Plasma Gasification With Municipal Solid Waste As A Method Of Energy Self Sustained For Better Urban Built Environment: Modeling and Simulation

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Abstract. The plasma gasification method is known as a new technology to produce hydrogen from MSW as a fuel for power generation. Recently, it has become a crucial issue due to the rapid increasing amount of waste, along with the increasingly national population in Indonesia. The goal of waste management is as a material recovery (MR), as an energy recovery (ER) and minimizing the environment impact. The plasma gasification modeling was developed based on plasma torch technology to estimate the syngas composition and energy potential. The process simulation is optimized for mixed steam and air as a gasifying agent. This study is to obtain the essential parameter to have the better content of H₂ in the syngas, better plant efficiency and lowest CO₂ emission for developing urban built environment with lesser greenhouse gases (GHG). Result shows that, the ratio of Steam to Waste: 0.08 %, the air mass flow rate: 1.11*10⁻⁴ kg/s and the steam mass flow rate: 0.11*10⁻⁴ kg/s gain the highest molar fraction of H₂ : 32.09%. Syngas Yield: 1.28 Nm³/kg, Carbon Conversion Efficiency: 5.83%, Cold Gasification Efficiency: 77.96% and the CO₂ emission: 2.23*10⁻⁴ kg/s.

Keyword: Plasma Gasification; Urban Build Environment; H₂ molar fraction; Gasifying Agent; CO₂ emission.

1. Introduction

The disposal of waste, especially in the urban built environment, such as municipal solid waste, in the open landfill site, expose a problem of contamination from hazardous materials and emission of greenhouse gases (GHG). Substituting the consumption of fossil fuels with renewable fuel, is one of the solution for overcoming the greenhouse gases [1]. The problem of hazardous material landfills or increasingly coverage area of municipal solid waste landfills can be resolved with waste management system, as the newly method is plasma gasification.

Plasma gasification is a method of waste disposal by introducing the high temperature plasma to decompose the waste into its decomposed chemical compound. In the decompose process, the thermal plasma is applied, generated by passing high electric current through gasifying agent. At high temperature, electrons dissociate from the gasifying agent molecules and an ionized gas / plasma stream is obtained [2]. The plasma stream breaks all the chemical bonds of the feedstock material, resulting the amount of highly active radicals, electrons, ions and excited molecules in the plasma gasification reactor.

The plasma gasification method has multiple benefits, such as a fast reaction time, due to high temperature and high energy density. Within compact reactors, a high material flow rate can be applied due to the fast reaction time. Desired result is as high as the molar fraction of H₂, in the composition of the syngas. No combustion takes place inside its reactors, resulting in lower CO₂ emission, compared
to the waste incineration. The heat sources of plasma gasification can be controlled to regulate the temperature inside the reactor, independent from the fluctuation of its feedstock flow rate, quality and mass flow of its gasifying agent. The disadvantage is that the required energy to generate the high temperature plasma is considered extensive, which might can be compensate by the energy potential generated from the plant, which is H2, by using Internal Combustion Engine (ICE) or Fuel Cells system.

Like gasoline or natural gas, H2 is a fuel that must be handled properly. H2 is colorless, odorless, tasteless, non-toxic and corrosive. Hydrogen has a high energy content by weight, but not by volume, which is a particular challenge for storage. In order to store sufficient quantities of hydrogen gas, it’s compressed and stored at high pressure. Liquid hydrogen has different characteristics and different potential hazards than gaseous hydrogen, so different control measures are used to ensure safety. An understanding of the properties of hydrogen, either gaseous or liquid, is critical for the proper design of a plasma gasification facility [3].

One of the success stories for the firstly installed integrated plasma gasification and fuel cell system, is in Cheongsong, South Korea. It has the capacity of 15 ton/day of municipal solid waste and can produce 50 kW of electricity from Fuel Cell (5kW Fuel Cell unit x 10 unit). Waste to energy technology with zero waste can’t be achieved if the public sector without government support for adequate policies and give opportunities to the public sector to contribute in the implementation of the policies [4].

