ADDIS ABABA UNIVERSITY

Addis Ababa Institute of Technology

School of Chemical and Bio Engineering

Simulation of Municipal Solid Waste Gasification in Updraft Fixed Bed Reactors

By

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A Thesis Submitted to the Graduate Studies of Addis Ababa University in Partial

Fulfillment of the Degree of Masters of Science in process Engineering

Addis Ababa Institute of Technology (AAiT)

Addis Ababa, Ethiopia

May, 2017

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(Process Engineering Stream)

Candidate

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Declaration

I hereby declare that the work which is being presented in this thesis entitled "Simulation of Municipal Solid Waste Gasification in Updraft Fixed Bed Reactors using Aspen Plus 8.8" is original work of my own, has not been presented for a degree of any other university and all the resource of materials used for the thesis have been duly acknowledged.

_____ _____

Samuel Gesesse Date

(Candidate)

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

_____ _____

Dr. Abubeker Yimam Date

Acknowledgments

First, I would like to thank God for giving me the health, the patience and the blessing that I have received from the beginning to the end of this thesis work. Next, I would like to express my deepest gratitude to my advisor Dr. Abubeker Yimam, dean of school of chemical and bio engineering. It would not have been possible to accomplish this thesis work without his sincere help, guidance, and support. My deepest gratitude is also for the staffs of environmental engineering lab. in the school and to Addis Ababa city government cleaning management agency workers for their genuine collaboration and for their generous provision of information and data. I am also heartily thankful to Miss. Mahlet Atlaw, for her valuable contributions and support towards the success of this work.

I would like also to take this opportunity to thank Mrs. Karin Opperdoes for her ideal and material support, I am always in debt. Last but not least, I would like to thank all my friends for their valuable ideas and moral support during my thesis work.

Abstract

A steady state simulation of syngas production from municipal solid waste gasification process using fixed bed gasification technology was performed using Aspen Plus. For the simulation, the average proximate and ultimate compositions of municipal solid waste obtained from the koshe open dump site were employed.

The simulation was applied to conduct sensitivity analyses in the air to solid fuel feed mass ratio and operating temperature over the key parameters: syngas molar composition, overall carbon conversion in the reactors, syngas lower heating value and heat conversion (thermal) efficiency. The achieved information allows the selection of critical operating conditions leading to improve system efficiency and environmental performance. The results indicate that the air to feed (equivalence) ratio is a key variable as it significantly affects both the syngas composition, lower heating value and thermal efficiency.

With huge organic composition of Addis Ababa municipal solid waste, the gasification simulation results are found to be satisfactory compared to gasifier database prepared for simulation purposes. At the optimum conditions of this study (T = 640 ^{o}C and equivalence ratio of 0.4), the best results found are 36.32% CO, 3.09% H_2, 0.94% CH_4 and a lower heating value of 6.819KJ/Nm^3.

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Acronyms

k	activity coefficient
P_c	Critical pressure, atm
R	Universal gas constant, atmm^3/K
T_c	Critical temperature, K
T_r	Reduced temperature
V_m	Liquid molar volume
V_c	Critical volume
V_{cm}	Molar critical volume
w	weight percent, %
x	Mass fraction
Z_m	Rackett model compressibility factor

Subscript

i	Component index
j	Constituent index

Superscript

d	dry basis
dm	dry, mineral free basis

Abbreviations

1D	One dimensional
AC	Ash content
ASPEN	Advanced system for process engineers
ASTM	American Society for Testing and Materials
CCE	Carbon conversion efficiency
CISOLID	Conventional solid

COMBUST	Combustion block
DCOALIGT	General Coal model for computing density in the Aspen
DECOMP	Decomposition block
ER	Equivalence ratio
FBR	Fixed bed reactors
FCC	Fixed carbon content
HC	Heat conversion
HCOALGEN	General Coal model for computing enthalpy in the Aspen
HHV	Higher heating value
IGT	Institute of Gas Technology
LHV	Lower heating Value
maf	moisture and ash free
MC	Moisture content
MSW	Municipal solid waste
NC	Non-conventional solid
PE	Polyethylene
RDF	Refuse derived fuel
RGibbs	Multiphase chemical equilibrium reactor (non-stoichiometric)
RSoic	Conversion reactor with known stoichiometry
RYield	Yield reactor with known product yields
SEP	Separation block
SSplit	Sub stream splitter
Syngas	Synthetic gas
VCM	Volatile combustible Matter

1. Introduction

1.1. Background

The increasing yield of municipal solid waste (MSW) is one of the main by-products of modern society. This increasing amount of MSW has brought great trouble to the economic development. Most of the countries, especially developing ones, use landfill as the final disposal option for MSW. But with the rapid development of these countries landfill is no longer economic because the lands around the cities have become more and more expensive. With the enormous amount of solid waste being produced on a daily basis in different municipal corporations, its usage as another form of valuable raw material for the production of combustible fuel is of great interest to the scientific community. The solid waste can be treated appropriately for the generation of clean fuel, as well as it reduces the burden to dispose of the material in an environment friendly manner. Thus the extraction of all the valuable gases from the solid waste can help in meeting the ever rising energy demands (Bhavanam and Sastry, 2011).

Currently, most of the electrical or thermal energy consumed in the world is generated through the use of nonrenewable energetic sources that, in the future, will increase their price strongly due to their potential shortage in the market. On the other hand, there are the renewable energy sources that can in the long term be used permanently without any exhaustion threat (Doherty *et al.*, 2013). Among these sources is the municipal solid waste which is being generated in large quantity in daily basis.

Among the different technologies available, energy recovery from MSW by gasification technology has attracted significant interest because it satisfies a key requirement of environmental sustainability by producing near zero emissions.

Gasification of MSW or biomass is mainly processed in two types of reactors: fluidized and fixed bed reactors. Fluidized beds are more complicated in operation and construction which are often adopted for larger capacity MSW gasification. They also require more investment compared to fixed bed reactors, which are more suitable for smaller capacity MSW treatment (Ansari, 2013).

There are mainly two types of fixed bed reactors: updraft and downdraft fixed bed reactors. Updraft gasifiers have the advantages of high reliability, high efficiency, low specific emissions and feedstock flexibility and disadvantage of high tar content which can be solved when the gasifiers are used for thermal applications. On the other hand, downdraft gasifiers have the advantage of relatively low tar content, but at the expense of a tar that is more stable than that from updraft gasifiers and this may result in problems of tar removal. Downdraft gasifiers also have the disadvantages of narrow specifications of both feedstock size and moisture content, and the internal heat exchange is not as efficient as it is in the updraft gasifier. With their additional drawback of limited capacity of operation, downdraft gasifiers may not be suitable for processing the relatively high yield of MSW (Doherty *et al.*, 2013).

Due to the existence of different complexities like, high temperature operation, difficulty of making measurements within the bed (measurements are only at the wall), presence of multiphase flow (many solids of differing density and size and many fluids), and lack of knowledge of particle, temperature and species concentration distribution in gasifiers, modelling and simulation is taken to be the only rational guide for efficient operation and control.

Hence a model and simulation of fixed bed type of reactor is developed in this paper using the very dynamic and useful software- Advanced system for process engineering (Aspenplusv8.8). The fixed bed reactor dealt here is an updraft type one with four sections: Drying, Pyrolysis, Gasification and Combustion. The performance of the reactor is investigated for carbon

conversion and heat conversion at different gasification temperature, air equivalence ratio and moisture content of the MSW.

1.2. Statement of the problem

Due to the fact that Ethiopia imports tremendous quantity of fossil fuel for its energy demand, the necessity of alternative energy sources is of no doubt. Although the technology of gasification is not a new one, the potential and feasibility of energy production by using the country's waste stream as a feedstock for gasification has not been widely studied. So, detailed experimental and numerical techniques are required to study the principle behind efficient gasifier for the production of syngas.

Large-scale development and optimization require mathematical modeling that— allowing quantitative representation of various phenomena—is a powerful tool for process design, prediction of gasifier performances, understanding of evolution of pollutants, analysis of process transients, and examination of strategies for effective control. To gain a better understanding on the working principle of a commercial scale fixed bed, it is necessary to study a vessel of that size. However, the capital cost of such a program can be prohibitive. Alternatively, software like Aspen plus with new modeling methods can simulate the system to a much higher level of reliability. Once a good numerical model has been defined, physical modeling of small scale pilot plants validates the numerical model, which will in turn be used to predict characteristics of large scale production plant. This will reduce the number of pilot plants required, hence, reducing the time and cost of scale-up.

1.3. Objective of the research

1.3.1. General objective

The general objective of this study is to simulate municipal solid waste gasification in updraft fixed bed reactors using Aspen plus 8.8.

1.3.2. Specific objectives

The specific objectives of this study are:

- To conduct MSW characterization and extract results for simulator input
- To investigate the effect of gasifier temperature and air equivalence ratio on syngas composition.
- To investigate the effect of gasifier temperature and air equivalence ratio on heat conversion and carbon conversion efficiency.

2. Literature review

2.1. Introduction

Nowadays the big terms of concern worldwide are ENERGY and the ENVIRONMENT. Energy, in addition to its huge impact on the economy of the globe, it has become a big political issue. However, while the uses that energy can be put to are endless, the conventional sources of energy are finite. Due to these the world is digging in order to explore other sources of energy that are more sustainable and would complement or even supplement the existing sources.

One of the energy sources which are referred as sustainable is waste that is available mainly as a byproduct of different human activities. Considering these refuses as one source of energy has become a more attractive field of interest due to its dual target (Kabalia *et al.*, 2016).

Municipal solid waste (MSW), often called garbage, is used to produce energy at waste-to-energy plants and at landfills. MSW contains biomass (or biogenic) materials like paper, cardboard, food waste, grass clippings, leaves, wood, leather products, and other non-biomass combustible materials like plastics and other synthetic materials made from petroleum which can be used as an input for energy production.

There are two traditional routes to go from biogenic materials to biofuel. These are biochemical and thermochemical routes. The biochemical conversion method goes through the production of sugars and ends up on fermenting them. When this route is followed, all the cellulotic materials are converted to biofuels with the production of large quantity of residue containing lignin and hemicellulose. Because of these considerable quantity of waste, this method is considered to be inefficient conversion (McKay, 2002).

The second route of conversion, that is most popular and most widely used, is the thermochemical conversion. Here the biomass is reduced to the basic molecules of CO and H_2. The processes which are categorized under this conversion methods are combustion, gasification and pyrolysis (Ardila and Lunelli, 2013).

Among the technologies implemented for the production of energy from waste through thermochemical conversion, gasification is the best candidate because of its features that it greatly lessens the burden on the environment and it produces a syngas which can be used as efficient energy or stored and it is expected to be a future energy carrier. In its widest sense, the term gasification covers the conversion of any carbonaceous fuel to a gaseous product with a useable heating value. This definition excludes combustion, because the product flue gas has no residual heating value. It does include the technologies of pyrolysis, partial oxidation, and hydrogenation (Rezaiyan and Cheremisinoff, 2005).

Gasification technologies have been commercially applied for more than a century for the production of both fuels and chemicals. Current trends in the power generation and refinery industries support the observation that advanced stages of the technology will continue to be applied toward the synthesis of syngas, with an increasing number of applications in power generation, fuels, and basic chemicals manufacturing(Hansson *et al.*, 2011).

Other attractive features of the technology include;

- Its ability to process a wide range of feedstocks including coal, heavy oils, petroleum coke, heavy refinery residuals, biomass, and solid wastes.
- Its ability to remove contaminants in the feedstock and to produce a clean syngas product.

- Its ability to minimize the amount of solid waste requiring landfill disposal.

2.2. MSW based power generation in Ethiopia

Currently Ethiopia has an installed power generating capacity of 2398 MW. From this the hydropower constitutes more than 85% of the total power generation. This is predictable considering the abundant water resource of the country which makes this power source relatively cheaper. But due to the variance of rainfall, overdependence on hydropower makes the power sector unstable and urges for the exploitation of other renewable sources of energy. The rest of the percentage is constituted from other energy sources like wind (around 13.5%), biomass and non-biomass wastes which is contributed by three sugar factories to the national grid(around 1.5%)(Ethio Resource Group, 2009).

The only effort made towards generating energy from MSW (which is a mixture of biomass and non-biomass wastes) is that of Reppi waste to energy facility which is under construction at Koshe open dump site with a projected capacity of 50MW of power consuming 500 tonnes of waste daily. Other biomass related power generations in Ethiopia are those that are being held in different sugar plants which are producing bioethanol from baggase for their own consumptions and a few extra that they contribute to the national grid. Considering the waste generated from different sectors of the municipality, very minimal effort has been made in consuming these potential wealth (Ethio Resource Group, 2009).

2.3. MSW Gasification

The increasing yield of municipal solid waste (MSW) is one of the main by-products of modern society. This increasing amount of MSW is becoming great drawback to the economic development. Most countries, especially developing

ones, use landfill as the final disposal option for MSW. But with the rapid development of these countries landfill is no longer feasible because the lands around the cities have become more and more expensive.

With an estimated population size of 3.4 million, a survey made in 2013 by French based company, ARTELIA, the waste production varies from 0.21 to 0.59 Kg/cap/day for households of low income to high income in Addis Ababa city. According to the survey, with 65% level of coverage of refuse collection, the amount of waste collected form households and streets is estimated to be 263,000 tonnes annually, while the remainder of the waste ends up on streets, public areas, water courses and the surrounding environment.

Before the installation of the Reppi WtE facility, the fate of the total waste collected and delivered to the 'Koshe' site was not much different from the uncollected one, that, it was either open dumped or land filled in uneducated manner. After this facility the greater proportion of the collected waste, if not the potential wealth, left uncollected and/or mishandled. This suggests the necessity of an efficient and robust waste management practice. One of the many management options are the thermochemical treatment processes (Artelia, 2013).

Thermochemical treatment processes are an essential component of a sustainable integrated municipal solid waste management system, as confirmed by several analyses and studies and, above all, by waste management systems that are operating successfully worldwide. They are characterized by higher temperatures and conversion rates so allowing an efficient treatment of different types of solid waste, in particular of unsorted residual waste which cannot be conveniently recycled from an environmental and economic point of view (Santos, 2004).

With the considerable amount of solid waste being produced on a daily basis in different municipal corporations, its usage as another form of valuable raw material for the production of combustible fuel is of great interest. The solid waste can be treated appropriately for the generation of clean fuel, as well as it reduces the burden to dispose of the material in an environment friendly manner. Thus the extraction of all the valuable gases from the solid waste can help in meeting the ever rising energy demands.

The realization of this is through an efficient thermochemical treatment of the wastes. Thermochemical conversion technologies include combustion, gasification and pyrolysis. Municipal solid waste combustion has advantages of energy recovery and weight/volume reduction. However, as environmental protection becomes more and more important, the emission control on MSW combustion is also increasingly important. To provide a more energy efficient and environmentally friendly solution, the study of a novel MSW thermal treatment (pyrolysis and gasification of MSW) has gained importance. Pyrolysis and gasification has many advantages over combustion. They have the advantage of lower dioxins and can use low-value feedstocks and convert them not only into electricity, but also into transportation fuels. Dioxin or furan refers to molecules or compounds composed of carbon and oxygen. These compounds when reacted with halogens such as chlorine or bromine acquire toxic properties. Most research on halogenated dioxin and furan has been concerned with chlorinated species. It is generally accepted that dioxin and furan are by-products of combustion processes including domestic and medical waste combustion or incineration processes.

Pyrolysis is the breaking down of a material by heat. It is the first step in combustion and gasification. When biomass is heated in the absence of air at about 350^0C, it forms char, gases (CO, CO_2, H_2, H_2O and CH_4) and tar. Gasification when compared with pyrolysis has an advantage of increased destruction of materials and increased yield of combustible gases due to the

gasification of char. The products can readily be used as energy sources or they can be used as basic building blocks for producing valuable products as chemicals and fuels. In addition, it includes the ability to house a wide variety of gaseous, liquid, and solid feedstocks. Conventional fuels such as coal and oil, as well as low- or negative-value materials and wastes such as petroleum coke, heavy refinery residuals, secondary oil-bearing refinery materials, biomass and crop residues and municipal solid wastes and sewage sludge, have all been used successfully in gasification operations (Reed, 1988). These features of gasification make it the best option both from the waste management and energy production point of view.

