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Moshi, Robert

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The Exergy Analysis for the Air Gasification in a Hybrid Fixed Bed Gasifier

**Robert Eliraison Moshi^{1,2}, Thomas Thomas Kivevele^{1,3},
and Yusufu Abeid Chande Jande^{1,3*}**

¹Department of Materials and Energy Sciences and Engineering, The Nelson Mandela African Institution of Science and Technology, P.O. Box 447, Arusha, Tanzania.

²Department of Automotive Engineering, Arusha Technical College (ATC). P. O. Box 296 Arusha, Tanzania.

³African Centre of Excellence in Water Infrastructure and Sustainable Energy Futures (WISE-Futures), The Nelson Mandela African Institution of Science and Technology, Nelson Mandela Road, Tengeru, P.O. Box 9124, Nelson Mandela, Arusha, Tanzania.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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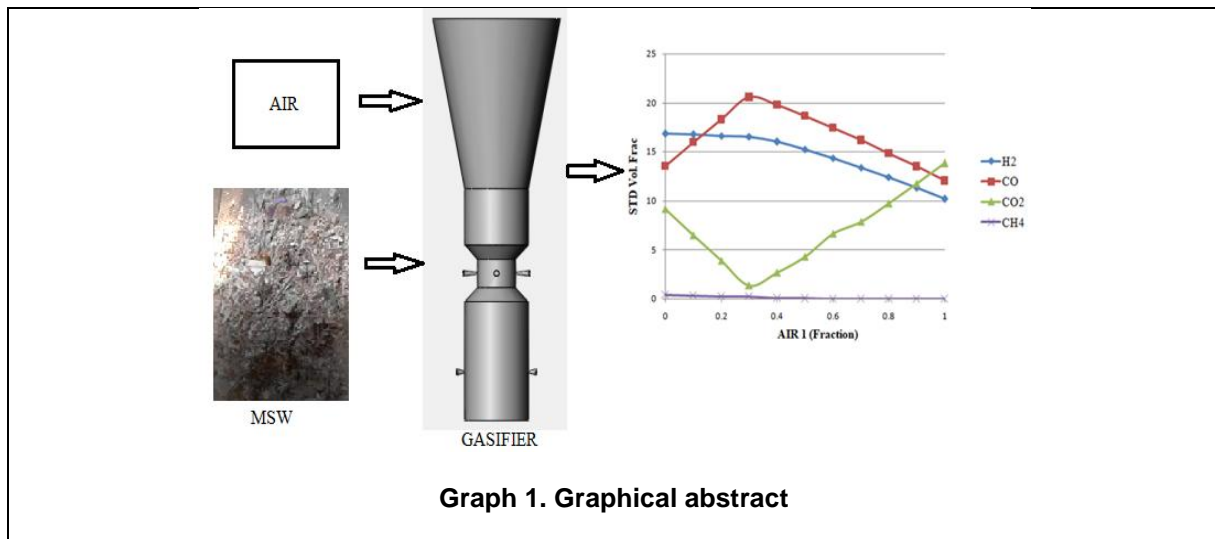
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ABSTRACT

Municipal solid waste (MSW) is becoming a concern as population in urban area is increasing. Several disposal methods (landfill and biochemical) have been used. However, waste to energy (WTE) particularly gasification technology is a potential technology for energy recovery. The system is used to convert biodegradable material into syngas under limited gasifying media. This study presents numerical analysis of producer gas for the two air paths in the hybrid fixed bed gasifier (HFBG). It was revealed that the optimum operating condition was achieved when the air ratio at the first air flow path (AIR1) was 0.3. Furthermore, the exergy efficiency of about 81.51% was achieved.



Keywords: Gasification; aspen plus; waste to energy; fixed bed gasifier; exergy.

STATEMENT OF NOVELTY

The aim of this study is to analyze the optimal operating parameter for the hybrid fixed bed gasifier. Although several studies have been undertaken on the performance of the gasifier, none have worked on the hybrid fixed bed gasifier which combines the crossdraft and downdraft features. Air was the main gasifying media involved in this study and the two air inlets were considered. The optimal air ratio between the two air paths was analyzed. The equilibrium model and exergy analysis for the HFBG was also studied in this work.

