Gasification of municipal solid waste in the Plasma Gasification Melting process

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\textbf{A B S T R A C T}

A new waste-disposal technology named Plasma Gasification Melting (PGM) was developed. A pilot PGM reactor was constructed in northern Israel. The reactor is an updraft moving-bed gasifier, with plasma torches placed next to air nozzles to heat the incoming air to 6000 °C. The inorganic substances of the feedstock are melted by the high-temperature air to form a vitrified slag in which undesirable materials such as heavy metals are trapped. The residual heat in the air supplies additional heat for the gasification process. A series of tests were conducted to study the performance of PGM gasification. The plasma power was varied from 2.88 to 3.12 MJ/kg of municipal solid waste (MSW), and the equivalence ratio (ER) was varied from 0.08 to 0.12. For air and steam gasification, the maximum steam/MSW mass ratio reached 0.33. The composition of the syngas product was analyzed in all tests; the lower heating value (LHV) of the syngas varied from 6 to 7 MJ/Nm\textsuperscript{3}. For air gasification, the syngas LHV decreased with increasing ER, whereas the gas yield and energy efficiency increased with ER. When high-temperature steam was fed into the reactor, the overall gas yield was increased significantly, and the syngas LHV also increased slightly. The positive effect may be attributed to the steam reforming of tar. In air and steam gasification, the influence of increased ER on syngas LHV was negative, while the effect of increased plasma power was positive. The maximum energy efficiency of the tests reached 58%. The main energy loss was due to the formation of tar.

\section{1. Introduction}

Rapid economic development has led to an annual increase in municipal solid waste (MSW) production. According to the concept of sustainable waste disposal, a successful treatment of MSW should be safe, effective, and environmentally friendly [1]. However, existing waste-disposal methods cannot achieve this goal. Conventional waste landfills occupy large amounts of land and lead to serious environment problems [2]. Incineration technology was developed to reduce the total volume of waste and make use of the chemical energy of MSW for energy generation [3,4]. However, the emissions of pollutant species such as \textit{NO}, \textit{SO}, \textit{HCl}, harmful organic compounds [5,6], and heavy metals [7,8] are high in the incineration process. Another problem with MSW incineration is the serious corrosion of the incineration system by alkali metals in solid residues and fly ash [7]. Furthermore, due to the low incineration temperature related to the low energy density of MSW, the energy efficiency of MSW incineration is relatively low [9,10].

The development of an environmentally benign gasification technology for processing MSW has been a topic of much research in the past decade, as summarized by Thomas [11]. Among various gasification technologies, high-temperature agent gasification (HiTAG) has been proven to be an efficient technology. The characterization of HiTAG for different waste materials has been studied [12–19], and several positive features have been reported. Experimental work by Lucas et al. showed that preheating the gasification agent can sharply reduce the air demand in a gasification process, so the concentration of noncombustible gases (\textit{N}\textsubscript{2} and \textit{CO}\textsubscript{2}) in the syngas product can be reduced correspondingly [12]. Another advantage of preheating the gasification agent is that the tar yield can be significantly reduced due to the high temperature [13]. Using a high-temperature gasification agent has other benefits including greater system stability. The syngas quality becomes less sensitive to variations in the particle size, heating value and moisture content of the MSW [14]. The characteristics of HiTAG are more significant if high-temperature steam is used as the gasification agent [15–17,19].

In a HiTAG process, most of the heavy and alkali metals (with the exception of mercury, zinc and lead, which can vaporize at high temperatures and be retained in fly ash and syngas [20]) are retained in the bottom ash produced during gasification [21]. To prevent secondary pollution from the bottom products, a melting technology has been widely applied in MSW incineration plants [22–24]. During the melting process, the solid residues are melted...
to form a vitreous slag in which heavy metals and other harmful components are locked. After cooling, the slag becomes a vitrified solid that can be used as a building material [25]. The same advantages are obtained if this melting technology is applied to MSW gasification. Various methods have been used in the solid-residue melting process of MSW incineration/gasification [26–28], among which plasma technology has proven successful. The state of the art of thermal plasma applications in MSW treatment was reviewed by Gomez et al. [29].

