Effects of Moisture Content in Biomass Gasification

Lugano Wilson [1], Geoffrey R. John[2]

[1]Ph.D Candidate, Department of Mechanical and Industrial Engineering, College of Engineering and Technology (CoET), University of Dar es Salaam, P O Box 35131, Dar es Salaam, Tanzania
Corresponding author email: luganowilson@yahoo.com
[2]Professor, Department of Mechanical and Industrial Engineering, College of Engineering and Technology (CoET), University of Dar es Salaam, P O Box 35131, Dar es Salaam, Tanzania

ABSTRACT
Coffee husk is an agricultural waste that has a potential application in harnessing energy via thermochemical processes like gasification. However, the characteristic properties of these materials in relation to thermochemical processes are largely missing in literature. This study was therefore invoked for the purpose of investigating the effects of coffee husk moisture content on the performance of high temperature gasification. During the study, the coffee husk moisture content was varied from 20, 40, to 60% with a temperature range of 700, 800, and 900ºC in the presence and absence of steam. Performance parameters that were investigated include gasification rate and syngas composition. The study findings show that the presence of moisture in the coffee husk increased the residence time during gasification. Comparatively, the biomass with higher moisture content took longer time to achieve a complete degradation. This effect was more pronounced in lower gasification temperatures (700ºC). At higher temperatures of 900ºC, the problem was bridged since it was partially visible during the initial degradation stages, which involves moisture release and devolatilization. While gasifying at 700ºC, after 300 seconds the biomass with 20% moisture had achieved 96% degradation whereas that with 40 and 60% moisture degraded by 89 and 75% respectively. A similar trend was observed during steam gasification. As a result of increasing moisture from 20 to 40% in presence of steam the achieved degradation level was 76.38% and 59.61% respectively. Compared to the no steam condition this is an improvement of 8.05 and 56.12% respectively. Syngas evolution in terms of CO component was also observed to decrease with moisture. By increasing moisture from 40 to 60% there was a CO concentration drop of 23.26%.

Keywords: Biomass Energy; Biomass Moisture Content; Coffee Husk; High Temperature Gasification (HTAG); Steam Gasification

1.0 INTRODUCTION

Biomass gasification is an efficient biomass-to-energy conversion technology. Through integrated gasification combined cycles (IGCC), it is possible to increase the conventional Rankine cycle power generation's efficiency from 30% to 50% (Bridgwater, 1995). Besides the syngas energy from biomass gasification, various other energy streams can be generated. These energy streams are conventionally used for electricity generation and for thermal applications. The renewable hydrogen can be produced by upgrading the producer gas from biomass gasification (Hulteberg and Karlsson, 2009; Koroneos *et al.,* 2008), whereas the two main biomass syngas components, H_2 and CO, are widely recognized as an important platform in the production of second generation bio-automotive fuels like methanol, ethanol, dimethyl-ether (DME), Fischer-Tropsch (FT)-diesel, synthetic natural gas (SNG), and hydrogen (Zhang, 2009). It is therefore foreseeable that the transport sector is the most important end use sector due to its poor environmental performance (Quadrelli and Peterson, 2007; El-Fadel and Bou-Zeid, 1999; Hekkert *et al.,* 2005).

In order to optimize the gasifiers' performance, researchers have investigated various influencing parameters such as materials (Hanaoka *et al.,* 2005; Chen *et al.,* 2003), mineral matter content (Obernberger *et al.,* 1997); and catalysts (Elliot *et al.,* 1984). Since water forms a major part of the plant cell structure, moisture content is an important controlling parameter in biomass gasification. Generally, biomass moisture content varies considerably as it may range from 15% for wood products whereas it exceeds 50% in wood thinnings (Faaij *et al.,* 1997). An attempt to investigate the effect of moisture content, Brammer and Bridgwater (1999) reported that moisture content up to 20% and 50% is acceptable to downdraft gasifiers and updraft gasifiers respectively. On the other hand, fluidized bed gasifiers have been reported to gasify higher moisture content materials, up to 70% (Holmberg and Ahtila, 2004). As the effect of moisture content has been widely investigated in the low temperature gasification range, this research was invoked to the high temperature gasification process. The benefits of high temperature gasification is from its capability to support endothermic gasification reactions like primary water-gas reaction (Equation 1), which progresses in the presence of steam.

$$C + H_2O \rightarrow CO + H_2 \qquad (1)$$

2.0 METHODOLOGY

The laboratory-scale high temperature gasification of biomass was carried out by utilizing the coffee husks whose analysis is detailed in Table 1. The coffee husks utilized under the laboratory investigation were prepared to achieve three different moisture levels of 20, 40 and 60%. These moisture levels were achieved by dozing the coffee husks by a pre-determined amount of water. The already prepared sample was stored in a desiccator for allowing no exchange of moisture between the coffee husks and ambient air. During the laboratory experimentation, the gasifier temperature was varied to three different ranges of 700, 800, and 900 °C. Nitrogen and oxygen flow into the chamber was also varied to achieve the desired oxygen concentration levels.

