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PROCESS AND EQUIPMENT MODELLING AND DESIGN OF A COFFEE HUSKS GASIFIER FOR DRYING OPERATION

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ABSTRACT

This study was conducted to test the viability of coffee husks as a potential feedstock in a gasifier-dryer system. The projection of the total amount of waste produced is necessary in determining the input for the process modelling, together with the proximate and ultimate analyses that were conducted thru standard testing. In the tests, the proximate analysis gave 12.30% moisture content, 64% volatile matter, 23.30% fixed carbon and 12.70% ash content. On the other hand, the ultimate analysis gave 38.50% carbon, 5.89% hydrogen and 42.91% oxygen. No traces of nitrogen and sulfur were found. Aspen Plus Version 11, a package that can be used for modelling reactors for biomass gasification was used to produce a model and determine the producer gas composition. To dry 2 tons of coffee fruits in a gasifier-dryer system, it requires 50 kg/hr of the biomass feedstock. By feeding 50 kg/hr of coffee husks and 0.578 kg/hr of air in the model, it produced simulation results of 925.85 °C gasification temperature in the reactor to gasify the coffee husks and air mixture to produce the producer gas composed of 84.2851 carbon monoxide (CO), 4.7104 carbon dioxide (CO2), 0.1063 methane (CH4), 6.9086 hydrogen (H2), 1.0164 nitrogen (N), and 2.9726 water (H2O) in mass percentages. Finally, the energy efficiency of the gasifier with respect to temperature and air to biomass ratio was computed. All the inputs are based on the actual elemental analysis of coffee husks feedstock. A valid point at 704 °C was established, indicating the realistic limit of the gasifier based on the simulations. The trend of the results was found to be consistent with the experimentally validated analysis of other biomass feedstocks in published investigations. The model developed in this study is intended to be validated through experimental verification in our future studies, and the results of the modelling and validation will be used in prototyping the specific gasifier.

Keywords: Waste to energy, gasifier-dryer system, proximate and ultimate analysis, producer gas

NONMENCLATURE

Abbreviations	
DOST-ITDI	Department of Science and Technology – Industrial Technology Development Institute
ER	Equivalence Ratio
HHV	Higher heating value
Eff	Efficiency

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RKS-BM	Redlich Kwong Soave cubic equation of state with Boston-Mathias alpha function
Symbols	
M	Gasifying medium
C	Carbon
H	Hydrogen
O	Oxygen
N	Nitrogen
S	Sulfur
CO2	Carbon Dioxide
CH4	Methane
H2	Hydrogen
H2O	Water
Subscripts	
da	Dry air
fa	Fuel air requirement
th	Theoretical air requirement
f	Fuel
cg	Combustible gases
db	Dry basis

1. INTRODUCTION

The problem on the sustainability of energy supply becomes a trend of issues in the world. The Philippines is considered as one of the countries that depend on fossil fuel for energy production. Since fossil fuel is a non-renewable resource and by any chance of continuous utilization, it might be out of supply. By ensuring the energy security, promotions of using renewable resources for energy production are considered. Biomass is one of the types of renewable resources that can be a substitute for fossil fuel [1]. They have the potential to be subjected to different energy conversion technology for energy production. One of these conversion technologies where biomass can be a potential input is thermochemical conversion, particularly gasification. Gasification is a process of converting feedstock into producer gas with a limited amount of oxygen. Producer gas can be generated from different types of biomass [2].

Biomass gasification is a promising conversion process to produce syngas. Agriculture is one of the major sources of biomass that could be a potential feedstock for gasification. The highest contributor to Philippine agriculture is crop production accounting for about 52.71 percent of the total agricultural output [3]. This largest percentage of land use in the country serves as an allusion for a large source of waste biomass.

Coffee husks are kind of these waste biomass materials. It is a type of agricultural residue that is available in the Philippines, being part of the coffee belt where coffee is mostly produced to grow and develop. As coffee beans are being processed to produce final products, coffee husks will exist. These residues can be a source of fuel for power generation via gasification technology. In this study, coffee husks were used as feedstock in a gasifier-drier system for drying operations. A design model for process and equipment aspects of the gasifier from the chemical analysis of the coffee husks was developed.

