A Steady-State Simulation of Downdraft Gasifier with Bamboo for the Production of Producer Gas

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Abstract*: Biomass Gasification is a chemical process that converts biomass into valuable, convenient gaseous fuels or chemical feedstock. It has emerged as a promising technology to fulfill the world's increasing energy demands and significantly reduce the volume of biomass waste generated in developing societies. A thermodynamic equilibrium model of a steady-state downdraft gasifier was developed using Aspen HYSYS. The model addressed the physical properties of the bamboo and the chemical reaction involved in the process. The gasifier consists of four reactor zones: Drying, Pyrolysis, Volatile Combustion, and Char Gasification. The pyrolysis yield reactor was used to model the bamboo constituent's decomposition in the pyrolysis zone. The combustion of char and volatile, including the gasification zone, was modeled using the equilibrium and conversion reactor. The model predicted the producer gas compositions, optimal temperatures for the gasifier, estimated the airflow to biomass ratio, steam flow to biomass ratio, and temperature to biomass ratio on the producer gas composition. Experimental and simulation results from literature were used to guarantee the accuracy of the modeled gasification process. At the end of this research, the final result shows that bamboo could be a potential material for energy resources and sustainability. An increase in steam to biomass ratio increased the net production of hydrogen and carbon dioxide to produce fuel and chemicals. An initial rise in the steam to biomass increases the net output of carbon monoxide (CO). More so, an increase in temperature increases the yield of the producer gas. Finally, it was observed that proper pre-treatment of feedstock improves the efficiency of the gasification process.

***Keywords*: Biomass, Gasification, Bamboo, Aspen HYSYS**

1. Introduction

The use of biomass as an environment friendly renewable energy source has received a tremendous amount of interest from all over the world in recent times, as evidenced by the fact that the use of biomass has been estimated to contribute approximately 10 – 14% of the world's power supply (Kendry, 2002). Biomass possesses an advantage over fossil fuels (natural gas, coal, and petroleum); it provides a continuous feedstock supply. Biomass is a CO_2 neutral resource for its lifecycle (Li S *et al.*, 2004) and (Li XT. *et al.*, 2004), and it also possesses zero CO_2 net emission energy (Mohammed *et al.,* 2011). Biomass wood combustion only recycles carbon that was only carbon cycle, adding no new CO_2 to the atmosphere (US biomass Energy Resource Centre., 2007). Compared to biomass, the constant uncertainties of the supply levels and the pricing of fossil fuels and the greenhouse effect and its consequences on climate change are drawbacks resulting from the extensive use of fossil fuels (Paula *et al.*, 2013). Burning fossil fuels takes carbon locked away underground (as crude oil, gas, and coal) and transfers it into the atmosphere as CO_2. However, fossil fuels are all non-renewable sources of energy and are finite. The continued burning of fossil fuels releases Greenhouse gases (GHGs) such as carbon dioxide, methane, and nitrogen oxide into the atmosphere resulting in to increase in the earth's atmospheric temperature; is termed global warming and has changed in the weather: for example, heatwaves, flooding, severe drought, and many other intensified natural disasters. Other disadvantages include environmental hazards, rising prices, acid rain, and human health (Olah *et al*. 2006).

Consequently, there is a need to create a clean environment while considering the adverse effect of increased greenhouse gas (GHGs) emissions on the environment. The increased environmental consciousness, accompanied by the need for a cleaner and safer energy source, has broadened the field of application to find a suitable replacement for fossil fuels. Established consequence due to climate change, rise in the emission of CO_2 worldwide exhibits that, although the stake of renewable energy (RE) in the primary energy supply is growing, all countries have to considerably intensify their efforts to reduce carbon and order GHGs in the future. (Elisha and George, 2020). However, It is generally conceded that the most visible way to attain this is the use of RE. Hence, several countries already use a continuously improving lot of their renewable resources to generate electricity, such as wind, solar, geothermal, or hydro energy. For instance, some countries have already attained very high shares of RE for electricity generation due to hydropower, such as Paraguay, Norway, China, and the USA had the most extensive established wind energy and solar capacity worldwide in 2019 (IRENA, 2020).

