

EXERGY ANALYSIS OF WASTE TO ENERGY CONVERSION OF MUNICIPAL SOLID WASTE

A DISSERTATION

submitted in the partial fulfillment of the
requirements for the award of the degree of

INTEGRATED DUAL DEGREE

(Bachelor of Technology & Master of Technology)

in

CHEMICAL ENGINEERING

(With specialization in Hydrocarbon Engineering)

by

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May, 2016

CANDIDATE'S DECLARATION

I hereby declare that the work, which is being presented in this dissertation report entitled “**Exergy Analysis of Waste to Energy Conversion of Municipal Solid Waste**” in partial fulfilment of the requirements for the award of the degree of Integrated Dual Degree (B. Tech. in Chemical Engineering and M. Tech. in Hydrocarbon Engineering), and submitted in the Department of Chemical Engineering of Indian Institute of Technology Roorkee, India, is an authentic record of my own work carried out during the period from May 2015 to May 2016, under the supervision of **Dr. Veeramani C. Nathan**, Assistant Professor, Department of Chemical Engineering, Indian Institute of Technology Roorkee, India.

The matter embodied in this report has not been submitted by me for the award of any other degree of this or any other Institute/University.

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CERTIFICATE

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

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JARPULA MOHAN

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ABSTRACT

Municipal solid waste (MSW) has been a menace due to rapid urbanization and uncontrolled population in India. MSW identified as the energy source and this energy is recovered through waste to energy conversion processes. It solves the dual problem of waste management and energy security. Waste to Energy (WTE) has become increasingly important. The feedstock dealt with here is municipal solid waste which is a liability to the present generation. Introduction to municipal solid waste, need for the waste to energy and typical waste to energy technology and exergy analysis has been discussed. Available literature and works so far done are thoroughly reviewed and objectives for future scope of work has been discussed. Plasma gasification model is developed based on Gibbs energy minimization method in Aspen Plus to simulate conversion process of MSW to syngas by plasma gasification process. Developed model is verified by using MSW feedstock and comparing the results with Zhang et al [3]. Using this model plasma gasification with air, steam and steam-air gasification are done and syngas yield and composition are tabulated. Exergy analysis for all three cases has been done and results are presented. Successful operation of WTE plants right in the middle of large cities testifies to the fact that gasification is the best technology. In this work, plasma gasification has been studied and results discussed.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Municipal solid waste (MSW) has been a menace due to rapid urbanization and uncontrolled population in India. Municipal solid waste production in India is estimated to be 62 million tons of MSW per annum and it is projected to increase at a rate of 5%. More than 80% of the waste is dumped in landfill sites without any treatment [26]. According to WHO 22 types of diseases can be prevented if there exists efficient MSW management system.

Scarcity of land and greenhouse gases emitted from land filling site caused land filling to be an unattractive method. MSW is identified as an energy source and this energy is recovered through waste to energy conversion processes. It solves the dual problem of waste management and energy security. Few incineration plants are already working in some cities in India like Timarpur - Okhla waste management plant in New Delhi operated by Jindal Group, but due to high emission of particulate matter, pollutant gases like NO_x, SO_x, dioxins and furans and foul smell from the plant, they are facing the wrath of people around the plant.

Plasma gasification process (PGP), although less efficient in terms of energy recovery it is more efficient with respect volume reduction of MSW and no or low emission of pollutants especially toxic pollutants. Because of very high temperature in the gasification, dioxins and furans are broken and converted to non-toxic compounds. Production of cleaner fuel and ability to gasify all materials makes PGP best alternative to the incineration plants in processing the MSW.

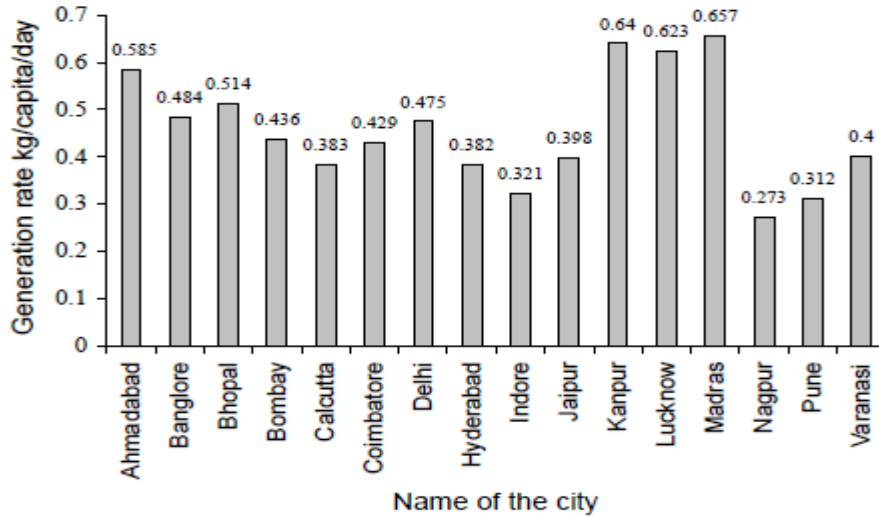


Figure 1.1: MSW generation in Indian cities [37].

After the introduction of Govt. of India's Swatch Bharat scheme, great attention has been given to waste processing and waste to energy plants. Ministry of New and Renewable energy estimated that potential for electricity production from MSW in India is 1500MW [23]. Disadvantages with characteristics of Indian MSW include high moisture content, low calorific value of MSW, lack of awareness & cooperation between municipalities and WTE plants, lax pollution regulations, unsuitability of western technology to Indian MSW, sub-optimal technologies available from Chinese manufacturers etc. Composting was not successful in India because of lack of infrastructure for segregation and technology of handling the process till now, hence attention was shifted to incineration plants and many plants are being set up. Although few plants are working successfully, they are facing the heat from people due to pollution. Hence, among all processes, plasma gasification can solve the problems caused due to incineration as it is clean process and processes the waste at a large capacity and produces very less volume of ash that too can be used as construction material for roads and building. Successful operation of WTE plants right in the middle of large cities in western countries can be the inspiration for gasification technology in India. In this work, plasma gasification has been studied and results are discussed.

1.2 Municipal Solid Waste (MSW)

MSW includes domestic waste, office & industrial refuse excluding toxic and nuclear waste but includes treated medical waste etc. MSW has always been a liability to human societies and it is also unavoidable.

Classification of MSW:

Biodegradable fraction of MSW can be classified as biogenic/organic and non-biodegradable part of MSW is classified as non-biogenic/inorganic. Organic fraction includes paper, cardboard, food wastes, agricultural residue etc. Inorganic fraction mainly consists of metals, alloys and glass.

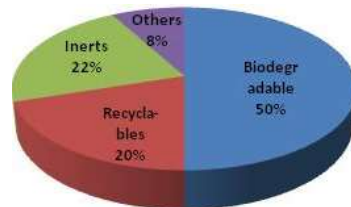


Figure 1.2: Composition of MSW in India [32].

MSW management in India till date has been done in an unscientific manner and dumped in open spaces. This lead to air pollution due to foul smell and leaked methane emissions from fermented landfill, groundwater pollution due to leachate which lead health hazards and environment pollution.

Different ways of MSW management:

- Reduce, Reuse & Recycle
- Land filling
- Pyrolysis (Thermal processing in absence of O₂)
- Incineration (Thermal processing in presence of controlled amount of O₂)
- Gasification (Conventional / Plasma)

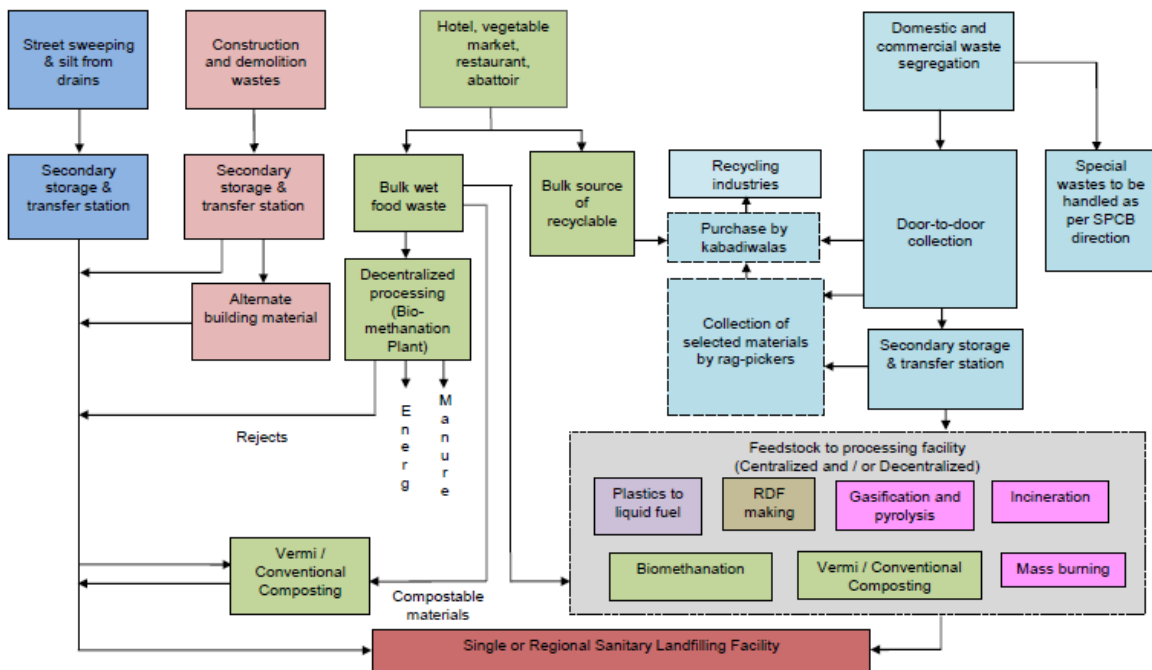


Figure 1.3: Integrated waste management of MSW.

1.2.1 Reduce, Reuse & Recycle

Sustainable management of municipal solid wastes requires that every possible effort be made to separate recyclable or compostable materials from the MSW stream. Use of resources at a rate more than the need leads to unwanted and avoidable waste in large quantities. Unscientific disposal of this waste causes environmental pollution and increases the burden on already burdened landfills. Rag pickers contribute a lot in reuse and recycle of recyclable materials. Both individuals & municipal authorities should adopt the methods to reduce the amount of waste discarded, reuse the recyclable materials. Recyclable materials include paper, cardboard, plastic, metals and glass etc. These should be recycled as these not only have economic value but also nuisance in the WTE plant.

Benefits of Recycling:

- Reduces the amount of waste sent to landfills and incinerators
- Conserves natural resources such as timber and minerals
- Reduces greenhouse gas emissions that are produced in landfills
- Reduces toxic emissions such as dioxins, furans and other polluting particulates.
- Helps sustain the environment for future generations
- Provide livelihood to the rag pickers through recycling and manufacturing industries

1.2.2 Land filling:

Landfilling is most prevalent and old method for MSW disposal and landfill site is a designated area, generally around the outskirts of urban areas where MSW is dumped openly or buried under the layer of the soil.

Types of landfilling method:

- Area method
- Trench method

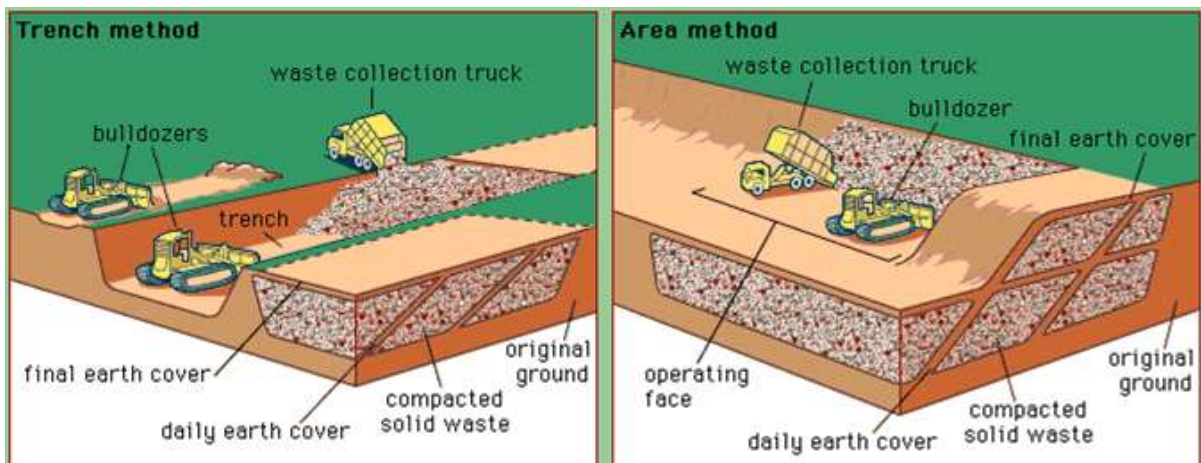


Figure 1.4: Types of landfilling methods

Currently 62 million tonnes of waste is being produced in urban areas alone and production of waste is projected to be 165 million tonnes by 2031 and 436 million tonne by 2050. If current practice of dumping waste without pre-treatment is continued then it will need 1240 hectare per annum (12.4 square km per year). India can't afford to lose that much land every year and also availability of land is diminishing due to rapid expansion of urban areas and migration of rural people to cities in search of employment.

Hazards of landfilling:

- Emission of greenhouse gases land fill gas (50% CH₄ & 50% CO₂)
- Pollution of ground water due to leachate
- Pollution of surface water sources such as lakes, rivers and oceans due to non-biodegradable wastes such as plastic.
- Air pollution due to foul smell and smoke produced due to burning
- High risk of catching of fire in summer which may become uncontrollable
- Diseases caused to people near landfill sites include poor chronic coughs, burning and swelling of eyes and high rates of tuberculosis.

As landfill can't be the ultimate solution for waste disposal, volume of waste going for dumping has to decrease considerably. Here comes the need of waste to energy technology.

1.2.3: Waste to Energy (WTE):

Waste to energy process converts every day refuse from various sources makes as feedstock for energy recovery process. Waste to energy conversion can produce biogas, syngas, ethanol and electricity depending on the process used.

