An Investigation on Gasification Conversions of Municipal Solid Waste Using Fixed Bed Downdraft: Study Case of Final Processing Site TPA Putri Cempo Surakarta Indonesia

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Abstract

Municipal solid waste (MSW) is still a problem in its management. In accordance with the government program contained in presidential regulation number 35 of 2018 that the acceleration of waste processing development into electric energy based on environmentally friendly technology needs to be developed. One of the technologies to convert waste into renewable energy is to use thermochemical processes or gasification. The aim of this paper is to investigate the conversion of municipal solid waste gasification (MSW) using a fixed bed downdraft gasifier by calculating the mass balance of municipal solid waste (MSW) to be converted into syngas with variation of air-fuel ratio (AFR) of 0.1 to 1.0 and gasifier temperature at 500-1000°C. The results showed that the fixed bed downdraft gasifier produced syngas with composition of CO (24.78%), CO_2 (18.65%), H_2 (15.6%), and CH_4 (4.06%), with an AFR of 0.3 at a gasification temperature of 600 °C.

Keywords: municipal solid waste, fixed bed downdraft, gasification, syngas

1 Introduction

Wastes are secondary biomass, as they are derived from primary biomass (trees, vegetables, meat) during different stages of their production or use. MSW is an important source of waste biomass, and much of it comes from renewables like food scraps, lawn clippings, leaves, and papers. Nonrenewable components of MSW like plastics, glass, and metals are not considered biomass. The combustible part of MSW is at times separated and sold as refuse-derived fuel (RDF). Sewage sludge that contains human excreta, fat, grease, and food wastes is an important biomass source. Another waste is sawdust, produced in sawmills during the production of lumber from wood.

Municipal solid waste (MSW) incineration has advantages of energy recovery and weight/volume reduction. However, as environmental protection be- comes more and more important, the emission control on MSW incineration is also increasingly important. Municipal solid waste (MSW) processing is still a present problem in Indonesia. Approximately 65 ton of waste is produced annually in Indonesia. Only 7% of the waste is recycled while 69% of waste is discharged into 94 Final Processing Site

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(landfill) throughout the country, and the rest 24% is discharged directly to the environment as illegal dumping [1][2]. The study case in his paper is Final Processing Site TPA Putri Cempo Surakarta in Central Java, Indonesia. TPA Putri Cempo in Surakarta have been operated since 1987, with capacity of 100,000 ton in 17 Ha of land [3]. Number of solid wastes produced in the township of Surakarta is presented in Table 1 and 2.

Table 1. Production of MSW in Surakarta [4]

Description	Volume (ton)
Daily waste production	346
Daily waste transported	295
Annual accumulation of waste in Final Processing Site	107,873

Table 2. Monthly MSW Production in Surakarta, year 2020 [5]

Month	Environmental Office	Trade Office	Village	Public	Total	Daily average
January	2.320	878	6.218	612	10.027	323
February	2.169	913	5.878	588	9.548	329
March	2.198	844	6.253	626	9.921	320
April	1.817	701	5.305	484	8.307	277
May	1.870	738	5.340	462	8.410	271
June	1.895	776	6.009	679	9.359	312
July	1.696	721	5.937	683	9.036	291
August	1.587	691	6.543	574	9.395	303
September	1.369	599	6.061	564	8.593	286
October	1.348	588	6.080	536	8.552	276
November	1.294	565	5.907	621	8.388	280
December	1.261	526	6.028	522	8.337	269
Total	20.824	8.539	71.558	6.952	107.873	295

Table 1 and 2 shows the mass of MSW produced in Surakarta is 107,873 ton in 2020. Composition of MSW is 70.34% organic and rubber/ leather waste 0.43%. This high amount of waste produced poses high environmental risk in the future if not managed properly. Currently, Indonesian government planned to develop 12 MSW-fed Power Plant in 2019-2022 with output target of 234 megawatt of electricity [6]. Government issue a Presidential Decree (PP) No. 18 year 2016 about Acceleration of MSW-fed Power Plant Development in Province of DKI Jakarta, Tangerang, Bandung, Semarang, Surakarta, Surabaya, and Makassar, in which in article 1 point 3 directing the implementation of thermal process such as incineration, gasification, and pyrolysis [7].

