

PROCESS MODELLING AND PERFORMANCE ANALYSIS OF A PGM GASIFIER

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Abstract Plasma Gasification Melting (PGM), a moving bed updraft plasma drive gasification technology, is a novel gasification technology which was developed by Environmental Energy Resources Israel Ltd. (EER-Israel). The PGM offers a promising treatment of low-heating-value fuels like municipal solid waste (MSW), medical waste (MW) and other types of waste. In a PGM gasifier, low enthalpy plasma torches are used to melt the inorganic of the waste, and also supply energy for the gasification reactions. Based on the test result of the demonstrate gasifier, a computer simulation model was developed using ASPEN Plus to predict the performance of a PGM gasifier. In this model, the gasifier was schematized into five different sections: MSW drying, MSW pyrolysis, char gasification, char combustion and slag melting. In pyrolysis section, pyrolysis yield was calculated according to the component and ultimate analysis of MSW feedstock, by using an empirical model. In the gasification section, Gibbs free energy method was used to calculate the products by assuming gas phase chemical and energy equilibrium. Non-equilibrium of solid and gas phases was also taken into account by specifying temperature approach of solid-gas reactions. Mass and energy balances were considered in all sections, and the heat exchange of different phases in each section was calculated by setting appropriate temperature differences between these phases. The simulation results were conformed by comparing with testing results. The Influence of performance parameters such as ER ratio expressed as air/waste mass ratio and steam/waste mass ratio. Steam/air ratio and plasma power were also evaluated. Finally, some optimizing suggestions of designing PGM gasifier were given.

Key words PGM MSW gasification pyrolysis modelling

INTRODUCTION

Gasification is one of the most promising technologies for thermal conversion of solid fuels which has been widely used in industrial application. A recent development of gasification technology is High Temperature Agent Gasification (HiTAG) which preheats gasification agent (air/steam) to a high

temperature (above 1000 C°). It has been proved that significant advantages can be achieved when HiTAG is applied to the gasification of low-heating-value fuels like MSW, MW and biomass [1-7]. Experiment study has been performed to investigate the influence of high temperature air and steam on the gasification of solid waste by Yoshikawa etc. The result shows that higher temperature of gasification agent leads to less tar production, higher energy concentration in syngas and higher energy efficiency [1]. Experimental work by Lucas etc. studies the influence of gasification agent parameters in HiTAG, like air/steam ratio and temperature, on the performance of the gasification process. It is found out that higher molar fraction of steam in the feed gas will leads to higher H_2 content and higher LHV of the product gas [2]. Further work by Anna etc. shows that the high temperature agent can ensure the system becomes relatively insensitive to the variations in particle size, heating value and moisture content typically associated with feedstock [3-4]. Numerical studies were also done by Anna etc. to further understand the features of HiTAG [5].

Plasma Melting Technology has been widely studied in incineration residue treatment, and has been proved to be a successful residual treatment technology [8-10]. When we combine the HiTAG and Plasma Melting, the advantages of both technologies can be expected, and that is the Plasma Gasification Melting (PGM) technology. The PGM technology provides not only an environment friendly method of treatment of MSW and other solid wastes, but also an effective way of energy generation. Some studies have been done on the gasification using plasma [11-15]. However, rare work has been found on detailed performance study, or the process optimization of PGM gasification, while experimental data of PGM gasification is also very limited. One possible solution for this problem is to develop an accurate model to simulate the gasification process, so as to study the characteristics of PGM gasification. Furthermore, process modelling result can give advices on the optimization of the gasification parameters, so as to find out the best operation condition.

Aspen Plus is well-known process simulation software which has been used to simulate many different solid-fuel thermal chemical processes like fluidized bed combustion [16], fixed bed gasification [17-18], fluidized bed gasification [19], co-generation plants [20] and waste incineration processes [21]. In this work, based on the result of a series of test of a demonstrate plant in Israel, a model of the PGM gasification process was set up. The influence of individual process parameters like steam/MSW mass flow ratio, air/MSW mass flow ratio and plasma power were investigated, the actual operation ranges of these parameters were determined by the requests and limitations of a real industrial

gasification process, like 100% carbon conversion ratio, air flow rate limitation due to plasma formation and temperature limitation due to gasifier material properties. The layout of characteristics parameters like syngas LHW, gasification efficiency, and tar production were discussed. Finally, some suggestions on the optimizing design of a PGM gasifier were given.

PGM GASIFIER

The Environmental Energy Resources Israel Ltd. (EER) have built up a demonstrate PGM gasifier in Ramat-Gan with a capacity of 12 to 20 t/day. Figure 1 demonstrates the typical Schematics of a PGM gasifier.

