Energy Proceedings
2022
ISSN 2004-2965

Theoretical and Experimental Study of Cocoa Pod Husk Gasification in a Fixed Bed Downdraft Gasifier

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ABSTRACT
Cocoa pod husk (CPH) has become a subject of research interest in Ghana because of its competitive energy density and abundance in rural communities. The composition of producer gas in a downdraft gasifier for CPH gasification is predicted using a thermodynamic equilibrium model presented in this research study. Experimental data from a 5kWe gasifier system burning cocoa pod husk was used to validate the thermodynamic model. Lower heating value (LHV), gas output, gasification efficiency, carbon conversion efficiency, engine conversion efficiency, and total biomass gasifier system efficiency were all measured. The carbon conversion efficiency was 75%, and the gasifier efficiency was 51%. Meanwhile, the gasifier system's overall efficiency was low. However, it can be increased by eliminating all sources of heat loss.

Keywords: gasification, cocoa pod husk, thermodynamic equilibrium model, downdraft gasifier

NOMENCLATURE

Symbols	
w	kmol of water per kmol of CPH
K	equilibrium constant
m	kmol of air per kmol of CPH
Vg	gas yield
Vgas	gas flow rate
m_{fuel}	mass consumption of CPH
Q_{fuel}	heat present in CPH
Q_{gas}	heat embodied in producer gas
W_{elec}	electrical power output
Y	individual gas volume fraction
η	efficiency
x,y,z	mole fraction

NOMENCLATURE

Abbreviations	
M	molecular weight
n	number of mole
ER	equivalence ratio
C	mass fraction of carbon
H	mass fraction of hydrogen
FC	fixed carbon
N	mass fraction of nitrogen
HHV	higher heating value
LHV	lower heating value
O	mass fraction of oxygen
S	mass fraction of sulphur
VM	volatile matter
CO	carbon monoxide
CO_2	carbon dioxide
H_2	hydrogen gas
N_2	nitrogen gas
CH_4	methane
PA	Proximate analysis
UA	Ultimate analysis

1. INTRODUCTION

Cocoa is considered one of the major strategic crops in Ghana due to its significant overall contribution to GDP. Currently, Ghana produces in excess of 850,000 tonnes of cocoa pod husk (CPH) annually, which is equivalent to 19% of total global production [1]. Although the utilization of CPH as a primary source of energy has not been exploited extensively, it is a subject of research and interest. According to World Bank collection of development indicators, Ghana has a rural population of 42.65% [2]. These rural populations are faced with either shortage or lack of electricity due to the many problems associated with extending electricity supply to remote

This is a paper for the 14th International Conference on Applied Energy - ICAE2022, Aug. 8-11, 2022, Bochum, Germany.

regions such as high cost of grid extension and transmission and distribution losses. CPH based decentralized power generation system could offer an attractive solution to the power crisis in rural Ghana.
Aside the use of CPH for power generation in rural communities, its application may be extended to cover the electricity needs of isolated industries, water pumping for irrigation, purification of drinking water, and other productive activities such as medical refrigeration. A previous study conducted by Nelson et al. [3] indicates that CPH has a higher heating value of 15.32–19.21 MJ/kg, which is relatively high in comparison with similar biomass resources. Considering the heating value and resource availability, it is essential that further tests be carried out in order to ascertain how the resource will perform during thermochemical conversion. A number of researchers, such as Zainal et al [4], Jarungthammachote and Dutta [5], and Barman et al [6], have developed mathematical models to predict the performance of biomass downdraft gasifiers. However, most of these models, apart from being generic, have relied on experimental data from the literature to validate their models.

In the present work, a thermodynamic equilibrium model has been developed to predict the composition of producer gas in a downdraft gasifier. Furthermore, an experimental study on a CPH-fed 5kWe downdraft gasifier was conducted and the data was used to validate the theoretical model. Thus, this study has moved beyond desktop-based research to actually test a downdraft gasifier that is fed with CPH. This work can therefore be used in countries with a large supply of CPH.