1. INTRODUCTION

One of the basic needs of a human being in daily life is energy. Commonly fossil fuel has remained the main source of energy worldwide [1]. However, the excessive use of fossil fuel has been the main source of green house gases emission which results in a global warming [2]. It is also known that fossil fuel deplete with time depends on consumption rates on a particular reserve area [4]. Therefore, the need for alternative and sustainable energy source has been a concern to many researchers. Currently, the most common source of renewable energy includes: solar, ocean tides, wind, geothermal and biomass [5-6]. The biomass outweigh the other renewable sources since it can be used in many ways to provide energy in form of heat and electricity [7]. Biomass comprises among other sources the municipal solid waste biological residue.

Municipal solid waste (MSW) is one of the contentious topics in the world due to its side effect when not handled properly [8]. These problems bring a concern for the continuous research on both areas: energy and municipal solid waste management (MSWM). Waste to energy (WtE) has been one of the proper methods for MSW disposal since some of the energy can be recovered from the waste [9-10]. The biomass WtE conversion technology depends on the proximate and ultimate analysis results. Proximate analysis is carried out to analyze the amount of moisture content, ash content, volatile matters and fixed carbon existing in the MSW, whereas ultimate analysis is carried out to determine the chemical composition of MSW. The High Heating Value (HHV) for MSW in Tanzania which was used as a sample is 12.42 MJ/kg. The HHV indicates that material can support burning although not as reactive as coal due to its high content of oxygen.

To improve MSW combustion reactivity require means of reducing oxygen content and this can be done by limiting the supply of oxygen for combustion [11]. Four methods are encountered on WtE conversion technology: thermo-chemical (torrefaction, plasma, gasification, pyrolysis and liquefaction), biochemical (fermentation and anaerobic digestion), thermal (incineration), and mechanical and thermal method (pulverization and drying) [12-13]. Among all these technologies, pyrolysis and gasification are the technologies which involve a limited supply of oxygen. While pyrolysis is carried out at nearly

0:1 air fuel ratio, gasification occurs at about 1.8:1 air fuel ratio [14]. Currently, incineration and gasification are becoming the most used WtE technology [15].

Gasification is a thermochemical process which converts carbonaceous solid fuel into syngas under restricted oxygen environment without having an intermediate product [16-17]. Conversely, MSW gasification requires a special attention due to its high moisture content (MC). Usually, combustion is considered possible for biomass with moisture content less than 50% [18-19]. Solid waste gasification is possible at a MC less than 20 % for downdraft and MC less than 50% for updraft gasifier [20]. However, random collected MSW is reported to have more than 50 % moisture content [21-23].

Generally, feedstock is dried and pyrolysed before being combusted by gasifying media, the last stage being reduction to release syngas [24]. These processes are done in fixed bed, entrained flow bed or fluidized bed gasifier depends on the factor such as size of the gasifier as well as the intended quality of producer gas. In this context fixed bed is chosen for small scale while fluidized bed is preferred for large scale systems [25].

Various types of fixed bed gasifier have been employed for biomass gasification in small scale unit. Initially, three types of fixed bed gasifiers were commonly employed for biomass gasification including updraft, downdraft and cross draft gasifiers [26]. In all the three fixed bed gasifier design, the feedstock is fed at the top flowing downwards. Updraft gasifier operates in a manner that allows feedstock to move in opposite direction to the gasifying media. In the updraft gasifier the feedstock moves in opposite direction to the gasifying media. However, in the downdraft gasifier the feedstock moves in the same direction to the gasifying media which is usually introduced in the gasifier just above the center. In the cross draft gasifier, gasifying media flows across the diameter of the reactor. In these three types of fixed bed gasifier each has advantages and disadvantages (Table 1) which makes them suitable for specific purpose.