Gasification is a thermo-chemical energy-production process which is classified between combustion and pyrolysis. The carbo- naceous matter of the inserted feedstock material undergoes several different processes during the gasification. The first chemical process which takes place inside a gasification reactor is the pyrolysis of the feedstock, where volatiles are released and char is produced. Afterwards, the volatile products and some of the pyrolysis char react with oxygen to primarily form carbon dioxide and small amounts of carbon monoxide in the combustion zone. Finally, during the gasification process itself, the char reacts with carbon dioxide and a gasification agent (air/steam/oxygen) to produce carbon monoxide and hydrogen [8].

Gasification process as method for MSW treatment has been implemented in various country such as Finland, Denmark, Thailand, Sri Lanka, and Cambodia [9]. Gasification process of MSW is projected to play an important role in energy production and conversion. Implementation of gasification process contributes in energy resilience, climate change mitigation, sustainable development of township. Gasification is a thermochemical process that convert carbon from biomass into syngas [8], [10], [11]. Gasification occurred when oxygen (O_2) or air is reacted with carbon from biomass, or any other carbon source, in a high temperature inside a gasifier. The process is consisting of three parts: pyrolysis, gasification, and partial combustion. Partial combustion is required to supply heat for endothermic gasification reaction [12]. The product is syngas which contain carbon monoxide (CO) and hydrogen (H_2) that can be use further for industry and household utilization. Gasifier is not only utilized in chemicals or petrochemicals industry, but also in various other industries.

A lot of research has been performed on the development of gasification simulation models. A main objective of these models has been to provide qualitative guidance on the effect of design, operational and feedstock parameters of a gasifier. These models may be classified in four groups: (1) Kinetic, (2) Computational Fluid Dynamics (CFD), (3) Thermodynamic equilibrium and (4) Artificial neural networks [8]. Research on gasification process modelling is relatively limited, even though there are some substantial research on gasification of MSW, sugar cane bagasse, plant waste, ang various other waste products.

Li Erping *et al.* [13] studied about modelling using ASPEN Plus, and the result shows conformity of experimental data and simulation. Operation using MSW feed on Fixed bed gasifier at atmospheric condition, temperature of 900 ºC, air to fuel ratio of 0.4, and steam to MSW ratio of 0.4 resulting in equilibrium mass balance and heat balance. Ramzan *et al.* [14] developed a steady state model using ASPEN Plus to study gasification of MSW from food waste and poultry waste, then validate the model using experimental data obtained from hybrid biomass gasifier. Ramzan *et al.* [14] also evaluate the effect of equivalent ration (ER), gasification temperature, and moisture content to the performance of gasification process. Other study conducted by Chen et al. [15] use ASPEN Plus simulator to predict result of gasification of MSW and gives several basic processes related to production of syngas. The effect of gasification temperature, air equilibrium ratio, and moisture concentration to the composition of syngas, low heating value (LHV), heat conversion efficiency, and carbon conversion has been discussed. The results shown that higher temperature can increase gasification process, air equilibrium ration could be higher therefore carbon conversion is increased while LHV deceased, heat conversion efficiency increased and reach maximum, then decreased with the increase of ai equilibrium ration. High moisture concentration increases carbon conversion and improve efficiency of heat conversion at lower ratio. At 650ºC and ER 0.2, resulting LHV is 5,000 kJ/m^3. Begum *et al.* [16] studied about gasifier temperature of 650 °C and air-fuel ratio of 0.3 is a good combination of operating conditions for all four feedstocks; concentration of CO of 60%–75% can be achieved at gasifier temperatures of 650 °C to 800 °C; an air-fuel ratio of more than 0.3 provides decreasing CO concentration for MSWs and green wastes, whereas the concentration of CO increases with an increase in air-fuel ratio for food wastes and coffee bean husks; and concentration of H2 decreases until gasification temperature reaches 700 °C, then increases with the increase in temperature. The developed model can be useful for other biomass feedstocks to predict the syngas composition. The purpose of this study was to investigate the conversion of municipal solid waste gasification (MSW) using a fixed bed downdraft gasifier by calculating the mass balance of municipal solid waste (MSW) to be converted into syngas with variation of air-fuel ratio (AFR) of 0.1 to 1.0 and temperature at 500-1000ºC. Furthermore, the impact of temperature and air equivalence ratio on yield and quality of syngas will be studied.