Broad classification of WTE Processes:

1. Bio-chemical conversion / Non-thermal technology
 - 1.1. Composting (Aerobic process)
 - 1.2. Bio-Methanation (Anaerobic process)
2. Thermal conversion process.
 - 2.1. Pyrolysis
 - 2.2. Incineration
 - 2.3. Conventional Gasification
 - 2.4. Plasma Gasification

Generally, bio-chemical methods are used for biodegradable wastes and thermal conversion processes are used for wastes with high calorific content.

Composting is aerobic decomposition of organic biodegradable waste. This technology is not suitable for large capacity processing of MSW.

Bio-Methanation is anaerobic digestion of MSW into combustible biogas which consists mainly of Methane (CH_4). Manure is by-product in this process.

Thermal treatment of solid waste consists of heating the waste to a temperature that results in volatilization of moisture and organic compounds usually followed by combustion of all organic compounds and carbon with atmospheric air. In thermal technologies, waste is incinerated or gasified to produce a combustible fuel gas (syngas) which can be used to produce electricity, raw material for petrochemical industry or produce H_2 from syngas can be used in fuel cells.

Pyrolysis decomposes MSW primarily into H_2 , CO , H_2O , CO_2 , light hydrocarbons, carbonaceous solid char and solid ash in absence of oxygen.

Incineration involves production electricity from steam turbines which run by steam produced from complete combustion of the MSW at $850\text{-}1000^\circ\text{C}$. Waste is mass-burned using natural gas or diesel to combust the waste and heat produced is recovered by means of steam production. Produced steam is used to rotate the gas turbines for electricity production.

Gasification combusts and convert the organic part of the waste into combustible gases like CO , CH_4 , H_2 and CO_2 . Operational differences and products of different thermal processes are shown in below figure.

Plasma gasification uses external heating source i.e. plasma torch to carry out endothermic gasification reactions. Feed is decomposed to elemental composition and products are formed. This technology is relatively new and poorly understood.

Table 1.1: Comparison of thermal technologies in operation worldwide

Variable	Pyrolysis	Gasification	Incineration	Plasma Gasification
O ₂ availability	No	Limited	Excess	Controlled amount
Temperature in the gasifier	450-550°C	>700 °C	850-1000°C	>1500 °C
Products	Bio-oil, char	Syngas, ash	Flue gas	Syngas, vitrified slag
Feed Pretreatment	Feed need to be dried. Segregation required	Segregation not required	Segregation required. PVC, Plastics & metals separated.	Segregation not required
Energy recovery	More	low	More	lower
Volume reduction of MSW	less	high	less	highest
Emission of pollutants	Pollution can be controlled	Less pollution	dioxins, furans	No/less toxic gases

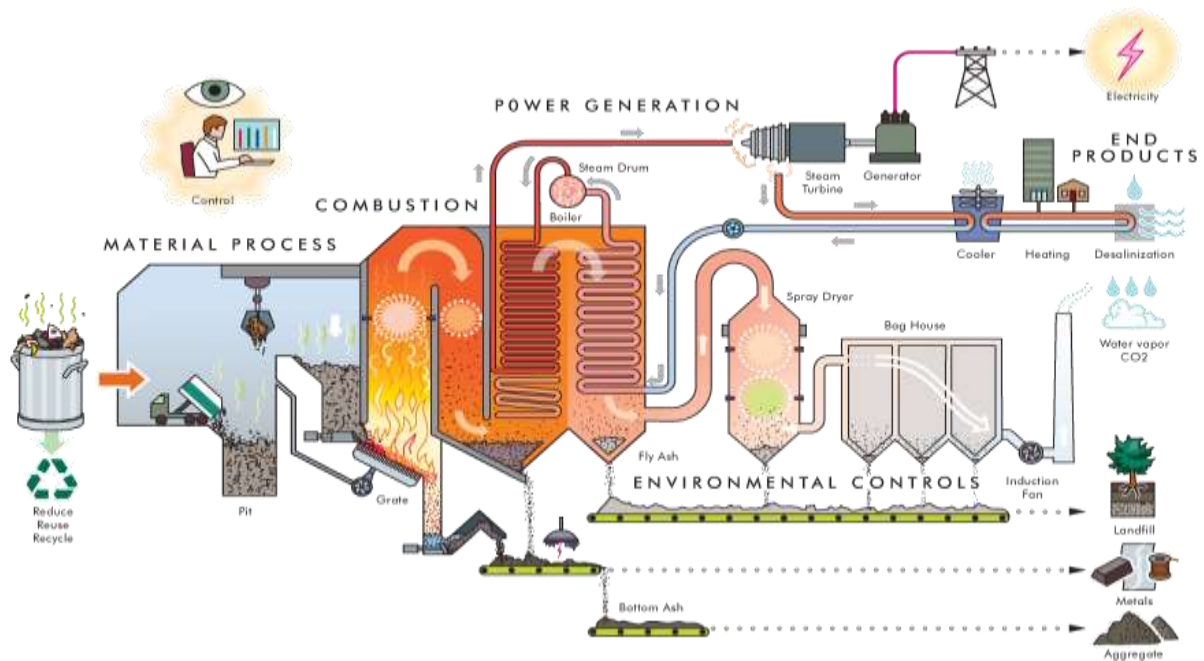


Figure 1.5: Detailed processes in a typical waste to energy plant.

1.3 Objectives

In this work, plasma gasification with different gasification agent has been studied. Although incineration is more energy efficient in terms of energy recovery, but it is not suitable for efficient waste disposal [27]. Plasma gasification is more efficient in terms of volume reduction of waste compared to incineration. Hence plasma gasification should be preferred if waste disposal is the main objective. Plasma gasification can gasify the solid waste even in absence of any gasifying agents like air, O_2 , CO_2 , steam. But this will lead to production of low value carbon product instead of valuable syngas [24]. This emphasizes the importance of gasification agent in the plasma gasification. Works on exergy analysis of plasma gasification process (PGP) with respect to gasification agent are rare and hence in this work, exergy analysis is done on PGP.

The objectives of this study are:

- Understanding the gasification characters of MSW in reactor
- Validation of my current model using data from Janajreh et al.(7)
- Apply that model to data given in Zhang et al. (3)
- Study of effect on syngas yield with changes in gasification agents.
- Compare composition of syngas and exergy efficiencies using air, steam and air & steam as gasification agents.

CHAPTER 2

LITERATURE REVIEW

2.1 Literature Review

Conversion of waste to energy is the topic of high interest now a days because of both the menace of MSW and scarcity of energy. Although the energy available from the process is not much attractive to investors, it caught the attention of governments in various countries as the one of sustainable technology for the waste management. Vast research has been done on WTE technology but it was poorly understood because of high temperature involved and complex chemistry of reactions at the high temperature in gasifier/incinerator.

In this work, literature available on MSW conversion to energy has been reviewed and results of the work so far done has been discussed.

Ahmed et al. [2] experimentally studied the difference in syngas yield of pyrolysis and steam gasification of paper waste at same thermal conditions. Presence or absence of char gasification waste to energy conversion of paper on the final syngas composition, tar yield and LHV is presented.

Dalai et al. [10] experimentally investigated the steam gasification of two refuse derived fuel (RDF) feedstock. Gasification done at various temperatures keeping the steam flow constant and effect of temperature on syngas yield with special focus on CO + H₂ is reported.

Mountouris et al. [1] developed an equilibrium model (GasifEq) for plasma gasification of solid waste to analyze plasma gasification technology thermodynamically. The model also predicts the synthesis gas yield, energy and exergy calculations. The model was developed with available thermodynamic data and also includes possibility of char formation. Effect of the most important process parameters on the energetic performance of the process has been presented. Plasma gasification process method is also applied to the treatment of sewage

sludge. The model mainly focussed on gasification of organic fraction to maximize the exergy. Results for a case study are presented and process was optimized with the use of the GasifEq equilibrium model.

Zhang et al. [3-6] developed a Eulerean multiphase model in Ansys Fluent to investigate the effect of air and steam gasification of municipal solid waste in a PGM reactor. The model is validated by experimental measurement from pilot updraft fixed bed PGM reactor and results of both model and pilot reactor were presented. Variation of yield and LHV of syngas was studied with variation in plasma power, ER and temperature in PGM reactor.

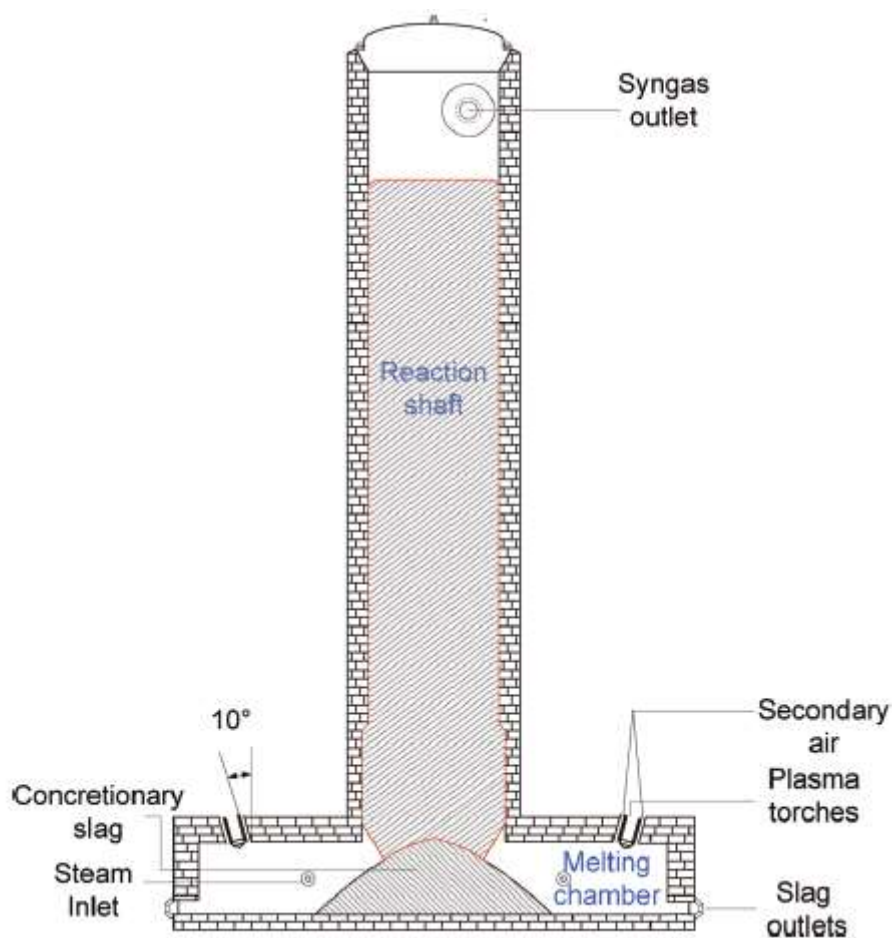


Figure 2.1: Scheme of pilot plant PGM reactor used in the experiment

A semi-empirical model developed considering the differences in behaviour between cellulosic fractions and plastics in PGM process. Compared the model predicted results with the experimental results and effect of ER, plasma energy ratio and steam air mass ratio on cold gas efficiency was discussed.

They studied PGM system using semi-empirical Aspen plus model to calculate yield of syngas. The measured results of MSW air and steam gasification in a PGM demo-reactor are demonstrated and compared with the model predicted results. The Light Hydrocarbons (LHC) are assumed to be CH_4 & C_2H_4 instead of pure CH_4 as assumed in previous works. To conduct the thermodynamic analysis, the process was divided into four sub sections such as drying of feed, pyrolysis, char gasification and melting of slag to evaluate the characteristics of the PGM.

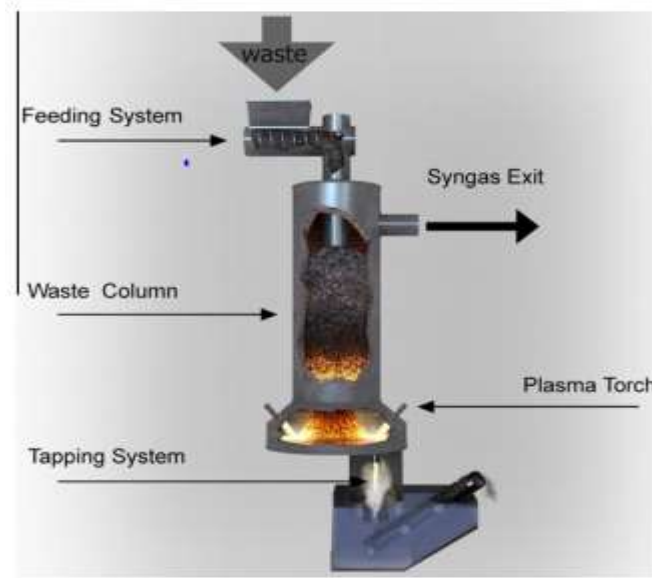


Figure 2.2: Scheme of Plasma gas melting process

Minutillo et al. [8] developed a thermochemical model EPJ (EquiPlasmaJet) using thermochemical code Aspen plus to investigate the plasma gasification process using RDF (Refuse derived fuel) as feedstock and air as gasification agent. The syngas yield and composition were tabulated and the energy efficiency of the process was estimated. Performance evaluation of integration of plasma gasification system with gas turbine combined cycle was done.

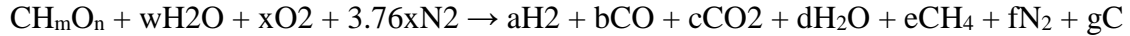
Janajreh et al. [7] developed an aspen plus model based on Gibbs free energy minimization method using conventional gasification with air as gasification agent and plasma gasification with steam-air as gasification agent for different feedstocks like MSW, coal, tyres, other biomass feed etc. Results for both types of gasification was presented and shown that conventional gasification is more energy efficient because of high energy needed in plasma gasification but the produced syngas is cleaner in plasma gasification. Plasma gasification is best suited if only volume reduction of waste is the main objective.

Hlina et al. [24] studied experimentally plasma gasification of biomass and waste using extreme conditions of plasma torch to analyse syngas composition and tar yield. Plasma gas used was H₂O/Ar with low mass flow rate and high gasification temperature. High quality syngas is reported although it was offset by high electric energy demand for plasma torch.