Renewable energy sources are environmentally friendly and non-finite. Renewable energy currently contributes 14% of the world's energy consumption, with biomass donating the more significant portion of about 10% (Filho and Badr, 2004). All have hailed the use of biofuel as a more reliable source of future energy. Therefore, its utilization for electricity generation is the next best option for developing countries like Nigeria, with an erratic electricity supply. For instance, in Nigeria, lack of access to a wide range of modern energy services has remained a significant barrier to improving critical human development indicators (Olah *et al.*, 2006). Presently over 60% of the country's population depends almost entirely on firewood for cooking and agro-processing activities. Despite Nigeria being an oil-producing country, petroleum products such as gasoline and kerosene are marked by acute shortages and mounting prices. Electricity, which is the foundation of modern economies, is non-available and is of poor quality or, better still, unreliable—an output less than 4000 Mw of the 7876 Mw installed electricity capacity it generates in Nigeria (Olah *et al.*,2006). Additionally, petroleum products are finite, and their combustion by-products are significant contributors to environmental degradation, climate change, and global warming.

In terms of environmental effect, biomass fuels possess a negligible sulfur concentration, producing and generating less air emission than fossil fuels. Biomass, in this sense, does not contribute to sulfur dioxide emission, which brings about acid rain, and the produced ash can be used as a soil additive for selections of farms. The amount of waste sent to landfills has been reduced through biomass utilization, significantly impacting waste disposal, particularly in the municipal area. The use of biomass energy will help in economic activities due to its ability not to affect the world price fluctuation or the uncertainties in the supplies of imported fuels. Therefore, reducing the dependency on fossil fuels, such as oil, would reduce the economic pressures of importing petroleum products (Demirbaş, 2001).

Sustainable development is a chain of activity that brings about continuity that meets the needs of the present without compromising the ability of future generations to meet their needs (Kayode, 2014). Due to the harm fossil fuel has caused to the environment, renewable energy using agricultural products such as bamboo, palm frond, and other agricultural products has been introduced to help build a sustainable environment for man. Evidence obtained from various research studies suggests that carbon dioxide content in the atmospheric air has increased at least 25 percent since the middle of the nineteenth century. Mainly because of the excessive use of fossil fuels all across the globe. For this reason, in the last 150 years, the earth's temperature has already gone up more than 1° F. It estimates that the temperature is going to increase further in the next hundred years. Hence, the earth will be warmer in the next century.

Bamboo is woody in nature and a member of the grass family. There are about 1250 species of bamboo in the world with a height of 10 cm to 40 m (Scurlock et al., 2000). Bamboo is known for there ability to withstand temperature region, although they originate from the tropics family. Its characteristics include low ash content and low alkali records with a low heating value higher than most agricultural residue, grasses, straw, and other woody biomass; these characters are all desirable fuel characteristics (Scurlock et al., 2000). Bamboo species exhibit no significant difference in the chemical and physical-mechanical property among the and species. The physical-mechanical property of bamboo varies with the age of the bamboo and the height of the culm (X Li, 2013). The main constituents of bamboo culms are cellulose and lignin; higher benzene ethanol extractives of some bamboo species are advantageous for decay resistance (X Li, 2013). Due to differences in vascular bundles, some anatomical differences may affect properties such as strength, density, bending behavior, and splitting (Liesa, 1992).

Aspen HYSYS Design software is a highly utilized process design application with diverse applications in multiple fields of science, engineering, and management to create steady-state and dynamic models for plant design, performance monitoring, troubleshooting, business planning, asset management; to aid the engineer in proferring optimum decisions in a context of multiple variables and criterion. Aspen HYSYS is a software program that enables the construction of steady-state and dynamic simulation process models within an integrated graphical environment. It also includes powerful tools which allow engineers to develop process optimization designs with lower project risks before committing to capital costs.

This paper develops a steady-state simulation of downdraft gasifier with bamboo to produce producer gas using Aspen HYSYS software. It also satisfies the following: Analyzing the biomass material in terms of its proximate and ultimate analysis; Ascertaining the effect of operating parameters like temperature, pressure, steam to biomass ratio, air to biomass ratio content, equivalence ratio on gasification process using Aspen HYSYS; The quality of producer gas obtained to be able to reduce the effect of In the environment as regards to its yield and composition.

