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Simulation of municipal solid waste gasification in two different types of fixed bed reactors

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ABSTRACT

Simulation of municipal solid waste (MSW) gasification with air in two different types of fixed bed reactors has been carried out by using Aspen plus. One type of the fixed bed reactors is an updraft fixed bed reactor which can be divided into four sections (drying, pyrolysis, gasification, and combustion), and the other type is different in the last two sections that the flue gas from the combustion section is not introduced into the gasification section. The effect of flue gas from the combustion section on the composition and lower heating value (LHV) of syngas, heat conversion efficiency, and carbon conversion at different gasification temperatures and air equivalence ratios are investigated. The results indicate that the introduction of flue gas from combustion section into the gasification section improves the heat conversion efficiency and the LHV of syngas. Carbon conversion increases with the increase of gasification temperature and air equivalence ratio in both reactors. The concentration of each component in syngas is different in the two types of reactors at lower air equivalence ratio, but no difference can be found at higher air equivalence ratio.

1. Introduction

The increasing amounts of MSW have brought great trouble to the economic development of the cities in China. Most of the areas, especially undeveloped areas, use landfill as the main disposal option for MSW. But the cities have developed rapidly since the last decade, and landfill is no longer economic because the lands around the cities have become more and more expensive. And MSW has been recognized as a type of fuel. As a result, the Chinese government has decided to invest more and more human and material resources in the development of MSW disposing technology.

Incineration has considered being a useful technology for MSW treatment since it can reduce the weight and volume of MSW and can also get energy recovery from MSW. However, this technology has still not been accepted by most of people in China because of the emissions, especially the PCDD/Fs, from MSW incineration [1–3]. And communities have heard of the concerns about waste incinerators in other localities, even though these are often older inefficient designs not the state-of-the-art technologies which could be used. Nevertheless, gasification has the advantage of lower emissions, compared to MSW incineration [1,4]. To provide a more energy efficient and environmental friendly solution, the study of gasification has attracted great interest. The syngas from gasification can be used directly or stored and it is expected to be a future energy carrier.

Gasification of MSW or biomass is mainly processed in two types of reactors [5]: fluidized bed reactors and fixed bed reactors. Fluidized bed is more complicated in operating and constructing which is often adopted for larger capacity MSW treatment [6]. However, fluidized bed requires more investment while fixed bed requires less investment and it is more suitable for smaller capacity MSW treatment. As a result, fixed bed is more suitable in counties and towns which have a relatively smaller MSW yield. There are mainly two types of fixed bed reactors: updraft fixed bed reactor and downdraft fixed bed reactor. From the review of gasification in fixed bed [7–9], it can be found that updraft gasifiers have the advantages of high reliability, high efficiency, low specific emissions and feedstock flexibility and the disadvantage of high tar content which can be solved when the gasifiers are used for thermal applications. Downdraft gasifiers have the advantage of relatively low tar content, however, the tar from downdraft gasifiers is more stable than that from updraft gasifiers and that may still result in problems in tar removal [8] and the internal heat exchange is not as efficient as in the updraft gasifier [10,11]. On the other hand, downdraft gasifiers have the disadvantages of narrow specifications of both feedstock size and moisture content, and limited capacity which may not be suitable for disposing the relatively high yield of MSW from counties and towns. In summary, it can be concluded that updraft fixed bed reactors are more suitable for MSW gasification in counties and towns.

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Nomenclature

n_{CO}	molar yield of CO (mol)	q	carbon conversion of MSW
n_{H_2}	molar yield of H_2 (mol)	Q	LHV of the syngas (dry) yield in the gasifier (kJ/N m^3)
n_{CH_4}	molar yield of CH_4 (mol)	m_{MSW}	weight of MSW fed into the system (kg)
V	volume of syngas (m^3)	θ	heat conversion efficiency of syngas (kJ/kg)
LHV	lower heating value (kJ/N m^3)		
m_1	weight of carbon in the syngas (kg)		

In this study, MSW gasification process with air in two different types of updraft gasifiers is proposed. Aspen plus is adopted to simulate the whole processes. The results of simulation are to demonstrate the specifications of these two gasifiers, and also to provide a way for deciding which type is more attractive under certain demands. The specifications consist of the composition and lower heating value (LHV) of syngas, heat conversion efficiency, and carbon conversion at different gasification temperature and air equivalence ratio.

2. Technical and modeling approach

Aspen plus has been widely used in the fields of chemical engineering, oil industry, coal gasification and others. Especially, it has been used in many researches on biomass or MSW gasification [12–17]. It is considered to be an excellent design tool because of its ability in simulating a variety of steady-state processes involving many units [18]. It is based on a minimization of the Gibbs free energy at equilibrium. This simulation is developed under the assumption that the residence time is long enough to allow the chemical reactions to reach an equilibrium state.