The combination of plasma melting and HiTAG leads to a new MSW disposal technology, named Plasma Gasification Melting (PGM). A demonstration Plasma-Gasification-Melting system was built by Moustakas et al. The basic performance behaviors of the system were determined, and the influences of operating parameters were discussed [30,31]. However, reports on the performance analysis of the PGM process remain rare. The available experimental data on Plasma Gasification Melting, especially industrial-scale operational data, is very limited. This situation serious has hindered the understanding and application of Plasma Gasification Melting technology.

An industrial-scale PGM plant was constructed in Israel by the Environmental Energy Resources, Israel Ltd., (EER); A series of trial runs was performed in this plant to investigate the characteristics of the PGM process. This study aimed to provide detailed results and analysis of the trial runs.

2. Test method and materials

2.1. The PGM system

The demonstration plant was constructed in Yblin Israel in 2007. The designed capacity of the plant is 20 tons of MSW per day. The process flow sheet is shown in Fig. 1. MSW is fed into the reactor through airtight feeding chambers placed at the upper part of the plasma chemical reactor, wherein gasification reactions occur. Syngas produced from gasification flows into the afterburner and is combusted there. The hot flue gas from combustion is sent to the boiler to produce steam, which drives a steam turbine connected to an electrical generator. The generated electricity, besides providing power for the plasma torches and the rest of the system, can be sold to outside users. The fly ash is removed from the flue gas in the scrubber-evaporator. SO\(_2\) is absorbed in the reactor absorber and removed using a bag filter. The solid residue from gasification is melted by the plasma jet and collected by the slag collectors.

The core of the PGM plant is the plasma chemical reactor, which is a typical fixed-bed updraft gasification reactor. The scheme of the reactor is shown in Fig. 2. MSW is fed into the reactor from the top. The gasification agents, which are air and high-temperature steam (1000 °C), are injected into the lower part of the reactor from various nozzles. A part of the air, called plasma air, is injected into the reactor from four plasma torches, which are embedded into the reactor at the upper surface of the melting chamber. Electrical arcs are formed between electrodes at the tip of the plasma torches, so that air flowing through the arc is ionized and forms a plasma jet that extends beyond the tips of the torches. The temperature of the plasma jet may reach up to 6000 °C. The power of the plasma torches can be controlled by the central control system. Additional air, known as secondary air, is fed into the reactor from nozzles surrounding the plasma torches. High-temperature steam nozzles are located at the lower part of the gasifier. The feed rates of both secondary air and steam are adjustable and controlled by the central control system.

2.2. Measurements

An isokinetic probe is located in the syngas conduit between the reactor and the afterburner to obtain syngas samples. The hot syngas sample is first sent to a water-cooled tar collector and then to a continuously operating gas analyzer to determine its composition. The total flow rate of syngas is measured by a flowmeter. Because the syngas goes to the afterburner without a cooling step, the flow rate is measured here on a wet basis (i.e., steam and some tar is included in the flow rate). The yield of dry syngas is calculated from an Aspen model developed specially for the PGM process.

To measure the temperature distributions inside the plasma chemical reactor, thermocouples are placed both along the gasifier shaft and in the syngas conduit. The thermocouple positions depend on their height above the reactor bottom, \(H(m)\). If \(1 < H < 2\) the thermocouples are placed in the reactor wall, behind the refractory layer, to prevent damage to the thermocouples at high temperatures. If \(1 < H < 2\), the thermocouples are placed both behind the refractory layer and inside the reactor. For \(H < 2\) thermocouples are placed inside the reactor. To obtain the actual temperature inside the reactor, temperature compensation must be made for the thermocouples placed behind the refractory layer. According to the heat conducting law, the heat flow through the reactor wall can be written as:

\[
\phi = \lambda_1 \frac{(T_1 - T_0)}{\Delta x_1} = \lambda_2 \frac{(T_2 - T_1)}{\Delta x_2},
\]

where \(\lambda_1\) is the average heat-conduction coefficient of the reactor wall outside the refractory layer, \(\lambda_2\) is the heat-conduction coefficient of the refractory layer, \(T_0, T_1,\) and \(T_2\) are temperatures at the outer wall surface, behind the refractory layer and inside the reactor, respectively, \(\Delta x_1\) is the thickness of reactor wall outside the refractory layer, and \(\Delta x_2\) is the thickness of the refractory layer.