2. Experimental

2.1 Feedstock

In the experiment, bamboo was used as feedstock. The species of bamboo used was between 2-3 years old. The bamboo was cut the bamboo into sizes to enable effective drying. After which, it was sundry for 40 days to reduce the moisture content. The tap sieve shaker, hammer mill, and milling machine were used to characterize the bamboo. The hammering machine and milling machine were used for grinding. They were sieved using a tap sieve shaker and mesh of different sizes to classify the bamboo material into separate particles. The material was further examined on the value of its proximate and ultimate analysis. A bomb calorimeter was used to investigate the heating value of the biomass. Using the Aspen-Hysys simulation package, the downdraft bed gasifier was simulated into four-stage: Drying, Pyrolysis, Volatile Combustion, and Char Gasification.

2.2 Experimental Setup

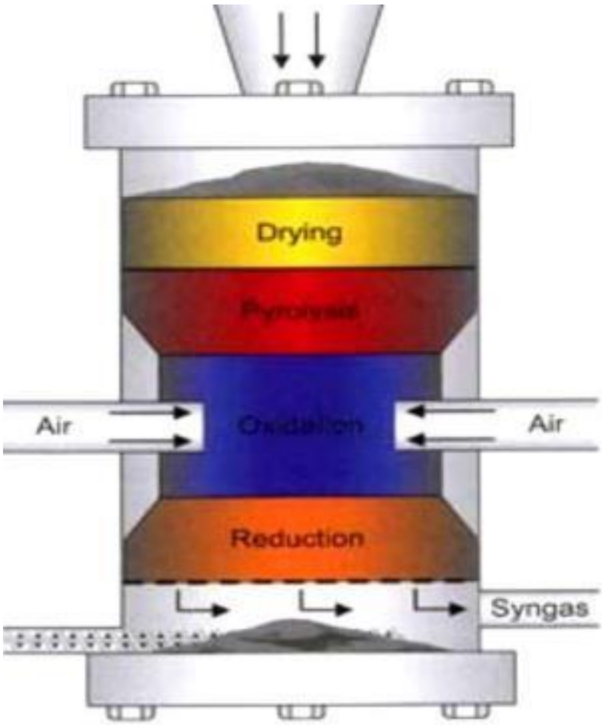

Figure 1: Downdraft Gasifier (Puig-Arnavat, 2011)

A downdraft gasifier is a gasification reactor with four distinct zones: the upper drying zone, upper-middle pyrolysis section, lower-middle oxidation zone, and lower reduction zone, as shown in figure 1 above.

2.2.1 Drying

The water content in the proximate analysis of the bamboo specified the yield of water. The downdraft gasifier was fed with wet biomass, which first entered the drying zone of the gasifier where moisture-form of water present in the biomass as determined by the proximate analysis was evacuated as steam, leaving dry biomass which enters the next unit. In the Aspen HYSYS model, a dryer represents the drying process. The process occurs at 300° C.

2.2.2 Pyrolysis

Biomass decomposition is what this stage represents. "Pyrolysis"- a conversion reactor model in Aspen HYSYS was used to simulate the biomass decomposition, which is a downdraft gasifier, in terms of its functionality, closely represents a pyrolysis process. Biomass is defined as a hypothetical component in Aspen HYSYS, is divided into its constituting conventional parts of carbon, hydrogen, nitrogen, oxygen, chlorine, and sulfur, using ultimate analysis. Based on the assumption, char from "Pyrolysis" consist of pure carbon. The streams "Comb Feed" and "char" in the simulation represent volatile matter and fixed carbon, respectively, defined following the proximate analysis of the parent fuel. The pyrolysis reaction is modelled with a yield reactor. At 500° C the pyrolysis reaction occurs.

2.2.3 Volatile Combustion

Based on the assumption, the combustion of volatile matter (VM) followed a conversion reaction; a reactor named "VM Combustor" was used to model it in Aspen HYSYS. Volatile feed to the VM Combustor called Hot Comb Feed contains a small amount of carbon, representing gaseous carbon in the volatile matter. The difference method, using proximate analysis details, was used to calculate Carbon in Hot Comb Feed. It Calculates what amount of the total amount of carbon in the fuel is volatile and fixed carbon. Based on the actual reactor model, the modelling of explosive matter combustion was carried out following the hydrodynamics of the downdraft gasifier. In the VM combustor, the Oxygen supply is limited. Volatile matter supplies heat to endothermic reactions in the gasification zone, where CO_2 and H_2O come from the combustion zone with char to form producer gas. Thus, combustion products (H_2O and small amounts of CO) of volatile matter share in the gasification reactions. Therefore, While the bottom product comb bottom proceeds into the next zone of the downdraft gasifier, the flue gas stream from VM Combustor in the simulation is sent to the gasification reactor Gasifier-B. The volatile matter combustion reaction takes place at ~850° C.

