

Comparative Analysis of Syngas Production via Gasification and Plasma Gasification of Municipal Solid Waste

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Municipal solid waste (MSW) is a significant environmental challenge. Gasification is a process that converts MSW into energy at temperatures ranging from 700 to 1,200 °C. Plasma gasification enhances this process by utilizing a 4,000 °C plasma torch, which helps eliminate hazardous components and produces high-purity syngas. Although plasma gasification requires a considerable amount of energy, it presents a promising pathway for efficiently producing syngas from waste. Thus, this work aims to investigate and compare syngas production between plasma gasification and conventional gasification of municipal solid waste (MSW). The model validation of gasification and plasma gasification was first considered. The effects of air and steam as agents for maximum syngas yield were investigated. Moreover, the system efficiency of both routes is analyzed. The results indicated that the simulation results of syngas production from MSW conventional gasification and plasma gasification are consistent with the experimental data. When considering syngas production from both gasification routes, it was found that the concentrations of hydrogen and carbon monoxide in the syngas from MSW plasma gasification were higher than those from conventional gasification.

1. Introduction

Waste management is a significant environmental issue; ineffective waste management affects the environment, such as air pollution from waste incineration. The widely used method for managing waste globally is landfill disposal. Nevertheless, simultaneously waste disposal while generating energy, called waste-to-energy (WtE), is a more sustainable waste management method than landfill disposal. WtE plants produce zero waste by reducing 90 % of the Municipal Solid Waste (MSW). WtE has several technologies to produce energy, such as incineration, pyrolysis, and gasification (Sunil et al., 2019). Several countries commonly use incineration despite the issues of emissions. Thus, gasification is interestingly used due to the benefit of producing clean fuel called synthesis gas (syngas) and producing various flexible products. Moreover, gasification causes less air pollution and highly efficient energy recovery. Gasification is a thermochemical process that produces energy with limited air or oxygen in a closed reactor called a gasifier to convert into syngas, including hydrogen (H₂), carbon monoxide (CO), carbon dioxide (CO₂), methane (CH₄), char (residue solid), and unwanted products as tar under conditions at high temperature around 700-1200 °C (Cortazar et al., 2023). Air gasification is prevalent due to its operational simplicity and cost-effectiveness; however, it typically produces a low heating value gas (4–6 MJ Nm⁻³) attributed to the dilution effect caused by nitrogen (Sansaniwal et al., 2017). In contrast, steam gasification presents a notable advantage by generating syngas with a higher hydrogen content and superior overall gas quality with a higher heating value compared to air gasification (Sansaniwal et al., 2017). Although steam gasification enhances the hydrogen concentration and the overall quality of syngas, it necessitates a greater energy input for steam generation and process maintenance, which may lead to increased operational costs and complexity (Sikarwar et al., 2016). To overcome these limitations, co-feeding of steam and air as gasifying agents has been proposed as a promising strategy. This approach seeks to integrate the advantages of both methodologies, thereby improving the hydrogen concentration and calorific value of the produced syngas while concurrently reducing the external energy demands associated with steam generation. Syngas from MSW

gasification contains high levels of impurities such as tar (condensable aromatic and polyaromatic hydrocarbons) and other ash contaminants including nitrogen compounds (NH_3 and HCN), sulphur containing inorganic compounds (H_2S , COS and CS_2), halogen compounds (HCl and Cl) and alkali (Na , K) and heavy metals (Sikarwar et al., 2016). Gasification integrated with the plasma torch was a new technology that helped burn MSW into syngas and slag (Molino et al., 2016). Plasma gasification is considered a clean technology with minimal environmental impact that operates at very high temperatures, up to approximately $5,000\text{ }^\circ\text{C}$, and is an effective method for managing solid and hazardous waste. Additionally, this approach has significant potential for energy recovery. Conventional gasification is cost-effective and suited for clean feedstocks but produces more impurities, while plasma gasification is more expensive yet cleaner, handling mixed waste with minimal emissions and producing high-purity syngas and inert slag.

Thus, this study aims to compare the performance of steam-air conventional gasification and plasma gasification for syngas production using municipal solid waste (MSW) as feedstock. The effects of the air-to-MSW and steam-to-MSW ratios on the gas products from both conventional and plasma gasification processes are first investigated. Furthermore, the overall efficiency of both processes is evaluated and compared.