We assume that the wall material of both the refractory layer and the reactor wall outside the refractory layer are uniform. The ratio of \(\lambda_1\) and \(\lambda_2\) can be calculated from the measured temperature at \(1 < H < 2\). The temperature inside the reactor at \(H < 1\) range can then be calculated as:

\[
T_2 = \frac{\lambda_1 \Delta x_2 (T_1 - T_0)}{\lambda_2 \Delta x_1} + T_1.
\]

2.3. Feedstock properties

MSW is fed into the reactor from airtight feeding chambers. The feedstock used in the trial runs was MSW collected in Israel, with a composition as shown in Table 1. Proximate and ultimate analyses were made on a sample of this MSW; the results are shown in Table 2.
2.4. Test procedure

In the trial runs, two groups of tests were carried out. The first was with air gasification of MSW (Cases 1 and 2), and the second was with air and steam gasification (Cases 3–6). The feed rate of MSW was set at 300 kg/h during all runs. Trial runs were conducted with different operating parameters, such as plasma power, secondary air feed rate and steam feed rate, as shown in Table 3. Before each run, the reactor was preheated for 12 h with plasma air.

3. Results and analysis

3.1. Syngas quality in air gasification

As basic cases, two tests were performed without steam feeds (Cases 1 and 2). In both cases, the plasma power is 2.88 MJ/kg MSW. In Case 1, the secondary air flow rate was set to zero. In Case 2, the feed rate of secondary air was calculated by assuming that the total air feed rate equals the stoichiometric demand for converting all fixed carbon in the feedstock into CO. The results from both cases are presented in Figs. 3 and 4. Here, the amount of available air per kilogram of MSW is represented by the equivalence ratio (ER), defined as:

\[
ER = \frac{(A/F)}{(A/F)_{\text{stoc}}}
\]

where \((A/F)\) is the air/fuel mass ratio in the real cases and \((A/F)_{\text{stoc}}\) is the air/fuel mass ratio for a stoichiometric combustion where the fuel is fully combusted.

Both cases showed good results in terms of the lower heating value (LHV) of the product syngas, here 6–7 MJ/Nm³. This was mainly due to the low ER in the PGM process (0.08 in Case 1 and 0.12 in Case 2). A low ER ratio prevents the dilution of syngas with nitrogen from air; a substoichiometric oxygen level suppresses the formation of CO₂, which is the other main noncombustible gas in syngas. Due to the concentration of combustible gases in the syngas, the total gas yields here (0.67 and 1.06 Nm³/kg MSW in Cases 1 and 2, respectively) were lower than that of traditional gasification. In both cases, the H₂/CO ratio was approximately 1.5, which is somewhat higher than that of common gasification processes, mainly due to the high contents of hydrogen and oxygen in the feedstock.

Despite the common features of the two cases, some important differences in syngas composition and yield were found. Firstly, a significant increase of gas yield was observed when a higher ER was used. This increase was partly due to the N₂ content of the secondary air, which led to the decrease of LHV in Case 2, and partly due to the cracking of tar favored by the higher temperature associated with increasing ER. Fig. 5 is the measured temperature distribution along the reactor chamber of Cases 1 and 2. It can be found that the temperature of Case 2 is 100–200 °C higher than that of Case 1, with an exception near the bottom. The bottom
The temperature of Case 2 is lower than that of Case 1 due to the additional low temperature air injection. Another reason for the increase in gas yield from Case 1 to Case 2 was likely the insufficient carbon conversion in Case 1, as shown by chemical-equilibrium calculations. A low ER ratio in the PGM ensures high syngas quality. However, when the ER is too low, as in Case 1, the gasification agent cannot supply enough oxygen to convert char into CO or CO\textsubscript{2}. Insufficient carbon conversion is an adverse condition for gasification as it reduces both the gas yield and energy efficiency. In Case 2, the feeding of secondary air solved this problem. The increased O\textsubscript{2} enhanced the CO content in syngas, as shown in Fig. 3. An interesting result from the two cases is that although the syngas yield changed significantly, the volume fraction of H\textsubscript{2} in the syngas was relatively unchanged. This indicates an increase of H\textsubscript{2} production with increasing ER. The positive effect on H\textsubscript{2} yield in response to increased ER is in accordance with the results by Pinto et al.\cite{32} and Anna et al.\cite{13}. The increased H\textsubscript{2} production with increased ER was likely the result of favorable conditions for the secondary pyrolysis of primary tar. According to the Boroson’s theory\cite{33}, pyrolysis can be divided into two steps: primary pyrolysis and secondary pyrolysis. H\textsubscript{2} is mainly produced from the secondary pyrolysis step, which is sensitive to pyrolysis temperature. A higher temperature due to increasing ER thus favored secondary pyrolysis, and more H\textsubscript{2} was produced. Another effect of increasing temperature with ER was the decrease in total light hydrocarbon (THC) content. The relationship between pyrolysis temperature and THC yield has been reported by Anh et al.\cite{34} and Li et al.\cite{35}, and the mechanism was explained by Anthony et al.\cite{36}.