2.2.4 Char Gasification

The gasification reactions are sets of equilibrium reactions. It facilitates modelling in Aspen HYSYS; the location of the responses are broken down and modelled in various reactors as follows:

2.2.4.1 Gasifier A
It is an equilibrium reactor that models char combustion in air. Feeding air into the gasifier indicates that the char combustion occurs in an oxygen-rich; hence, the char combustion is very exothermic, it supplies heat to endothermic reactions in gasification, char combustion reaction takes place at ~940° C

2.2.4.2 Gasifier B
The exiting streams from gasifier A, char, flue gases mixed with steam enters gasifier B; A converter reactor modelling gasification zone of downdraft gasifier. Its models were gas, boudouard, and methanation reactions. The water gas and boudouard reactions are endothermic, while the methanation reaction is exothermic.

2.2.4.3 Gasifier C (Shift Reactor)
It is an equilibrium reactor that models water gas shift reactions and methane steam reforming reactions.

2.2.4.4 H2S/HCL Reactor
This unit focused on modeling the hydrogen sulfide (H_2S) / hydrogen chloride (HCL) production reaction where hydrogen reacts with sulfur (S) / chlorine (CL) to form hydrogen sulfide (H_2S) and hydrogen chloride (HCL).

2.3 Experimental Procedure
Before starting up the simulation, the components to be used were identified. These components involved in this simulation include Hydrogen (H), Carbon (C), Nitrogen (N), Sulphur (S), Methane (CH_4), Hydrogen sulfate (H_2S), Water (H_2O), Carbon Dioxide (CO_2), Carbon Monoxide (CO), Oxygen (O_2), and Bamboo (which is the hypothetical component used for the simulation). Other elements considered during this simulation include moisture content, ash content, fixed carbon, volatile matter, average density, the particle size of the bamboo, and flow rate.

The Aspen HYSYS environment was opened, after which the fluid package (Peng-Robinson) was added. At the top of the environment, there is an inscription 'component list selection'. The above components, including the hypothetical component (bamboo), were added by clicking on the view. After this, the simulation environment was accessed.

2.3.1 Simulation Environment
The simulation environment has a palette comprised of the energy stream, material stream, separator, and other equipment which aided in the work stimulation.

The simulation was started by picking a material palette, renamed "the stream to wet biomass", and the compositions; Temperature, pressure, flow rate, Biomass (bamboo), and H_2O, were inputted. Furthermore, a component splitter that serves in place of the dryer was added from the column palette. It enables water separation out of the dry biomass. The necessary parameters, namely, temperature, pressure, and the component to be split, including water and the dry biomass, were filled inside the component splitter, through which the process was converged. After the procedure was converged, the yield reactor, which serves as the pyrolysis reactor, was added. All necessary flows (inlet, outlet, and energy duty) were inputted by double-clicking on the yield reactor, after which the parameters were clicked, and the pressure drop was added as cited in our assumptions. After that was done, the model configuration was clicked, which enabled us to select suitable design variables for the process. After the model configuration was carried out, the composition shift was opened, and the base yield, datasets, and bases were filled in. After this process, the pyrolysis temperature, which is 500° C, was added to converge.

The next step was adding another component splitter that separated the volatile matter from the char. After the splitter converged, a splitter that served as a de-sulphurize was added. The de-sulphurize enabled the splitting out of Sulphur from other compositions to avoid corrosion of equipment. After this process, a TEE was added, which served as a char splitter to separate the char composition from char gases.

After this stage, the reaction stated below were brought into consideration in the simulation environment. The reactions involved include:

1. Volatile combustion
2. Char reaction; Gasifier A, Gasifier B and Gasifier C
3. H_2S Reactor

A mixer was introduced to the H2S reactor to enable a perfect mixing of the product. A cooler was added. It cooled the products before they went into the splitter, which separated the syngas produced from water.