2. Process description

This study investigates two types of gasification models: conventional gasification and plasma gasification, both aimed at producing methanol. Both processes were modeled using Aspen Plus software. Details of the models are provided below, and the proximate and ultimate analyses of municipal solid waste (MSW) can be found in Table 1.

Table 1: Proximate analysis and ultimate analysis of MSW

(Proximate analysis) (%wt.)		(Ultimate analysis) (%wt.)	
Moisture content	27.3	C	45.6
Fixed carbon	7.7	H	6.0
Volatile matter	71.5	N	0.8
Ash	20.8	S	0.3
		O	26.5
		Ash	20.8

2.1 Gasification

Air and steam are used as gasifying agents in the Aspen Plus model shown in Figure 1. Solid MSW, classified as non-conventional, is defined using ultimate/proximate analysis with HCOALGEN for enthalpy and DCOALIGT for density. The dry feed passes through a DECOMP block, breaking down into C, H_2 , N_2 , S, O_2 , and ash. The stoichiometric reactor forms the impurity components (H_2S and NH_3). A separator (SEP) removes impurity components (INORG), the volatile stream (VOLATILE) enters the separator (SEP-H2) to separate some hydrogen into the gasifier and form tar, and the char stream (CHAR) enters to split carbon solid for gasifier and tar production. Gasifier with air and steam under isothermal conditions ($800\text{ }^\circ\text{C}$ and 1 bar). The output (DRYSYNG) contains dry syngas, H_2S , NH_3 , and solid carbon.

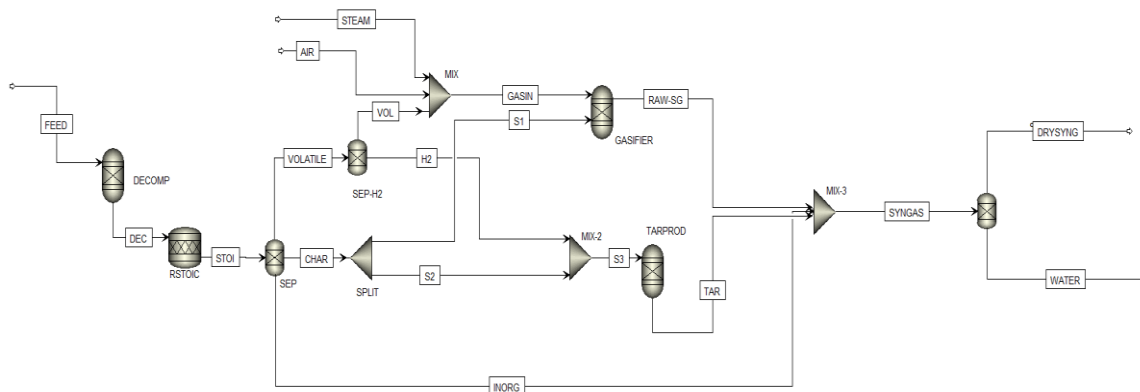


Figure 1: Conventional gasification process

2.2 Plasma gasification

The plasma reactor model is based on a non-transferred arc plasma torch operating within an insulated reactor chamber under adiabatic conditions. Figure 2 shows the schematic flow sheet of the process, which was modeled in Aspen Plus. The feedstock, supplied via the stream labeled MSW, is a solid, non-conventional material. Its properties are determined in Aspen Plus using ultimate and proximate analyses, with the HCOALGEN model applied for enthalpy estimation and the DCOALIGT model for density calculation. Initially, the feedstock enters a dryer to remove moisture before proceeding to the DECOMP block, where it is decomposed into components such as C, H₂, N₂, Cl₂, S, O₂, and ash. The DECOMP block is followed by a separator that extracts the ash from the remaining feedstock. The processed feedstock (GASIN) then enters the high-temperature plasma reactor (GASIFIER), where it mixes with the input plasma gas stream. The plasma torch is modeled as a heat exchanger (TORCH) with a heat duty of 4.0 MW, heating the gas stream before it enters the GASIFIER block. The output from the syngas process is designated as DRYSYNG, which includes both dry syngas and residue components such as H₂S, NH₃, and solid carbon.

