

***The Properties and Suitability of Corn Stover for Co-Gasification with Coal in a Computer Simulated Downdraft Gasifier System***

Anthony Anukam, University of Fort Hare, South Africa  
Sampson Mamphweli, University of Fort Hare, South Africa  
Polycarp Mabizela, University of Fort Hare, South Africa  
Edson Meyer, University of Fort Hare, South Africa

The European Conference on Sustainability, Energy and the Environment 2015  
Official Conference Proceedings

**Abstract**

Characterization of corn stover and coal were undertaken in order to compare their properties and determine the combustion characteristics of both feedstocks. The study was also intended to establish whether corn stover is a suitable feedstock for blending with coal for the purpose of co-gasification based on composition and properties. Proximate and ultimate analyses as well as energy value of both samples including their blends were undertaken and results showed that corn stover is a biomass material well suited for blending with coal for the purpose of co-gasification, given its high volatile matter content which was measured and found to be 75.3%, and its low ash content of 3.3% including its moderate calorific value of 16.1%. The results of the compositional analyses of both pure and blended samples of corn stover and coal were used to conduct computer simulation of the co-gasification processes in order to establish the best blend that would result in optimum co-gasification efficiency under standard gasifier operating conditions. The final result of the co-gasification simulation process indicated that 90% corn stover/10% coal resulted in a maximum efficiency of about 58% because conversion was efficiently achieved at a temperature that is intermediate to that of coal and corn stover independently.

Keywords: Proximate analysis, ultimate analysis, calorific value, co-gasification, coal, corn stover.

**iafor**

The International Academic Forum  
[www.iafor.org](http://www.iafor.org)

## 1 Introduction

Coal is the most widely used primary fuel internationally, accounting for about 36% of the total fuel consumption of the world's electricity production [1]. An excess of 255 million tons of coal is produced in South Africa and almost three quarters of that is consumed domestically with 77% of South Africa's energy needs directly derived from coal [1, 2, 3]. Although a non-renewable feedstock, coal can be effectively combined with biomass feedstock to produce a synergistic effect during gasification [4]. This process produces a low carbon footprint on the environment. Gasification is an alternative energy conversion technology that converts organic materials into usable energy in the form of syngas. On the one hand, the technology has attracted enormous interest for the past several years within thermochemical conversion technologies as it has been proven to offer higher efficiencies in comparison to combustion [5], while on the other hand it has been a promising renewable energy technology for the supply of thermal energy and generating electrical power. However, there are challenges associated with the use of this technology such as biomass supply which is limited and varies with season, low energy density of biomass which results in low production, expensive for long distance transportation etc. These challenges result in higher capital and production cost. Coal gasification on the other hand, though an established technology is also faced with the issues of high reaction temperature which most gasifiers cannot achieve and if achieved in most cases, combustion of the resultant syngas usually occur leading to low conversion efficiency. The risk of reaching extremely high temperatures that may result in pressure build up is another shortcoming related to coal gasification as this may lead to explosions. Taking these challenges into account therefore, it is more economically attractive and less technically challenging to co-gasify biomass with coal.

Co-gasification of biomass with coal has its own challenges which are related to the uncertainties associated with how to mix them. The optimum percentages of various biomass and coal blends required for enhanced conversion efficiency under standard gasifier operating conditions remains an issue yet to be addressed. Other issues related to co-gasification of biomass and coal includes gasifier type as well as choice of gasifier operating parameters which, to a great extent, determines the product gas composition and quality. Biomass and coal differ greatly in terms of properties and composition. While coal contains mainly carbon, biomass is a complicated mixture of complex compounds such as cellulose, hemicellulose, and lignin as well as extractives and minerals with relatively high amount of oxygen which makes them low energy density fuels [6]. These properties play a vital role during co-gasification because they come as factors which influence the co-gasification process [7, 8]. Various researchers have reported an increase in the efficiency of a co-gasification process by increasing the ratio of biomass in the blend. Kezhong et al., 2010 [9] reported an increase in  $H_2$  and  $CO_2$  yield when the biomass ratio was increased from 20% to 33% during co-gasification. Kumabe et al., in 2007 [7] studied the influence of the amount of biomass with respect to the molar ratio of CO,  $H_2$  and  $CO_2$  in the product gas when they co-gasified varying proportions of blended Mulia coal and Japanese cedar in a downdraft gasifier system at 1173 K. They reported that the syngas composition varied according to the ratio of biomass in the blends. This study, therefore sought to establish the properties and composition as well as proportion of corn stover and coal that would be suitable for co-gasification and that would in itself result in optimum efficiency of the co-gasification process, employing computer simulation.