2. MATERIALS AND METHOD

2.1 Biomass feedstock characterization

The raw materials used in this study were coffee husks locally produced from coffee processing in Amadeo, Cavite, Philippines. Coffee husks generated were hypothetically characterized based on the total production of coffee from all the barangays in Amadeo. The study conducted by Bressani [4] states that 28.7 percent of the coffee cherry is the husks, this was used to project the total number of generated coffee husks from the total production.

2.2 Chemical analysis

One kg of coffee husks sample from Amadeo, Cavite was tested and analyzed at the Department of Science and Technology – Industrial Technology and Development Institute (DOST-ITDI) thru standard testing.

2.3 Process design modelling

Modelling and simulation of gasification processes were made with the use of the Aspen Plus V11 Simulator. Due to the complexity of the processes present in the gasification, it will be helpful to model and analyze the results using a software [5]. As a cost-effective and time-saving method for modelling reactors in biomass gasification, the simulator utilizes the estimation calculation of physical, chemical and biological processes inside a gasifier [5]. This software determines the producer gas composition including CO2, H2, CH4 and CO. The values obtained for proximate analysis, ultimate analysis and producer gas composition were compared to the existing literature values of coffee husks.

3. RESULTS AND DISCUSSION

3.1 Philippine coffee production

Coffee in the Philippines was first introduced in Lipa, Batangas in 1740 by a Spanish Franciscan monk; coffee farms have spread to other parts of Batangas like Ibaan, Lemery, San Jose, Taal, and Tanuan. During the 1880s, the Philippines became the fourth largest coffee-producing nation. However, in the 1880s to 1890s, the Philippine has experienced a decline in production due to insect infestation, called coffee rust. The coffee seedlings that survived in the coffee rust were transferred to Cavite from Batangas, as some of Batangas coffee farmers shifted into growing other crops. The top provinces that produced coffee are shown in figure 1.

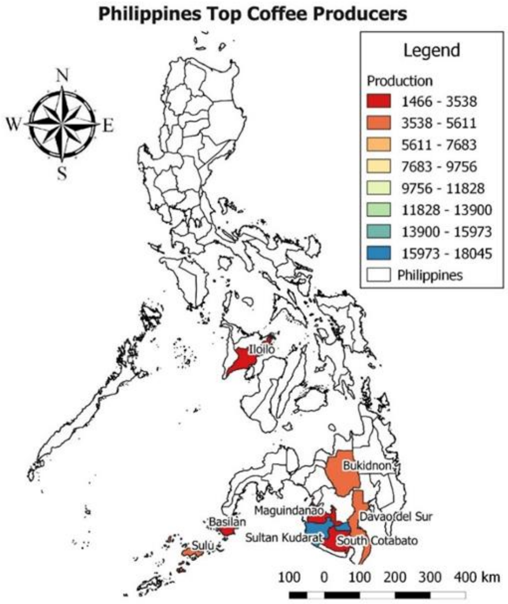

Figure 1 Top Coffee Producers in the Philippines.

The coffee industry faces multiple challenges such as high cost of labor, high cost of seedlings and fertilizer, lack of processing facilities and equipment, and poor trading practices leading to the continuous decline of coffee production from 2014 to 2018 as seen in figure 2. It can be seen that out of the hundred thousands of area planted and harvested, approximately seventy-five thousand survived and developed.

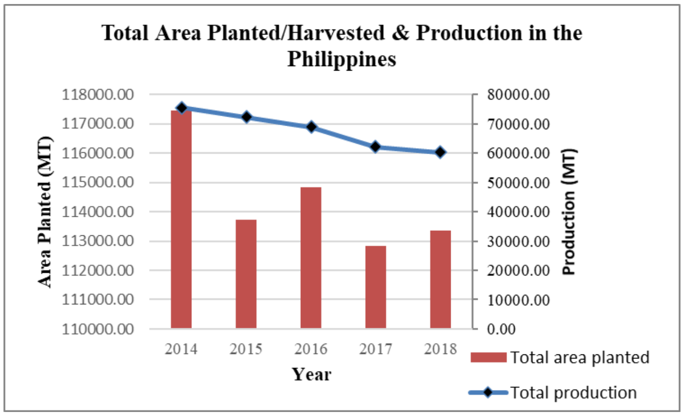

Figure 2 Philippine coffee production.