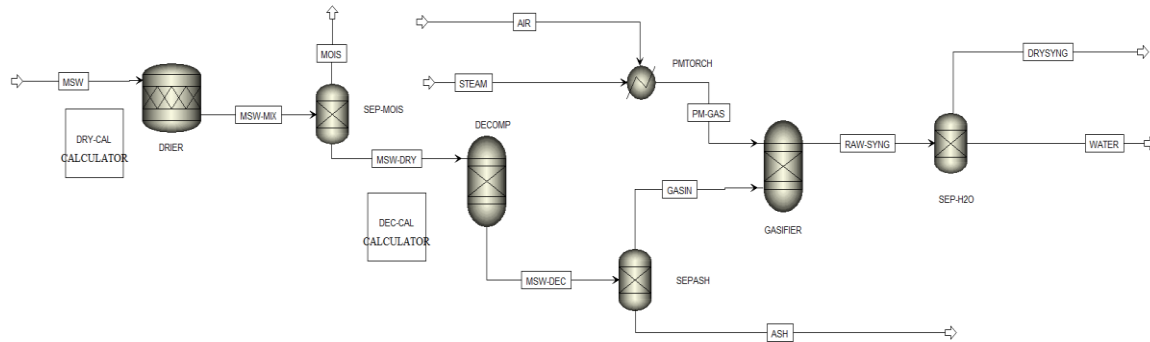


Figure 2: Plasma gasification process

2.3 Efficiency analysis

The efficiency of both gasification processes is calculated using the gasification efficiency in Eq(1).

$$\eta_{CG} = \frac{\sum m_{syngas} \times LHV_{syngas}}{m_{msw} \times LHV_{msw} + W_{torch} / \eta_{elec}} \quad (1)$$

Here, m_{syngas} and m_{msw} represent the mass flow rates of syngas and feedstock, respectively; LHV_{syngas} denotes lower heating values; W_{torch} is the electric power consumption of the plasma torch; and η_{elec} is the average efficiency of a fossil-based (coal) power plant, assumed to be 31.55 %.

2.4 Equivalence ratio

Equivalence ratio (ER) represents the fraction of the gasifying agent used relative to the amount needed for stoichiometric combustion of the feedstock (Zhang et al., 2012), as shown in Eq(2).

$$ER = \frac{(O_2/m_{msw})}{(O_2/m_{msw})_{stoichiometric}} \quad (2)$$

2.5 Steam/MSW ratio

Steam is considered an effective gasifying agent, as it enhances the hydrogen molar fraction in the produced syngas. The ratio of steam to feedstock, which significantly affects gas composition and efficiency (Zhu et al., 2016), can be determined using Eq(3).

$$S/MSW = \frac{STEAM \text{ Flow}}{MSW \text{ Flow}} \quad (3)$$

3. Model validation

3.1 Gasification

The simulation results of gas products were compared to the literature data from Marcantonio et al. (2019) to validate the gasification model. The validation was conducted using hazelnut shells as the feedstock and steam as the gasifying agent. The operating conditions included a temperature of 800 °C, pressure of 1 bar, a steam-to-biomass ratio of 0.8, and a biomass feed rate of 0.06 kg/h. Figure 3 illustrates the comparison between the simulation results and the literature. The results of the comparison of syngas composition between the literature and the simulation of the conventional gasification process found that the simulation results are close to the literature, with Hydrogen and Carbon monoxide, which are the main components of the product syngas.

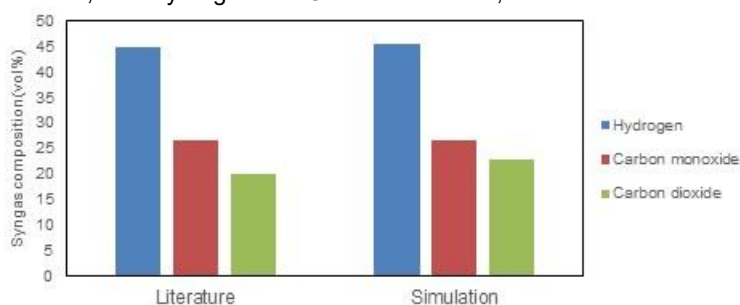


Figure 3: Comparison of the simulation results and the experiment with temperature 800 °C

3.2 Plasma gasification

The model validation of plasma gasification was compared with the literature by Tavares et al. (2019), which investigates the plasma gasification process of MSW using specified proportions of air and steam as agents. The MSW feed rate was set at 1 kg/s, with air at 0.36 kg/s and steam at 0.56 kg/s feed to the plasma torch with a heat duty of 4.0 MW. The results from simulations were compared to the literature, as illustrated in Figure 4.