2 MATERIAL AND METHODS

Municipal Solid Waste (MSW) Characterisation

Municipal solid waste (MSW) characteristics and input parameter of operating condition of gasifier is presented in Table 3 and Table 4, respectively.

Table 3. Characteristics of MSW

Parameter	Value	Unit
Moisture Content	20	%
Proximate analysis (dry basis)		
volatile matter	56,85	wt %
fixed carbon	9,78	wt %
ash	33,37	wt %
Ultimate analysis (dry basis)		
C	39,21	wt %
H	5,53	wt %
O	20,86	wt %
N	0,73	wt %
S	0,31	wt %
Ash	33,37	wt %

Table 4. Operating condition of gasification

Parameter	Description	Value
Feed	Flow rate (kg/h)	1788
	Pressure (bar)	1
	Temperature (°C)	25
Air	Flow rate (kg/h)	1-10
	Pressure (bar)	1
	Temperature (°C)	25
Gasifier	Pressure (bar)	1
	Temperature (°C)	500-1000

Gasification Process

The gasification process of the continuous solid waste gasification (MSW) system is designed with a municipal waste feed capacity (MSW) of 1788 kg/hour, Air to fuel ratios were 0.1-1,0 Mass equilibrium was at gasification process condition of 1 bar and 600 ºC with the assumptions used are: (a) steady state conditions, free kinetics reaction, and isothermal, ; (b) The chemical reaction occurs in equilibrium in the gasifier and no pressure loss occurs; (c) all elements except sulfur are included in chemical reactions; (d) all gases are considered Ideal Gases, including hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), water vapor (H_2O), nitrogen (N_2), and methane (CH_4); (e) Char contains only carbon and ash in solid form. This model was developed based in minimalization of Gibbs free energy in equilibrium. Assumption that residence time is sufficient for reaction reach equilibrium was also used in model development. The gasification process flow diagram is shown in fig. 1.