Gasification, or "indirect combustion", in particular, is the conversion of solid waste to fuel- or synthesis-gases through gas forming reactions: it can be defined as a partial oxidation of the waste in the presence of an oxidant amount lower than that required for the stoichiometric combustion. Basically, part of the fuel is combusted to provide the heat needed to gasify the rest (autothermal gasification), as in the case of air gasification, or heat energy is provided by an external supply (allo-thermal gasification), as in the case of plasma torch utilization. The result is not a hot flue gas as in the conventional direct combustion of wastes but a hot fuel gas ("producer gas" or "syngas"), containing large amounts of not completely oxidized products that have a calorific value, which can be utilized in a separate process equipment, even at different times or sites. During the gasification of waste, the material is heated to a high temperature, which causes a series of physical and chemical changes that result in the evolution of volatile products and carbonaceous solid residues. The amount of volatiles produced and their compositions depend on the reactor temperature, type, and characteristics of fuel material. It is generally accepted that the char gasification stage is the rate limiting in the gasification of biomass because the devolatilization stage is very fast. The organic content of the waste is converted mainly to carbon monoxide, hydrogen

and lower amounts of methane, although the syngas is generally contaminated by undesired products such as particulate, tar, alkali metals, chloride and sulfide (Santos, 2004). The composition of the final product gas is also dependent on the degree of equilibrium achieved by various gas-phase reactions, particularly the water-gas shift reaction.

2.3.1. Types of Gasifiers

Many different designs of gasifiers have been built and are described in the literatures extensively. A gasifier system includes the gasification reactor itself, along with the auxiliary equipment necessary to handle the solids, gases, and effluents going into or coming from the gasifier (Reed, 1988). The choice of gasifier is dictated both by the fuels that will be used and the use to which the gas will be put. Gasification of MSW or biomass is mainly processed in two types of reactors: fluidized bed reactors and fixed (moving) bed reactors.

A. Fluidized Bed Reactors

In a fluidized bed, air raises through a grate at high enough velocity to levitate the particles above the grate, thus forming a "fluidized bed." Above the bed itself the vessel increases in diameter, lowering the gas velocity and causing particles to recirculate within the bed itself. The recirculation results in high heat and mass transfer between particle and gas stream.

At the lower part of the equipment there is a gas distributor, which promotes a uniform flux of gas needed to ensure homogeneous fluidization conditions throughout the cross section of the equipment.

Above the distributor, there is the bed, which is composed by two main phases: emulsion and bubbles. The emulsion is a combination of solids and gases. It retains almost all particles in the bed, which are percolated by the gas. Therefore, most of the gas-solid reactions occur within the emulsion. The

circulation rate of particles in the emulsion is very high and provides a certain degree of homogeneity of temperature and composition among all particles throughout most of the bed (Di Blasi *et al.*, 2004). In addition, due to the intimate contact between gases and particles in the emulsion, their temperatures tend to be very close throughout most of the bed.

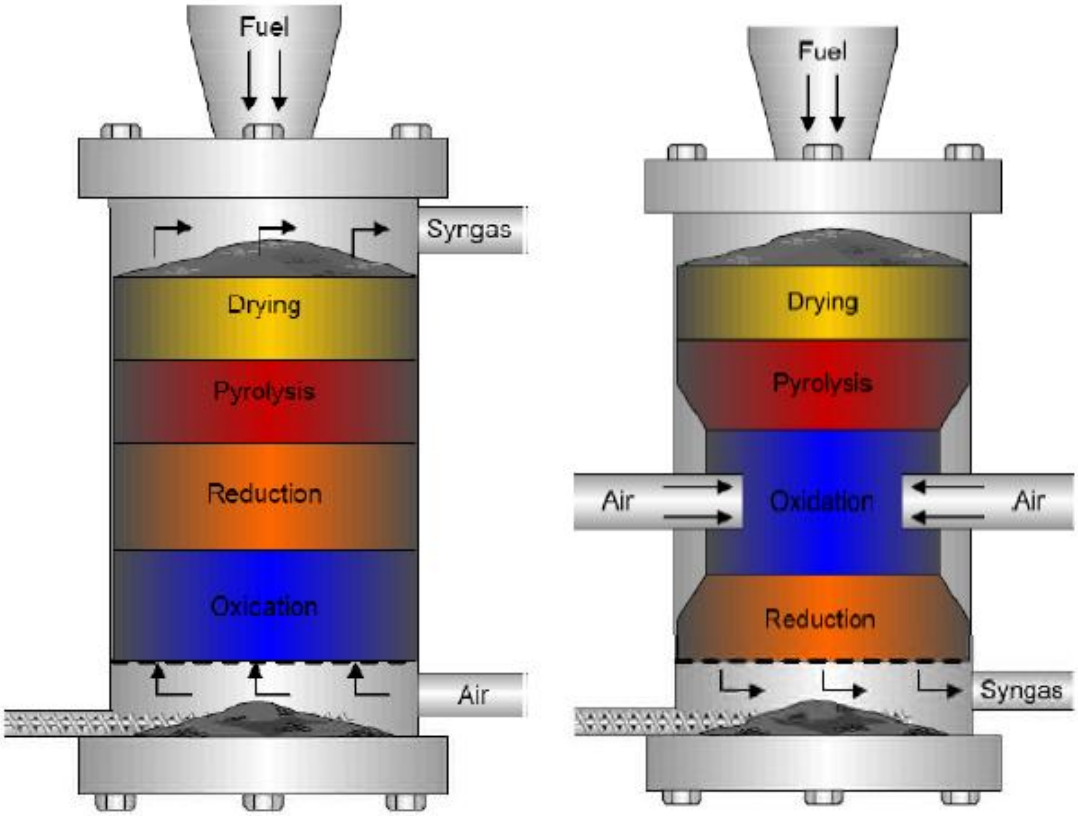
The main advantage of fluidized bed gasifiers over fixed bed gasifiers is their uniform temperature distribution in the gasification zone. This is achieved using fine particles of an inert material like sand or alumina. The inert particles are heated at start-up, and then serve as an ignition source and thermal energy carrier at steady state conditions. The operation of fluid-bed gasifiers is generally restricted to temperatures below the softening point of the ash, since ash slagging will disturb the fluidization of the bed. This relatively lower temperature operation of fluid-bed processes means that they are more suited for gasifying single reactive feedstocks, such as low-rank coals and clean biomass like wood and large scale applications.

B. Fixed Bed Reactors

These are reactor types that are being applied in many industries for the synthesis of large scale basic chemicals and intermediates. In these reactors, the reaction takes place in the form of a heterogeneously catalyzed gas reaction on the surface of catalysts that are arranged as a so-called fixed bed in the reactor. In the gasifier simulated in this study, however, the feedstock (waste) is going to form the bed on top of a grid chamber inside the reactor. Thus intermediate products and the producer gas move within this bed.

Fixed bed (sometimes called moving bed) gasifiers use a bed of solid fuel particles through which air and gas pass either up or down. They are the simplest type of gasifiers and are the only ones suitable for small-scale application (Kabalia *et al.*, 2016).

In a fixed (or moving) bed gasifier a deep bed of waste is present in almost all the volume of the reactor and different zones can be distinguished, with a sequence that depends on the flow direction of the waste and gasification medium. These zones are not physically fixed and move up- and downwards depending on operating conditions, so that they can be to some extent in overlapping (Santos, 2004).



a) b)

Figure 1: Different types of fixed bed gasifiers (a) updraft type (b) downdraft type (Hansson et al., 2011)

In the countercurrent or updraft type the solid carbonaceous particles are fed at the top of the reactor and slowly flow to the base where the solid residual is withdrawn. The combustion and gasification agents, normally air and steam,

are injected through the distributor at the base so that the feedstock moves counter-currently to the gases, and passes through different zones (drying, pyrolysis, reduction and oxidation) successively. The fuel is dried in the top of the gasifier, so that high moisture content fuel, such as waste, can efficiently be used as feedstocks. Some of the resulting char falls and burns to provide heat and the tar-rich gas leave at the top of the gasifier the ash then falls from the grate for collection at the bottom (Reed, 1988).

The updraft type of the fixed bed reactor has a unique feature which, for gasification, has a great advantage in increasing the efficiency of the process. This feature is that the hot gas (syngas) passes through the fuel bed and leaves the gasifier at the top section. On its way out the gas dries and preheats the feed by the sensible heat and leaves the gasifier at low temperature. The disadvantage of this type of setup is that the produced gas may carry high amount of tar vapor which affects the later application of the gas. This disadvantage is tolerable compared to the downdraft stable tar that seriously damages the gasifier unless some mechanism is devised.

In the downdraft reactors, the carbonaceous fuel is fed in at the top of the gasifier while the oxidant from the top or the sides: then the fuel and gases move in the same direction. It is possible to distinguish the same zones as updraft gasifiers but in a different order. Some of the feedstock is burnt, falling through the gasifier throat to form a bed of hot char which the gases have to pass through. This ensures a fairly high quality syngas (with a relatively low tar content), which leaves at the base of the gasifier, with ash collected under the grate.

2.3.2. Gasifying Mediums

In general, gasification involves the reaction of carbonaceous materials with air, oxygen, steam, carbon dioxide, or a mixture of these gases at higher

temperature to produce a gaseous product that can be used to provide electric power and heat or as a raw material for the synthesis of chemicals, liquid fuels, or other gaseous fuels such as hydrogen. In another expression, the gasification reactions transform the carbon contained in the fuel in to syngas by means of these media. Thus depending on the medium the major products that are expected to be produced can be summarized as follows (Higman *et al.*, 2008):

Table 1: Gasification media and major products

Material	Media	Major Products
Carbon	Pure oxygen	CO
	Steam	CO and H_2
	Hydrogen	CH_4
	Air	CO and N_2

In addition to the type of the carbonaceous feedstock, both the quality of the product gas downstream in terms of energy density and percent composition of constituent gases, vary in great extent depending on the type of gasifying medium used.

Table 2: Gasification media and LHV of resulting gas

Type of medium	LHV, MJ/Nm^3
Air	4 – 7
Steam	10 – 18
Oxygen	12 – 28

The simplest gasification process uses air as a gasifying agent. Excess char formed by the pyrolysis process within the gasifier is burned with a limited supply of air in order to further enrich the producer gas and to supply additional heat for the process. The product is a low-energy gas containing primarily hydrogen and carbon monoxide diluted with the nitrogen from the air.

2.4. Chemistry of gasification

The substance of a solid fuel is usually composed of the elements carbon, hydrogen and oxygen. In addition there may be nitrogen and sulfur, but these are present only in small quantities. Depending on the gasification process, reactions that take place in a gasifier include (Hansson *et al.*, 2011):

$C + O_2 \rightarrow CO_2$	+393 KJ/mol	(1)
$C + ½\ O_2 \rightarrow CO$	+110 KJ/mol	(2)
$H_2 + ½\ O_2 \rightarrow H_2O$	+242 KJ/mol	(3)
$C + H_2O \rightarrow CO + H_2$	-132 KJ/mol	(4)
$CH_4 + H_2O \rightarrow CO + 3H_2$	-206 KJ/mol	(5)
$C + CO_2 \rightarrow 2CO$	-173 KJ/mol	(6)
$C + 2H_2 \rightarrow CH_4$	-75 KJ/mol	(7)
$CO + H_2O \rightarrow H_2 + CO_2$	+41.1 KJ/mol	(8)
$CO + 3H_2 \rightarrow CH_4 + H_2O$	+227 KJ/mol	(9)

Most of the oxygen injected into a gasifier, either as pure oxygen or air, is consumed in reactions (a) through (c) to provide the heat necessary to dry the solid fuel, break up chemical bonds, and raise the reactor temperature to drive

gasification reactions (d) through (i). Reactions (d) and (e), which are known as water-gas reactions, are the principal gasification reactions, are endothermic, and favor high temperatures and low pressures. Reaction (f), the Boudourd reaction, is endothermic and is much slower than the combustion reaction (a) at the same temperature in the absence of a catalyst. Reaction (g), hydro-gasification, is very slow except at high pressures. Reaction (h), the water-gas shift reaction, can be important if H_2 production is desired. Reaction (i), the methanation reaction, proceeds very slowly at low temperatures in the absence of catalysts. Due to this, the maximum concentration of methane in the product gas stream in very small compared hydrogen and carbon monoxide. Reaction (j) is relatively thermal neutral, suggesting that gasification could proceed with little heat input but methane formation is slow relative to reactions (d) and (e) unless catalyzed.

2.5. Reasons for Simulation

Nature is very sophisticated and the process of modeling is an effort to represent it as closely as possible. The best that can be done is to improve the approximations in order to decrease deviations from the reality. A good simulation program should be capable of reproducing measured operational data within an acceptable level of deviation. This deviations in some cases, like limitations due to lack of precisions of measurements which brings intrinsic errors in correlation obtained through experimental procedures and due to level of modeling adopted (zero, one, or more dimensions), deviations will have a limit that cannot be surpassed (Higman *et al.*, 2008).

Process simulation software is being widely-used across the industry to model steady-state or dynamic processes and to conduct studies by which improvement of process design, increase in plant efficiency and reduction of their impact on the environment is realized and there is continuous development of such innovative software. Therefore it is of no doubt that the

task of process design and development should be equipped with such process simulation tools (Arena, 2011).

The development of a mathematical model, and its respective computer simulation program, is not a linear sequence where each step follows the one before but it is composed of a series of forward and backward movements where each block or task is repeatedly revisited. Among the importance of a mathematical model and its respective simulation, the principal ones are (Cakaj, 2010);

- Mathematical modeling requires much fewer financial resources than the experimental investigation.
- It allows a much better understanding of the experimental data and results and therefore can be used to complement the acquired knowledge from experimental tests.
- It can be employed during the scaling-up phase in order to achieve an optimized design of the equipment or process unit.
- The model and respective program are not "static." In other words, they can be improved at any time to expand the range of application, reliability, or to decrease the time necessary for the computations.

Gasification model can be divided into different categories. Considering the time dependence, gasification models can be divided into kinetic models and kinetic free models. Considering the geometry dependent, gasification can be divided into zero-dimensional models, one-dimensional models, two-dimensional model and three dimensional models (Di Blasi *et al.*, 2004).

The earliest and simplest gasification models are equilibrium models. The equilibrium models are zero-dimensional kinetic free models, in which the gasification products are calculated by equilibrium assumption. This models

have a drawback of inadequate accuracy since reality usually deviates from equilibrium predictions. The stratified models are developed in order to overcome the drawbacks of equilibrium models in which, the gasification process is divided into several zones such as drying, pyrolysis, char gasification and combustion. In each zone, different chemical reactions are considered. Heat and mass balances are also simulated in every individual zone.

Steady state modeling is more advanced than unsteady state modeling approach because of the complexities arise in the unsteady condition and the additional information needed.

2.6. Review on Biomass and Waste FB gasification

Millich *et al* (1998) studied the energy from biomass and waste gasification. In their study, they found that biomass and waste, amongst the renewable energy sources, have the highest potential in contributing to a more sustainable environment. They have found, in their study, that on a dry basis using air as the oxidant, a syngas of lower heating value of 5-7 MJ/Nm^3 were found, while gasification with oxygen and steam which eliminates the nitrogen dilution of the product gas, resulted in a heating value of 12-14 MJ/m^3. The typical fuel gas components were found as hydrogen, carbon monoxide, methane and some other hydrocarbons. They concluded that the product gas from gasification process can be cleaned from acid components prior to combustion and thus was found to be environmentally superior to direct combustion.

Pinto *et al.* (2002) experimentally studied gasification of mixtures of biomass and plastic wastes. In the study it is shown that addition of plastics, especially the polyethylene (PE), clearly favored the production of hydrogen and the decrease in CO content. The productions of light hydrocarbons were also favored by plastics addition. The authors suggested that the steam/waste mass ratio should be higher than 0.6 to ensure complete gasification. It was also suggested that gasification process was strongly dependent on run

temperature. A gasification temperature up to 900°C helped the increase of hydrogen formation and reduced tars and hydrocarbons through thermal cracking. The study finally indicated that gasification is a technically viable option for the solid waste conversion, including residual waste from separate collection of municipal solid waste. It is able to meet existing emission limits and can have a remarkable effect on reduction of landfill disposal option.