2. THERMODYNAMIC EQUILIBRIUM MODEL OF A DOWNDRAFT GASIFIER

2.1 Formulation of the model

A thermodynamic equilibrium approach based on equilibrium constants was used to model the biomass gasification process presented in this study. The equilibrium model was developed on the basis of the following main assumptions:

- CPH is considered to be made up of Carbon, Hydrogen, Oxygen and Nitrogen.
- Nitrogen is assumed to form inert gas.
- The gasification system is considered to be in steady state and isothermal conditions.
- All gases and their properties assume an ideal gas behaviour.
- The creation of char is thought to be impossible since all the carbon in the CPH is supposed to be gasified.
- H_2, CO, CO_2, CH_4 and N_2 make up the syngas.
- It is supposed that Tar undergoes complete conversion into permanent gases, hence it is not considered in the model.

Considering the chemical formula of CPH as CHxOyNz, CPH gasification reaction based on the above assumptions can be written as;

$$CHxOyNz + wH_2O + m(O_2 + 3.76N_2) \rightarrow n_{H_2}H_2 + n_{CO}CO + n_{CO_2}CO_2 + n_{H_2O}H_2O + n_{CH_4}CH_4 + (^{z}/_{2} + 3.76m)N_2 \quad (1)$$

Where n_{H_2}, n_{CO}, n_{CO_2}, n_{H_2O}, n_{CH_4}, and n_{N_2} are the number of moles of H_2, CO, CO_2, H_2O, CH_4, and N_2 respectively, m is the amount of air per kmol of CPH and w is the amount of water per kmol of CPH. All inputs on the left side of Eq. (1) are defined at 298 K (25 °C). On the right side, the number of moles of the individual product species (n_i) are unknowns. The amount of water per kmol of CPH can be calculated using the equation as follows;

$$w = \frac{M_{CPH} \times MC}{M_{H_2O} \times (1-MC)} \quad (2)$$

where M_{CPH} and M_{H_2O} are the masses of the CPH and water respectively, and MC is the moisture content.

Equivalence ratio (ER) can be expressed as:

$$ER = \frac{m}{1+\frac{x}{4}-\frac{y}{2}} \quad (3)$$

Subscripts x, y and z are numbers of atoms of hydrogen, oxygen, and nitrogen per one atom of carbon in the feedstock, respectively and are determined by the ultimate analysis of the CPH as follows;

$$x = \frac{HM_C}{CM_H} \quad (4)$$

$$y = \frac{OM_C}{CM_O} \quad (5)$$

$$z = \frac{NM_C}{CM_N} \quad (6)$$

M_C, M_H, M_O and M_N are the molecular weight of carbon, hydrogen, oxygen and nitrogen respectively and C, H, O and N are the mass fractions of those elements.
Based on the gasification reaction in Eq. (2), there are five unknown product species which can be calculated simultaneously using the mass balance relationships between carbon, hydrogen, and oxygen, and the

thermodynamic equilibrium constants of water gas shift reaction and methane reaction given as follows;

Carbon balance,

$$n_{CO} + n_{CO_2} + n_{CH_4} - 1 = 0 \quad (7)$$

Hydrogen balance,

$$2n_{H_2} + 2n_{H_2O} + 4n_{CH_4} - x - 2w = 0 \quad (8)$$

Oxygen balance,

$$n_{CO} + 2n_{CO_2} + n_{H_2O} - w - 2m - y = 0 \quad (9)$$

During gasification, a number of chemical reactions take place. Water gas shift reaction and methane reaction are two of such key reactions.

Water gas reaction

$$C + H_2O \rightarrow CO + H_2 \quad (10)$$

Methane reaction,

$$C + 2H_2 \rightarrow CH_4 \quad (11)$$

Assuming the equilibrium constant for the water gas shift reaction is K_1,

$$K_1 = \frac{n_{CO_2} \times n_{H_2}}{n_{CO} \times n_{H_2O}} \quad (12)$$

Using K_2 as the equilibrium constant for the methane reaction,

$$K_2 = \frac{n_{CH_4} \times n_{total}}{(n_{H_2})^2} \quad (13)$$

Where n is the number of moles of the individual components in the product gas. The equilibrium constants K_1 and K_2 are dependent on temperature and can be calculated using equation 14 and 15 respectively.

$$K_1 = exp\{\left(\frac{4276}{T}\right) - 3.961\} \quad (14)$$

$$K_2 = exp(\frac{7082.848}{T} - 6.567 \, In \, T + \frac{7.466 \times 10^{-3}}{2} T - \frac{2.164 \times 10^{-6}}{6} T^2 + \frac{0.701 \times 10^{-5}}{2T^2} + 32.541) \quad (15)$$

The composition of the product gas (n_{H_2}, n_{CO}, n_{CO_2}, n_{H_2O}, and n_{CH_4}) were obtained by solving Eqs. 7, 8, 9, 12, and 13 simultaneously in MATLAB using Newton-Raphson method.