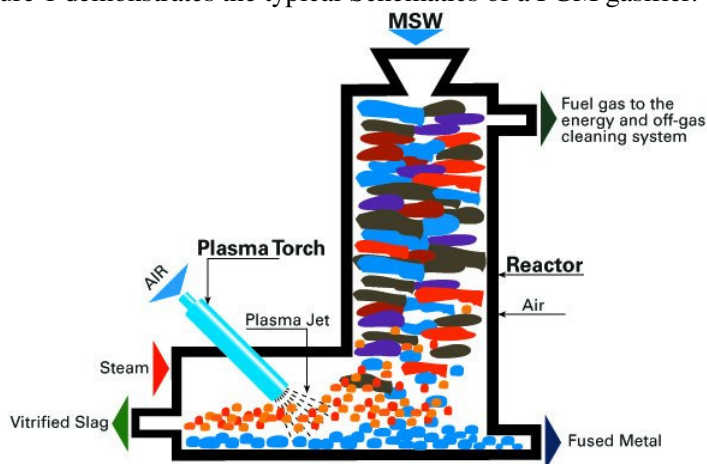


Figure 1. Typical Schematics of a PGM gasifier

The gasifier is a moving-bed updraft gasifier. MSW or other waste is fed into the gasifier by means of airtight feeding chambers at the upper part of the system. High temperature steam and air are used as gasification agents. Steam of 1000 °C is fed into the system by steam nozzles placed at the lower part of the gasifier. Air nozzles are located at the bottom of the gasifier. Plasma Torches are placed at the end of air nozzles where an electric arc forms between electrodes. Air flowing through the arc is ionized so forming a Plasma jet which extends beyond the tip of the torch. The temperature of the plasma jet may reach up to

5000°C. The plasma jet melts the inorganics of the feedstock, which reached the bottom of the reactor. The actual melting/vitrifying of the inorganics occurs at 1500 to 2000°C.

The feedstock used by the PGM gasifier is MSW collected in Ramat-Gan. Details about the feedstock properties are given in Table 1. The feeding rate of MSW is 500 kg/h.

Table 1. Feedstock properties

Proximate analysis		
<i>Moisture</i>		15.0 %
<i>Fixed carbon (dry basis)</i>		10.7 %
<i>Volatile (dry basis)</i>		77.6 %
<i>Ash (dry basis)</i>		11.7 %
Ultimate analysis		
<i>Carbon</i>	<i>C</i>	47.9%
<i>Hydrogen</i>	<i>H</i>	6.0%
<i>Nitrogen</i>	<i>N</i>	1.2%
<i>Chlorine</i>	<i>Cl</i>	<0.1%
<i>Sulphur</i>	<i>S</i>	0.3%
<i>Oxygen</i>	<i>O</i>	32.9%

NUMERICAL MODEL

In this work, a steady state model of the PGM gasification process was developed using Aspen Plus. From the top to the end, the gasifier was schematized into several different zones: drying, pyrolysis, char gasification/combustion, and plasma melting. During the whole process, the moisture, volatiles char and ash are removed from the solid phase by drying, pyrolysis, gasification/combustion, and plasma melting, respectively. Mass and energy balance were considered individually in each zone. The simplified scheme of the PGM gasifier model is shown in figure 2.

The following assumptions are used to validate the model:

1. The system is zero-dimensional. The material properties like temperature (of gas phase and solid phase), gas composition and solid composition in each zone is expressed by “mean” values, which are calculated from the mass and energy balance.

2. The flow of solid is from top to the end, while the gas flow is from the bottom to the top. No reflux for each phase is allowed.
3. The fuel is composed of C, H and O. The gas-phase species included in this model are CO , CO_2 , H_2O , CH_4 , H_2 , O_2 , N_2 and tar.
4. the heat lose of each section can be calculated from the temperature layout of gasifier outer surface and the gasifier structure.

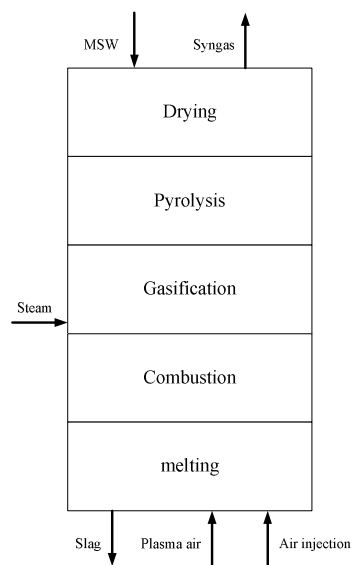


Figure 2. Scheme of the PGM gasifier model

Drying

In the drying section, wet MSW is heated by exchanging the sensible heat of the syngas and separated into steam and dry MSW. Dry MSW is sent to the pyrolysis zone, while steam mixes with the syngas from pyrolysis section.