With these multiple challenges faced by the Philippine coffee industry, efforts have been made to revive and revitalize the coffee production in the country. The Philippine Coffee Industry Roadmap 2017-2022 has been implemented effective March 17, 2017, which aims to boost the country’s domestic coffee output from 37,000 metric tons to 215,000 metric tons by 2022. The increase is projected to raise the country’s self-sufficiency level from the present 41.6 percent to 161 percent.

3.2 Coffee husks characterization

With the use of the total production, the total number of coffee husks generated were projected. It was stated that 28.7% percent of the coffee cherry is the coffee husks [4]. These 25 barangays (local geographic and political divisions of a municipality) of Amadeo contribute to the total generation of 928.84 metric tons of coffee husks from the total production of 3,236.38 metric tons of coffee cherries. Based on the projected total number of coffee husks generated, the feed can have a corresponding maximum biomass flow rate of 106 kg/hr.

3.3 Chemical characteristics of coffee husks from Amadeo, Cavite, Philippines

Table 1 shows the result of the proximate and ultimate analyses of coffee husks from Amadeo, Cavite, Philippines. The tests were conducted and analyzed at the Department of Science and Technology-Industrial Technology Development Institute (DOST-ITDI) of the Philippine government.

Table 1. Chemical characteristics of coffee husks from Amadeo, Cavite, Philippines

Analysis Method	Coffee Husks
Proximate Analysis	
Moisture Content	12.30
Volatile Matter	64.00
Fixed Carbon	23.30
Ash Content	12.70
Ultimate Analysis	
Carbon (C)	38.70
Hydrogen (H)	5.89
Oxygen (O)	42.91
Nitrogen (N)	0.00
Sulfur (S)	0.00
Heating Value (MJ/kg)	15.35

3.4 Process model development

Basic assumptions:

1. The model is on steady-state, kinetic free and adiabatic.
2. No pressure loss in the system. Operation at atmospheric pressure (~ 1 bar).
3. Chemical reactions take place at an equilibrium state in the gasifier.
4. The volatile products of biomass are mainly comprised of H2, CO, CO2, CH4, and H2O.
5. All gases are ideal gases, including H2, CO, CO2, steam (H2O), N2 and CH4.
6. Neglecting the particle size distribution of coffee husk into the gasifier.

The coffee husks gasifier was modeled using Aspen Plus V11, a process modelling software suitable to use for fuels like biomass while the only input needed for the modelling process is the elemental composition. Modelling started with specifying the components.

After setting up the specified components used in the simulation, the physical property method was selected. This simulation process used the Redlich Kwong Soave cubic equation of state with Boston-Mathias alpha function (RKS-BM) to estimate all physical properties of the conventional components in the gasification process. It is common and recommended for use in gas processing, refinery, and petrochemical applications. Biomass and ash are defined as non-conventional components. Only the enthalpy and density can be calculated for non-conventional components with the model HCOALGEN and DCOALIGT. These models require the proximate and ultimate analyses of the biomass feedstock. The ash content is set to 100%.

Four sequential unit operation blocks were used to develop the model. Ryield with a block name "DECOMP" was used to decompose non-conventional biomass components to conventional components according to its proximate and ultimate analyses. It represents the process of pyrolysis in an actual gasification process. After decomposing non-conventional biomass to conventional biomass, the decomposed biomass is mixed with the gasification medium (air) with the aid of a mixer. The mixture of biomass and air was gasified using RGibss reactor to produce syngas. Lastly, the gas and ash components are separated using Ssplit. The coffee husks gasifier model is shown in figure 3.

3.4.1 Equivalence ratio and stoichiometric air requirement

The equivalence ratio for gasification must not be greater than 1. It is believed that at ER greater than 1, feedstocks are combusted rather than gasified according to Basu [6]. In this study, the equivalence ratio used is 0.25 since it is the ideal basis or first guess in a gasifier design process [6].