## 2 Materials and method

### 2.1 Sample preparation and characteristics

The biomass material used for this study was corn stover, and the coal used was a low grade sub-bituminous coal. Both samples were obtained in the Eastern Cape Province of South Africa. A coning and quartering method was applied for size reduction of the samples using a Condux-Werk Wolfgang bei Hanau mill so as to obtain smaller fractions as required by the analytical instruments for analysis. The size obtained for the samples were in the range of 25 $\mu$ m to approximately 1mm. The blends of corn stover and coal were prepared in the following ratios: 100% CS (Pure material), 90% CS/10% CL, 80% CS/20% CL, 70% CS/30% CL, 60% CS/40% CL, 50% CS/50% CL, 40% CS/60% CL, 30% CS/70% CL, 20% CS/80% CL, 10% CS/90% CL, 100% CL (Pure material). Where CS and CL represents corn stover and coal respectively.

Calculating the usefulness of a fuel requires an understanding of its characteristics [10]. The following sub-sections present the most important analyses relevant to the thermal conversion of the materials under study.

#### 2.1.1 Calorific value of samples

The calorific value of both pure and blended samples of corn stover and coal were determined by a CAL2K model oxygen bomb calorimeter. This was done by calibration with a 0.5 g of benzoic acid before taking measurements. A 3 000 kpa pressurized oxygen environment was used to achieve this. Figure 1 show the oxygen bomb calorimeter used during the analysis.



Figure 1: An oxygen bomb calorimeter

#### 2.1.2 Elemental analysis

The weight fractions of the individual elements contained in both pure and blended samples were determined by a ThermoQuest elemental analyser. About 5 mg of each sample were combusted in the instrument at approximately 1000°C after mixing with an oxidizer in a tin capsule. Figure 2 presents the elemental analyser used for this study.

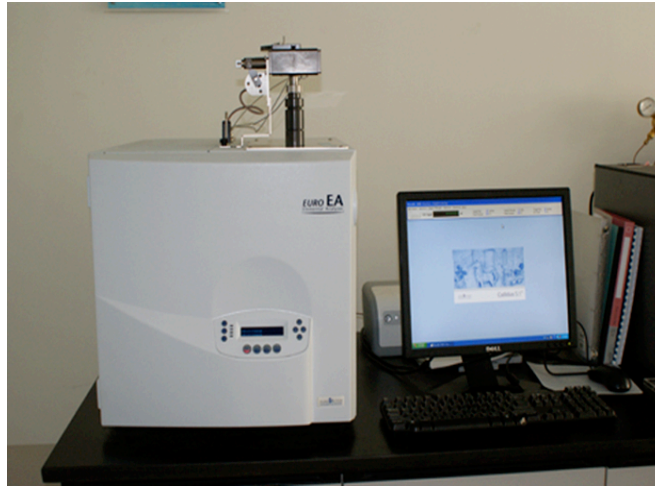


Figure 2: A thermoquest elemental analyser

There are catalysts downstream of the combustion chamber of the instrument to ensure complete oxidation. Combustion products such as  $\text{CO}_2$ ,  $\text{NO}_2$ ,  $\text{SO}_2$  were produced and were catalytically reduced to C,  $\text{N}_2$  and S. The gases were then separated by gas chromatography and their concentration measured by a thermal conductivity detector.

### 2.1.3 Thermal analysis

A TGA 7 thermogravimetric analyzer was used to study the thermal degradation behavior of both pure and blended samples of corn stover and coal. A 5.08 mg of each sample was heated over a temperature range of  $20^\circ\text{C}$ - $1000^\circ\text{C}$  under a nitrogen atmosphere at  $20^\circ\text{C}/\text{min}$  heating rate. This analysis was undertaken in order to establish the thermal behaviour and the temperature of the co-gasification processes of both pure and blended samples of corn stover and coal. The thermogravimetric analyser used for the thermal analysis of both pure and blended samples of corn stover and coal is presented in Figure 3.



Figure 3: A thermogravimetric analyser

### 2.1.4 Co-gasification simulation process

A mathematical model modified by Jayah *et al.*, 2003 [11] and designed specifically to simulate the gasification performance of a typical downdraft gasifier system was

used to conduct computer simulation of the co-gasification processes of both pure and blended samples of corn stover and coal for maximum efficiency. The proximate and ultimate analyses as well as the calorific value results of the samples obtained in section 3 were used during calculation of the conversion efficiency of the co-gasification processes of the samples. A detailed description of the simulation programme has been presented in our previous paper [10]. For optimum co-gasification efficiency, the normal operating parameters/conditions of a downdraft gasifier are presented in Table 1.

Table 1: Normal operating parameters of a downdraft gasifier [11].