Because of the aforementioned advantages, a number of researchers have shown an interest on investigating MSW gasification process. Arena [20] carried out a review study on the MSW gasification technology. The author concluded that gasification technology is a viable

option for waste conversion. Bhoi *et al.* [29] investigated the gasification of MSW with switch grass using downdraft gasifier. They concluded that the co-gasification of about 40 % MSW offer better results accompanied by better reduction of ash agglomeration. Therefore MSW gasification is viable option for MSWM.

Although gasification is common process for biomass waste, the process is currently considered as alternative method for MSW management [30] [31]. When employed as MSWM method gasification process offers two advantages: energy recovery and MSW volume reduction of almost 90%. Maya *et al.* [32] conducted a review study on MSW gasification for power generation. They concluded that gasification is a technically viable option for MSWM with high reduction of mass and volume of about 70-80% and 80-90% respectively. The main advantage of gasification process over incineration and pyrolysis is low environmental pollution [33] [34].

Generally, simulators are used to investigate the performance of the system before the actual process implementation. ASPEN Plus is one among other simulators which have been used to simulate MSW gasification processes [35] [36] [34]. Begum *et al.* [37] performed a numerical investigation of a fixed bed gasifier for MSW gasification using ASPEN Plus. They reported that, results obtained using Aspen plus were in good agreement with experimental results. Chen *et al.* [38] develop a numerical model for predicting the syngas output in a fixed bed gasifier using aspen plus. They concluded that factors such as temperature, air equivalent ratio, and moisture content affect syngas composition.

Based on the aforementioned factors, the critical analysis is required for the successful design of the gasification system. Additionally, in order to analyze the performance of the system the energy efficiency should be determined. On the other hand, the exergy analysis has been used to evaluate the potential efficiency of the system. This thermodynamic concept reveals the energy loss due to irreversibility.

At presents, many researchers have discussed the exergy analysis for the gasification system involving downdraft, updraft, and fluidized bed gasifier. Zhong *et al.* [39] carried out an exergy analysis for the hydrothermal upgrading of biomass (HTU) process. They revealed that the exergy efficiency of the process was as higher as

86 %. With respect to the gasifying media, it has been reported that the energy and exergy efficiencies are higher when air is used as compared to steam [40]. However, none of them have performed the exergy analysis for the combined system such as HFBG. Therefore, the aim of this study was to investigate a lab scale HFBG for its exergy efficiency.

2. MATERIALS AND METHODS

The study of the gasifier unit (Fig. 1) was based on the HFBG that combines advantages of downdraft and cross draft into one gasifier. The dimensions of the gasifier were adapted from the previous published article by the same author [41]. In this design air was supplied into the gasifier through two inlet path, one being on the throat few millimeters above the narrow diameter and the second below the throat. The overall length and its diameter were 1250mm and 280 mm respectively. The narrow part of the gasifier (throat) was designed with a diameter of about 80mm. On top of the gasifier is a hopper with outer diameter of 780mm.

The gasifier involves a number of reaction zones (drying, pyrolysis, first combustion gasification, and second combustion). In the drying section, the water content contained in the feedstock is reduced before the decomposition of the feedstock into conversional components including sulphur, oxygen, hydrogen, nitrogen, carbon and ash. Air is supplied for the first and second combustion reactions by varying their ratio. In between the two combustion zones is gasification section which involves partial oxidation of feedstock to produces fuel gas commonly hydrogen, methane, carbon monoxide and carbon dioxide [42].

The feedstock characteristic was adapted from the previous published data as shown in Table 2 [43]. This includes the proximate and ultimate analysis of the MSW randomly collected at Arusha municipality. It was revealed that the collected wastes have high moisture content (MC) of almost 59.79 wt% which is beyond the level suitable for gasification [43].