Temperature change of MSW and gases is calculated from mass and energy conservation equations. The mass balance is described as

$$m_{MSW-wet} = m_{MSW-dry} + m_{steam} \quad (1)$$

The ratio of $m_{MSW-dry}$ to m_{steam} is given by the proximate analysis of MSW. Energy balance of heat exchanger is described as

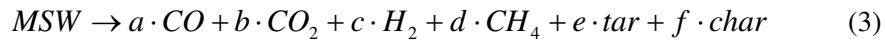
$$\sum_i m_i \int_{T_{syngas-out}}^{T_{syngas-in}} C_{p,i} dT = m_{MSW-dry} \int_{T_{MSW-in}}^{T_{MSW-out}} C_{p,MSW-dry} dT + m_{steam} \left(\int_{T_{MSW-in}}^{T_{syngas-out}} C_{p,steam} dT + L_{steam} \right) \quad (2)$$

where $C_{p,i}$ represents the specific heat capacity of the component i , while L_{steam} is the latent heat of the component i . T_{MSW-in} , $T_{syngas-in}$, $T_{MSW-out}$ and $T_{syngas-out}$ represent the temperature of MSW and syngas flowing in and out of the drying zone, respectively. In this equation, left hand and right hand describe the change of the sensible heat of product gas and MSW.

According to the definition of drying, $T_{MSW-out}$ should not be too higher than 100 °C, because the boiling temperature of water is 100 °C at the pressure of 1 bar. Considering the impact of heat gradient inside MSW particles, we assume that the temperature of dried MSW and steam is 105 °C.

Pyrolysis

Compared with coal, MSW have higher content of volatiles. For an updraft gasifier model, the pyrolysis process is especially important because most of the gas and tar yield in this section will join the gas produced in the char gasification section and be released from the outlet of the gasifier without further reactions. In our model, a one-step global model [22] is used to represent the chemical reactions during the pyrolysis process. In order to simplify the model, in this work, all the light hydrocarbons were considered as CH_4 , so the reaction can be written as:



It has been proved that for an updraft gasifier, the tar production is sensitive to the pyrolysis temperature. In this model, the expression of tar yield as a function of pyrolysis temperature introduced by Fagbemi et al. [23] was used:

$$Y_T = Y_{T_0} \exp(-A(T - T_0)) \quad (4)$$

where T is the highest pyrolysis temperature and $T_0 = 500^\circ\text{C}$ represents the temperature at which the maximum yield of tar will be produced. The maximum tar yield Y_{T_0} , as well as the constant A varies for different feedstocks, and can be calculated from the experiment result. The composition and properties of tar is obtained from literature data [24]. The mass percentage of carbon in tar remains approximately at 54.5%, the percentage of hydrogen at 6.5% and the percentage of oxygen was 39%.

It has been proved that cracking of tar will produce solid carbon and gas products. The yield of solid carbon from tar cracking was calculated from the experimental data from the real gasifier test.

Char was considered as a mixture of ash, solid carbon from tar cracking and fixed carbon, so the yield and composition of char can be calculated directly from the ultimate and proximate analysis of MSW.

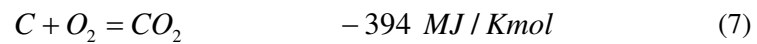
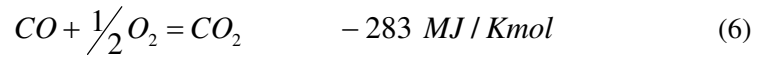
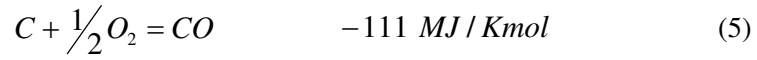
It has been proved that CH_4 will decompose at temperature higher than 700°C with the existence of char [25-28], while the highest pyrolysis temperature is much higher than 700°C . Considering the sensitivity of CH_4 yield on pyrolysis temperature, the CH_4 yield is estimated from the experiment data by Sanner et al. [29]. Then the yields of CO , CO_2 and H_2 can be calculated from the atomic balances for C, H and O.

Heating values of MSW and char are calculated with the HCOALGEN model [30], which includes a number of empirical correlations for heat of combustion, heat of formation and heat capacity, while densities of MSW and char are calculated using the DCOALIGT model.

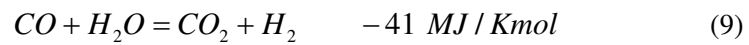
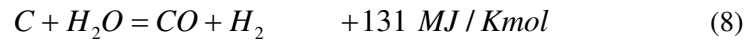
Gasification and Combustion

Char coming from the pyrolysis zone will meet and react with gasification agents (H_2O and O_2) in the gasification and combustion section. Lots of chemical reactions are involved in this process.

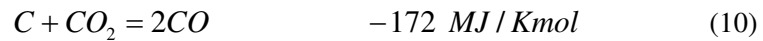
Combustion reactions:



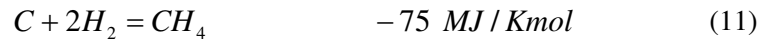
Water shift reactions:



Boudouard reaction:



Methanation reactions:



For a moving bed gasification process, the residual time for solid fuel is very long (hours), so the chemical reactions occurring in this zone can be considered as at chemical equilibrium.