The stoichiometric air based in the traces of C, H, O, and S of coffee husks is 0.0462 kg per kg of dry fuel. It was computed using the formula:

$$M_{da} = 0.1153C + 0.3434\,(H - O/8) + 0.0434S \qquad (1)$$

3.4.2 Gasifying medium

Air was the chosen gasifying medium for this study since it is the most widely used gasifying medium and requires less capital cost compared to steam and oxygen [6]. The air requirement was computed using the formula:

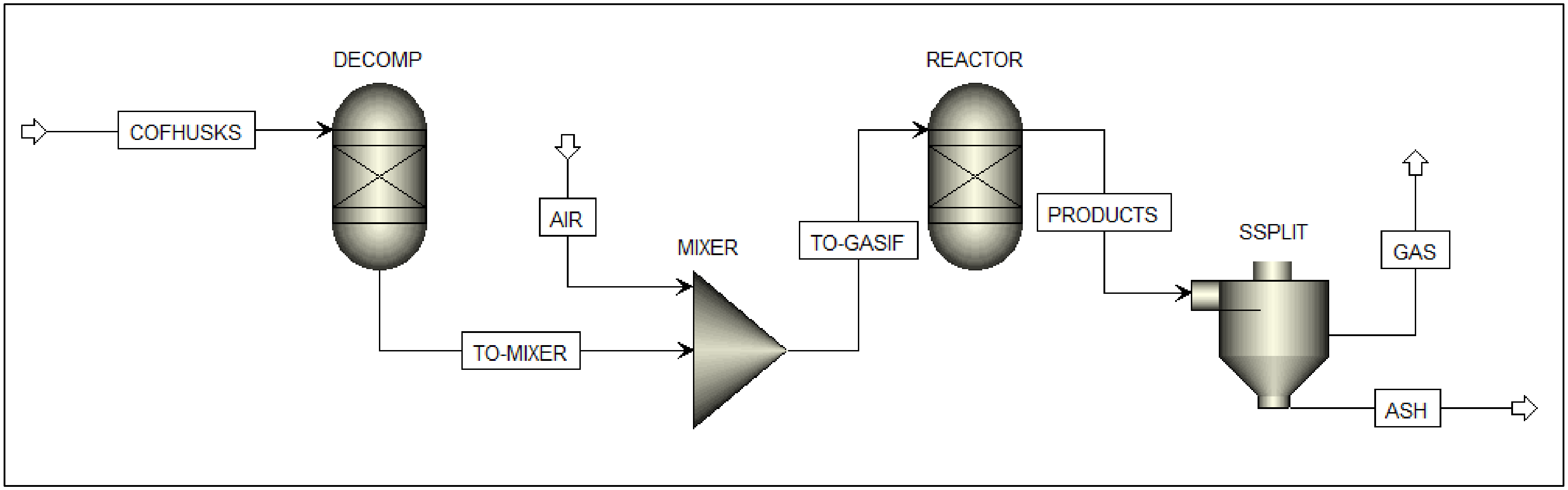

Figure 3 Coffee husks gasifier model.

$$Mfa = Mth * ER * Mf \qquad (2)$$

Based on the computation, the airflow rate needed for coffee husks gasification was 0.578 kg/hr.

3.4.3 Higher Heating Value (dry basis)

The higher heating value of the coffee husks feedstock was provided by the results of the analysis made by the DOST-ITDI, however, this study used the computed higher heating value in dry basis so that the result will be congruent with the higher heating value of the combustible gases of the producer gas. It will provide a meaningful comparison with the theoretical results of the heat from producer gas. The higher heating value in dry basis was computed using the formula [6]:

$$HHV_{db} = 0.3491\,C + 1.1783\,H + 0.1005\,S - 0.0151\,N - 0.1034\,O - 0.0211\,ASH \qquad (3)$$

3.4.4 Gasifier Energy Efficiency

The gasifier energy efficiency was computed using the formula:

$$\text{Eff} = \frac{HHV_{cg}}{HHV_{db}}\, x\, \frac{Producer\ gas\ flowrate}{Biomass\ flowrate}\, x \sum CO, CH4\ and\ H2 \qquad (4)$$

3.5 Baseline simulation results

By feeding 50 kg/hr of coffee husks in the DECOMP, it was decomposed into conventional components. Air as gasifying medium with a flow rate of 0.578 kg/hr was mixed with the conventional components ready to be gasified. The model predicted a 925.85 °C gasification temperature in the reactor to gasify the coffee husks and air mixture to produce the gas composed of 84.2851 carbon monoxide, 4.7104 carbon dioxide, 0.1063 methane, 6.9086 hydrogen, 1.0164 nitrogen, and 2.9726 water. Figure 4 shows the schematic diagram of the gasification process.