Table 1. Advantages and disadvantages of fixed bed gasifier [27] [28]

Gasifier type	Advantages	Disadvantages
Updraft	Produces gases with low temperature	High tar output in the producer gas
Downdraft	Low tar content in the producer gas	Difficult in handling biomass with higher moisture content
Cross draft	Has shorter startup time. Produce low tar in the produced gas. Suitable for small scale plant as well as high moisture feedstock.	High temperature in the producer gas High producer gas velocity

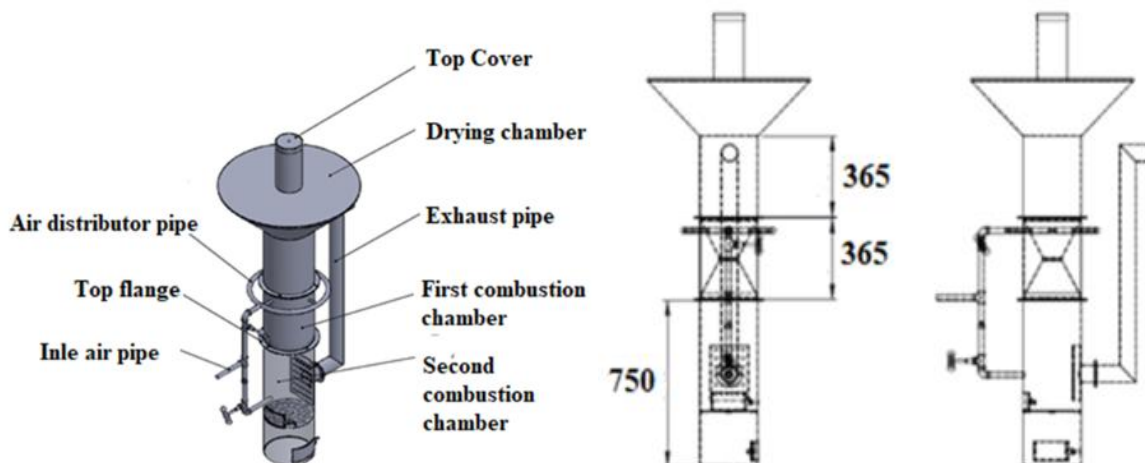


Fig. 1. The gasifier air path

Table 2. Arusha MSW proximate and ultimate data [43-44]

Ultimate Analysis(wt%)	Carbon	54.82
	Hydrogen	5.29
	Oxygen	34.62
	Nitrogen	2.36
	Sulfur	0.30
	Chlorine	0.05
	Phosphorous	0.11
Proximate Analysis(wt%)	MC	59.79
	VM	78.91
	FC	10.54
	Ash	10.55

The information's from Table 2 was used in the ASPEN Plus to simulate the gasifier output [45]. In order to study the performance of the HFBG, the study was carried out in both: Equilibrium modeling and numerical simulation using ASPEN Plus software.

2.1 Numerical Simulation

Biomass gasification is a complex process in which any changes in feedstock characteristics or the fluctuation of operating parameters will lead into variations of syngas output. Gasifier operating parameter include gasifying media (air, steam, carbon dioxide and pure oxygen), and operating temperature. Furthermore, the gasifier design plays the important role on the quality and quantity of the output syngas. In this context it is important to simulate the designed gasifier so as to predict the output before manufacturing [46].

Assumption: Several assumptions were taken into consideration in the simulation process:

1. Carbon and ash are the key components of the char
2. Tar was not taken into consideration throughout the entire process.
3. The main constituent of volatile products were H_2 , H_2O , CO , CO_2 , and CH_4 while N_2 was considered to be inert.

In this study, comparative performance simulation of the air feed as gasifying media for the two paths (AIR 1 and AIR 2) in Fig. 2 was analyzed. Five reactor blocks namely Rstoic, Rgibbs were used for drying, pyrolysis, first combustion, gasification, and second combustion respectively. The selection of these reactor models were based on their properties and its application (Table 3). An IDEAL property method

was used since conversional components such as H_2 , H_2O , CO , and O_2 were used under low pressure.

Addition to these reactor blocks the model consists of one Fsplit block and three Ssplit block. Rstoic were used to lower the MSW moisture content under stoichiometry reaction 1, supported by the Fortran expression 2 [37].

$$Biomass = 0.0555084H_2O \quad 1$$

$$H_2ODRY = 16$$

$$CONV = (H_2OIN - H_2ODRY) / (100 - H_2ODRY) \quad 2$$

Ash and Biomass (MSW) were represented as non-conventional components where HCOALGEN and DCOALIGT models were used to calculate the enthalpy and density of these components respectively.