Fuel properties	Value	Gasifier operating conditions	Value
Carbon (%)	39.6	Throat diameter (cm)	94.0
Hydrogen (%)	6.7	Throat angle (°)	90.0
Oxygen (%)	52.1	Insulation thickness (cm)	0
Nitrogen (%)	1.59	Thermal conductivity (W/cm K)	0.87
Fixed carbon (%)	19.3	Temperature of input air (K)	293
Bulk density (kg/m <sup>3</sup> )	0.25	Air input (kg/hr)	44.5
Diameter of particle (cm)	1.0	Heat loss (%)	12.8
Moisture content (%)	8.7	Feed input (kg/hr)	40

### 3 Results and discussion

#### 3.1 Energy content of pure and blended samples

The calorific values gave a clear indication of the energy contained in the samples and were obtained after analysis by the oxygen bomb calorimeter. Increasing the biomass content during co-gasification enhances calorific value due to higher composition of hydrocarbons in biomass [12, 13]. The results of the calorific value of the pure and blended samples of corn stover and coal are presented in Figure 4.

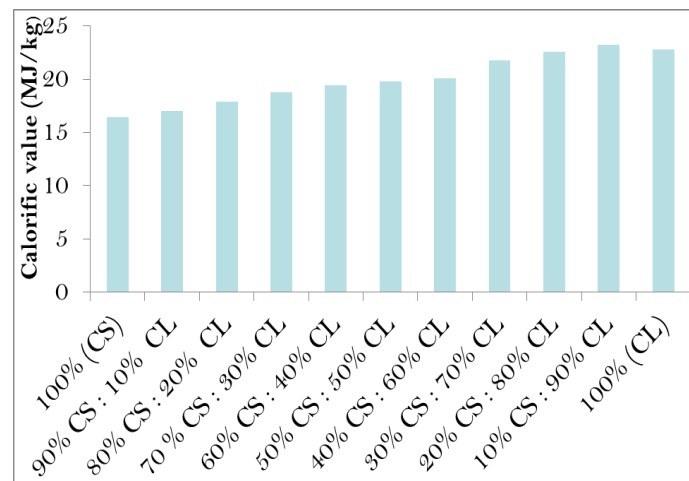


Figure 4: Energy content of pure and blended samples of corn stover and coal

The difference in calorific value between the pure materials as well as their blends is quite noticeable from Figure 4. The pure coal sample has a much higher calorific value (22.8 MJ/kg) compared to the 100% corn stover with ca 17 MJ/kg. This difference in calorific value could also be correlated to the concentration of C and O<sub>2</sub> in the samples (elemental composition in Figure 5). A 1% increase in carbon

concentration will elevate the calorific value by approximately 0.39 MJ/kg and coals generally have calorific values greater than biomass because of lower degree of oxidation [14]. In contrast, the calorific values of the blends vary in accordance with the ratio of coal to corn stover in the blends. Calorific value increases with increasing ratio of coal in the blends.

### 3.2 Proximate analysis of pure and blended samples

Table 2 shows the proximate analysis results of both pure and blended samples of corn stover and coal. These were obtained from the TGA plots in Figure 6. This analysis was undertaken in order to compare the physical properties of corn stover with those of coal including their blends and establish the properties that would influence the co-gasification processes of both pure and blended samples under standard gasifier operating conditions. The weight percentages of fixed carbon in the pure and blended samples were obtained by difference.

Table 2: Proximate analysis of pure and blended samples of corn stover and coal

Pure samples									
Coal (wt%)					Corn stover (wt%)				
MC	VM	FC	AS		MC	VM	FC	AS	
0.2	25	24	50.8		8.7	75.3	19.3	3.3	
Blended samples									
Blend					CL:CS (wt%)				
Ratio (%)					MC	VM	FC	AS	
90:10					2.5	23	29.5	45.2	
80:20					2.6	27.3	27	43.1	
70:30					3.1	32.5	25.4	39	
60:40					3.4	35.4	36.9	24.3	
50:50					4.2	48.9	29.6	17.3	
40:60					5.4	53.6	28.2	12.8	
30:70					5.9	55.1	28.4	10.6	
20:80					6.5	66.4	19.8	7.3	
10:90					7.6	69.8	17.9	4.7	

Note: MC= Moisture content, VM= Volatile matter content, FC= Fixed carbon, AS= Ash content, CL = Coal, CS = Corn stover

The values obtained for both pure and blended samples in Table 2 are within acceptable ranges found in the literature. Comparing the properties of the pure samples with those of the blended, it could be easily noticed that a typical South

African sub-bituminous coal used for this study has high amount of ash in comparison to corn stover which showed quite a relatively low ash composition. Ash content of coal varies over a wide range and this variation occurs not only in coals from different geographical areas or from different seams in the same region, but also from different parts of the same mine which results primarily from a wide range of conditions that introduces foreign materials during or following the formation of coal [15]. The reason for the high amount of ash in the pure coal is most likely due to the influence of extraneous mineral matter introduced during mining operations where the coal was obtained. The difference in the pure and blended samples is also quite evident from Table 2 as the blends with higher percentages of coal exhibited higher ash contents. Some of the blends with higher ratios of corn stover also exhibited higher ash contents. This is also due to the nature and source including other conditions such as growth processes, growing conditions and handling before analysis of corn stover as well as doses of fertilizer and pesticides used during growing season, which are highly important for some elements such as K, N, P, S and certain trace elements. However, high amount of ash is undesirable as it could cause agglomeration, slagging and fouling as well as deposition and corrosion during gasification; therefore, to avoid these challenges during co-gasification, feedstock ash content must be below 6% [10, 16].