Dalai *et al.* (2009) experimented steam gasification of refuse derived fuels (RDF) in a fixed-bed gasifier. In their study, they were able to ascertain the positive effects of temperature on gasification speed but syngas composition and hence LHV. The optimum gasification temperature for CO and H_2 production was found to be 725 °C. The steam/waste mass ratio also showed a notable effect on syngas LHV, and a ratio of 2 was suggested to be optimum in terms of syngas yield at 725 °C. The flow rate of carrier gas did not show any significant effect on products yield or their distributions.

Qinglin Zhang (2011) conducted an experimental air gasification test in a fixed-bed melting reactor and cultivated a product gas of lower heating value of 6.0-7.0 MJ/Nm^3. In this type of gasification processes, high temperature plasma flows are injected onto the solid fuel surface and provides the sensible heat which decreases the request of chemical heat from partial combustion. The reduced combustion can be directly reflected by decreased equivalence ratio as low as 0.06. As a result, the syngas LHV value and gasification efficiency increase. In this study pure air and steam air combination gasification were compared by their syngas lower heating value and composition and found that adding high-temperature steam is favorable for the process. The total gas yield increased significantly, and the gas LHV also increased with steam feeding (Zhang, 2011).

Chen *et al.*, (2010) in their study of Simulation of municipal solid waste gasification for syngas production in fixed bed reactors, used Aspen plus to

model MSW gasification and investigated the effects of gasification temperature, air equivalence ratio and moisture concentration on the composition of syngas, lower heating value (LHV) of syngas, heat conversion, and carbon conversion efficiency. They have found a syngas with maximum value of LHV of about 4500 kJ/Nm^3 with gasifier temperature of 700 °C and an ER of 0.4 from a waste having the characteristics shown in the fig. 2.

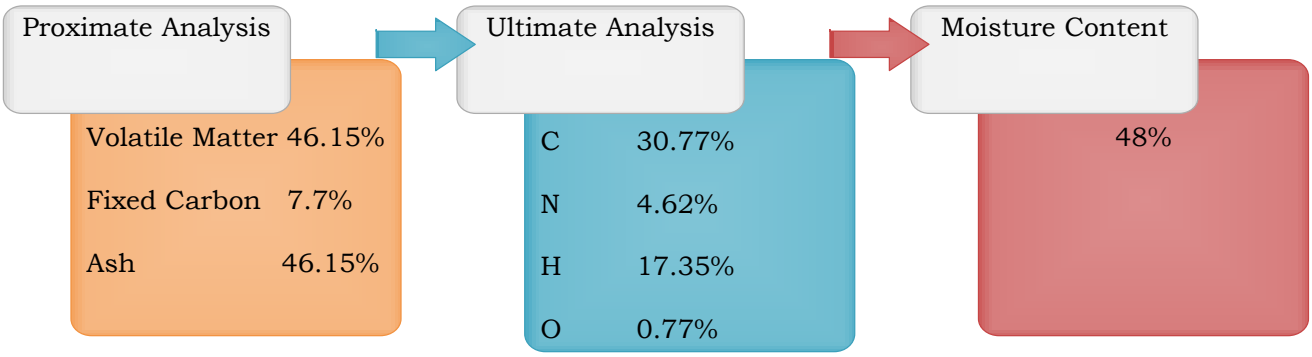


Figure 2: Results of proximate and ultimate analysis of MSW from different provinces in China (Chen *et al.*, 2010).

Molino *et al.* (2013) experimented refuse derived fuel (RDF) steam gasification in a rotary kiln pilot plant. In this study the syngas features were evaluated by varying the feeding ratio (FR), in the range 0.4-2.67, at a constant temperature equal to 850 °C. Several experimental tests were carried out in order to evaluate the best values for the main operating variables: kiln temperature, gas and solid residence time, etc., before evaluating the effect of the FR increase on the gas energy content and composition. The Results of the study show that the gas energy content decreases as the FR increases and, in the range of the FR studied, it achieves the maximum for FR=0.4, which corresponds to a volumetric gas composition of H_2 = 59.1 %vv, CO =16.8 %v/v, CO_2 =20.1 %v/v, CH_4=3 %v/v (not considering N_2) and the highest lower heating value (LHV) equal to 16 MJ/kg is obtained.

3. Theoretical Description of the Model

In this study a zero-dimensional kinetic free model is built to investigate the influence of different operational parameters on syngas production from MSW. The model is developed using the advanced process simulation software, Aspen Plus version 8.8. Before simulating the gasifier, it will be of utmost importance to understand the units and processes involved in it.

The updraft type fixed bed gasification process in this model, is basically divided into four layers: drying, pyrolysis, gasification, and char combustion. Mass and energy balances were considered in all layers. The model has been proved to give a good agreement of the syngas yield and composition with previous models and simulations that can be found as open literatures. The model in this study is used to investigate the influence of air ER, and average gasification temperature on syngas composition and yield.

With the definition of MSW as the collection of residential, commercial and institutional wastes, its quantity is rising significantly with population size and urbanization. Many factors, like the socioeconomic status of the society, season of the year and geographical location affect the composition and the physical characteristics of the municipal solid waste generated. Irrespective of these factors, in the cities of developing countries, like Addis Ababa, the waste stream consists many reusable, recyclable and/or potential feedstocks for waste to energy facilities as shown in the table.

With this huge potential, it will be feasible to treat the waste thermochemically. Because of its ability to produce high value gaseous products (syngas), which can either be used directly in power generation, stored as manageable energy carriers or be used as inputs for higher hydrocarbons, gasification is the best alternative among other thermochemical conversion methods.

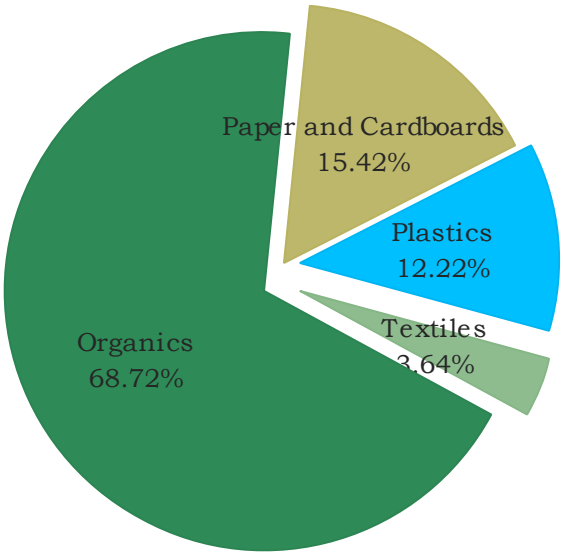


Figure 3: Composition of Addis Ababa Municipal Solid Waste (Artelia, 2013)

The developed gasifier model in this study is developed based on the principle of fixed bed reactors. In ASPEN plus simulator, since there is no single block to model such a gasifier, the different hypothetical layers with in the reactor are assumed and modelled with different blocks that can approximately represent the phenomena occurring in the different regions. The different layers of sections of the reactor (shown in the figure 4) are explained in the subsequent sub sections.

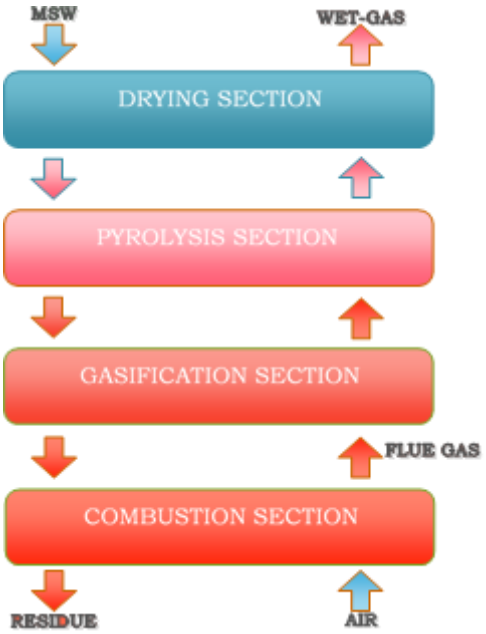


Figure 4: Schematic design of updraft fixed bed reactor

3.1. Drying

Drying is the first process to take place during the heating of a solid fuel. This process generally refers to the removal of moisture from certain substance (Treybal, 1981). But this meaning of drying may create ambiguity in its application in this study because this definition includes the mechanical means of moisture removal by expressing and centrifuging. Drying here refers to the process of moisture removal by making contact with a dry, hot gas stream. Thus as the feedstock is heated with the hot gas stream and its temperature increases, water is the first constituent to evolve.

$$\text{Moist feedstock} + \text{Heat} \rightarrow \text{Dry feedstock} + H_2O \qquad (10)$$

In the drying of the fuel handled (MSW), it is the surface moisture, contained outside individual particles, that is going to be removed. In this process the drying rate is considered to be dependent on the rate of the heat transferred to the material being dried. Thus the drying rate is heat transfer limited.

Initially a MSW, in the form of a refuse derived fuel, is fed to the reactor and forms a bed of fuel. In order to initiate the reaction, a preheated air is fed to the bottom of the reactor and this warm air combusts part of the fuel and hot flue gases are released to the upper part. This hot flue gas and few air passes up through the bed of the waste and creates a gasification medium. The hot gaseous products flow up to the exit section which is situated at the same location of the waste feed. When the aforementioned processes occur continuously, the feed side of the gasifier starts to act as a drying section. Due to the very high temperature assumed in the combustion and gasification section, the temperature at drying section gets elevated and attain a value as high as 240 ^{o}C. This temperature is high enough to completely remove the moisture contained in the waste.

In Aspen Plus simulator, since there is no a special block for this drying process, the Rstoic reactor block, which handles reactions with unknown or unimportant kinetics and known stoichiometry, by specifying the fractional conversion of the key component, is used together with sub stream splitter (SSplit) block. In order to balance the material, over the dried, it is controlled by a calculator block defined by writing statement on the built in FORTRAN sheet.

3.2. Pyrolysis

Pyrolysis is a case of thermolysis, and is most commonly used for organic materials, being, therefore, one of the processes involved in charring. This process is defined as a thermochemical decomposition of organic material at elevated temperatures without the participation of an oxidant. That is by the indirectly supplied heat from the hot gas from the combustion and gasification section, the waste is going to experience an irreversible change in its chemical composition and physical phase.

In this hypothetical section the fed waste whose surface moisture is assumed to get dried and decomposed in to its constituents. Therefore after this section the waste is considered to decompose into the constituting elements and ash that are detected and reported in the ultimate analysis result. It should be emphasized that there is no real phenomena that corresponds to this section.

This process in Aspen plus is simulated by the RYield reactor block. This block models reactions with known yield distribution but unknown or unimportant reaction stoichiometry and kinetics. As in the case of the drying, the yield distribution and hence the pyrolysis RYield model is also controlled by calculator block.

3.3. Gasification

This is the next ideal section in which the desired products of the process are formed. In this section the elements from the decomposition stage are assumed to react with limited gasifying medium. The resulting gas mixture from this section is called syngas and this is an energy carrier by itself that can directly be combusted to produce energy or it can also be used as an input for higher hydrocarbons.

At this stage the full combustion reactions are considered to provide the heat necessary to raise the reactor temperature high enough to drive gasification reactions. The principal reactions that are expected to occur at this stage are listed below.

$C + H_2O \rightarrow CO + H_2$	-132 KJ/mol	(11)
$C + CO_2 \rightarrow 2CO$	-173 KJ/mol	(12)
$C + 2H_2 \rightarrow CH_4$	+93.8 KJ/mol	(13)
$CO + H_2O \rightarrow H_2 + CO_2$	+41.98 KJ/mol	(14)

$CH_4 + H_2O \rightarrow CO + 3H_2$ -206 KJ/mol (15)

$CH_4 + H_2O \rightarrow CO_2 + 4H_2$ -165 KJ/mol (16)

Since, as it can be understood from the reactions above, multiphase reactions are going to take place. For this reason the RGibbs reactor block is the appropriate candidate to model this section. RGibbs is used to model reactions that come to chemical equilibrium and it calculates chemical equilibrium and phase equilibrium by minimizing the Gibbs free energy of the system. Due to this it will be unnecessary to feed the reactions that should take place and their stoichiometry to the reactor model.

3.4. Combustion

Combustion is defined as the phenomena of an exothermic chemical reactions between a fuel and an oxidant followed by the production of heat and irreversible conversion of chemical species. In this final hypothetical stage, the unreacted char is assumed to be combusted with supply of excess oxidant and the heat necessary to trigger the gasification reaction is given off.

The same as the preceding stage, the combustion is modelled in Aspen plus using the RGibbs reactor block. This block considers, based on its input, all the possible reactions that will take place and products. By default, RGibbs assumes that all of the components listed are potential products in the vapor or the liquid phase. This default is not appropriate for this simulation, since any carbon that remains after combustion would be solid. Thus from the list of the possible products, the appropriate phases are required to be assigned manually.

4. Numerical Methodology

4.1. Model Development

In this study a zero-dimensional steady model, which doesn't consider neither time nor dimension as variable, is developed for the gasification plant. This is the simpler level of modeling and simulation for an equipment or set of equipment's and this is strongly recommended approach, at least for a first Verification of the basic characteristics of the equipment or system operation. Depending on the complexity of the gasification internal phenomena and the limited availability of information of the actual process, this is believed to be the only achievable level of modeling. When beginning the modeling in Aspen plus simulator, all the components, conventional and non-conventional, involved in all stages of the process, must be specified.

4.1.1 Specifying Methods of Calculation of Physical Properties

The Aspen plus simulator incorporated number of chemical components, and different unit operation blocks, that can model different number of processes and each unit functioning block is solved as per certain sequences. In this study, since there is no single block that can simulate gasification, four hypothetical layers are assumed and approximately represented using three different reactor blocks. The specific fuel feedstock used in this study is not available in the Aspen plus components stock. Therefore the simulator considers this as a non-conventional component and calculates its physical property by built in correlations based on the different analysis results, known as component attributes in the simulator, that are going to be fed to the reactor block that handles it. This analysis results are characteristics of the fuel like proximate analysis, ultimate (elemental) analysis and sulfur analysis that are determined by experimental procedures.

Before any further in the model development, the very first task is selecting a physical property method, which assists to perform the simulation calculations, based on the process type. Choosing the appropriate property method is often the key decision in determining the accuracy of the simulation results. This property method is a collection of methods and models that Aspen Plus uses to compute thermodynamic and transport properties. The properties to be determined in this study are;

- Enthalpy
- Volume and
- Density of different conventional and nonconventional streams.

Aspen Plus includes a large number of built-in property methods that are sufficient for most applications. For this specific study regarding the feedstock, MSW (in the form of refuse derived fuel, RDF) is resembled with a non-conventional solid component, coal, whose enthalpy and density can be determined by built in physical property methods using the component attribute input. This property methods are known as non-conventional property methods and are stated under the general physical property method selected to handle the conventional liquids and vapors of the process. The non-conventional property methods are the same for all conventional property methods and thus the choice of property relation for conventional components can be made irrespective of the type of solid involved in the process.

