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Simulation and performance analysis of municipal solid waste gasification in a novel hybrid fixed bed gasifier

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SIMULATION AND PERFORMANCE ANALYSIS OF MUNICIPAL SOLID WASTE GASIFICATION IN A NOVEL HYBRID FIXED BED GASIFIER

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A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of PhD in Sustainable Energy Science and Engineering of the Nelson Mandela African Institution of Science and Technology

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ABSTRACT

Municipal Solid Waste (MSW) is a main challenge to municipalities in developing countries due to the increase in its production caused by technology development, community culture, population growth, and urbanization. The challenge is heightened by the scarcity of dumping sites within municipalities and the environmental impact associated with improper disposal management. Thermo-chemical conversion technologies (gasification, pyrolysis and incineration) have become to be known as practicable technologies for municipal solid waste management (MSWM). In this study, the Hybrid Fixed Bed Gasifier (HFBG) model was developed using Aspen Plus in order to merge the advantages of both downdraft and cross draft gasifiers and suppress their disadvantages. Furthermore, experimental analysis of the flue gas was carried out on the HFBG. The TESTO 327-1 flue gas analyzer was used to analyze the concentration of CO, CO_2 and O_2. The simulated results showed that the feedstock MC of about 59.8 wt% was lowered to 6.8 wt%. The developed hybrid fixed bed gasifier demonstrated an increase in H_2 and CO of about 29.29 % and 37.05 % mole fraction in the producer gas respectively. The syngas output was highly affected by the changes in the ER as well as change in temperature. The composition for H_2 and CO increases with increase in temperature while the composition decreases with ER between 0.1 to 0.4. However, at this ER CO_2 and H_2O tend to increases but above 0.4 CO_2 and H_2O decrease gradually. Experimental results show that after the elapse of 30 minutes CO and CO_2 concentration was 9.69% and 5.85% respectively. Furthermore, after 150 minutes of the gasification process, the output concentration for O_2 was 17.2 % while the concentration for CO and CO_2 was 0.0 % and 3.77 % respectively. The experimental results revealed that, during the entire gasification process the concentration for CO and CO_2 were decreasing with time while O_2 concentration was increasing. This result shows diversion from the simulated results due to gasifier leakages. With high MC of MSW, the study has shown that, HFBG can handle up 60 wt% as compared to downdraft which is limited to 20 wt%.

DECLARATION

I, Robert Eliraison Moshi do hereby declare to the Senate of Nelson Mandela African Institution of Science and Technology that this dissertation is my own original work and that it has neither been submitted nor being concurrently submitted for degree award in any other institution.

Robert Eliraison Moshi

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The above declaration is confirmed is confirmed by:

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Name and Signature of Supervisor 1 Date

Dr. Thomas Thomas Kivevele

Name and Signature of Supervisor 2 Date

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CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the Nelson Mandela African Institution of Science and Technology a dissertation titled "*Simulation and Performance Analysis of Municipal Solid Waste Gasification in A Novel Hybrid Fixed Bed Gasifier*" in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy in Sustainable Energy Science Engineering of the Nelson Mandela African Institution of Science and Technology.

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DEDICATION

To my beloved parents: The late Mr. Eliraison David Moshi and My Mother Ms. Elinjiana Hagai Marima and to my beloved wife Ms. Paullina and sons; Erick, Godlove as well as Ivan.

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LIST OF ABBREVIATIONS AND SYMBOLS

$\Delta g^{-0}{}_{f,T}$	Standard Gibbs function of formation
K_{shift}	Equilibrium constant for gas-shift
K	Equilibrium constant
C_P	Specific heat capacity
$H^0{}_{fi}$	The enthalpy of formation of the species
$\Delta H^0{}_T$	Change in enthalpy
$G^0{}_T$	Standard Gibbs free energy
H_{MSW}	Caloric value of MSW
H_g	Calorific value of syngas
B_g	Hearth load
B_s	The ratio between the dry fuel consumed in the gasifier to the surface area of the throat
d_h	Hearth diameter
A_n	Areas of the nozzle
d_t	The throat diameter.
ASPEN Plus	Advanced System for Process Engineering Plus
ATC	Arusha Technical College
CISOLID	Conventional solid
DCOALIGH	Coal model in the Aspen plus for computing density
ER	Equivalence Ratio
HCOALGEN	Coal model in the Aspen plus for computing enthalpy
HFBG	Hybrid fixed bed gasifier
Hp	Horse power
HTC	Hydrothermal Carbonization
HTL	Hydrothermal Liquefaction
HTT	Hydrothermal Treatment Technology
kW	Kilowatt
MC	Moisture content
MSW	Municipal solid waste

MSWM	Municipal solid waste management
RGibbs	Aspen plus chemical equilibrium reactor
RStoic	Aspen plus reactor with known stoichiometry
RYield	Aspen plus reactor with known product yield
SEP	Aspen plus separation block
SIDO	Small Industries Development Organization
WTE	Waste to Energy

CHAPTER ONE

INTRODUCTION

1.1 Background of the Problem

Energy is a key resource for economic development in all aspects of human endeavor. At present, about 81% of all the energy used globally is derived from fossil fuel and thus contributing to local environmental degradation including air pollution, and global climate change (Siedlecki *et al.*, 2011). Over-dependence on fossil fuel has increased greenhouse gaseous emissions which in turn into intensify multiple challenges including the effect of global warming, geopolitical conflicts and significant fuel price fluctuations (Schwartz, 1993; Dewallef, 2015; Ogundipe *et al.*, 2020). These problems indicate an unsustainable development situation. Notwithstanding its negative impacts on the environment, fossil fuels are also known to deplete with time as shown on the Hubbert curve (Dewallef, 2015). To meet the growing energy demand, different studies in the past few decades have focused on clean and sustainable alternative energy resources (Friederike, 2014; Etutu *et al.*, 2016).

Currently, the commonly used renewable sources of energy are biomass, wind, hydropower, and solar energy all of which collectively contribute up to 14% of world energy demand of which 2.1% come from biomass waste (Rafati *et al.*, 2016). Biomass referrs to all resources from plants and animals including organic waste from agricultural wastes, forest wastes and animal wastes (Kauriinoja & Huuhtanen, 2010). In Sub-Saharan Africa especially in rural areas, people practice inefficient use of biomass for cooking, drying, lighting and heating (Kitty *et al.*, 2013; Wassie *et al.*, 2021). Energy use in Tanzania mainly relies on biomass (charcoal and firewood) for about 90% (Doggart *et al.*, 2020). Petroleum products and electricity contribute about 8% and 1.5% respectively, while the remaining percentages are contributed by other renewable energy sources (Msyani, 2013; Doggart *et al.*, 2020). Furthermore, Bensch *et al.* (2019) reported that about 80% of the energy from biomass is used in rural areas whereas, only 17% of the population in the country are connected to the National Grid for electricity. The high percent utilization of biomass subjects the developing countries to a high rate of deforestation.

While there have been claims of deforestation and depletion of fossil fuel worldwide, on the other hand there has been a tremendous increase of municipal solid waste (MSW) generation. This increase in MSW generation is due to the increase in production of commodities caused by technology development, community culture, population growth, and urbanization (Kazuva *et al.*,

2018; Kazuva & Zhang, 2019). Globally MSW generation is expected to increase to 2.2 billion tonnes by 2025 (Al Seadi *et al.*, 2013; Ouda & Raza, 2014). In sub-Saharan Africa, the MSW generation is estimated to be sixty-two (62) million tonnes per year (Mohammed & Elias, 2017). In Tanzania as one of the developing countries, it is estimated that by 2025 the urban MSW generation will increase to 11 566 tonnes/day and the trend shows that this rate of generation in Tanzania is higher as compared to the other five countries in East Africa, Fig. 1 (Hoornweg & Bhada-Tata, 2012). This is due to its high population ratio compared to the other countries in the east Africa region.

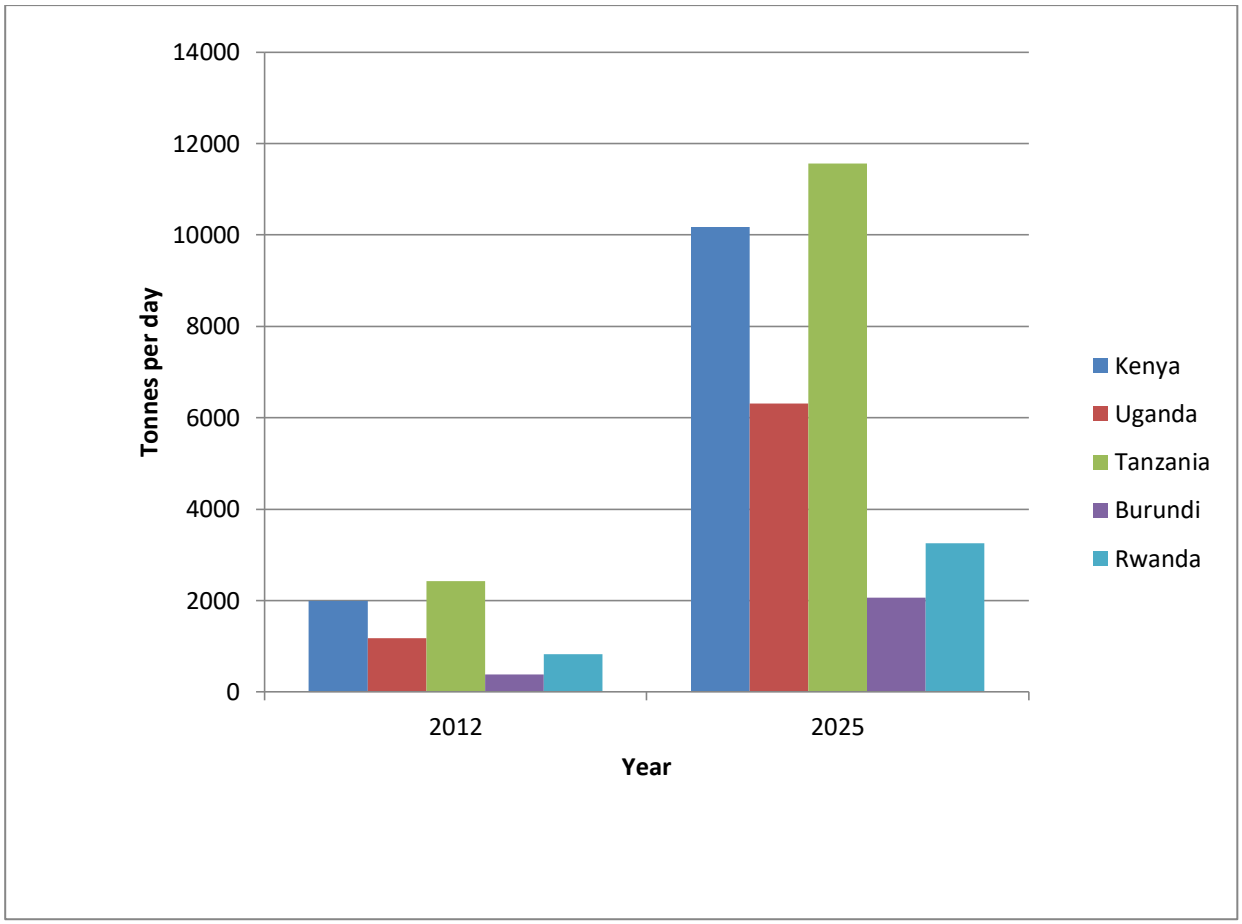


Figure 1: Trend of MSW Generations in East Africa (Hoornweg & Bhada-Tata, 2012)

Despite the fact that MSW has become a menace to many municipalities; it is one of the potential renewable energy sources. However, if not managed properly MSW results into several negative effects such as blockage of drainage and spread of some diseases due to the increase in insects breeding (Ejaz *et al.*, 2010; Singh *et al.*, 2014). Several methods have been employed for treating MSW including biological and thermo chemical methods. Biological methods can be either composting or anaerobic digestion (similar to landfill) of organic waste while thermo chemical method includes the following: incineration, pyrolysis and gasification. Open landfill has remained

as the major method for waste disposal in developing countries although to some extent metal and plastic wastes have been recycled. With this method there has been a concern on health issues and environmental pollution especially in air, water and land (Sipra *et al.*, 2018).

Energy recovery from Municipal solid waste (MSW) through Waste to Energy (WTE) technologies can be used as a strategy for MSW management (De Almeida, 2012; Awasthi *et al.*, 2019). There have been several WTE technologies for converting MSW into energy including biological (anaerobic digestion and fermentation), and thermal conversion technologies (hydrothermal liquefaction, incineration, pyrolysis and gasification). Biological conversion is time consuming technology thus thermal technologies become more preferred. Due to its low environmental pollution, gasification technology is found to be more encouraging.

Gasification is one of the WTE technology currently in use. Gasification process is carried out in the device known as gasifier. Several types of biomass gasifiers have been in use namely: fluidized bed, fixed bed, entrained and plasma gasification (Sansaniwal *et al.*, 2017). Although fluidized bed gasifier has been employed for MSW gasification, it is more complicated in construction and its initial cost is higher than in fixed bed. Therefore, fixed bed gasifier is mostly preferred due to its low initial cost.

Fixed bed gasification is one of the simplest systems among the other three, however it has some limitations. According to Atnaw *et al.* (2012) in the experimental study of the temperature profile for the fixed bed gasifier, reported that the major problem with downdraft gasifier is bridging and channeling which is usually caused by fuel downflow behavior of which it was recommended that gasifiers can be equipped with shakeable grate. Bridging and channeling occur when less dense feedstock forms a bridge across the gasifier and prevent continuous and uniform downflow of biomass, hence contribute to the increase of tar produced (Chopra & Jain, 2007). Apart from tar content in biomass gasification, the gasification technology like other thermal conversion technologies is limited by particle size. Larger particle sizes reduce the contact area of the particles hence affect the quality of the gas produced (Medic, 2012).

Commonly, fixed bed gasifiers are grouped into three types: updraft, downdraft and cross draft. Among the three types downdraft gasifier is more appropriate for gasification of MSW since the feedstock obtained from wastes has bulk density such that they can flow down easily. Downdraft fixed bed has low initial costs; however, it has several shortfalls including tar content output, bridging and the requirement for low MC feedstock. Bridging and channeling have been reported

as major problems for downdraft gasifier especially with non-uniform feedstock which is also the case for MSW. Tar has been also reported as a challenge for the clean producer gas. Furthermore, MC recommended for gasification in downdraft gasifier is supposed to be less than 20%. Zhang *et al.* (2005) reported that the MC for green wastes and food waste are at an average of 65% and 74% respectively. The randomly collected MSW has an average of 60% MC for the case of Arusha which need drying before gasification process.

1.2 Statement of the Problem

The MSW is a result of daily human activities which produce solid waste that need to be collected and thereafter either be disposed off or recycled. The MSW comprises the daily used and thrown bits and pieces such as food waste, furniture, glass, papers, plastics and all wastes similar to household waste excluding hazardous wastes from industries and hospitals (Shin, 2014; Tozlu *et al.,* 2016). The increase of MSW generation in the developing countries does not match with the capacity of many municipalities to dispose it.

In Tanzania, and many other developing countries, open dumping disposal method has been used for a number of decades. This method has a number of disadvantages including among others the leachate and the release of methane in the air. The method pollutes underground water as well as air. Depending on the calorific value, MSW can be converted to non-renewable energy through gasification process. Municipal solid waste management (MSWM) by gasification can generate syngas using either fluidized bed or fixed bed gasifier. The types of fixed bed gasifier (Updraft, downdraft, cross draft) used have several limitations including low Moisture content (MC) feedstock, high tar output, and bridging and channeling. Therefore, the necessity of further research on MSWM is of no doubt particularly focusing on developing a novel hybrid fixed bed gasifier that can handle biomass with high MC typical to MSW.

1.3 Rationale of the Study

The MSW has drawn the attention of the researcher due to its related health effects as well as its generation increase influenced by life style, population and urban growth. Employing sustainable WTE technology is therefore, a feasible way for reducing MSW in the cities. The WTE would also create new employment opportunities. Gasification is a better technology as it converts MSW to energy with less pollutant gases. The suitable type of gasifier for energy conversion from MSW is the downdraft type although other types can also be used with their limitations. However, the outstanding challenge with downdraft gasifier is the bridging and channeling and also the

requirement of low MC feed stock. The developed HFBG aimed at utilizing high MC feed stock, as well as low tar producer gas. It is envisaged that urban authorities will benefit from the HFBG.

1.4 Objectives of the Study

1.4.1 General Objective

To carry out Simulation and performance analysis of municipal solid waste gasification in a novel hybrid fixed bed gasifier.

1.4.2 Specific Objectives

In order to achieve the main objective, the following specific objectives was undertaken:

(i) To develop and evaluate the performance of the novel HFBG using Aspen Plus.

(ii) To develop MSW hybrid gasifier prototype and test its performance.

1.5 Research Questions

(i) What is the simulation and performance analysis of the novel HFBG using Aspen Plus?

(ii) What is MSW hybrid gasifier prototype expected from this study?

1.6 Significance of the Study

The developed hybrid gasifier model was expected to disclose the optimal operating conditions which favor good quality producer gas with low tar output where operating temperature is expected to be more than 800 ºC. The factors influencing energy conversion efficiency of a hybrid gasifier was optimized and the quality and quantity of producer gas from the MSW hybrid gasifier was observed to increase as compared to conventional gasifier. Thus, proper utilization of a developed MSW hybrid gasifier model as well as simulated results enabled the development of a novel MSW gasifier that would reduce the scattered waste. Furthermore, cities are expected to be clean and eliminate the possibility of water and land pollution hence eliminating the possibility of disease spread including cholera and dengue.

1.7 Delineation of the Study

The present study mainly focused on developing a novel hybrid fixed bed gasifier that can handle biomass with high MC typical to MSW. Therefore, the study carried out Simulation and

performance analysis of municipal solid waste gasification in a novel hybrid fixed bed gasifier base high MC feed stock, as well as low tar producer gas. To develop and evaluate the performance of the novel HFBG, the study did make use of Aspen Plus.

CHAPTER TWO

LITERATURE REVIEW

2.1 Municipal Solid Waste Management

The rapidly growing cities in developing countries are facing serious challenges in MSW management (Awasthi *et al.*, 2019). This is due to lack of sufficient administrative and financial resources (Khatib, 2011). In Tanzania, MSW management consumes almost 50% of the municipality limited budget while only about 60% of MSW is collected from residence areas as a result of poor infrastructure and lack of adequate funds (Kalwani, 2010). This has caused inappropriate disposal of MSW in many of the municipalities in the country. In Morogoro municipality, for example, many residences where waste collection service is not provided they usually dig an open pit near their house and burn unsorted wastes (Ryogo, 2015).

Landfill has remained as chief MSW disposal method in Dar es Salaam, Arusha and Mwanza cities. The dumpsites in these three cities have been planned to be upgraded to sanitary landfill (Ntakamulenga, 2012). However, the upgrading has not been achieved to the required standard. In the Pugu Kinyamwezi dumpsite in Dar es Salaam, the wastes are dumped without catchment for landfill gas and leachate and yet wastes are not covered for safe composting (Huisman *et al.*, 2016). Small percent of MSW was reported to be composed in small scale waste composting sites. One among the compositing sites includes the pilot-scale which was constructed in 1984 by the University College of Land and Architectural Studies (UCLAS), composting site known as Kisiwani Environmental Group (KEG) and KIWODET project (Mbuligwe *et al.*, 2002; Oberlin & Szántó, 2011; Membe, 2015). The aforementioned methods reveal that energy from MSW is not effectively harvested in Tanzania.