The total air flow rate supplied in the gasifier (AIR) was kept at 8.95 kg/hr and the feedstock flow rate was kept at 6 kg/hr. The simulation of a gasifier output was achieved by varying the air ratio for both air paths where air ratio at the first path (AIR1) was varied from 0 to 1 in the mixer at an interval of 0.1. When the air ratio was varied at AIR1 in the mixer (Fig. 2) the air ratio in the second air path (AIR2) was also affected.

Operating parameters for the simulation process

The operating parameters for the entire simulation process are described in Table 4

2.2 Heating Values

The amount of heat acquired when the biomass is incinerated is termed as heating value. The heating value usually is divided into two

categories: the high heating value (HHV) and the lower heating value (LHV). The HHV is the total amount of heat energy contained in a particular fuel including the energy available in the water vapor that has been exhausted. The LHV does not include the energy contained in the water vapor. In this study, the syngas HHV was

calculated using equation 3 whereas the LHV was calculated using equation 4[47].

$$\begin{aligned}
 \text{HHV} &= 12.76(\%H_2) + 12.63 (\%CO) + 39.75 (\%CH_4) \dots\dots\dots 3 \\
 \text{LHV} &= 10.8(\%H_2) + 12.63 (\%CO) + 35.8 (\%CH_4) \dots\dots\dots 4
 \end{aligned}$$

Table 3. Properties and uses of the reactors

S/N	Type of reactor	Properties	Uses
1	Rstoc	i. This is the reactor model which can model reaction that occur simultaneously	i. Used when reaction kinetics is not important ii. Used when stoichiometry for each reaction is known
2	Rgibbs	i. This reactor predicts the product in the system through Gibbs energy minimization concepts	i. Used when the reaction kinetics is not known ii. Used when the system involves many products

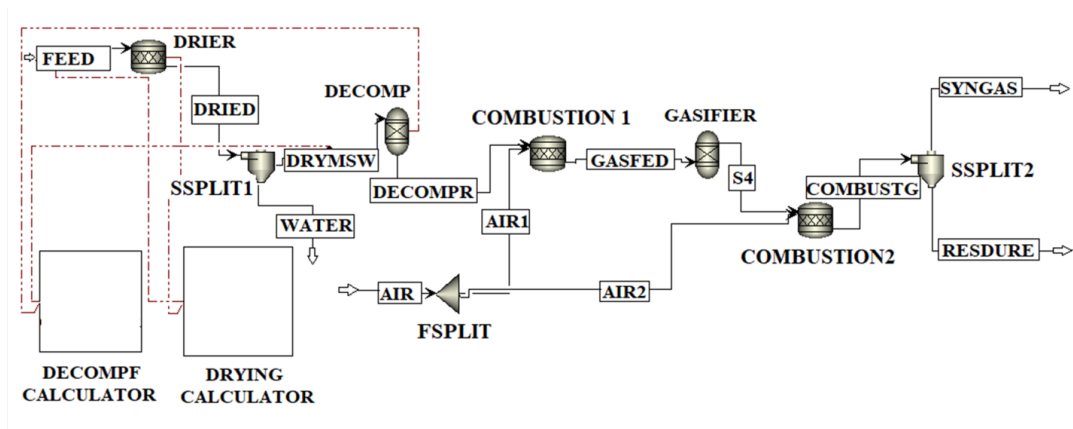


Fig. 2. Aspen plus simulation model [45]

Table 4. The description of operating parameters

Streams and reactors	Parameter	Value
Feed	Temperature	25 °C
	Pressure	1 bar
	Flow rate	6 kg/hr
Air	Temperature	25 °C
	Pressure	1 bar
	Flow rate	8.95 kg/hr
Drier	Temperature	25 °C
	Pressure	1 bar
Decomp	Temperature	500 °C
	Pressure	1 bar
Combustion1	Temperature	1000 °C
	Pressure	1 bar
Gasifier	Temperature	800 °C
	Pressure	1 bar
Combustion2	Temperature	1500 °C
	Pressure	1 bar