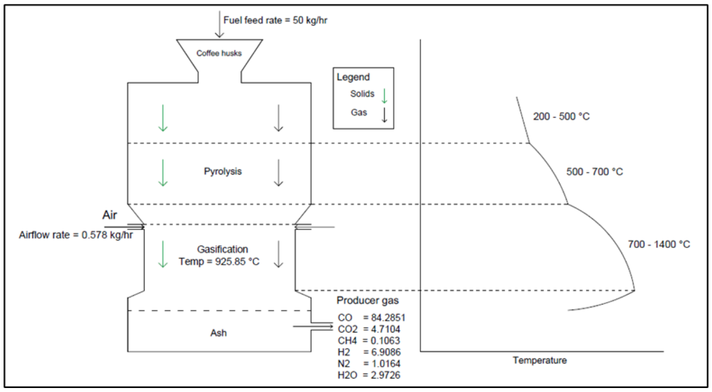

Figure 4 Schematic diagram of the gasification.

The summarized results of the simulation using Aspen Plus V11 are presented in Table 2. These results were used as baseline parameters for sensitivity analysis and validation.

Table 2. Simulation results

Producer Gas Composition	
CO	84.2851
CO2	4.7104
CH4	0.1063
H2	6.9086
N2	1.0164
H20	2.9726
Mass balance	
Product gas volume flow rate (cum/hr)	302.267
Product gas flow rate (kg/hr)	44.902
Fuel feed rate (kg/hr)	50
Airflow rate (kg/hr)	0.578
Equivalence Ratio	0.25
Energy balance	
Gasification temperature	925.85 °C

3.6 Sensitivity analysis and validation of results

Additional simulation run was conducted to determine the effects of airflow rate, temperature and pressure on the producer gas composition. This was intended to perform a sensitivity analysis relative to varying parameters and validate the results of the model based on realistic operation of a downdraft gasifier.

3.6.1 Airflow rate

Gasification is a thermochemical conversion process with a limited amount of gasification agent (air, oxygen, and steam). In this study, air was used as the gasifying agent. The airflow rate was varied from 0 to 100 kg/hr. The effect of the airflow-rate to producer gas production is shown in figure 5. As the airflow rate increases, the amount of CO2 and N2 in the producer gas also increase while H2, CO, and CH4 decrease.

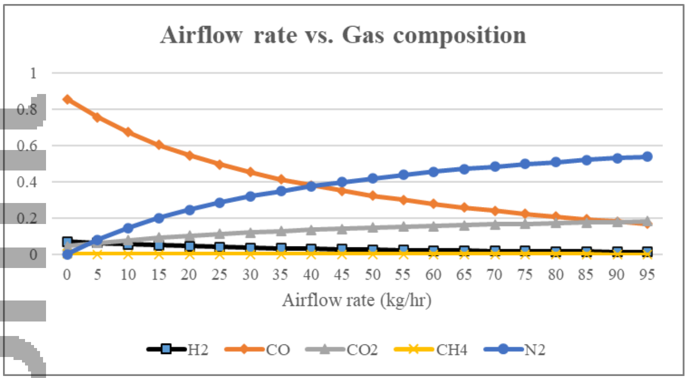

Figure 5 Effect of airflow rate on producer gas composition.

3.6.2 Temperature

The temperature was varied from 400 °C to 1400 °C and all of the other parameters remain constant. Based on the results shown in figure 6, both compositions of CO and H2 increase as temperature increases, while on the other hand, compositions of CO2 and CH4 decrease. It is also observed that after reaching 800 °C, the production of the producer gas composition gradually increases until it remains constant. A critical region was observed between 400 °C and 925.85 °C (gasifier temperature based on the model), where the behaviors of the gas compositions seem to occur.