Land scarcity in the cities, and the problem associated with MSW disposal have led to a revival in research and development studies investigating alternative MSW disposal methods. Thus, attention is given to the studies of MSWM methods which involve the conversion of waste into energy. Thermo-chemical conversion method seems to be one of the best methods for energy harvesting from MSW. Under thermo-chemical method there are three processes involved which are combustion, gasification and pyrolysis. These methods are carried out depending on the feedstock characteristics.

2.2 Characteristics

To determine the combustion characteristics of MSW requires proximate and ultimate tests. Proximate analysis is carried out to analyze the amount of MC, 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 characteristics obtained herein are useful for the gasification process model development. Table 1 represents proximate and ultimate information for MSW at Arusha. This information was used as a sample to represent the characteristics of MSW in Tanzania.

The High Heating Value (HHV) is another factor considered for MSW to support combustion. According to Omari (2013) the HHV for MSW in Tanzania is 12.42 MJ/kg which indicates the ability of these materials to support burning although not as reactive as coal due to high content of oxygen. To improve MSW combustion reactivity requires means of reducing oxygen content and this can be done by limiting the supply of oxygen for combustion (Omari *et al.*, 2014a). Thus pyrolysis and gasification are the methods which use a limited supply of oxygen. Currently, incineration and gasification are becoming the most used WTE technology (Cheng & Hu, 2010).

Table 1: MSW Characteristics-Arusha

Location	Proximate Analysis				Ultimate Analysis						
	Moisture (wt%)	**Volatile (wt%)**	**Ash (wt%)**	**Fixed Carbon (wt%)**	**C (wt%)**	**H (wt%)**	**O (wt%)**	**N (wt%)**	**S (wt%)**	**CL (wt%)**	**P (wt%)**
Kaloleni	59.67	30.02	3.29	7.02	55.57	5.34	34.88	4.09	0.31	0.04	0.10
Central Market	55.70	34.69	5.97	3.64	53.20	5.24	34.71	2.86	0.37	0.04	0.11
Sakina	62.85	32.01	3.42	1.72	55.74	5.36	35.06	1.87	0.31	0.12	0.16
Tengeru	64.03	30.77	3.19	2.01	55.92	5.34	34.81	1.846	0.24	0.09	0.21
Average	**60.56**	**31.87**	**3.97**	**3.60**	**55.23**	**5.31**	**34.75**	**2.559**	**0.29**	**0.07**	**0.14**

Omari (2013)

2.3 Municipal Solid Waste Management in Tanzania

2.3.1 Current Status

In Tanzania MSW management depends on some factors including country environmental policy and municipal council capacity. The trends of MSW generation, collection from residential areas and management methods are shown in Table 2. From the information provided in the Table, it can be revealed that waste collection is not achieved as required indicating that residents use improper disposal methods.

Table 2: MSW generation vs recycling in Municipality

City/Municipality	Population (Census 2012)	MSW Generation (Tonnes/day)	Collection capacity (Tonnes/day)	Recycling (Tonnes/day)
Tanga	313 625	185.3	166.8	14.09
Arusha	507 903	550	302	8.8
Mwanza	706 453	338	227	unrevealed
Mbeya	385 279	400	140	unrevealed
Moshi	210 000	225	203	unrevealed
Dodoma	507 350	305	100	unrevealed
Lindi	78 841	23	11	unrevealed
Mtwara mikindani	108 299	97.5	59	unrevealed

Yhdego and Kingu (2016)

2.3.2 Challenges and Opportunities

(i) Challenges

The main challenge in Municipalities in Tanzania is the MSW management from its collection to the point of disposal. This is heightened by the scarcity of dumping sites and environmental impacts associated with improper MSW management and disposal in urban areas. Successful WTE requires waste sorting and separation especially at the source. In developed countries MSW separation is done at the source using a colored container with clearly labeled instructions (Zhang *et al.*, 2010). Despite the Government emphasizing the use of specified dust bins for storage at the collection points, this has not been implemented due several factors including high cost and security of the dust bins and therefore raises more difficulties in waste collection and separation (Ntakamulenga, 2012). Furthermore, according to Ntakamulenga (2012), another challenge with MSW collection and separation is lack of awareness as a result; households mixed up waste in containers and sometimes throw them by the roadsides.

There is a low investment and inadequate capacity in the renewable energy sector such that people are not well educated on how to separate solid waste for collection (Bauner *et al.*, 2012). Landfills dump site currently used in Tanzania are still in poor operating condition, this can be revealed in Pugu Kinyamwezi dumpsite where there are serious lack of adequate equipment (bulldozers, compactors and cranes), and the construction does not account for environmental protection as there is no provision for tapping landfill gas and leachate (Huisman *et al.*, 2016).

Incineration, pyrolysis and gasification are the renewable energy technologies currently considered for energy recovery from wastes. Biomass incineration likewise gasification is characterized by high mass and volume reduction of about 70% and 90% respectively (Marsh, 2009; Zhang *et al.*, 2010). However, incineration is associated with toxic and solid particle emission as well as high costs (Zhang *et al.*, 2010). Omari *et al.* (2015) investigated mass and energy balance of a local made fixed bed incinerator installed at Bagamoyo hospital Pwani region-Tanzania for hospital waste incineration. The analysis was carried out using Arusha MSW and it was revealed that the incinerator was characterized by low performance and high emissions (Omari *et al.*, 2015).

(ii) Opportunity

Tanzania being in a tropical region implies that its solid waste has HHV suitable for combustion (incineration, pyrolysis, and gasification) therefore instead of throwing them and polluting the environment they can be converted to energy. The government has shown concern on the existing waste collection and disposal problem; this shows a political will for government support of MSW management projects (Huisman *et al.*, 2016). Employing appropriate technology for MSW management could reduce the amount of unattended solid waste as well as creating employment opportunities. Hence WTE technology is therefore considered the best method for MSW management.

2.4 Waste to Energy Technologies

Biomass including MSW can be converted into useful energy. Currently, it accounts for about 10% of primary energy used in the world (Shrivastava, 2012). Energy from MSW can be recovered through two main technologies namely biological processes sometimes known as biochemical conversion method and thermal conversion technology (Scarlat *et al.*, 2015; Moya *et al.*, 2017). However, some physical treatments including separation of waste materials may be performed before thermal and biological treatment. The technological process used to extract energy from waste is termed a WTE technology. The WTE technology is becoming an attractive area of interest

for MSW management (MSWM). Various roots for converting waste into various form of energy are shown on Fig. 2

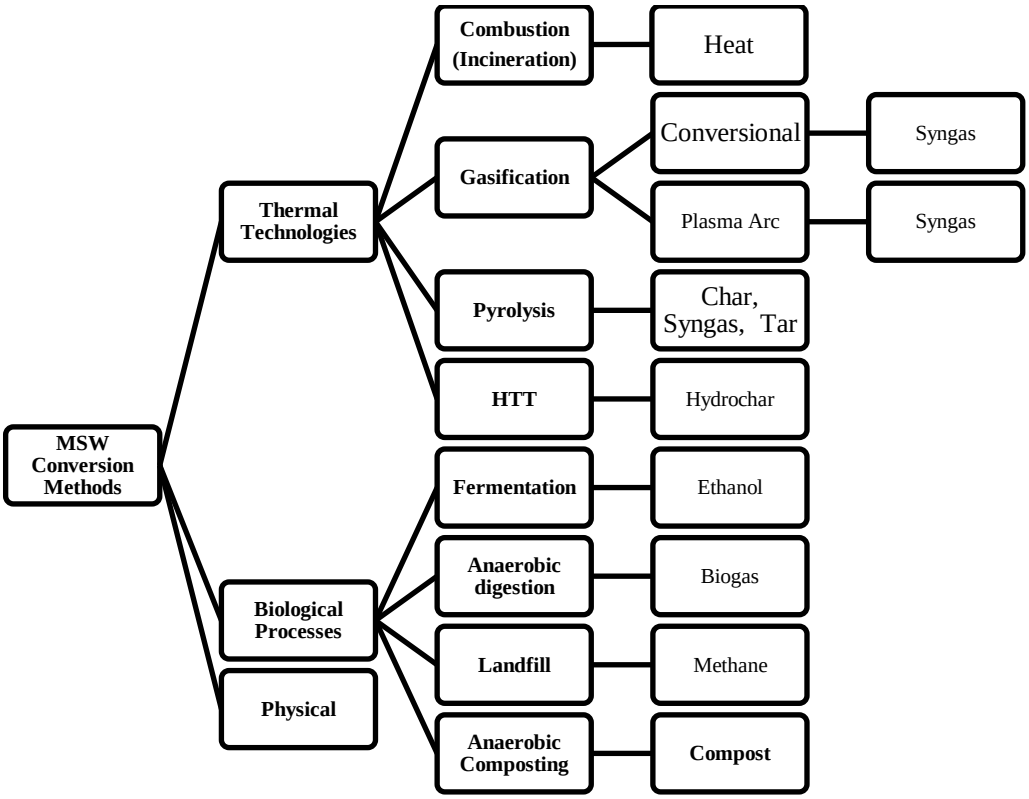


Figure 2: Waste Conversion Technology routes with Potential Products (Omari *et al.*, 2014b; Rafati *et al.*, 2016)

Biological methods include composting, anaerobic digestion, and landfill. Wallström (2000) defined composting as aerobic decomposition of biodegradable wastes under controlled conditions in the presence of oxygen and moisture to convert biodegradable material into humus by the action of micro and macro-organisms. Anaerobic digestion (AD), unlike aerobic digestion, is a biochemical conversion process in which microorganisms decompose organic materials under the absence of oxygen to produce methane, carbon dioxide, ammonia and hydrogen sulfide (Verma, 2002). Land filling process involves AD of organic wastes which releases carbon dioxide and methane (Wikner, 2009). The main disadvantage of the Biological method is the time consumed in the conversion process. Agarwal (2014), Gu *et al.* (2020) and Gu *et al.* (2020) reported that biological process requires more time for energy conversion from MSW as compared to the thermal process since the natural organisms decompose organic materials slowly.

The sanitary landfills are still a dominant method used worldwide for MSWM. In this system, land area is prepared thereafter the layers of MSW are covered in order to decompose and release

combustible gases such as methane and carbon dioxide (Tozlu *et al.*, 2016; Hemidat *et al.*, 2019). Landfills have been employed in the developed countries including New York City, Toronto, Canada and Mexico City, however, the dumping sites are situated away from the cities such that wastes are to be transported through trucks, barge and train (Curry & Pillay, 2012). Although landfill is the most common method used in Malaysia land scarcity and environmental pollution has been a serious concern. In China, according to Zhang *et al.* (2010) 1.5% of generated MSW was processed through a composting method, 4.5% was incinerated, 24% were dumped in a controlled landfill, 30% were not collected, and 40% were dumped in uncontrolled landfill.

On the other hand, in developing countries the population is increasing rapidly, such that land scarcity is also increasing in the cities, therefore increasing the need for alternative MSW conversion methods. Due the aforementioned land fill shortfall, the WTE technology especially thermal conversion technology has become a concern for MSWM. In Malaysia for example Manaf *et al.* (2009) reported that WTE technology employed includes sanitary landfills, incineration and gasification. There are several advantages associated with the use of WTE technology in comparison with other methods as detailed in Table 3.

Thermal conversion technology is characterized by large mass and volume reduction of about 80% and 90% respectively (Zhang *et al.*, 2010). Furthermore, it can be employed in a limited space as compared to landfill (www.SoCalConversion.org). In thermo-chemical conversion process wastes are heated in different amount of oxygen and different temperature range. This has resulted into different thermal technologies such as hydrothermal, pyrolysis, incineration and gasification (Kumar *et al.*, 2009; Moustakas & Loizidou, 2010; Kumar & Samadder, 2017).

Hydrothermal Treatment Technology (HTT), Hydrothermal Carbonization (HTC) also known as wet pyrolysis process and Hydrothermal Liquefaction (HTL) are emerging technology where high moisture wastes are heated under pressure and temperature ranging between 160℃ and 350℃ for upgrading waste materials (Staley, 2013; Areeprasert *et al.*, 2016).

In Pyrolysis, process wastes are heated under an oxygen-free environment to release gases, tars, and char depend on the heating rate and resident time. Pyrolysis being the initial stage of biomass gasification as well as combustion is classified into two categories: Slow or conversional pyrolysis and fast pyrolysis. Their main difference is based on the heating rate where the slow pyrolysis heating rates are usually below 100 K/min whereas for fast pyrolysis the heating rates exceeding 1000 K/min.

On the other hand incineration process decomposes waste at a high temperature above 800℃ to generate ash, heat and flue gases under excess air whereas pyrolysis in process wastes are heated under oxygen free environment to release gases, tars and char (Agarwal, 2014). The bio char produced by pyrolysis can be further treated through gasification process to release the remaining constituents (Brownsort, 2009). Gasification is carried out with limited amount of air/oxygen to produce syngas (CO and H_2) (Kadafa *et al.*, 2012). Incineration has been taking over slowly because of the low heating value of MSW. In China, for example, the heating value for the MSW is at an average of 5 MJ/Kg due to high MC, this value is less than a minimum value of 7 MJ/Kg required for incineration. However, depositing MSW in the waste pit for about seven days reduces its MC and increase heating value (Zhang *et al.*, 2010).

Several researchers have investigated the gasification process of MSW in comparison with other MSW energy conversion methods. Gasification is carried out in a limited amount of air/oxygen to produce syngas (CO and H_2) (Kadafa *et al.*, 2012). From the literature, it has been revealed that gasification is a readily available technology for energy recovery from wastes (Arafat & Jijakli, 2013; Liu, 2019). Al Naami (2015) reported that the gasification process is less polluting and has higher overall efficiency when used in combined heat and power (CHP) generation system as compared to incineration.

In terms of power generation incineration is estimated to generate about 550 kilowatt-hours of electricity in one tone of MSW while the gasification process can convert one tone of MSW to generate about 1000 kilowatt-hours of electricity (Gasification Technologies Council [GTC], 2014). Phillips and Mondal (2014) reported on their mathematical model of the MSW disposal technology that gasification is the best technology since its side effect towards environment pollution is less compared to other methods. Thus these given descriptions provide evidence that gasification is a better technology in converting MSW and other biomass resources into energy.

Table 3: Capital Costs, Advantages and Disadvantages of WtE Technology

Technology	Capital cost (US$/tonne of MSW/year)	Advantages	Disadvantages
Land filling	10–30	✓ Most economical technology ✓ Require less skilled personnel	✓ Leachate from the system contaminate underground water ✓ Require Large land area ✓ Pollution in rain season due to Surface runoff ✓ Transportation cost is high ✓ Can Yields about 30%–40% of the total gas generated ✓ Risk of exploration due to methane build up
Biochemical Conversion	-	✓ Require less land area ✓ Does not require external source of power for turning and mixing up wastes ✓ Better leachate and GHG emission control	✓ Waste sorting for feedstock with highly organic matter is required
Anaerobic digestion	50–350	✓ It does not require any external source of power ✓ The land required for the system is ideal	✓ Has low efficiency when feedstock sorting is not done ✓ Require feedstock with much higher organic content
Gasification	250–850	✓ Biomass gasification is well proven technology ✓ The process produce fuel gas which can be used for power generation	✓ Less efficient with highly moisture content above 30% as it create ignition difficult and reduces the syngas CV

Technology	Capital cost (US$/tonne of MSW/year)	Advantages	Disadvantages
		✓ In using the fuel gas the system reduce CO, NOx, furans, and dioxins hence better Pollution control. ✓ The system can be located within the cities hence reduce transport costs.	
Pyrolysis	400–700	✓ Better air pollution control	✓ Less efficient with high moisture content ✓ The burning and transportation of pyrolysis oil is difficult due to high viscosity ✓ It is less mature technology in comparison to gasification
Incineration	400–700	✓ Less land area is required ✓ Provides maximum volume reduction	✓ The system require skilled personnel ✓ It involves High Initial cost ✓ The system is highly pollutant due to particulate emissions, SOx, NOx and the high toxic metal concentration in ash

2.5 Gasification

2.5.1 Feedstock

The gasifier feedstock commonly used includes: coal, petroleum coke, and biomass such as wood, agriculture waste (coffee bean husks, bagasse, green waste etc) herbaceous. Currently the world has developed interest on MSW gasification as an alternative method for MSWM. The feedstock composition obtained through proximate and ultimate analysis is the main factors considered for gasification. Several literature have reported different compositions of MSW as shown in Table 4.

Table 4: Feedstock composition as discussed in different studies

Feedstock	Source	Proximate analysis				Ultimate analysis				
		MC	VM	FC	Ash	C	H	O	N	S
MSW	Chen *et al.* (2013)	48	46.15	7.7	46.15	30.77	4.62	17.3	0.77	0.39
MSW	Erping *et al.* (2019)	51.87	54.37	24	21.63	40.44	4.75	21.13	0.94	1.72
MSW	Ramzan *et al.* (2011)	50.9	18.8	7.6	22.7	39.35	4.96	10.13	1.43	0.83
MSW-pellets	Saleh and Sudarmanta (2018)	9.82	65.78	20.19	4.21	47.26	6.7	45.54	0.49	0.01

From Table 4 it is revealed that the MC of MSW is higher beyond gasification limit for fixed bed gasifier. Furthermore, the ash content is also observed to be higher compared to the pelletized MSW. However, the high MC for the MSW has low oxygen content hence low oxidative behavior.

2.5.2 Gasification Process

Gasification process employs oxygen starved environment to convert organic compounds in the MSW into synthesis gases. The produced gases include methane, carbon monoxide, hydrogen and small amount of gases such as carbon dioxide, nitrogen etc, as shown in the following chemical reaction:

$CH_xO_y + O_2 = CH_4 + CO + CO_2 + H_2 + H_2O + C + Tar$ (Kumar *et al.*, 2009).

The quality of syngas produced is characterized by among other factors, the type of feedstock, temperature and the type of gasifying agent (Air, oxygen, water) (Kumar *et al.*, 2009). According to Pilusa and Muzenda (2014), gasification of MSW in form of refuse-derived fuel (RDF) is more effective for heat generation and production of syngas. This and some other reactions takes place in the device known as gasfier in which some of MSW is combusted to generate heat for facilitating gasification process (Klein, 2002).

Generally, fixed bed and fluidized bed are the common gasifier designs in use depending on the intended purpose. Fluidized bed gasifier design is more preferred for large scale application while fixed bed is commonly employed for small scale range (Kramreiter *et al.*, 2008). In fluidized bed gasifiers, the fuel and gasifying media behave like fluids (Siedlecki *et al.*, 2011). A blower is used to force gas vertically upward through the loosely packed solid particles in the gasifier. This causes the particles to exert opposing force so as to balance the drag force applied by the gas. As gas velocity increases, it reaches a point where the weight of the particles becomes the same as the drag force and the bed becomes fluidized (Latif, 1999). However, fluidized bed gasifier has high initial cost as well as complexity in design as compared to fixed bed gasifier. These are the reasons that makes fixed bed type more preferred for small scale application.