Heating power of the MSW was calculated using equation 5 where LHV of biomass was taken to be 12 MJ/kg and fuel consumption rate was 6 kg/h which resulted into heating power of 20 kW.

$$P_B = LHV_B \cdot FCR \cdot \frac{1}{3.6} \dots\dots\dots .5$$

Stoichiometric air ratio (SR) needed the biomass combustion was calculated using equation 6 where C_C, C_H, C_O and C_A are the percentage of carbon hydrogen oxygen and ash respectively determined through ultimate analysis. Substituting these values in equation 6, the SR was determined to be 5.907 kg air for 1 kg of MSW

$$SR = \left(\frac{C_C}{12} + \frac{C_H}{4} - \frac{C_O}{32}\right) \cdot \left(1 + \frac{79}{21}\right) \cdot \left(1 - \frac{C_A}{100}\right) \cdot \frac{28.84}{100} \dots\dots\dots 6$$

The simulated Syngas flow rate (GFR) results for path AIR1, AIR2 and Hybrid (combined) was 54.5721, 57.0202, and 38.3070, NM³h⁻¹ respectively. Therefore thermal power of producer gas was evaluated using equation 7.

$$P_G = LHV_G \cdot GFR \cdot \frac{1}{3.6} \dots\dots\dots 7$$

The thermal power obtained in equation 7 was used to calculate the cold gas efficiency using equation 8.

$$\eta_{CG} = \frac{P_B}{P_G} \cdot 100\% \dots\dots\dots 8$$

3. ENERGY AND EXERGY ANALYSIS

3.1 Energy Balance

Usually, energy balance tends to obey the relationship between the energy inputs to the system with respect to its surroundings as realized in equation 9. In gasification process, the input energy includes the energy in feedstock, agent gas, and the addition heat. The energy output sum up the useful energy and energy loss to the surroundings including gas products, fly ash, tar and char [48].

$$\sum E_{out} = \sum E_{useful} + \sum E_{loss} \dots\dots\dots 9$$

3.2 Exergy Balance

Exergy value for gas is grouped into two main classes which are physical and chemical exergy. The physical exergy is further sub divided into mechanical exergy (kinetic & potential) and thermo-mechanical exergy (temperature based and pressure based) whereas the chemical exergy is divided into mixing & separation and chemical reaction. Usually, mechanical exergies are neglected since it involves relatively small values [49]. Therefore the exergy for the material stream is represented using equation 10.

$$E^x = E^x_{ch} + E^x_{ph} \dots\dots\dots 10$$

$$E^x_{ph} = (h - h_o) - T_o(s - s_o) \dots\dots\dots .11$$

Where

$$h - h_o = \int_{T_o}^T C_p dT \dots\dots\dots 12$$

$$s - s_o = \int_{T_o}^T \frac{C_p}{T} dT \dots\dots\dots 13$$

Where h and h_o are the specific enthalpy on a given temperature and enthalpy under standard temperature (T_o=298K) and pressure (1 atm) respectively. The s and s_o denotes entropy under the specified temperature and entropy under standard temperature (298K) and pressure (1 atm) respectively.

The chemical exergy for gaseous is evaluated using equation 14

$$E^x_{ch} = \sum_i x_i \cdot ex_i^{ch} \dots\dots\dots .14$$

The number mole of gas (x_i), specific enthalpy (h_o), specific entropy (S_o), standard chemical exergy (ex_i^{ch}) for each components are shown in Table 5 [50].

3.3 Exergy Efficiency

The gasifier exergy efficiency is usually expressed based on the chemical exergy efficiency. It is expressed in terms of a ratio between chemical exergy of the producer gas to the total exergy input as shown in equation 15.

$$\eta_{ex}^x = \frac{E_{x(producer)}^{ch}}{E_{x(input)}} \dots\dots\dots 15$$

$$E_{MSW}^x = m_{MSW} \beta LHV_{MSW} \dots\dots\dots 16$$

The total exergy input is obtained from the feedstock and equation 16 has been used to calculate the MSW exergy.

Where m_{MSW} is the feed rate of MSW in kg/h, the correlation factor (β) and the low heating value (LHV) are calculated by the use of equation 17 and 18 respectively [51].