2.2 Chemistry of Gasification

In the gasifier H₂, O₂, N₂, S, Cl₂ and solid carbon are present. They undergo series of reactions with complex stoichiometry. Unlike incineration which takes place in presence of excessive oxygen, gasification takes place in Oxygen starved environment [29]. Products of the gasification and temperature distribution in the gasifier depends upon the supply of air/steam [30].

The overall gasification reaction is given below. Waste material is described by its ultimate analysis (CH_mO_n) [1].



Where *w* is the amount of water per mole of waste material, *m* is the amount of O₂ per mole of waste, *a*, *b*, *c*, *d*, *e*, *f* and *g* are the coefficients of the gaseous products and soot (all stoichiometric coefficients in moles).

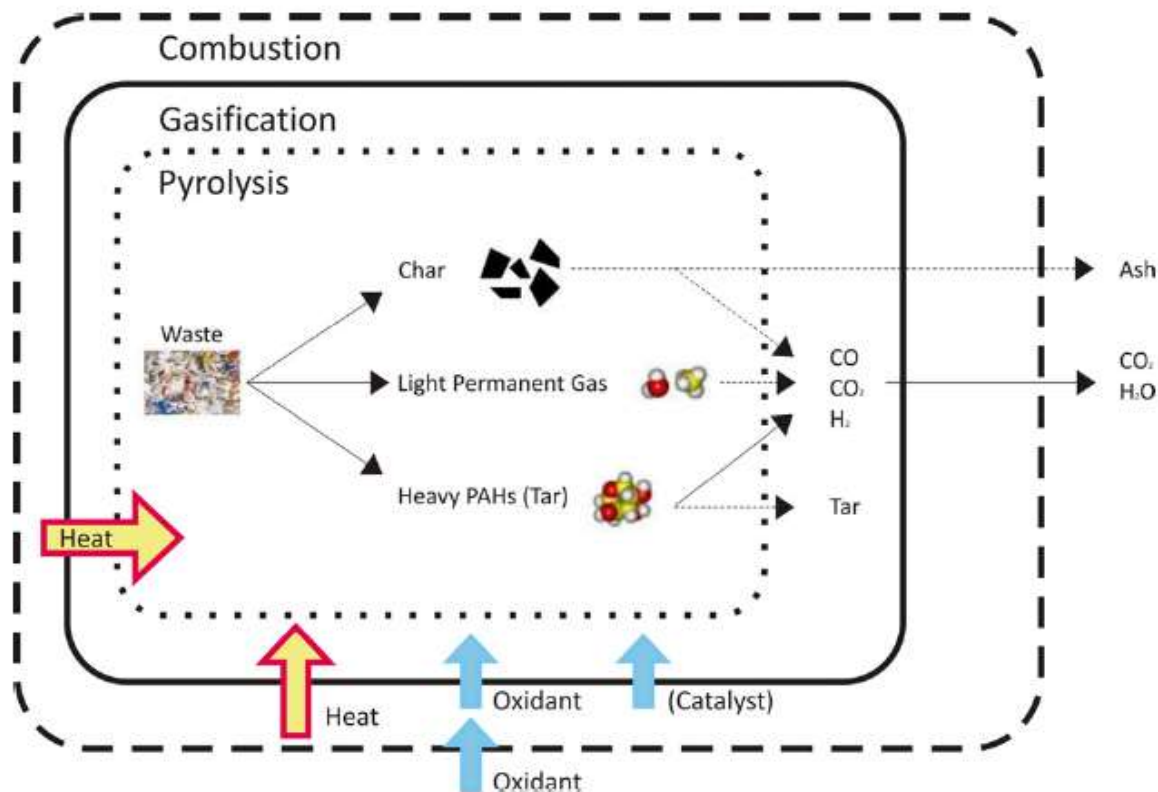


Figure 2.3: Schematic of comparison of chemistry of different WTE technologies

The main desirable and undesirable reactions are given below. All desirable gasification are endothermic reactions while undesirable ones are exothermic.

Table 2.1: Desirable Reactions

S.No.	Reaction	Remarks
1.	$C(s) + H_2O(g) \rightarrow CO(g) + H_2(g)$	Water gas shift reaction
2.	$C(s) + CO_2(g) \rightarrow 2CO$	Boudouard reaction
3.	$CO + H_2O \rightarrow CO_2 + H_2$	Shift reaction, CO is converted to H ₂ because heating value of CO is significantly lower than that of H ₂ . Hence it is a desirable.
4.	$C + 2H_2 \rightarrow CH_4$	Methanation reaction is exothermic

Undesirable Reactions: Combustion reactions are undesirable because the products have no heating value.

Table 2.2: Undesirable reactions

S.No.	Reaction
1.	$C + 1/2 O_2 \rightarrow CO$
2.	$CH_4 + O_2 \rightarrow CO_2 + 2H_2$
3.	$H_2 + 1/2 O_2 \rightarrow H_2O$
4.	$C + O_2 \rightarrow CO_2$

2.3 Plasma Gasification

2.3.1: Plasma Gasification process:

Plasma gasification process consists of gasifier and a DC-Plasma torch to provide high temperature (about 4000 °C) environment in the gasification section to convert the MSW completely to its elemental composition [23] there by reducing the volume of MSW to lesser volume than any other competing processes such as combustion and incineration along with energy recovery by syngas production. Co-product of plasma gasification vitrified slag comprising metals and silica glass. Syngas produced in plasma gasification process can be converted to liquid fuels via Fischer–Tropsch synthesis.

Before entering plasma furnace, feed is generally pre-treated/dried in a dryer and then pyrolysed before entering the gasifier. Gasifier is lined with refractory to withstand extreme conditions of reactor. The product gases from gasifier are at high temperatures and heat exchangers are employed to recover the heat energy and this heat is used in drying of feed.

Advantages of plasma gasification include less ash formation compared to incineration, low emission of pollutants and hence low cost to meet the environmental regulations, cleaner gas [1], and option of recovering and recycling the metals from inert slag etc. Slag can be used for construction of roads and building [6]. The main disadvantage of process is it uses significant amount of recovered energy to power the plasma torch thereby leading to less energy efficiency compared to conventional gasification [6].

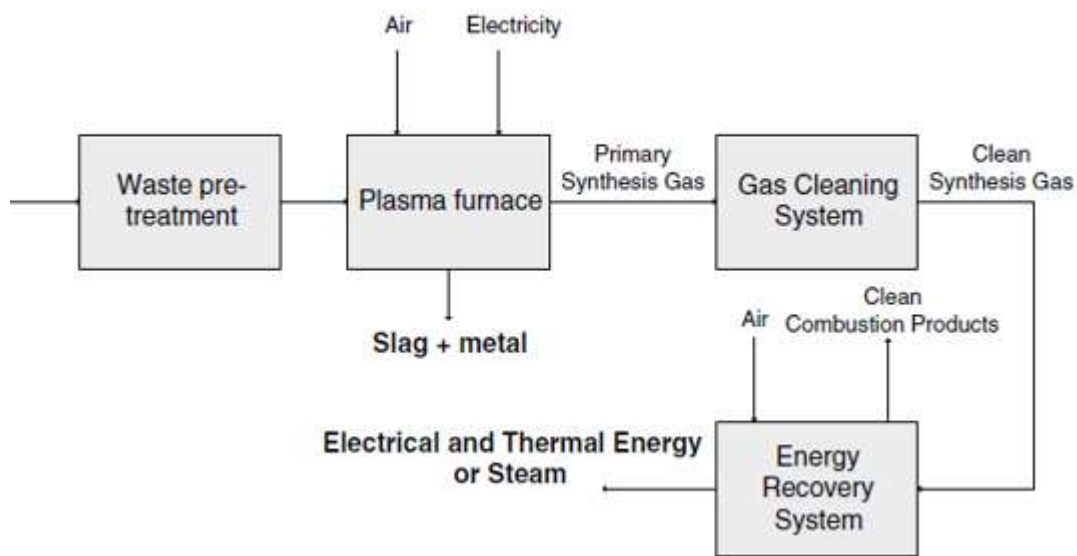


Figure 2. 4: Typical plasma gasification block flow diagram [1]

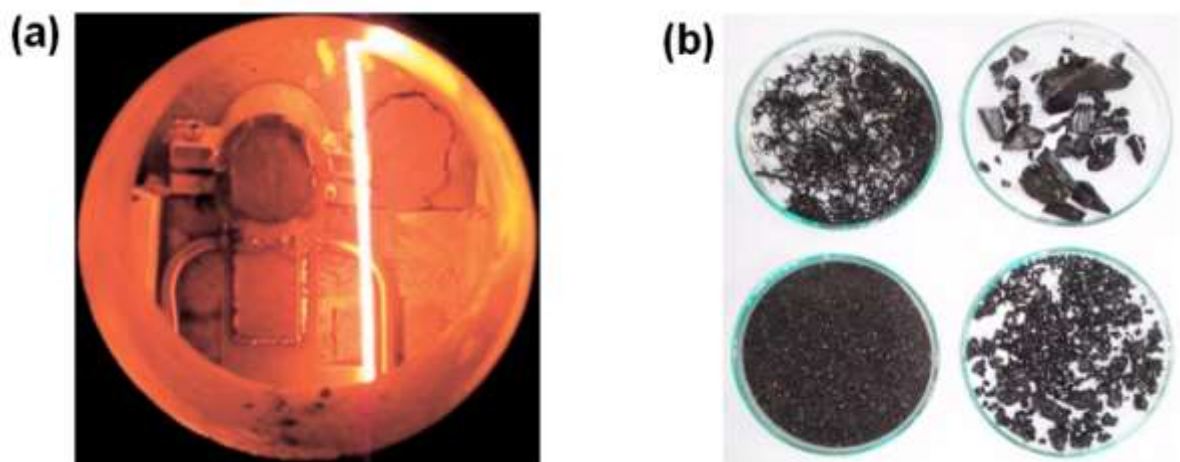


Figure 1.5: (a) Molten slag produced in PGM process before cooling, (b) inert vitrified slag after cooling

2.3.2: Types of Plasma torches:

Plasma torches are classified as transferred arc plasma torch and non- transferred arc plasma torch. Transferred torch is used for metallurgical purposes while non-transferred arc plasma is used for processing of waste. Air, water, O₂ and Ar can be used as plasma gases in the

plasma torch. These gases gets ionized due to high temperatures in the plasma and heats the gasifier feed. Water needs more torch power than air for the same mass flow rate.

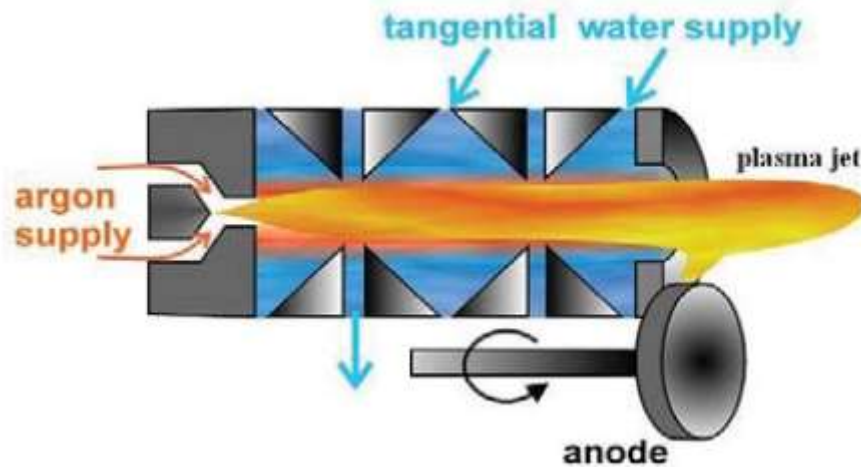


Figure 2.6: Schematic figure of hybrid plasma torch with steam & argon as plasma gas.

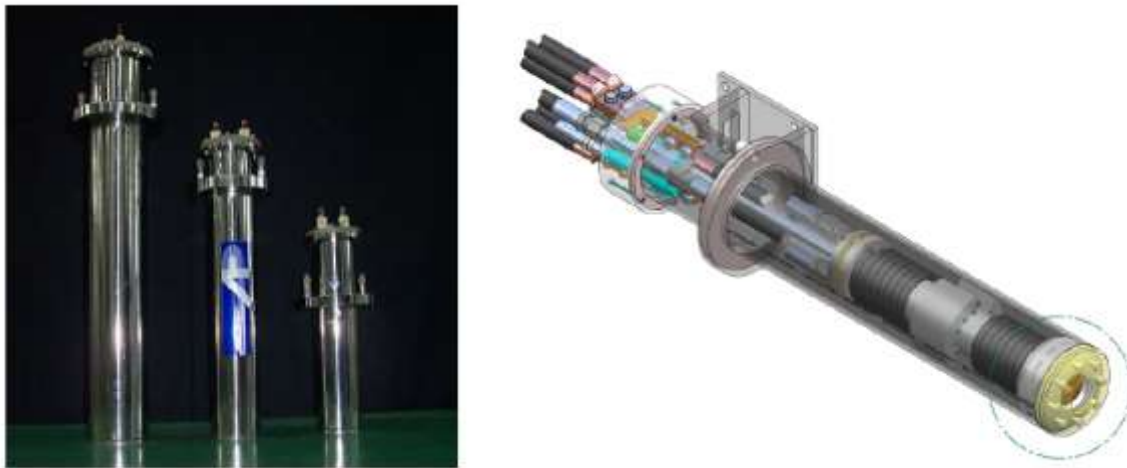


Figure 2.7: Left: Images of Plasma torches available in market; Right: Inner view of thermal plasma torch.

2.4 Theory of Exergy Analysis

Exergy analysis can help to calculate the net energy output from a process and can be used to find losses within the system, to improve the process efficiency and to compare various

feedstock in a waste to energy conversion process [22]. Exergy of a system may be defined as the maximum work that can be obtained when system is brought from initial state to environmental state. Maximum work obtained when system's temperature and pressure are brought to environment's temperature and pressure is called physical exergy and maximum work obtained when composition of system (or fuel) is brought environment's composition is called chemical exergy. When physical exergy is extracted system becomes in thermal and mechanical equilibrium with the environment and when chemical exergy is extracted, chemical potentials of system and environment becomes equal there by achieving chemical equilibrium [20].