The second law of thermodynamics can be expressed as

$$(dG)_{T,P,m} \leq 0 \quad (12)$$

which states that the Gibbs function always decreases for a spontaneous, isothermal, isobaric change of a fixed-mass system in the absence of all work effects except boundary work. This principle allows us to calculate the equilibrium composition of a mixture at a given temperature and pressure.

The Gibbs function for a mixture of ideal gases can be expressed as

$$G_{mix} = \sum N_i \bar{g}_{i,T} = \sum [\bar{g}_{i,T}^0 + R_u T \ln(P_i / P^0)] \quad (13)$$

where N_i is the number of moles of the i th species, $\bar{g}_{i,T}$ is the Gibbs function of the pure species, the superscript ⁰ means properties at standard pressure.

For fixed temperature and pressure, the equilibrium condition becomes

$$dG_{mix} = 0 \quad (14)$$

In our char gasification reaction, the main species to participate in the reaction are H_2O , H_2 , CO , CO_2 , CH_4 , O_2 and C . C can be treated as the naturally occurring element, and the other species can be treated as ideal gases.

According to Rudolf [33], during the char gasification process, there will be a temperature difference between the solid and gas phase. This temperature difference will influence the equilibrium of the heterogeneous reactions during the process. In our model, an equilibrium temperature difference of 200 °C was set between the homogeneous and heterogeneous reactions to restrict the chemical equilibrium.

Plasma Melting

The inorganic components (ash) of the MSW coming from the gasification and combustion zone were melted by high temperature plasma air in the plasma melting zone. The properties of the inorganic components were taken from Zhao et al. [32]. The temperature of slag flowing out of the gasifier was calculated from energy balance by setting an appropriate temperature difference between air and slag. No chemical reaction was considered in the melting process.

RESULT AND DISCUSSION

Influence of Air/MSW Mass Ratio

For a traditional gasifier, the energy needed for feedstock heating up, pyrolysis and char gasification is mainly from the partial combustion of char. So the equivalence ratio (ER) for traditional gasifier should be around 0.3 to fulfil the need of energy. For a PGM gasifier, energy can be supplied by plasma and high temperature steam, so the ER number for a PGM gasifier will be much lower (0.05-0.1). It is worthwhile to study the characteristics of a gasification process in low ER ratio condition, and the influence of air/MSW mass ratio (α) on the performance of a PGM gasifier.

Simulations of different air flow rate were carried out to study the influence of the air/MSW mass ratio on gasification properties. The MSW feeding rate, plasma power, steam flow rate and steam temperature were set to 500kg/h, 200kW, 100kg/h and 1000 °C, respectively, which are typical operation parameters of the PGM gasifier. The flow rate of air thereby varied from 120 kg/h, which is a little above the limitation of 100% C conversion, to 270 kg/h.

The influence of air/MSW mass ratio on gasification temperature is shown in Figure 3. With the increase of air/MSW mass ratio, the gasification temperature increases from 940 °C to about 1350 °C. This phenomenon could be explained by more heat released from combustion due to higher air feeding rate.

Figure 4 shows the yield of individual products for different air/MSW mass ratio. From the figure it can be found that the yield of tar and CH_4 decrease as the air/MSW mass ratio increase. A possible reason is that the higher gasification temperature leads to higher temperature of pyrolysis, which prompts the cracking of tar and the decomposition of CH_4 during pyrolysis process. Higher gasification also suppresses the methanation reactions, which will produce CH_4 in the gasification zone. The cracking of tar and decomposition of CH_4 ensure that more carbon and hydrogen can be released. Most of the carbon will turn to CO by partial oxidization or water shift reaction, so the yield of CO and H_2 increases with the air/MSW mass ratio. The yield of CO_2 , however, remains a relatively low level, and does not change too much. This might be the consequence of lower ER ratio compared to traditional gasification.

Figure 5 shows the volume fractions of gas products in syngas. As we can see, only the volume fraction of CH_4 and N_2 is obvious. While the volume fractions of CO , CO_2 and H_2 do not vary too much. Generally speaking, the volume fractions of combustible species in syngas decrease slightly. As a consequence, the LHV of syngas, as we can see in Figure 6, decreases when the air/MSW mass ratio increases.