3. EXPERIMENTAL PERFORMANCE EVALUATION OF A 5kWe DOWNDRAFT GASIFIER

3.1 Experimental setup

The experimental set up consist of a blow-type downdraft gasifier, a feeding system, a start-up system, an air supply system, gas cleaning and cooling system, a resistive load, three-phase power generator, PID controller, and a gas analyzer.

The gasifier is a cylindrical reactor with an internal diameter of 460 mm and a total height of 900 mm. It is built of carbon steel with an internal coating of refractory material, surrounded by an insulating blanket for safety and also to control heat loss. Biomass is fed into the gasifier through the hopper at the top of the reactor. An ignition pot and a blower sit at the upper part of the reactor. The blower supplies air to the reactor via the ignition pot and an air valve. An agitator is mounted at the top of the gasifier to avoid bed bridging during gasifier operation. The agitator produces mild vibrations at intermittent intervals which ensures continuous downward flow of feedstock into the reactor. The intermittent vibrations also help to remove the ash deposits produced during gasification. At the bottom of the gasifier is a perforated cast iron rotating grate to continuously dispose of ash from the gasifier bed. Six K-type thermocouples are used to measure the temperature distribution inside the gasifier. The generator is subjected to an electrical load, and the engine's power output is measured. A power metre on the control panel was used to measure electrical factors such as voltage, current, and frequency. To measure CO, CO_2, CH_4, and H_2, a gas sample point is placed at the gas entry point and linked to a wall-mounted gas analyzer. The gas engine generator is a two-cylinder, four-stroke gas engine that is naturally aspirated and water cooled. At 1500rpm/50Hz, the A.C. alternator generates a single-phase 415V.

3.2 Test procedure

The gasifier was fired up from the ignition pot and the blower was turned on to supply air into the gasifier from the central air distribution nozzle and bustle pipes. A flammable gas was generated after about 15 minutes, which was directed through a number of filters to remove particulates and tar that were capable of damaging the gas engine. Following filtration, the producer gas was fed into the gas engine and burnt.

3.3 Test calculation

To assess the performance of the CPH gasifier, important performance indicators such as calorific value, cold gas efficiency, carbon conversion efficiency, electrical power, engine efficiency, and overall efficiency were calculated using the equations presented below. The higher heating value (HHV) was determined from the composition of the CPH using the results of the PA and UA as given in equations 16 and 17, respectively.

For PA;

$$HHV = 0.3536FC + 0.1559VM - 0.0078ASH \quad (16)$$

Where FC is the fixed carbon and VM is the volatile matter

For UA;

$$HHV = 0.3491C + 1.1783H + 0.105S - 0.1034O - 0.0151N - 0.0211ASH \quad (17)$$

Where C, H, S, O, and N are Carbon, Hydrogen, Sulphur, Oxygen, and Nitrogen respectively.

The energy available in the CPH (Qfuel) is expressed in equation 18;

$$Q_{fuel} = m_{fuel} * HHV \quad (18)$$

Where m_{fuel} is the mass consumption rate of CPH

The energy available in the combustible gas (Q_{cg}) is calculated from equation 19.

$$Q_{cg} = V_{gas} * (Y_{CO} * LHV_{CO} + Y_{CH_4} * LHV_{CH_4} + Y_{H_2} * LHV_{H_2}) \quad (19)$$

Where V_{gas} is the gas flow rate, Y is the volumetric concentration of the individual gases and LHV is the lower heating value. The values for HHV, LHV_{CO}, LHV_{CH4} and LHV_{H2} used in equations 18 and 19, were taken as 17MJ/kg, 11.6MJ/Nm^3, 32.8MJ/Nm^3 and 9.9MJ/Nm^3, respectively.