Total exergy of the system is given by the following relation [19]

$$Ex^{total} = Ex^{ph} + Ex^{ch} + Ex^K + Ex^P \quad (1)$$

In this work, kinetic and potential exergies are neglected compared to the physical and chemical exergies and hence

$$Ex^{total} = Ex^{ph} + Ex^{ch} \quad (2)$$

The physical exergy of the syngas stream is calculated as [7]:

$$Ex^{ph} = (h - h_o) - T_o(s - s_o) \quad (3)$$

Where, h and s are enthalpy and entropy of syngas stream and h_o, s_o are enthalpy and entropy of environmental state (T_o = Temperature of the environment state)

In the model developed in this work, it has been assumed that the pressure is constant throughout the system. Therefore, the physical exergy for ith component is given by [1]

$$Ex_i^{ph} = \int_T^{T_o} C_{p,i} * \left(1 - \frac{T_o}{T}\right) * dT \quad (4)$$

Total physical exergy flow of syngas stream

$$Ex^{ph} = \sum n_i * Ex_i^{ph} \quad (5)$$

Where, n_i= mole flow rate of component i in syngas stream, Ex_i^{ph}= physical exergy for ith component. Expressions for C_p are available in the literature and tabulated in the Table below:

$$C_p = a + b \cdot T + c \cdot T^2 + d \cdot T^3 \quad (6)$$

Table 2.3: Standard chemical exergy and Specific heat expressions [16], [17], [3]

Component	$Ex_{i,o}^{ch}$, kJ/kmol	a	$b \times 10^2$	$c \times 10^5$	$d \times 10^9$	Temperature Range, K
H ₂	2,36,100	29.11	-0.1916	0.4003	-0.8704	273–1800
CO	2,75,100	28.16	0.1675	0.5327	-2.222	273–1800
CO ₂	19,870	22.26	5.981	-3.501	7.469	273–1800
N ₂	720	28.90	-0.1571	0.8081	-2.873	273–1800
CH ₄	8,31,650	18.89	5.024	1.269	-11.01	273–1500
H ₂ O	9,500	32.24	0.1923	1.055	-3.595	273–1500
HCl	3,31,300	26.239	0.518	-1.255	-	273–1500
H ₂ S	812000	32.68	1.238	1.9288	-1.2554	273–1500
NH ₃	337900	27.568	2.563	0.99072	- 6.6909	273–1500
C (graphite)	409870	14.724	0.641	-7.208	-	298.1 -2000
C ₂ H ₂	1265000	21.8	9.2143	-6.527	18.21	273–1500

Chemical exergy of syngas stream is calculated by [21]:

$$Ex_i^{ch} = Ex_{i,o}^{ch} + R * T_o * \ln\left(\frac{n_i}{\sum n_i}\right) \quad (7)$$

where, $Ex_{i,o}^{ch}$ = standard chemical exergy of the species 'i', total chemical exergy flow of gaseous stream

$$Ex^{ch} = n_i * Ex_i^{ch} \quad (8)$$

Finally, the chemical exergy of solid fuel i.e. MSW in this work is calculated by correlations from [9]:

$$Ex_{fuel}^{ch} = \beta * LHV_{fuel} \quad (9)$$

where,

$$\beta = 1.0438 + 0.0158 * \frac{H}{C} + 0.0813 * \frac{O}{C} \quad \text{for } \frac{O}{C} \leq 0.5$$

$$\beta = \frac{\left[1.0414 + 0.0177 * \frac{H}{C} - 0.3328 * \frac{O}{C} * \left(1 + 0.0537 * \frac{H}{C}\right)\right]}{1 - 0.4021 * \frac{O}{C}} \quad (10)$$

for $0.5 < O/C \leq 2$

and LHV_{fuel} is calculated from correlation:

$$LHV_{fuel} = 0.943 \times HHV_{fuel} \quad (11)$$

and HHV of solid fuel is calculated from correlation from [15] which is given as

$$HHV_{fuel} = 0.3491 \times M_C + 1.1783 \times M_H + 0.1005 \times M_S - 0.1034 \times M_O - 0.0151 \times M_N - 0.0211 \times M_{Ash} \quad (12)$$

where M_i =mass fraction on dry basis in ultimate analysis of solid fuel (here MSW)

Exergy efficiency is given by

$$\Psi_{exergy} = \frac{\dot{E}x^{ph} + \dot{E}x^{ch} - \dot{E}x_{O_2}^{ch} - \dot{E}x_{H_2O}^{ch}}{\dot{m} * \dot{E}x_{fuel,in}^{ch} - \dot{E}x_{fuel,out}^{ch} + Torch\ power} \quad (13)$$

where, \dot{m} =mass flow rate of MSW feed input. Torch power is calculated assuming 31.35% electric efficiency of power plant [7]

$$Torch\ power = \frac{Net\ heat\ duty\ of\ plasma\ torch\ in\ the\ model}{0.3135} \quad (14)$$

First law efficiency of process is calculated by [7]:

$$\eta = \frac{\dot{m}_{syngas} * LHV_{syngas}}{\dot{m}_{feed} * LHV_{feed} + Torch\ power} \quad (15)$$

Calculation of LHV of syngas [38]:

$$LHV = X_{H_2} \times LHV_{H_2} + X_{CO} \times LHV_{CO} + X_{CH_4} \times LHV_{CH_4} \quad (16)$$

Where, LHV_{H_2} = LHV of H_2 =11.2 MJ/Nm³

LHV_{CO} = LHV of CO =13.1 MJ/Nm³

LHV_{CH_4} =LHV of CH₄ =37.1 MJ/Nm³

Conversion of m³ to Nm³:

$$V\ (Nm^3/s) = V(m^3/s) * T_o/T \quad (17)$$

Where T_o =normal temperature =298.15K

T = temperature of syngas stream, of which volume flow rate is calculated

$$\begin{aligned}\Rightarrow \dot{LHV} \text{ (in MJ/s)} &= LHV \text{ (MJ/Nm}^3\text{)} * V \text{ (Nm}^3\text{/s)} \\ &= LHV \text{ (MJ/Nm}^3\text{)} * V \text{ (m}^3\text{/s)} * T_o/T\end{aligned}\tag{18}$$

CHAPTER 3

PROCESS SIMULATION

3.1 Model Description

In this process, the feed is processed by plasma gasification and model developed is based on non-stoichiometric Gibbs energy minimization method in Aspen Plus and accounts for the components in Table below.

Assumptions for the model:

- Steady state process at atmospheric pressure
- No pressure drop throughout the system (constant pressure)
- Arc DC plasma torch is working in an insulated reactor and adiabatic environment
- Heat loss from process is neglected
- Drying of feed and reactions in gasification are instantaneous.

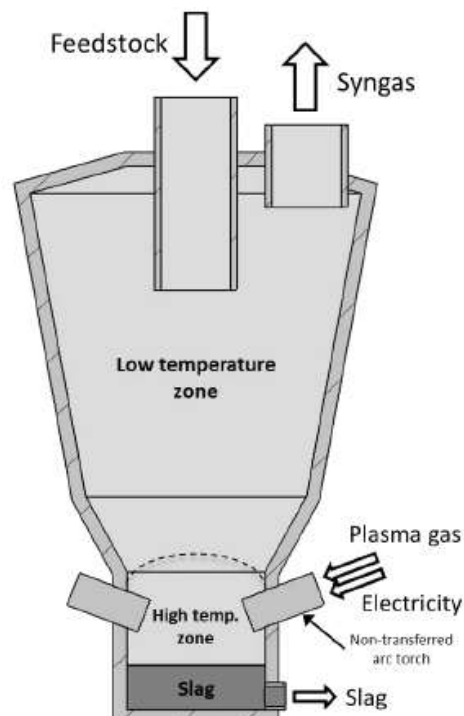


Figure 3.1: Plasma gas reactor equipped with non-transferred arc plasma torch [7].

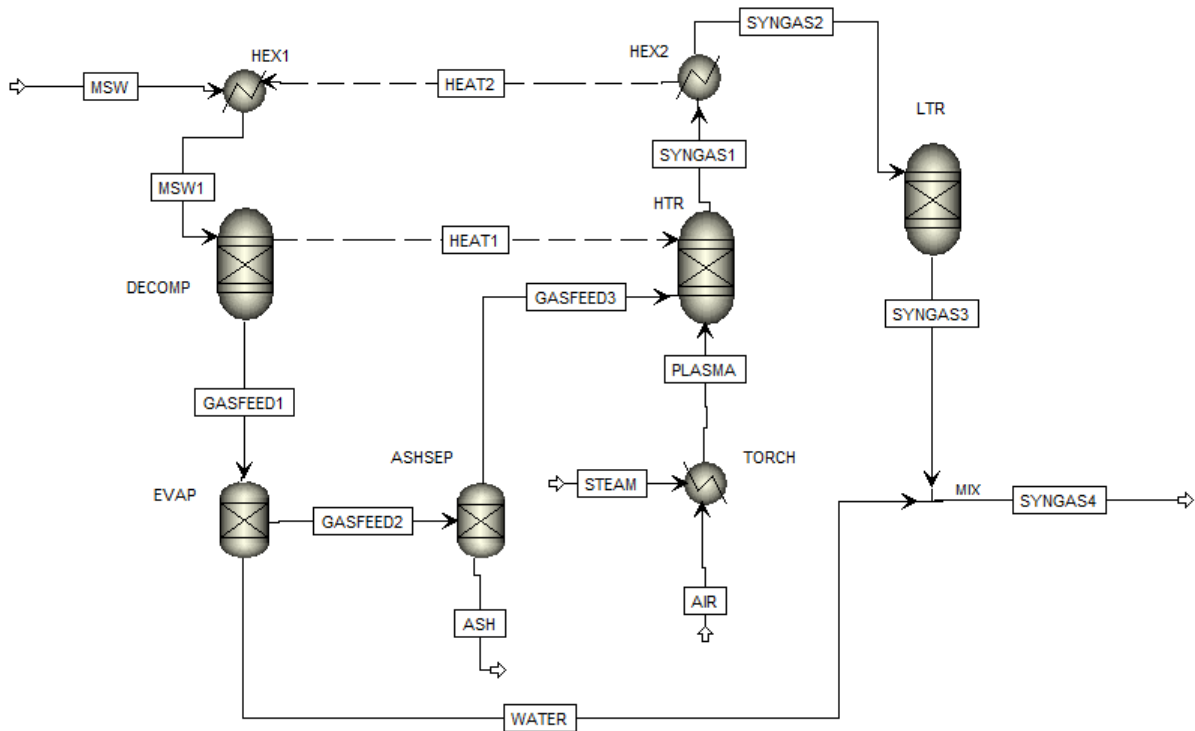


Figure 3.2: Flow sheet for Aspen Plus simulation of plasma gasification of MSW

Table 3.1: Description of Flow sheet blocks

Block	Type	Description
HEX1,HEX2	Heater	Heater/coolers are modelled as heat exchangers
DECOMP	R Yield	Used when yield distribution and component attributes of feed is known and reaction stoichiometry is unknown.
HTR	R Gibbs	When only products known without any information stoichiometry, this reactor model provides equilibrium products by solving Gibbs free energy minimization.
LTR	R Gibbs	-do-
DC-TORCH	Heater	Plasma torch is modelled as a heater
EVAP	Separator	A component separator to separate water
ASHSEP	Separator	A component separator to separate solid ash/MSW

Table 3.2: Components considered in the model

Components ID	Type	Component Name	Alias
N ₂	Conventional	Nitrogen	N ₂
CH ₄	Conventional	Methane	CH ₄
H ₂ O	Conventional	Water	H ₂ O
O ₂	Conventional	Oxygen	O ₂
NO ₂	Conventional	Nitrogen-dioxide	NO ₂
NO	Conventional	Nitric-oxide	NO
SO ₂	Conventional	Sulfur-dioxide	O ₂ S
SO ₃	Conventional	Sulfur-trioxide	O ₃ S
HCN	Conventional	Hydrogen-cyanide	CHN
H ₂ S	Conventional	Hydrogen-sulfide	H ₂ S
COS	Conventional	Carbonyl-sulfide	COS
C ₂ H ₂	Conventional	Acetylene	C ₂ H ₂
NH ₃	Conventional	Ammonia	H ₃ N
ASH	Non-Conventional		
CHLORINE	Conventional	Chlorine	Cl ₂
S	Conventional	Sulfur	S
MSW	Non-Conventional		
CARBON	Solid	Carbon-graphite	C
H ₂	Conventional	Hydrogen	H ₂
CARBO-01	Conventional	Carbon-monoxide	CO
Ar	Conventional	ARGON	Ar
HCl	Conventional	Hydrogen-chloride	HCl

3.2 Process Description

Process of MSW gasification is based on Gibbs free energy minimization and solid MSW fed as input stream which undergoes drying, decomposition, gasification and separation of solid ash from product gases. All the possible products in gasification are considered as conventional components in the model and taken from Aspen Plus data bank. Char from gasification is assumed to consist entirely carbon (graphite) and modelled as solid carbon. The municipal solid waste (MSW) and ash are non-data bank components in this model and they are defined as non-conventional solid stream. Proximate and ultimate analysis of MSW is entered from Zhang et al (9) in the MSW input stream and ash is modelled to contain 100% ash as the component attributes.

HCOALGEN enthalpy model and the DCOALIGT density model in aspen plus are used to calculate properties of non-data bank components MSW and ash. Global stream class is selected as MIXNC as model contains both MIXED & NC streams and base method for property calculations is chosen as UNIQUAC.

Air and/or water are used as gasification agents in gasifier. Air is assumed to contain 79% mole N₂ and 21% mole O₂. Steam is assumed as pure water and contain only water.

MSW enters the drying section where it is dried by SYNGAS1 which is output of gasifier (HTR). This is modelled as preheating by HEX1 heat exchanger through HEAT2 energy stream. Then dried MSW enters the decomposition where it is decomposed to elements according to yield distribution calculated from ultimate analysis of MSW.