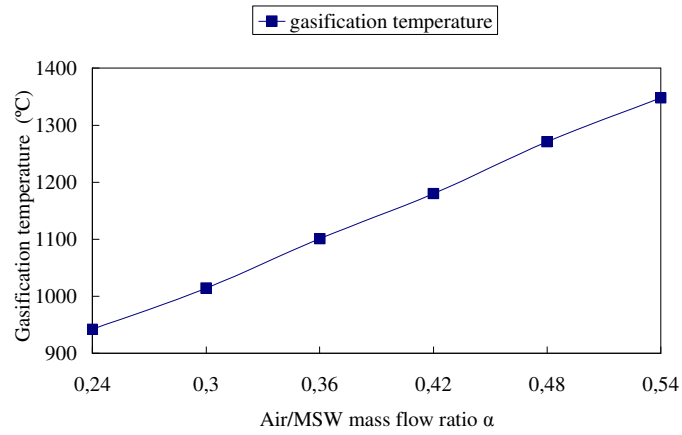


Figure 3. Influence of air/MSW mass ratio on gasification temperature

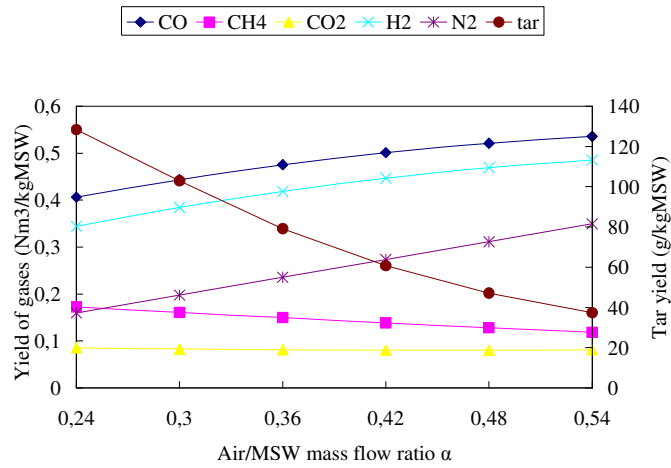


Figure 4. Influence of air/MSE mass ratio on product yields

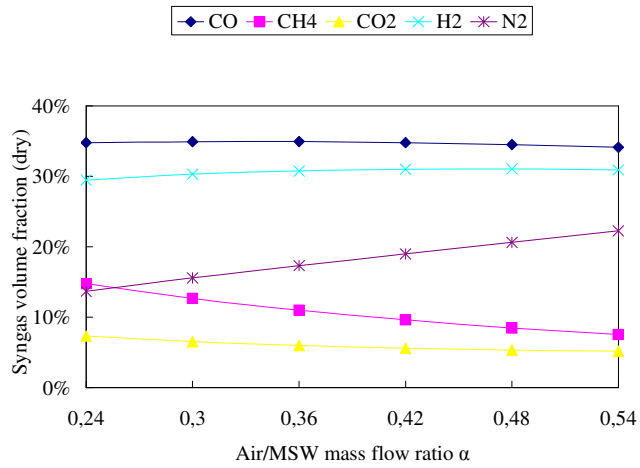


Figure 5. Influence of air/MSW mass ratio on syngas content

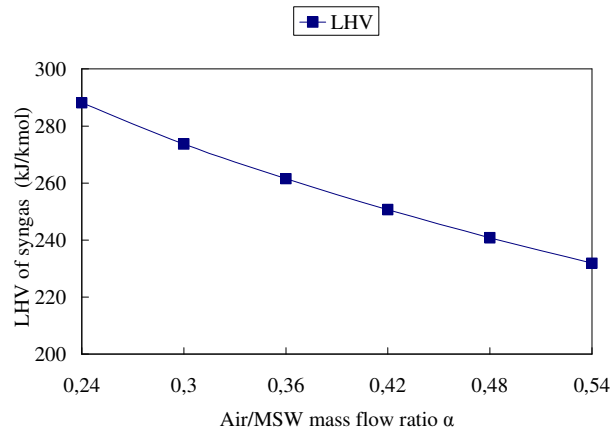


Figure 6. Influence of air/MSW ratio yield and LHV of syngas

Influence of Steam/MSW Mass Ratio

The influence of steam/MSW mass ratio (μ) on the gasification performance can be found in Figure 7, 8, 9 and 10. From Figure 7 it can be found that the gasification temperature does not change too much when μ changes from 0.15 to 0.4. this mainly due to that the steam temperature (1000 is as the same range as

Figure 8 shows the effect of μ value on the yields of products. The result shows that with the increase of steam/MSW mass ratio, the yield of H_2 and CO_2 increase, while the yield of CO reduces. As discussed before, the most important reactions for steam is water shift reactions (equation 8 and 9). In our case, the transition of C is assumed to be 100%, so the addition of steam mainly affects the equilibrium of reaction 9, and prompt the reaction to the right side. The same conclusion can also be gained from Figure 9.

Figure 10 shows the influence of steam/MSW mass ration on the LHV of syngas. When the μ value increases from 0.15, to 0.4, the LHV of syngas decreases slightly from 255 to 240 kJ/kmol. Reaction 9 affects the syngas LHV from two aspects. Firstly, reaction 9 increases the amount of gas products. Secondly, reaction 9 is an exothermic reaction, so it reduces the chemical energy stored in gas product.