The general coal model for computing enthalpy in the Aspen Physical Property System is known as HCOALGEN. This model includes a number of different correlations for the calculation of the heat of combustion, heat of formation and heat capacity of the non-conventional solid by the use of the proximate, ultimate (elemental) and sulfur analysis results fed to the system. There are four option codes along with HCOALGEN method that specify a calculation

method for properties. Each element in the option code vector is used in the calculation of a different property. Among the different enthalpy changes, the concern of this study is to determine the enthalpy change of combustion. These heat of combustion correlations were evaluated by the Institute of Gas Technology (IGT) by considering data for 121 samples of coal from the Penn State data base and 457 samples from a USGS report. The heat of combustion of RDF in the HCOALGEN model is a gross calorific value. It is expressed on a dry mineral-matter-free basis. ASTM Standard D5865-07a defines standard conditions for measuring gross calorific value. Products of the combustion are assumed to be in the form of ash; liquid water; and gaseous CO_2, SO_2, and NO_2. Net calorific value can be calculated from gross calorific value by making a deduction for the latent heat of vaporization of water. Heat of combustion values are converted back to a dry, mineral-matter-containing basis with a correction for the heat of combustion of pyrite, the assumed mineral to be contained within the RDF, using equation 17 along with Boie bias corrections obtained from the IGT study equation 18 (Perry et al., 1997).

$$\Delta_c h_i^{\,d} = \left(1 - w_{MM,i}\right)\Delta_c h_i^{\,dm} + 5400 w_{sp,i} \tag{17}$$

$$\Delta_c h_i^{\,dm} = \left(a_{1i} w^{dm}{}_{C,i} + a_{2i} w^{dm}{}_{H,i} + a_{3i} w^{dm}{}_{St,i} + a_{4i} w^{dm}{}_{O,i} + a_{5i} w^{dm}{}_{N,i}\right)10^2 + a_{6i} \tag{18}$$

Table 3: Boiec bias correction coefficients

Parameter Name/Element	Symbol	Default
BOIEC/1	a_{1i}	151.2
BOIEC/2	a_{2i}	499.77
BOIEC/3	a_{3i}	45.0
BOIEC/4	a_{4i}	-47.7
BOIEC/5	a_{5i}	27.0
BOIEC/6	a_{6i}	-189.0

The other physical property intended to be determined is the density of the RDF. This is determined by the same approach as that of enthalpy, using the built in coal density model (DCOALIGT). The DCOALIGT model gives the true (skeletal or solid-phase) density of coal on a dry basis. It uses ultimate and sulfur analyses. The model is based on equations from IGT (1976) (Aspen Physical Property System, 2013):

$$\rho_i = \frac{\rho_i^{dm}}{\left[\rho_i^{dm}(0.42 w_{A,i}{}^{d} - 0.15 w_{sp,i}{}^{d}) + 1 - 1.13 w_{A,i}{}^{d} - 0.5475 w_{sp,i}{}^{d}\right]} \quad (19)$$

$$\rho_i^{dm} = \frac{1}{a_{1i} + a_{2i} w_{H,i}{}^{dm} + a_{3i}(w_{H,i}{}^{dm})^2 + a_{4i}(w_{H,i}{}^{dm})^3} \quad (20)$$

$$w_{H,i}{}^{dm} = \frac{10^2 (w_{H,i}{}^{d} - 0.013 w_{A,i}{}^{d} + 0.02 w_{sp,i}{}^{d})}{(1 - 1.13 w_{A,i}{}^{d} - 0.475 w_{sp,i}{}^{d})} \quad (21)$$

Where ρ_i = density of coal (MSW for this study case)

ρ_i^{dm} = dry, mineral free density

ω_A = weight fraction of ash

Table 4: Default values of coefficients of coal density model

Parameter Name/Element	Symbol	Default
DENIGT/1	a_{1i}	0.4397
DENIGT/2	a_{2i}	0.1223
DENIGT/3	a_{3i}	-0.01715
DENIGT/4	a_{4i}	0.001077

The other principal assignment of physical property method is for that of the conventional chemical components appear in the gasification process. Since gases at high temperature and low pressure are dealt with in this process, the properties can be assumed as ideal gas properties. Therefore, the ideal gas

equation of state can be selected from the simulator database. The IDEAL property method accommodates both Raoult's law and Henry's law. This method uses the ideal activity coefficient (*Y*) model, which represents ideality of the liquid phase, ideal gas equation of state (P*V* = RT) and Rachett model (equation 5) for liquid molar volume determination.

$$V_m^{\ l} = \frac{RT_c(Z_m^{\ RA})^{1+(1-T_r)^{2/7}}}{P_c} \tag{22}$$

Where:

$$T_c = \sum_i \sum_j \frac{x_i x_j V_{ci} V_{cj} (T_{ci} T_{cj})^{1/2} (1-k_{ij})}{V_{cm}^{\ 2}}$$

$$\frac{T_c}{P_c} = \sum_i x_i \frac{T_{ci}}{P_{ci}}$$

$$Z_m^{\ RA} = \sum_i x_i Z_i^{\ *\mathrm{RA}}$$

$$V_{cm} = \sum_i x_i V_{ci}$$

$$T_r = \frac{T}{T_c}$$

4.1.2 Model block selection

Once the property method selection is done, the next decisive procedure is assigning the right reactor block that can best model each hypothetical layers. In the Aspen Plus reactor model, blocks are classified on the basis of balance based, equilibrium based and kinetics based. The following assumptions are made in developing this model;

- The residence time is long enough the different reactions reach chemical equilibrium.

- Char contains only carbon and ash;
- Ash is inert and it doesn't participate in chemical reactions.
- The heat exchange within the bed is ideal.
- The whole process operates isothermally and the same pressure of 1 atm throughout.
- The product gas is tar free and composed of H_2, CH_4, H_2O, CO, CO_2, SO_2, N_2 and NO.

In the first hypothetical layer, drying section, all the moisture contained in the RDF is assumed to evolve. This process can be explained by the reaction;

$$\text{Moist RDF} + \text{heat} \rightarrow \text{dry RDF} + H_2O \qquad (23)$$

Thus the major desire in this section is the extent at which the moisture contained in the RDF is removed. Therefore this can be assumed as a conversion reaction with unimportant and/or unknown reaction kinetics and known stoichiometry by specifying the extent of reaction or fractional conversion of the key component (RDF). From the Aspen plus model palette, RStoic, a balance based block, is the reactor block that can model such a reaction. Aspen Plus treats all nonconventional components as if they have a molecular weight of 1.0. The reaction indicates that 1 mole (or 1 lb.) of MSW reacts to form 0.0555084 mole (or 1 lb.) of water.

$$\text{MSW (wet)} \rightarrow 0.0555084\ H_2O \qquad (24)$$

After writing this reaction and the operating conditions in this reactor block it will completely be specified once the extent of reaction is assigned a value and sample value for the proximate analysis (moisture content specifically).

The next section, the pyrolysis, can be assumed as a reaction with known yield distribution. The ultimate (elemental) analysis result can be considered as the yield of individual components of the RDF (products of the decomposition reaction). With this assumption, the RYield, a balance based block, can efficiently model such reaction. The **DECOMP** (RYield) is used to simulate a reactor with a known yield, and does not require reaction stoichiometry and kinetics. This reactor block is completely specified after the operating conditions, sample yield distribution and sample component attributes are assigned. The component attribute fed in this block is for any remaining non-conventional component after the decomposition reaction. The very purpose of assuming this hypothetical layer, which doesn't exist in the reality, is that the equilibrium based blocks that can model the critical reactions of the process (gasification and combustion), cannot handle any non-conventional component i.e. the Gibbs free energy of non-conventional components cannot be calculated. Therefore, after the RYield block, the only non-conventional component present is ash and hence, the component attribute fed for this block is for ash.

The third and fourth section of this this process are the gasification and combustion sections in which number of chemical reactions are assumed to take place. This reactions are considered to be equilibrium reactions. Therefore, in selecting a block, the major criteria to consider is whether the block is equilibrium based. Based on this criteria, the RGibbs reactor block is the exact model of the two sections. This block is completely specified once its operating conditions are determined. RGibbs models chemical equilibrium by minimizing Gibbs free energy. By default, RGibbs assumes that all of the components are potential products in the vapor phase or the liquid phase. This default is not appropriate for this simulation, since any carbon that remains after the reactions would be solid. Therefore the possible phases need to be

adjusted manually. In the simulator at hand, liquid and vapor (gas) phases are represented as MIXED and the remaining carbon is assigned as PURE SOLID.

Other than the reactor blocks defined earlier, three splitter blocks are used to complete the modeling. The material splitters, known as SSplit in the simulator, combine material streams and divide the resulting stream into two or more outlet streams. The split fraction of each sub stream, for all but one outlet stream must be specified to completely model the process. SSplit calculates the flow rate of each sub stream in the unspecified outlet stream.

Table 5: Summary of model of the different sections

Block ID	Section	Model
DRIER	Drying	RStoic
SPLIT1	Splitting the Moisture	SSplit
DECOMP	Pyrolysis	RYield
GASIFIER	Gasification	RGibbs
SPLIT2	Splitting Unreacted Char	SSplit
COMBUST	Combustion	RGibbs
SEP	Splitting the Residue	SSplit

4.1.3 Stream class definition

There are three stream classes defined in Aspen Plus: material, heat and work streams. The material stream is used to define chemical composition, thermodynamic conditions and flow rates of the input and output streams. The heat streams are used to pass heat duties from one process unit to another. Similarly, work streams carry power between two blocks. In this simulation works, there are 14 material streams and a single heat stream that passes the heat produced from the decomposition reaction to the gasification section.

Material streams other than those between and after blocks are defined manually. The rest are automatically computed after the simulation has run.

The FEED, AIR and AIR2 are the streams that are defined manually in this simulation work. The exact component attribute values of the RDF are fed here in the FEED stream. It is from this fed information that the HCOALGEN and DCOALIGT property methods that determine the enthalpy and density of this non-conventional component. Other than the proximate, ultimate and sulfur analysis, the assumed flow rate of 100kg/hr, temperature of 25 ^{o}C and pressure of 1 atm are the information fed to the FEED material stream.

The other manually defined material stream is the AIR stream. In here air at ambient temperature of 25 ^{o}C and atmospheric pressure of 1 atm, is assumed to be fed to the gasification section at a molar flow rate of 1.0472kmole/hr. This value of molar flow rate is 20 % of the stoichiometric quantity of air that completely combust the 100kg/hr RDF determined after the stoichiometric quantity of air is computed. The last defined material stream is the AIR2 stream. As the case of the other two streams, the thermodynamic condition of this stream is also entered as 50 oC (assuming a preheated air to initiate the process) and 1 atm. The molar flow rate assigned in this stream is 2.0944kmole/hr, which is an excess quantity to completely combust any unreacted char to supply heat for the process. The two air streams (AIR and AIR2) are defined in the stream as 21% O_2 and 79% N_2.

The properties and conditions of the other material streams (DRIED, DRYMSW, DECOMPD, GASIFIED, syngas, WETSYGAS, CHAR, COMBUSTD, FLUEGAS and RESIDUE) are determined after the simulation calculations are progressed.

4.2. Initial Conditions

The MSW is fed at the top in the form of RDF, which is prepared by shredding, and baling the combustible components of municipal solid waste, is assumed

to be fed at the top of the gasifier at a rate of 100kg/hr and at a room temperature of 298K. Air at temperature of 298K, fed at the bottom section, is initially regulated to flow in at a rate of 30.212kg/hr (computed to be an air ER of 0.2). The feed material is assumed to be a feedstock of unknown particle size, and the whole gasifier is assumed to operate isobarically at a pressure of 1atm.

4.3. Simulation

In Aspen Plus, the blocks are chosen so that the different parts of the process can be specified as realistically as possible. The blocks are connected with proper linking streams to develop the flow diagram. The simulated model of the MSW gasification process flow diagram is presented in fig. 3.

Basic data input was required in different stages of the model development process. This input data requirements are in global data specifications, components specifications, properties, streams and blocks. The global data specification is the first thing to set when entering the simulation environment of Aspen plus. In this setting, input mode (dynamic or steady state), stream class, flow basis, ambient pressure, temperature (for dynamic runs only), valid phases and operational time of the year are specified.

The input mode for the simulation in this study is set as steady state, the stream class as MIXCINC that incorporate MIXED (liquid and vapor), CISOLID (conventional solid) and NC (non-conventional solid with unknown particle distribution), the flow basis as mass and pressure as 1atm are specified in the global setting sheet.

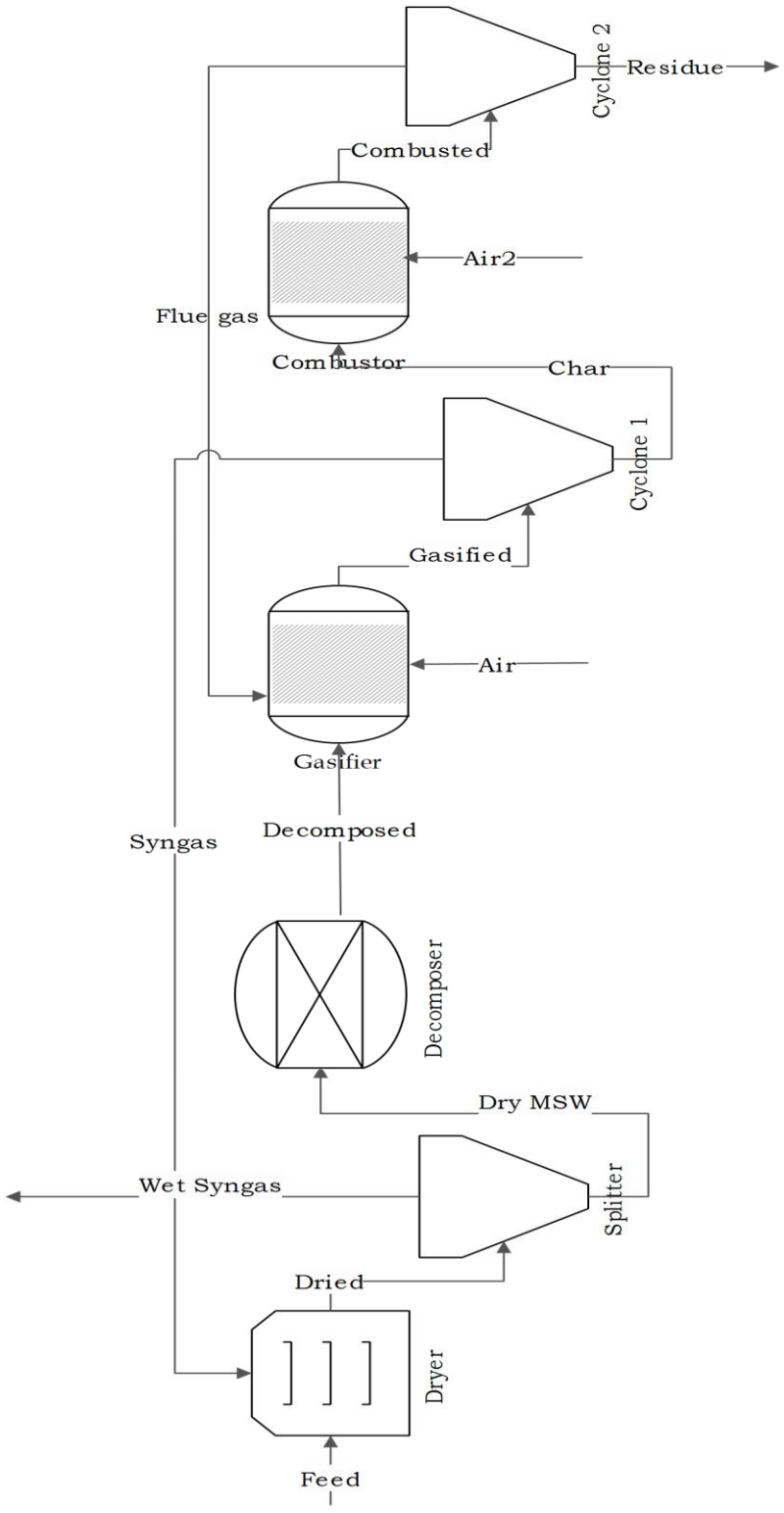


Figure 5: Model of the gasification plant

After all the specifications, streams and blocks are defined and connected the model is ready to be simulated. In the first stage, heating and drying of the feed MSW were performed. The “RStoic” block was used for instantaneous drying of the RDF. A FORTRAN statement is written to define a calculator block “drying calculator” (shown in the flow sheet above) that is used to control the drying process. Once this calculator block is defined, the moisture content of the output stream of the RStoic reactor block is going to be updated from the sample proximate analysis value entered at the beginning of the model development. The SPLIT1 block then separates the DRYMSW from the moisture. This DRYMSW stream is then enters the RYield reactor block. The output of this block is also controlled by a calculator block defined by a FORTRAN statement written for the decomposition of the non-conventional component. The ‘DECOMPOS calculator’ controls the process and defines the true yield distribution by overwriting the sample value of the yield written at the beginning of the modelling. The decomposed stream then enters the RGibbs (GASIFIER) block. This block is operated at an initial temperature of 700 ^{o}C and pressure of 1 atm. The dry product gas (syngas) from the gasifier is led to the drier block and leaves the splitter block (SPLIT1) as wet gas (WETSYGAS). The char (CHAR) is separated from the gasified stream by the separator block (SPLIT2) and led to the RGibbs (COMBUST) block. This block is set to operate at a temperature of 900 ^{o}C and a pressure of 1 atm. The unreacted char is completely combusted in the combustion section (COMBUST) and the gas (FLUEGAS) is separated from the residue and returned to the GASIFIER block. This simulated process of gasification is tested for different operating temperature of the gasifier and air mole flow rates (ER) to the gasifier.