This study follows the work of Minutillo et al [5], where the developed EPJ (equiplasmajet) was the modelling of thermal equilibrium of plasma gasification and using the municipal solid waste characteristics from the works of Khuriatie et al [6]. The carbon conversion efficiency, the CO2 emission aside the quality of syngas and reactor efficiencies also hasn’t been explained in previous research papers. The purpose of this study is to obtain the essential parameter to have the better content of H2 in the syngas, better plant efficiency and lowest CO2 emission by using mix steam and air as a gasifying agent and its variation to the feedstock mass flow to be considered, which refer to the Favas et al [7].

2. Material and methodology

2.1 Material

Municipal solid waste from Jatibarang Landfill is used as a plasma gasification feedstock. Its characteristics are defined as Proximate Analysis, Ultimate Analysis and Calorivic Value, can seen in Table 1.

| Table 1. Waste Characteristic of MSW [6] |
|-----------------------------------------|
| **Ultimate Analysis (wt. % db)**        |
| Ash                                     | 9.51 |
| C                                       | 43.71|
| H                                       | 7.74 |
| N                                       | 1.95 |
| Cl                                      | 0    |
| S                                       | 0.40 |
| O                                       | 36.69|
| **Proximate Analysis (wt. %)**          |
| Fixed Carbon                            | 12.82|
| Volatile Matter                         | 77.66|
| Ash                                     | 9.51 |
| Water Content                           | 20   |
| **Calorivic Value (kJ/kg)**              |
| HHV                                     | 18530.4|
| LHV                                     | 16013.6|
2.2 Method

The method of simulation for this study, rely on the sequence workflow of the developed model, with the feedstock properties as in the Tabel 2 to be inputted in the as the ingredients. The boundary conditions of plasma gasification process modeling are process parameters along with the decomposing formula and chemical reaction in the thermochemical equilibrium stoichiometry. Molar fraction of desired syngas compound with its process temperature, density and mass flow rate is the output parameters from the simulation. Validating the modified model output parameters from the reference model [5], with the similar feedstock properties and process parameters resulting in the little variance. The observed process parameters will work as the prepared scenario, in order to compare among those results. The syngas molar fraction as well as the other process parameter in the simulation results will be used to calculate the performance parameters such as Syngas Yield, Syngas LHV, Carbon Conversion Efficiency and Cold Gasification Efficiency. Analyst will be done to those performance parameters obtained to observe the best scenario of H2 generation along with the lowest CO2 emission.

2.3 Modelling

Within this study, the plasma gasification has been investigated and analyzed through numerical model which properly developed by applying the thermochemical equilibrium approach as mentioned in the references. Fig. 1 shows the flowsheet of plasma gasification model, called modified EquiPlasmaJet (EPJ), firstly developed by Minutillo, namely EquiPlasmaJet, with the little modification by the introduction of RStoic for the chemical stoichiometric approach to determine the molar fraction of each syngas compound compositions [5].

![Fig. 1. Gasification Process model (modified EPJ model).](image)

Table 2, shows the short description of the block used in the model. Since only the organic fraction of the MSW is gasified, the modified EPJ model will abandon the inorganic fraction, which will be vitrified, and not in the focus of this study.
Table. 2. Process Block Description of Modified EquiPlasmaJet

| Block Name | Block Type | Description |
|------------|------------|-------------|
| DRYER      | RYield     | Non-Stoichiometric reactor based on known Yield Element Distribution from Calculator Feature |
| HTR        | RGibbs     | Rigorous Hydrate Reactor and multiphase equilibrium based on Gibbs Free Energy Minimization without known chemical reaction |
| LTR        | RStoic     | Stoichiometric reactor with known chemical reaction from its reactant and product |
| HEX1 & HEX2| Heater     | Simple Thermal heat exchanger with only 1 material stream |
| SEP        | Separator  | Water separation from Feedstock due to the high temperature |
| DC-ARC     | Heater     | Simple Electric Thermal Conversion within DC environment |
| MIX        | Mixer      | Material Stream Mixer from two or more streams. |

A DRYER block is located before the HTR block as a means of decompose the feedstock into an organic fraction. Inside dryer block, material yield distribution is specified by the help of the FORTRAN calculator according to the proximate analysis and ultimate analysis. The result of calculator is used to estimate the decomposition of material into molecular elements. The excess heat from the gasification process is associated with the HTR block is balanced as a “heat stream” (HEAT1) that connect the DRYER with the HTR block.