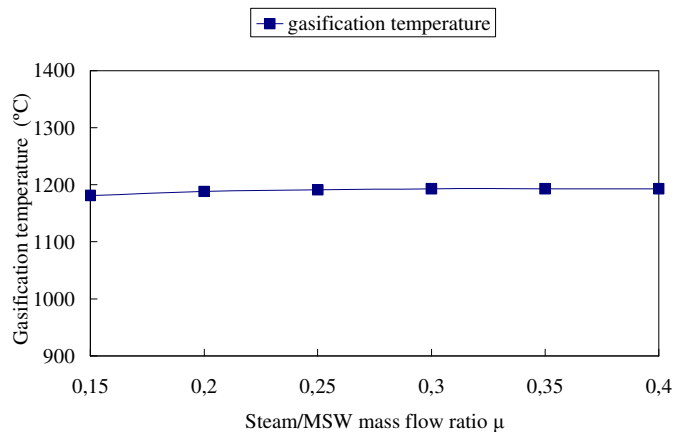


Figure 7. Influence of steam/MSW mass ratio on gasification temperature

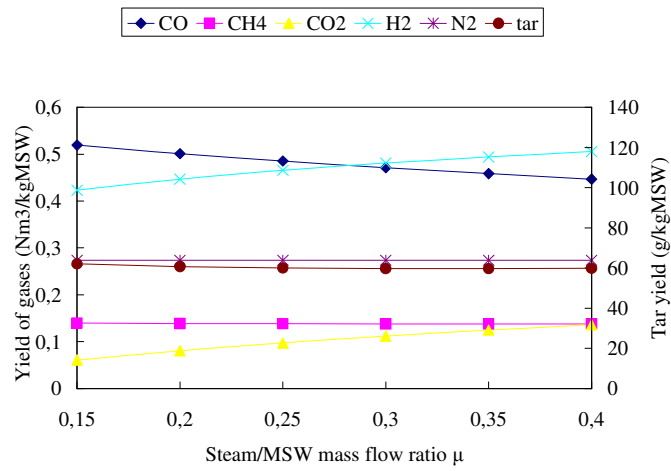


Figure 8. Influence of steam/MSE mass ratio on product yields

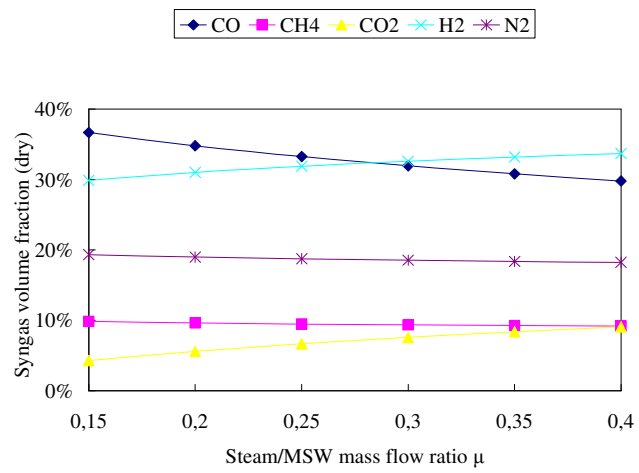


Figure 9. Influence of steam/MSW mass ratio on syngas content

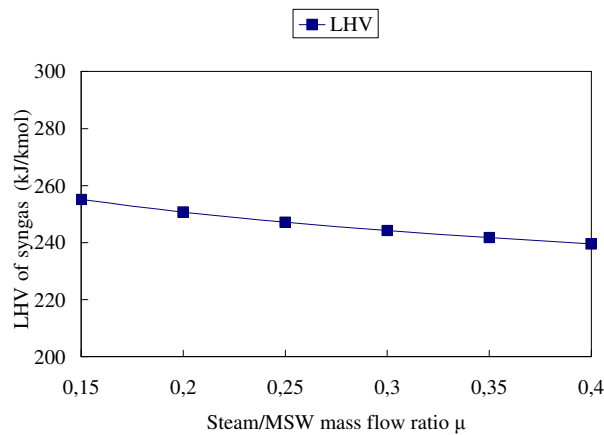


Figure 10. Influence of steam/MSW ratio yield and LHV of syngas

Influence of Plasma Power

In a PGM gasifier, plasma torches are used to produce high temperature plasma flow which melts the inorganic component of MSW after gasification reactions. At the same time, part of the plasma energy turns into the sensible heat of feeding air. In this way, the power of plasma affects the energy equilibrium of the whole gasification process. When the power of plasma injection increases, no doubt the temperature of the gasification (see Figure 11) and pyrolysis zone will enhance (see Figure 11).