The difference in volatile matter content between coal and corn stover can also be observed in Table 2. This is linked to differences in properties between the two feedstocks. Fuels with high volatile matter content is always better for gasification because they tend to vapourize before combustion compared to fuels with low volatile matter content which burns primarily as glowing char and this affects the performance of the combustion chamber of the gasifier which is usually taken into account when designing gasification systems [17]. Moisture content of the pure coal material is relatively low compared to the corn stover and varies in the blends according to the percentage of corn stover in the blends. High feedstock moisture content lowers the temperature inside the combustion unit of the gasifier and will lead to an increased fuel throughput, thereby increasing the volume of flue gas released [18]. The fixed carbon of coal is higher (24%) than that of corn stover which is again as a consequence of the difference in physical properties between corn stover and coal. In contrast, the fixed carbon content of the blends showed a slight variation due to the ratio of volatiles in the pure coal. Fixed carbon is calculated as a function of moisture, volatile matter and ash content, and the uncertainties of these properties affect the uncertainty in the concentration of fixed carbon [10]. The fixed carbon content of the blends were also in narrow ranges due to the amount of volatile matter and moisture as well as ash driven off in the sample during thermal analysis.

### **3.3 Ultimate analysis of pure and blended samples**

Figure 5 shows the ultimate analysis data obtained after CHNS analysis of the pure and blended samples of corn stover and coal.