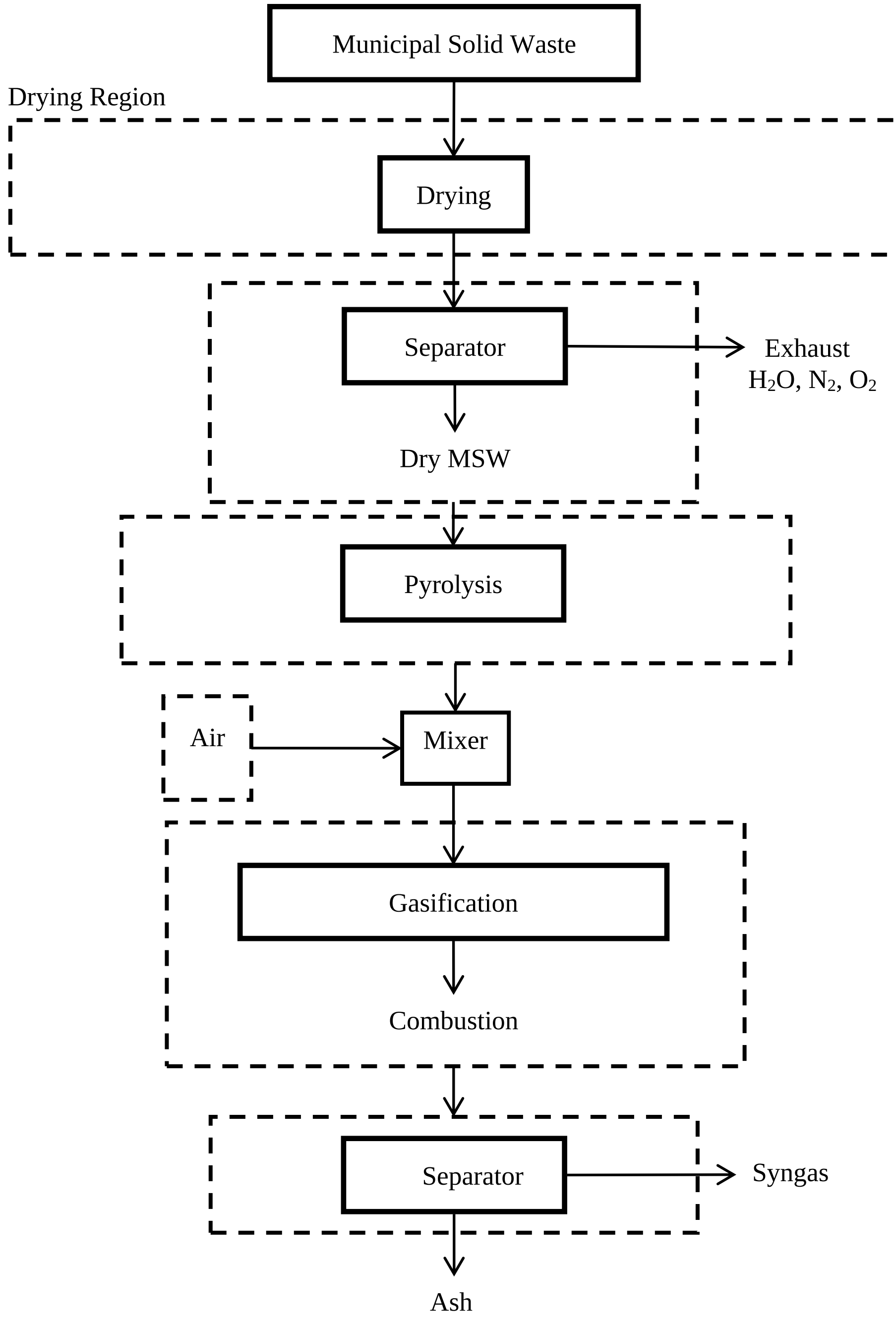


Fig. 1. Flowsheet of MSW gasification

Gasification begin from decomposition (pyrolysis) followed with combustion. The following reactions (1)-(7) were included in the process [15][17].

$$C + O_2 \rightleftharpoons CO_2 \text{ (carbon combustion)} \quad (1)$$

$$C + 0.5O_2 \rightleftharpoons CO \text{ (carbon combustion)} \tag{2}$$
$$C + CO_2 \rightleftharpoons 2CO \text{ (Boudouard)} \tag{3}$$
$$C + H_2O \rightleftharpoons CO + H_2 \text{ (water – gas)} \tag{4}$$
$$CO + H_2O \rightleftharpoons CO_2 + H_2 \text{ (CO shift)} \tag{5}$$
$$C + 2H_2 \rightleftharpoons CH_4 \text{ (methanation)} \tag{6}$$
$$H2 + 0.5O_2 \rightleftharpoons H_2O \text{ (hydrogen combustion)} \tag{7}$$

Dryer

In this step, each raw material moisture contents were partly evaporated and separated using separation through separating fractionation of component. Dry raw material shifted to next region for decomposition after evaporation. Operating condition was mass flow rate of 1,788 kg/h, 25 ^oC, and 1 bar pressure. MSW was fed into drying unit to be dried, together with nitrogen. The nitrogen feed flow rate was 22,679.6 kg/hour at 132.2^oC, 1 bar pressure. Dryer reduce the moisture content of the feed MSW and the output H_2O from dryer was known to be 100.605 kg/h. Drying convert part of feed to form water which require reaction level of:

$$\text{Feed} \rightarrow 0{,}0555084\ H_2O \tag{8}$$

Separator

Output of dryer was then fed into separator (Dry Flash) unit. The objectives were to separate dried MSW (dry MSW) with the output of exhaust which contain H_2O, N_2, and O_2. Input stream of Dry Flash use operating condition dryer at temperature of 100.8 ^oC, 1 bar pressure, and mass flow rate of 24,466.1 kg/h while output stream of dry flash with operating condition exhaust was 100.8 ^oC, pressure of 1 bar, and mass flowrate of 22,876.7 kg/h. Input stream from dried MSW with operating condition of temperature of 100.8 ^oC, 1 bar pressure and mass flow rate of 1,589.33 kg/h.

Decomposition

Decomposition is one of the steps of gasification where raw material was being decomposed into its element. During this step, decomposition was used to convert MSW into feeding input to a yield into components like H_2O, H_2, O_2, N_2, S, ash, C, and CH_4. Operating condition was at temperature of 100 ^oC, 1 bar pressure.