Commonly there are three types of fixed bed gasifier (FBG): Downdraft, updraft and cross flow (Fig. 3). These are named with respect to the direction of the flow of gasifying media (air, oxygen and steam). In these three types of gasifiers the feedstock enters from the top and flows downward, their difference being the gasifying media flow direction as well as the direction of produced sygas. In the downdraft type the gasifying media enters at the center and flow downs the gasifier. In the

updraft type, the gasifying media enters at the bottom and flows up the gasifier whereas the cross flow type gasifying media enters at one side and flow across the gasifier.

Cross flow gasifier on the other hand has been used in small scale ranges. This type of FBG is not affected by the feedstock MC as it can handle biomass with considerable MC especially when the top of the gasifier is open for moisture to escape. However, the fuel particle size is considered to be as small as 20 mm while the maximum size that can be handled by updraft as well as downdraft gasifier is about 70 mm in size respectively.

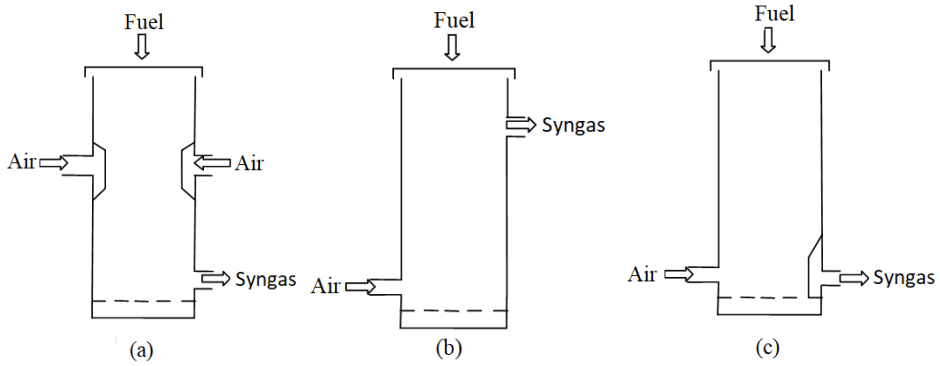


Figure 3: Types of fixed bed gasifiers: (a) Downdraft, (b) Updraft, (c) Cross draft (Shrivastava, 2012)

Downdraft gasifiers (DDG) have the advantage of producing gaseous fuel with low tar; this makes it more superior to updraft gasifier for clean producer gas. Tar is an aromatic condensable hydrocarbon that causes fouling on pipes and equipment where producer gas is being used if not cranked into combustible particles. In downdraft gasifier tar produced in the pyrolysis zone is carried along with incoming air through hot oxidation zone where tar cranking occurs, however complete tar separation is not well achieved on the DDG.

Updraft gasifier is one of the most common FBG in use especially when the temperature of producer gas is considered. It produces gases with low temperature as compared to the other two types since the gases produced dry the feedstock before exit. However, the tar content in the syngas is higher than that obtained in the other two types hence requires extensive clean up.

Rajvanshi and Goswami (1986) reported that chemical reaction at the downdraft gasifier throat does not allow complete separation of tar from producer gas. Asadullah (2013) reported several methods for producer gas cleaning including filtration, catalytic and thermal cranking. However, the use of filtration and catalytic conversion methods requires additional cost to the gasification system, thus the best option would be to develop a design model that can deliver optimal operating temperature and longer residence time hence increase thermal energy for tar cranking.

Therefore, further minimization of tar in DDG can be achieved through improving the thermal cranking technique to achieve temperature higher than the downdraft gasifier combustion zone temperature which ranges between 800℃to 1000℃ (Shelke *et al.*, 2014). The recommended temperature at which tar cracking occurs is about 1000℃ (Fjellerup *et al.*, 2005).

Furthermore, Amos (1999) reported that using dry fuel results in high temperature hence increase system efficiency as well as low emission. The MSW is associated with high MC; however, co-gasification has been used for controlling MC (Anukam *et al.*, 2016). The MC affects energy recovery from MSW greatly. Omari (2013) reported that the average mc for the MSW produced in Arusha is about 60%. The reported amount was higher than the recommended MC for the general gasification process which is 50%.

It has been reported that the biomass MC of less than 20% is suitable for the gasification process in the imbert downdraft gasifier (Bhavanam & Sastry, 2013). Since MSW has high MC the common gasifier cannot handle such feedstock without pre drying.

2.5.3 Gasification Kinetics

The entire gasification process occurs in three steps namely: Biomass decomposition, volatile reactions and char gasification. These steps involve several chemical reactions which are influenced by among other factors, the operating parameter of the gasifier. Furthermore, to achieve optimal gasifier design requires mostly the information on the char gasification step. The char physical characteristics depend on the conditions of the gasifier operating parameters during its formation. The parameter includes among others: the reactor temperature, gasifying agent, feed stock type and its particle size.

These parameters also affect the char reaction rates usually known as gasification kinetics. Several studies have been carried out to investigate the char gasification kinetic. Many of these studies involved the following chemical reactions (Roy *et al.*, 2009; Catalanotti *et al.*, 2020):

$$C + CO_2 \leftrightarrow 2CO \quad (1)$$

$$C + H_2O \leftrightarrow CO + H_2 \quad (2)$$

$$C + 2H_2 \leftrightarrow CH_4 \quad (3)$$

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad (4)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (5)$$

These chemical reactions were used to evaluate the reaction rate using Arrhenius expression:

$$r = A\exp\left(\frac{-E}{RT}\right) \quad (6)$$

Where r is the reaction rate constant, A is the exponential factor, E is the activation energy, R is the universal gas constant, and T is the temperature. This expression results into the following reaction rate developed from chemical reactions 1 to 5:

$$r_1 = A_1\exp\left(\frac{-E_1}{RT}\right)\cdot\left(P_{CO_2} - \frac{P^2{}_{CO}}{K_1}\right) \quad (7)$$

$$r_2 = A_2\exp\left(\frac{-E_2}{RT}\right)\cdot\left(P_{H_2O} - \frac{P_{CO}P_{H_2}}{K_2}\right) \quad (8)$$

$$r_3 = A_3\exp\left(\frac{-E_3}{RT}\right)\cdot\left(P^2{}_{H_2} - \frac{P_{CH_4}}{K_3}\right) \quad (9)$$

$$r_4 = A_4\exp\left(\frac{-E_4}{RT}\right)\cdot\left(P_{CH_4}P_{H_2O} - \frac{P_{CO}P^3{}_{H_2}}{K_4}\right) \quad (10)$$

$$r_5 = A_5\exp\left(\frac{-E_5}{RT}\right)\cdot\left(P_{CO}P_{H_2O} - \frac{P_{CO}P^3{}_{H_2}}{K_5}\right) \quad (11)$$

The value of equilibrium constant K_i for the chemical reactions 7 to 11 is evaluated in Equation 12 to16 respectively.

$$K_1 = \exp\left(\frac{g^{-0}{}_{CO_2}}{RT} - \frac{g^{-0}{}_{CO}}{RT}\right) \quad (12)$$

$$K_2 = \exp\left(\frac{g^{-0}{}_{H_2O}}{RT} - \frac{g^{-0}{}_{CO}}{RT} - \frac{g^{-0}{}_{H_2}}{RT}\right) \quad (13)$$

$$K_3 = \exp\left(2\frac{g^{-0}{}_{H_2}}{RT} - \frac{g^{-0}{}_{CH_4}}{RT}\right) \quad (14)$$

$$K_4 = \exp\left(\frac{g^{-0}{}_{CH_4}}{RT} + \frac{g^{-0}{}_{H_2O}}{RT} - \frac{g^{-0}{}_{CO}}{RT} - 3\frac{g^{-0}{}_{H_2}}{RT}\right) \quad (15)$$

$$K_5 = \exp\left(\frac{g^{-0}_{CO}}{RT} + \frac{g^{-0}_{H_2O}}{RT} - \frac{g^{-0}_{CO2}}{RT} - \frac{g^{-0}_{H_2}}{RT}\right) \quad 16$$

Therefore, the net rate of formation for hydrogen, carbon monoxide, carbon dioxide, water, methane, nitrogen and char is evaluated in Equation 17 to 23

For Hydrogen the net rate is $R_{H_2} = r_2 - 2r_3 + 3r_4 + r_5$ 17

For Carbon monoxide is $R_{CO} = 2r_1 + r_2 + r_4$ 18

For carbon dioxide is $R_{CO_2} = r_5 - r_1$ 19

For wateris $R_{H_2O} = -r_2 - r_4 - r_5$ 20

For methaneis $R_{CH_4} = r_3 - r_4$ 21

For Nitrogen is $R_N = 0$ 22

For Char $R_C = -r_1 - r_2 - r_3$ 23

2.5.4 Gasifying Media

In biomass gasification system the output depends on among other factors the following: The type of feedstock, and the gasifying agent. The most common gasifying agent are: Pure oxygen, steam, carbon dioxide and air (Oyugi *et al.*, 2018). The selection of the gasifying media depends on the intended quality of producer gas. Air produce syngas with the HHV between 4-7 MJm^{-3} while steam and pure oxygen produce syngas with HHV ranging between 10 to 18 MJm^{-3} respectively (Latif, 1999; Sadhwani *et al.*, 2016). Although pure oxygen and steam produce a high quality producer gas, it has an addition cost of obtaining the steam as well as pure oxygen.

2.5.5 Gasification Modeling

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. Furthermore, the gasifier design plays the important role on the quality and quantity of the output snygas. In this context it is important to simulate the designed gasifier so as to predict the output before manufacturing. Depends on the type of simulator, there have been several gasification model. These

include: Mathematical modeling, Computational Fluid Dynamic (CFD) model, Artificial Neural Network, Thermodynamic equilibrium model, and ASPEN plus model. The modes are brief explained in the following sub-sections.

(i) Mathematical Modeling

Mathematical modeling is used to interpret problems from the actual area into mathematical formulas so as to provide guidance towards getting solutions. Donskoy *et al.* (2016) studied a staged fixed bed gasification process using mathematical modeling, and they were able to model air ratio and heat flux at pyrolysis zone. Furthermore, Mandl *et al.* (2010) employed a set of differential Equations to model the combustion and gasification process in the updraft fixed bed gasifier. They indicated that there was good agreement between the calculated and experimental results regarding the axial temperature profile. However, the predicted composition of produced syngas was inadequate.

(ii) Artificial Neural Network

Artificial Neural Network (ANN) has found its application for modeling gasifiers especially circulating fluidized bed and bubbling fluidized bed. The study done by Puig-Arnavat *et al.* (2013) show the application of ANN in both types of gasifiers. They reported that the producer gas results for biomass fluidized bed gasifier can be well predicted using ANNs model.

(iii) Thermodynamic Equilibrium Modeling

Thermodynamic equilibrium model is preferred when gasifier design features are found unnecessary, as compared to gasifier operating parameters. This model is based on chemical equilibrium of the system at minimum Gibbs free energy (Sadhwani, 2017). Equilibrium model are mostly suitable for simulating entrained-flow gasifier as well as downdraft fixed bed gasifier at higher throat temperature and gas residence time respectively (Puig-Arnavat *et al.*, 2013).

(iv) Computational Fluid Dynamic

Computational fluid dynamic (CFD) is a mathematical model tool which is used to analyze the characteristic and interaction of the fluid in motion. A number of simultaneous equations inserted in the software determine the conservation of mass, momentum and species in the gasifier. The CFD simulation provides two options: Euleriun-Lagrange approach and Euleriun- Euleriun approach. The former approach is not feasible for the simulation of a large scale fluidized bed

system since it requires enormous amount of computational resources while the later approach requires less amount of computation. Many of the CFD simulation conducted by various researchers based on coal. Currently biomass gasification modeling has been carried out using CFD. Liu *et al.* (2013) used Eulerian-Eulerian approach to simulate the biomass gasification in a fluidized bed reactor. They investigated the impact of the following model: turbulence, radiation, water gas shift reaction and equivalent ratio (ER). The results obtained were in good agreement with the one obtained experimentally.

(v) ASPEN Plus Model

Although CFD model has been used for modeling gasification system, it requires availability of all necessary equations (Begum *et al.*, 2013). The system which incorporates physical characteristics of the reactor as well as gasification reactions is well modeled by the use of ASPEN plus simulator. The ASPEN plus model have been used to predict the output syngas composition (Ding *et al.*, 2019).

Various researchers have used an Aspen Plus simulator to carry out modeling and simulation of gasification processes for biomass including sawdust, wood, bagasse and corn cobs (Nikoo & Mahinpey, 2008; Keche *et al.*, 2015; Awais *et al.*, 2018). However few have worked on the simulation of MSW gasification using aspen plus simulator. Begum *et al.* (2013) developed a computational model based on Gibbs free energy minimization for simulating wood, coffee bean husks, green wastes and MSWs gasification. They revealed that varying parameters such as air-fuel ratio and temperature affect syngas composition. Li *et al.* (2013) developed a gasifier model for solid waste gasification based on Gibbs free energy minimization, and it was observed that the optimal operating condition was achieved at an air ER of 0.4 and gasifier temperature of 600°C by preheating the incoming air to 600°C.

Begum *et al.* (2014a) developed and investigated an MSW fixed bed gasification model. The model was validated with experimental data published by Naveed *et al.* (2009). Furthermore, they investigated the effect of varying air-fuel ratio and also the effect of temperature for syngas composition. The author revealed that the gasification of MSW in a fixed bed gasifier was optimum at a temperature of 700℃ and an air-fuel ratio of 0.3. Recently, Dahmani *et al.* (2017) developed a numerical fixed bed gasifier model using aspen plus and investigated the effect of temperature and ER on syngas composition. It was revealed that the ER of 0.1 at 900℃ was the optimal value.

Using aspen plus, sub system can be modeled separately before being integrated in a single complex system (Sadhwani, 2017). This makes aspen plus more useful compared to the other computer

simulation softwares. The software is equipped with seven reactor model: RStoic, RYield, REquil, RGibbs, RCSTR, PPlug and RBatch. Each of these reactor are selected depends on the input and the expected output. To connect the reactor model: materials, heat and work streams are used. Generally, ASPEN plus have been used to model coal gasification specified in the software as non-conversional component where enthalpy and density are evaluated by Aspen physical properties known as HCOALGEN and DCOALIGT respectively.

2.6 Summary

In this chapter, literature review relating to the research objectives related to MSW gasification has been presented, which covers: MSW characteristics, its challenges and opportunities, the WTE technology used for MSWM, MSW gasification and types of gasifier as well as gasification modeling. From this chapter several key points emerged: The MSW generation in developing countries is tremendously increasing. However, in these countries the MSWM to some extent does not take into account energy that would be harvested from MSW.

The MSW characteristics in many of these countries contain energy content enough for WTE processing. Regardless the gasifier has been used for MSW gasification, the literature study revealed that many of them faces challenges such as bridging and channeling, high tar output, and low MC feedstock. Different researchers have developed several MSW gasification models; which however still show presence of high levels of MC. Therefore, the reliable models should be developed and analyzed.

CHAPTER THREE

MATERIAL AND METHODS

3.1 Overview

The methods adopted in this study was based on three areas: Mathematical modeling, numerical investigation using ASPEN Plus and lastly an analytical design of the hybrid fixed bed gasifier. Comparative analysis was carried out to investigate the validity of the study. For analytical design procedures, the various gasifier parameters were investigated including throat diameter, gasifier diameter, nozzle position and its size and the height of the gasifier.

3.2 Modeling

3.2.1 The Gasifier Modeling

(i) Municipal Solid Waste Gasification Equilibrium Model

Gasification is a thermo-chemical process that involves several complex chemical reactions to transform solid fuel into gaseous fuel mainly dominated by H_2 and CO usually called syngas. For the equilibrium model, it is assumed that boudouard, water-gas and methane reactions attain equilibrium in the reactor. The three reactions involve chemical reactions for the species as follows:

$$C + CO_2 \Leftrightarrow 2CO \quad \text{Boudouard reaction} \qquad 24$$

$$C + H_2O \Leftrightarrow CO + H_2 \quad \text{Water-gas reaction} \qquad 25$$

$$C + 2H_2 \Leftrightarrow CH_4 \quad \text{Methane reaction} \qquad 26$$

According to Koroneos and Lykidou (2011b), the two equilibrium reactions 24 and 25 are combined to form Equation 27 well-known as water-gas shift reaction.

$$CO + H_2O \Leftrightarrow CO_2 + H_2 \quad \text{Water-gas shift} \qquad 27$$

Literature have reported several biomass gasification models which include different chemical elements. Zainal *et al.* (2001) developed an equilibrium model with three-element: Carbon, hydrogen and oxygen (CHO) (Melgar *et al.*, 2007) with five elements carbon, hydrogen, oxygen, nitrogen and sulfur (CHONS) (Vaezi *et al.*, 2008; Diji & Popoola, 2015) with four-elements carbon,

hydrogen, oxygen and nitrogen (CHON), in this study seven-elements (CHONSCLP), have been considered and the procedure for evaluating the output is shown in Fig. 4.

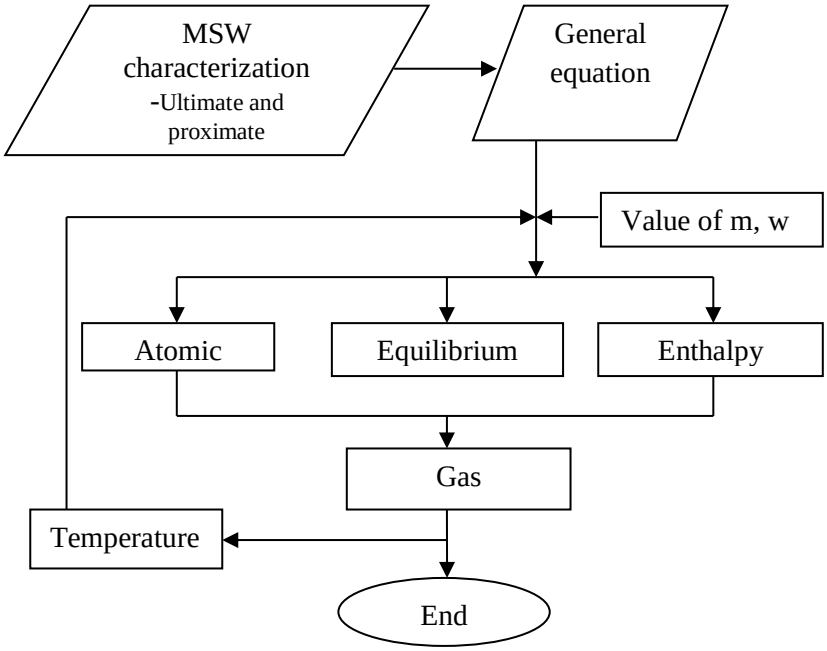


Figure 4: Procedure for calculating end product

The characteristics for the MSW indicated in Table 1 generates the following chemical formula:

$$C_{4.6025}H_{5.31}O_{2.17}N_{0.18}S_{0.009}CL_{0.002}P_{0.005}$$

Based on single atom of carbon the general chemical formula for the MSW becomes:

$$CH_{1.23}O_{0.47}N_{0.039}S_{0.002}CL_{0.0004}P_{0.001}$$

This formula is used as a reference to formulate the general equation of MSW base on Table 1. Assuming that all carbon is converted into gaseous state (Diji & Popoola, 2015), the general Equation is as follows:

$$CH_qO_rN_tS_uCL_vP_y + wH_2O + m(O_2 + 3.76N_2) \leftrightarrow$$
$$x_1H_2 + x_2CO + x_3CO_2 + x_4CH_4 + x_5H_2O + x_6HCL + x_7SO_2 + x_8NO + xP_4O_6 + (\tfrac{t}{2} + 3.76\ m)N_2 \quad (28)$$

From the gasification reaction 28 there are two unknown on the left hand side, w and m represents the amount of moisture and the amount of air per kmol of fuel respectively, on the right hand side $x_1 \ldots\ldots x_{10}$ represents the unknown coefficients of the species in the product gaseous. Nitric oxide (NO) is involved in Equation 28 since it contributes more nitrogen oxide in comparison to nitrogen

dioxide NO_2 and N_2O. The amount of water per kmol of MSW represented by letter w can be determined by using Equation 29.

$$w = \frac{24\ MC}{18(1-MC)} = \frac{24\times 0.6056}{18(1-0.6056)} = 2.05 \quad (29)$$

Whereas from Table 1 the MC for the MSW is 0.6056. The value of molar quaintly of air (m) according to Melgar *et al.* (2007) is inversely proportional to the product of ER and stoichiometric air-fuel ratio. According to Jenkins and Legrand (2005) the air-fuel ratio for biomass range between 4 to 7, whereas the ER for biomass gasification is between 0.2 to 0.3 (Molino *et al.*, 2018), by considering the higher value of the ER, the amount of oxygen per kmol of MSW (m) is evaluated as follows:

$$m = \frac{1}{ER\times F_{St}} = \frac{1}{0.3\times 7} = 0.48 \quad (30)$$

Furthermore, taking into account the atom balance on both sides for chemical reaction 28 the following Equations are formulated for the unknowns.