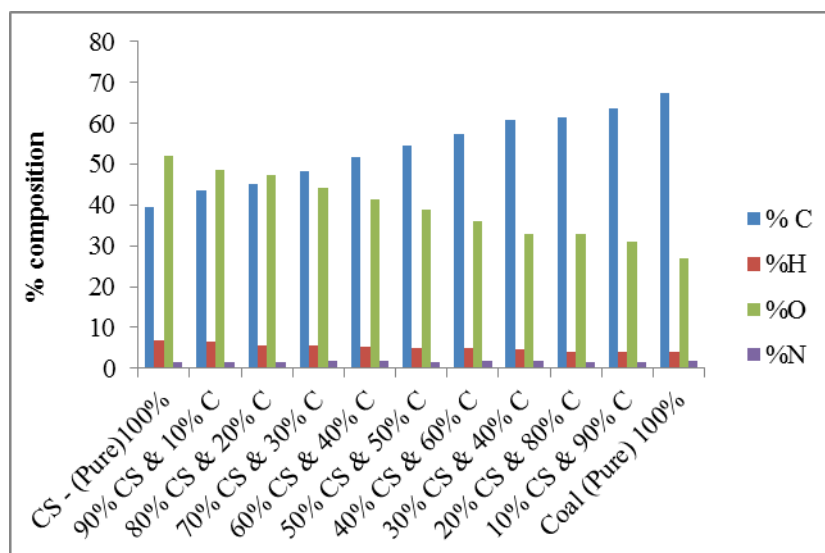


Figure 5: Ultimate analysis of pure and blended samples of corn stover and coal

The elemental analysis of corn stover and coal including their blends showed that the main chemical constituents of the samples are C, H<sub>2</sub> and O<sub>2</sub>, which is due mainly to the organic nature of both feedstocks. However, the percentage composition of C in pure coal (67.5%) is almost double that of pure corn stover (39.6%), which supports the fact that coal chiefly, contains C. According to the trend in Figure 5, the percentage composition of C increased with increasing percentage of coal in the blends, while that of O<sub>2</sub> decreased with decreasing ratios of corn stover in the blends. H<sub>2</sub> composition also decreased quite slightly with decreasing percentage of corn stover in the blends. This is attributed to the differences in properties between corn stover and coal. C and H<sub>2</sub> are oxidized during co-gasification by exothermic reactions forming CO<sub>2</sub> and H<sub>2</sub>O. The content of C and H<sub>2</sub> has a positive contribution to the calorific value of the fuel and the CO<sub>2</sub> formed is emitted as a major product of complete combustion because incomplete combustion in the oxidation zone of the gasifier can lead to emissions of unburnt carbon based pollutants such as hydrocarbons, polycyclic aromatic hydrocarbons, tar and soot [10]. O<sub>2</sub> will reduce the energy density of the fuel [19]. However, the presence of O<sub>2</sub> is important to start the syngas formation process as it reacts with C and H<sub>2</sub> in the feedstock to form CO<sub>2</sub> and H<sub>2</sub>O. The CO<sub>2</sub> formed reacts with C in the feedstock to produce CO as described by equation 1.5 in section 1.1. N<sub>2</sub> in the fuel is almost entirely converted into gaseous N<sub>2</sub> and nitric oxides (NO<sub>x</sub>, [NO, NO<sub>2</sub>]) during co-gasification. One of the main environmental effects of combustion of coal and biomass is caused by the emission of NO<sub>x</sub> [20]. NO<sub>x</sub> can be formed through reaction pathways such as reaction of N<sub>2</sub> with O<sub>2</sub> radicals at high temperatures (above 1300°C) and the amount increases with increasing temperature. It could also be formed from airborne N<sub>2</sub> at yet again, temperatures above 1300°C but under low O<sub>2</sub> conditions in the presence of hydrocarbons [21, 22]. The most important mechanism in gasification systems is the formation of NO<sub>x</sub> from the oxidation of fuel N<sub>2</sub> during a series of elementary reaction steps and emission increases with increasing fuel N<sub>2</sub> content [23]. However, the major influencing parameters for NO<sub>x</sub> formation include air supply, combustion zone geometry and temperature, as well as type of gasification technology used [24]. Emission related problems for solid fuels exceeding emission limits can be expected



at fuel N<sub>2</sub> concentrations above 0.6 wt.%. N<sub>2</sub> composition in the blends is quite minimal and poses no environmental concern during co-gasification.

### 3.4 Thermal behavior of pure and blended samples of corn stover and coal

The rate of degradation of a sample during thermogravimetric analysis is an indication of the thermal behavior of the sample under gasification [10]. Figure 6 shows the weight loss of pure and blended samples of corn stover and coal obtained after thermal analysis using a thermogravimetric analyzer, and carried out under a nitrogen flow rate of 20 ml/min. The maximum temperature reached was 900°C at 20°C/min heating rate.

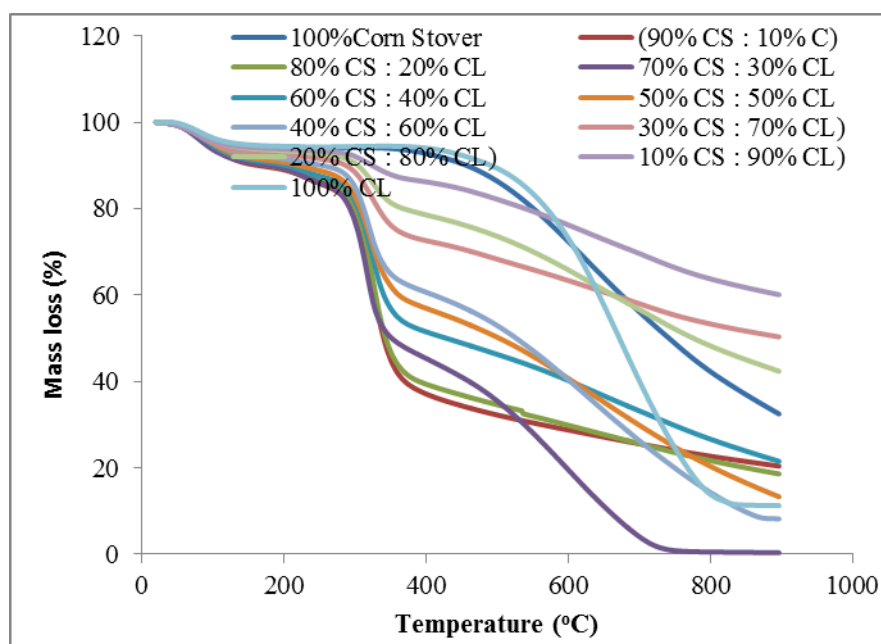


Figure 6: TGA of pure and blended samples of corn stover and coal

It is quite clear from Figure 6 that pure coal degrades over a wider temperature range when compared to pure corn stover. The blends with higher percentages of coal assumed essentially the same shape with degradation occurring at a much wider temperature range due to reduced content of volatile matter in coal (according to Table 2 in section 3.2). However, an initial mass loss occurred at 105°C temperature for all samples except for the 70% CS:30% CL (70% corn stover: 30% coal) with initial mass loss occurring at a much higher temperature (130°C). This initial mass loss is due to the evaporation of moisture from the samples. Rapid weight loss due to devolatilization in the 100% corn stover started at 400°C which is considerably lower than the temperature corresponding to the start of devolatilization of 100% coal at 530°C. At all mix ratios, the curves corresponding to the blends maintained essentially the same shape and position and displayed three stage weight losses with the last stage of devolatilization occurring at a much higher temperature (600-800°C) due to char oxidation. This observation is again excluding the 70% CS:30% CL blend which is characterized by four weight loss stages due to much higher volatile matter content of corn stover in the blend, with its last stage of weight loss occurring at 715°C. In general, and in relation to co-gasification, starting from room temperature, to a temperature corresponding to 1000°C, all samples would have completely degraded leaving some amount of ash whose concentration would depend on the

composition of the mineral matter content of the feedstocks for co-gasification, and the conditions of co-gasification.