Table 3.3: MSW proximate & ultimate analysis of MSW feed taken from Zhang et al [6]

Proximate Analysis (wt. %)		Ultimate Analysis (wt. %) (Dry)	
Moisture	20.0	C	50.5
Volatile matters (dry)	77.6	H	5.6
Fixed carbon (dry)	10.7	N	1.1
Ash (dry)	11.7	Cl	0.1
		S	0.3
		O	30.7
		Ash	11.7

Products stream (GASFEED1) from DECOMP block consists of Carbon, H₂, N₂, Cl₂, S, O₂, H₂O and ash enters the evaporator block which is modelled as component separator with split fraction 1 for water mixed stream separates water from gas stream and then mixes with SYNGAS3 at the outlet of LTR to form final SYNGAS4. Gas feed from EVAP enters the ASHSEP where the non-conventional solid ash is separated before entering the gasifier as HTR does not handle non-conventional component in Gibbs free energy minimization approach. The separated ash is cooled inert glass-like slag and can be used as construction material or to recover metal from it.

Plasma gasifier contains two zones within the reactor. Bottom zone is high temperature reaction zone and upper part of gasifier is low temperature reaction zone as it is away from plasma gas input nozzle. In the Aspen Plus model, the entire gasifier is modelled as two gasifiers namely HTR & LTR in series with one cooler (HEX2) in between them to approximate the two reaction zones of the actual gasifier. Plasma gas from DC-Torch, a direct current electric torch being modelled as heater block enters the HTR from bottom. DC-Torch is given a temperature of 4000 °C and this temperature quickly drops in the HTR to about 2500 °C and gasification takes place at this temperature and atmospheric pressure. All the possible product components are identified and valid phase is mixed with exception for carbon of which valid phase is pure solid to distinguish it from char (i.e. solid carbon). In HTR, phase equilibrium chemical equilibrium are solved using Gibbs free energy minimization approach. Product gases from HTR cooled by MSW input stream in drying section and then enters the LTR and the gasification takes place at low temperature in near absence of oxygen as all oxygen is consumed in HTR itself. The syngas product stream from LTR mixes with WATER stream from EVAP as the outlet SYNGAS4.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Validation of Model

The model is validated by using MSW feed from Janajreh et al [7] in the present simulation. The feedstock attributes and results obtained are tabulated below.

Table 4.1: MSW proximate & ultimate analysis of MSW.

Proximate Analysis (wt. %)		Ultimate Analysis (wt. %) (Dry):	
Moisture	27.3	C	45.6
Volatile matters (dry)	71.5	H	6.0
Fixed carbon (dry)	7.7	N	0.8
Ash (dry)	20.8	Cl	0.0
		S	0.3
		O	26.5
		Ash	20.8

The results came in close comparison with data from the literature. This model which is developed for MSW in this work can be used to gasify other solid wastes such as biomass, coal, rice husk etc.

Table 4.2: Results Comparison

Component	Mole percent (Janajreh et al.[7])	Current Simulation
H₂	43.5	43.6
CO	34.5	32.3
CO₂	0.03	0.0271
N₂	5.63	5.8
CH₄	0.01	0.0099
H₂O	16.22	16.9
HCl	0.00	0.00
H₂S	0.09	0.0802
COS	0.00	0.00

Using this simulation model gasification of MSW with different gasification agents was analysed in three cases namely air gasification, steam gasification and steam-air gasification and variation in syngas yield & LHV of syngas was studied.

Simulation conditions such as feed flow rate, plasma gas flow rate and steam to air ratio and product mole fractions for different components, net heat duty used by plasma torch and outlet gas temperatures for all three cases are tabulated.

4.2 Calculations

Calculation of mass yield from ultimate analysis:

- Feed attributes taken from ultimate analysis
- Mass yield is the required input in R-Yield reactor (DECOMP block in present simulation) in aspen plus simulation model.
- Table: Calculation of Yield distribution in DECOMP block

Table 4.3: Yield distribution in DECOMP block

Component	Ultimate analysis (in wt.% dry)	Mass Yield $m_i=(1-X_{moisture})*X_i*m_{feed}$
C	50.5	$=(1-0.2)*0.505*1 = 0.404$
H	5.6	$=(1-0.2)*0.056*1=0.0448$
N	1.1	$=(1-0.2)*0.011*1=0.0088$
Cl	0.1	$=(1-0.2)*0.001=0.0008$
S	0.3	$=(1-0.2)*0.003*1=0.0024$
O ₂	30.7	$=(1-0.2)*0.307*1=0.2456$
Ash	11.7	$=(1-0.2)*0.117*1=0.0936$
H ₂ O	20	0.2

Calculation of stoichiometric air requirement for complete combustion:

- Feed attributes taken from ultimate analysis
- Stoichiometric air is used in equivalence ratio (ER) calculations to study combustion behaviour

Table 4.4: O₂ required for complete combustion

Component	Mass per kg	O ₂ required (in kg)	Products(in kg)
C	0.505	=0.505*32/12 =1.3467	=0.505*44/12 =1.8517
H	0.056	=0.056*16/12 =0.07467	=0.056*18/2 =0.504
S	0.003	=0.003*32/32 =0.003	=0.003*64/32 =0.006
O	0.307	= -0.307	0
N	0.011	0	0
Ash	0.117	0	0
Cl ₂	0.001	0	0

Total O₂ required to completely burn the given MSW feed = 1.8567+0.504+0.006 =2.3667kg

Total air required =O₂ required in kg / O₂ mass fraction in air

$$=2.366 / (0.21*32/28.84)$$

$$=10.154\text{kg air per 1kg MSW}$$

Sample calculation for LHV of syngas for steam-air gasification:

$$\Rightarrow \text{LHV} = 11.2*0.27068+13.1*0.06766+0.04653*37.1 =5.644\text{MJ/Nm}^3$$

$$\text{Volume flow rate at T is } V \text{ (m}^3/\text{s)} =11.7729 \text{ m}^3/\text{s}$$

$$\text{Temperature of syngas stream } T= 1178.5$$

$$\Rightarrow \text{LHV} \left(\frac{\text{MJ}}{\text{s}} \right) =5.644*11.7729*298.15/1178.5 =16.811\text{MJ/s}$$

Calculation of chemical exergy of fuel:

$$\begin{aligned} \text{HHV of Feed} &=0.3491*50.5+1.1783*5.6+0.1005*0.3-0.1034*30.7-0.0151*1.1-0.0211*11.7 \\ &=20.820\text{MJ/kg} \end{aligned}$$

=> LHV of feed = 0.943*20.820 = 19.633MJ/kg

$$\beta = \frac{1.0414 + 0.0177 * \frac{5.6}{50.5} - 0.3328 * \frac{30.7}{50.5} * (1 + 0.0537 * \frac{5.6}{50.5})}{1 - 0.4021 * \frac{30.7}{50.5}}$$

=> $\beta = 1.11$

=> Chemical exergy of fuel $Ex_{ch}^{fuel} = 1.11 * 19.633 = 21.8238 \text{ MJ/kg}$.

First law efficiency $\eta = 16.811 / (1 * 19.633 + 4.16162 / 0.3135) = 0.51 = 51\%$

Table 4.5: Syngas composition for gasification with different gasifying agents

Component	Air	Air + Steam	Steam
H₂	0.233	0.3832	0.4684
CO	0.3157	0.3556	0.3890
CO₂	7.63*10 ⁻⁵	9.63*10 ⁻⁵	0.0001145
N₂	0.2926	0.0984	0.00367
CH₄	0.0001	0.00028	0.0004
H₂O	0.1175	0.1286	0.1310
HCl	0.00024	0.00026	0.000265
H₂S	0.00075	0.00083	0.00085
NH₃	2.9*10 ⁻⁶	0.000176	0.00018
C(solid)	0.0392	0.0324	0.00619
C₂H₂	2.93*10 ⁻⁶	3.21*10 ⁻⁶	3.27*10 ⁻⁶
COS	0.00269	3.531*10 ⁻⁵	3.27*10 ⁻⁵
HCN	0.00027	0.000199	4.25*10 ⁻⁵
Feed flow (kg/s)	1	1	1
Plasma gas flow(kg/s)	1	0.5	0.32
Steam/air ratio	-	0.1667	-
Torch power(MW)	4.892	4.162	4.310
Outlet Temperature(K)	1426.9	1415.1	1411

The chemical energy of the solid fuel is converted into both the thermal and chemical energy of the gas. The chemical energy contained within the gas is a function of its chemical composition. Thus the chemical composition of the syngas determines its quality as a fuel. High concentrations of combustible gases such as H₂, CO and CH₄ heating value of the gas.

4.3 Sensitivity Analysis

4.3.1 Air Gasification

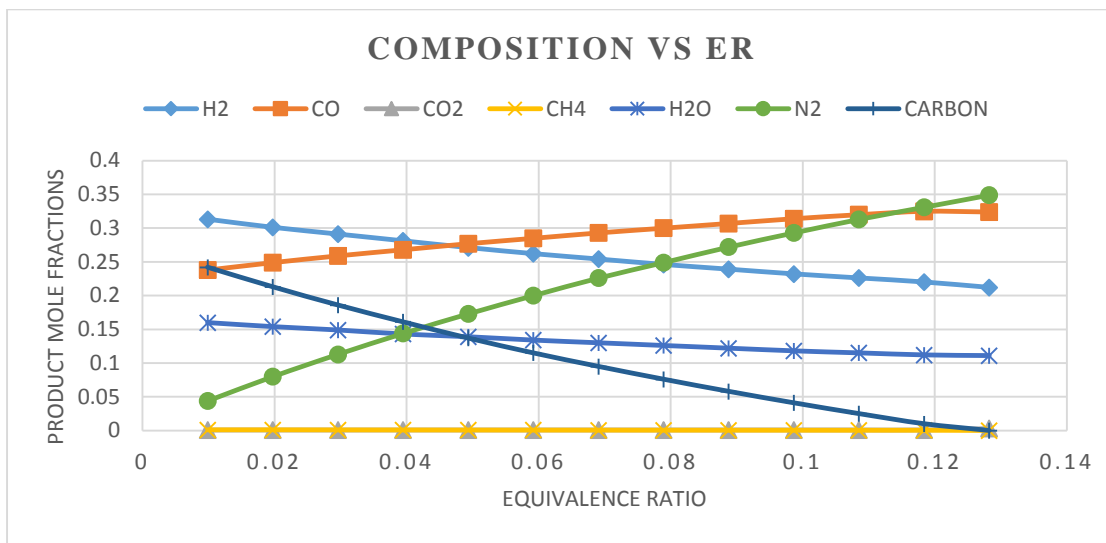


Figure 4.1 Effect of Equivalence Ratio(ER) on syngas composition

Equivalence ratio is defined as ratio of actual air to MSW mass ratio and stoichiometric air to mass ratio. Mole fraction of CO increases as with increase of ER, conversion of char increases and is in agreement with the results of Zhang et al [5]. As CO₂ is in very small amount, water gas shift reaction does not occur to produce hydrogen. Low value of LHV is because of lower proportion H₂ which has high heating value than CO and due to the diluting effect of N₂.

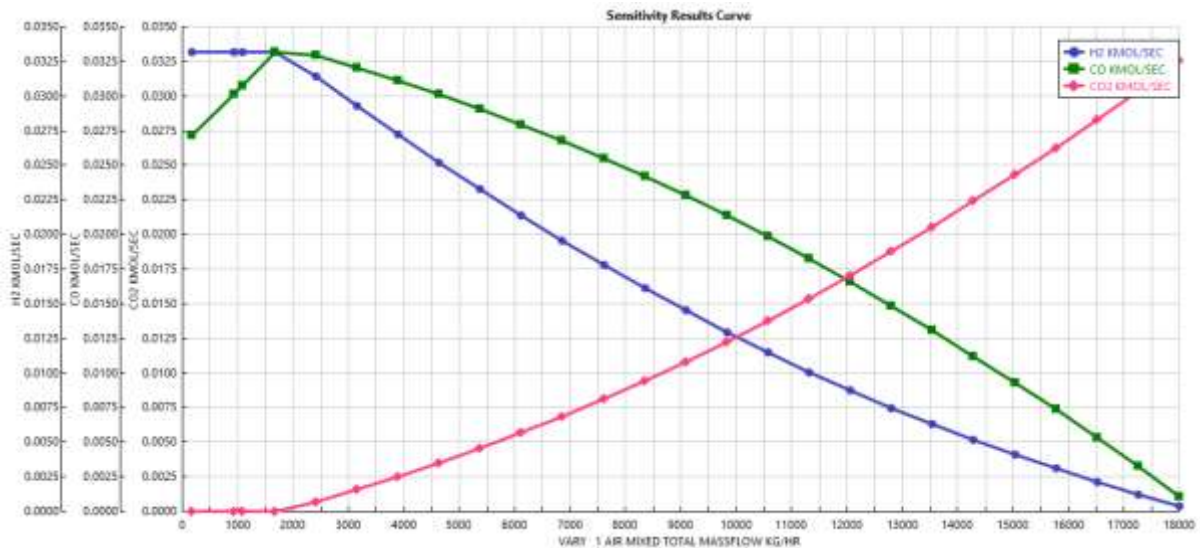


Figure 4.2: Variation of syngas composition with variation of air flow rate.

Initially, Carbon and H₂ are in abundance and O₂ is scarce and hence C and O₂ react to form CO; H₂ and O₂ react to form H₂O at an increasing rate. As it is O₂ starved environment for low air flow rate, combustion of C to CO₂ is significantly less than gasification of C to CO. But as air flow increases, availability of O₂ increases in the gasification section and hence both C and CO are oxidized to form CO₂ and hence CO₂ is steadily increasing with air flow rate. Increasing trend of N₂ with air flow is obvious as air contains significant amount of N₂.