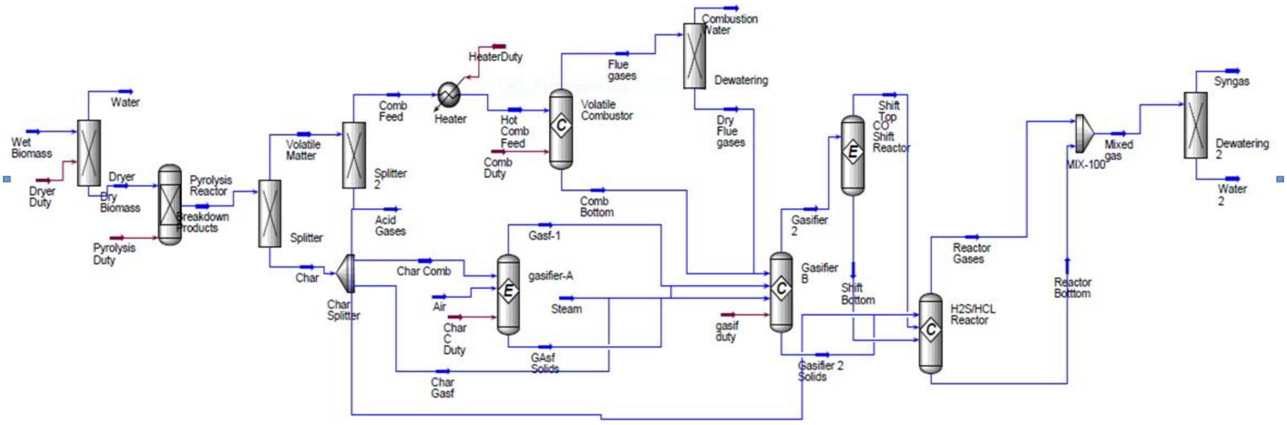

Figure 2: The Simulation Flow Diagram

2. Results and Discussion

The illustration for the proximate, ultimate property of the biomass used for the simulation and the Optimum simulation result of temperature in the various zones of the gasifier is shown in Tables 1, 2 and 3 respectively.

Table 1: Results for Proximate and Ultimate Analysis

Proximate Analysis		Ultimate Analysis	
Parameter	**Compositions (%)**	**Component**	**Composition (%)**
Volatile Matter	78.43	Carbon	50.6400
Fixed Carbon	14.77	Hydrogen	16.9900
Ash Content	3.20	Oxygen	31.4000
Moisture Content	3.60	Nitrogen	0.9200
		Sulfur	0.0400
		Chlorine	0.0053
Total	**100.00**	**Total**	**100.0000**

Table 2: Properties of Bamboo used for Simulation (Aspen HYSY)

Properties	Values
Average density	260 kg/m^3
Particle size	Less than 0.425 mm
Higher calorific value	21220.77 kj/kg
Flow rate	100 Kg/Hr
Steam	Saturated steam at 101.4 kPa and 250° C

Table 3: Optimum Simulation Result of Temperature in the Various Zones of the Gasifier

Zone	Temperature (°C)
Drying	300
Pyrolysis	500
Volatile Matter Combustion	850
Gasification (Gasifier A, B, C and HS reactor)	940, 207, 550, 654

3.1 The Effect of Air-Biomass Ratio

It examines the effect of the air-biomass ratio on the producer gas composition. The Simulation results for producer gas composition were analyzed when air molar flow ranged between 0-5. Figures 3 and 4 show that the production of H_2, including CO, decreases due to air increase, while the volume of inert gas (N_2) in the producer gas increases due to air increase. CO_2 estimated from figure 4 is not stable. At points 0 to 3 of the graph, there is a slight decrease and a slight increase between points 3 to 4 of the graph. Between points 4 through 5, the flow became stable as the airflow increased.