Gasifier Reactor (R-Gibbs)

Gasifier reactor is the reactor for multiphase chemical equilibrium based on minimizing Gibbs free energy. R-Gibbs was used to simulate biomass gasification. Gibbs free energy from biomass could not be calculated because it is a non-conventional component. Therefore, prior to inputting biomass into R-Gibbs block, it was decomposed into its elements (C, H, O, N, S) using reactor R-Yield. Reactor calculate the syngas composition by minimizing Gibbs free energy and assuming chemical equilibrium. Heat of reaction associated with decomposition of feed passed through heat stream into Gibbs reactor where gasification occurred. Feed and decomposed air enter reactor where partial oxidation reaction occurred and leftover carbon was in solid form. Minimum heat produced during gasification exited through heat stream. A separation was used to separate ash from gas mixture using split component fractionation. Gasification reaction with mechanism as follow:

$$C + CO_2 \rightleftharpoons 2CO$$
$$C + H_2O \rightleftharpoons CO + H_2$$
$$C_nH_m + nH_2O \rightarrow nCO$$
$$C_nH_m + nCO_2 \rightarrow 2nCO + \frac{m}{2}H_2$$
$$CO + H_2O \rightleftharpoons CO_2 + H_2$$
$$C + 2H_2 \rightarrow CH_4$$

Combustion

To complete the gasification process, another reactor was used in combustion region with minimal air mixing. Combustion process was based on minimizing Gibbs free energy as well. To identify syngas component from by-product. The following reactions occurred during combustion:

$C + 0{,}5O_2 \rightarrow CO$
$CO + 0{,}5O_2 \rightarrow CO_2$
$H_2 + 0{,}5O \rightarrow H_2O$
$CnHm + (n + \frac{m}{4})O_2 \rightarrow nCO_2 + \frac{m}{2}H_2O$

3 Result and Disscusion

Effect of Air to Fuel Ratio

Air to fuel ratio is defined as the amount or air required for certain unit of fuel to complete the combustion, which affects the production of syngas. Fig. 2. shows the effect of air-fuel ratio to the composition of syngas at gasifier temperature of 600 ^{o}C.

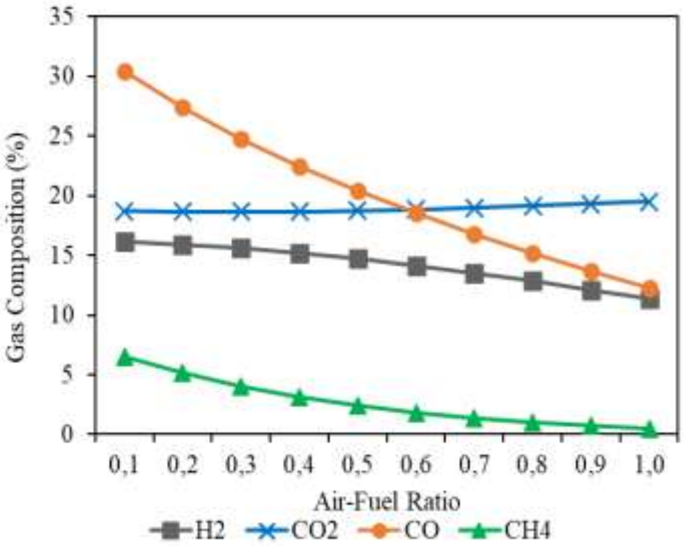
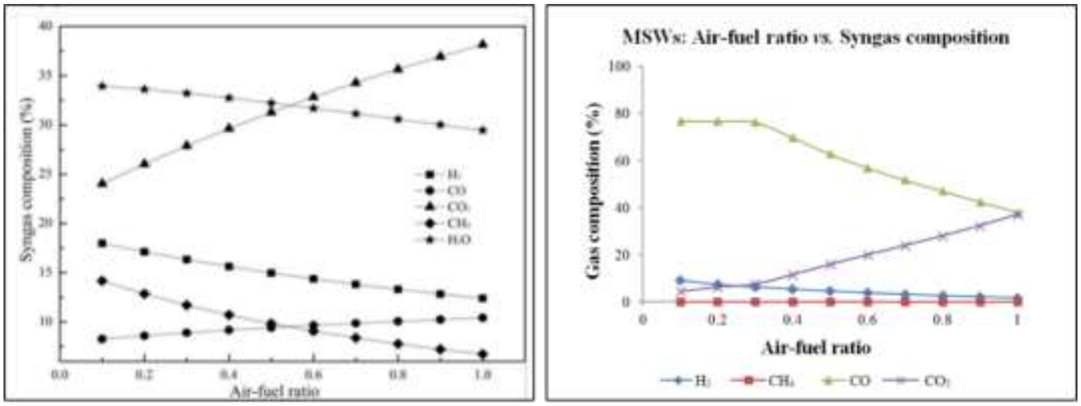