As the temperature inside the reactor will vary between certain zones, the temperature divided into two reaction zones for the convention of the modelling. There are two reactors, which will represent the two different temperature zones. The first reactor is the HTR (high temperature reactor), in which thermochemical equilibrium is gain by a non-stoichiometric method in high temperature environment and LTR (low temperature reactor), in which the thermochemical equilibrium is gain by a stoichiometric method in low temperature environment. Inside the HTR, the equilibrium composition is gain by direct minimization of the Gibbs free energy for a given set of expected products without the specific known chemical reaction. The HTR reactor operating temperature on the average of 2500 degC, is the main zone of the plasma gasification reactor, where the plasma jet directly impacted the treated MSW. Inside the LTR reactor, the operating temperature on the average of 1250 degC, where the plasma gasification process is completed with the known chemical reaction, and the organic decomposed element is converted into syngas.

Plasma torch device, modeled by a DC-ARC block which supplied the heat required to generate the hot plasma gas. The plasma stream and estimated power consumption of the plasma torch is calculated by the thermal power transferred into the mixed of steam and oxygen as gasifying agent in the DC-ARC heat exchanger with the assumption of its efficiency, which is ratio between the heat energy transferred and the consumption of energy.

Since the feedstock, which is municipal solid waste is gravitationally flow downward of the gasification reactor, it is preheated by the hot syngas that flow upward of the reactor. The moisture content from the solid waste evaporates due to the hot syngas and leaves the reactor along with the flow of syngas. The block model HEX2 for solid waste (ORG1) and HEX1 for syngas (HOTGAS). And the separation block model (SEP) and the mixer block model (MIX) have been selected in the reactor model.

2.4 Model validation

The result of the EPJ model which developed by Minutillo et al 2009 is used as the validation reference for the modified EPJ model which used by this study. The validation will use the same feedstock characteristics, the same type of gasifying agent and the other process parameters. Below is the feedstock characteristics from Minutillo et al, which used the RDF (refuse derived fuel)
Table 3. RDF characteristics [5]

| Proximate (% mol) | Moisture | FC       | VM     | Ash     |
|-------------------|----------|----------|--------|---------|
|                   | 20       | 10.23    | 75.96  | 13.81   |

| Ultimate (% mol) | Ash     | C        | H      | N       | Cl      | S       | O      | MSW HHV (MJ/kg) |
|------------------|---------|----------|--------|---------|---------|---------|--------|----------------|
|                   | 13.81   | 48.23    | 6.37   | 1.22    | 1.13    | 0.76    | 28.48  | 17.8           |

A result comparison between the molar fractions of syngas composition by modified EPJ model (see Fig. 1) and those obtained by Minutillo et al are summarized in Table 4, showing tolerable results. The results in Table 4 are using the air as plasma gas and RDF as the feedstock material.

Table 4. Validation Result

| Syngas Composition (%mol) | Simulation from modified model | Minutillo, Perna and Bona, 2009 | error (%) | RMSE |
|---------------------------|--------------------------------|---------------------------------|-----------|------|
| N2                        | 27.43                          | 26.97                           | 1.69      |      |
| CO                        | 32.28                          | 33.79                           | 4.48      | 0.85 |
| CO2                       | 0.00                           | 0.00                            | 0.00      |      |
| H2                        | 20.01                          | 21.04                           | 4.89      |      |
| CH4                       | 5.73                           | 5.97                            | 3.96      |      |

The variation between the reference [5] and the simulation result from the modified model, especially on the molar fraction of CO, H₂ and CH₄ are less than 10%, considered tolerable.