The flowcharts of those two types of gasifiers (Types (a) and (b)) are shown in Fig. 1. Both of them can be divided into four sections: drying section, pyrolysis section, gasification section and combustion section. As shown in Fig. 1 (Type (a)), MSW is fed from the top into drying section where MSW is dried by the syngas from pyrolysis section; then the dried MSW is pyrolyzed in pyrolysis section. The solid products from pyrolysis section are gasified in gasification section with flue gas from combustion section. In combustion section, the gasified solid products are combusted with the air introduced from the bottom. The combusted products in combustion section are residue and flue gas which is go up into the gasification section. As shown in Fig. 1 (Type (b)), this type of gasifier is different at the area between gasification section and combustion section. It can be found that the flue gas from combustion section is not introduced into gasification section while a secondary air is introduced.

The Aspen plus simulation flowcharts are shown in Figs. 2 and 3 respectively. The simulations of the MSW gasification process were based on balance of mass and energy, and chemical equilibrium among the overall process. The Aspen system is based on ‘‘blocks’’ corresponding to unit operations as well as chemical reactors, through which most industrial operations can be simulated. It includes several databases containing physical, chemical and thermodynamic data for a wide variety of chemical compounds, as well as a selection of thermodynamic models required for accurate simulation of any given chemical system [19]. In this study, several Aspen plus units were used. The main reactors were simulated by three blocks in Aspen plus: Rstoic, Ryield and Rgibbs. In the Aspen plus process simulator, Rstoic is a block that can be used to simulate a reactor with the unknown or unimportant reaction kinetic and known stoichiometry by specifying the extent of reaction or the fractional component of the key component. Thus in this simulation, it was used to simulate the drying process (moisture evaporated). Ryield is a block which can be used to model a reactor by specifying yield distribution data or correlation when reaction stoichiometry and kinetics are unknown. While pyrolysis is a process of decomposition of the dried MSW, therefore, Ryield was used to model this process by specifying the yield distribution vector according to the MSW ultimate analysis [12–14,16,18,20] (calculated using a FORTRAN program). Rgibbs block is a rigorous reactor and multiphase equilibrium based on Gibbs free energy minimization [14]. And gasification involves numerous decomposition, recombination and elementary reactions, thus, Rgibbs was preferred because it is based on the minimization of the total Gibbs free energy of the product mixture [12,13,15,16]. It can be used to predict the equilibrium composition of the produced syngas [16]. However, Rgibbs cannot handle char which is referred to as ‘‘non-conventional’’ [16], therefore, the assumption that char contains only carbon was considered. In the combustion process which is also based on the principle of minimization of Gibbs free energy, Rgibbs can also be suitable [14,20]. The gasification process begins with pyrolysis and continues with combustion, and in summary, the reaction (1)–(6) in these processes considered are [21]:

$$C + O_2 = CO_2, \quad +393 \text{ kJ/mol} \tag{1}$$

$$C + 1/2O_2 = CO, \quad +110 \text{ kJ/mol} \tag{2}$$

$$C + CO_2 = 2CO, \quad -173 \text{ kJ/mol} \tag{3}$$

$$C + H_2O = CO + H_2, \quad -132 \text{ kJ/mol} \tag{4}$$

$$CH_4 + H_2O = CO + 3H_2, \quad -206 \text{ kJ/mol} \tag{5}$$

$$CH_4 + 2H_2O = CO_2 + 4H_2, \quad -165 \text{ kJ/mol} \tag{6}$$

In these simulations, the ambient temperature was 25 °C and the temperature of gasification section was ranged from 500 °C to 700 °C while that of combustion section was kept at 900 °C; system pressure was set at atmosphere pressure; air flow rate depends on the air equivalence ratio which was varied from 0.2 to 0.8; the heat duty was 0 kJ/h in drying section; the solid residue from gasification section consisted of carbon and ash; the characteristics of MSW was an average value of MSW from different provinces in China and the MSW feed rate was 1.0 kg/h. The characteristics of MSW are shown in Table 1.

3. Results and discussion

3.1. Effect of flue gas and air equivalence ratio on syngas production

In this study, air equivalence ratio represents the ratio of the amount of introducing air to the amount of air needed for complete combustion. Obviously, vary of air equivalence ratio will change the amount of air introduced into the reactor. Therefore, three different reaction conditions can be identified: complete combustion to CO_2, complete gasification to CO and partial combustion (gasification) to CO_2 and CO. This ratio has a strong effect on syngas production. Air equivalence ratio was varied from 0.2 to 0.8 in this simulation. Effect of flue gas and air equivalence ratio on syngas