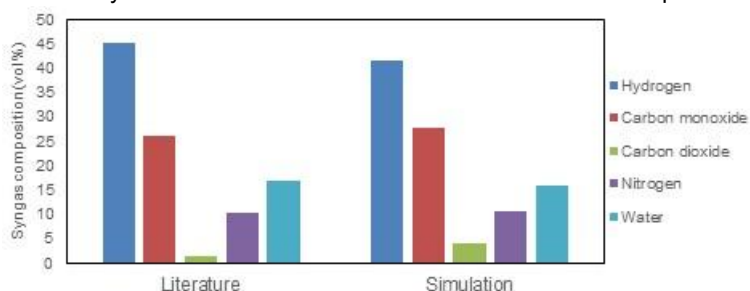


Figure 4: Comparison of syngas composition (mol%) between the literature and simulation

The comparison of syngas composition between the literature and simulation results indicates that the simulation closely reflects the experimental outcomes, particularly regarding hydrogen and carbon monoxide, which are the main components of the produced syngas. Therefore, this model can be applied to simulate and improve the plasma gasification process.

4. Results and discussion

4.1 Effect of S/MSW and ER

Steam is considered an effective gasification agent due to increasing the molar fraction of hydrogen (H₂). The steam-to-MSW (S/MSW) ratio is defined as the ratio of steam inlet flow to the MSW inlet flow. In this work, S/MSW varies from 0.1 to 1.0, with the equivalence ratio (ER) fixed at 0.1, the plasma torch power of 4 MW in the plasma gasification case, and an MSW inlet flow of 1 kg/s.

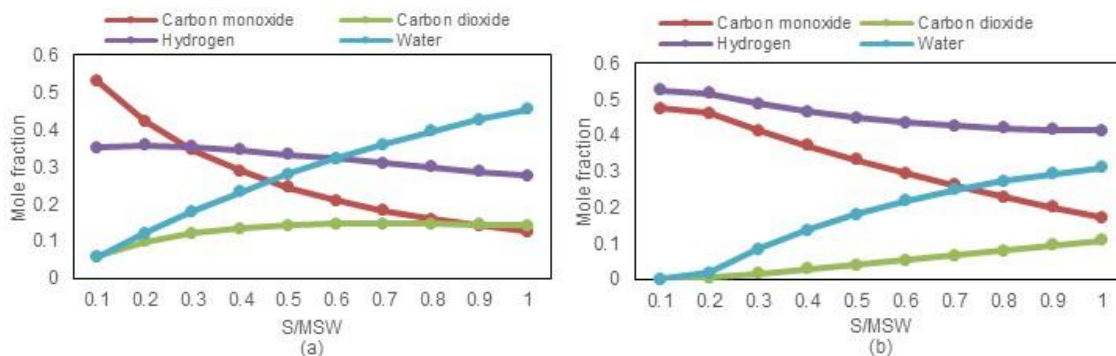


Figure 5: Influence of S/MSW ratio on the gasification process (a) and the plasma gasification process (b)

Figure 5 illustrates the variation of syngas molar composition with S/MSW. It was observed that initially, the mole fraction of H_2 increased with increasing amount of inlet steam. This is because the introduction of steam into the process promotes the water-gas reaction, steam methane reforming, and water-gas shift reaction, thereby increasing the molar flow rate of hydrogen. However, when S/MSW increased above 0.2, the mole fraction of hydrogen decreased. An excessive amount of steam reduced the hydrogen concentration, as the molar flow rates of other products, including carbon dioxide and water, increased, while the rise in hydrogen production was less significant than in the initial stage. Consequently, the hydrogen concentration decreased with higher S/MSW ratios. Moreover, increased steam flow enhances char gasification and promotes tar cracking, thereby improving overall conversion efficiency. The optimum of S/MSW is about 0.2.

Equivalence ratio (ER) is defined as the fraction of the gasifying agent required for the gasification reaction to be completed. ER ranged between 0.1 and 1, with the S/MSW ratio fixed at 0.2 with the MSW flow rate of 1 kg/s, and the plasma torch power of 4 MW in the plasma gasification case.