Table 1: Coffee husks ultimate analysis (dry basis)

Proximate Analysis	
Ash content (550 ºC), %	2.50
Volatiles content, %	83.20
Fixed carbon, %	14.30
HHV, MJ/kg	18.34
Ultimate Analysis	
Carbon (C), %	49.40
Hydrogen (H), %	6.10
Oxygen (O), %	41.20
Nitrogen (N), %	0.81
Sulphur (S), %	0.07
Chlorine (Cl), %	0.03

HTAG laboratory investigation was carried out at the Energy and Furnace Division's laboratories of the Royal Institute of Technology in Stockholm Sweden. Layout of the HTAG test rig that was utilized in the study is shown in Figure 1. The rig is batch type, which is preheated to predetermined temperature using a methane burner (7). Honeycomb (9) stores heat energy from primary combustion chamber (8). The heat stored in the honeycomb is then released to heat the secondary combustion chamber (10) to a constant desired experimental temperature. A thermocouple (15) records the secondary chamber temperature, when it reaches the desired level the burner is switched off. Oxygen concentration (%) is achieved by setting oxygen and nitrogen flow through respective inlets (3) and (4) that are controlled by Bronkhorst EL-Flow mass flow meters and controllers (6). Steam is injected through inlet pipe (1) whereas inlet pipes (2) and (5) are available for more oxidants. The sample (18) is inserted into the furnace through inlet flange (13) where it is also cooled through the chamber (11). Nitrogen (12) is used to purge air infiltrated while inserting the sample and it is also used to cool down the sample before exiting the furnace. Sample temperature is monitored at the cooling chamber and during the experiments through thermocouples (17) and (16) respectively. The behaviour of the sample during the experiment can be observed through glass window (14). The syngas exits through pipe (20) where the sampling probe (21) collects gas for analysis. Prior to composition analysis, the sampled syngas is cleaned by passing through sampling train (22). The syngas enters the first flat bottomed flask which is in ice bath that allows the collection of syngas condensates that includes water vapour. Further condensation is enhanced by a condenser. On exiting the condenser the syngas enters a series of three bottles that are contained in a second ice bath. Further syngas condensates and particulates are collected in the first bottle that contains water. The second bottle and third bottle contains isobutanol (isobutyl alcohol), which allows absorption of all tars remaining in the syngas after exiting the first bottle. A clean syngas exits the third bottle and enters the fourth dry bottle that contains a dry cotton wool. The cotton wool allows further cleaning of the gas and traps all the escaping particulates. Online carbon monoxide and carbon dioxide analyzer type Maihak Multor 610 was utilized to monitor flue gas composition whereas mass loss data was measured by a digital online balance (19) type Radwag model WPX 1500. Furthermore, a micro GC monitored the syngas composition with respect to CO, CO_2, CH_4, C_2H_4, C_2H_6, and C_2H_2 species. All data generated by the thermocouples, gas analyzer, micro GC, and digital balance were collected in a laptop computer via TCP/IP multiplexer type Keithley 2710.