Fig. 2. The effect of air-fuel ratio to syngas composition at gasifier temperature of 600^{o}C

Fig. 2 describes that percentage of CO_2 is increasing from 18.70% to 19.50% (increase of 4.3%) with the increase of air-fuel ration. Percentage of CO decrease from 30.42% to 12.22% with the increase of air-fuel ration stepwise from 0.1 to 1.0. Percentage of H_2 decrease from 16.14% to 11.35% (deceasing 42.2 %) while CH_4 is also decreasing from 6.54% to 0.50%. In the reaction, carbon reacted with steam and resulting syngas component CO and H_2. Consecutively, shifting reaction CO resulting in CO_2 and H_2 which react with steam and CO. According to Fig. 2, it is observable that AFR 0.3 is the air-fuel ratio that has been simulated and referring to correlated journal (Fig. 3).

Fig. 3(a) shows the influence of air-fuel ratio on syngas under 900°C. CO_2 concentration increased from 24% to 38.1% and CH4 decreased from 14.2% to 6.7% when ratio of air-fuel increased from 0.1 to 1. H_2 concentration decreased from 18% to 12.4% with a rising air-fuel ratio, but CO concentration increased by 2.2%. Increasing in air-fuel ratio benefits the oxidization reactions, but reduces the flammable gases content (CO, CH_4 and H_2) [13]. The composition of syngas produced from MSW gasification (gasifier temperature: 700 °C) is shown in Fig. 3(b) [16]. It can be seen from Fig. 3(b) that the concentration of CO_2 increases (10% to 40%) with increasing air-fuel ratio and that of CO decreases (75% to 40%) after the air-fuel ratio increases from 0.3 to 1.0. It can also be seen that the concentration of H_2 decreases (10% to 2%), whereas CH_4 does not vary with air-fuel ratio [16].



(a) (b)

Fig. 3. Validation of effect of Air-Fuel Ratio to syngas composition [13], [16]

Effect of Temperature

Gasifier temperature was varied from 500°C to 1000°C. The effect of gasifier temperature to mol fraction of syngas from MSW is presented in Fig. 4.

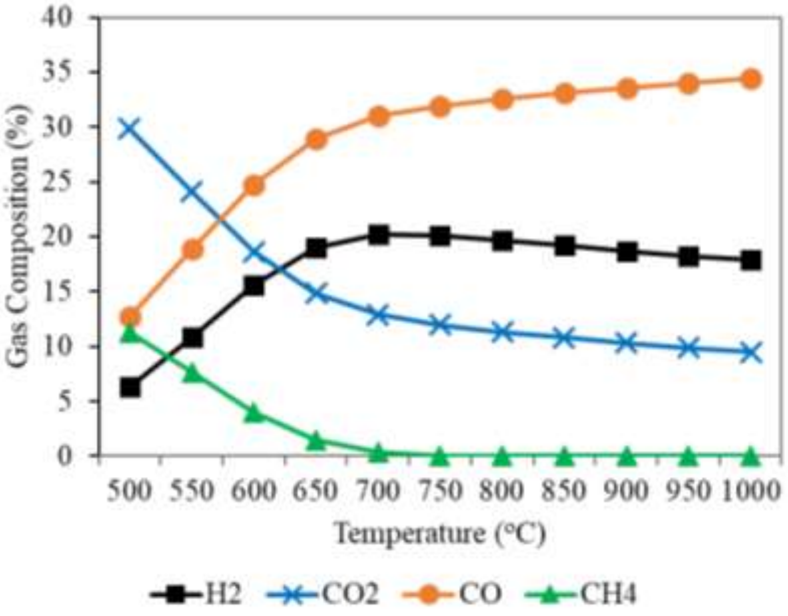
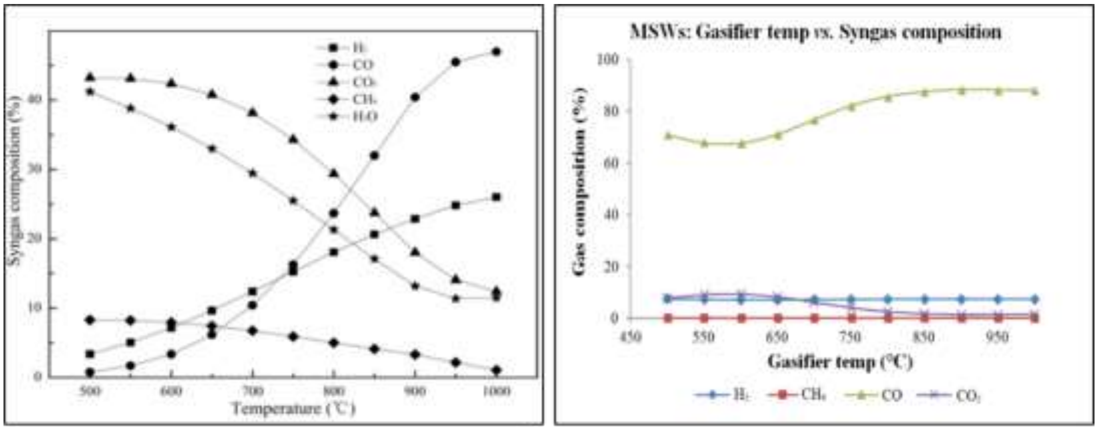