Figure 12 shows the yield of products with different plasma power. Due to the increase of pyrolysis temperature, the tar cracking and CH_4 decomposition reactions are prompted, so tar and CH_4 yields reduce as the plasma power increases. The cracking of tar and decomposition of CH_4 release more C which can be gasified, while the amount of gasification agents remains the same. As a result, yield of CO and H_2 increase, while CO_2 yield decreases slightly.

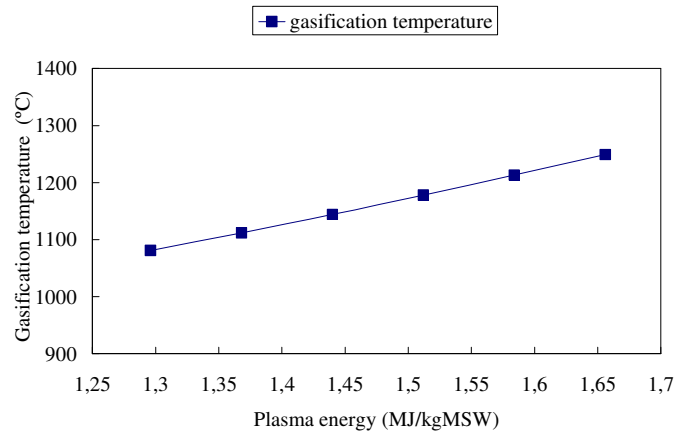


Figure 11. Influence of plasma power on gasification temperature

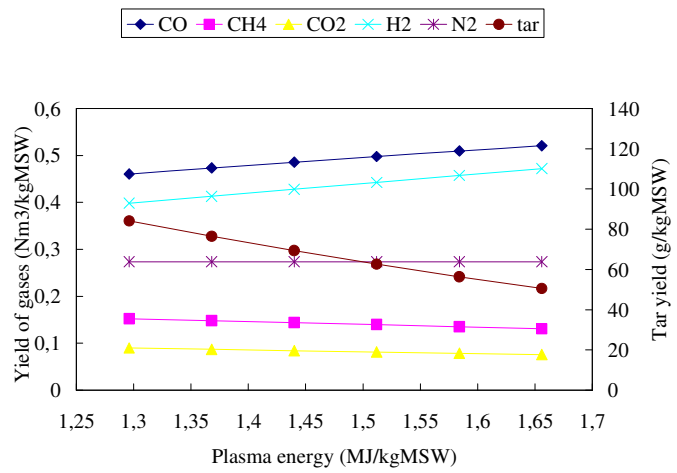
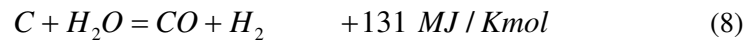
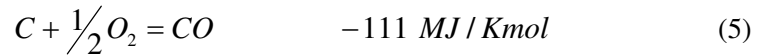


Figure 12. Influence of plasma power on product yields

Optimizing process conditions

As we discussed before, an important advantage of PGM gasification is lower ER ratio compared to conventional moving-bed gasification. Looking at equation (5) and (8), which are two typical reactions of combustion and gasification section, respectively, only one molecules of combustible gas can be produced from per atom of carbon by equation (5), while two molecules of combustible gas can be produced by equation (8). Moreover, when air is used as gasification agent to supply O_2 for reaction (5), syngas will be diluted by N_2 , so the LHV of syngas will decrease. In order to gain more and better syngas, gasification by steam is more preferable. However, reaction (8) is an endothermal reaction, which means extra energy should be supplied to ensure the reaction. For a traditional gasifier, the energy can only be supplied by partial oxidization of char, while for a PGM gasifier, the energy comes from plasma, steam preheating and partial oxidization of char. In order to optimize the process conditions in a PGM gasifier, the relationship among air feeding rate, steam feeding rate and plasma power should be considered synthetically.



The cold gas efficiency (CGE) [34] is a standard criteria that is frequently quoted for traditional gasification process. This conception is modified and applied to PGM gasification process in this work:

$$\eta = \frac{\dot{m}_{syngas} \cdot LHV_{syngas}}{\dot{m}_{feedstock} \cdot LHV_{feedstock} + P_{steam} + P_{plasma}} \times 100\% \quad (15)$$

Where \dot{m}_{syngas} and $\dot{m}_{feedstock}$ denote the mass flow rates of syngas and feedstock, while LHV_{syngas} and $LHV_{feedstock}$ mean the low heating values of syngas and feedstock on mass basis. P_{steam} denotes the power used to heat up steam to 1000 °C, and P_{plasma} is the power of plasma.

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Figure 13 and Figure 14 is the iso-gasification temperature, iso-LHV and iso-CGE lines for PGM gasification with a plasma power of 150kW and 200kW, respectively.

