Equilibrium Modeling for Optimum Design of Operation Parameters of MSW Plasma Gasification

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Guiquan WANG[1], Yaojian LI[1], Yongxiang XU[1] and Hongzhi SHENG[1]

[1]Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

E-mail: wangguiquan@imech.ac.cn

Tel&Fax: +86-10-82544222

Add.: No.15 Bei-Si-Huan Xi-Lu, Haidian District, Beijing 100190, China

ABSTRACT

Plasma gasification technology has been demonstrated as one of the state of the art and environmentally friendly technologies for the treatment of municipal solid waste (MSW), due to its large volume reduction ratio, high generation efficiency and extremely low emission of secondary pollutants. This work aims to calculate and optimize process parameters for the demo plant of MSW plasma gasification in Beijing which has been made by the Institute of Mechanics, Chinese Academy of Sciences (IMECH, CAS). Duration time of the MSW in the reaction section is beyond 5 seconds, so equilibrium assumption is efficient to simulate gasification processes. Furthermore, a simplified chemical reaction model is develop that can be used to predict concentration distribution of syngas under different operating parameters including gasification temperature, excess air ratio, feeding rate and moisture content. When doing optimum design, two types of constraint conditions are considered, including: 1) fixing ratio of CO to H_2 equal to 0.8, 0.9 and 1.0, respectively, corresponding optimum object is plasma torch and heating value of syngas; 2) fixing plasma torch power to 900 kW, corresponding optimum object is compositions and heating value of Syngas. The calculation results show that product distribution is strongly affected by moisture content and gasification temperature (<1,200 K).

Although the equilibrium models do not represent the reactions that occur at relatively high temperatures (≈1,273 K) very well, these models can be useful to show some tendencies on the working parameter variations of a gasifier.

INTRODUCTION

The treatment of municipal solid waste (MSW) has become a very crucial issue in many countries, especially in developed regions with lack of landfill land. The main strategies for MSW treatment is to achieve harmless disposal, large volume reduction and energy recovery[1]. Incineration technology as a conventional waste-to-energy process and consists of a controlled combustion process in an oxygen-rich environment in which the heat is generated from the feedstock in a grate or fluidized bed incinerator[2]. During incineration, numerous complex oxides among which are hazardous materials (such as NO_x, SO_x, dioxins and furans) are inevitably formed[3].

Recent studies have been focused on plasma gasification technology, which offers many unique advantages[4-5], such as large volume reduction ratio, high generation efficiency and very low emission of secondary pollutants. However, a large number of process parameters have to be controlled, and in many cases the processes occur in a split second, which requires a high level of automation[6].

The kinetic models, involving parameters such as reaction rate, residence time, are very complex and not generic to implement computationally. In order to predict the operation of a gasifier, the availability of a fairly simplified method is important, and at the same time, it should be reliable and accurate. Particularly, the chemical equilibrium theory based on minimization of the Gibbs free energy is very general and relatively easy to implement in a computer routine to determine the fuel gas composition produced in a gasifier. The chemical equilibrium model meets these prerogatives because it involves only thermodynamic parameters. However, this method is only effective to simulate gasification processes carried out at high temperatures (>1,500 K). At low reaction temperatures (<1,000 K), the reaction rate is smaller, and the residence time is higher, so the kinetic theory is more suitable to deal with this reaction[7].

This paper is concerned with the design and optimization of an innovative plasma gasifier by thermodynamic equilibrium calculation. Consequently, this work aims to develop a simplified chemical reaction model that can be used to calculate and optimize process parameters.

NUMERICAL SIMULATION

Thermodynamic equilibrium model implementation

The thermal chemical conversion process that takes place inside the plasma furnace can be described better by the gasification process. Nevertheless, models based on thermodynamic equilibrium have been used widely, and they are convenient enough for process studies on the influence of the most important process parameters[8-9]. When using equilibrium modeling, the most important point in the modeling procedure is whether the plasma gasification process reaches an equilibrium state. It is stated the equilibrium state for conventional gasifiers cannot be reached because the gasification temperature is far below 1,073 K, while for plasma gasifiers it can be reached due to its high temperature above 1,273 K [7,10]. Consequently, an equilibrium model can be developed to predict terminal product distribution of gasification reaction for plasma gasifiers. Under the conditions of given temperature and pressure, thermodynamic equilibrium compositions from reactants (MSW and gasifying agents) can be calculated according to principal of Gibbs free energy minimization. Furthermore, base on previous calculation results of products, input power of plasma torches can be obtained by principal of energy conservation.