2.5 Gasification Reaction

The chemical reactions which occur in the gasification reactor can be summarized as follows [8]:

\[
C + H₂O \leftrightarrow CO + H₂ (\text{Heterogenous Water Gas})
\]

\[
C + 2H₂ \rightarrow CH₄ (\text{Methanation of Carbon})
\]

\[
CO + H₂O \leftrightarrow CO₂ + H₂ (\text{Water Gas Shift})
\]

\[
C + O₂ \rightarrow CO₂ (\text{Carbon Combustion})
\]

\[
H₂ + 0.5O₂ \rightarrow H₂O (\text{Hydrogen Partial Combustion})
\]

Those chemical reactions are fits in with the chemical composition of the feedstock (see Table 4) and the product results from the simulation software (see Table. 5)

2.6 Boundary condition assumptions and variable

Boundary condition assumption are as follow:
- Steady state process
- The gasification process is considered isobaric and adiabatic.
- The HCoalgen and DCoalligt property models were used to estimate biomass formation enthalpy, specific heat capacity in constant pressure and chemical density based on the proximate and ultimate analysis.
- The chemical element & compound used are: H₂, O₂, N₂, CO, CO₂, CH₄, H₂O, C, Cl, S, H₂S, S and COS.
• Ash is considered as a non-reactive and non-conventional solid.
• Modeling approach use is thermochemical equilibrium non-stoichiometric Boundary condition variable are as follows:
  • Steam Gasifying Agent Temperature: 120 °C [9]
  • Torch Plasma Temperature: 4000 °C [5]
  • Ambient Temperature: 25 °C
  • Plasma Generation Efficiency: 90 % [5]
  • Steam Generation Power Consumption: 4.27 MW per 1 kg/s
• Gasification Pressure: 1 atm

3. Results and Discussion

3.1 Simulation result

The modified EPJ model has been employed to predict the syngas composition, syngas yield, syngas LHV, Carbon Conversion Efficiency, Cold Gasification Efficiency and the CO₂ emission. To define the optimal performance parameter of the Plasma Gasification Process, five difference scenarios can be seen on Table 5.

| Steam & Air case | Steam to waste ratio [10] | Feedstock massflow [10] (kg/s) | Steam massflow (kg/s) | Air mass flow (kg/s) | Air actual | ER [10] | Air Stoic |
|------------------|---------------------------|-------------------------------|----------------------|---------------------|------------|---------|-----------|
| 1                | 0.080                     | 1.39.E-03                     | 1.11.E-04            | 1.11.E-03           | 0.801      | 0.180   | 4.450     |
| 2                | 0.225                     | 1.39.E-03                     | 3.13.E-04            | 1.53.E-03           | 1.101      | 0.248   | 4.450     |
| 3                | 0.370                     | 1.39.E-03                     | 5.14.E-04            | 1.95.E-03           | 1.402      | 0.315   | 4.450     |
| 4                | 0.515                     | 1.39.E-03                     | 7.15.E-04            | 2.36.E-03           | 1.702      | 0.383   | 4.450     |
| 5                | 0.660                     | 1.39.E-03                     | 9.17.E-04            | 2.78.E-03           | 2.003      | 0.450   | 4.450     |

The performance parameter formula as our concern in this study, will be as follows:

\[
LHV_{\text{Syngas}} = HHV - 10.79Z_{\text{CO}} + 12.62Z_{\text{H}_{2}} + 35.81Z_{\text{CH}_{4}} (1)
\]

Where Z is the % volume of mentioned syngas components and LHV in (MJ/Nm³)

\[
Yield = \frac{L}{K}\quad (2)
\]

Syngas Yield, with \( \frac{L}{K} \) as the volumetric flow rate (Nm³/s) and \( m \) as the mass flow rate (kg/s)

\[
\text{CGE} = \frac{O_{\text{Syngas}}}{O_{\text{W/VXZ1/T}} \times T} \times 100\% \quad (3)
\]

CGE as the Cold Gasification Efficiency, \( LHV_{\text{Syngas}} \) in (MJ/Nm³), \( F_{\text{Syngas}} \) as the volumetric flow rate of syngas (Nm³/s), \( LHV_{\text{MSW}} \) as the low heating value of the feedstock in (MJ/kg), \( m_{\text{MSW}} \) as the feedstock mass flow rate (kg/s) and \( P_{\text{plasma}} \) as the power consume to supply the plasma torch.

\[
X_b = \frac{\% \text{co}_x \% \text{CO}_y \% \text{H}_2 \% \text{CH}_4 \% \text{H}_{2} \text{O}}{\% \text{N}_2 \% \text{O}_2} \times 100\% \quad (4)
\]
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\(X_c\) as the Carbon Conversion Efficiency, \(Y\) is the Syngas Yield (Nm\(^3\)/kg), and C, CO, CO\(_2\), CH\(_4\), COS is the mol fraction of those chemical compound existed in the syngas composition.