Several limitations were firstly defined to restrict the logical operation range. They are as follows:

- The Plasma Air limitation. In order to produce plasma jet, a certain amount of air has to be injected into the system. In this work, it was called Plasma Air. The Plasma Air restricts the minimum of air flow ratio, which means the air flow rate have to be higher than the Plasma Air.
- The carbon conversion limitation. In a successful gasification process, nearly all the carbon content in feedstock should be released from the solid phase. In this work, the carbon conversion rate is assumed to be 100%. The amount of gasification agents (air/steam) should be higher than the 100% carbon conversion limitation.
- The gasification temperature limitation. The design for a gasification process should consider not only the efficiency and product quality, but also safety issues. If the peak temperature of the process is too high, it might damage the material of the gasifier. In this work we control the peak temperature by set a highest temperature limitation of the gasification process, which is set to 1300 °C.

From Figure 12 it can be found that in the logical operation zone, the highest CGE value appears in high air and low steam situation. The possible reason might be higher temperature due to more combustion in high air condition, which prompt the cracking of tar, so that the energy in syngas increases. The superfluous steam injection, however, will reduce the efficiency because the energy consumption during the preheating process.

The highest syngas LHV, however, appears in the low air low steam condition. This matches the result from the individual parameter study.

Similar trend for syngas LHV and CGE can be found in Figure 13. when comparing Figure 12 and Figure 13, it can be found that when the plasma power increase from 150kW to 200kW, the logical operation zone becomes narrow. To get the same CGE level, less air needed, so higher syngas LHV can be obtained. Take CGE=72% for example, the highest syngas LHV changes from 10.2 MJ/Nm³ to 11.5 MJ/Nm³.

It can also be found that the changing trends of syngas LHV and cold gas efficiency are different, so, it is impossible to make a judgement which kind of condition is definitely “good” or “bad”. The choice of operation parameters should be based on the detailed terms for different projects.

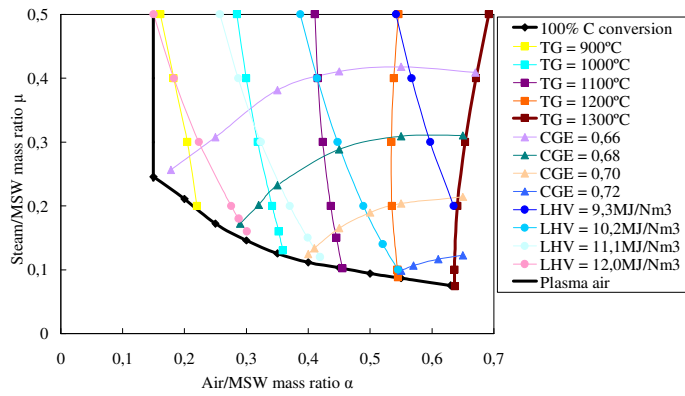


Figure 13. Iso-gasification temperature, iso-LHV and iso-CGE lines at 150kW plasma power level

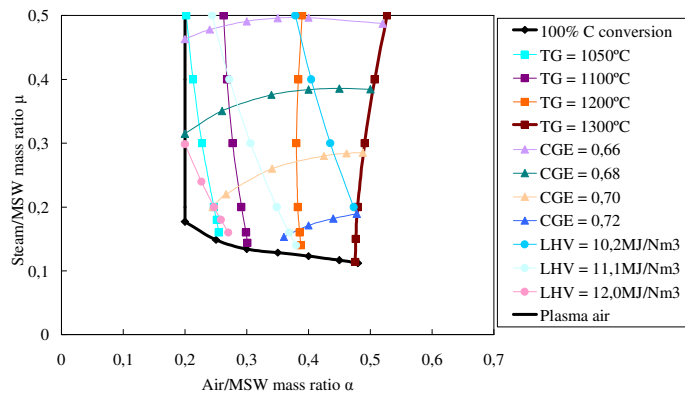


Figure 14. Iso-gasification temperature, iso-LHV and iso-CGE lines at 200kW plasma power level

CONCLUSION

A model of Plasma Gasification Melting has been built up and validated by experiment carried out by EER. The result shows that when the air/MSW mass ratio enhances, the gasification temperature will increase linearly, and the yield of CO , H_2 and N_2 will increase, while tar and CH_4 yield will reduce. The syngas LHV will reduce as well. When the steam/MSW ratio enhance, the gasification temperature does vary too much, but the H_2 and CO_2 production increase, while the CO production decreases. When the plasma power increases, the gasification temperature will increase, while the CO , H_2 yield increases obviously, but the increase of N_2 is very limited.

A logical range of operation parameters has been determined by defining several restrictions like plasma air limitation, 100% carbon conversion and high temperature restriction. A modified definition of CGE has been made to meet the situation of a PGM gasification process. The layout of syngas LHV and CGE have been calculated and analyzed. It was found out that the highest CGE value appears in high air and low steam condition, while the highest syngas LHV appears in the low air low steam condition. The optimizing direction for a gasification process can only be determined after considering the detailed aim and situation of the very project.

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