The decrease in hydrogen and carbon monoxide contents was expected, and it was due to a nitrogen dilution effect. O_2 from the estimate shows neither increase nor decrease at the initial start, which is between points 0 to 3. At points 3-5, there was an increase as the airflow increased. Higher airflow can also cause producer gas quality to degrade because the airflow rate decreases the combustion zone temperature and, subsequently, the temperature in the gasification zones. The increased air-fuel ratio implies increased airflow and lower combustor temperature, which yields lower reaction conversion for the gasification reaction and low producer gas composition. The endothermic reactions depend on the heat received from the combustion zone to drive the reaction to higher conversion.

Table 4: Effect of Air-Flow Ratio to Producer Gas Composition

Air-mole Flow (kg mole/h)	**CO_2**	**H_2**	**N_2**	**O_2**	**CO**
0	0	0.3837	0.0048	0	0.6113
1	0.0289	0.3242	0.1130	0	0.5337
2	0.0535	0.2735	0.2053	1.109e-15	0.4675
3	0.0747	0.2298	0.2849	1.167e-14	0.4105
4	0	0.2401	0.2985	0.0786	0.3826
5	0	0.2196	0.3406	0.0898	0.3499

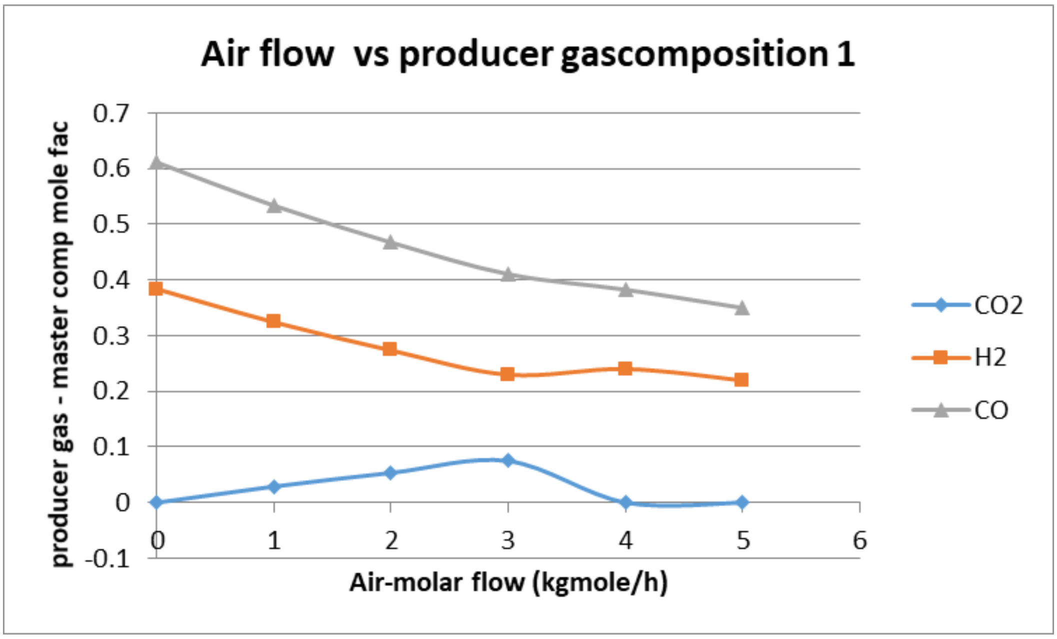

Figure 3: Effect of Air Flow vs Producer Gas Compositions 1 (CO_2, H_2 and CO)