4.3.2 Air and Steam gasification

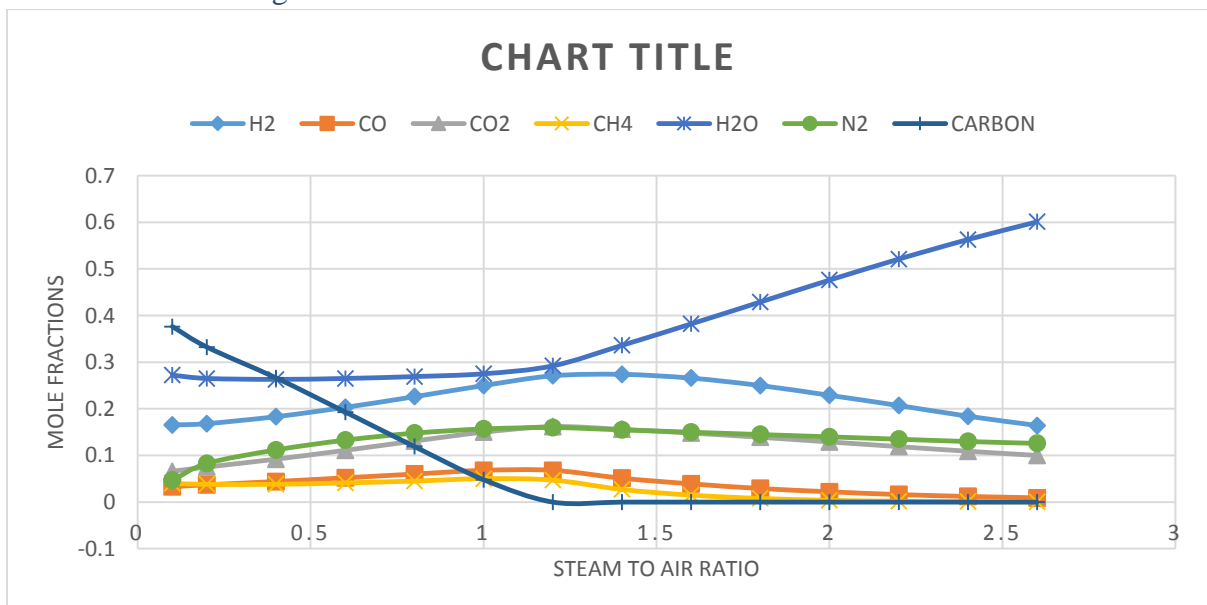


Figure 4.3: Variation of syngas composition with variation of steam to air ratio

Behaviour of steam-air gasification is in between two extreme behaviour and can be predicted if we know air and steam gasification behaviour.

4.3.3 Steam gasification

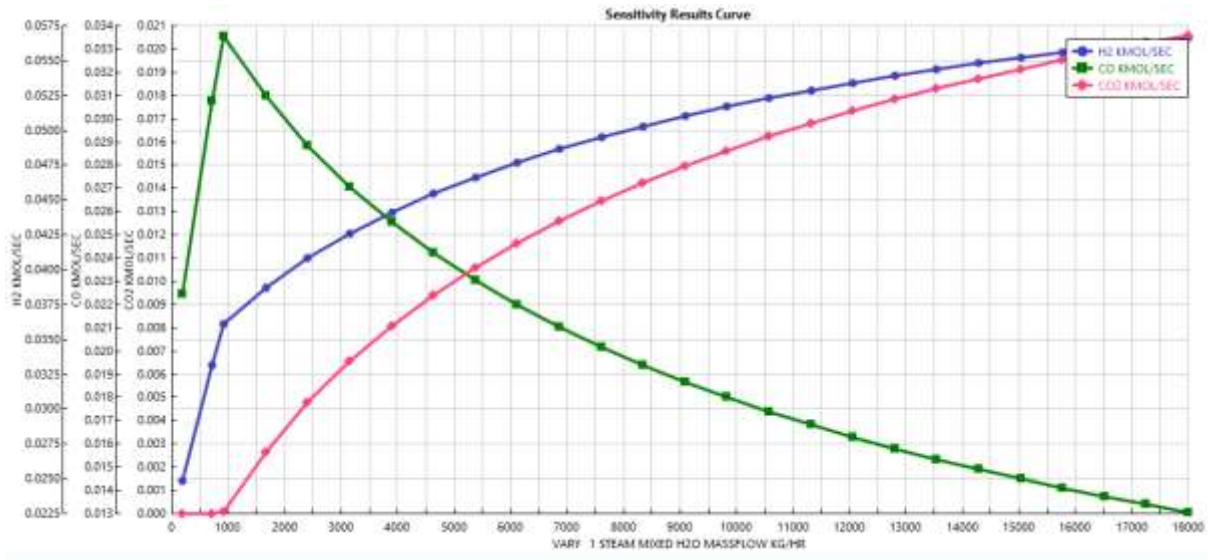


Figure 4.4: Variation of syngas composition with variation of steam flow rate

From the above graph, H₂ and CO₂ are on the product side of water shift reaction and hence these are produced abundantly with the presence of steam in the steam gasification and as CO is on reactant side so it self explains it's decreasing trend.

4.4 Exergy Analysis

Table 4.6: Chemical exergy of MSW feed

Parameters	Values
Feed flow rate	1kg/s
HHV (of MSW)	20.82 MJ/kg
β	1.1078
LHV feed	19.63MJ/kg
Chemical exergy of MSW (E_{ch}^{fuel})	21.824 MJ/kg

Table 4.7: Calculation of chemical exergy of syngas for air gasification

Component	n_i (kmol/s)	$Ex_{i,o}^{ch}$ (kJ/kmol)	$RT_o \ln \frac{n_i}{\sum n_i}$ (kJ/kmol)	$Ex_{i,o}^{ch} + RT_o \ln \frac{n_i}{\sum n_i}$ (kJ/kmol)	$n_i Ex_i^{ch}$ (kJ/s)
H2	0.0221	2,36,100	-4230.46	2,31,870	5123.029
CO	0.0299	2,75,100	-3482.55	2,71,617	8114.65
CO2	$7.2 \cdot 10^{-6}$	19,870	-24126.39	-4,256	-0.0307
N2	0.0276	720	-3671.40	-2,951	-81.71
CH4	$9.7 \cdot 10^{-6}$	8,31,650	-23389.52	8,08,260	7.858
H2O	0.011	9,500	-5933.34	3,567	39.65
HCl	0.000022	3,31,300	-21309.42	3,09,991	6.975
H2S	$7.0 \cdot 10^{-5}$	812000	-18476.25	7,93,524	55.99
NH3	$2.78 \cdot 10^{-7}$	337900	-32203.08	3,05,697	0.0849
C(graphite)	0.0037	409870	-8650.69	4,01,219	1490.307
O2	0	3970	-	-	0
Total	0.095	--	--	-	14752.7

Table 4.8: Calculation of physical exergy for syngas for air gasification

Component	$h - h_o$ (kJ/kmol)	$s - s_o$ (kJ/kmol.K)	Ex_i^{ph} (kJ/kmol)	$n_i Ex_i^{ph}$ (kJ/s)
H₂	-33933.39	-46.476	-20076.6	-443.582
CO	-36229.58	-49.0338	-21610.2	-645.609
CO₂	-57486.64	-75.44	-34992.9	-0.25273
N₂	-35891.64	-48.571	-21410.2	-592.717
CH₄	-71022.85	-88.07	-44763.7	-0.4352
H₂O	-44667.966	-59.469	-26937.3	-299.438
HCl	-34660.00	-46.9279	-20668.5	-0.46504
H₂S	-48950.7	-65.152	-29525.5	-2.08319
NH₃	-58655.8	75.317	-81111.6	-0.02253
C(graphite)	-70519.67	-75.32	-92975.4	-345.352
O₂	0	0	0	0
T (K)	1426.9	1426.9	1426.9	1426.9
Total	--	--		-2330.83

Table 4.9: Calculation of chemical exergy of syngas for steam-air gasification

Component	n_i (kmol/s)	$Ex_{i,o}^{ch}$ (kJ/kmol)	$RT_o \ln \frac{n_i}{\sum n_i}$ (kJ/kmol)	$Ex_{i,o}^{ch} + RT_o \ln \frac{n_i}{\sum n_i}$ (kJ/kmol)	$n_i Ex_i^{ch}$ (kJ/s)
H₂	0.03316	2,36,100	-3223.96	2,32,876	7722.17
CO	0.0307	2,75,100	-3408.97	2,71,691	8361.37
CO₂	8.3*10 ⁻⁶	19,870	-23771.65	-3,902	-0.0325
N₂	0.00852	720	-6592.688	-5,873	-50.03
CH₄	2.4*10 ⁻⁵	8,31,650	-21160.93	8,10,489	19.36
H₂O	0.0111	9,500	-5931.04	3,569	39.71
HCl	0.0000225	3,31,300	-21309.42	3,09,991	6.975
H₂S	7.2*10 ⁻⁵	812000	-18427.93	7,93,572	57.09
NH₃	1.5*10 ⁻⁵	337900	-22269.06	3,15,631	4.822
C(graphite)	0.0028	409870	-9343.9	4,00,526	1124.8
O₂	0	3970	-	-	0
Total	0.086	--	--	-	17286.12

Table 4.10: Calculation of physical exergy for syngas for steam-air gasification

Component	n_i (kmol/s)	$h - h_o$ (kJ/kmol)	$s - s_o$ (kJ/kmol.K)	Ex_i^{ph} (kJ/kmol)	$n_i Ex_i^{ph}$ (kJ/s)
H₂	0.0329	-33556.11	-46.21	-19778.52	-651.757
CO	0.00824	-35817.51	-48.74	-21284.55	-175.308
CO₂	0.0197	-56802.38	-74.963	-34452.21	-679.905
N₂	0.0195	-35484.38	-48.284	-21088.386	-410.685
CH₄	0.0057	-70027.95	-87.37	-43977.58	-249.109
H₂O	0.0356	-44125.6	-59.087	-26508.7	-942.724
HCl	0.0000225	-34263.53	-46.65	-20355.17	-0.458
H₂S	7.4*10 ⁻⁵	-48357.33	-64.73	-29056.66	-2.14696
NH₃	1.1*10 ⁻⁶	-57891.223	74.779	-80186.57	-0.0891
C(graphite)	2.78*10 ⁻⁷	-69656.02	-91.46	-42387.61	-0.01177
O₂	0	0	0	0	0
T (K)	1415.1	1415.1	1415.1	1415.1	1415.1
Total	0.12174	--	--		-3112.19

Table 4.11: Calculation of chemical exergy of syngas for steam gasification

Component	n_i (kmol/s)	$Ex_{i,o}^{ch}$ (kJ/kmol)	$RT_o \ln \frac{n_i}{\sum n_i}$ (kJ/kmol)	$Ex_{i,o}^{ch} + RT_o \ln \frac{n_i}{\sum n_i}$ (kJ/kmol)	$n_i Ex_i^{ch}$ (kJ/s)
H₂	0.0398	2,36,100	-2771.44	2,33,329	9286.67
CO	0.03306	2,75,100	-3231.45	2,71,869	8987.97
CO₂	9.7*10 ⁻⁶	19,870	-23389.518	-3,520	-0.034
N₂	0.000312	720	-14789.26	-14,069	-4.3927
CH₄	3.42*10 ⁻⁵	8,31,650	-20273.87	8,11,376	27.72
H₂O	0.0111	9,500	-5929.56	3,570	39.75
HCl	0.0000225	3,31,300	-21309.42	3,09,991	6.975
H₂S	7.2*10 ⁻⁵	812000	-18418.38	7,93,582	57.3
NH₃	1.53*10 ⁻⁵	337900	-22269.06	3,15,631	4.822
C(graphite)	0.00053	40987	-13495.75	3,96,374	208.54
O₂	0	3970	-	-	0
Total	0.085	--	--	-	18615.51

Table 4.12: Calculation of physical exergy for syngas for steam gasification

Component	$h - h_o$ (kJ/kmol)	$s - s_o$ (kJ/kmol.K)	Ex_i^{ph} (kJ/kmol)	$n_i Ex_i^{ph}$ (kJ/s)
H₂	-33425.156	-46.1175	-19675.2	-783.089
CO	-35674.44	-48.64	-21171.7	-699.935
CO₂	-56564.82	-74.795	-34264.8	-0.33313
N₂	-35342.99	-48.184	-20976.8	-6.54943
CH₄	-69682.9	-87.129	-43705.3	-1.49327
H₂O	-43937.53	-58.95	-26360.3	-293.471
HCl	-34125.94	-46.5515	-20246.6	-0.45555
H₂S	-48151.56	-64.589	-28894.3	-2.08681
NH₃	-57626.00	-74.59	-35386.6	-0.54063
C(graphite)	-69356.495	-74.59	-47117.1	-24.7888
O₂	0	0	0	0
T (K)	1411	1411	1411	1411
Total	--	--		-1812.87

Table 4.13: Calculated exergy of different streams in the process

Gasification agent	$E^{ch,syngas}$ (kJ/s)	$E^{ph,syngas}$ (kJ/s)	$E^{ch,fuel}$ (kJ/s)	E^{ch,O_2} (kJ/s)	E^{ch,H_2O} (kJ/s)
Air	14752.7	-2330.83	21.823	0	-299.4
Steam + Air	17286.1	-3112.2	21.823	0	-942.7
Steam	18615.51	-1812.87	21.8238	0	-293.4

Table 4.14: Exergy efficiency of different gasification agents

Gasification agent	syngas LHV(MW)	First law efficiency	Exergy efficiency
Air	15.0237	0.4263	0.3398
Steam + air	16.811	0.5108	0.430
Steam	21.399	0.641	0.48

The trend of exergy efficiency can be explained as follows: From the table of mole fractions, it is evident that more H₂ is produced in steam gasification than in air gasification although is only slightly more. High LHV of steam gasification compared to air gasification because of higher H₂ products of steam gasification as heating value of H₂ is significantly more than that of CO and also because of diluting . High exergy efficiency of steam gasification is attributed has high heating value of syngas produced in steam gasification.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

For the future, advanced gasification and fuel cells promise to double efficiencies while reducing air pollution and waste ash. The ultimate goal of this work is to divert biodegradable municipal waste away from landfills, and this reduce the potential for methane generation.

In this work, plasma gasification model in Aspen Plus based on non-stoichiometric Gibbs free energy minimization approach is developed and characteristics of plasma gasification has been studies with special focus on gasifying agents. MSW feedstock with feed attributes taken from Zhang et al [6] has been studied and results are presented. Using this model, plasma gasification with air, steam and steam-air gasification are done and syngas yield and composition are tabulated. Exergy analysis for all three cases has been done and results are presented.