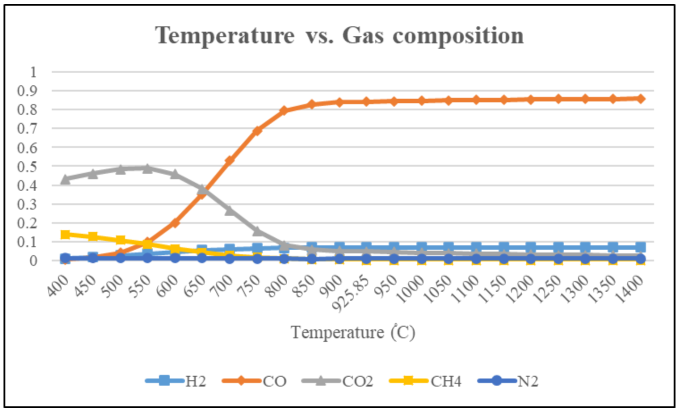

Figure 6 Effect of temperature on producer gas composition.

3.6.3 Gasifier pressure

The effect of the gasifier pressure on producer gas production is shown in figure 7. Pressure variation was set from 1 to 10 bar. Compositions of CH4 and CO2 are directly proportional to the gasification pressure, while those of CO and H2 are inversely proportional. N2 compositions is observed to be nearly constant as pressure increases.

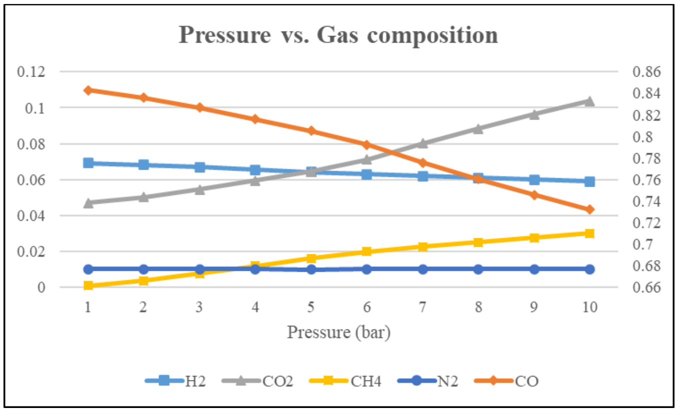

Figure 7 Effect of pressure on producer gas composition.

3.6.4 Behavior of gas composition in the critical region

Based on the results of the effect of the temperature on the gas composition varied from 400 °C to 1400 °C, a critical region which range from 400 °C to 925.85 °C was observed. Another simulation run was carried on to determine and analyze the behavior of gas composition in the mentioned critical temperature range. The results of the simulation are shown in figure 8. The trends of the compositions of combustible gases (CO, CH4 and H2) gradually move whether increasing or decreasing from 815 °C to 925.85 °C (the predicted gasifier temperature from the model). It shows that the gasifier can perform its best even at temperatures lower than 925.85 °C.

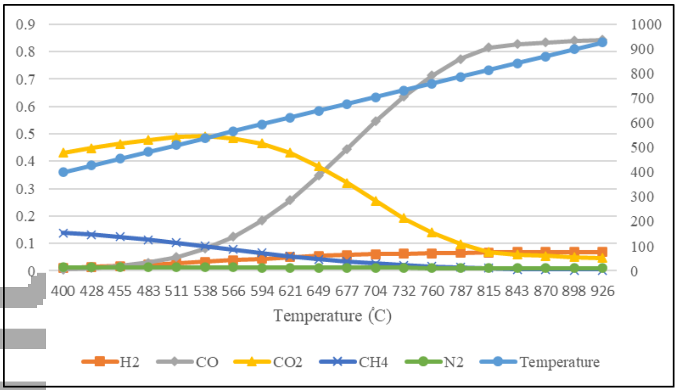

Figure 8 Gas composition in the critical region.

