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Performance analysis of municipal solid waste gasification with steam in a Plasma Gasification Melting reactor

Qinglin Zhang [a,*], Liran Dor [b], Lan Zhang [a], Weihong Yang [a], Wlodzimierz Blasiak [a]

[a] Energy and Furnace Technology Division, Royal Institute of Technology, Brinellvägen 23, S-10044 Stockholm, Sweden
[b] Environmental Energy Resources Ltd., 7 Jabotinski St., 52520 Ramat-Gan, Israel

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ABSTRACT

Plasma Gasification Melting (PGM) is a novel gasification technology which offers a promising treatment of low-heating-value fuels like municipal solid waste (MSW), medical waste (MW) and other types of waste. By considering the differences in pyrolysis characteristics between cellulosic fractions and plastics in MSW, a semi-empirical model was developed to predict the performance of the PGM process. The measured results of MSW air and steam gasification in a PGM demo-reactor are demonstrated and compared with the model predicted results. Then, the effects of dimensionless operation parameters (ER, PER, and SAMR) are discussed. It was found that all three numbers have positive effects on system cold gas efficiency (CGE). The reasons can be attributed to promoted tar cracking by enhanced heat supply. The effects of PER and ASME on syngas LHV are also positive. The influence of ER on syngas pyrolysis can be divided into two parts. When $0.04 < ER < 0.065$, the effect of ER is on LHV positive; when $0.065 < ER < 0.08$, the effect of ER is positive. This phenomenon was explained by two contradictory effects of ER. It is also found that interactions exist between operation parameters. For example, increasing PER narrows the possible range of ER while increasing SAMR broadens possible ER range. Detail extents for those operation parameters are demonstrated and discussed in this paper. Finally, the optimal point aiming at obtaining maximum syngas LHV and system CGE are given.

1. Introduction

The increment of municipal solid waste (MSW) yield gives prominence to sustainable waste disposal. Among various methods of waste disposal, gasification is one of the promising technologies. During gasification, the chemical energy inside MSW can be recovered through production of a combustible syngas. Meanwhile, the volume of solid waste can be sharply reduced [1]. Compared to direct incineration, MSW gasification prevented largely dioxin formation and reduced thermal NO_x formation due to low temperature and the reduction condition. Moreover, Moreover, the volume of produced syngas was much lower than that of flue gas from incineration. The reduction of gaseous volume produced positive reflects in a decreasing size of gas cleaning equipment [2]. The state-of-art of MSW gasification technology was summarized by Thomas [3].

If additional sensible heat is provided to the gasification process, the efficiency of gasification can be increased [4]. Meanwhile, other benefits like higher syngas quality, better system stability, and lower tar yield can be obtained [5,6]. When the temperature of gasification residual reaches its melting temperature, the solid residual would be melted and form vitrified slag. In that case, corrosion and emission by retaining heavy metals (with the exception of mercury, zinc and lead, which can vaporize at high temperatures and be retained in fly ash and syngas [7]) would be prevented since they were trapped by slag [8–11]. Based on above studies, a new MSW gasification technology called Plasma Gasification Melting (PGM) has been developed. In this technology, MSW gasification and plasma melting of gasification residual are achieved in a single fixed-bed reactor by a continuous one-step process. By applying PGM technology, benefits like less investment and operation cost, reduced emissions, and overall environmental friendliness can be achieved.

Steam is a widely used gasification agent which affects energy and mass balance of the gasification process. The previous experimental study on the characteristics of steam added gasification [6], [12] showed that the addition of steam favors the formation of H_2 and CO_2, and restrains the CO formation by water–gas and water–gas-shift reactions. Total syngas yield will decline since the addition of steam decreases the temperature inside the fixed-bed. It was also discovered that the steam temperature has a positive effect on both syngas LHV and syngas yield, so high-temperature steam feeding is more favorable for gasification.

In our previous work, experimental test has been performed and analysis has been carried out to study the characteristics of a

* Corresponding author. Tel.: +46 8 790 6545; fax: +46 8 207 681.
E-mail address: qinglin@kth.se (Q. Zhang).