5. Result and Discussion

5.1 Determining chemical formula of the solid waste

Solid waste is composed of materials with different chemical components and chemical formula. But for the understanding of the cumulative behavior of these solid wastes, it is appropriate to write a chemical formula that can best describe the composition of the waste.

With the following composition of the Addis Ababa city municipal solid waste that is collected and delivered to the Reppi site, representative sample was taken and the proximate and ultimate analysis of the waste are determined.

Step 1: Determine the ultimate and proximate analysis of the solid waste

Table 6: Ultimate analysis results

Element	Composition, %
Ash	4.85
Carbon	42.331
Hydrogen	6.723
Nitrogen	1.587
Sulfur	0.119
Oxygen	44.39

Table 7: Results of proximate analysis

Element	Composition, %
Ash	4.85
Moisture	28.92
Volatile Matter	60.25
Fixed Carbon	5.98

Step 2: subtract the moisture from the total feed to compute the mass of dry MSW.

From the 28.92Kg moisture content;

Amount of dry MSW = Total feed – Moisture Content (25)

Amount of dry MSW = 100kg/hr – 28.92kg/hr = 71.08kg/hr

Step 3: compute the mass of individual constituents

Table 8: Mass of individual constituents of the fed waste

Element	Mass, Kg/hr
Carbon	0.42331 * 71.08 = 30.089
Hydrogen	0.06723 * 71.08 = 4.779
Oxygen	0.4439 * 71.08 = 31.552
Nitrogen	0.01587 * 71.08 = 1.128
Sulfur	0.00119 * 71.08 = 0.084

Since the ultimate analysis is reported in dry basis, the mass of individual constituents can be calculated by multiplying the dry mass with their respective compositions.

Step 4: Compute molar composition of individual constituents and normalize it to the mole of carbon.

Table 9: Molar composition of constituents

Elements	Mole flow, Kmol/hr	Element mol/Carbon mol
Carbon	2.507	1
Hydrogen	4.779	1.906
Oxygen	0.081	0.787
Nitrogen	1.972	0.032
Sulfur	0.003	0.001

The chemical formula of the sampled Addis Ababa MSW is then,

$$\mathbf{CH}_{1.906}\mathbf{O}_{0.787}\mathbf{N}_{\mathbf{0.032}}\mathbf{S}_{\mathbf{0.001}}$$

5.2 Determining the amount of air Feed

From the ultimate analysis result, table above, the total quantity of oxygen, hence air, which is needed to fully combust the dry fuel can be calculated by relating it with the individual constituents. That is, by calculating the sum of the stoichiometric quantities of oxygen for the amount of carbon, hydrogen, nitrogen and sulfur and subtracting that of oxygen that are specified as compositions in the ultimate analysis. This can be summarized as follows;

Table 10: Oxygen demand of constituents

i	Stoichiometric combustion of *i*	Oxygen needed for the actual amount of *i* in the feed, mol
Carbon	$C + O_2 \rightarrow CO_2$	
	1 mol O_2 for 1 mol C	1
Hydrogen	$H_2 + ½\ O_2 \rightarrow H_2O$	
	¼ mol O_2 for 1 mol H	1.906/4 = 0.476
Nitrogen	$N_2 + O_2 \rightarrow 2NO$	
	½ mol O_2 for 1 mol N	0.032/2 = 0.016
Sulfur	$S + O_2 \rightarrow SO_2$	
	1 mol O_2 for 1 mol S	0.001

Therefore, the total quantity of O2 for full combustion will be;

Stoic. O_2 = 1 + 0.476 + 0.016 + 0.001 – 0.787/2(O in the dry feed) = 1.1 mole

Since air is consisted of 79% N_2 and 21% O_2, or in the ratio of $3.76N_2$:$1O_2$, the equivalent amount of air that is needed for the full combustion of the dry feed will be;

$$\text{Stoic. Air} = (1 + 3.76) * \text{Stoic. } O_2 \quad (26)$$

$$\text{Stoic. Air} = 1.1 * (1 + 3.76) = 5.236\text{kmole/hr}$$

With the definition of the air equivalence ratio, ER, as being the ratio between the actual amount of air fed to the gasifier and the calculated stoichiometric amount of air in relation to the quantity of dry MSW feed, it is assumed, in this study, as the different level of fraction of the stoichiometric amount.

5.3 Sensitivity Analysis

Once the simulation is completed, the model is tested how it responds for the variance of the gasifier temperature and air ER with respect to the output syngas composition and lower heating value (LHV). The air ER sensitivity is also tested with respect to the gasifier carbon conversion efficiency.

5.3.1 Effect of gasifier temperature on syngas composition

The effect of gasifier temperature ranging from 500 to 700 ^oC on syngas composition have been studied for three different equivalence ratios of 0.2, 0.4 and 0.6.

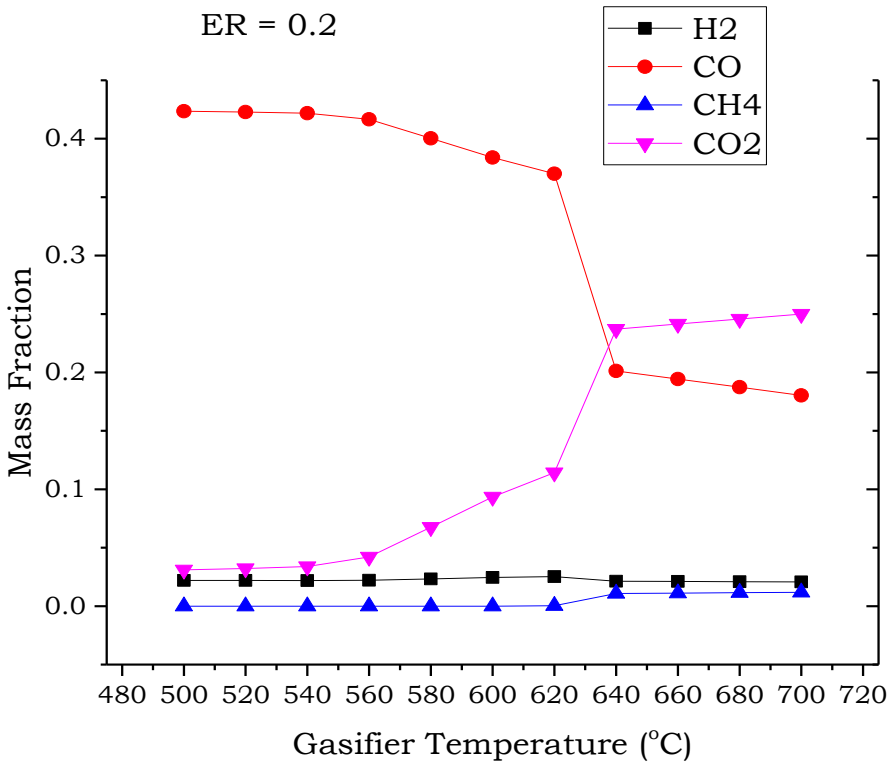


Figure 6: Effect of gasification temperature on the gas composition for an ER of 0.2

As it can be seen from the graph for an ER of 0.2, CO concentration increased (from 3.41% at 500 °C to 41.02% at 700 °C) with the increase of gasification temperature while CO_2 concentration followed the opposite trend (from 36.12% at 500 °C to 18.76% at 700 °C). Though this effect is minimal for the composition of H_2 and CH4, one can still identify from the graph that with the increase of the gasifier temperature, H_2 composition tend to slightly increase (from 1.86% at 500 °C to 4.17% at 700 °C) and that of CH_4 shows slight decrease (from 6.28% at 500 °C to 1.55% at 700 °C).

For an ER of 0.4, the same trend of composition variance with slight magnitude difference is observed. CO concentration increased (from 3.14% at 500 °C to 36.32% at 700 °C) with the increase of gasification temperature, CO_2 concentration

decreased (from 33.03% at 500 °C to 16.27% at 700 °C), H_2 composition slightly increases (from 1.42% at 500 °C to 3.09% at 700 °C) and that of CH_4 decreased (from 3.92% at 500 °C to 0.94% at 700 °C).

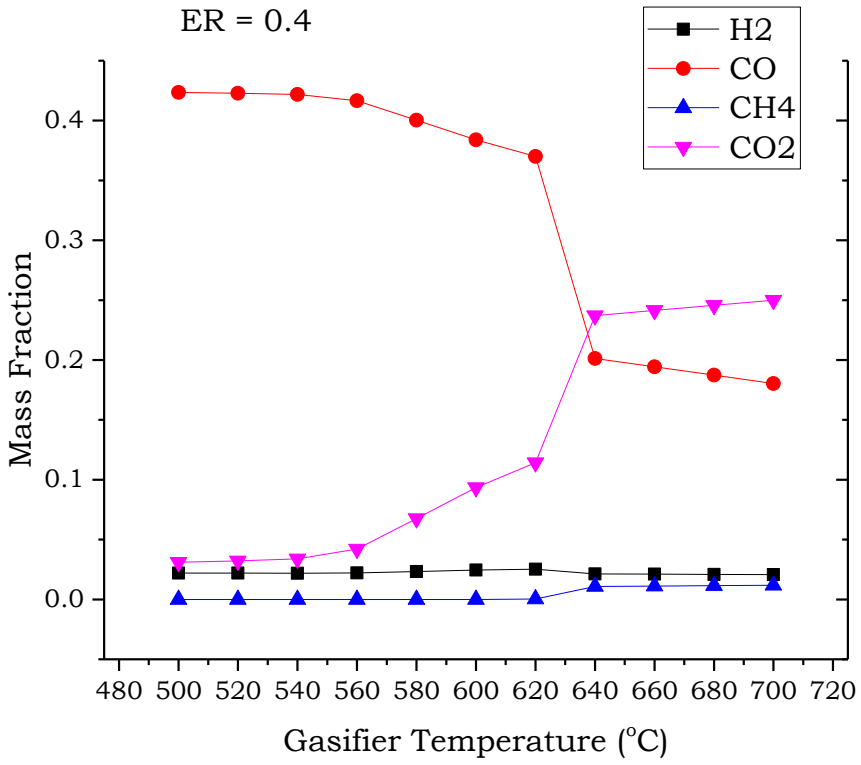


Figure 7: Effect of gasification temperature on the gas composition for an ER of 0.4

With 0.6 ER, the same effect of gasification temperature has been seen but the magnitudes of individual compositions tend to decrease. CO fraction increased from 2.98% at 500 °C to 33.55% at 700 °C, CO_2 decreased from 31.33% to 14.81%, while H_2 increased from 1.14% at 500 °C to 2.44% at 700 °C and CH_4 fraction decreased from 2.68% at 500 °C to 0.63% at 700 °C as shown below.

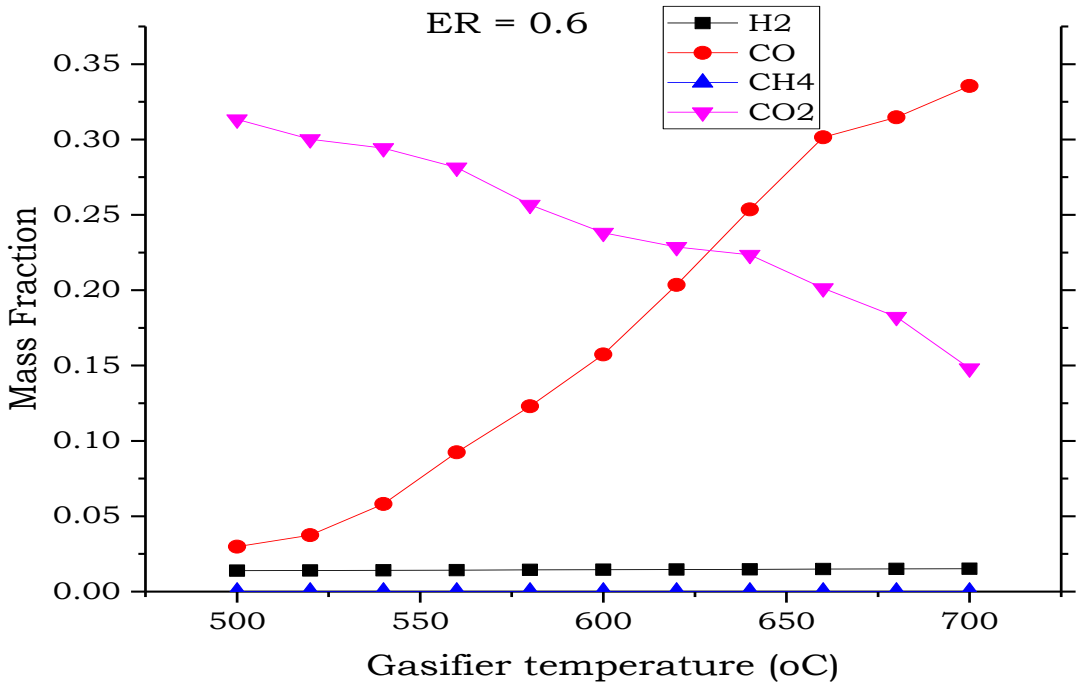


Figure 8: Effect of gasification temperature on the gas composition for an ER of 0.6

Therefore an equivalence ratio of 0.2 is taken as the optimal equivalence ratio for further analysis of effect of temperature since the magnitudes of the desired products (H_2, CO and CH_4) composition decreased with the increment of molar flow rate of air fed to the gasifier.

5.3.2 Effect of gasifier temperature on LHV of syngas

The effect of gasifier temperature on the LHV of the syngas for an optimum ER ratio of 0.2 is clearly shown on the graph plot. It has increased from the initial value 6196 KJ/Nm^3 at 500 ^{o}C to 6731 KJ/Nm^3 at the final temperature 700 ^{o}C. These heating value results of MSW gasification with air as a medium, are the common values of LHV that can be found in open literatures. The lower heating value is defined by;

$$LHV = \frac{119950.4n_{H_2} + 10103.9n_{CO} + 50009.3n_{CH_4}}{V} \quad (27)$$

Where; nH_2, nCO and nCH_4 are the molar yields of H_2, CO and CH_4

V = the volume of syngas produced, m^3

LHV = lower heating value of syngas, KJ/Nm^3

From this plot, it can be noticed that as the temperature increased the heating value of the product gas which in turn can be explained from the equation by the increment of the desired component of the syngas product. Though the magnitude difference of the LHV between the initial and final temperature values small, it can be reported that the LHV change is sensitive to the temperature change within the gasifier. It is stated so because of the common low value of the LHV of syngas produced from the gasification of MSW. Thus any small change can be considered as significant one.