3.6.5 Gasifier energy efficiency

The percentage energy value of the producer gas over feedstock with respect to temperature and air to biomass ratio was determined in this study. The gasifier energy efficiency was computed by multiplying the ratio of the higher heating value of combustible gases (CO, CH_4 and H_2) on the producer gas and the computed higher heating value (dry basis) based on the ultimate analysis (eq. 3), the ratio of producer gas flowrate and biomass flowrate and the summation of the components of combustible gases (CO, CH_4 and H_2) (eq. 4). All the inputs to come up with the gasifier energy efficiency are based on the actual elemental analysis of the coffee husks feedstock. The actual higher heating value from the analysis of DOST-ITDI was not used in getting the energy efficiency because it requires to have the actual higher heating value of the combustible gases of the producer gas. Refprop 9.1 [7] was used to obtain the values of HHVs of the combustible substances for the computation of effective HHV of the producer gas. The parameters for theoretical computation of HHV of C, H and O as input and HHV of the combustible gases in the producer gas (CO, CH_4 and H_2) are shown in table 3. The comparison of the actual heating value of the feedstock and the producer gas was beyond the scope of the study. It requires experimental data and was recommended for further studies.

Table 3. Theoretical higher heating values

Higher Heating Value	**Value (MJ/kg)**	**Operating Condition**
Feedstock based on C, H and O [6]	15.686	Dry basis
Combustible components in the producer gas (CO, CH_4 and H_2) [7]		T = 30 °C P = 101.325 kPa
CO	10.104	
CH_4	55.487	
H_2	141.710	

The pertinent parameters such as pressure, airflow rate, and biomass flowrate are set to the values of 1 bar, 0.578 kg/hr, and 100 kg/hr, respectively, during the simulation for the energy efficiency with respect to temperature. On the other hand, the temperature at 400 °C was kept constant for the simulation of the energy efficiency with respect to the air to biomass ratio. Based on the simulation, as the temperature increases, energy efficiency also increases. A valid point was established at 704 °C. It is the realistic limit of the gasifier, wherein, the higher heating value of the output will not exceed the higher heating value of the input.

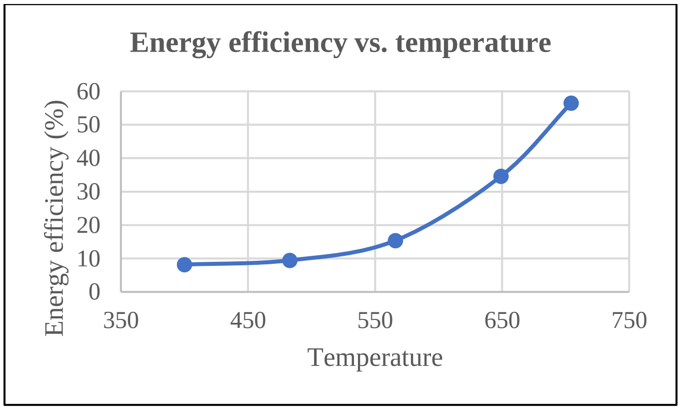

Figure 9 Energy efficiency with respect to temperature.

The results of the simulation of the energy efficiency with respect to the air to biomass ratio was shown in figure 10. The air to biomass ratio was varied from 0 to 2.5. The data shows that as the air to biomass ratio increases, the more inefficient the gasification process becomes and less carbon is being converted.

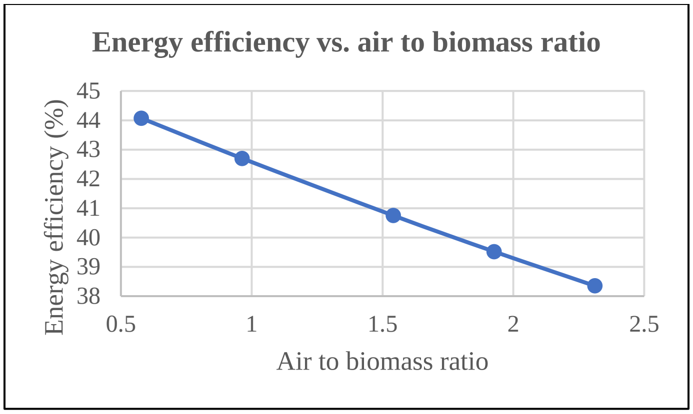

Figure 10 Energy efficiency with respect to air to biomass ratio.