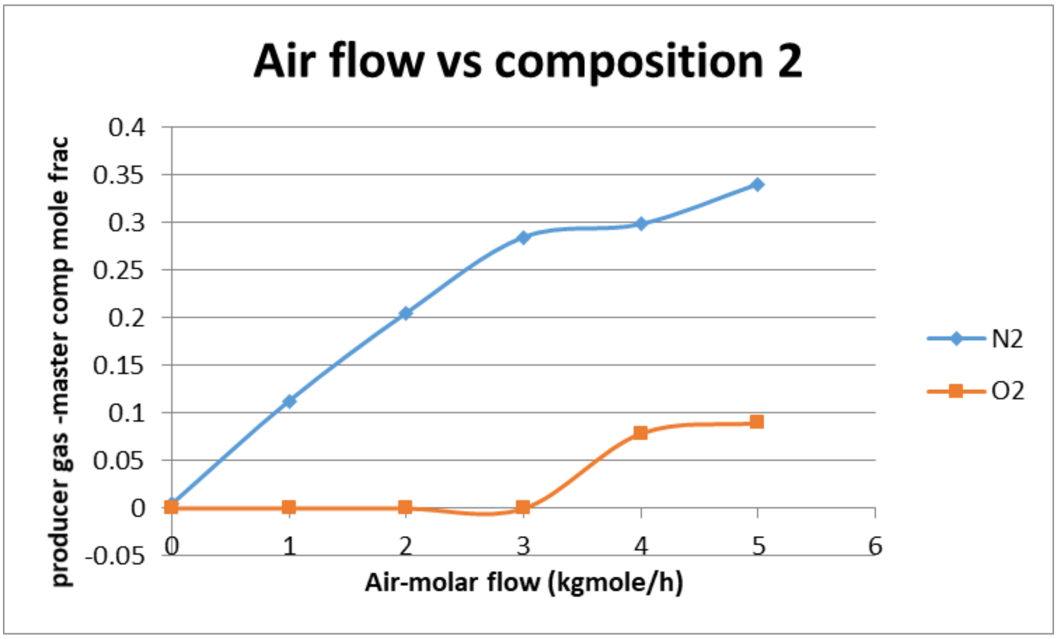

Figure 4: Effect of Air Flow vs Producer Gas Composition 2 (N2 and O2)

4.2 Effect of Steam-Biomass Ration to Producer Gas

The effect of the increase in steam to biomass ratio (S/B) was studied in downdraft gasifier using Aspen HYSYS, and the simulation results were plotted in figure 5. Saturated steam at 101.4 kPa and 250° C was used, and the S/B ratio was varied from 0 to 5. Injecting steam shifts the equilibrium to the right in water gas reaction producing carbon monoxide and hydrogen. Initially, there was an increase in the concentration of CO, which became stable (neither increase nor decrease) between points 1 and 2. More so, between points 2 and 5, H_2 concentration increased. In contrast, the concentration of H_2O remains stable due to the increase in the steam/biomass ratio, as there is only a fixed amount of air supplied at 0.1 kg/h with an increasing steam-biomass ratio.

Table 5: Effect of Steam Ratio on Producer Gas Composition

Steam	CO	H_2O	N_2	CH_4	CO_2	H_2
0	0	0	0	0	0	0
1	0.7009	0	0.0264	0.1643	0	0.3331
2	0.6261	0	0.0176	0.0223	0	0.3670
3	0.6115	0	0.0167	0.0044	0	0.3670
4	0.6115	0	0.0167	0.0044	0	0.3670
5	0.6115	0	0.0167	0.0044	0	0.3670

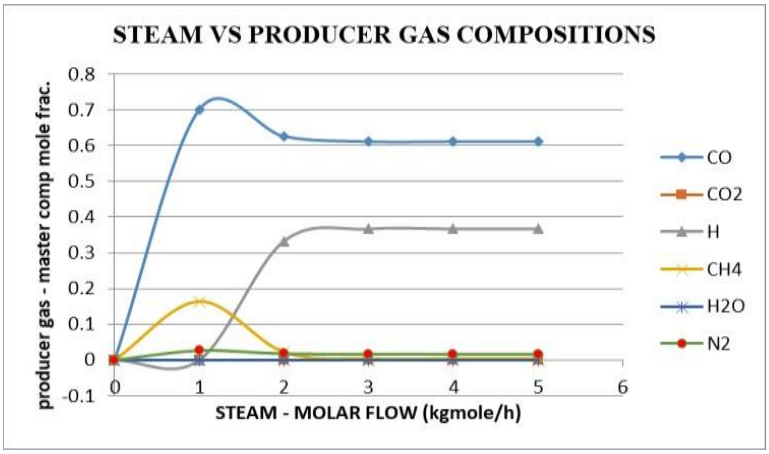

Figure 5: Effect of Steam Ratio to Producer Gas Composition

The concentration of N2 from table 7 above neither increases nor decreases; instead, it remains at a steady state. The concentration of CO_2 from the graph shows a slit increase in the concentration.