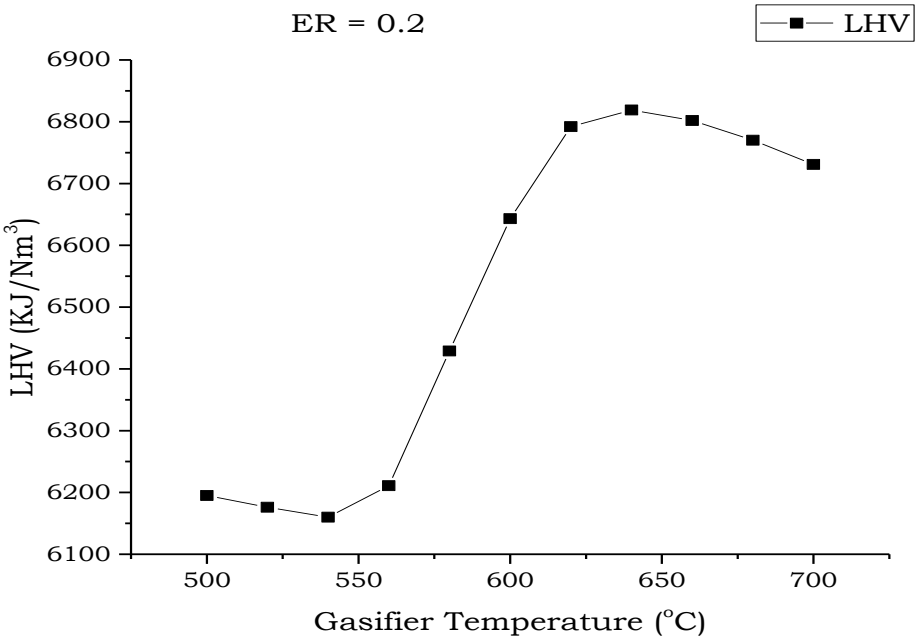


Figure 9: Effect of gasification temperature on the LHV of product gas.

5.3.3 Effect of temperature on carbon and heat conversion

As it can be expected, the gasification temperature has a visible effect on the heat conversion of the gasification process. From the graph plot, it can be understood that, the temperature rise favors the conversion efficiency of the heat. That is, the magnitude of the LHV increased from 2321.13 KJ/kg for a temperature of 500 ^{o}C and an ER of 0.2 to 2527.93 KJ/kg for temperature of 700 ^{o}C and ER of 0.2 with the highest value (2602.37 KJ/kg) being seen at a bed temperature of 640 ^{o}C.

$$HC = \frac{LHV * V}{m_{MSW}} \tag{28}$$

Where; HC = the heat conversion, KJ/kg

LHV = lower heating value of the gas, KJ/Nm^3

V = the volume of the product gas, m^3

m_{MSW} = the mass of dry MSW, kg

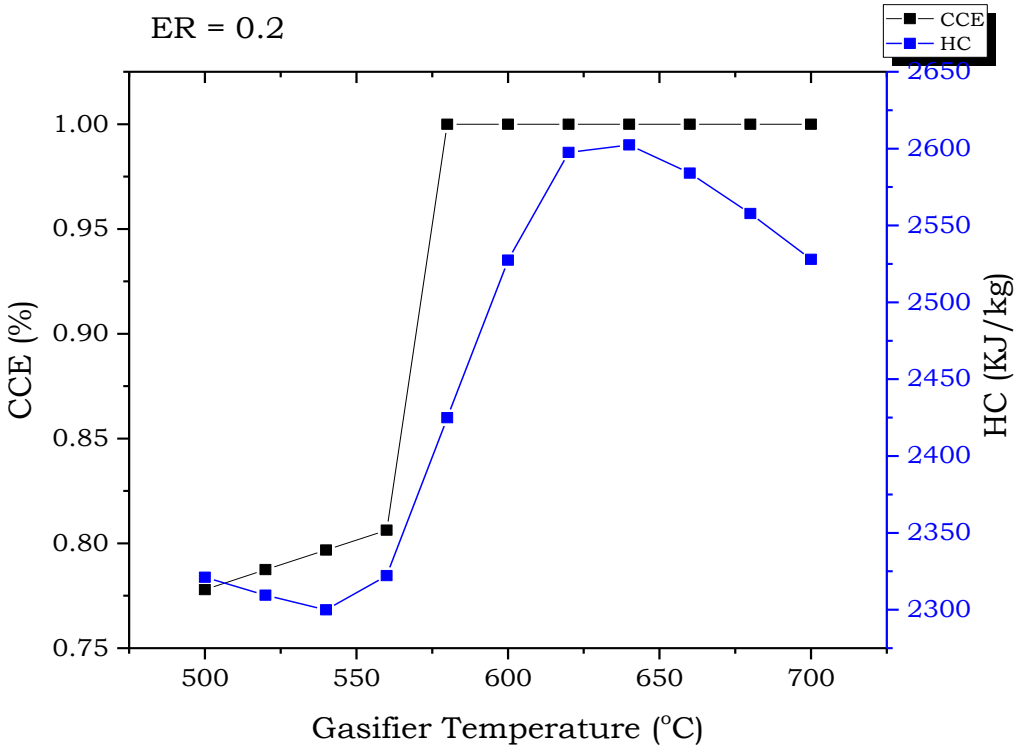


Figure 10: Effect of gasifier temperature on the heat and carbon conversion

When the equation is examined, the observed trend will not be of no surprise, because the temperature is already seen to affirmatively affect the composition, and hence, LHV of the gas.

5.3.4 Effect of air equivalence ratio on syngas composition

The sensitivity analysis of the effect of ER on syngas composition at three different temperatures (500, 600, and 700 °C) has been studied and presented in this document. The graphs prove that with the increment of molar flow, hence, the ER of air, the yield of syngas decreases. This effect tends to magnify as the gasifier temperature increased.

When the ER sensitivity is tested for gasifier temperature of 500 °C, the composition of H_2 and CH_4 slightly falls as the air mole flow increased while

that of CO maintained almost constant value. This shows that the lower temperature in the bed lowers the sensitivity of the gas composition with regard to the ER. This effect becomes more detectable and clearer when the temperature is increased to 700 °C. As it can be seen on the graph (fig. 9), the composition of CO decreased from about 40.23% to 19.3% and H_2 also decreased from 4.2% to around 1.92%. The same trend can be seen happening on the concentration of CH_4. Oppositely, the concentration of CO_2 can be seen increasing with ER as expected, since the rise in air supply favors the reaction towards complete combustion.

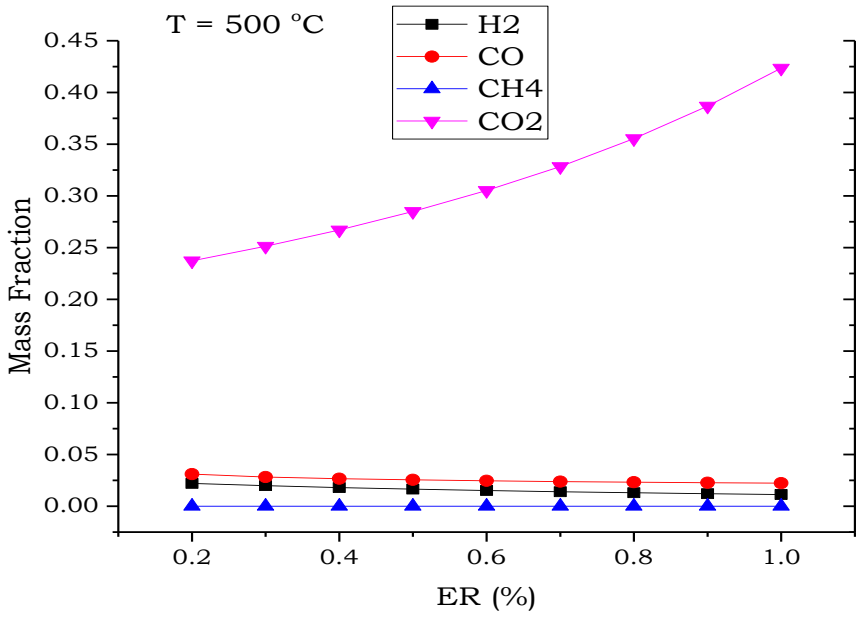


Figure 11: Effect of air mole flow on gas composition for T = 500 °C

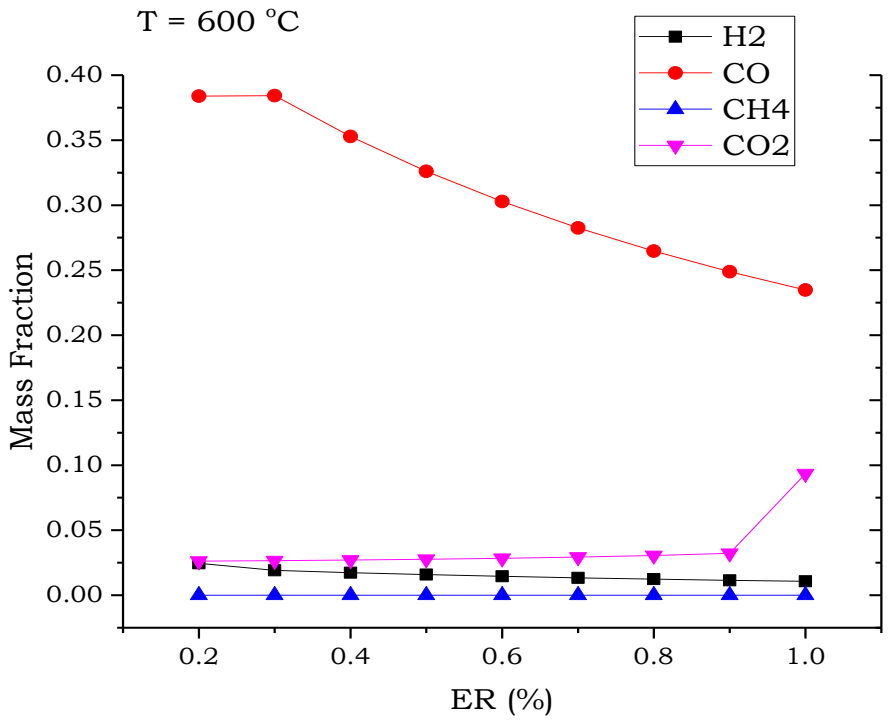


Figure 12: Effect of air mole flow on gas composition for T = 500 °C

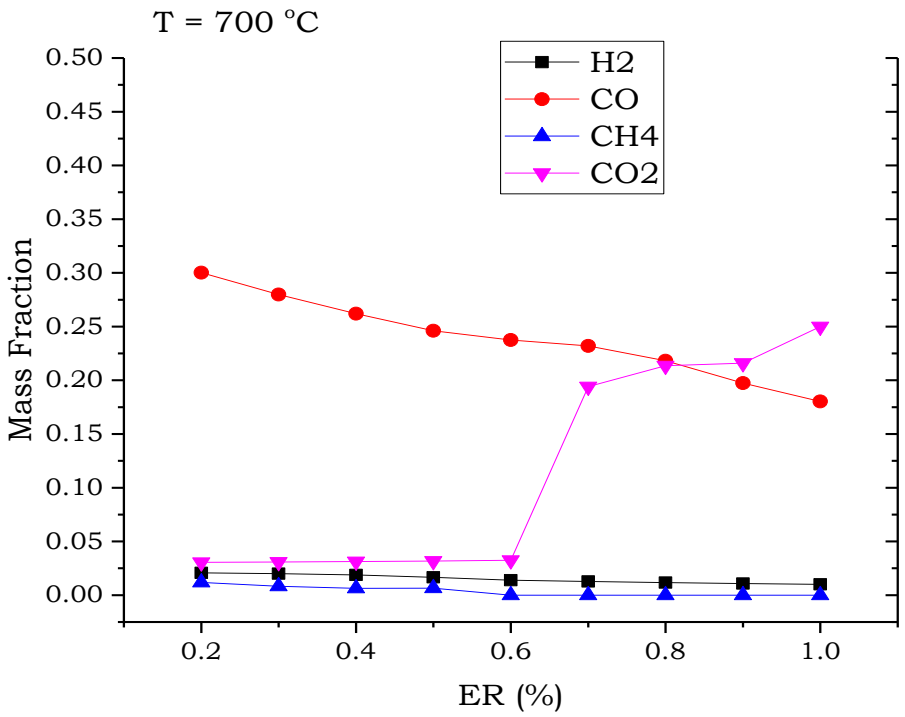


Figure 13: Effect of air equivalence ratio on carbon and heat conversion

As it can be seen on the fig. , the CCE increased from 0.778 for an ER of 0.2 (1.0472kmole/hr) to 1 for an ER of 0.4 (2.0944kmole/hr) and stayed constant at this maximum conversion efficiency point as the feed air mole flow (ER) increased. The equation for the calculation of the carbon conversion efficiency (CCE) is written as;

$$CCE = \frac{C_2}{C_1} = 1 - \frac{C_{out}}{C_1} \tag{29}$$

Where; C_1 = the amount of carbon in the feed, kg/hr

C_2 = the amount of carbon in the product gas, kg/hr

C_{out} = the amount of carbon in the residue, kg/hr

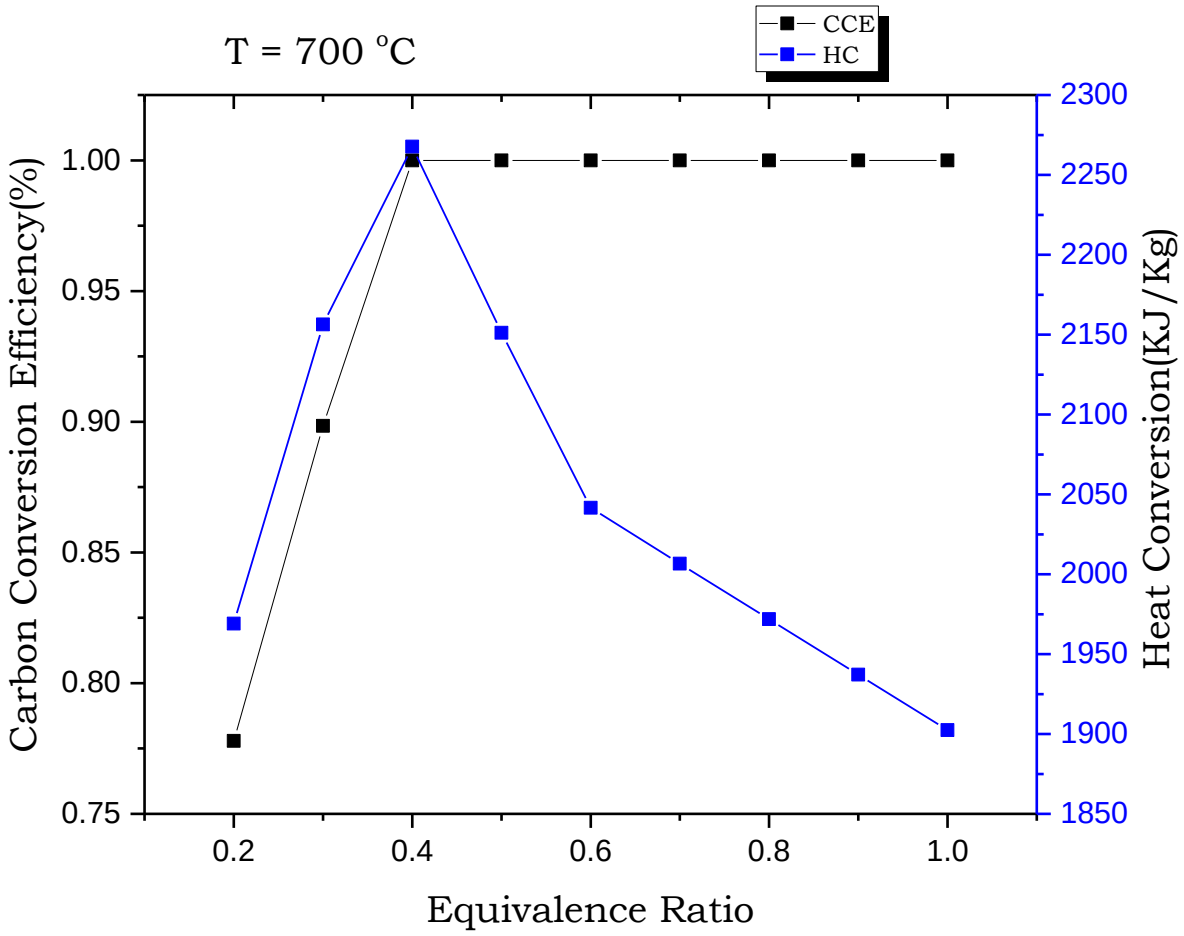


Figure 14: Effect of ER on CCE and heat conversion for T = 700 °C

The increment can be explained as, with the rise of air supply to the gasifier at high enough temperature, all the available carbon in the bed is consumed by combustion either partially or completely. Thus no carbon can be found in the residue stream as the supply of air increased.