Table 5. Producer gas, Specific enthalpy, specific entropy, standard chemical exergy and mole frac

Producer Gas	h_o (kJ/kmol.)	S_o (kJ/kmol.K)	ex_i^{ch} (kJ/kmol)	x_i	$x_i \cdot ex_i^{ch}$
O_2	8682	205.033	3,970	0.0597	237.009
N_2	8669	191.502	720	0.5339	384.408
$H_2O_{(g)}$	9904	188.720	9,500	0.0098	93.1
H_2	8468	130.574	236,100	0.1671	39,452.31
CO	8669	197.543	275,100	0.1345	37000.95
CO_2	9364	213.685	19,870	0.091	1808.17
CH_4	-	-	831,650	0.00366	3043.84

$$\beta = \frac{1.044 + 0.016(\frac{H}{C}) - 0.3493(\frac{O}{C})[1 + 0.0531(\frac{H}{C})] + 0.0493(\frac{N}{C})}{1 - 0.4124(\frac{O}{C})} \dots\dots\dots 17$$

$$LHV = 0.0041868(1 + 0.15O)(7837.667C + 33888.889H - \frac{O}{8}) \dots\dots\dots 18$$

4. RESULTS AND DISCUSSION

4.1 Numerical Simulation

The analysis of the study was carried out through numerical simulation using Aspen plus. Fig. 3 shows the simulation results versus air ratio on path one (AIR 1) at an interval of 0.1. In the analysis, measurements of flue gas composition were recorded by varying the air flow in both inlet paths (AIR1 & AIR2). The result shows that as air ratio increases in path AIR1 there was an increase of CO which attained its maximum when AIR1 was 0.3. At this interval CO₂ decreases with increase in CO as shown in Fig. 3. Further increase of air ratio in AIR1 results into the gradually increase of CO₂ while CO decreases. The H₂ was decreasing gradually throughout the entire process as the air ratio in AIR1 was increasing.

It can be revealed from Fig. 3 that the optimum operating condition was achieved when air ratio at AIR1 was 0.3. At this ratio the composition of CO₂ was at minimum while CO was at its maximum. Also the result shows that when the ratio at AIR1 was 1 the flue gas contains more CO₂ than CO. Furthermore, when the air ratio at AIR1 was 0 the composition of CO₂ was observed to be low compared to the CO composition. However, the entire process shows that when the air ratio in path AIR1 is 0 < AIR1 < 1 the HFBC model had better results. Therefore, these results show that, when operating at the HFBC mode, H₂ and CO content has better output compared to the results for both downdraft mode (AIR1=1) and cross draft mode (AIR2=1).

4.2 Heating Values

The value of LHV, HHV and gas composition for the simulated results are shown in Table 6. As shown in the Table, the value of HHV for the hybrid model (combined) is slightly higher compared to the other two models when the air path operates independently. This shows that the energy conversion when the two air paths operates together is much better compared to when each path operate independently. Therefore at an air ratio of 0.3 on path AIR1 gives better results.

4.3 Cold Gas Efficiency

According to Kirsanovs and Zandeckis [52] the gasifier cold gas efficiency ranges between 52.7 to 65.4%. In this study, the result shows that air path that combines the flow of AIR1 and AIR2

has better cold gas efficiency as compared to the results obtained when air paths operates independently as revealed in Table 7.

4.4 Exergy Efficiency

The chemical exergy for the system was 78661.0001kJ/kmol while the physical exergy was 169790.22 as revealed in Table 8. Therefore, the gas exergy was the sum of the two which equals to 248,451.2201 KJ /kmol.