3.2. Syngas quality in air and steam gasification

3.2.1. Influence of steam feed rate

Along with Case 2, experiments for Cases 3 and 4 were performed to investigate the influence of the steam feed rate. The plasma and air settings of Cases 3 and 4 were the same as for Case 2 but with different steam feed rates (70 and 100 kg/h, respectively). The results from Cases 2, 3, and 4 are presented in Figs. 6 and 7.

We found that adding high-temperature steam is favorable for the PGM process. The total gas yield increased significantly, and the gas LHV also increased with steam feeding. Generally, it is believed that the increase of gas yield with steam feeding is due to the water–gas shift reaction:

\[ \text{CO} + \text{H}_2\text{O} = \text{CO}_2 + \text{H}_2 \quad (4) \]

This reaction undoubtedly played some role in the yield increase, especially with excess steam. However, the increase of LHV in our cases cannot be explained solely by this reaction. Examining the composition of the syngas, we found that as the steam feed rate was increased from Case 2 to 4, the THC content increased significantly. The CO content, in contrast, increased from Case 2 to Case 3 but decreased from Case 3 to Case 4. In all three cases, the fluctuation in H\textsubscript{2} content was very small. Similar results were reported by Blasiak et al.\cite{37}, who studied the high-temperature air and steam gasification of biomass in an updraft fixed-bed gasifier. A possible explanation for this phenomenon is the steam...
reforming of tar at high temperature. The mechanism and kinetics of tar steam reforming have been reported by Li et al. [38]. The global reaction can be written as follows:

\[
C_m H_n + a H_2O = b CO + c H_2 + d C_x H_y; \tag{5}
\]

where \( C_m H_n \) represents tar and \( C_x H_y \) the light hydrocarbons.

A strict restriction of the steam-reforming reaction is that it can only occur at high temperature. It was pointed out by Jess [39] that at a temperature of approximately 1200 °C, the steam reforming of tar can go to completion in less than 10 s. As we measured during the tests, the global gasification temperature was in the range of 1000–1200 °C. Considering the scale of the reactor, it is very likely that there was a strong steam-reforming reaction during the air and steam gasification process. Therefore, the steam reforming of tar and the water–gas shift reaction together resulted in the increased syngas yield.

Comparing the results of Cases 3 and 4, a notable difference is that the\( H_2/CO \) ratio increased greatly. This may be due to the promotion of the water–gas shift reaction by the excess steam in Case 4. According to Li et al. [38], the priority of tar steam reforming is higher than the water–gas shift reaction at high temperature due to the occurrence of the following reaction:

\[
C_m H_n + m CO_2 = 2m CO + n/2H_2; \tag{6}
\]

When there is insufficient steam for reforming, as in Case 3, the water–gas shift reaction is, in a sense, suppressed. When steam is supplied in excess, the water–gas shift reaction then becomes much more intensive, resulting in a high \( H_2/CO \) ratio.

3.2.2. Influence of plasma power and ER

The experiments in Cases 5 and 6 were conducted to investigate the influence of plasma power and ER in air and steam gasification. In both cases, the steam feed rate was 70 kg/h, the same as in Case 3; the plasma power and ER were then varied. Detailed information for each case is given in Table 3. The results from Cases 5 and 6 are presented in Figs. 8 and 9 with Case 3 for comparison.