This model can be employed to optimize operation parameters of MSW plasma gasification process, including moisture content, gasification temperature and excess air ratio. In this work, the EQUIL subroutine is used to carry out the equilibrium calculation under given atmospheric pressure. When doing optimum design, the two types of constraint conditions are considered, including: 1) fixing ratio of CO to H2 equals to 0.8, 0.9 and 1.0, respectively, corresponding optimum object is plasma torch and heating value of Syngas; 2) fixing plasma torch power of 900 kW, corresponding optimum object is compositions and heating value of Syngas.

Surrogate MSW

The conceptual design for a demo plant of MSW plasma gasification in Beijing has been made by IMECH, CAS. The treatment capacity is 70t/d (2,916.67kg/h) pre-processed MSW, treatment temperature is 1,273K, this study aims to calculate and optimize process parameters for the demo system by equilibrium model.

In order to simplify the calculation procedure, surrogate MSW is used to substitute the real MSW in Haidian District, Beijing. Table 1 shows the proximate compositions of the surrogate MSW as well as element content.

Table 1 proximate compositions and element content of the surrogate MSW

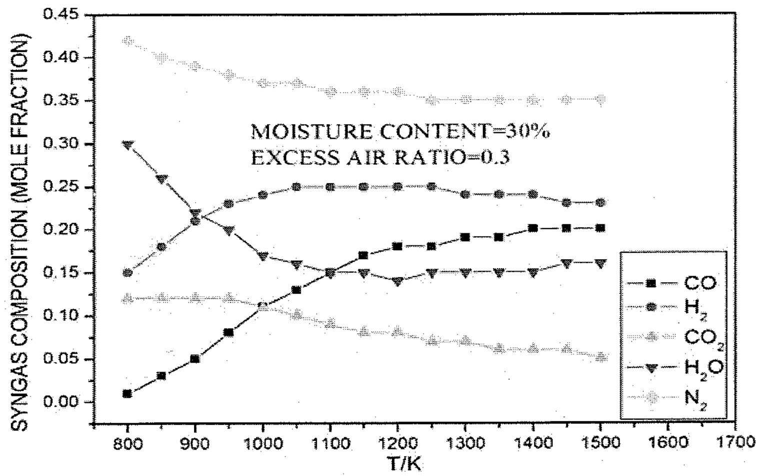
element content	Wt% (dry matter)	Proximate compositions	Wt% (raw fuel)
C	28.0	Moisture	30
H	9.7	Plastics	15
O	62.0	Textiles/Papers	45
Cl	0.3	Non-combustibles	10
		Latent Heating Value	13.26MJ/kg

RESULTS and DISCUSSIONS

Effect of gasification temperature on syngas's compositions

Figure 1 shows the point-fold line of syngas composition versus gasification temperature under the conditions of excess air ratio of 0.3 and moisture content of 0.3. The gasification temperature varies in the range of 800-1,500 K. The calculation results show that CO, CO_2, H_2, H_2O and N_2 are mostly of gasification products. With increasing temperature, the sum of H_2 and CO contents increases from 0.24 to 0.52 (dry basis), heating value of syngas increases from 2.1 to 5.33 MJ/Nm^3 (dry basis), and input power of plasma torches increases from -2.04 to 3.08 MW (Under the conditions that excess air ratio of 0.3, moisture content of 0.3 and no heat (power of the torches) added in, the gasification temperature is 970 K by calculation. So the minus indicates that the calculation temperature is lower than 970 K.). However, it should be noted that mole fractions of main compositions vary greatly with temperature below 1,200 K and slightly between 1,200 K and 1,500 K (see figure 1), and so does the heating value of syngas. However input power increases relatively high from 1,200 to 1,500 K (from 1.84 to 3.08 MW). Consequently, it is reasonable to control gasification temperature to approximately 1,200 K in consideration of heating value of syngas and input power.