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Nomenclature

Abbreviation

CGE	cold gas efficiency
ER	equivalence ratio
LHCs	light hydrocarbons
LHV	lower heating value
MSW	municipal solid waste
MW	medical waste
PER	plasma energy ratio
PGM	Plasma Gasification Melting
SAMR	steam air mass ratio

Symbols

C_p	heat capacity (J kg^{-1} °C^{-1})
h	thermal enthalpy of plasma air (J kg^{-1})
L	latent heat (J kg^{-1})
LHV	lower heating value (J kg^{-1})
$\dot{m}$	mass flow rate (kg h^{-1})
P	power (W)
T	temperature (°C)
Y	extent of primary tar cracking
ω	mass fraction

Subscripts

air	air
ash	ash
i	species *i*
MSW	municipal solid waste
pla	plasma
pyr	pyrolysis
steam	steam
stoic	stoichiometric reaction

trial PGM reactor [13]. Several test runs were performed at different operation conditions where both air and steam are used as gasification agents. For each test run, the temperature and pressure distribution inside the reactor, as well as syngas composition, were measured. Due to the limitation of test condition, it is not practical to test all possible operation conditions by experimental measurement. For further understanding of the gasification characters of MSW in the PGM reactor, it is necessity of develop an accurate model to predict the performance of PGM process under various operating conditions, and determine the optimal operating conditions according to the desired target.

Process simulation is an important tool which has been widely applied in various energy-engineering processes. For gasification, various models have been developed. For most models, a global chemical equilibrium was assumed [14–19]. The equilibrium might be available for entrained-flow, fluidized-bed and downdraft fixed-bed gasification, but not an appropriate approach for updraft fixed-bed gasification. Firstly, in updraft fixed-bed gasification process, the pyrolysis gases go straight out of the reactor. The chemical equilibrium model cannot correctly predict the yields of pyrolysis. Secondly, the equilibrium model always underestimates the yield of light hydrocarbons from gasification [18]. Vittorio tried to simulating fixed-bed coal gasification by using several individual reactors, and consider the whole gasification process as an assembly of there reactors. In his work the pyrolysis process is simply assumed as a constant yield reaction, the influence of pyrolysis temperature on pyrolysis yields is not considered [20]. When modeling MSW gasification, the pyrolysis mechanism is more complicated than that of coal and biomass, because the composition of MSW is complex. In a common MSW sample, the mass fraction of volatile species is 60–80%. An accurate simulation of the pyrolysis is the key for a successful simulation of MSW gasification in a fixed-bed gasifier. However, very few works has been found on this topic.

In this study, a semi-empirical model for the PGM process of MSW is developed using Aspen Plus. Results from the test runs of air and steam gasification inside the PGM reactor are demonstrated, and compared with the predicted results. The effects of operating parameters such as air feeding rate, steam feeding rate and plasma power on characteristics of MSW gasification in the PGM process are discussed. The interactions between operating parameters are also considered from view points of both energy and chemical equilibrium. Finally, the optimal operation conditions by considering highest syngas lower heating value (LHV) and cold gas efficiency (CGE) are suggested.

2. Methodology

2.1. Feedstock

The feedstock used in this study is MSW collected in Israel. The main components of this MSW are paper, wood, cloth vegetation material, plastics, rubber and debris. The proximate and ultimate analysis was performed for a sample of this MSW, and the results are shown in Table 1.

2.2. The PGM reactor

A PGM demonstration reactor has been built up in Northern Israel, with a capacity of 12–20 tons of MSW per day. The PGM reactor is generally a moving-bed counter current updraft gasifier, with a melting chamber placed at its bottom. The scheme of the reactor is shown in Fig. 1. Air is fed into the melting chamber through plasma torches at high speed, and forms high temperature plasma jets which melt the inorganic components which fall from the fixed-bed. Then, air with residual heat mixes with steam fed through steam nozzles placed at the side wall of the melting chamber, and flows into the fixed-bed. The feeding rates of air and steam are controlled by central control system. Feedstock is fed into the reactor from airtight feeding chambers located at the top of the reactor. MSW is fed intermittently every half an hour.

In order to measure the temperature distribution inside the reactor, thermocouples are placed along the gasifier shaft. Additionally, a probe is placed in the syngas outlet to obtain syngas samples, which are sent to a gas analyzer for composition analysis.

Table 1
Proximate and ultimate analysis of MSW.

Proximate analysis		
Moisture		20.0%
Fixed carbon (dry basis)		10.7%
Volatile (dry basis)		77.6%
Ash (dry basis)		11.7%
Ultimate analysis		
Carbon	C	47.9%
Hydrogen	H	6.0%
Nitrogen	N	1.2%
Chlorine	Cl	<0.1%
Sulfur	S	0.3%
Oxygen	O	32.9%