Atomic balance for carbon:

$$x_2 + x_3 + x_4 = 1 \quad (31)$$

Atomic balance for hydrogen:

$$2w + q = 2x_1 + 4x_4 + 2x_5 + x_6 \quad (32)$$

Atomic balance for oxygen:

$$w + r + 2m = x_2 + 2x_3 + x_5 + 2x_7 + x_8 + 6x_9 \quad (33)$$

Atomic balance for nitrogen:

$$t + 2(3.76)m = x_8 + 2(\frac{t}{2} + 3.76) \text{ but } x_8 = 0 \text{ and } t = 0.039 \quad (34)$$

Atomic balance for sulphur, chlorine and phosphorus are described in Equation 35 respectively

(i) $u = x_7 = 0.002$ (ii) $v = x_6 = 0.0004$ (iii) $y = 4x_9 = 0.001$

35

The equilibrium constant for methane reaction was represented as follows:

$$K_{methane} = \frac{P_{CH_4}}{P^2_{H_2}} = \frac{x_4}{x^2_1} \text{ hence } \quad x^2_1 K_{methane} = x_4 \qquad 36$$

And the equilibrium constant for gas-shift reaction was represented as follows:

$$K_{shift} = \frac{P_{CO_2} P_{H_2}}{P_{CO} P_{H_2O}} = \frac{x_3 x_1}{x_5 x_2} \text{ hence } \qquad x_5 x_2 K_{shift} = x_3 x_1$$

37

From Equation 28, there are ten unknown, $m, x_1 - x_9$ these requires ten Equations 30-35 (i, ii, iii) 36, and 37. Also $q = 1.23$, $r = 0.47$, $t = 0.039$, $u = 0.002$, $v = 0.0004$, $y = 0.001$ and from Equation 34, $x_8 = 0$

The system of Equations above was rearranged to form the following Equations:

Atomic balance for carbon:

$$x_2 + x_3 + x_4 = 1 \text{ Therefore } \quad x_4 = 1 - x_2 - x_3 \qquad 38$$

Atomic balance for hydrogen:

$$2w + q = 2x_1 + 4x_4 + 2x_5 + x_6$$

Therefore,

$$x_5 = -x_1 - 2x_4 + w + 0.6148$$

Substitute Equation 38,

$$x_5 = -x_1 + 2x_2 + 2x_3 + w - 1.3852 \qquad 39$$

Atomic balance for oxygen:

$$w + r + 2m = x_2 + 2x_3 + x_5 + 2x_7 + x_8 + 6x_9$$

$$w + 0.47 + 2m = x_2 + 2x_3 + x_5 + 0.004 + 0.0015$$

Substitute m=0.48 and Equation 39 into above Equation gives:

$$2m = -x_1 + 3x_2 + 4x_3 - 1.8497$$

Therefore,

$$-x_1 + 3x_2 + 4x_3 - 1.8897 = 0 \qquad 40$$

$$K_{methane} = \frac{P_{CH_4}}{P^2_{H_2}} = \frac{x_4}{x^2_1} \quad \text{and} \quad x^2_1 K_{methane} = x_4$$

Substitute Equation 38 gives:

$$x^2_1 K_{CH_4} - 1 + x_2 + x_3 = 0 \qquad 41$$

And the equilibrium constant for gas-shift reaction can be represented as follows:

$$K_{shift} = \frac{P_{CO_2} P_{H_2}}{P_{CO} P_{H_2O}} = \frac{x_3 x_1}{x_5 x_2} \quad \text{and} \quad x_5 x_2 K_{shift} = x_3 x_1$$

Substitute w=2.05 and Equation 39 in Equation above gives

$$(-x_1 + 2x_2 + 2x_3 + 0.6648) x_2 K_{shift} - x_3 x_1 = 0 \qquad 42$$

Equation 40, 41, and 42 can be used to solve for x_1, x_2 and x_3 after determine the value of K_s. The equilibrium constants (Equations 36 and 37) depend on the temperature of the gasification zone. This dependence is expressed by Gibbs free energy; therefore having $G°_T$ for gaseous equilibrium constant can be evaluated.

$$\ln K = \frac{-\Delta G^o_T}{RT} \text{ this is equivalent to } \quad K = \exp(-\frac{\Delta G^o_T}{RT}) \qquad 43$$

where R is the universal gas constant and $\Delta G°$ is the standard Gibbs free energy function of formation usually at a temperature of 25°C and pressure of 1atm (Arafat & Jijakli, 2013).

$$\Delta G^o_T = \sum_i V_i \Delta g^{-0}_{f,t,i} \quad \text{and}$$

$$\Delta g^{-0}_{f,T} = h^{-0}_{f} - aT\ln(T) - bT^2 - \frac{c}{2}T^3 - \frac{d}{3}T^4 + \frac{e}{2T} + f + gt \qquad 44$$

Where v_i represents stoichiometric coefficient for the reactant (-ve) and products (+ve). The values of coefficient a-g are indicated in Table 4.

(ii) Enthalpy Balance

To determine the equilibrium constant (Equation 36-38) the gasification temperature should be known. This temperature was determined using the concept that the enthalpy of the reactants is equal to the enthalpy of the products. As for the law of conservation of energy, the total enthalpy of chemical reactions remains constant; this means that the enthalpy of the reactants is equal to the enthalpy of the products involved in the chemical reactions. Assuming that the gasification process is adiabatic, the enthalpy balance for Equation 28 becomes:

$$aH^0_{f(MSW)} + wH^0_{f(H_2O-L)} + wH_{(H_2O-vap)} + m(H^0_{f(O_2)} + 3.76H^0_{f(N_2)}) = \sum x_i H^0_{f(Product)} + \Delta H^0_T \qquad 45$$

$$\Delta H^o_T = \int_{T_0}^{T} C_P(T)dT \qquad 46$$

Equation 46 is summarized to Equation 47 as follows:

$$\sum_{j=React} H^0_{f,j} = \sum_{i=Prod} x_i(H^0_{f,i} + \Delta H^0_{T,i}) \qquad 47$$

Assuming $a = 1$ Equation 45 transforms to Equation 48

$$\begin{aligned} &H^0_{f(MSW)} + wH^0_{f(H_2O-L)} + wH_{(H_2O-vap)} + m(H^0_{f(O_2)} + 3.76H^0_{f(N_2)}) = x_1H^0_{fH_2} + x_2H^0_{fCO} \\ &+x_3H^0_{fCO_2} + x_4H^0_{fCH_4} + x_5H^0_{fH_2O-Vap} + x_6H^0_{fHCL} + x_7H^0_{fSO_2} + x_8H^0_{fNO} + x_9H^0_{fP_4O_6} \\ &+(\frac{t}{2} + 3.76m)H^0_{fN_2} + \Delta T(x_1C_{P(H_2)} + x_2C_{P(CO)} + x_3C_{P(CO_2)} + x_4C_{P(CH_4)} + x_5C_{P(H_2O-Vap)} + x_6C_{P(HCL)} \\ &+x_7C_{PSO_2} + x_8C_{PNO} + x_9C_{P(P_4O_6)} + [\frac{t}{2} + 3.76]C_{P(N_2)}) \end{aligned} \qquad 48$$

Where a, w, and m are the number of moles of the reactants and x_i is a number of moles of the product gaseous, H^0_{fi} is the enthalpy of formation of the species i, H is the heat of vaporization, ΔH^0_T is the change in enthalpy as a results of temperature change as well as specific heat capacity

C_p in $KJ/kmolK$ (Melgar *et al.*, 2007; Koroneos & Lykidou, 2011a; Arafat & Jijakli, 2013). Expanding Equation 40 assuming that at standard temperature and pressure the enthalpy of formation for chemical elements $H^0_{f(O_2)}$, $3.76H^0_{f(N_2)}$ and $H^0_{f(H_2)}$ are considered to be zero (Zainal *et al.*, 2001; Vaezi *et al.*, 2008; Koroneos & Lykidou, 2011a) then, the general Equation 43 is formulated.

$$\begin{aligned} &H^0_{f(MSW)} + wH^0_{f(H_2O-L)} + wH_{(H_2O-vap)} = x_2H^0_{fCO} + x_3H^0_{fCO_2} + x_4H^0_{fCH_4} + x_5H^0_{fH_2O-Vap} \\ &+x_6H^0_{fHCL} + x_7H^0_{fSO_2} + x_8H^0_{fNO} + x_9H^0_{fP_4O_6} + \Delta T(x_1C_{P(H_2)} + x_2C_{P(CO)} + x_3C_{P(CO_2)} \\ &+x_4C_{P(CH_4)} + x_5C_{P(H_2O-Vap)} + x_6C_{P(HCL)} + x_7C_{PSO_2} + x_8C_{PNO} + x_9C_{P(P_4O_6)} + [\frac{t}{2} + 3.76]C_{P(N_2)}) \end{aligned} \quad 49$$

Where, $H^0_{f(MSW)}$ is the heat of formation of MSW; $\Delta T = T - T_0$ where T, is the gasification temperature and T_0 is the ambient temperature. The specific heat capacity $C_p(T)$ is usually calculated by the empirical relation elaborated by Jarungthammachote and Dutta (2007) as follows:

$$C_P(T) = a + bT + cT^2 + dT^3 \text{ in } KJ/kg \quad 50$$

Integrating Equation 50 gives:

$$\int_{T_0}^{T} C_p(T)dT = aT + bT^2 + cT^3 + dT^4 + k \text{ in } KJ/kg \quad 51$$

Using the concept of Equation 51, Equation 47 can be expanded to Equation 52

$$\sum_{j=React} H^0_{f,j} = \sum_{i=Prod} x_iH^0_{f,i} + [(\sum_i x_ia_i)T + (\sum_i x_ib_i)T^2 + (\sum_i x_ic_i)T^3 + (\sum_i x_id_i)T^4 + \sum_i x_ik_i] \quad 52$$

Where k is constant of integration, a-d are the gaseous coefficient extracted from (Poling *et al.*, 2001). Heat of formation for 1 mol of solid MSW $CH_{1.23}O_{0.47}N_{0.039}S_{0.002}CL_{0.0004}P_{0.001}$ formed by the solid elements: Carbon, hydrogen, oxygen, Nitrogen, neglecting sulfur, chlorine and phosphorous since has small value, is calculated using the following Equation:

$$C_{sol} + 0.615H_2 + 0.235O_2 + 0.0195N_2 = CH_{1.23}O_{0.47}N_{0.039}S_{0.002}CL_{0.0004}P_{0.001}$$

This is an ideal reaction and it can't happen in real sense. Neglecting nitrogen, sulfur, chlorine and phosphorous since has small value, and has less effect as shown in Equation 34 and 35 the following reactions are the bases for formulation of $CH_{1.23}O_{0.47}$:

$$C_{sol} + 0.615\ H_{2(g)} + 0.235\ O_{2(g)} = CH_{1.23}O_{0.47}$$

$C + O_2 = CO_2$ and $\Delta H_C = -393.5$

$0.615\ H_2 + 0.308\ O_2 = 0.615\ H_2O$ and $\Delta H_C = -241.8(0.615)$

$CO_2 + 0.615\ H_2O + 0.235\ O_2 = CH_{1.23}O_{0.47}$ and $\Delta H_C = 499.6$

$C + 0.615\ H_2O + 0.235\ O_2 = CH_{1.23}O_{0.47}$ and $\Delta H_f = 499.6 - (393.5 + 148.7) = -42.607\ {}^{KJ}\!/_{mol}$

Hence the heat of formation for this particular MSW is $-42.607\ {}^{KJ}\!/_{kmol}$

In finding the value of x_i the equilibrium constant K in Equations 36 and 37 are determined and substituted in Equation 41 and 42, whereas it forms system of Equations to be solved simultaneously. In this study an ambient temperature is $T_0 = 25^0 C = 298$ K and initial gasification temperature is assumed to be $T_1 = 750^0 C = 1023$ K. Assuming the gasification temperature $T = 1023$ K Equation 43 and 44 are used to find the value of K_s hence by substituting the values of a-g from Table 5 in equation 44 gives the value of $\Delta g^{-0}_{f,T}$ for each species.

Table 5: coefficient for the $\Delta g^{-0}_{f,T}$

Species	a	b	c	d	e	f	g	h^{-o}_{f}
CO	5.62×10^{-3}	-1.19×10^{-5}	6.38×10^{-9}	-1.85×10^{-12}	-4.89×10^{-2}	0.868	-0.0613	-110.5
H_2O	-8.95×10^{-3}	-3.67×10^{-6}	5.21×10^{-9}	-1.48×10^{-12}	0	2.87	-0.0172	-241.8
CH_4	-4.62×10^{-2}	1.13×10^{-5}	1.32×10^{-8}	-6.65×10^{-12}	-4.89×10^{-2}	14.1	-0.223	-74.8
CO_2	-1.95×10^{-2}	3.12×10^{-5}	-2.45×10^{-8}	6.95×10^{-12}	-4.89×10^{-2}	5.27	-0.0172	-393.8

Jarungthammachote and Dutta (2007)

$$\Delta g^{-0}{}_{f,T} = h^{-0}{}_{f} - aT\ln(T) - bT^2 - \frac{c}{2}T^3 - \frac{d}{3}T^4 + \frac{e}{2T} + f + gt$$

For CO, $\Delta g^{-0}{}_{f,T} = -202.73$

For H_2O, $\Delta g^{-0}{}_{f,T} = -194.92$

For CO_2, $\Delta g^{-0}{}_{f,T} = -395.88$

For CH_4, $\Delta g^{-0}{}_{f,T} = 478.7$

For $C + 2H_2 \leftrightarrow CH_4$ Methane reaction

$$\Delta G^{0}{}_{T} = 478.7\,{}^{KJ}\!/_{mol} = 47800\,{}^{KJ}\!/_{Kmol}$$

For $CO + H_2O \leftrightarrow CO_2 + H_2$ water gas reaction

$$\Delta G^{0}{}_{T} = 1.85\,{}^{KJ}\!/_{mol} = 1850\,{}^{KJ}\!/_{Kmol}$$

To solve for K_s $\ln K_{shift} = \dfrac{1850}{8.314 \times 1023}$ hence $K_{shift} = 0.805$

$$\ln K_{CH_4} = \frac{-478700}{8.314 \times 1023} \text{ hence } K_{CH_4} = 3.6 \times 10^{-25}$$

The value of x_1, x_2 and x_3 can be evaluated using Equation 40, 41, and 42

$$-x_1 + 3x_2 + 4x_3 = 1.8897 = 0$$

$$(3.6 \times 10^{-25})x^2{}_1 - 1 + x_2 + x_3 = 0$$

$$(-x^2{}_1 + 2x_2 + 2x_3 + 0.6648)x_2 0.805 - x_3 x_1 = 0$$

Solving for the values of x_s by the use of MATLAB software gives:

$x_1 = 1.4963,\quad x_2 = 0.6140,\quad x_3 = 0.3860,\quad x_4 = 0.0,$ and $x_5 = 1.1685$

From Equation 35

$x_6 = 0.0004,\ \ x_7 = 0.002$ and $x_9 = 2.5 \times 10^{-4}$

The results obtained were compared to the published mathematical model by Bhavanam and Sastry (2013).

3.2.2 Aspen Plus Simulation

In order to develop and simulate the HFBG model a proper computer simulator has to be chosen. Specialized physical property models for solid component is required to simulate heat and mass balances of a solids process. In this regard ASPEN plus simulation software was chosen because it contains the physical property models suitable for solids.

A hybrid gasifier model was developed for MSW gasification process analysis as shown in Fig. 5. The gasifier was divided into five sections: drying, pyrolysis, first combustion, gasification, and second combustion. It combines downdraft and cross draft gasifier features (hybrid). The model was used to study the behavior of MSW gasification in Tanzania. The findings envisaged in this study were compared with results from other published literature (Kumararaja *et al.*, 2010; Bhavanam & Sastry, 2013; Thakare & Nandi, 2016; Dahmani *et al.*, 2017).

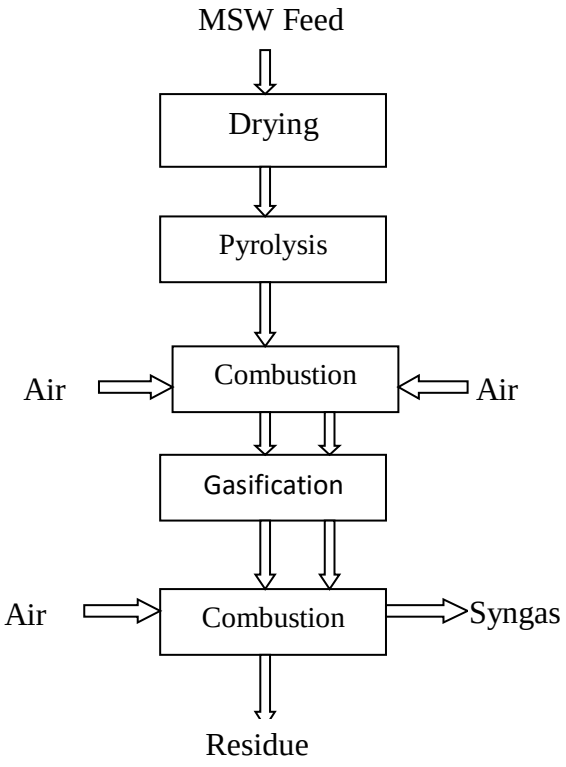


Figure 5: Schematic design of the hybrid fixed bed gasifier

The MSW was crushed into proper particle sizes and introduced at the top into the drying section where moisture was removed by heat generated inside the gasifier. Dry solid product from this section flowed into the pyrolysis zone to be pyrolyzed before combustion. In the first combustion zone the amount of air less than stoichiometric quantity was introduced to assist the combustion reaction. Furthermore, the second combustion zone was provided at the bottom for further combustion of char to take place. Between the two combustion zones is the gasification zone where the temperature is assumed to vary from 400°C to 1400°C while the temperature in the first and second combustion section is kept at 1100°C and 1500°C respectively.