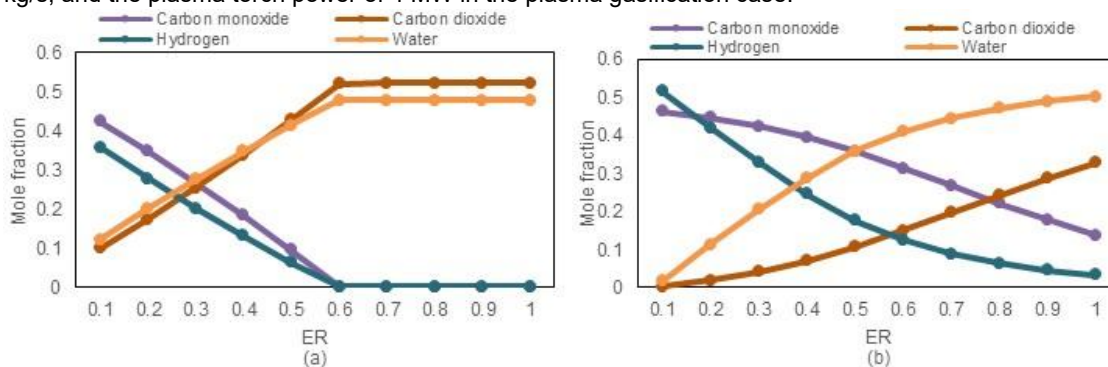


Figure 6: Influence of ER ratio on the gasification process (a) and the plasma gasification process (b)

Figure 6 illustrates that the concentrations of CO and H_2 decrease with an increasing equivalence ratio (ER). A higher ER indicates that more oxygen is being introduced into the system, which promotes oxidation reactions over gasification reactions. Consequently, syngas components like H_2 and CO are partially oxidized, resulting in the formation of carbon dioxide and water. In conventional gasification, the optimal ER is approximately 0.1, which strikes a balance between heat generation and syngas quality.

4.2 Comparison of gasification and plasma gasification

Both processes operate under the conditions with the gasifier of adiabatic temperature, at atmospheric pressure, the optimum ER of 0.1, S/MSW of 0.2, the plasma torch using a heat duty of 4.0 MW, and an MSW feed inlet flow of 1 kg/s. Table 2 shows the comparison of syngas composition between conventional and plasma gasification. From Table 2, the comparison of syngas compositions between conventional gasification and plasma gasification shows that plasma gasification has a higher main product syngas as H_2 and CO content than conventional gasification. The high H_2 concentration is advantageous conversion into chemical products such as methanol and dimethyl ether, etc. The hydrogenation of CO to methanol is both exothermic and more efficient, requiring less hydrogen compared to the hydrogenation of CO_2 . In contrast, CO_2 is more stable and requires more energy and hydrogen to convert to methanol, making the process less efficient and more costly. Plasma gasification has lower impurity components (H_2S and NH_3) than conventional gasification.

The system efficiency of conventional gasification is compared with plasma gasification; conventional gasification of 54 % has a higher system efficiency than plasma gasification of 45 %, since in plasma gasification, an ample amount of process energy is utilized to sustain the plasma torch.

Table 2: Syngas composition of conventional gasification and plasma gasification

Syngas composition (dry mol%)	Gasification	Plasma Gasification
H ₂	30.16	43.08
CO	35.66	38.59
CO ₂	8.30	0.24
N ₂	24.69	18.01
H ₂ S	0.17	0.0002
NH ₃	1.02	0.000002

5. Conclusion

In this work, the conventional and plasma gasification were compared the syngas composition and system efficiency. The air and steam are used as agents to feed the gasifier under adiabatic conditions with using municipal solid waste (MSW) as feedstock. The effect of agents the ER value increases, and H₂ concentration will decrease. The S/MSW finds that the mole fraction of H₂ increased with increasing amount of inlet steam. This is because the introduction of steam into the process promotes the water-gas reaction, steam methane reforming, and water-gas shift reaction, thereby increasing the molar flow rate of hydrogen. However, when S/MSW increased above 0.2, the mole fraction of H₂ decreased. The optimum ER and S/MSW are 0.1 and 0.2, respectively. Plasma gasification gives a higher H₂ and CO concentration and has lower impurity components (H₂S and NH₃) than conventional gasification. The system efficiency of conventional gasification of 54 % is higher than plasma gasification is 45 %, due to the plasma torch using an amount of energy to utilize in the process.

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