- High H_2 content is observed in steam followed by steam-air gasification due to water-gas shift reaction.
- N_2 is significantly more in air gasification which leads to diluting of syngas quality
- For the same flow rate of plasma gas, steam feed takes more torch power than air.
- In air gasification, H_2 and CO are steadily decreasing and dilution effect of N_2 is increasing while in steam gasification H_2 and CO_2 are steadily increasing.
- LHV of syngas is highest for steam followed by steam + air followed by air gasification.
- First law efficiency for steam is greater than steam + air and for air is the least.
- Exergy efficiency of gasification is highest for steam followed by steam-air and then by air gasification.

5.2 Recommendations:

Although plasma gasification can process unprocessed MSW, pre-processing may be needed for higher energy efficiency. Ideal feed should have high organic content and low moisture. High moisture content reduces energy efficiency as a part of energy is used for drying of feed. Low organic content feed gives low quality syngas.

Main hurdles for WTE processes in Indian context is high moisture content and low calorific MSW. The technologies available in market are either from developed countries in west or not so advanced Chinese technology. There is no particular technology available for Indian context. More research on plasma gasification for MSW is the need of the hour.

- Although Plasma gasification is relatively clean process, syngas produced is not absolutely clean. Hence gas clean up system must be integrated. Unconverted feed and solid carbon produced in the gasification has to be separated in the gas clean up equipment. Although H_2S & HCl formed are very less, but their effect on equipment corrosion is high. These should be separated before using syngas for production of electricity or chemicals/liquid fuels
- Plasma gasification can be integrated with F-T process and Gas combined cycle. A study on these process in Indian context can be carried out in order to determine which is best suited.
- Study on effect of variation of gasifier types on syngas quality/yield can be done
- Study on effect of variation in feedstock composition on syngas yield can also be done.
- Kinetics of plasma gasification is unknown. A study on complex reaction involved in the process to determine the kinetics of gasification may be done
- Pinch analysis of entire process to improve energy and exergy efficiency can be done to further increase the energy recovery of the process.

REFERENCES

1. Mountouris, A., E. Voutsas, and D. Tassios. "Solid waste plasma gasification: equilibrium model development and exergy analysis." *Energy Conversion and Management* 47.13 (2006): 1723-1737.
2. Ahmed, I., and A. K. Gupta. "Syngas yield during pyrolysis and steam gasification of paper." *Applied Energy* 86.9 (2009): 1813-1821.
3. Zhang, Qinglin, et al. "A thermodynamic analysis of solid waste gasification in the Plasma Gasification Melting process." *Applied Energy* 112 (2013): 405-413.
4. Zhang, Qinglin, et al. "Gasification of municipal solid waste in the Plasma Gasification Melting process." *Applied Energy* 90.1 (2012): 106-112.
5. Zhang, Qinglin, et al. "Performance analysis of municipal solid waste gasification with steam in a Plasma Gasification Melting reactor." *Applied Energy* 98 (2012): 219-229.
6. Zhang, Qinglin, et al. "Modeling of steam plasma gasification for municipal solid waste." *Fuel processing technology* 106 (2013): 546-554.
7. Janajreh, Isam, Syed Shabbar Raza, and Arnar Snaer Valmundsson. "Plasma gasification process: Modeling, simulation and comparison with conventional air gasification." *Energy conversion and management* 65 (2013): 801-809.
8. Minutillo, M., A. Perna, and D. Di Bona. "Modelling and performance analysis of an integrated plasma gasification combined cycle (IPGCC) power plant." *Energy Conversion and Management* 50.11 (2009): 2837-2842.
9. Prins, Mark J., Krzysztof J. Ptasinski, and Frans JJG Janssen. "From coal to biomass gasification: Comparison of thermodynamic efficiency." *Energy* 32.7 (2007): 1248-1259.
10. Dalai, Ajay K., et al. "Gasification of refuse derived fuel in a fixed bed reactor for syngas production." *Waste Management* 29.1 (2009): 252-258.
11. Pinto, F., et al. "Co-gasification study of biomass mixed with plastic wastes." *Fuel* 81.3 (2002): 291-297.
12. Chen, Chong, et al. "Simulation of municipal solid waste gasification in two different types of fixed bed reactors." *Fuel* 103 (2013): 58-63.
13. Byun, Youngchul, et al. *Thermal Plasma Gasification of (MSW)*. INTECH Open Access Publisher, 2012

14. Nikoo, Mehrdokht B., and Nader Mahinpey. "Simulation of biomass gasification in fluidized bed reactor using ASPEN PLUS." *Biomass and Bioenergy* 32.12 (2008): 1245-1254.
15. Channiwala, S. A., and P. P. Parikh. "A unified correlation for estimating HHV of solid, liquid and gaseous fuels." *Fuel* 81.8 (2002): 1051-1063.22
16. Smith, J. M., H. C. Van Ness, and M. M. Abbott. "Chemical engineering thermodynamics. 6th edition, Appendix C P.no: 636" *Sat* 18 (1996): 3-1.
17. Çengel, Yunus A., and Michael A. Boles. *Thermodynamics: an engineering approach Appendix 1*, P.no: 913. McGraw-Hill Education, 2015.
18. 24 L Sørum, M.G Grønli, J.E Hustad, *Pyrolysis characteristics and kinetics of municipal solid wastes*, *Fuel*, Volume 80, Issue 9, July 2001, Pages 1217-1227, ISSN 0016-2361
19. Tsatsaronis, George. "Definitions and nomenclature in exergy analysis and exergoeconomics." *Energy* 32.4 (2007): 249-253.26.
20. Kotas, Tadeusz Jozef. *The exergy method of thermal plant analysis*. Elsevier, 2013.
21. Wu, Yueshi, Weihong Yang, and Wlodzimierz Blasiak. "Energy and exergy analysis of high temperature agent gasification of biomass." *Energies* 7.4 (2014): 2107-2122.28.
22. nptel.ac.in/courses/112103016/8
23. Lyubina, Yu L., and A. L. Suris. "Thermodynamic model of the plasma gasification of organic solid wastes." *Chemical and petroleum engineering* 35.7 (1999): 403-406.
24. Hlina, M., et al. "Production of high quality syngas from argon/water plasma gasification of biomass and waste." *Waste management* 34.1 (2014): 63-66. 1, January 2014, Pages 63-66, ISSN 0956-053X
25. <http://pib.nic.in/newsite/PrintRelease.aspx?relid=138591>
26. <http://www.eai.in/ref/ae/wte/typ/clas/msw.html>
27. Gray, Larry. "Plasma Gasification as a Viable Waste-to-Energy Treatment of Municipal Solid Waste." (2014).
28. Arafat, Hassan A., and Kenan Jijakli. "Modeling and comparative assessment of municipal solid waste gasification for energy production." *Waste management* 33.8 (2013): 1704-1713.
29. Umberto Arena, *Process and technological aspects of municipal solid waste gasification. A review*, *Waste Management*, Volume 32, Issue 4, April 2012, Pages 625-639.

30. Higman, Christopher, and Maarten Van der Burgt. Gasification. Gulf professional publishing, 2011.
31. Aspen Plus, "Getting started modelling processes with solids." Aspen Engineering Suite V 8.4 (2013).
32. Schefflan, Ralph. Teach yourself the basics of Aspen Plus. John Wiley & Sons, 2011.
33. Plus, Aspen. "Aspen Plus user guide." Aspen Technology Limited, Cambridge, Massachusetts, United States (2003).
34. Valmundsson, Arnar S., and Isam Janajreh. "Plasma gasification process modeling and energy recovery from solid waste." ASME 2011 5th International Conference on Energy Sustainability. American Society of Mechanical Engineers, 2011.
35. Begum, Sharmina, M. G. Rasul, and Delwar Akbar. "A Numerical Investigation of Municipal Solid Waste Gasification Using Aspen Plus." *Procedia Engineering* 90 (2014): 710-717.
36. Knoef, H., 2005. Practical aspects of biomass gasification, chapter 3 in *Handbook Biomass Gasification* edited by H. Knoef. BTG-Biomass Technology Group (BTG), ISBN: 90-810068-1-9. Enschede, Netherlands.
37. Sharholly, Mufeed, et al. "Municipal solid waste management in Indian cities—A review." *Waste management* 28.2 (2008): 459-467.
38. Tasma, Daniela, Krisztina Uzuneanu, and Tănase Panait. "The effect of excess air ratio on syngas produced by gasification of agricultural residues briquettes." *Carbon* 29.24.85 (2012): 22-60.
39. Morrin, Shane, et al. "Two stage fluid bed-plasma gasification process for solid waste valorisation: Technical review and preliminary thermodynamic modelling of sulphur emissions." *Waste management* 32.4 (2012): 676-684.
40. Chen, Chong, et al. "Simulation of municipal solid waste gasification in two different types of fixed bed reactors." *Fuel* 103 (2013): 58-63.
41. <http://www.moef.nic.in/legis/hsm/mswmhr.html>
42. Report of the Task Force on Waste to Energy (Volume I) (In the context of integrated MSW management), Planning Commission, May 12, 2014
43. <https://www.e-education.psu.edu/egee439/node/607>
44. Hrabovsky, Milan, et al. "Properties of hybrid water/gas DC arc plasma torch." *Plasma Science, IEEE Transactions on* 34.4 (2006): 1566-1575.

45. Franco, Carlos, et al. "The study of reactions influencing the biomass steam gasification process☆." *Fuel* 82.7 (2003): 835-842.

APPENDIX I

Stream Tables

Table A.1 Steam Gasification

MSW TO ENERGY CONVERSION														
Stream ID		ASH	GASFEED1	GASFEED2	GASFEED3	MSW	MSW1	PLASMA	STEAM	SYNGAS1	SYNGAS2	SYNGAS3	SYNGAS4	WATER
Temperature	K		723.1	723.1	723.1	298.1	298.1	4273.1	298.1	937.1	1223.2	1540.2	1411.0	723.1
Pressure	atm	1.000	1.000	1.000	1.000	0.987	0.987	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Vapor Frac			0.552	0.474	0.474			1.000	0.000	0.824	0.824	0.993	0.994	1.000
Mole Flow	kmol/hr	0.000	270.135	230.169	230.169	0.000	0.000	63.946	63.946	248.295	248.295	265.953	305.919	39.966
Mass Flow	kg/hr	0.000	3263.040	2543.040	2543.040	0.000	0.000	1152.000	1152.000	3695.040	3695.040	3695.039	4415.039	720.000
Volume Flow	l/min	0.000	147411.200	107885.572	107885.572	0.000	0.000	373696.055	19.317	262365.037	342438.522	556190.372	586668.085	39525.628
Enthalpy	Gcal/hr		-1.628	0.537	0.537			-0.659	-4.365	-3.951	-3.324	-0.690	-2.855	-2.165
Mass Flow	kg/hr													
CO2										1041.853	1041.853	1.520	1.520	
N2			31.680	31.680	31.680					31.614	31.614	31.491	31.491	
CH4										143.698	143.698	1.966	1.966	
H2O			720.000					1152.000	1152.000	486.134	486.134	2.040	722.040	720.000
O2			884.160	884.160	884.160					trace	trace	trace	trace	
NO2										trace	trace	trace	trace	
NO										trace	trace	trace	trace	
SO2										trace	trace	trace	trace	
SO3										trace	trace	trace	trace	
HCN										< 0.001	< 0.001	0.353	0.353	
H2S										9.183	9.183	8.857	8.857	
COS												0.575	0.575	
C2H2										trace	trace	0.029	0.029	
NH3										0.080	0.080	0.007	0.007	
CHLORINE			2.880	2.880	2.880					trace	trace	trace	trace	
S			8.640	8.640	8.640					trace	trace	< 0.001	< 0.001	
CARBON			1454.400	1454.400	1454.400					523.485	523.485	22.751	22.751	
H2			161.280	161.280	161.280					199.036	199.036	288.842	288.842	
CARBO-01										1256.995	1256.995	3333.646	3333.646	
AR														
HCL										2.962	2.962	2.962	2.962	
Mole Flow	kmol/hr													
CO2										23.673	23.673	0.035	0.035	
N2			1.131	1.131	1.131					1.129	1.129	1.124	1.124	
CH4										8.957	8.957	0.123	0.123	
H2O			39.966					63.946	63.946	26.984	26.984	0.113	40.079	39.966
O2			27.631	27.631	27.631					trace	trace	trace	trace	
NO2										trace	trace	trace	trace	
NO										trace	trace	trace	trace	
SO2										trace	trace	trace	trace	
SO3										trace	trace	trace	trace	
HCN										< 0.001	< 0.001	0.013	0.013	
H2S										0.269	0.269	0.260	0.260	
COS												0.010	0.010	
C2H2										trace	trace	0.001	0.001	
NH3										0.005	0.005	< 0.001	< 0.001	
CHLORINE			0.041	0.041	0.041					trace	trace	trace	trace	
S			0.269	0.269	0.269					trace	trace	trace	trace	
CARBON			121.092	121.092	121.092					43.585	43.585	1.894	1.894	
H2			80.005	80.005	80.005					98.734	98.734	143.283	143.283	
CARBO-01										44.876	44.876	119.016	119.016	
AR														
HCL										0.081	0.081	0.081	0.081	
Mole Frac														
CO2										0.095	0.095	130 PPM	113 PPM	
N2			0.004	0.005	0.005					0.005	0.005	0.004	0.004	
CH4										0.036	0.036	461 PPM	401 PPM	
H2O			0.148					1.000	1.000	0.109	0.109	426 PPM	0.131	1.000
O2			0.102	0.120	0.120					trace	trace	trace	trace	
NO2										trace	trace	trace	trace	
NO										trace	trace	trace	trace	
SO2										trace	trace	trace	trace	
SO3										trace	trace	trace	trace	
HCN										71 PPB	71 PPB	49 PPM	43 PPM	
H2S										0.001	0.001	977 PPM	849 PPM	
COS												36 PPM	31 PPM	
C2H2										trace	trace	4 PPM	4 PPM	
NH3										19 PPM	19 PPM	1 PPM	1 PPM	
CHLORINE			150 PPM	176 PPM	176 PPM					trace	trace	trace	trace	
S			997 PPM	0.001	0.001					trace	trace	37 PPB	32 PPB	
CARBON			0.448	0.526	0.526					0.176	0.176	0.007	0.006	
H2			0.296	0.348	0.348					0.398	0.398	0.539	0.468	
CARBO-01										0.181	0.181	0.448	0.389	
AR														
HCL										327 PPM	327 PPM	305 PPM	266 PPM	
Mass Flow	kg/hr	336.960	3600.000	2880.000	2543.040	3600.000	3600.000	1152.000	1152.000	3695.040	3695.040	3695.039	4415.039	720.000
Enthalpy	Gcal/hr	-0.034	-1.662	0.503	0.537	-5.491	-5.491	-0.659	-4.365	-3.951	-3.324	-0.690	-2.855	-2.165
Temperature	K	723.1	723.1	723.1		298.1	298.2							
Pressure	atm	1.000	1.000	1.000	1.000	0.987	0.987	1.000	1.000			1.000	1.000	1.000
Vapor Frac		0.000	0.000	0.000		0.000	0.000							
Mass Flow	kg/hr	336.960	336.960	336.960	0.000	3600.000	3600.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Enthalpy	Gcal/hr	-0.034	-0.034	-0.034		-5.491	-5.491							
Mass Flow	kg/hr													
ASH		336.960	336.960	336.960										
MSW						3600.000	3600.000							
Mass Frac														
ASH		1.000	1.000	1.000										
MSW						1.000	1.000							