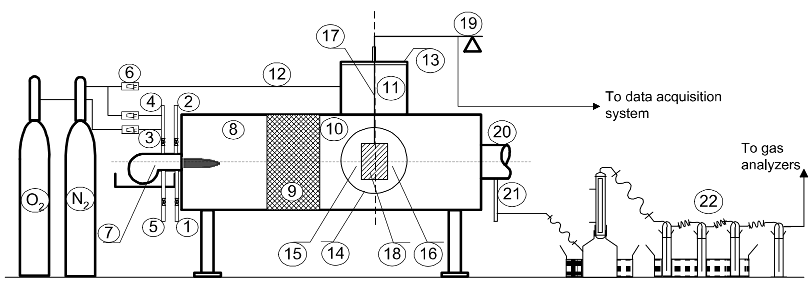


Figure 1: The high temperature gasification test rig

3.0 RESULTS AND DISCUSSION

3.1 Mass Loss Characteristics

Addition of moisture to the coffee husks affected negatively the mass loss characteristic of the material. Though the effect of degradation time was almost bridged by high temperature condition, generally high moisture materials took more time to achieve a complete degradation. At a temperature of 900 °C almost all materials achieved a complete degradation after 200 seconds. On the other hand, at temperature of 800 and 700 °C complete degradation was achieved after 300 seconds. Thus while gasifying at 700 °C, after 300 seconds the biomass with 20% moisture had achieved 96% degradation whereas that with 40 and 60% moisture degraded by 89 and 75% respectively. Figure 2 shows that though both materials achieved complete degradation after 300 seconds, but the effect of increasing material's moisture from 20 to 40% the respective degradation after 100 seconds was 70.69 and 38.18%.

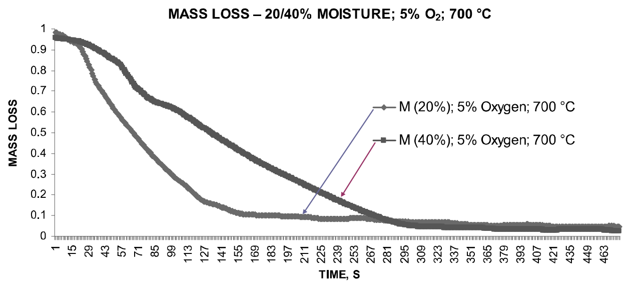


Figure 2: Effect of increasing moisture from 20 to 40% on mass loss characteristics (at 700 °C and 5% O_2 concentration)

3.2 Effects of Steam Injection on Mass Loss Characteristics

The presence of steam induced two positive effects, which include to reduce the time of achieving complete degradation and that the degradation time gap between two different moisture levels was also reduced. For instance, as a result of increasing moisture from 20 to 40% in presence of steam the achieved degradation level was 76.38% and 59.61% respectively (Figure 3). Compared to the no steam condition this is an improvement of 8.05 and 56.12% respectively. Furthermore, at 900 °C almost all materials were completely degraded after 170 seconds compared to 200 seconds of the no steam counterpart. It can therefore be inferred that the chief advantage of the presence of steam is from the fact that it supports gas phase reactions namely water-gas shift (Equation 1) and steam reforming of methane (Equation 2) which at higher temperature result in more CO and H_2 formation. These two reactions are endothermic and hence their progress is remarkable in higher temperature regime.

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (2)$$

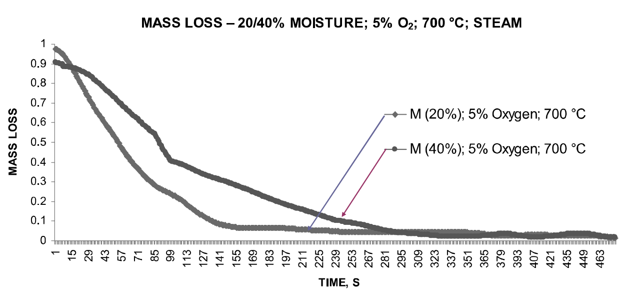


Figure 3: Effect of steam presence while increasing moisture from 20 to 40% on mass loss characteristics (at 700 °C and 5% O_2 concentration)

3.3 Syngas Evolution Characteristics, CO

Carbon monoxide evolution characteristics had the same feature as observed in the mass loss behaviour. At high temperature (900 °C) peak CO evolution was higher compared to what was observed at lower temperature counterparts (800 and 700 °C). As detailed in Table 2, peak CO at 900 °C was relatively the highest and that at 700 °C the lowest. This is an indication of temperature-induced gasification and thermocracking enhancement with regard to syngas evolution as reported by other researchers (Becidan *et al.,* 2007; Jeguirim and Trouvé, 2009).

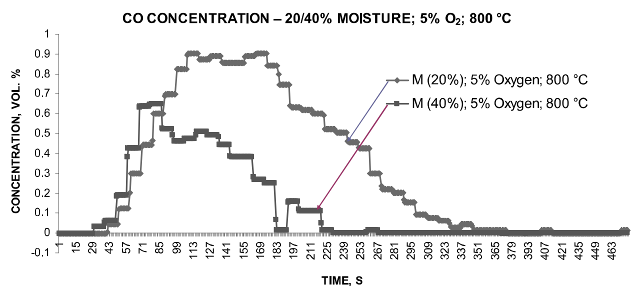
3.4 Effects of Steam Injection on CO Evolution

In all the experimental cases, the effect of steam was to enhance the CO evolution with respect to all moisture levels. On the average, the CO evolution was doubled as a result of steam addition to the 20% moisture materials. Furthermore, the difference in CO evolution to the different high-moisture materials was bridged due to the presence of steam. As can be seen in Figure 4, the absolute mean difference in CO evolution between the 20 and 40% moisture material is doubled (0.72 Vol. %) for the case of without steam compared to the steam case, which had an average absolute difference of 0.36 Vol. %.