The following figure show the trends as per the configuration 1 to configuration 5

![Fig. 2. Trends on Syngas LHV and Cold Gasification Eff.](image)

![Fig. 3. Trends on Syngas Yield and Carbon Conversion Eff.](image)
3.2 Simulation result analysis

The decrease of CO and molar fraction of H₂ are influenced by the temperature values, since a greater temperature values is required by the endothermic chemical reaction, causing lower rate of the Water Gas Shift reaction and automatically reduce these chemical elements, since water gas shift is an endothermic reaction. The reason to use mix steam-air as the gasifying agent is to enrich the molar fraction of H₂ in the syngas [7] and has the advantage by introducing more hydrogen atom into the system, thereby increasing the quality of the syngas, instead of using normal air. Disadvantage of using mix steam-air is the greater cost of power consumed. As expected, the use of mix steam-air, resulting in higher partial pressure of water vapor inside the reactor, which required by the water gas shift reaction, leading to the increase molar fraction of H₂.

Combining the three of process parameter mentioned previously, steam to waste ratio (SWR), MSW mass flow, and equivalent ratio, resulting the variation of the molar fraction of H₂ in syngas, also the other process parameter such as syngas volumetric flow, syngas density, the syngas temperature and CO₂ emission. Among the five configurations as per Table 5, the 1st configuration give the highest H₂ molar fraction, which is 32.09%, also give the lowest CO₂ emission, which is 2.23 *10⁻⁴ kg/s, highest CGE, which is 77.96%, highest Xc, which is 5.83%, highest syngas LHV, which is 1.387 MJ/Nm³ and highest syngas yield, which is 1.281 Nm³/kg. The 1st configuration, shows the smallest steam flow rate and the smallest SWR and the 5th configuration, shows the highest steam flow and the highest SWR. The injection of mix steam-air as gasifying agent has to be in proportional with the MSW mass flow rate.

The lower the SWR, the better result of molar fraction of H₂ thus there is an option to save energy from generating steam, save the water as a raw material to generate steam and reduce the CO₂ emission (see Fig. 4). The more mix steam-air introduce to the reactor, the carbon conversion efficiency becoming worse and syngas yield also decreasing (see Fig. 3). Therefore, higher
concentration of water is found in the syngas and automatically decreasing the gasification efficiency. The less fraction of carbon and the more oxygen fraction in the ultimate analysis of feedstock, implied a low LHV of the feedstock, resulting in the more plasma power consume to reach the required gasifier temperature. Plasma power requirement also determined by the type of gasifying agent used. The syngas LHV and Cold Gas efficiency should decrease with the increasing SWR (see Fig. 2).

4. Conclusions

The highest reactor efficiency, the highest quality of syngas and the lowest CO₂ emission when the SWR is on 0.080 and the MSW mass flow rate is on $1.39 \times 10^{-3}$ kg/s and equivalent ratio is on 0.180. The results indicate that low SWR is more favorable for the production of H₂ than the high SWR, because the syngas has lesser moisture, which also increase the gasification efficiency. When the SWR is only 0.080, the molar fraction of H₂ is 32.09%, the reactor efficiency (CGE) is 77.96%, $X_c$ is 5.83%, the syngas LHV is 1.387 MJ/Nm³, syngas Yield is 1.281 Nm³/kg and CO₂ emission is only $2.23 \times 10^{-4}$ kg/s. These data are crucial to describe scenarios concerning the method to be applied to increase the production of H₂ while minimizing the impact of CO₂ emission to the environment.

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