### 3.5 Computer simulation of the co-gasification processes of pure and blended samples of corn stover and coal

Gasification efficiency is an expression of the energy content of gaseous products to energy content of biomass, coal or a mixture of them as solid fuel [25]. It is an important factor that determines the actual technical operation and the economic viability of using a gasification system. The computer simulation programme described in section 2.1.4 was used to undertake the simulation of the co-gasification processes of both pure and blended samples of corn stover and coal. Figure 7 shows the efficiency plot of the co-gasification processes of all samples obtained after computer simulation.

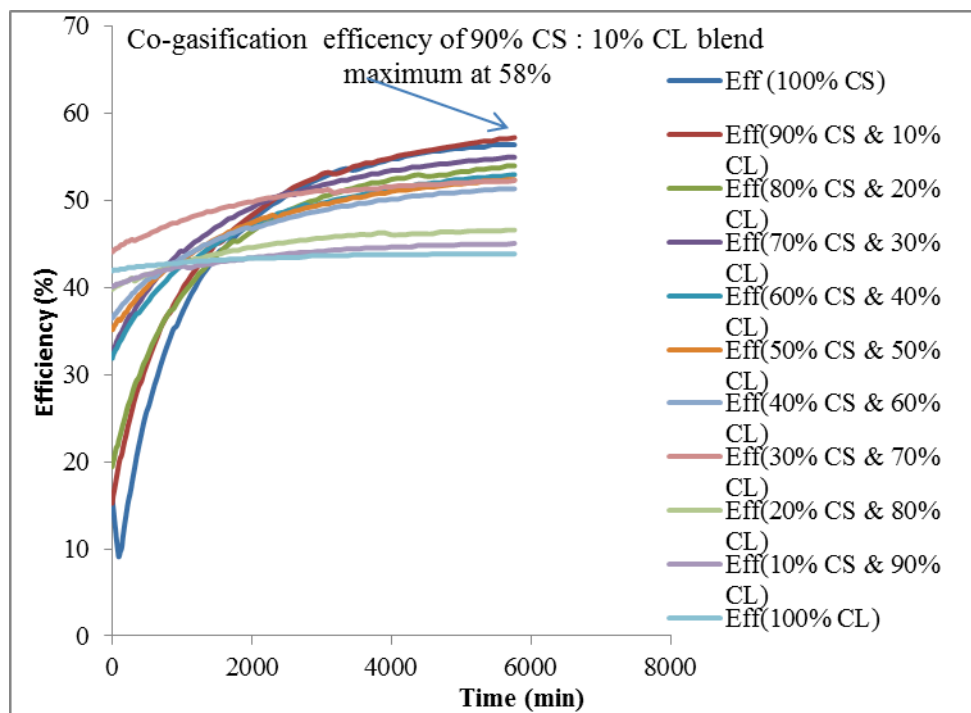


Figure 7: Simulated efficiency of the co-gasification processes of pure and blended samples of corn stover and coal

As evident from Figure 7, although there are no significant differences in the efficiency of some of the blends, while for some other blends a significant difference could be noticed. The blend 90% CS/10% CL resulted in maximum efficiency of approximately 58%. This optimum efficiency was achieved because conversion was efficiently reached at a temperature that is intermediate to that of coal and corn stover independently. Another reason for the optimum efficiency may also be due to catalytically active components in corn stover. The conversion efficiency of a gasification process among other factors also depends on the catalytically active components in the feedstock [26]. The gasifier operating parameters/conditions presented in Table 1 were also other factors responsible for the optimum co-gasification efficiency shown by the blend (90% corn stover/10% coal), as well as the ratio of corn stover in the blend. Raising the ratio of biomass in a co-gasification process increases the efficiency of the process [27].

### 3.6 Comparison with experimental data

A comparison between the simulated process studied and experimental data from the literature was undertaken for this study and results presented in Table 3.

Table 3: A comparison of the simulated results from this study with experimental data from the literature.