Three types of the Aspen Plus reactor model were selected for the hybrid gasifier simulation based on chemical reactions involved in gasifier sections. The selections were made through the experience obtained from other published literature. The summary of the models is shown in Table 6.

Table 6: Aspen Plus unit operation models descriptions

Aspen Plus ID	Process block id (In the study)	General purpose	Use	Literature
RSTOIC	DRIER,	This is a reactor model used when the stoichiometry is known but reaction kinetics is unknown or unimportant.	Drying	Begum *et al.* (2014b) Ding *et al.* (2019) Ansari (2013)
	COMBUST1, COMBUST2		Drying, Decomposition, Combustion	Wu *et al.* (2014)
			Char Gasification	Nayak and Mewada (2011) Fatoni *et al.* (2014)
RYIELD	DECOMP	When Yield distribution data is known but stoichiometry and kinetics are unknown this reactor model is employed.	Decomposition	Begum *et al.* (2013a) Nayak and Mewada (2011) Nikoo and Mahinpey, (2008), Adeniyi *et al.* (2019)

Aspen Plus ID	Process block id (In the study)	General purpose	Use	Literature
			Tar Cranking	Barrera *et al.* (2014) Wu *et al.* (2014)
RGIBBS	GASIFER	It is an equilibrium rector model mainly used when reaction stoichiometry is unknown, but temperature and pressure are known.	Gasification &Combustion Volatile reactions Gasification	Begum *et al.* (2013a) Nikoo and Mahinpey (2008) Nayak and Mewada (2011) Barrera *et al.* (2014), Wu *et al.* (2014)

The entire system was assumed to be in steady-state and isothermal, MSW gasification product gases is mainly dominated by N_2, CO_2, H_2O, H_2, CO and CH_4 while NO_x was not considered in the products since most of N_2, is transformed into NH_3. Pressure in the system is considered to be constant (Chen *et al.*, 2010; Ramzan *et al.*, 2011):

(i) Modeling Sequence

The Aspen Plus process simulation model for hybrid gasifier is shown in Fig. 6. Five aspen plus reactor blocks were involved for the gasification process simulation and three types of reactor models, RSTOIC, RYIELD and RGIBBS were employed. Additionally, a FSPLIT were added in the system to divide air feed onto both combustion zones whereas the two SSPLIT units were employed in the simulation model to split sub-stream accordingly.

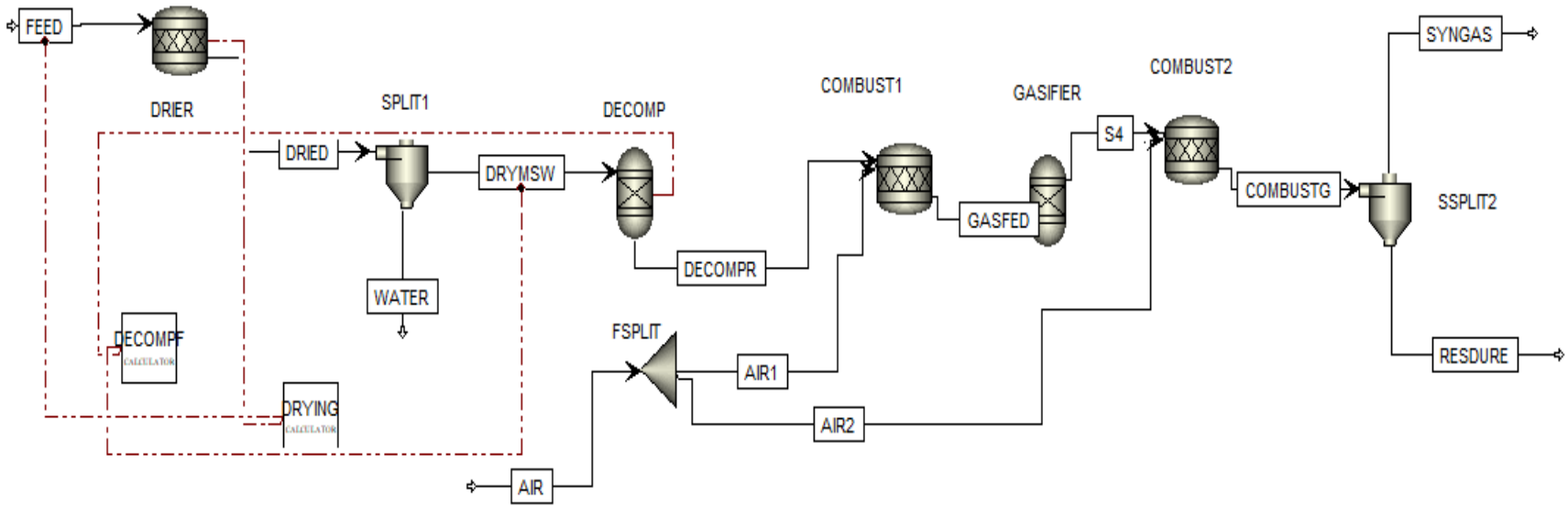


Figure 6: Aspen Plus process simulation model for hybrid gasifier

Drying

The MC is one of the parameters which affect the efficiency of a gasifier if not kept at the required limits. This gasifier section aims to minimize MC of the MSW. For biomass, the drying process is considered to take place at solid particle temperature between 105°C and 300°C. In this study, an Aspen Plus RSTOIC reactor model (Process block id: DRIER in Fig. 6.) was employed for MSW drying process simulation. To achieve proper simulation of drying process FORTRAN statement was used in calculator Block (Drying), whereas in RSTOIC reactor the chemical reaction is written in the following form: BIOMASS (MSW) = $0.0555084H_2O$ was linked to calculator Block for converting a fraction of biomass into water. The dry MSW and moisture produced in RSTOIC reactor model were separated through a split model whereas dry MSW was directed to the RYIELD reactor for decomposition.

Pyrolysis/Decomposition

This is the second step in the biomass gasification process whereas dry MSW is transformed into its constituent elements including hydrogen, oxygen, carbon, sulfur, nitrogen and Ash. The decomposition of dry MSW was simulated by the Aspen Plus RYELD reactor model (block id: DECOMP in Fig. 6) together with a calculator block employed for specifying component yield distribution using FORTRAN statement. The RYIELD products were directed to the first combustion section where initial char combustion takes place.

Combustion

In the first combustion zone, Aspen plus RSTOIC reactor model (Process block id: COMBUST1 in Fig. 6) was used for initial char combustion. This was achieved by specifying the reactor temperature, pressure and char reaction using reactions R1, R2, R6 and R7 as shown in Table 1. In the second combustion zone, Aspen Plus RSTOIC reactor model (block id: COMBUST2 in Fig. 6) was also used for the combustion of the remaining un-reacted char.

Gasification

The Aspen Plus RGIBBS reactor was used to carry out char gasification since it is a rector that can handle reactions that involve solids (Ramzan *et al.*, 2011). In this study a single RGIBBS (Process block id: GASIFIER in Fig. 6) reactor is used to simulate the gasification section.

Solid Separation

Two splits blocks, SPLIT1 and SPLIT2 were used to separate streams into solid and gaseous, the first split model (SPLIT1) was used after drying RSTOIC reactor model to separate water from MSW whereas the second split model (SPLIT2) was located after the second combustion to separate the residue and gaseous.

(ii) Physical Property Method

The property method used in this simulation is IDEAL since it can be used for processes with both condensable and, non-condensable components (Begum *et al.*, 2014b). Furthermore, an IDEAL method is used in the system with conversional components under low pressure (Han *et al.*, 2017). The Aspen plus stream class MIXCINC was used to accommodate the gases, conventional inert solids and, non-conventional solids materials. Aspen Plus uses different methods to calculate thermodynamic properties, in this study HCOALGEN and DCOALIGT model were selected for computing enthalpy and density related to non-conventional components respectively. The proximate and ultimate analysis parameters are shown in Table 7 and were extracted from the research article by Omari *et al.* (2015) and were used in the present study for validating the developed model.

Table 7: Arusha MSW proximate and ultimate data

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

Omari *et al.* (2015)

Carbon Conversion Efficiency

In this study, the percentage conversion efficiency for gasification was analyzed using Equation 53. The simulated amount of char obtained was 0.1032 KMOL/hr using feedstock flow rate of 6 kg/hr, 54.82% carbon at the duration of four hours. The amount of carbon in the fuel then was evaluated using the following expression: [6* 4* (**1000**)]g * 05482/12 = 13152/12 = 1096 Mol. Converting 0.1032 KMOL/hr in mole the amount of carbon (char) after decomposition is: 0.1032 KMOL/hr *4hr* (1000)=412.8 mol. The carbon conversion efficiency (CCE) was calculated by the use of Equation 53:

$$Carbon\ Conversion\ Efficiency = 1 - \frac{Carbon\ in\ gasification\ residure\ (\frac{mol}{s})}{Carbon\ in\ feedstock\ (\frac{mol}{s})} \times 100 \qquad 53$$

Conversion Efficiency of Gasifier

Equation 54 was used to calculate the conversion efficiency of the gasifier:

$$\eta = \frac{H_g \times Q}{H_{msw}} \times 100 \qquad 54$$

Where Q is gas flow in $\mathrm{MJ}/\mathrm{Nm_3}$ and the material feed was 6kg and was in 4 hrs. Since the standard volume flow was $63.93\ \mathrm{Nm^3}$ therefore, $\mathrm{Q} = \frac{63.9242\ \mathrm{Nm^3}}{6 \times 4} = 2.6764\ \mathrm{Nm^3}$

$\mathrm{H_{MSW}}$ and $\mathrm{H_g}$ were the caloric value of MSW and the calorific value of syngas respectively.

The calorific value for $\mathrm{H_2}, \mathrm{CO}$ and $\mathrm{CH_4}$ are $10.1\mathrm{MJ}/\mathrm{Nm^3}$, $12.64\mathrm{MJ}/\mathrm{Nm^3}$ and $38\mathrm{MJ}/\mathrm{Nm^3}$ respectively and the average calorific value of MSW used in this study is 12MJ/kg:

$$\mathrm{H_g} = \frac{(\mathrm{H_{2(vol)}} \times \mathrm{CV_{H_2}}) + (\mathrm{CO_{(vol)}} \times \mathrm{CV_{CO}}) + (\mathrm{CH_{4(vol)}} \times \mathrm{CV_{CH_4}})}{100}$$

$$\mathrm{H_g} = \frac{(9.734 \times 10.1) + (11.64 \times 12.64) + (0.00253 \times 38)}{100} = 2.4554\ \mathrm{MJ}/\mathrm{Nm^3}$$

3.3 Sensitivity Analysis

In this study, sensitivity analysis was carried out to determine the response of the system on varying key operating parameters. The parameters which were considered include temperature and

equivalence ratio. The model analysis tools in Aspen plus were used to simulate the analysis where the temperature was varied from 400℃ to 1500℃.

3.4 Experimental Study for the Lab scale Hybrid Fixed Bed Gasifier

3.4.1 Methods and Design Procedures

The experimental procedure used in this study is presented in this section. The procedure involves the following: The gasifier design and fabrication, the random collection of MSW and performing experimental study. The gasifier components dimensions are categorized into two design parameters which are:

(i) Principal design parameters which involve specific gasification rate and area of air nozzle.

(ii) Derived parameters which include different gasifier lengths, the gasifier diameters and number of nozzle (Sivakumar *et al.*, 2014).

According to Zafar (2009), downdraft fixed bed gasifier thermal capacity ranges between 1 kW to 1 MW. In this study, the gasifier output was assumed to be 5-10 kW. To achieve the abovementioned gasifier output the angle of inclination for the throat and the nozzle air inlet velocities were considered to be within 45° - 60° and 30 – 35 m/s respectively (Montes, 1986). Design parameters such as specific gasification rate, gas residence time, area of air nozzle, throat diameter, hearth and nozzle diameters, and the number of nozzles were determined. Furthermore, the air velocity and length of the reduction zone as well as the length of combustion zone were determined. These parameters were also evaluated in the study done by Sivakumar *et al.* (2014).

(i) Power Output

The gasifier thermal output power (TOP) was assumed at 20 kWth and the energy content (HHV) of MSW at Arusha was 12 MJ/kg as reported earlier by Omari *et al.* (2014a). These two factors were used to evaluate the biomass consumption rate (BCR) for the gasifier which is given by Equation 55.

$$\mathrm{BCR} = \frac{\mathrm{TOP}}{\mathrm{HHV}} \qquad 55$$

(ii) Throat Diameter

The gasifier throat diameter is calculated by the use of hearth load (B_g) using the expression given in Equation 56.

$$B_g = 2.5B_s \quad 56$$

Where B_g stand for the ratio of the amount of producer gas to the surface area of the smallest circumference commonly expressed in $m^3/cm^2/h$. Generally, the hearth load is considered to be at a range of 0.1-0.9 Nm^3 per hcm^2. The ratio of dry fuel consumed divided by the surface area of the smallest gasifier constriction is represented by the symbol B_s. The factor of 2.5 in Equation 56 represent the amount of sygas output in cubic meter produced from 1 kg of dry fuel.

Hence:

$$B_s = \frac{6 \, kg/h}{A} \quad 57$$

Therefore substituting the Equation 57 into 56 results to Equation 58:

$$\frac{B_g}{2.5} = \frac{6}{A} \quad 58$$

The area of the throat was determined by substituting the value $B_g = 0.3$, into Equation 58.

(iii) Diameter of Hearth

The relationship between hearth diameter (d_h) and throat diameter (d_t) is expressed in Equation 59:

$$\frac{d_h}{d_t} = 3.5 \quad 59$$

(iv) Height of the Reactor

The height of the reactor was determined depending on the amount of feedstock to be gasified in relation to the following factors: Duration of gasification process, the feedstock density, and the feedstock flow rate as shown in Table 8.

Table 8: Feedstock flow rate

S/N	Description	Values
1	Density	314.9 kg/m^3
2	Duration	4 hrs
3	Flow rate	6 kg/h
4	Total flow	24 kg

Equation 60 was used to calculate the volume of the reactor using mass and density while the volume of the gasifier was a parameter for calculating the height of the gasifier.

$$\text{Volume} = \frac{\text{mass}}{\text{density}} \qquad 60$$

(v) Reduction Zone Height

The mathematical expression in Equation 61 was used to calculate the height of reduction zone.

$$\frac{H_r}{D_t} = 2 \qquad 61$$

The height of the gasifier reduction zone was obtained by substituting the value of throat diameter into Equation 61.

(vi) Design of the Nozzle Position

The nozzle position is among the factors which influence the gasifier performance. Therefore, this factor was determined using the mathematical expression shown in Equation 62. Usually, the position of the nozzle should be above the smallest cross sectional area (CSA) normally known as throat where d_t is the throat diameter.

$$\frac{h_{nz}}{d_t} = 1.6 \qquad 62$$

(vii) Nozzle Area

Normally, the area of the nozzle is related to the area of throat in the following Equation $\frac{A_n}{A_t} = 0.07$.

Therefore; the area occupied by the nozzle is 350 mm^2. Four nozzles were used in the first combustion zone and one nozzle in the second combustion zone, using the expression given above

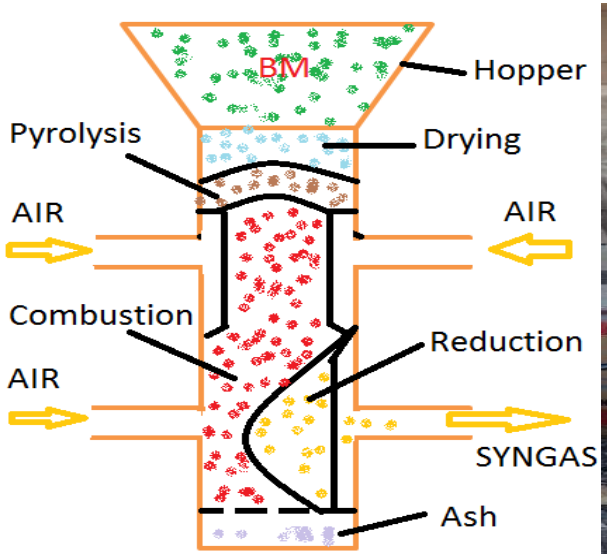
the cross sectional area for all five nozzles would be 70 mm^2, therefore, the diameter of a single nozzle is 10 mm each at an inclination angle of 10-25^o.

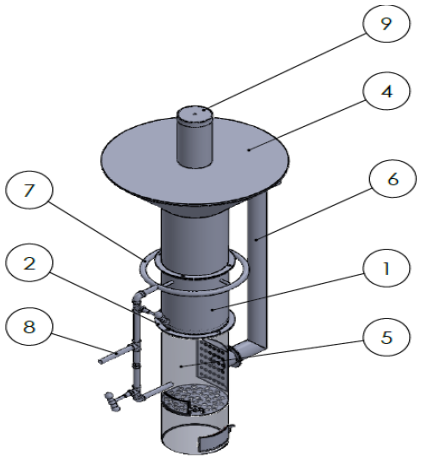
3.4.2 Gasifier Fabrication and Experimental Setup

(i) Gasifier Fabrication

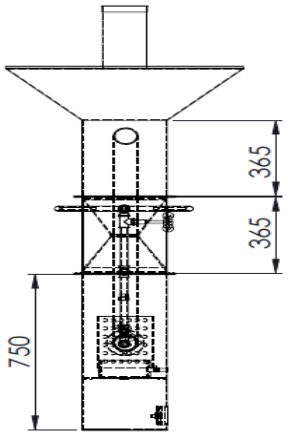
The gasifier combustion zones were fabricated using the stainless steel (SS 304) material with 2 mm thickness. The mild steel sheet of the same thickness was used to fabricate the other components of the gasifier. The mild steel conical shaped fuel hopper was fabricated with bottom and top diameters 280 mm and 780 mm respectively. The cone angle for the hopper was kept at 45^o so as to support the flow of feedstock while its height was estimated at 250 mm. Four nozzles were positioned at 128 mm above the throat into to supply air at the first combustion whereas one nozzle was located at 522.5 mm below the throat to supply air to the second combustion. Figure 8 shows the arrangement of the components in the Hybrid fixed bed gasifier (HFBG).

Reaction zones consist of drying, pyrolysis, first combustion, reduction, and second combustion which are located below the hopper. The HFBG consists of the following parts: Hopper, gasification zone, a casing for gasification zone, ash collection tray, gas outlet, air inlet pipes and gasifier housing.