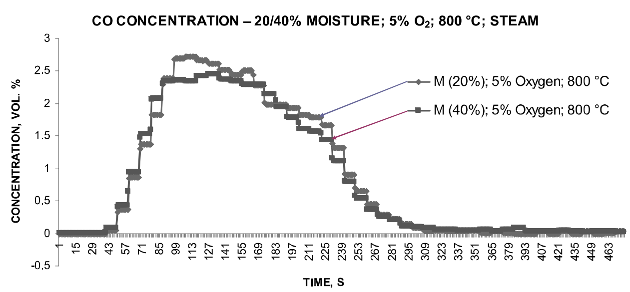
Table 2: Peak CO concentration at 10.1, 40, and 60% moisture and 4% oxygen concentration

Temperature	Moisture level and peak CO (Vol. %) at 4% O_2 concentration		
	10.1	40	60
900	5.63	2.33	1.79
800	4.10	2.01	2.03
700	3.25	0.96	0.99

The generalized characteristic behaviour of the CO evolution profile shown in Figure 4 is to increase to a maximum value after which it decreases. The increase is a result of the active progression of gasification and thermocracking where as the evolution will diminish while the material is continuously consumed.



(a) Without steam



(b) With steam

Figure 4: CO evolution at 800 °C (with and without steam) comparing 20 versus 40% moisture materials.

3.5 Syngas Heating Value

Sample Micro-GC profile showing the syngas composition (vol. %) as measured using the Varian Micro-GC model CP-4900 for 700 °C and 5% O_2 (steam injected) is shown in Figure 5. Syngas LHV was therefore estimated from the individual combustible components' heating value using the algorithm shown in Equation 3 (Kantarelis, 2009). The overall effect of the presence of moisture has shown to decrease the syngas heating value. Steam injection almost doubled the syngas heating value for the 40 and 60% moisture materials.

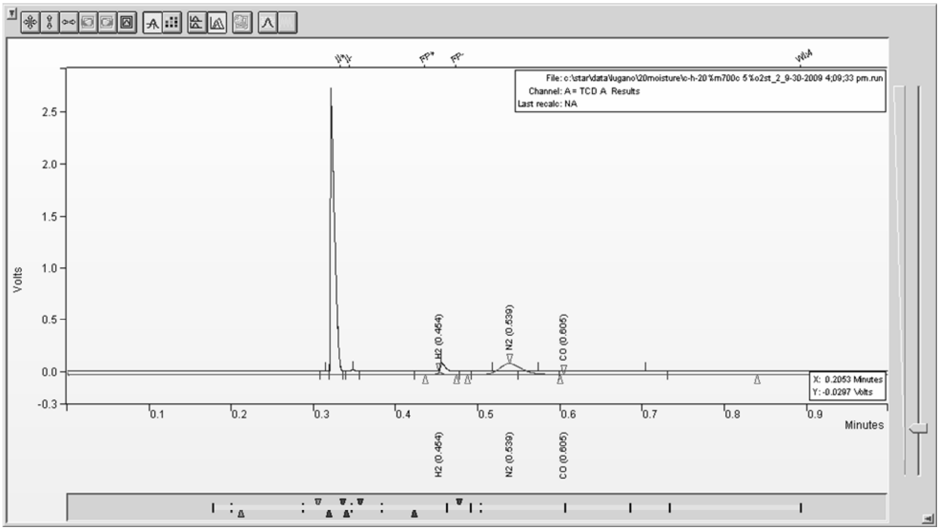


Figure 5: Micro-GC profile for 700 °C and 5% O_2 (steam injected)

$$LHV = \frac{(30 * CO + 25.7 * H_2 + 85.4 * CH_4 + 151.3 * C_m H_n) * 4.2}{1000} MJ / nm^3 \quad (3)$$

4.0 CONCLUSIONS

Following are the main conclusion of the study:

(i) Materials with high moisture content took more time to achieve a complete degradation. For instance, the effect of increasing material's moisture from 20 to 40% the respective degradation after 100 seconds was 70.69 and 38.18%. However, steam injection induced mass loss improvement by 8.05 and 56.12% respectively

(ii) The effect of steam was to enhance the CO evolution with respect to all moisture levels. On the average, CO evolution was doubled to the 20% moisture materials

(iii) The overall effect of increasing moisture has shown to decrease the syngas heating value. Steam injection almost doubled the syngas heating value for the 40 and 60% moisture materials

5.0 ACKNOWLEDGEMENTS

The financial support granted by the College of Engineering and Technology (CoET) of the University of Dar es Salaam (UDSM) is highly acknowledged for supporting this study.