The results for Cases 3 and 5 were similar. The slight difference in gas yields can be explained by the reduced air feed and lower tar cracking and reforming related to the reduced combustion due to the lower ER. However, some significant differences in syngas composition were found when comparing Case 6 with Cases 3 and 5 taken together. The overall increase of combustible gases, especially of \( H_2 \), may be mainly due to the sensitivity of tar cracking and reforming to temperature. In the PGM process, more than half of the energy need for gasification is from the plasma torches. The increased plasma power in Case 6 led to a significant increase of gasification temperature, which prompted the cracking and reforming of tar. The reforming reaction of light hydrocarbons may have also taken place, as in Eq. (7), enhancing the yield of \( H_2 \).

\[
C_x H_y + x H_2O = xCO + (x + 2/y)H_2; \tag{7}
\]

3.3. Energy efficiency

The cold-gas efficiency (CGE) is a standard criterion frequently quoted to express the energy efficiency of a gasification process. For a PGM process, the definition of CGE was modified by Qinglin et al. [40] to.
\[
\eta = \frac{m_{\text{syngas}} \cdot LHV_{\text{syngas}}}{m_{\text{feedstock}} \cdot LHV_{\text{feedstock}} + P_{\text{steam}} + P_{\text{plasma}}} \times 100\%.
\]  

where \(m_{\text{syngas}}\) and \(m_{\text{feedstock}}\) denote the mass flow rates of the syngas and the feedstock, respectively, while \(LHV_{\text{syngas}}\) and \(LHV_{\text{feedstock}}\) are their lower heating values on a mass basis. \(P_{\text{steam}}\) denotes the power used to heat the steam, and \(P_{\text{plasma}}\) is the plasma power.

The combustion value of the MSW was calculated from an empirical expression given by Boie [41]:

\[
\text{HHV} = 83.22C + 274.3H - 25.8O + 15N = 9.4Cl + 65P.
\]

The CGE results of all six cases are shown in Fig. 10. Here, the CGE varies from 30% to 60%. The energy efficiency of air gasification is lower than that of air and steam gasification. The CGE was the lowest for Case 1; Case 6 had the highest. For air gasification, increasing ER was beneficial for increasing energy efficiency, whereas the influence of ER was not obvious for air and steam gasification.

There are three main sources of energy loss in gasification: the chemical energy in the tar, the sensible heat of the syngas, and the heat loss of the system. Because a PGM reactor is an updraft fixed-bed reactor, the sensible heat of the syngas cannot be the main energy loss. The normal system heat loss is approximately 2−5% of the total energy, so the main energy loss for PGM should be chemical energy in the tar.

4. Slag properties

The inorganic components of MSW were melted to form a slag. The discharging of slag was not continuous in the trial reactor. Instead, it was controlled by a valve placed at the exit of the melting chamber. At most times, the valve is closed, and the volume of slag inside the combustion chamber increases continually. When it reaches a certain level, the valve is opened. The melted slag flows out of the melting chamber and into the slag collector. When the collector is full, the valve is closed again, and the collector is transmitted into the open air for cooling. When it exits the melting chamber, the slag is a glowing liquid. After four hours of cooling, it becomes a black, vitreous solid. The appearance of the slag during tap-out and after cooling is shown in Figs. 11a and 11b.

During these tests, the output of slag was approximately 25 kg/h. Due to the high density of this slag (2300 kg/m³), the volume ratio of slag to raw MSW is approximately 1:50. The composition can vary with the feedstock, but the main contents should be SiO₂ and CaO. Undesirable materials such as heavy metals are locked in the slag, so that the slag is virtually inert, meeting the most demanding TCLP Standards. This slag can be used as a good building material.

5. Conclusions

The syngas produced from the PGM has a high LHV (6–7 MJ/Nm³). In air gasification, the syngas yield increased significantly with increasing ER, whereas the LHV decreased slightly. Feeding high-temperature steam into the PGM reactor greatly increased syngas yield, with even higher gas LHV. The feeding of high-temperature steam can further reduce the air demand for gasification.

The energy efficiency of air and steam gasification was much higher than that of air gasification. The CGE of PGM air and steam gasification can reach approximately 60%. Tar formation represents the main energy loss for the PGM reactor.

References