Figure 1: Effect of the temprature on the syngas composition

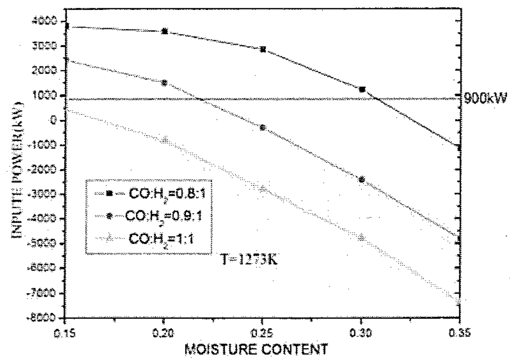


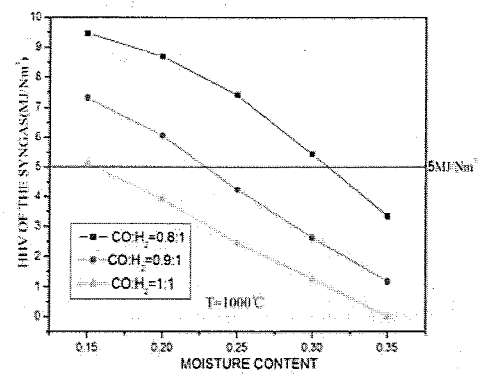
Effect of moisture content

In order to make good use of syngas, one must control percentage of its individual composition, especially CO and H_2. It is appropriate to control CO/H_2 in the range of 0.8-1 for generating electricity by internal-combustion engine. Consequently, both input power and heating value of syngas can be calculated under constraint conditions of CO/H_2=0.8, 0.9 and 1. Base on discussions in the previous section, gasification temperature is fixed at 1,273 K. The calculation results are shown in figures 2 and 3, respectively, which reveal that they greatly decrease with moisture content. The smaller the moisture contents, the higher the heating value of syngas, and the bigger the input power. Figures 2 and 3 provide important information that one must control proper moisture content of MSW before feeding into plasma gasifier.

Figure 2: Effect of the moisture content on input power at different ratio of CO to H_2, T= 1,273 K

Figure 3: Effect of the moisture content on heating value of syngas at different ratio of CO to H_2, T= 1,273 K





The treatment capacity of a gasifier largely depends on input power of plasma torches in total. The effect of the moisture content on heating value and compositions of syngas is an interesting issue under given input power, and figures 4 and 5 show corresponding calculation results with given input power of 900 kW. The gasification temperature is also set to 1,273 K. It can be seen that CO and H_2 content decreases with increasing moisture (from figure 4), and so does heating value (from figure 5), which does not facilitate to make use of syngas.

Figure 4: Effect of the moisture content on the syngas compositions at T=1,273 K, input power = 900 kW

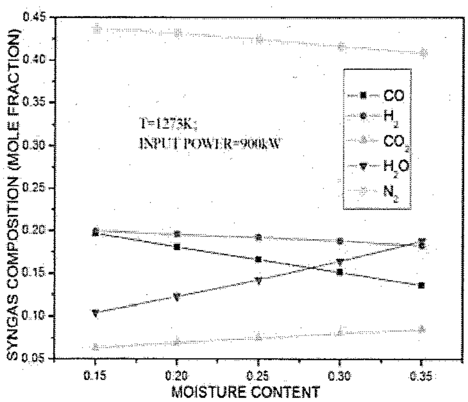
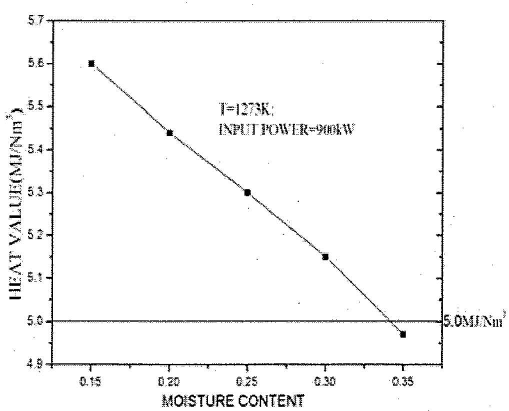