6.0 REFERENCES

Becidan, M., Skreiberg, Ø. and Hustad, J. E. (2007), *Products distribution and gas release in pyrolysis of thermally thick biomass residues samples*, Journal of Analytical and Applied Pyrolysis, Vol. 78, pp. 207 – 213

Brammer, J. G. and Bridgwater, A.V. (1999), *Drying technologies for an integrated gasification bio-energy plant*, Renewable and Sustainable Energy Reviews, Vol. 3, pp. 243 – 289

Bridgwater, A. V. (1995), *The technical and economic feasibility of biomass gasification for power generation*, Fuel, Vol. 74, pp 631 – 653

Chen, G., Andries, J., Luo, Z., Spliethoff, H. (2003). *Biomass pyrolysis/gasification for product gas production; The overall investigation of parametric effects.* Energy Conversion and Management, Vol. 44, pp. 1875 – 1884

Elliott, D. C., Hallen, R. T. and Sealock, L. J. Jr. (1984), *Alkali catalysis in biomass gasifica-*

tion. Journal of Analytical and Applied Pyrolysis, Vol. 6, pp. 299 – 316

El-Fadel, M. and Bou-Zeid, E. (1999), *Transportation GHG emissions in developing countries: the case of lebanon*, Research Part D: Transport and Environment, Vol. 4, Issue 4, pp. 251 – 264

Faaij, A. Doorn, J. V., Curvers, T., Waldheim, L., Olsson, E., Wijk, A. V., and Ouwens, C. D. (1997): *Characteristics and availability of biomass waste and residues in the netherlands for gasification*, Biomass and Bioenergy, Vol. 12, issue 4, pp. 225 –240

Hanaoka, T., Inoue, S., Uno, S., Ogi, T., and Minowa, T. (2005), *Effect of woody biomass components on air-steam gasification,* Biomass and Bioenergy, Vol. 28, pp. 69 – 76

Hekkert, M. P., Hendriks, F. H. J. F., Faaij, A. P. C. and Neelis, M. L. (2005), *Natural gas as an alternative to crude oil in automotive fuel chains well-to-wheel analysis and transition strategy development*, Energy Policy, Vol. 33, pp. 579 – 594

Holmberg, H. and Ahtila, P. (2004), *Comparison of drying costs in biofuel drying between multi-stage and single-stage drying*, Biomass and Bioenergy, Vol. 26, issue 6, pp. 515 – 530

Hulteberg, P. C. and Karlsson, H. T. (2009), *A study of combined biomass gasification and electrolysis for hydrogen production, International Journal of Hydrogen Energy*, Vol. 34, pp. 772 – 782

Jeguirim, M. and Trouvé, G. (2009), *Pyrolysis characteristics and kinetics of arundo donax using thermogravimetric analysis,* Bioresource Technology, Vol. 100, pp. 4026 – 4031

Kantarelis, E. (2009), *Thermochemical treatment of electric and electronic waste for energy recovery*, a Licentiate Thesis in Furnace Technology, Stockholm, Royal Institute of Technology

Koroneos, C., Dompros, A. and Roumbas, G. (2008), *Hydrogen production via biomass gasification – A life cycle assessment approach*, Chemical Engineering and Processing, Vol. 47, pp. 1261 – 1268

Obernberger, I., Biedermann, F., Widmann, W. and Riedl, R. (1997), Concentrations of inorganic elements in biomass fuels and recovery in the different ash fractions, Biomass and Bioenergy, Vol. 12, pp. 211 – 224

Quadrelli, R. and Peterson, S. (2007), *The energy–climate challenge: Recent trends in CO2 emissions from fuel combustion*, Energy Policy, Vol. 35, pp (5938 – 5952)

Zhang, W. (2009), *Automotive fuels from biomass via gasification*, Fuel Processing Technology, doi:10.1016/j.fuproc.2009.07.010