When the HCE is examined, the magnitude has increased from 1969.1 KJ/kg for an ER of 0.2 to its maximum point of 2267.72 KJ/kg when the ER gets a value of 0.4. After this point the HCE value drops with the increase of the air supply. After comparing the two curves (HCE and CCE), it can be concluded

that the ER ratio of 0.4 is the best ratio to obtain high efficiency at high temperatures.

5.3.5 Effect of air equivalence ratio on LHV of syngas

The effect of the air equivalence ratio on the lower heating value of syngas, for the optimum gasifier temperature of 700 ^{o}C, is plotted on the graph below. The initial LHV value of 6.731MJ/Nm3 at an air ER of 0.2 (1.0472kmole/hr) suddenly falls to 5.471MJ/Nm3 when the ER is changed to 0.4 (2.0944kmole/hr) and then the LHV gradually decreases and attains its final value of 3.305MJ/Nm3 at the stoichiometric air molar flow of 5.236kmole/hr. With the above definition of LHV (equation 7), this decreasing trend can directly be related to the decrease in the yield of partial combustion gases (CO, CH_4 and H_2) with the air supply increment.

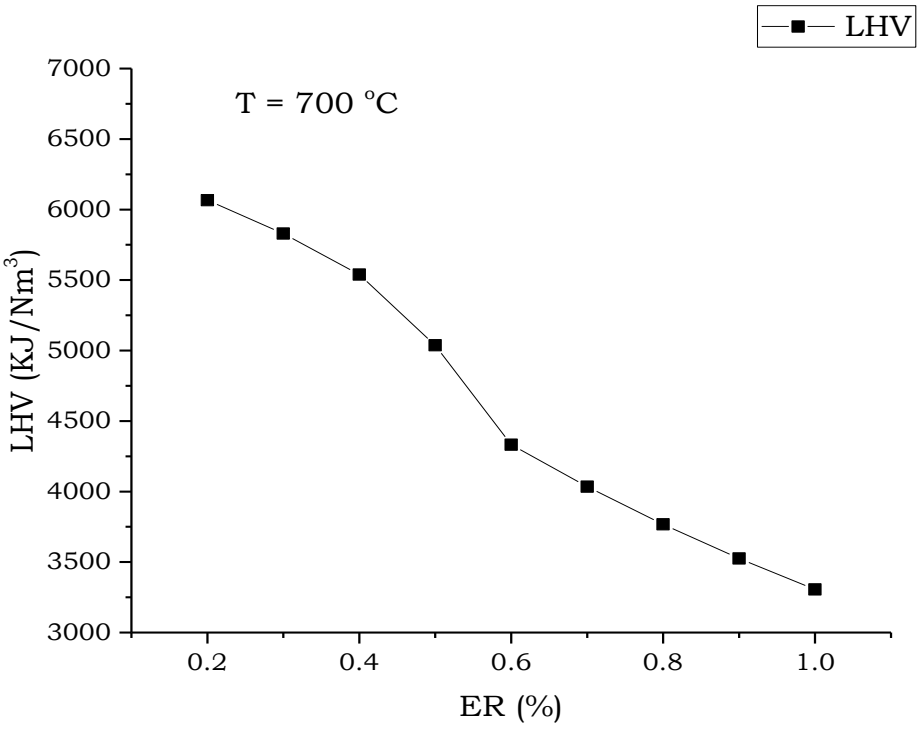


Figure 15: Effect of air mole flow on LHV for T = 700 oC

5.4 Model validation

The gasification of MSW, in this study, is simulated in series of trials regulating the operating temperature and air mole flow rate with sample feedstock flow rate of 100 kg/hr. The simulation process was generated by burning non-condensable gaseous products. Regarding the yield, it can be observed that a higher temperature is needed when the air flow rate is less. In order to compare the results of the simulation study, the biomass gasifier database for computer simulation purpose, organized by Svenskt Gastekniskt Center is used. The center collected the experimental results of number of different gasifiers by different developers. Among these the gasifier developed by Nexterra systems (supplier of biomass gasification solutions) resembles the gasification process simulated in this study. Nexterra's gasification systems are specifically designed to address the needs of industrial and institutional customers wanting to reduce both their fuel costs and their carbon footprint. The status and results of the experiment are revised in the tables below for the purpose of validation of these study's simulation results (Hansson *et al.*, 2011).

Table 11: Specifications of the Nexterra gasification experiment

Specification	Status
Gasifier Type	Updraft fixed bed gasifier
Gas Flow Direction	Updraft
Operating Pressure	Atmospheric
Operating Temperature (°C)	<900
Feedstock	woody biomass
Moisture Content of Feedstock	6-60%
Approximate Size (cm)	<7 cm
Feedstock Energy Content, LHV (kJ/kg)	18150
Air Input (kg/s)	20-30% of Stoichiometric rate

Table 12: Compositions of Nexterra updraft fixed bed gasification product gases

Outlet gas		
Composition (dry basis)	Mass (%)	Volume (%)
H_2	1.2-1.6	15-20
CO	21.7-28.5	20-25
CO_2	20.5-25.1	12-14
CH_4	1.2-2.6	2-4
C_2H_6	0.6-1.2	0.5-1
N_2	54.8-41	50.5-36
H_2O	8-25	10-30

Table 13: Conditions of Nexterra updraft fixed bed gasification product gas

Outlet gas	Experiment result
Energy Content, LHV (kJ/kg)	8-10 (dry basis)
Temperature (°C)	<400
Pressure (bar)	1
Product Efficiency (LHVprod/LHVin)	60-72%

When the results of this study is compared with that of the database report of Nexterra gasifier systems, the highest values of the compositions of CO (21.7-28.5%), H_2 (1.2-1.6%) and CH_4 (1.2-2.6%) were attained. At the optimum conditions of this study (T = 700 ^oC and ER = 0.4), 36.32% CO, 3.09% H_2 and 0.94% CH_4 were able to be found. When this magnitudes are compared with the database results, even some exaggerated results of this study can be observed. The reason behind this is, the study taken number of assumptions which may shift its results from experimental results a bit. These assumptions

are like, long enough residence time to reach equilibrium, neglected tar content in the product gas stream, and the likes.

When examining the LHVs, the reported result's range from 8 – 10 KJ/kg (7.1 – 8.87 KJ/Nm^3). The highest LHV value (6.819KJ/Nm^3) of this study seem to almost satisfy the minimum value of the experiment. Therefore this simulation work can be stated as one that is on the right track of study the gasification process.

6. Conclusion and Recommendation

6.1 Conclusion

A 0D steady model of gasification of MSW in updraft type of fixed bed reactors is conducted in this study and satisfactory results are cultivated from the analysis of the simulation. Aspen plus 8.8, is used in order to study the physical properties and effects of gasification temperature and air molar flow on the yield and lower heating value of the product gas, on the overall carbon conversion efficiency and heat conversion of the gasification process. The physical properties of the dry MSW are computed to be:

Density = 1247.19 kg/m^3, and

Enthalpy = -0.096 Gcal/hr

Generally, from the conducted analysis, the best results of the syngas composition are; 41.02% CO, 4.17% H_2 and 1.55% CH_4. This results are observed at a temperature of 700 ^oC and an air ER of 0.2. Concerning the LHV, the best observed value is 6.819 MJ/Nm^3 at temperature 640 ^oC and ER of o.2. Therefore, the following conclusion can be drawn from the study;

- The huge fraction of organics in the AA MSW stream makes the gasification option a sound one.
- The high temperature is seen to favor the composition and LHV of the syngas when combined with low flow rates of air feed.
- The highest values of LHV and heat conversion are observed at a temperature of gasifier of 640 ^oC
- The air feed rate plays the vital role in altering the gas composition, the heating value, the heat conversion and carbon conversion efficiencies.

- The pick values for CCE, heat conversion and LHV are seen to be observed when the air ER is equal to 0.4.

- Therefore the optimum values of gasification temperature and air equivalence ratio are found to be 640 ^{o}C and 0.4.

6.2 Recommendation

The results of the simulation are seen to agree with related works found from open literature. With proper waste management strategy, a huge potential feedstock can be cultivated from the waste stream as there is no any such facility in the country.

Compared to the real operation of FB gasifier, the handled solid fuel does not have uniform size which has huge influence on the operation that can be considered as the limitation of this study. Further study should be made by incorporating the particle size distribution of the feedstock and by reducing the assumptions made for the sake of better understanding of the exact potential of gasifying the waste stream.

The Aspen plus simulator is a very powerful tool that can help to clearly investigate the effect of different parameters of very sophisticated operations like gasification. I recommend further study of different types of gasifiers using Aspen plus together with other simulation tools that can efficiently model the geometry of the gasifier in addition to the process simulation.

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Appendix

A. Blocks Report

```
 BLOCK:  COMBUST  MODEL: RGIBBS
 ------------------------------
   INLET STREAMS:         CHAR        AIR2
   OUTLET STREAM:         COMBSTD
   PROPERTY OPTION SET:   IDEAL     IDEAL LIQUID / IDEAL GAS

                       ***  MASS AND ENERGY BALANCE  ***
                              IN           OUT       GENERATION   RELATIVE
DIFF.
 CONV. COMP.(KMOL/HR )     2.09440       2.09440     -0.342626E-05 -
0.212036E-15
            (KG/HR   )     60.4243       60.4243
0.00000
 NONCONV COMP(KG/HR   )    3.44738       3.44738
0.00000
   TOTAL BALANCE
      MASS(KG/HR   )       63.8717       63.8717
0.00000
      ENTHALPY(GCAL/HR ) 0.240291E-03  0.138528E-01               -
0.982654

                       ***  CO2 EQUIVALENT SUMMARY ***
    FEED STREAMS CO2E             0.00000      KG/HR
    PRODUCT STREAMS CO2E          0.00000      KG/HR
    NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
    UTILITIES CO2E PRODUCTION     0.00000      KG/HR
    TOTAL CO2E PRODUCTION         0.00000      KG/HR

                          ***  INPUT DATA  ***

   EQUILIBRIUM SPECIFICATIONS:
     ONLY CHEMICAL EQUILIBRIUM IS CONSIDERED, THE FLUID PHASE IS VAPOR
     SYSTEM TEMPERATURE    C                                    900.00
     TEMPERATURE FOR FREE ENERGY EVALUATION    C              900.00
     SYSTEM PRESSURE       BAR                                  1.0132

   FLUID PHASE SPECIES IN PRODUCT LIST:
     WATER METHA-01 HYDRO-02 OXYGE-01 NITRO-01 SULFU-01 CARBO-01

     CARBO-02 NITRO-02 SULFU-02

   SOLIDS IN PRODUCT LIST:
     CARBON

   ATOM MATRIX:
   ELEMENT      H    C    N    O    S
```

```
     WATER      2.00 0.00 0.00 1.00 0.00
     CARBON     0.00 1.00 0.00 0.00 0.00
     METHA-01   4.00 1.00 0.00 0.00 0.00
     HYDRO-02   2.00 0.00 0.00 0.00 0.00
     OXYGE-01   0.00 0.00 0.00 2.00 0.00
     NITRO-01   0.00 0.00 2.00 0.00 0.00
     SULFU-01   0.00 0.00 0.00 0.00 1.00
     CARBO-01   0.00 1.00 0.00 1.00 0.00
     CARBO-02   0.00 1.00 0.00 2.00 0.00
     NITRO-02   0.00 0.00 1.00 2.00 0.00
     SULFU-02   0.00 0.00 0.00 2.00 1.00

                          ***  RESULTS  ***
   TEMPERATURE           C                                   900.00
   PRESSURE              BAR                                 1.0132
   HEAT DUTY             GCAL/HR                           0.13612E-01
   VAPOR FRACTION                                            1.0000
   NUMBER OF FLUID PHASES                                         1

   FLUID PHASE MOLE FRACTIONS:

   PHASE              VAPOR
   OF TYPE            VAPOR
   PHASE FRACTION     1.000000
   PLACED IN STREAM   COMBSTD
     OXYGE-01        0.2099971
     NITRO-01        0.7899997
     NITRO-02        0.3271831E-05

   KMOL/HR            2.094397

 BLOCK:  DECOMP   MODEL: RYIELD
 ------------------------------
   INLET STREAM:          DRYMSW
   OUTLET STREAM:         DECOMPD
   OUTLET HEAT STREAM:    Q-DECOMP
   PROPERTY OPTION SET:   IDEAL     IDEAL LIQUID / IDEAL GAS

                       ***  MASS AND ENERGY BALANCE  ***
                              IN          OUT       GENERATION   RELATIVE
DIFF.
 CONV. COMP.(KMOL/HR )    0.00000       5.90460       5.90460
0.00000
            (KG/HR   )    0.00000       67.6326                     -
1.00000
 NONCONV COMP(KG/HR   )   71.0800       3.44738
0.951500
   TOTAL BALANCE
      MASS(KG/HR   )      71.0800       71.0800
0.199928E-15
      ENTHALPY(GCAL/HR )-0.935279E-01 -0.935279E-01
0.00000
```

```
                    ***  CO2 EQUIVALENT SUMMARY ***
    FEED STREAMS CO2E             0.00000      KG/HR
    PRODUCT STREAMS CO2E          0.00000      KG/HR
    NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
    UTILITIES CO2E PRODUCTION     0.00000      KG/HR
    TOTAL CO2E PRODUCTION         0.00000      KG/HR

                         ***  INPUT DATA  ***
   TWO    PHASE  TP  FLASH
   SPECIFIED TEMPERATURE C                                  25.0000
   SPECIFIED PRESSURE    BAR                                 1.01325
   MAXIMUM NO. ITERATIONS                                   30
   CONVERGENCE TOLERANCE                                     0.000100000

    MASS-YIELD
     SUBSTREAM MIXED   :
     HYDRO-02  0.672E-01    OXYGE-01  0.444        NITRO-01  0.159E-01
     SULFU-01  0.119E-02
     SUBSTREAM CISOLID :
     CARBON    0.423
     SUBSTREAM NC      :
     ASH       0.485E-01

                           ***  RESULTS  ***
   OUTLET TEMPERATURE    C                                   25.000
   OUTLET PRESSURE       BAR                                  1.0132
   HEAT DUTY             GCAL/HR                             0.93032E-01
   VAPOR FRACTION                                            0.99922



   V-L PHASE EQUILIBRIUM :

      COMP              F(I)           X(I)           Y(I)           K(I)
      HYDRO-02         0.69732        0.49019E-04    0.69786
14237.
      OXYGE-01         0.29006        0.37306E-03    0.29028
778.12
      NITRO-01         0.11845E-01    0.12173E-04    0.11854E-01
973.84
      SULFU-01         0.77595E-03    0.99957        0.12798E-06
0.12803E-06

 BLOCK:  DRIER    MODEL: RSTOIC
 ------------------------------
   INLET STREAMS:         FEED        SYNGAS
   OUTLET STREAM:         DRIED
   PROPERTY OPTION SET:   IDEAL     IDEAL LIQUID / IDEAL GAS

                       ***  MASS AND ENERGY BALANCE  ***
                              IN          OUT       GENERATION   RELATIVE
DIFF.
```

```
 CONV. COMP.(KMOL/HR )    9.37356       10.9789       1.60530
0.00000
           (KG/HR   )    218.693       247.613                    -
0.116795
 NONCONV COMP(KG/HR   )   100.000       71.0800
0.289200
   TOTAL BALANCE
      MASS(KG/HR   )      318.693       318.693
0.573192E-07
      ENTHALPY(GCAL/HR )-0.290269     -0.290269                    -
0.572213E-07

                     ***  CO2 EQUIVALENT SUMMARY ***
    FEED STREAMS CO2E             7.10143      KG/HR
    PRODUCT STREAMS CO2E          7.10143      KG/HR
    NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
    UTILITIES CO2E PRODUCTION     0.00000      KG/HR
    TOTAL CO2E PRODUCTION         0.00000      KG/HR

                          ***  INPUT DATA  ***
   STOICHIOMETRY MATRIX:

    REACTION #   1:
     SUBSTREAM MIXED   :
     WATER     0.555E-01
     SUBSTREAM CISOLID :
     NO PARTICIPATING COMPONENTS
     SUBSTREAM NC      :
     MSW       -1.00


   REACTION CONVERSION SPECS: NUMBER=    1
     REACTION #   1:
     SUBSTREAM:NC       KEY COMP:MSW      CONV FRAC: 0.2892




   TWO    PHASE  PQ  FLASH
   SPECIFIED PRESSURE    BAR                                  1.01325
   SPECIFIED HEAT DUTY   GCAL/HR                              0.0
   MAXIMUM NO. ITERATIONS                                    30
   CONVERGENCE TOLERANCE                                      0.000100000
   SIMULTANEOUS REACTIONS
   GENERATE COMBUSTION REACTIONS FOR FEED SPECIES          NO

                          ***  RESULTS  ***
   OUTLET TEMPERATURE    C                                    309.03
   OUTLET PRESSURE       BAR                                  1.0132
   VAPOR FRACTION                                             1.0000
```