Figure 5: Effect of the moisture content on heating value of the syngas at T=1,273 K, input power= 900 kW



Effect of excess air ratio

Under the constraint conditions, excess air ratio does not depend on moisture content at T=1,273 K. Figure 6 shows the relationship of moisture content and excess air ratio under the different constraint conditions from which it can be seen that excess air ratio always increases with increasing moisture content. This phenomenon should be explained in terms of two kinds of mechanisms:

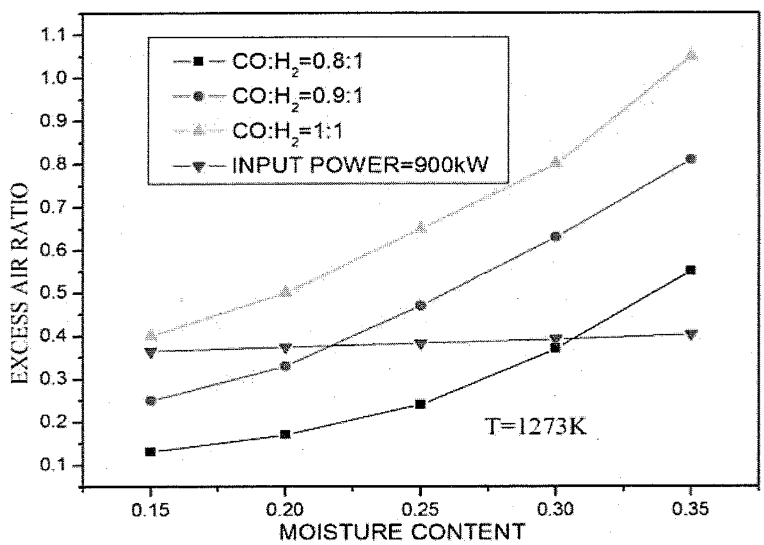
1) fixed ratio of CO to H_2

The principal of Gibbs free energy minimization determines this phenomenon. If keeping gasification temperature unchanged, the bigger the moisture content, the more air must be added to meet constraint conditions of CO/H_2=0.8, 0.9 or 1.0 according to calculation results of thermodynamic equilibrium products.

2) fixed input power

The principal of energy conservation determines this phenomenon. The bigger the moisture content, the lower the heating value of surrogate MSW. If keeping gasification temperature and input power unchanged, approximately the same amount of chemical energy should be released, so more air must be fed into gasifier.

Figure 6: relationship of moisture content and excess air ratio under the different constraint conditions



CONCLUSIONS

In this paper, the equilibrium model is developed based on principals of Gibbs free energy minimization and energy conservation, which is employed to optimize operation parameters of MSW plasma gasification process, including moisture content, gasification temperature and excess air ratio.

The calculation results show that CO, CO_2, H_2, H_2O and N_2 are mostly of gasification products. Main compositions vary greatly with temperature below 1,200 K and slightly between 1,200 K and 1,500 K and so does heating value of syngas. However input power increases relatively greatly from 1,200 to 1,500 K. It is proper to control gasification temperature approximately to 1,200 K.

Input power and heating value of syngas greatly decrease with moisture content. The smaller the moisture content, the higher the heating value of syngas, and the bigger the input power is under constraint conditions of CO/H_2=0.8, 0.9 and 1.0. The content of CO and H_2 decreases with increasing moisture content, and so does heating value with given input power of 900 kW.

Under the different constraint conditions, excess air ratio always increases with increasing moisture content. The research results can be used to make optimum design for process parameters of MSW plasma gasification. Next step, the commercial CFD (Computational Fluid Dynamics) code will be employed to study the influence of coupling flow field, temperature field and chemical reaction in the gasifier.

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