3.7 Model validation

The work of Begum [8] was used to validate the Aspen Plus V11 coffee husks gasifier model. The parameter inputs in their simulation study were also used as inputs to the developed coffee husks gasifier model and the results of the model were analyzed.

The model developed by Begum [8] used Redlich Kwong Soave cubic equation of state with Boston-Mathias alpha function (RKS-BM) as a physical property method to calculate thermodynamic properties in the process. They used three reactors for the simulation: Rstoich, Ryield, and Rgibbs. Rstoich was intended for the drying process. Ryield, on the other hand, was used to decompose the feedstocks elements since biomass is a nonconventional component and cannot be computed by the Gibbs free energy, it will be decomposed into its elements C, H, O, N, and S. Lastly, Rgibbs serves as the actual reactor in the gasifier where gasification process takes place.

The comparison of the results of the coffee husks gasifier model and the model developed by Begum et al. [8] with the same parameter inputs are shown in figure 11. The coffee husks gasifier model predicted a producer gas composition of 2.27 hydrogen (H2), 18.54 carbon monoxide (CO), 27.17 carbon dioxide (CO2), 1.41 methane (CH4), and 42.60 nitrogen (N). CO2 and N2 from the two models seem to have significant discrepancies in their values. This is because, in the model of Begum [7], they introduced air two times producing a higher amount of nitrogen (N2).

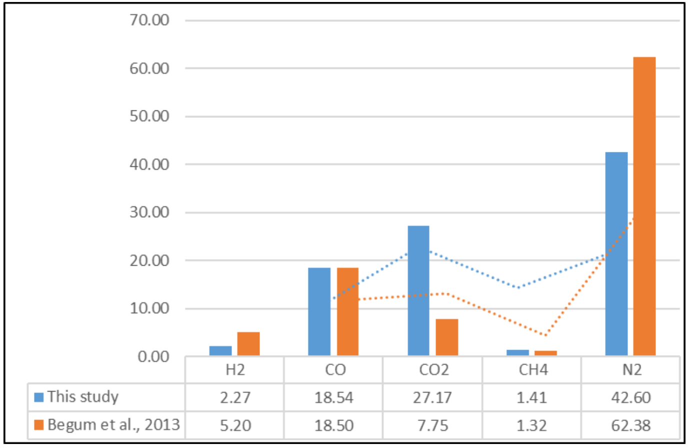

Figure 11 Model validation.

3.8 Gasifier sizing

The coffee husks gasifier is intended for the drying operation of two tons of coffee fruits or coffee beans in a flatbed dryer. The computed energy requirement for the drying operation is $5.4\text{x}10^{5}$ kJ/hr with a fuel consumption rate of 43.93 kg/hr. By using the energy requirement and energy input for drying, the reactor geometry of the gasifier, i.e., diameter and height, were calculated, resulting in 0.85 m and 1.25 m, respectively.

4. CONCLUSION AND PLANS FOR FUTURE WORK

This study developed a fixed bed downdraft gasifier model with coffee husks as feedstock using Aspen Plus V11. The process modelling has been carried out using a non-stoichiometric equilibrium model. Two reactors, Ryield and Rgibbs were used in the Aspen Plus V11 model to simulate the gasification process and predicted the gasification temperature of 925.85 ˚C and producer gas composition of 84.2851 carbon monoxide (CO), 4.7104 carbon dioxide (CO2), 0.1063 methane (CH4), 6.9086 hydrogen (H2), 1.0164 nitrogen (N), and 2.9726 water (H2O) in mass percentages with airflow rate and fuel feed rate of 0.578 kg/hr and 50 kg/hr respectively as initial inputs for the gasification process. The simulation results for the model validation gave a good agreement regarding the producer gas composition with the work of Begum [8]. Results show that the gasifier can perform its best even at a lower temperature, lower than 925.85 °C. A realistic limit of the gasifier based on the simulation established a valid point at 704 ˚C. The trend of the results was found to be consistent with the experimentally validated analysis of other biomass feedstocks in published investigations. The results of the modelling and validation will be used in prototyping the specific gasifier. Further, if a prototype has been developed, the gasifier model of this study must be intended to be validated through the experimental results of the gasifier.

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