Cold gas efficiency (CGE) is defined as;

$$CGE = Q_{cg}/Q_{fuel} \quad (20)$$

The engine conversion efficiency (η_{conv}) is calculated from equation 21.

$$\eta_{conv} = W_{elec}/Q_{cg} \quad (21)$$

Where Welec is electrical power which can be calculated using equation 22

$$W_{elec} = I * V * sqrt(3) \quad (22)$$

I is current and V is voltage

The overall efficiency of the biomass gasifier system (η_{ov}) is given as

$$\eta_{ov} = W_{elec}/Q_{fuel} \quad (23)$$

The lower heating value (LHV) of the producer gas in MJ/m^3 can be estimated from the gas composition as follow;

$$LHV = [(10.79 * H_2) + (12.636 * CO) + (35.82 * CH_4)] \quad (24)$$

Where H_2, CO, and CH_4 are the volumetric concentrations of the components in the producer gas.

Carbon conversion efficiency (CCE) can be calculated as follow;

$$CCE = \frac{12*(CO+CO_2+CH_4)}{22.4*C} * V_g * 100\% \quad (25)$$

Where C is the mass fraction of carbon in the biomass, from the ultimate analysis and Vg is the volume of the producer gas per unit weight of CPH (m^3/kg).
Vg which is also the gas yield (m^3/kg) can be calculated using the gas flow rate (Vgas) and the mass consumption as follow;

$$Vg = {V_{gas}}/{m_{fuel}} \quad (26)$$

4. RESULTS AND DISCUSSION

4.1 Material characterization of CPH

In a previous study [3], CPH from all the cocoa growing regions in Ghana were characterized. In the present paper, we used data from the past research obtained via ultimate and proximate analysis together with performance data from the experimental study of the 5KWe biomass gasifier to validate our model.

4.2 Validation of the theoretical model

The developed thermodynamic equilibrium model was validated by comparing its results with the experimental data of a 5kWe downdraft biomass gasifier fed with CPH. A fixed temperature setting of 1100K and ER of 0.3 were used in line with the experimental results reported by both Jarungthammachote and Dutta [5] and Jayah et al [7]. Fig. 1 compares the results of the developed model with the experimental data of the 5kWe downdraft biomass gasifier.

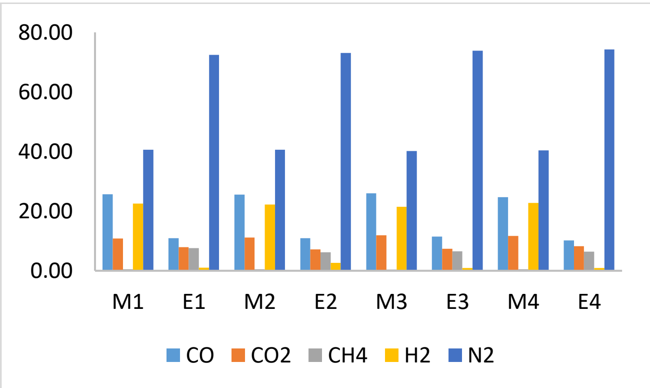

Fig. 1 Comparison of developed model with experimental results

The comparison demonstrates a model pattern in which hydrogen and carbon monoxide are overestimated while methane is underestimated. This is typical in thermodynamic equilibrium models due to the assumptions established to simplify the model, such as all gases being considered to be ideal, no residue formation, no tar, and so on. Higher quantities of hydrogen and smaller volumes of methane were anticipated by the equilibrium models evaluated in literature, such as [8], [9] and [10], than the obtained data from tests. In the case of methane, the developed model projected a low concentration, as expected. This is due to the equilibrium constant of the methane reaction tending to be zero at high temperatures for all equilibrium models. Furthermore, in an actual gasifier, devolatilization of fuel produces large volumes of methane and higher hydrocarbons that do not undergo complete interaction with the equilibrium concentrations of carbon monoxide, carbon dioxide, and hydrogen gas. As a result, in an experimental scenario, equilibrium is never attained, resulting in a significant level of methane detection [11].

