14% and 15% moisture contents. This means that material moisture content has an important influence on the efficiency of a gasification process.

4 Conclusion

The paper investigated the possibility of gasifying sugarcane bagasse as an efficient conversion technology, establishing the effect of moisture content on the syngas volume and conversion efficiency of the gasification process of bagasse. Results indicated that moisture content has an important influence on the volume of the product gas as well as on the conversion efficiency of the gasification process. Thermal analysis of the material also established the gasification temperature of bagasse which was approximately 700°C. The degradation behaviour of the material was also determined using the TGA which indicated that rapid decomposition of the material occurred between the temperature ranges of 200-400°C at both heating rates (15 and 20°C/min). The composition of sugarcane bagasse, as evident in Table 2, is comparable with what is found in the literature and suggests that bagasse is a suitable feedstock for gasification because of its high volatile matter content as well as its low ash composition including its low moisture content. The oxygen composition in Table 3 is about 8.16% more than the composition of carbon, as a result, higher reactivity of the material under much less severe operating gasification conditions is expected which is typical of biomass materials.

5 References

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