This study		
Blend ratio (%)	Materials blended	Gasification efficiency (%)
90:10	Corn stover : Coal	58
80:20		53.5
70:30		54.4
60:40		52.6
50:50		51.3
40:60		50.8
30:70		49.3
20:80		46.1
10:90		44.9
Previous authors		
Blend ratio (%)	Materials blended	Gasification efficiency (%)
90:10	Wood : Coal [28]	50 – 95
80:20	Wood : Coal [28]	43
70:30	Pine chips : Coal [29]	Improved H <sub>2</sub> eff. From 17% to 22%
60:40	Mulia coal: Japanese cedar [7]	47.9
	Coal : Pine chips [30]	Improved efficiency
50:50	Woody biomass : Coal [7]	65 – 85
	Indonesian Tinto coal : Sawdust [30]	45
40:60	Coal : pinewood [28]	48 – 62
	Coal : pine chips [31]	Improved efficiency
30:70	Bagasse : Coal [32]	55.03
20:80	Pine chips : Coal [29]	Continuous and stable operation/Improved efficiency
10:90	Coal : Pine sawdust [12]	82.3
	Coal : Almond shell [12]	77.7
	Coal : Olive stones [12]	81.6

It can be clearly seen from Table 3 that there is only about 5 to 8% variation between measured and simulated results. Therefore, it is fair to say that the model used for the simulation of the co-gasification processes of pure and blended samples of corn stover and coal can be applied for further analysis with acceptable accuracy. The validated model was used to study the effect of process efficiency. The simulations result concur with the experimental data found in the literature and are useful in predicting experimental observations reasonably well based on process efficiency.

### 4 Conclusions

The properties and suitability of corn stover for co-gasification with coal in a computer simulated downdraft gasifier was investigated in this study and the most suitable corn stover/coal blend for co-gasification established based on efficiency. The blend established was 90% CS/10% CL because conversion was independently achieved at a temperature that is intermediate to that of corn stover and coal. However, results also showed that the suitability of corn stover and coal for co-

gasification depends on a number of factors which included the composition and properties of both feedstocks and the ratio of blending as well as the operating conditions of the gasifier. Furthermore, a comparison of the simulated data from this study and experimental data from the literature showed similar results in terms of efficiency, implying that a laboratory scale or a large scale downdraft gasification system for the purpose of co-gasification of corn stover and coal can be designed using simulation results. The study established that corn stover is a carbonaceous feedstock suitable for co-gasification with coal in a downdraft gasification system properly designed to accommodate the properties of both feedstocks.

### **Acknowledgements**

The authors wish to acknowledge the Fort Hare Institute of Technology, University of Fort Hare, Eskom, the National Research Foundation and the Govan Mbeki Research and Development Centre for providing financial support for this research. Their support is deeply appreciated.

## References

- [1] Department of Energy, Republic of South Africa (2010). An overview of coal resources. [http://www.energy.gov.za/files/coal\\_frame.html](http://www.energy.gov.za/files/coal_frame.html). Last accessed May 2014.
- [2] BP Statistical review of World Energy (2012). A review. British Petroleum. <http://bp.com/statisticalreview>. Last accessed May 2014.
- [3] United Nations Development Programme (UNDP) (2000). World energy assessment: Energy and the challenge of sustainability. <http://www.undp.org/content/dam/aplaws/publication/en/publications/environment-energy/www-ee-library/sustainable-energy/world-energy-assessment-energy-and-the-challenge-of-sustainability/World%20Energy%20Assessment-2000.pdf>. Last accessed July 2015.
- [4] Sjöström K., Chen G., Yu Q., Brage C., Rosén C. (1999). Promoted reactivity of char in cogasification of biomass and coal: synergies in the thermochemical process. *Fuel*, 78, 10: 1189-1194.
- [5] Ardila Y, Figueroa J, Lunelli B, Maciel F, Maciel M. (2011). Syngas production from sugarcane bagasse in a circulating fluidized bed gasifier using AspenTM, Laboratory of optimization, design and advanced control. School of Chemical Engineering, State University of Campinas, Sao Paulo, Brazil.
- [6] Siedlecki M., de Jong W., Verkooyen A.H.M. (2011). Fluidised bed gasification as a mature and reliable technology for the production of bio-syngas and applied in the production of liquid transportation fuels- A review. *Energies* 4: 389-434.
- [7] Kumabe K., Hanaoka T., Fujimoto S., Minowa T., Sakanishi K. (2007). Co-gasification of woody biomass and coal with air and steam. *Fuel*, 86, 5-6: 684-689.
- [8] Vélez J., Chejne F., Valdés C., Emery E., Londoño C. (2009). Co-gasification of Colombian coal and biomass in fluidized bed: An experimental study. *Fuel*, 88, 3: 424-430.
- [9] Kezhong L., Zhang R., Bi J. (2010). Experimental study on syngas production by co-gasification of coal and biomass in a fluidized bed. *International Journal of Hydrogen Energy*, 35, 7: 2722-2726.
- [10] Anukam A., Mamphweli S., Meyer E., Okoh O. (2014). Computer simulation of the mass and energy balance during gasification of sugarcane bagasse. *Journal of Energy*, Article ID 713054.
- [11] Jayah T.H., Aye L., Fuller R.J., Stewart D.F. (2003). Computer simulation of a downdraft wood gasifier for tea drying. *Biomass and Bioenergy*, 25, 4: 459-469.
- [12] Feroso J., Arias B., Plaza M., Pevida C., Rubiera F., Pis et al. (2009). High-pressure co-gasification of coal with biomass and petroleum coke. *Fuel Process Technology*, 90, 7-8: 926-32.