Fig. 4. Effect of gasifier temperature to mol fraction of syngas

Fig. 4. shows that at 500 ºC, carbon in MSW is not fully converted therefore the syngas production is low. With the increase of temperature, more carbon was being oxidised and conversion in increased. At low temperature, both carbon which is not combusted and methane both present in syngas, however with the increase of temperature carbon was converted into carbon monoxide according to Boudouard reaction. Methane was converted into hydrogen through methanation reaction. This increase the temperature of gasifier which promoted production of hydrogen and carbon monoxide. As results gas calorific value increases. According to Boudouard reaction, when gasifier temperature increases mol fraction of carbon monoxide will increase and mol fraction of carbon dioxide decrease. Reaction shows that high temperature increases the production of carbon monoxide and hydrogen. According to methanation reaction (6), mol fraction of methane in syngas will decrease and hydrogen fraction increase with the increase of temperature. At higher temperature above 650 ºC, H_2 and CO start to reduced. Methane production is decreased at temperature higher than 650 ºC. Gasification temperature control the chemical reaction equilibrium [18]. Using air-fuel ratio of 0.3, temperature of gasifier varied from 500 ºC to 1000 ºC, on MSW the concentration of CO increases (12,71% to 34,41%) with the increase of gasifier especially higher than 650 ºC. On the other hand, CO_2 decreases (29,86% to 9,52%) as shown in Fig. 4. Composition of H_2 is increases (6,37% to 17,87%) and CH_4 decreases (11,28% ke 0,1%), while closing to 800 ºC and beyond the curve tend to be unaffected by increase of gasification temperature.



(a) (b)

Fig. 5. Effect of gasifier temperature to mol fraction of syngas [13], [16]

Fig. 5(a) shows the influence of gasification temperature on the compositions of syngas. As it shown, the H_2 and CO concentrations increased significantly when the temperature increases while CO_2 and H_2O concentrations decreased. On the other hand, the concentration of CH_4 decreases from 8.2 % to 1.1 % with temperature increasing [13]. Concentration of CO increases (75% to 90%) with increasing gasifier temperature, particularly after 650 °C; conversely, CO_2 decreases as shown in Fig. 5(b). H_2 and CH_4 both vary slightly with increasing temperature [16].

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4 Conclusion

This study aims to determine the conversion of municipal waste gasification (MSW) using a fixed bed downdraft gasifier by calculating the mass balance of municipal waste (MSW) to be converted into syngas. Resulted in syngas with composition of CO (24.78%), CO_2 (18.65%), H_2 (15.6%), and CH_4 (4,06%) at air-fuel ratio 0.3 and gasification temperature 600 ºC. Gasification temperature varied from 500 ºC to 1000 ºC gives the effect of increasing CO composition (12.71% to 28.92%) and increase of H_2 (6.37% to 19.03%) with the increase of gasification temperature especially higher than 650 ºC. On other side, CO_2 and CH_4 decrease 29.85% to 14.82% and 11.28% to 1.49%, respectively.

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