The input exergy was evaluated to be 304819.2MJ and therefore the exergy efficiency was

$$\eta_{ex}^x = \frac{248451.22}{304819.2} \times 100 = 81.51\% \dots\dots\dots 19$$

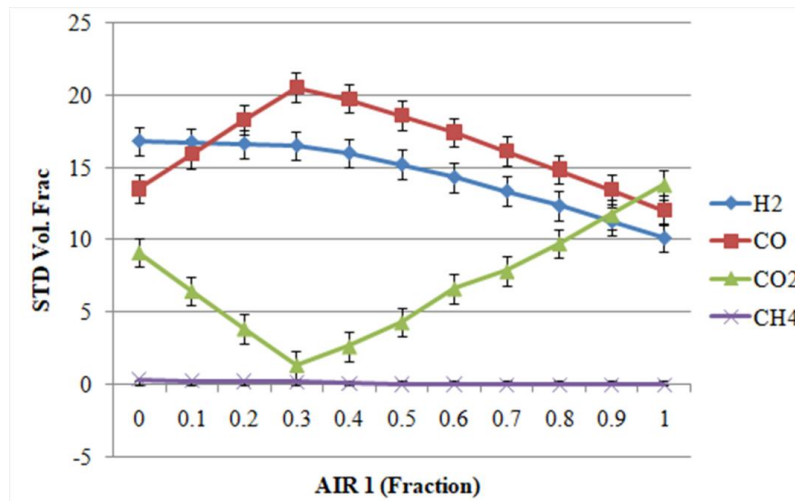


Fig. 3. Simulated gas composition (error bars with standard deviation of 1 %)

Table 6. Comparison of the producer gas on the air path

Description	Path AIR1	Path AIR2	Combined (Hybrid)
H2 (%)	10.17	16.82	16.50
CO (%)	12.05	13.54	20.56
CH4 (%)	0.000627	0.368	0.211
LHV (MJNm ⁻³)	2.621	3.658	2.846
HHV (MJNm ⁻³)	2.820	4.003	4.789
H2 (%) / CO (%)	0.844	1.24	0.804

Table 7. Cold gas efficiency

Air Path	Simulated GFR (NM ³ h ⁻¹)	P _B (kW)	P _G (kW)	η _{CG} (%)
AIR1	54.57	20	39.59	50.52
AIR2	57.02	20	57.94	34.52
Combined	38.31	20	30.28	66.05

Table 8. Physical exergy for some components at 800 °C

Component	H_2	O_2	N_2	$H_2O_{(g)}$	CO	CO_2	CH_4
Cp (kJ/kmol.K)	30.68	35.28	33.24	42.312	33.48	55.65	74.78
$h-h_o$	24544	28224	26592	33849.6	26784	44520	59824
$s-s_o$	40.009	46.0086	43.35	55.18	43.66	75.57	97.52
$T_o(s-s_o)$	11922.92	13710.56	12918.3	16443.64	13010.68	22519.86	29061.14
E^x_{ph}	12621.08	14513.44	13673.7	17405.96	13773.32	67039.86	30762.86

5. CONCLUSION

The present study has provided a room to conclude that HFBG is a viable option for MSW gasification. Two air flow paths were provided and the ratio of air in both paths were varied. A total air flow rate of 8.95kg/hr was introduced into the gasifier. A means of dividing the air into the two paths for numerical analysis was managed by FSPLIT. In the analysis data were recorded by varying the air ratio in the first air path (AIR1) at an interval of 0.1. Numerical results show that when the air ratio at AIR1 was 0.3 a maximum of 20.56 % CO and a minimum of 1.35 % CO₂ at STD VOL Fraction were obtained. For an air ratio above 0.3 the CO decreases gradually while CO₂ increases gradually with an increase of air ratio at AIR1. At this air ratio the cold gas efficiency for the HFBG model was 66.05% while for path AIR1 and AIR2 was 50.52 and 34.52% respectively. Furthermore, the exergy efficiency for the HFBG model was analysed to be 81.51%. Therefore, this shows that when air is supplied at both paths (HFBG) at a given ratio gives better results than when air is supplied to the air paths independently.

6. RECOMMENDATIONS

The numerical analysis of the study was carried out by investigating the performance of the air flow path. The analysis mostly based on the simulation of the results on gas composition, LHV, and cold gas efficiency. It was revealed that the combined air flow had better results compared to independent air flow. However, the experimental comparative studies for the air flow path should be carried out.

DATA AVAILABILITY

The authors prove that the data supporting the findings of this study are accessible within the article [and/or] its supplementary materials.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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