9	Top Cover
8	Inlet Air Piping
7	Air Distributor Piping
6	Exhaust Piping
5	Second Comb Chamber
4	Drying Chamber
3	Clay
2	Top Flange
1	First Combustion Chamber



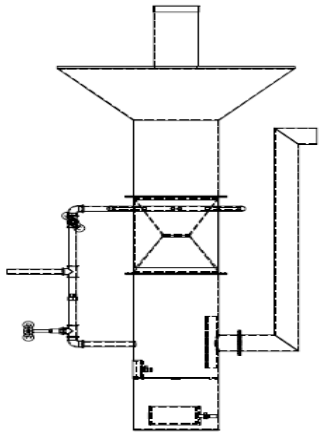


Figure 7: **Gasifier main parts**

(ii) Experimental Setup and Procedures

The MSW was prepared into small particle size range between 10 mm to 30 mm so as to allow smooth down flow of feedstock through the throat as well as to allow the heat penetration. The MSW weighing 6 kg was introduced to the gasifier hopper whereas at the bottom of the gasifier wood charcoal placed at the fire grate was used to initiate the fire. The feedstock was allowed to flow under gravitation force to the drying section. The heat generated at the first combustion was used in the drying section to reduce the MC of the MSW. Under gravitation force the dried MSW flowed to the pyrolysis section then to the first combustion section.

In the first combustion zone the amount of air less than stoichiometric value was introduced to assist the combustion reaction. The electric blower was used to supply air to both combustion zones. The combustion of the remaining char was undertaken at the second combustion zone located at the bottom of the gasifier. Between the two combustion sections is where the gasification zone is located. The flue gas analyzer TESTO 327-1 was used to record results at an interval of every 30 minutes. The CO_2 and O_2 output results obtained from the experimental analysis were used to calculate the value of CO by using Karjakin diagram shown in Fig. 9.

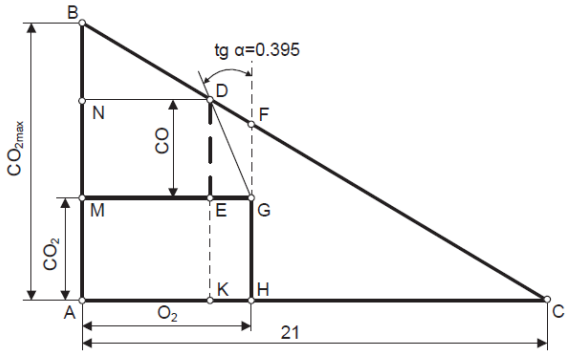


Figure 8: Karjakin diagram (Suzdalenko *et al.*, 2014)

Heating Values

The heating value is described as the amount of heat acquired when the biomass is incinerated. Generally, there are two categories: The lower heating value (LHV) and the high heating value (HHV). The HHV is the total amount of heat energy obtained in a particular fuel together with the energy available in the exhausted water vapor. The LHV does not take into count the energy contained in the exhausted water vapor. In this study, the syngas HHV was evaluated using Equation 63 while Equation 64 was used to evaluate the LHV (Dalmiş *et al.*, 2018).

$$HHV = 12.76(\%H_2) + 12.63(\%CO) + 39.75(\%CH_4) \quad 63$$

$$LHV = 10.8(\%H_2) + 12.63(\%CO) + 35.8(\%CH_4) \quad 64$$

Equation 65 was used to determine the heating power of the MSW while the LHV of biomass was taken to be 12 MJ/kg and MSW consumption rate was 6 kg/h which resulted into heating power of 20 kW.

$$P_B = LHV_B \cdot FCR \cdot \frac{1}{3.6} \quad 65$$

Stoichiometric air ratio (SR) for biomass combustion was calculated using Equation 66 where C_C, C_O, C_H and C_A are the percentages of carbon, oxygen, hydrogen and ash respectively determined through ultimate analysis. Substituting these values in Equation 66, the SR was determined to be 5.907 kg air for 1 kg of MSW.

$$SR = (\frac{C_C}{12} + \frac{C_H}{4} - \frac{C_O}{32}) \cdot (1 + \frac{79}{21}) \cdot (1 - \frac{C_A}{100}) \cdot \frac{28.84}{100} \quad 66$$

The simulated Syngas flow rate (GFR) results for path AIR1, AIR2 and Hybrid (combined) was 54.5721, 57.0202 and 38.3070, NM^3h^{-1} respectively. Therefore, thermal power of producer gas was evaluated using Equation 67.

$$P_G = LHV_G \cdot GFR \cdot \frac{1}{3.6} \quad 67$$

The thermal power obtained in Equation 67 was used to calculate the cold gas efficiency using Equation 68.

$$\eta_{CG} = \frac{P_B}{P_G} \cdot 100\% \quad 68$$

3.4.3 Energy and Exergy Analysis

(i) Energy Balance

Usually, energy balance tends to obey the first law of thermodynamics which describes the relationship between the energy inputs to the system with respect to its surroundings as realized in Equation 69. In gasification process the input energy includes the energy in feedstock, agent gas, and the addition heat. The energy output sums up the useful energy and energy loss to the surroundings including gas products, fly ash, tar and char (Tang *et al.*, 2016).

$$\sum E_{out} = \sum E_{useful} + \sum E_{loss} \quad (69)$$

(ii) 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 and separation and chemical reaction. Usually, mechanical exergies are neglected since it involves relatively small values (Wu *et al.*, 2014). Therefore, the exergy for the material stream is represented using Equation 70.

$$E^x = E^x_{ch} + E^x_{ph} \quad (70)$$

$$E^x_{ph} = (h - h_O) - T_O(s - s_O) \quad (71)$$

Where

$$h - h_O = \int_{T_O}^{T} C_P dT \quad (72)$$

$$s - s_O = \int_{T_O}^{T} \frac{C_P}{T} dT \quad (73)$$

Where h and h_o are the specific enthalpy on a given temperature and enthalpy under standard temperature (T_o=298 K) and pressure (1 atm) respectively. The s and s_o denotes entropy under the specified temperature and entropy under standard temperature (298 K) and pressure (1 atm) respectively. The value of universal gas constant (R) is 8.314 kJ/kmol.K and x_i is a mole number of gas. The specific enthalpy, specific entropy, standard chemical exergy are shown in Table 8 (Moran *et al.*, 2010).

Table 9: Producer gas, Specific enthalpy, specific entropy, standard chemical exergy and mole fraction

Producer Gas	$h_o(kJ/kmol.)$	$S_O(kJ/kmol.K)$	$ex_i^{ch}(kJ/kmol)$	x_i
O_2	8682	205.033	3,970	0.0597
N_2	8669	191.502	720	0.5339
$H_2O_{(g)}$	9904	188.720	9500	0.0098
H_2	8468	130.574	236 100	0.1671
CO	8669	197.543	275 100	0.1345
CO_2	9364	213.685	19 870	0.091
CH_4	-	-	831 650	0.00366

(iii) Exergy Efficiency

The gasifier exergy efficiency is usually expressed based on the chemical exergy efficiency in terms of a ratio between chemical exergy of the producer gas to the total exergy input as shown in Equation 74.

$$\eta^{x}_{ex} = \frac{E_{x(producer)}}{E_{x(input)}} \quad 74$$

The total exergy input is obtained from the feedstock and Equation 75 has been used to calculate the MSW exergy.

$$E^{x}_{MSW} = m_{MSW}\beta LHV_{MSW} \quad 75$$

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 76 and 77 respectively (Xiang *et al.*, 2020).

$$\beta = \frac{1.044 + 0.016(\frac{H}{C}) - 0.3493(\frac{O}{C})[1 + 0.0531(\frac{H}{C})] + 0.0493(\frac{N}{C})}{1 - 0.4124(\frac{O}{C})} \quad 76$$

$$LHV = 0.0041868(1 + 0.15O)(7837.667C + 33888.889H - \frac{O}{8}) \quad 77$$

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

Results discussed in this section involve mathematical modeling results, ASPEN Plus simulation results and lastly the experimental results for the developed hybrid fixed bed gasifier. Comparative analysis was carried out to investigate the validity of the study in both mathematical model and numerical simulation model. For analytical design procedures, the various gasifier parameters were investigated including throat diameter, gasifier diameter, nozzle position and its size and the height of the gasifier.

4.1.1 Mathematical Model Results

The results obtained through mathematical modeling are presented in Table 10. It represents comparison between the results obtained and that obtained by Bhavanam and Sastry (2013).

Table 10: Producer Gas Percentage composition based on the mathematical model

Species	Model at 1023K, MC 60% Percentage composition based on the present study	Percentage composition based on Literature (Bhavanam and Sastry 2013)
CO	17	4.06
H_2O	32	-
CH_4	0	1.34
CO_2	11	23.8
H_2	41	10.63
HCL	0.011	-
SO_2	0.055	-
P_4O_6	6.82×10^{-3}	-
NO	0	-
N_2	-	60.14

It can be realized form Table 10 that there was a variation of results for the two represented models. This was due to the fact that the MSW employed in both studies had different proximate and ultimate analysis data.

4.1.2 Aspen plus Model Validation

In numerical analysis the model was validated by using biomass employed in Dahmani *et al.* (2016) as shown in Table 11. The MSW feed rate was kept at 10 kg/hr whereas the air feed rate was 5 kg/hr

respectively. The air feed rate was further subdivided into AIR1 and AIR2 in the fraction of 0.8 and 0.2 respectively to facilitate both gasifier combustion sections.

Table 11: Model validation

Components	Dahmani *et al.* (2016) (Mol. Fraction (%))	The model results (Mol. Fraction (%))
H_2	35.19	35.38
CO	42.25	42.28
CO_2	2.24	2.15
H_2O	2.37	2.79
N_2	17.89	17.40
CH_4	$0.531*10^{-3}$	$2.617*10^{-3}$
NH_3	$0.193*10^{-4}$	$8.0146*10^{-4}$

The proposed model results are presented in Table11 in comparison to other related published literature. The MC was controlled at 16% using FORTRAN statement in the calculator block while the gasifier temperature was kept at 800°C. The results indicate that the MC was lowered from 59.9 wt% to 6.82 wt%. As shown in Table 12 it has been revealed that composition of the gaseous including H_2 and N_2 was in good agreement with the previously published model by Thakare and Nandi (2016) as well as Bhavanam and Sastry (2013). The H_2 indicated in this model was higher than indicated by Thakare and Nandi (2016) but slightly lower than the one produced by Bhavanam and Sastry (2013). Furthermore, CO produced in the model was higher than the one reported by Bhavanam and Sastry (2013). However, the generated CH_4 was a bit lower due to the composition of MSW used in the model. Furthermore, at high temperatures, the amount of CH_4 produced reacts with O_2 to produce CO and H_2 as per reaction R10 in Table 3 hence the producer gas results into low content of methane.

Table 12: Performance of the model in comparison with published data

	(Kumararaja *et al.*, 2010) (experimental)	(Thakare & Nandi, 2016) (vol. %)	(Bhavanam & Sastry, 2013) (vol. %)	Present model (vol. %)
Biomass	**Wood**	**MSW**		**Arusha MSW**
Feed rate (kg/h)	6	6	-	6
Air flow rate (kg/h)	8.95	8.95	-	8.95
Syngas flow rate (kg/h)	11.95	12.45	-	11.58
H_2		7.5	10.63	9.73
CO		20.23	4.06	11.64
CO_2		7.90	23.80	13.87
CH_4		1.55	1.34	$2.53*10^{-3}$
N_2		62.72	60.14	61.07

(i) Effect of Varying Gasifier Temperature

The performance of a fixed bed gasifier depends among other factors the gasifier temperature. In this study, the gasifier temperature was assumed to vary from 400°C to 1400°C at an interval of 100°C while MSW and airflow rate were kept constant at 6 kg/hr and 8.95 kg/hr respectively. The influence of varying gasifier temperature versus producer gas composition is shown in Fig. 9.

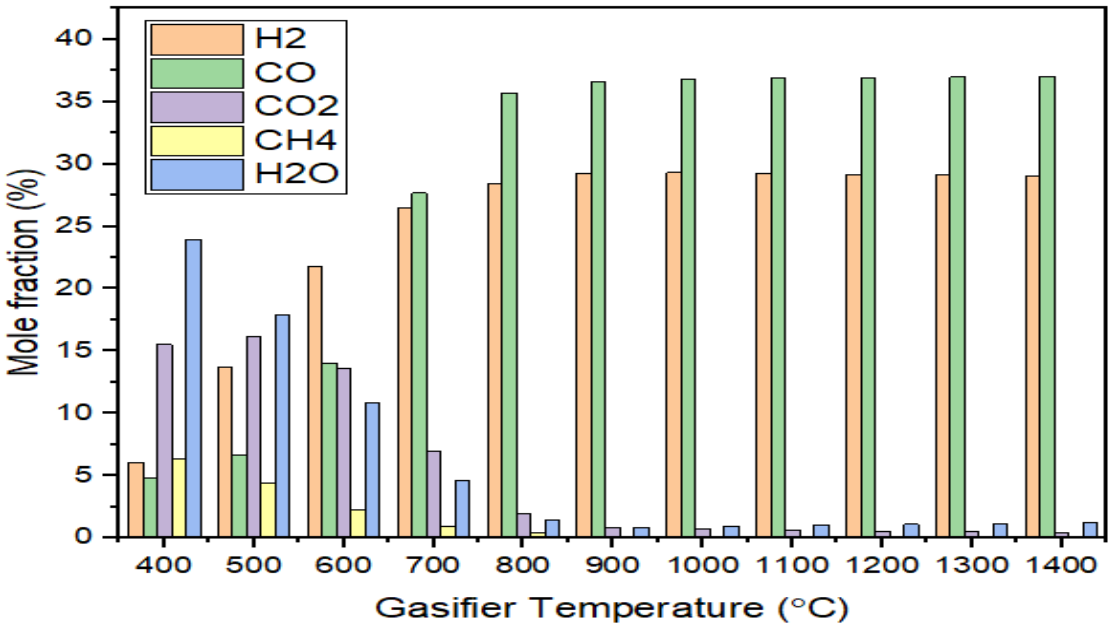


Figure 9: Influence of gasifier temperature on syngas composition

It is revealed from Fig. 9 that as gasification temperature increases the composition of CO_2 decreases while CO keeps increasing. This is because the conversion of carbon to syngas is highly

achieved at higher temperatures than at low temperatures. Additionally, H_2 increases steadily to a maximum of 29.29% mole fraction when the gasification temperature of about 1000°C was achieved. The CH_4 composition decreases as temperature increases due to the prolonged steam methane reforming as well as methane oxidation as reflected in reaction 4. The trend of results is almost similar to model results reported by other literature (Deng *et al.*, 2017; Han *et al.*, 2017; Tungalag *et al.*, 2020).

(ii) Effect of Equivalence Ratio

Generally, excess air supplied in the gasifier boosts up combustion reactions. This fact is revealed in Fig. 10 at which equivalence ratio (ER) was varied from 0.1 to 0.9 at an interval of 0.1. The results indicated that CO_2 and H_2O increases while H_2 and CO decreases rapidly at ER between 0.1 and 0.4. The variation was due to the increase in oxygen supplied to the gasifier as a result of the increase in ER. The increase of oxygen supplied boosts up the combustion and hence the production of carbon dioxide as well as water increases. However, the ER above 0.4 results in gradually decreases of CO_2 and H_2O while H_2 and CO was negligible since MSW feed rate was kept constant.

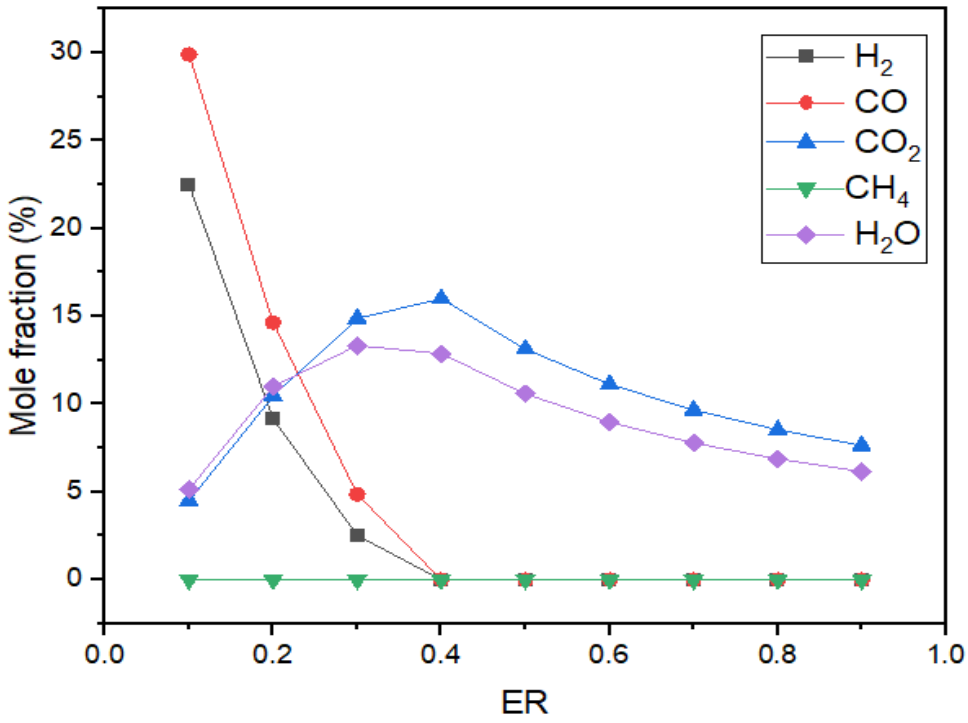


Figure 10: Effect of equivalence ratio

(iii) Effect of Varying air in the Two Paths

The simulation of air flow was done by varying the air ratio between AIR1 and AIR2 in the mixer (Fig. 6) where AIR1 was varied from 0 to 1 in an interval of 0.1. The total air supplied in the gasifier (AIR) was kept at 8.95 kg/hr and the feedstock flow rate was kept at 6 kg/hr. This means that when AIR1=0, AIR 2 =1 and vice versa. When the ratio of air in AIR1=1 it reflects downdraft feature while the cross draft features is obtained by supplying air through AIR2 where the ratio of AIR1 = 0 as shown in Fig. 6.

The result shows that as air ratio increases in path AIR 1 there was an increase of CO which attained its maximum when AIR 1 was 0.3. At this interval CO_2 decreases with increase in CO as shown in Fig. 11. From when AIR 1 was 0.3 the CO_2 increase gradually while CO decreases. Through the entire variation of the air ratio between AIR 1 and AIR 2, hydrogen was decreasing gradually. The optimum operating condition was achieved when AIR 1 was 0.3 of the total air flow. The result indicates that the air ratio below 0.3 in path AIR1 had partial combustion in the combustion zone one. The increase of air above 0.3 in path one indicates complete combustion in the first combustion zone hence more the increase in carbon dioxide production.