REACTION EXTENTS:

REACTION NUMBER	REACTION EXTENT KMOL/HR
1	28.920

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
WATER	0.22509	0.90452E-01	0.22509	96.188
METHA-01	0.12787E-11	0.17505E-14	0.12787E-11	2190.8
HYDRO-02	0.13705	0.13213E-04	0.13705	14237.
OXYGE-01	0.29015E-01	0.22593E-04	0.29015E-01	3305.9
NITRO-01	0.38043	0.27103E-03	0.38043	3255.9
SULFU-01	0.16497E-03	0.90903	0.16497E-03	0.81412E-01
CARBO-01	0.21348	0.15724E-03	0.21348	3253.0
CARBO-02	0.14697E-01	0.46843E-04	0.14697E-01	1878.0
NITRO-02	0.34902E-05	0.79835E-07	0.34902E-05	1683.8
SULFU-02	0.75296E-04	0.18009E-05	0.75296E-04	423.40

BLOCK: GASIFIER MODEL: RGIBBS

INLET STREAMS:	AIR	DECOMPD	FLUEGAS
INLET HEAT STREAM:	Q-DECOMP		
OUTLET STREAM:	GASIFIED		
PROPERTY OPTION SET:	IDEAL	IDEAL LIQUID / IDEAL GAS	

*** MASS AND ENERGY BALANCE ***

	IN	OUT	GENERATION	RELATIVE DIFF.
CONV. COMP.(KMOL/HR)	11.1406	9.37356	-1.76704	-0.193435E-06
(KG/HR)	218.693	218.693		-0.779769E-15
NONCONV COMP(KG/HR)	3.44738	3.44738		0.00000
TOTAL BALANCE				
MASS(KG/HR)	222.141	222.141		-0.767668E-15
ENTHALPY(GCAL/HR)	-0.797517E-01	-0.797533E-01		0.201624E-04

```
                  ***  CO2 EQUIVALENT SUMMARY ***
 FEED STREAMS CO2E             0.00000      KG/HR
 PRODUCT STREAMS CO2E          7.10143      KG/HR
 NET STREAMS CO2E PRODUCTION   7.10143      KG/HR
 UTILITIES CO2E PRODUCTION     0.00000      KG/HR
 TOTAL CO2E PRODUCTION         7.10143      KG/HR

                       ***  INPUT DATA  ***

EQUILIBRIUM SPECIFICATIONS:
  ONLY CHEMICAL EQUILIBRIUM IS CONSIDERED, THE FLUID PHASE IS VAPOR
  SYSTEM TEMPERATURE    C                                    700.00
  CALCULATED TEMPERATURE APPROACH    C                     2756.3
  TEMPERATURE FOR FREE ENERGY EVALUATION    C              3456.3
  SYSTEM PRESSURE       BAR                                  1.0132
  DUTY FROM INLET HEAT STREAM(S)  GCAL/HR                 -0.93032E-01

FLUID PHASE SPECIES IN PRODUCT LIST:
  WATER METHA-01 HYDRO-02 OXYGE-01 NITRO-01 SULFU-01 CARBO-01

  CARBO-02 NITRO-02 SULFU-02

SOLIDS IN PRODUCT LIST:
  CARBON

ATOM MATRIX:
ELEMENT      H    C    N    O    S
  WATER      2.00 0.00 0.00 1.00 0.00
  CARBON     0.00 1.00 0.00 0.00 0.00
  METHA-01   4.00 1.00 0.00 0.00 0.00
  HYDRO-02   2.00 0.00 0.00 0.00 0.00
  OXYGE-01   0.00 0.00 0.00 2.00 0.00
  NITRO-01   0.00 0.00 2.00 0.00 0.00
  SULFU-01   0.00 0.00 0.00 0.00 1.00
  CARBO-01   0.00 1.00 0.00 1.00 0.00
  CARBO-02   0.00 1.00 0.00 2.00 0.00
  NITRO-02   0.00 0.00 1.00 2.00 0.00
  SULFU-02   0.00 0.00 0.00 2.00 1.00

                       ***  RESULTS  ***
TEMPERATURE           C                                    700.00
TEMPERATURE APPROACH  C                                    2756.3
PRESSURE              BAR                                  1.0132
HEAT DUTY             GCAL/HR                           -0.93032E-01
NET DUTY              GCAL/HR                              0.0000
VAPOR FRACTION                                             1.0000
NUMBER OF FLUID PHASES                                            1

FLUID PHASE MOLE FRACTIONS:

PHASE              VAPOR
OF TYPE            VAPOR
PHASE FRACTION     1.000000
```

```
   PLACED IN STREAM   GASIFIED
     WATER           0.9237945E-01
     METHA-01        0.1497726E-11
     HYDRO-02        0.1605163
     OXYGE-01        0.3398363E-01
     NITRO-01        0.4455822
     CARBO-01        0.2500384
     CARBO-02        0.1721452E-01
     NITRO-02        0.4087842E-05
     SULFU-02        0.8819180E-04
     SULFU-01        0.1932219E-03

   KMOL/HR            9.373554

   NO SOLIDS PRESENT AT EQUILIBRIUM

 BLOCK:  SEP      MODEL: SSPLIT
 ------------------------------
   INLET STREAM:          COMBSTD
   OUTLET STREAMS:        FLUEGAS     RESIDUE
   PROPERTY OPTION SET:   IDEAL     IDEAL LIQUID / IDEAL GAS

                      ***  MASS AND ENERGY BALANCE  ***
                                    IN              OUT        RELATIVE
DIFF.
       CONV. COMP.(KMOL/HR )     2.09440         2.09440         0.00000
                  (KG/HR   )     60.4243         60.4243         0.00000
       NONCONV. COMP(KG/HR   )   3.44738         3.44738         0.00000
    TOTAL BALANCE
       MASS(KG/HR   )            63.8717         63.8717         0.00000
       ENTHALPY(GCAL/HR )       0.138528E-01    0.138528E-01     0.00000

                      ***  CO2 EQUIVALENT SUMMARY ***
    FEED STREAMS CO2E             0.00000      KG/HR
    PRODUCT STREAMS CO2E          0.00000      KG/HR
    NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
    UTILITIES CO2E PRODUCTION     0.00000      KG/HR
    TOTAL CO2E PRODUCTION         0.00000      KG/HR

                          ***  INPUT DATA  ***

  FRACTION OF FLOW
   SUBSTRM=          STRM=            FRAC=
            MIXED          FLUEGAS                  1.00000
            CISOLID        FLUEGAS                  0.0
            NC             FLUEGAS                  0.0

                          ***  RESULTS  ***

  STRM= FLUEGAS    SUBSTRM= MIXED    SPLIT FRACT=          1.00000
                            CISOLID                        0.0
                            NC                             0.0
```

```
 STRM= RESIDUE    SUBSTRM= MIXED    SPLIT FRACT=          0.0
                           CISOLID                       1.00000
                           NC                            1.00000

 BLOCK:  SPLIT1   MODEL: SSPLIT
 ------------------------------
   INLET STREAM:          DRIED
   OUTLET STREAMS:        DRYMSW      WETSYGAS
   PROPERTY OPTION SET:   IDEAL     IDEAL LIQUID / IDEAL GAS

                      ***  MASS AND ENERGY BALANCE  ***
                                      IN              OUT        RELATIVE
DIFF.
      CONV. COMP.(KMOL/HR )     10.9789         10.9789          0.00000
                 (KG/HR   )     247.613         247.613          0.00000
      NONCONV. COMP(KG/HR   )   71.0800         71.0800          0.00000
   TOTAL BALANCE
      MASS(KG/HR   )            318.693         318.693          0.00000
      ENTHALPY(GCAL/HR )      -0.290269       -0.290269          0.00000

                      ***  CO2 EQUIVALENT SUMMARY ***
   FEED STREAMS CO2E             7.10143      KG/HR
   PRODUCT STREAMS CO2E          7.10143      KG/HR
   NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
   UTILITIES CO2E PRODUCTION     0.00000      KG/HR
   TOTAL CO2E PRODUCTION         0.00000      KG/HR

                          ***  INPUT DATA  ***

  FRACTION OF FLOW
   SUBSTRM=          STRM=            FRAC=
            MIXED          DRYMSW                    0.0
            CISOLID        DRYMSW                    0.0
            NC             DRYMSW                    1.00000

                          ***  RESULTS  ***

  STRM= DRYMSW     SUBSTRM= MIXED    SPLIT FRACT=          0.0
                            CISOLID                       0.0
                            NC                            1.00000

  STRM= WETSYGAS   SUBSTRM= MIXED    SPLIT FRACT=          1.00000
                            CISOLID                       1.00000
                            NC                            0.0

 BLOCK:  SPLIT2   MODEL: SSPLIT
 ------------------------------
   INLET STREAM:          GASIFIED
   OUTLET STREAMS:        SYNGAS      CHAR
   PROPERTY OPTION SET:   IDEAL     IDEAL LIQUID / IDEAL GAS

                      ***  MASS AND ENERGY BALANCE  ***
```

```
                                    IN              OUT        RELATIVE
DIFF.
       CONV. COMP.(KMOL/HR )      9.37356         9.37356         0.00000
                  (KG/HR   )      218.693         218.693         0.00000
       NONCONV. COMP(KG/HR   )    3.44738         3.44738         0.00000
    TOTAL BALANCE
       MASS(KG/HR   )             222.141         222.141         0.00000
       ENTHALPY(GCAL/HR )       -0.797533E-01   -0.797533E-01   -0.333178E-
07

                     ***  CO2 EQUIVALENT SUMMARY ***
    FEED STREAMS CO2E             7.10143      KG/HR
    PRODUCT STREAMS CO2E          7.10143      KG/HR
    NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
    UTILITIES CO2E PRODUCTION     0.00000      KG/HR
    TOTAL CO2E PRODUCTION         0.00000      KG/HR

                          ***  INPUT DATA  ***

  FRACTION OF FLOW
   SUBSTRM=          STRM=            FRAC=
            MIXED          SYNGAS                    1.00000
            CISOLID        SYNGAS                    0.0
            NC             SYNGAS                    0.0

                          ***  RESULTS  ***

  STRM= SYNGAS     SUBSTRM= MIXED    SPLIT FRACT=          1.00000
                            CISOLID                       0.0
                            NC                            0.0

  STRM= CHAR       SUBSTRM= MIXED    SPLIT FRACT=          0.0
                            CISOLID                       1.00000
                            NC                            1.00000
```

B. Calculator block report

```
 CALCULATOR BLOCK:   DECOMPOS
 ----------------------------

   SAMPLED VARIABLES:
     ULT      : COMP-ATTR-VA IN STREAM DRYMSW SUBSTREAM NC ID: ULTANAL
     WATER    : COMP-ATTR-VA IN STREAM DRYMSW SUBSTREAM NC ID: PROXANAL
     H2O      : SENTENCE=MASS-YIELD VARIABLE=YIELD ID1=MIXED ID2=WATER IN
UOS
                BLOCK DECOMP
     ASH      : SENTENCE=MASS-YIELD VARIABLE=YIELD ID1=NC ID2=ASH IN UOS
BLOCK
                DECOMP
     CARB1    : SENTENCE=MASS-YIELD VARIABLE=YIELD ID1=CISOLID ID2=CARBON
IN
                UOS BLOCK DECOMP
     H2       : SENTENCE=MASS-YIELD VARIABLE=YIELD ID1=MIXED ID2=HYDRO-02
IN
                UOS BLOCK DECOMP
     N2       : SENTENCE=MASS-YIELD VARIABLE=YIELD ID1=MIXED ID2=NITRO-01
IN
                UOS BLOCK DECOMP
     SULF     : SENTENCE=MASS-YIELD VARIABLE=YIELD ID1=MIXED ID2=SULFU-01
IN
                UOS BLOCK DECOMP
     O2       : SENTENCE=MASS-YIELD VARIABLE=YIELD ID1=MIXED ID2=OXYGE-01
IN
                UOS BLOCK DECOMP
     ULT2     : COMP-ATTR-VA IN STREAM DRYMSW SUBSTREAM NC ID: ULTANAL
     ULT3     : COMP-ATTR-VA IN STREAM DRYMSW SUBSTREAM NC ID: ULTANAL
     ULT4     : COMP-ATTR-VA IN STREAM DRYMSW SUBSTREAM NC ID: ULTANAL
     ULT5     : COMP-ATTR-VA IN STREAM DRYMSW SUBSTREAM NC ID: ULTANAL
     ULT1     : COMP-ATTR-VA IN STREAM DRYMSW SUBSTREAM NC ID: ULTANAL

   FORTRAN STATEMENTS:
   C     FACT IS THE FACTOR TO CONVERT THE ULTIMATE ANALYSIS TO A WET
BASIS
   .
         FACT = (100 - WATER) / 100
         H2O = WATER / 100
         ASH = ULT / 100 * FACT
         CARB1 = ULT1 / 100 * FACT
         H2 = ULT2 / 100 * FACT
         N2 = ULT3 / 100 * FACT
         SULF = ULT4 / 100 * FACT
         O2 = ULT5 / 100 * FACT


   EXECUTE BEFORE BLOCK DECOMP

   VALUES OF ACCESSED FORTRAN VARIABLES ON MOST RECENT SIMULATION PASS:
```

```
    VARIABLE        VALUE READ      VALUE WRITTEN    UNITS
    --------        ----------      -------------    -----
    ULT              4.85000          4.85000
    WATER            0.00000          0.00000
    H2O              0.00000          0.00000
    ASH             0.485000E-01     0.485000E-01
    CARB1           0.423310         0.423310
    H2              0.672300E-01     0.672300E-01
    N2              0.158700E-01     0.158700E-01
    SULF            0.119000E-02     0.119000E-02
    O2              0.443900         0.443900
    ULT2             6.72300          6.72300
    ULT3             1.58700          1.58700
    ULT4            0.119000         0.119000
    ULT5             44.3900          44.3900
    ULT1             42.3310          42.3310

 CALCULATOR BLOCK:   DRYING
 --------------------------

   SAMPLED VARIABLES:
     FEEDH2O  : COMP-ATTR-VA IN STREAM FEED SUBSTREAM NC ID: PROXANAL
     CONV     : SENTENCE=CONV VARIABLE=CONV ID1=1 IN UOS BLOCK DRIER
     DRYH2O   : SENTENCE=COMP-ATTR VARIABLE=VALUE ELEMENT=1 ID1=1 IN UOS
BLOCK
                DRIER

   FORTRAN STATEMENTS:
         DRYH2O = 0.0
         CONV = (FEEDH2O - DRYH2O) / (100 - DRYH2O)


   EXECUTE BEFORE BLOCK DRIER

   VALUES OF ACCESSED FORTRAN VARIABLES ON MOST RECENT SIMULATION PASS:
     VARIABLE        VALUE READ      VALUE WRITTEN    UNITS
     --------        ----------      -------------    -----
     FEEDH2O          28.9200          28.9200
     CONV            0.289200         0.289200
     DRYH2O           0.00000          0.00000
```

C. Block diagram of the gasifier's Aspen plus Model