4.3 Modification of the model

Assumptions are used to create thermodynamic models. One of these assumptions is that the gasification system is in thermodynamic equilibrium, so non-equilibrium phenomena are not taken into account in the model. Because equilibrium is never attained in real-world situations, there is a discrepancy in findings between the created model and the experimental data. It was therefore important to make some basic changes to the theoretical model in order to improve its veracity. A correction factor (A) was introduced to the equilibrium constant equations in order to overcome the limitations of the present model and increase the accuracy of the predicted results. A coefficient of 90 was multiplied with the equilibrium constant (K_2) of the methanation reaction whiles the equilibrium constant of the water gas shift reaction (K_1) was multiplied by a coefficient of 0.43. The coefficient of K_1 was obtained by finding the average value of the ratio of CO from the experimental data to CO calculated from the developed model. The coefficient of K_2 was initially considered as 30 and then it was gradually increased by a factor of 10. Fig. 2 shows how the modified model compares with experimental results of the 5kWe CPH downdraft gasifier. As shown in Fig. 2, altering the model leads to improved agreement between the model's forecast and the experimental data. Hydrogen has been drastically reduced, but methane has increased greatly as a result of the adjustment to demonstrate a better contrast to the experimental data.

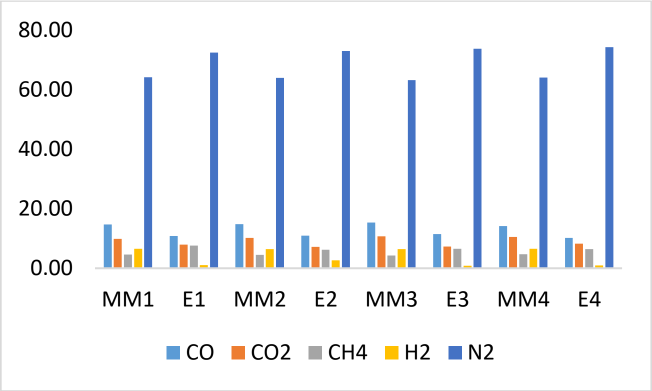

Fig. 2 Comparison of modified model with experimental results

4.4 Experimental analysis of CPH gasification system

The results of this CPH gasification study in a 5kWe gasifier-generator setup are presented in Figs. 3 and 4. Since the generator set is rated at 5kWe, it is fully operational at a continuous maximum load of 4kWe. A 4kWe variable resistive load was therefore applied to the generator and the power output measured. The energy output of the gasifier, the consumption rate of the feed, the mass conversion efficiency of the feedstock from raw biomass to producer gas, the conversion efficiency from producer gas to electricity, and the combined efficiency of the gasifier system, which encompasses both the efficiency of the gasifier and the efficiency of the engine, are all presented in Figs 3 and 4. The gasification test was run at four different loads. At an electrical load of 1 kWe, the gasifier system consumed CPH at a rate of 11.16 kg/h to produce combustible gas with a power potential of 26.95 kW from an energy input of 52.71 kW, which is equivalent to about 51% conversion efficiency (see Fig. 3). 2.4% of the produced gas was converted to electricity, giving an overall efficiency of 1.2% for the CPH gasifier system. The performance indicators after running the system at the other electrical loads are all shown in Figs. 3 and 4.

The average efficiency of the gasifier was 44.52%, with a maximum of 51.13% at peak performance. The average engine efficiency was 5.99% with a maximum of 8.21% and the average overall efficiency was 2.55% with a maximum of 3.59%.

The overall efficiency of the gasifier-generator system was low due to heat losses and also the high moisture content of the feedstock. To improve the overall efficiency of the system, the gasifier must be well insulated to cut off all sources of heat loss. The moisture content of feedstock must also be reduced.

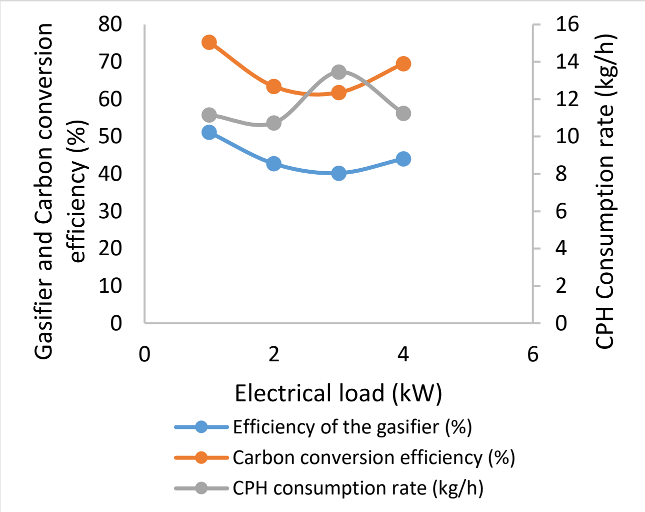

Fig. 3 Variation in gasifier and carbon conversion efficiency with consumption rate