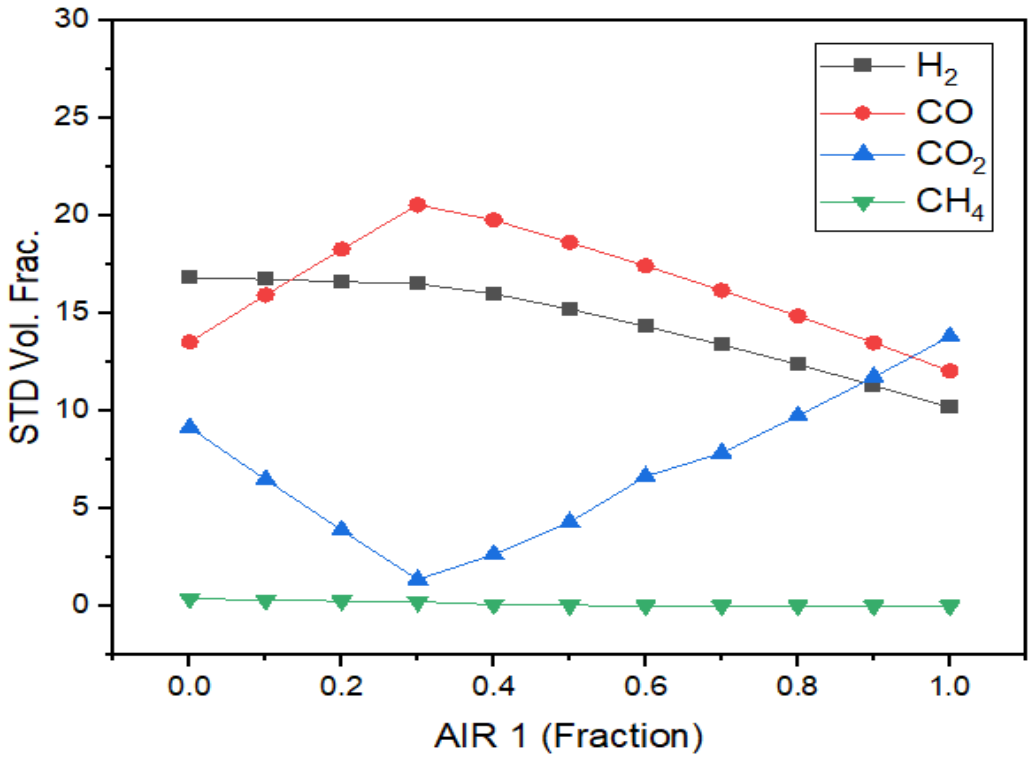


Figure 11: Effect of varying air in the two paths

The experimental analysis was performed for the purpose of comparing the results with numerical analysis. Figures 12 and 13 compare the results of flue gas composition for numerical and experimental data. Figure 12 shows the numerical and experimental result comparison for carbon

monoxide production. It can be revealed that at an air ratio of 0.3 (AIR1) the maximum value for carbon monoxide was achieved for both: numerical and experimental analysis. However, a simulated result was better compared to the experimental results.

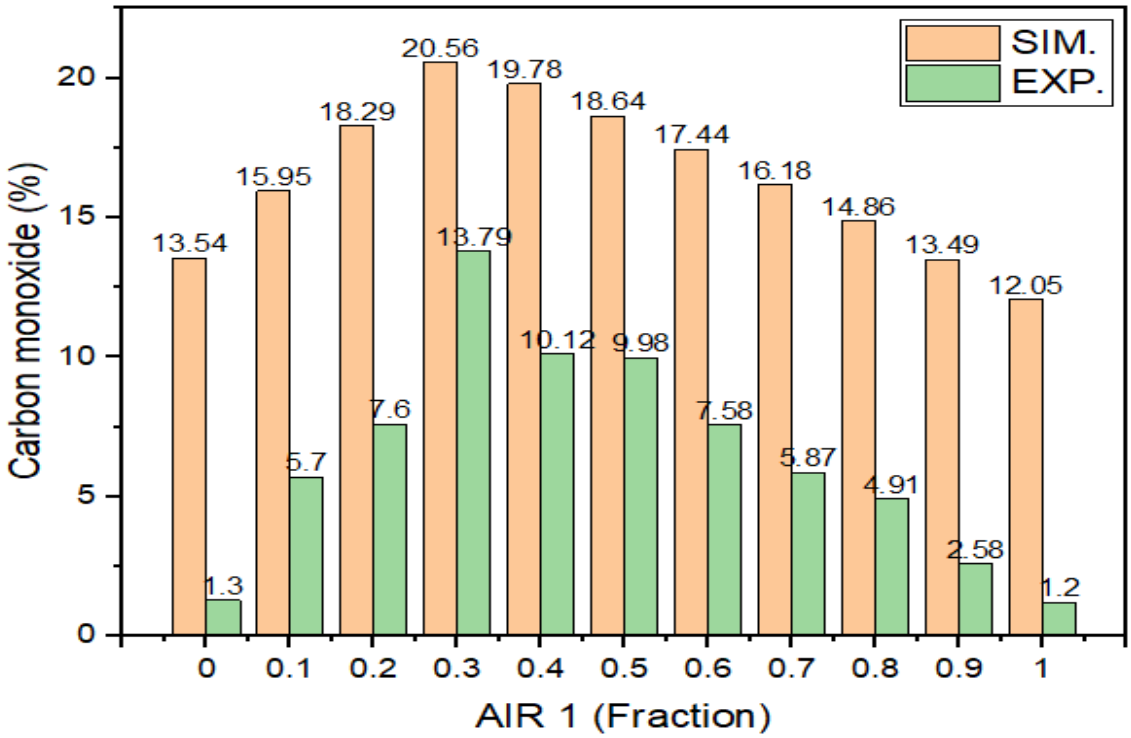


Figure 12 : Effect of varying Air ratio on the two air path for carbon monoxide production

Figure 13 shows a comparison between the numerical and experimental results for carbon dioxide production. From the figure it can be revealed that at an air ratio 0.3 (AIR1) the carbon dioxide was at its minimum value. Furthermore, it was revealed that simulation results had more output than experimental data.

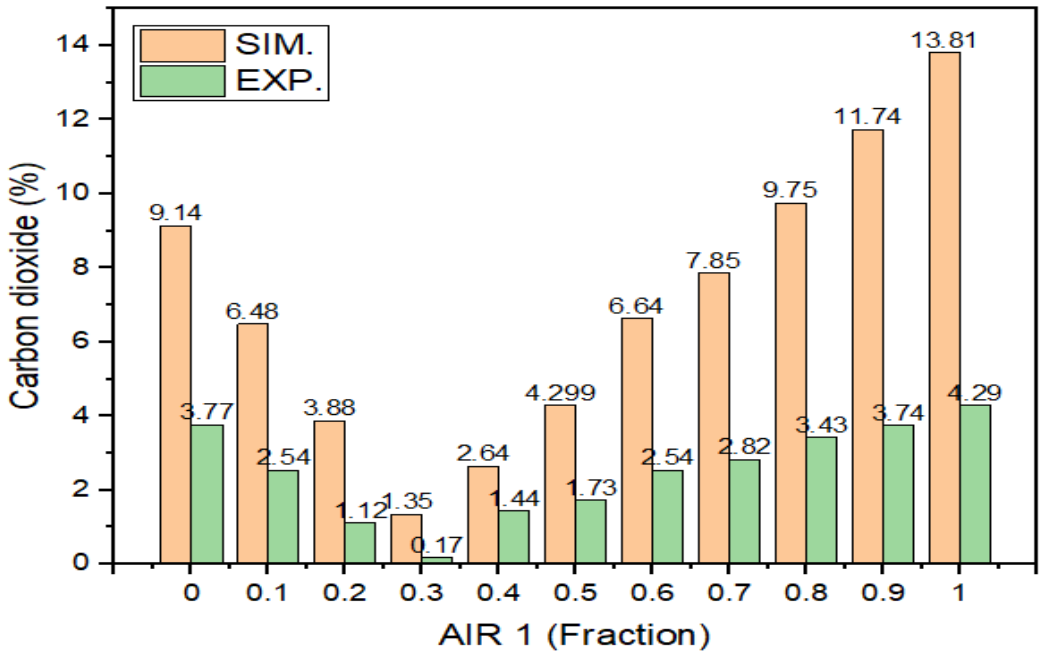


Figure 13: Effect of varying Air ratio on the two air path for carbon dioxide production

(iv) Efficiency

The carbon conversion efficiency was evaluated in order to determine how much carbon is converted into useful energy. The efficiency was evaluated to be:

Carbon Conversion Efficiency $= (1 - \frac{412.8}{1096.4}) \times 100$ =62.35%. This result confirms that the model was viable for MSW gasification.

Furthermore, the conversion efficiency of the entire gasifier was evaluated as follows:

$\eta = \frac{2.4554 \times 2.664}{12} \times 100 = 54.5\%$ this is an indication that the developed model can be used for MSW gasification.

(v) Sensitivity Analysis Results

In gasification process temperature increases favor the production of hydrogen and carbon monoxide. This is because high temperature favors endothermic reactions. The results shown in Fig. 14 reveal that carbon monoxide was increasing with increase in Temperature throughout the entire process whereas hydrogen increased sharply from 400℃ to 650℃, then decreased steadily. The behavior of this results was in good relation with the study conducted by Sezer and Özveren (2020).

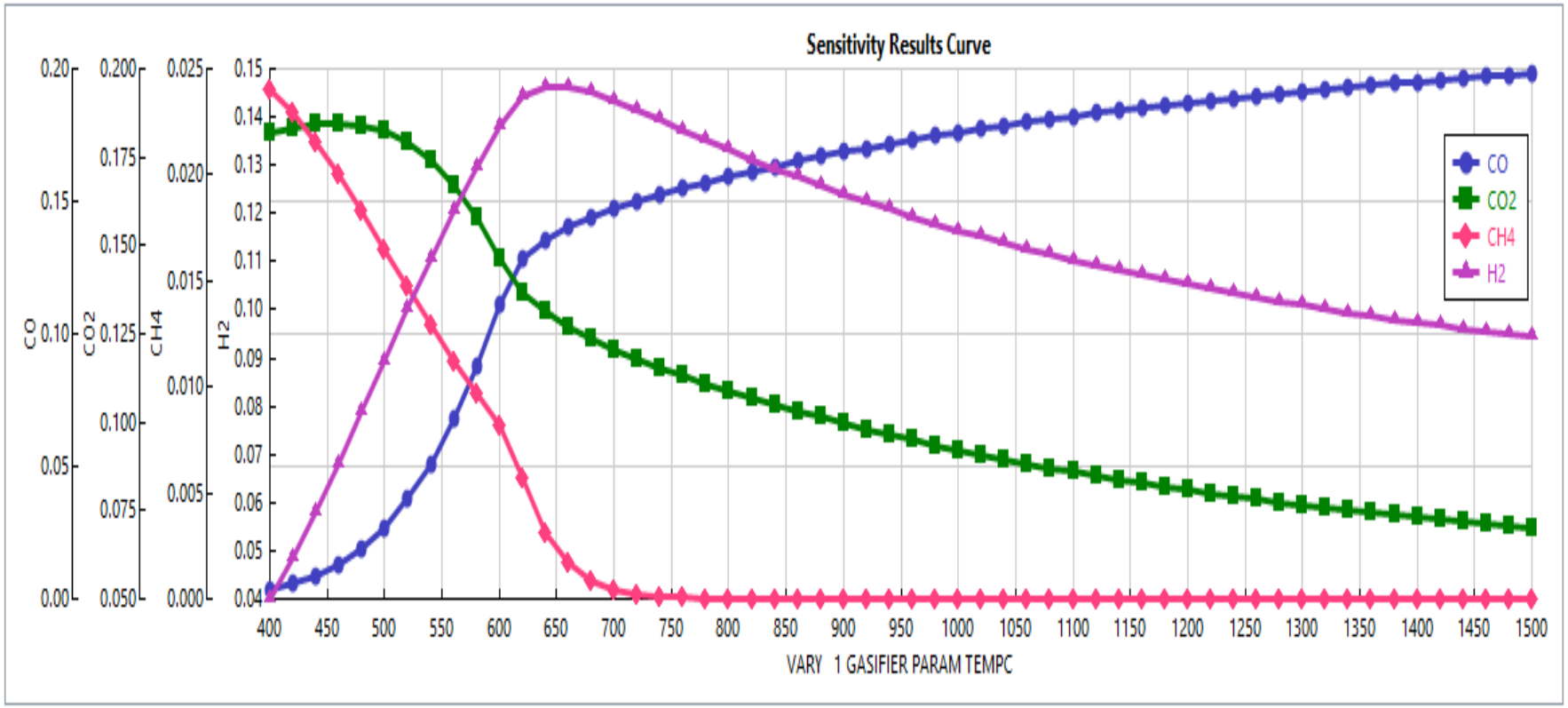


Figure 14: The effect of temperature on the gasifier output

4.1.3 Experimental Results for the Designed Hybrid Fixed Bed Gasifier

The experimental analysis for the HFBG was conducted in this section. The procedure for the design of the gasifier included the findings of various key parameters including throat, nozzle and hearth diameters, reactor and reduction zone heights, and the nozzle position above the throat. The gasifier parameters determined using various formulas are presented in Table 13.

Table 13: Results of the gasifier design

S/N	Parameters	Results
1	Diameter of the throat	80 mm
2	The height of Throat	365 mm
3	Diameter of the Hearth	280 mm
4	Reactor Height	1250 mm
5	Height of reduction zone	160 mm
6	Inner diameter of the hopper	280 mm
7	Outer diameter of the hopper	780 mm
8	Height of the hopper	250 mm
9	Diameter of the nozzles	10 mm
10	Location of the nozzle above the throat	128 mm

Moshi *et al.* (2020)

Thermal output power of about 20 kW was used as initial information for the gasifier design. The initial temperature of the gasifier was measured by thermocouple type K and was found to be 100℃ to 300℃. Due to the low temperature at this initial stage the quality of the gas was low in the gasifier. At this stage usually called cold start phase, the composition of flues gas was not recorded. The phase last for about 30 minutes from when the fire was initiated in the gasifier.

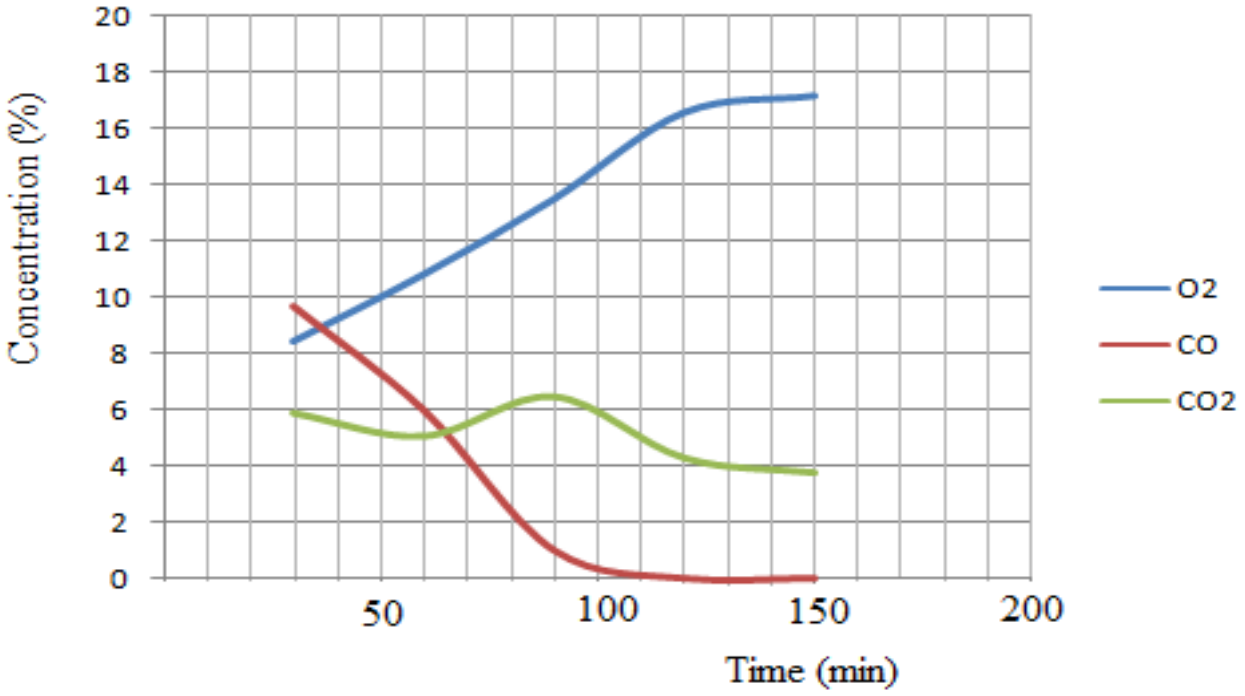


Figure 15: Concentration of O_2, CO and CO_2 with time

It was revealed that after the first 30 minutes, O_2 concentration was increasing as time increases while the concentration for CO and CO_2 were decreasing with time increase (Fig. 15). This was an indication that the developed model was viable for MSW gasification.

(i) Heating Values

The value of LHV, HHV and gas composition for the simulated results are shown in Table 14. 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 path operates together is much better. Therefore, at an air ratio of 0.3 on path AIR1 gives better results.

Table 14: 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

(ii) Cold gas Efficiency

According to Kirsanovs and Zandeckis (2015) 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 15.

Table 15: Cold gas efficiency

Air Path	Simulated GFR (NM^3h^{-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

(iii) Exergy Efficiency

The Chemical exergy for the system was 78661.00 kJ/kmol while the physical exergy was 169 790.22 kJ/kmol as revealed in Table 16. And therefore the gas exergy was the sum of Chemical exergy and physical exergy which equals to 248 451.22 kJ/kmol.

Table 16: Physical exergy for some components at 800ºC

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

The input exergy was evaluated to be 304 819.2 MJ and therefore the exergy efficiency was 81.51% evaluated using Equation 77. From gasification point of view the achieved high efficiency implies that there was minimal incomplete char gasification as a result of increase in residence time as well as raise of temperature in the gasifier.

4.2 Discussion

Generally, in this study the intensive analysis on WTE technology including critical review of previous studies was undertaken. The simulation of HFBG was conducted using ASPEN plus software to investigate its viability. Furthermore the design and experimental study of the HFBG was done whereas flue gas was analyzed using TESTO 327-1 gas analyizer.

4.2.1 Mathematical Modeling

In this section the gasification process model suitable for MSW was proposed. The gasification model developed has included seven elements (C, H, O, N, S, CL, P), of which the results show that hydrogen and water in the product gases are 17 % and 32 % respectively due the high MC of the MSW.

4.2.2 Simulation of Hybrid Fixed Bed Gasifier

Appropriate simulation software was carefully selected for developing the HFBG model whereas ASPEN Plus software was found to fit the simulation of the HFBG. The four gasification steps involved in the model (drying, pyrolysis, first combustion and second combustion, gasification) were simulated. The developed model aimed at harmonizing the advantages of both: downdraft and cross draft gasifier design while suppressing their disadvantages. The model was developed such that it can manage feedstock with high MC while improving the quality of producer gas composition. In this study the feedstock with MC of about 60 % was used while analyzing the operating parameters where temperature and ER were investigated. In the simulation process it was revealed that the feedstock MC of 59.8 wt% was reduced to 6.8 wt%. The composition of producer gas was highly influenced by the changes in gasifier operating parameters aforementioned whereas high temperature influences the increase in H_2 as well as CO output composition.