Table A.2 Air Gasification

MSW TO ENERGY CONVERSION														
Stream ID		AIR	ASH	GASFEED1	GASFEED2	GASFEED3	MSW	MSW1	PLASMA	SYNGAS1	SYNGAS2	SYNGAS3	SYNGAS4	WATER
Temperature	K	298.1		723.1	723.1	723.1	298.1		4273.1	1901.6	1223.2	1540.2	1426.9	723.1
Pressure	atm	1.000	1.000	1.000	1.000	1.000	0.987	0.987	1.000	1.000	1.000	1.000	1.000	1.000
Vapor Frac		1.000		0.552	0.474	0.474			1.000	0.957	0.957	0.956	0.961	1.000
Mole Flow	kmol/hr	124.782	0.000	270.135	230.169	230.169	0.000	0.000	124.782	300.306	300.306	300.682	340.648	39.966
Mass Flow	kg/hr	3600.000	0.000	3263.040	2543.040	2543.040	0.000	0.000	3600.000	6143.040	6143.040	6143.040	6863.040	720.000
Volume Flow	l/min	50879.855	0.000	147411.200	107885.572	107885.572	0.000	0.000	729221.036	747429.085	480769.589	605165.835	638654.468	39525.628
Enthalpy	Gcal/hr	> -0.001		-1.628	0.537	0.537			4.207	0.914	-0.794	-0.028	-2.193	-2.165
Mass Flow	kg/hr													
CO2										0.130	0.130	1.141	1.141	
N2		2761.497		31.680	31.680	31.680			2761.497	2786.072	2786.072	2791.873	2791.873	
CH4										0.113	0.113	0.557	0.557	
H2O				720.000						0.164	0.164	0.940	720.940	720.000
O2		838.503		884.160	884.160	884.160			838.503	trace	trace	trace	trace	
NO2										trace	trace	trace	trace	
NO										trace	trace	trace	trace	
SO2										trace	trace	trace	trace	
SO3										trace	trace	trace	trace	
HCN										13.692	13.692	2.479	2.479	
H2S										9.118	9.118	8.663	8.663	
COS												0.915	0.915	
C2H2										0.266	0.266	0.016	0.016	
NH3										0.010	0.010	0.024	0.024	
CHLORINE				2.880	2.880	2.880				trace	trace	trace	trace	
S				8.640	8.640	8.640				0.062	0.062	0.001	0.001	
CARBON				1454.400	1454.400	1454.400				154.931	154.931	160.607	160.607	
H2				161.280	161.280	161.280				160.079	160.079	160.343	160.343	
CARBO-01										3015.440	3015.440	3012.520	3012.520	
AR														
HCL										2.962	2.962	2.962	2.962	
Mole Flow	kmol/hr													
CO2										0.003	0.003	0.026	0.026	
N2		98.578		1.131	1.131	1.131			98.578	99.455	99.455	99.662	99.662	
CH4										0.007	0.007	0.035	0.035	
H2O				39.966						0.009	0.009	0.052	40.018	39.966
O2		26.204		27.631	27.631	27.631			26.204	trace	trace	trace	trace	
NO2										trace	trace	trace	trace	
NO										trace	trace	trace	trace	
SO2										trace	trace	trace	trace	
SO3										trace	trace	trace	trace	
HCN										0.507	0.507	0.092	0.092	
H2S										0.268	0.268	0.254	0.254	
COS												0.015	0.015	
C2H2										0.010	0.010	0.001	0.001	
NH3										0.001	0.001	0.001	0.001	
CHLORINE				0.041	0.041	0.041				trace	trace	trace	trace	
S				0.269	0.269	0.269				0.002	0.002	< 0.001	< 0.001	
CARBON				121.092	121.092	121.092				12.899	12.899	13.372	13.372	
H2				80.005	80.005	80.005				79.409	79.409	79.540	79.540	
CARBO-01										107.655	107.655	107.551	107.551	
AR														
HCL										0.081	0.081	0.081	0.081	
Mole Frac														
CO2										10 PPM	10 PPM	86 PPM	76 PPM	
N2		0.790		0.004	0.005	0.005			0.790	0.331	0.331	0.331	0.293	
CH4										24 PPM	24 PPM	115 PPM	102 PPM	
H2O				0.148						30 PPM	30 PPM	174 PPM	0.117	1.000
O2		0.210		0.102	0.120	0.120			0.210	trace	trace	trace	trace	
NO2										trace	trace	trace	trace	
NO										trace	trace	trace	trace	
SO2										trace	trace	trace	trace	
SO3										trace	trace	trace	trace	
HCN										0.002	0.002	305 PPM	269 PPM	
H2S										891 PPM	891 PPM	845 PPM	746 PPM	
COS												51 PPM	45 PPM	
C2H2										34 PPM	34 PPM	2 PPM	2 PPM	
NH3										2 PPM	2 PPM	5 PPM	4 PPM	
CHLORINE				150 PPM	176 PPM	176 PPM				trace	trace	trace	trace	
S				997 PPM	0.001	0.001				6 PPM	6 PPM	62 PPB	55 PPB	
CARBON				0.448	0.526	0.526				0.043	0.043	0.044	0.039	
H2				0.296	0.348	0.348				0.264	0.264	0.265	0.233	
CARBO-01										0.358	0.358	0.358	0.316	
AR														
HCL										271 PPM	271 PPM	270 PPM	238 PPM	
Mass Flow	kg/hr	3600.000	336.960	3600.000	2880.000	2543.040	3600.000	3600.000	3600.000	6143.040	6143.040	6143.040	6863.040	720.000
Enthalpy	Gcal/hr	> -0.001	-0.034	-1.662	0.503	0.537	-5.491	-5.491	4.207	0.914	-0.794	-0.028	-2.193	-2.165
Temperature	K		723.1	723.1	723.1		298.1	298.2						
Pressure	atm	1.000	1.000	1.000	1.000	1.000	0.987	0.987	1.000		1.000		1.000	1.000
Vapor Frac			0.000	0.000	0.000		0.000	0.000						
Mass Flow	kg/hr	0.000	336.960	336.960	336.960	0.000	3600.000	3600.000	0.000	0.000	0.000	0.000	0.000	0.000
Enthalpy	Gcal/hr		-0.034	-0.034	-0.034		-5.491	-5.491						
Mass Flow	kg/hr													
ASH			336.960	336.960	336.960									
MSW							3600.000	3600.000						
Mass Frac														
ASH			1.000	1.000	1.000									
MSW							1.000	1.000						

Table A.3 Steam + Air gasification

MSW TO ENERGY CONVERSION															
Stream ID		AIR	ASH	GASFEED1	GASFEED2	GASFEED3	MSW	MSW1	PLASMA	STEAM	SYNGAS1	SYNGAS2	SYNGAS3	SYNGAS4	WATER
Temperature	K	298.1		723.1	723.1	723.1	298.1		4273.1	298.1	1013.9	1223.2	1540.2	1415.1	723.1
Pressure	atm	1.000	1.000	1.000	1.000	1.000	0.987	0.987	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Vapor Frac		1.000		0.552	0.474	0.474			1.000	0.000	0.889	0.889	0.963	0.968	1.000
Mde Flow	kmol/hr	37.435	0.000	270.135	230.169	230.169	0.000	0.000	77.401	39.966	264.979	264.979	271.570	311.536	39.966
Mass Fbw	kg/hr	1080.000	0.000	3263.040	2543.040	2543.040	0.000	0.000	1800.000	720.000	4343.040	4343.040	4343.039	5063.039	720.000
Volume Flow	l/min	15263.957	0.000	147411.200	107885.572	107885.572	0.000	0.000	452326.346	12.073	326481.406	393844.382	550716.607	583354.414	39525.628
Erthalpy	Gcal/hr	> -0.001		-1.628	0.537	0.537			0.850	-2.728	-2.442	-1.994	-0.412	-2.577	-2.165
Mass Fbw	kg/hr														
CO2											510.180	510.180	1.330	1.330	
N2		828.449		31.680	31.680	31.680			828.449		859.942	859.942	859.234	859.234	
CH4											54.664	54.664	1.378	1.378	
H2O				720.000					720.000	720.000	201.986	201.986	1.598	721.998	720.000
O2		251.551		884.160	884.160	884.160			251.551		trace	trace	trace	trace	
NO2											trace	trace	trace	trace	
NO											trace	trace	trace	trace	
SO2											trace	trace	trace	trace	
SO3											trace	trace	trace	trace	
HCN											0.009	0.009	1.685	1.685	
H2S											9.183	9.183	8.820	8.820	
COS													0.640	0.640	
C2H2											trace	trace	0.024	0.024	
NH3											0.222	0.222	0.027	0.027	
CHLORINE				2.880	2.880	2.880					trace	trace	trace	trace	
S				8.640	8.640	8.640					trace	trace	< 0.001	< 0.001	
CARBON				1454.400	1454.400	1454.400					354.772	354.772	121.431	121.431	
H2				161.280	161.280	161.280					204.842	204.842	240.649	240.649	
CARBO-01											2144.277	2144.277	3103.263	3103.263	
AR															
HCL											2.962	2.962	2.962	2.962	
Mde Flow	kmol/hr														
CO2											11.592	11.592	0.030	0.030	
N2		29.573		1.131	1.131	1.131			29.573		30.698	30.698	30.672	30.672	
CH4											3.407	3.407	0.086	0.086	
H2O				39.966					39.966	39.966	11.212	11.212	0.089	40.055	39.966
O2		7.861		27.631	27.631	27.631			7.861		trace	trace	trace	trace	
NO2											trace	trace	trace	trace	
NO											trace	trace	trace	trace	
SO2											trace	trace	trace	trace	
SO3											trace	trace	trace	trace	
HCN											< 0.001	< 0.001	0.062	0.062	
H2S											0.269	0.269	0.259	0.259	
COS													0.011	0.011	
C2H2											trace	trace	0.001	0.001	
NH3											0.013	0.013	0.002	0.002	
CHLORINE				0.041	0.041	0.041					trace	trace	trace	trace	
S				0.269	0.269	0.269					trace	trace	< 0.001	< 0.001	
CARBON				121.092	121.092	121.092					29.538	29.538	10.110	10.110	
H2				80.005	80.005	80.005					101.614	101.614	119.376	119.376	
CARBO-01											76.554	76.554	110.791	110.791	
AR															
HCL											0.081	0.081	0.081	0.081	
Mde Frac															
CO2											0.044	0.044	111 PPM	97 PPM	
N2		0.790		0.004	0.005	0.005			0.382		0.116	0.116	0.113	0.098	
CH4											0.013	0.013	316 PPM	276 PPM	
H2O				0.148					0.516	1.000	0.042	0.042	327 PPM	0.129	1.000
O2		0.210		0.102	0.120	0.120			0.102		trace	trace	trace	trace	
NO2											trace	trace	trace	trace	
NO											trace	trace	trace	trace	
SO2											trace	trace	trace	trace	
SO3											trace	trace	trace	trace	
HCN											1 PPM	1 PPM	230 PPM	200 PPM	
H2S											0.001	0.001	953 PPM	831 PPM	
COS													39 PPM	34 PPM	
C2H2											trace	trace	3 PPM	3 PPM	
NH3											49 PPM	49 PPM	6 PPM	5 PPM	
CHLORINE				150 PPM	176 PPM	176 PPM					trace	trace	trace	trace	
S				997 PPM	0.001	0.001					trace	trace	43 PPM	37 PPM	
CARBON				0.448	0.526	0.526					0.111	0.111	0.037	0.032	
H2				0.296	0.348	0.348					0.383	0.383	0.440	0.383	
CARBO-01											0.289	0.289	0.408	0.356	
AR															
HCL											307 PPM	307 PPM	299 PPM	261 PPM	
Mass Fbw	kg/hr	1080.000	336.960	3600.000	2880.000	2543.040	3600.000	3600.000	1800.000	720.000	4343.040	4343.040	4343.039	5063.039	720.000
Erthalpy	Gcal/hr	> -0.001	-0.034	-1.662	0.503	0.537	-5.491	-5.491	0.850	-2.728	-2.442	-1.994	-0.412	-2.577	-2.165
Temperature	K			723.1	723.1	723.1	298.2	298.2							
Pressure	atm	1.000	1.000	1.000	1.000	1.000	0.987	0.987	1.000	1.000				1.000	1.000
Vapor Frac				0.000	0.000	0.000	0.000	0.000							
Mass Fbw	kg/hr	0.000	336.960	336.960	336.960	0.000	3600.000	3600.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Erthalpy	Gcal/hr		-0.034	-0.034	-0.034		-5.491	-5.491							
Mass Fbw	kg/hr														
ASH			336.960	336.960	336.960										
MSW							3600.000	3600.000							
Mass Frac															
ASH			1.000	1.000	1.000										
MSW							1.000	1.000							