- [13] Valero A., Usón S. (2006). Oxy-co-gasification of coal and biomass in an integrated gasification combined cycle (IGCC) power plant. *Energy*, 31, 10-11: 1643-1655.
- [14] Jenkins B.M., Physical properties of biomass, in: O. Kitani, C.W. Hall Eds., *Biomass Handbook*, Chap. 5.2, Gordon & Breach, New York, NY, 1989.
- [15] Inside Power Station, Ash content of coal, <http://antohendarto.blogspot.com/2011/09/ash-content-of-coal.html>. Last accessed June 2014.
- [16] Gustafsson E. (2011). Characterization of particulate matter from atmospheric fluidized bed biomass gasifiers. Ph.D. thesis, Linnaeus University.
- [17] Ciolkosz D. (2010). Characteristics of biomass as a heating fuel. Renewable and Alternative Energy Fact Sheet, Penn State College of Agricultural Sciences. Agricultural Research and Cooperative Extension. [www.energy.extension.psu.edu](http://www.energy.extension.psu.edu). Last accessed June 2014.
- [18] Khan A.A., de Jong W., Jansens P.J. and Spliethoff H. (2009). Biomass combustion in fluidized bed boilers: potential problems and remedies. *Fuel Process Technology*, 90: 21-50.
- [19] Kumar A., Jones D.D., Hanna M.A. (2009). Thermochemical biomass gasification: A review of the current status of the technology. *Energies*, 2, 3: 556-581.
- [20] Nussbaumer T. (2002). Combustion and co-combustion of biomass. *Proceedings of the 12th European Biomass Conference*, vol. I, ISBN 88-90042-5-X: 31-37.
- [21] Miller J.A and Bowman C.T. (1989). Mechanism and modelling of nitrogen chemistry in combustion. In: *Prog. Energy Combustion Science*, 15, 287-338.
- [22] Fenimore C.P. (1971). Formation of nitric oxide in premixed hydrocarbon flames. *Proceedings of the 13th symposium (International) on combustion*. The combustion Institute (ed.), Pittsburgh, 373-380.
- [23] Leckner B. and Karlsson M. (1993). Gaseous emissions from circulating fluidized bed combustion of wood. *Biomass and Bioenergy*, 4, 5: 379-389.
- [24] van Loo S. and Koppejan J. (2002). *Handbook of biomass combustion and co-firing*. IEA Bioenergy Task 32, ISBN 9036517737: 171-213.
- [25] Mamphweli S. (2009). Implementation of a 150KVA biomass gasifier system for community economic empowerment in South Africa, Ph.D. thesis, University of Fort Hare.
- [26] Moilanen A. (2006). Thermogravimetric characterisations of biomass and wastes for gasification processes. A Technical Report. VTT Publications 607.

- [27] Lapuerta M., Hernández J.J., Pazo A., López J. (2008). Gasification and co-gasification of biomass wastes: effect of the biomass origin and the gasifier operating conditions. *Fuel Processing Technology*, 89, 9: 828-837.
- [28] Aigner I., Pfeifer C., Hofbauer H. (2011). Co-gasification of coal and wood in a dual fluidized bed gasifier. *Fuel*, 90, 7: 2404-2412.
- [29] Li K., Zhang R., Bi J. (2010). Experimental study on syngas production by co-gasification of coal and biomass in a fluidized bed. *Int'l J Hydrogen Energy*, 35, 7: 2722-2726.
- [30] Seo M.W., Goo J.H., Kim S.D., Lee S.H., Choi Y.C. (2010). Gasification characteristics of coal/biomass blend in a dual circulating fluidized bed reactor. *Energy Fuel*, 24: 108-118.
- [31] Pan Y.G., Velo E., Roca X., Manyá J.J., Puigjaner L. (2000). Fluidized-bed co-gasification of residual biomass/poor coal blends for fuel gas production. *Fuel*, 79, 11: 1317-1326.
- [32] Long H.A and Wang T. (2011). Case studies for biomass/coal co-gasification in IGCC applications. *Proceedings of ASME Turbo Expo 2011 GT2011 June 6-10, Vancouver, Canada.*

**Contact email:** [aanukam@ufh.ac.za](mailto:aanukam@ufh.ac.za)