4.2.3 The Design and Experimental Study of the Hybrid Fixed Bed Gasifier

The experimental study was carried out based on the HFBG designed to deliver 20 kW thermal power. The study mainly focused on the MSW gasification where the analysis indicated that oxygen composition was increasing with increase in time. However, carbon dioxide and carbon monoxide were decreasing. In the experimental analysis, results were recorded in the duration of 2.5 hours at an interval of every 30 minutes. Results recorded after 2.5 hours of the gasification process, indicated that O_2 concentration was 17.2 % while CO and CO_2 were 0.0 % and 3.77 %, respectively. However, this result shows a bit of diversion from the simulated results due to gas leakages. Therefore, this indicates that the novel gasifier is feasible for the gasification of MSW.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this study, a steady-state HFBG model for gasification was developed using the Aspen Plus simulation software. The analysis was carried out based on Gibbs free energy minimization principle whereas the results were validated with published experimental data. The MSW was used as fuels whereas the performance analyses were carried out. The effects of the ER and gasifier temperature were examined. The results revealed that an ER of 0.1 and gasification temperature of 800°C gave better syngas output for the carbon dioxide as well as hydrogen of about 35.7% and 28.46% respectively. At 800°C and ER of 0.1, the maximum concentration of CO and H_2 was attained. Both gas composition increases with temperature but decreases with an increase in ER. Furthermore, the result shows that MC was reduced from 59.79 wt% to 6.8183 wt%, an indication that the developed model can be used for gasification of materials with high MC with similar or improved producer gas composition and reduces costs and time of pre-drying.

In the comparative analysis data were recorded by varying the air ratio in the first air path (AIR1) at an interval of 0.1. Numerical results shows that when the air ratio at AIR1 was 0.3 a maximum of 20.56 % CO and a minimum of 1.35 % CO_2 at STD VOL Fraction. From an air ratio 0.3 the CO decrease gradually while CO_2 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 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 at one path.

5.2 Recommendations

The simulation conducted in this study was carried out on different operation parameters. Furthermore, the experiments conducted were based on the scope of the study as well. The HFBG were used to study various characteristic of the MSW gasification process. The results obtained were specific for objectives of the study. However, the recommendations outlined in this section may be helpful for the improvement of MSW gasification process. Further study on both: simulation and experimental analysis of the HFBG involving the particle size distribution of the feedstock is recommended for the future.

In the experimental study investigation on the composition for CO, CO_2 and O_2 was conducted. The analysis considered the percentage composition of the aforementioned gases that can be produced by the HFBG. However, further investigation for the gases including Hydrogen, methane, nitrogen and sulfur dioxides is recommended for future studies. Also, tar output analysis for the HFBG requires more investigation.

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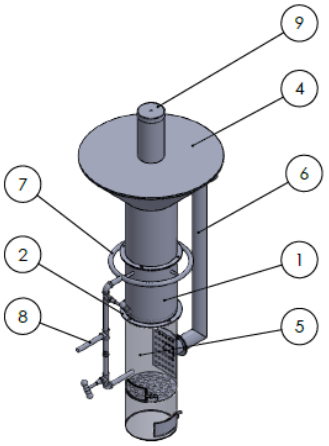
APPENDICES

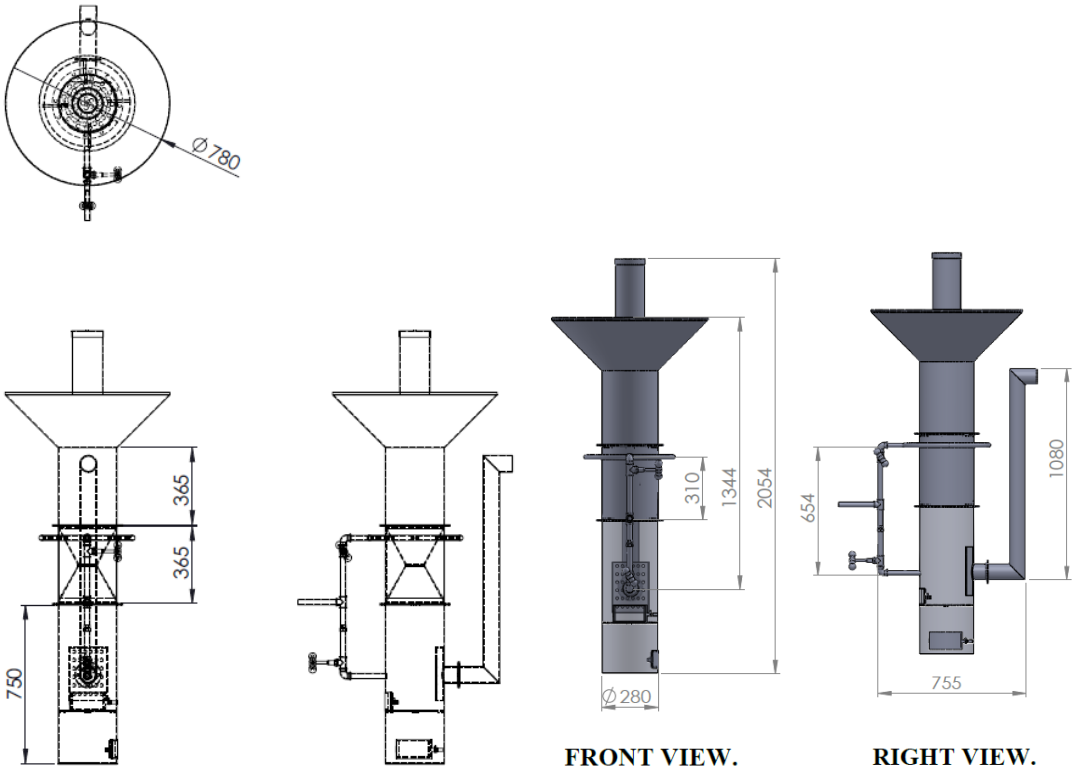
Appendix 1: Solid works detail and assembly drawings for the HFBG

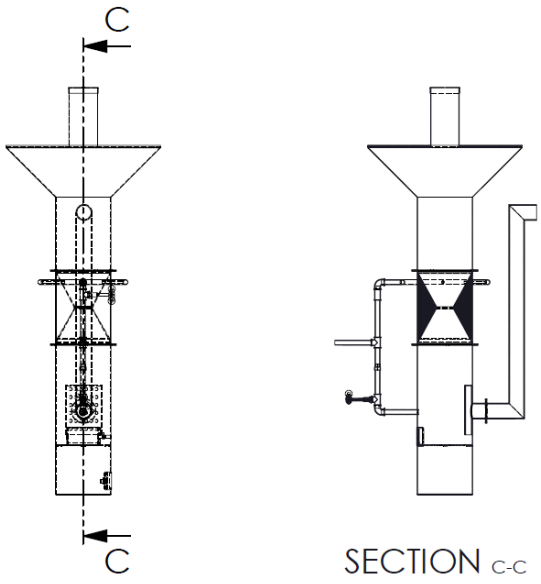


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
9	20	Top Cover	1
8	15	Inlet Air Piping	1
7	14	Air Distributor Piping	1
6	13	Exhaust Piping	1
5	2	Second Comb Chamber	1
4	1	Drying Chamber	1
3	8	Clay	1
2	3	Top Flange	2
1	7	First Combustion Chamber	1

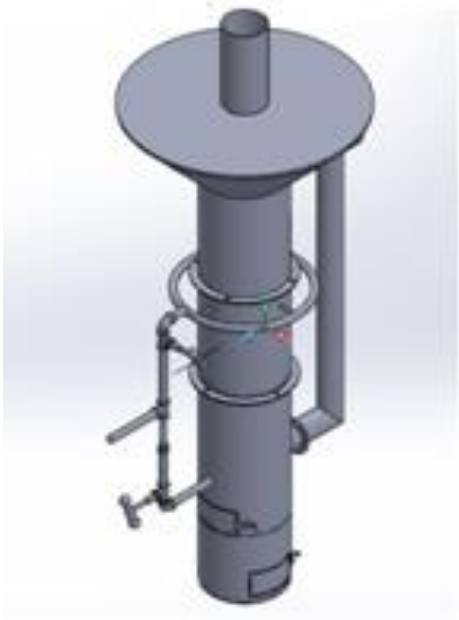
4	Hybrid Gasifier Unit	2 mm Stainless Steel			
PART No	PART NAME	MATERIAL	SPECIFICATION	QUANTITY	REMARKS
	SCALE:1:20	DRAWN: ROBERT E. MOSHI		SHEET 1 OF 5	
	DIMENSION: mm	CHECKED:		DEBUR AND BREAK SHARP EDGES	
	DATE: AUGUST 2019	APPROVED:			
NM-AIST P.O.Box 447 ARUSHA		HYBRID FIXED BED GASIFIER		DRG. No. 4	FORMAT A4

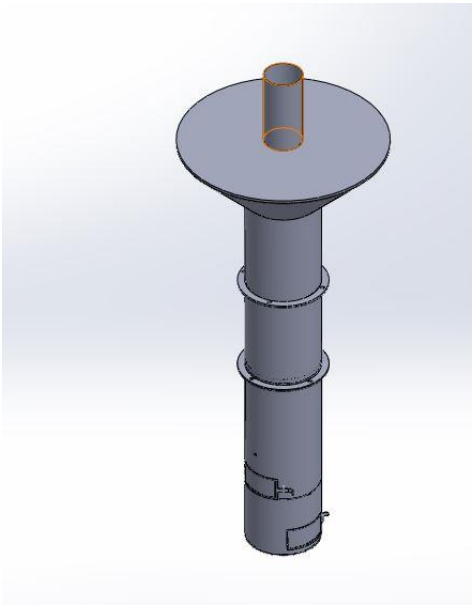
A1: Solid works detail and assembly drawings for the HFBG

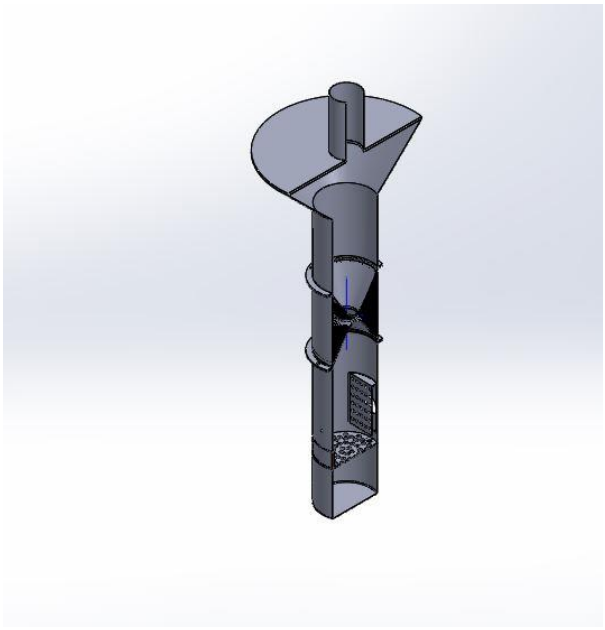




A2: Assembly drawing for the HFBG







A3: Section view for the HFBG

Appendix 2: Gasifier components

B1: Gasifier grate and second combustion section

B2: Gasifier hopper

B3: Gasifier throttle assembly

B4: Gasifier complete assembly

B5: Testo 327-1 and sample of printed results

Appendix 3: MATLAB solution

```
function [F] = basicfuny(x)
   F = [-x(1) + 3*x(2) + 4*x(3) - 1.8897;
      (3.6*10^(-2))*x(1).^2 + x(2) + x(3) - 1;
      0.805*(-x(1)+ 2*x(2)+ 2*x(3)+0.6648)*(x(2))-x(3)*x(1)];
End
```

Appendix 4: D Fortran subroutine code for ASPEN plus model simulation

```
      SUBROUTINE Robert (SOUT,   NSUBS,  IDXSUB,   ITYPE,  NINT,
     2                   INT,    NREAL,  REAL,     IDS,    NPO,
     3                   NBOPST, NIWORK, IWORK,    NWORK,  WORK,
     4                   NC,     NR,     STOIC,    RATES,  FLUXM,
     5                   FLUXS,  XCURR,  NTCAT,    RATCAT, NTSSAT,
     6                   RATSSA, KCALL,  KFAIL,    KFLASH, NCOMP,
     7                   IDX,    Y,      X,        X1,     X2,
     8                   NRALL,  RATALL, NUSERV,   USERV,  NINTR,
     9                   INTR,   NREALR, REALR,    NIWR,   IWR,
     *                   NWR,    WR,     NRL,      RATEL,  NRV,
     1                   RATEV)
C
C
      IMPLICIT NONE
C
C     DECLARE VARIABLES USED IN DIMENSIONING
C
      INTEGER NSUBS, NINT,  NPO,   NIWORK, NWORK,
     +        NC,    NR,    NTCAT, NTSSAT, NCOMP,
     +        NRALL, NUSERV,NINTR, NREALR, NIWR,
     +        NWR
C
#include "ppexec_user.cmn"
      EQUIVALENCE (RMISS, USER_RUMISS)
      EQUIVALENCE (IMISS, USER_IUMISS)
C
C.....RCSTR...
#include "rcst_rcstri.cmn"
#include "rxn_rcstrr.cmn"
C
C.....RPLUG...
#include "rplg_rplugi.cmn"
```

```
#include "rplg_rplugr.cmn"
      EQUIVALENCE (XLEN, RPLUGR_UXLONG)
      EQUIVALENCE (DIAM, RPLUGR_UDIAM)
C
C     .....RBATCH...
#include "rbtc_rbati.cmn"
#include "rbtc_rbatr.cmn"
C
C   .....PRES-RELIEF...
#include "prsr_presri.cmn"
#include "rbtc_presrr.cmn"
C
C   .....RADFRAC/RATEFRAC
#include "rxn_disti.cmn"
#include "rxn_distr.cmn"
C
C    .....REACTOR (OR PRES-RELIEF VESSEL OR STAGE) PROPERTIES...
#include "rxn_rprops.cmn"
      EQUIVALENCE (TEMP, RPROPS_UTEMP)
      EQUIVALENCE (PRES, RPROPS_UPRES)
      EQUIVALENCE (VFRAC, RPROPS_UVFRAC)
      EQUIVALENCE (BETA, RPROPS_UBETA)
      EQUIVALENCE (VVAP, RPROPS_UVVAP)
      EQUIVALENCE (VLIQ, RPROPS_UVLIQ)
      EQUIVALENCE (VLIQS, RPROPS_UVLIQS)
C
C     INITIALIZE RATES
C
C     DECLARE ARGUMENTS
C
      INTEGER IDXSUB(NSUBS),ITYPE(NSUBS), INT(NINT),
     +        IDS(2),NBOPST(6,NPO),IWORK(NIWORK),
     +        IDX(NCOMP),   INTR(NINTR),  IWR(NIWR),
     +        NREAL, KCALL, KFAIL, KFLASH,NRL,
```

```
     +       NRV,   I

      INTEGER IPCO, IPS, IPCL2, IPH2, IPCH4,
     +       IPH2O,    ICL2,  IPO2,  IPN2, IPC,
     +IPTAR, IPNO2,     IPNO, IPO2S, IPO3S, IPHCL,
     +    IPCO2

      REAL*8 SOUT(1),      WORK(NWORK),
     +       STOIC(NC,NSUBS,NR),  RATES(1),
     +       FLUXM(1),     FLUXS(1),     RATCAT(NTCAT),
     +       RATSSA(NTSSAT),      Y(NCOMP),
     +       X(NCOMP),     X1(NCOMP),    X2(NCOMP)
      REAL*8 RATALL(NRALL),USERV(NUSERV),
     +       REALR(NREALR),WR(NWR),      RATEL(1),
     +       RATEV(1),     XCURR
C
C     DECLARATION FOR VARIABLES
C
      INTEGER IMISS
      REAL*8 REAL(NREAL),  RMISS, XLEN,  DIAM,  TEMP,
     +       PRES,  VFRAC, BETA,  IDXP(14), NCP, VVAP,  VLIQ,VOLV,
     +       VLIQS
C
C ================================================================
C Declare local variables
C Specify your own codes (INTEGER and REAL)
C ================================================================
      INTEGER  KV,  J,  KDIAG, KER,
     +DMS_KFORMC,  DMS_KNCIDC
C
      REAL*8     ALPHA,        BETAA, DVMX, Ksg, VOLFLOW, KM,
     +    XSG,   XCO, YCH4,  YCO,   YCO2,   MWC,
     +  YH2,     CMOLAR KCHO2,
     +  YH2O, YNO2, YNO,    YN2,    YO2,
```

```
     + DNC, YC, YS, YCL2,  YO2S, YO3S, YHCL

      REAL*8 xmolar(NC), VMX, cmolar(NC),VMXL,
     +       vel(5), Eac(5), Kfor(5), XP(6), FLOW, Rg
C=======================================================================
C     BEGIN EXECUTABLE CODE
C=======================================================================

C DECLARATION FOR MOLAR FRACTION

      DO J=1, NC
       xmolar(J) = (SOUT(J)/SOUT(NC+1))
      END DO

      Eac = (/13523.0,  19544.0,   19544.0,   19544.0,  19544.0/)
      Kfor = (/0.046*(10.0**6.0), 6474.7*(10.0**7.0),
     + 6474.7*(10.0**7.0),  6474.7*(10.0**7.0), 6474.7*(10.0**7.0)/)

C DECLARE THE RATES FOR C, CO2, CO, H2O, H2, CH4
      Rg=8.314
      XCO=0.6
      XSG=0.4
      DNC=1300
      MWC= 12.011
      KV = 1
      KDIAG = 2
      CALL PPMON_VOLV (TEMP, PRES, xmolar, NC, IDX, NBOPST, KDIAG, KV,
     +               VMX, DVMX, KER)
C SPECIFY VARIABLES AND FUNCTIONS
      DO J=1, NC
      Cmolar(J) = (SOUT(J)/SOUT(NC+1))/VMX
      END DO
      vel(1)=Kfor(1)*EXP(-Eac(1)/Rg/TEMP)*PRES*cmolar(1)*cmolar(2)
      vel(2)=Kfor(2)*EXP(-Eac(2)/Rg/TEMP)*PRES*cmolar(1)*cmolar(4)
```

```
vel(3)=Kfor(3)*EXP(-Eac(3)/Rg/TEMP)*PRES*cmolar(1)*2*cmolar(5)
vel(4)=Kfor(4)*EXP(-Eac(4)/Rg/TEMP)*PRES*cmolar(6)*cmolar(4)
vel(5)=Kfor(5)*EXP(-Eac(5)/Rg/TEMP)*PRES*cmolar(3)*cmolar(4)
RATES(1) = -(vel(1)+vel(2)+vel(3))
RATES(2) = -vel(1)+vel(5)
RATES(3)= 2*vel(1)+vel(2)+vel(4)- vel(5)
RATES(4)=-(vel(2)-vel(4)-vel(5)
RATES(5) = -(vel(2) + vel(3)+2*vel(4) + BETAA*vel(5))
RATES(6) = vel(3) - vel(4)

RETURN
END
```

RESEARCH OUTPUTS

(i) Publications

Moshi, R. E., Kivevele, T. T., & Jande, Y. A. C. (2021). The Exergy Analysis for the Air Gasification in a Hybrid Fixed Bed Gasifier. *Current Journal of Applied Science and Technology*, 40(18), 18-30. https://doi.org/10.9734/cjast/2021/v40i1831441

Moshi, R. E., Kivevele, T. T., Jande, Y. A. C. & Kim, W. S. (2020): Simulation and performance analysis of municipal solid waste gasification in a novel hybrid fixed bed gasifier using Aspen plus. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 2020, 1-14. DOI: 10.1080/15567036.2020.1806404

(ii) Poster Presentation