4.3 Effect of Temperature on Producer Gas Composition

Table 6: Effect of Temperature on Producer Gas Compositions

Steam	CO	H_2	HCL	N_2	CH_4
500	0.6115	0.3670	4.121e-05	0.0167	0.0044
600	0.6135	0.3710	4.121e-05	0.0167	0.0034
700	0.6155	0.3750	4.121e-05	0.0167	0.0024
800	0.6175	0.3790	4.121e-05	0.0167	0.0014
900	0.6195	0.3830	4.121e-05	0.0167	0.0004
1000	0.6215	0.3870	4.121e-05	0.0167	6.0e-03
1100	0.6235	0.3910	4.121e-05	0.0167	6.1e-03

The effect of gasifier temperature on produced syngas composition is shown in table 6.

The temperature considered varies from 500° C to 1100° C. An increase in temperature improves the gasification process. Hydrogen and carbon monoxide increase while methane decreases. The results obtained from this research work were compared with the result obtained by Abdullah Hassom Nouh in his work simulation of biomass gasification.

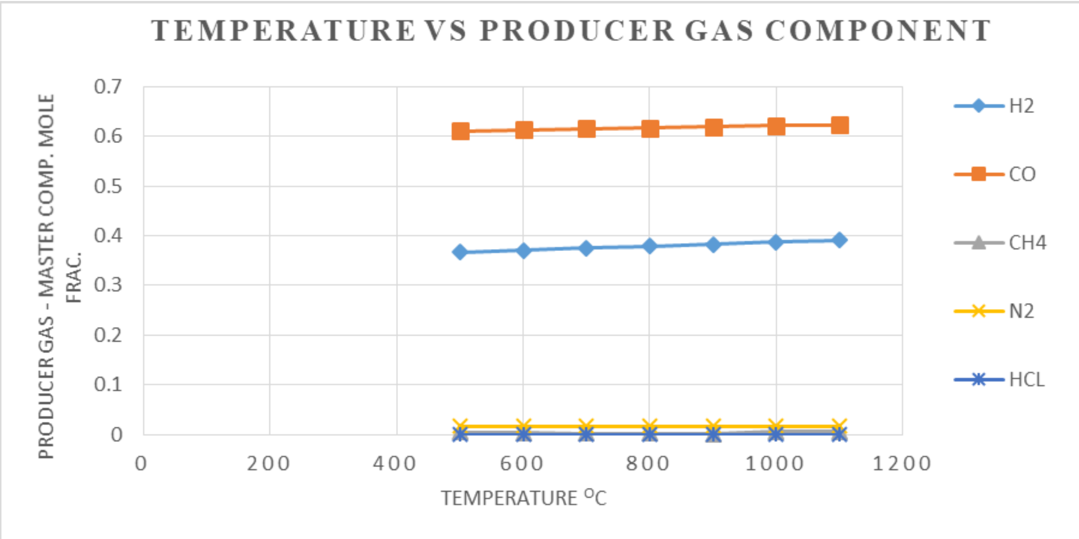

Figure 6: Effect of Temperature on Producer Gas Composition

5. Conclusion

Using Aspen HYSYS, a computer simulation model of a downdraft bed biomass gasifier of a steady-state equilibrium was developed, using bamboo as the hypothetical component for the simulation process. This simulation comprises chemical reactions and calculations on the mass and heat balance performed on each unit operation. The producer gas processed was obtained through a set of conversion and equilibrium air-steam gasification reactions. The model analyzed the effect of operating parameters such as gasifier temperature, steam to biomass ratio, and air-fuel ratio content on the producer gas composition. The final result obtained from this research is in agreement with other publications. The conclusion and result achieved from the simulation include:

1. Hydrogen and carbon dioxide increases with an increase in steam to biomass ratio, while the volume of inert gas Nitrogen decreases.
2. The volume of inert gas Nitrogen increases with an increase in air, while a decrease occurs in hydrogen and carbon monoxide.
3. An increase in temperature improves the gasification process. Hydrogen and carbon monoxide increase while methane decreases.
4. Feedstock preparation, such as sun drying to reduce its moisture contents, helps in gasification processes.

The study shows that bamboo from its Ultimate and Proximate analysis is a potential energy crop, with a good yield of producer gas and less ash content. The feedstock cost is zero, as bamboo is regarded as waste in developing countries such as Nigeria. Consequently, biomass (bamboo) as a renewable form of energy, if properly harnessed, will provide a reliable energy source, which will further create a well sustained and clean environment.

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