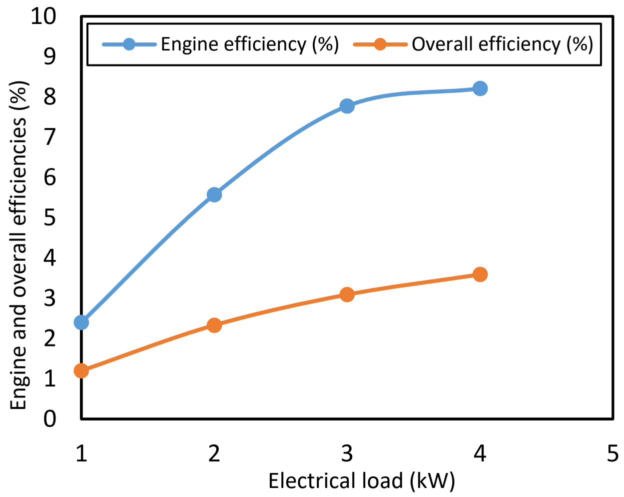

Fig. 4 Variation in engine and overall efficiency

The calorific value, gas yield, and cold gas efficiency of the present study was compared with literature values in Fig. 1. In Dogru et al.'s [12] gasification experiment on hazelnut shells, an optimum calorific value of approximately 5 MJ/m^3 and a gas yield of 2.22 Nm^3/kg were obtained at a gas flow rate of 8-9 Nm^3/h and a biomass consumption rate of 4.06–4.48 kg/h. Zainal et al. [13] carried out an experimental investigation of a downdraft biomass gasifier using furniture wood and wood chips. In their study, they realised an optimum calorific value of 5.34 MJ/m^3 at a biomass consumption rate of 2 kg/h.

Sheth and Babu [14] also investigated the performance of a downdraft biomass gasifier using rose wood and obtained an optimal calorific value of 6.34 MJ/Nm^3, a gas yield of 1.62 Nm^3/kg and a cold gas efficiency of 56.87% at a biomass consumption rate of 1.00-3.63 kg/h. Whilst the cold gas efficiency and calorific value of the present study appear low compared to other studies in Fig. 1, the gas yield in the present study was the highest among the lot.

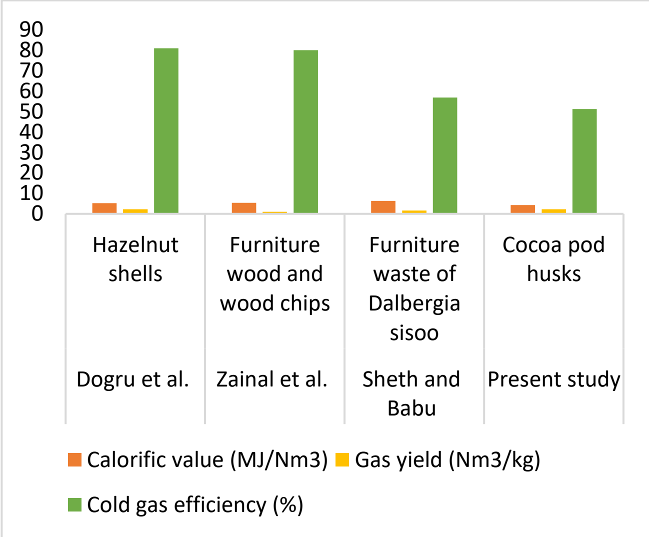

Fig. 5 Comparison of experimental results with published literature

5. CONCLUSION

A thermodynamic equilibrium model for fixed bed biomass downdraft gasifiers was developed and used to predict the composition of producer gas in a CPH gasification. There was a fairly good correlation between the results of the model and those of the experiment. The study has demonstrated that the gasification of CPH is a promising option for the generation of producer gas. At peak performance, the efficiency of the gasifier was approximately 51% and the carbon conversion efficiency was 75%. The efficiency of the gas engine was 6% and the overall efficiency of the CPH gasifier system was 2.6%. Both the gas engine and overall efficiencies were better with a higher electrical load. Although the overall efficiency of the gasifier system was low, it can be improved by isolating all sources of heat loss and reducing the moisture content of the feedstock.

ACKNOWLEDGEMENT

This project was supported by the University of Nottingham under GCRF (Grant No. H54500).

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