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Direct chemical-looping gasification of municipal solid waste: Process analysis and evaluation

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Abstract

Municipal solid waste (MSW) can be considered a potential fuel for energy production. However, due to the high moisture content in this fuel type, conventional energy conversion processes (e.g., combustion and gasification) usually require an additional pre-drying process. In this study, the direct chemical looping gasification (DCLG) is proposed to directly convert MSW into synthesis gas (syngas). The moisture contained in MSW is used as a gasifying agent. Modeling of the DCLG is performed using existing process models in Aspen Plus. The validated model is employed to simulate and evaluate the performance of DCLG using MSW, regarding the syngas production and energy usage. Effects of moisture content, gasification temperature, and oxygen carrier-to-carbon in MSW feed molar ratio (Ω), on the composition and heat requirement of the DCLG are evaluated as well. The simulation results indicate that under the gasifier temperature of 850 ºC , moisture content of 48 wt.% and Ω of 0.25, the obtained syngas consists of 41.92 mol% H_2, 19.80 mol% CO, 24.40 mol% CO_2, and 13.87 mol% CH_4 with the lower heating value of 11.99 MJ m-3 . Increased Ω factor results in the significant increase of carbon dioxide in the syngas obtained from the DCLG process.

Keywords: Chemical looping gasification, Waste-to-Energy, Municipal solid waste, Synthesis gas

Introduction

The rapid growth of the world population has resulted in rising energy demand and increased solid waste. Presently, the main sources of energy are derived from fossil fuels which cause the emissions of greenhouse gases. As the global warming crisis is the major concerns, finding clean and environmentally friendly energy sources has been received considerable attention. As a result, changing this waste into energy is the solution that can decrease the environmental impact and response to the increased energy demand.

The widely-used waste-to-energy technology involves thermochemical processes because they can handle a large quantities of wastes in less time. Various thermochemical processes include combustion, gasification, pyrolysis and chemical looping [1]. For the gasification process, the steam gasification is extensively employed because steam as a gasifying agent, can improve the hydrogen (H_2) yield in the synthesis gas (syngas) product. However, the steam gasification is not suitable for high-moisture biomass like a municipal solid waste (MSW) due to the negative impact of high moisture on the gasification process, decreasing a quality of the syngas product and increasing a heat demand for the process[2]. The direct chemical looping gasification (DCLG) is a modified gasification technique using oxygen carriers instead of molecular oxygen in air. This process consists of two reactors, i.e., a fuel reactor and an air reactor. Mattison et al. [3] analyzed the energy balance of the chemical looping process using Cu-based and Ni-based oxygen carriers. They reported that the heat of endothermic reaction in the fuel reactor was supplied by oxygen carriers that circulated from the air reactor and thus, the process did not require the external heat. Zeng et al. [4] studied the syngas production from biomass in the chemical looping gasification using self-moisture in biomass feedstock. They found that the moisture content in biomass increased gas yield and the mixture of oxygen carrier and moisture content encouraged the reactivity in the process.

The aim of this work is to evaluate and analyze the direct chemical looping gasification using MSW as feedstock and moisture content in MSW as gasifying agent. Modeling the gasification process is performed by using

Aspen Plus simulator. Cu-based material is used as an oxygen carriers because it has higher reactivity than Fe-based oxygen carrier and cheaper than Ni-based oxygen carrier [5]. The effect of key operating parameters such as moisture content, temperature of fuel reactor and oxygen carrier-to-carbon in MSW feed molar ratio, on the syngas composition and heat required in process is investigated.

Modeling of the direct chemical looping gasification process

1. Municipal solid waste

In this study, the properties of MSW is obtained from the proximate and ultimate analysis as reported by Laxmi et al. [6] and given in Table 1.

Table 1 Properties of municipal solid wastes used in this study

Proximate analysis (wt.%, dry basis)		Ultimate analysis (wt.%)	
Volatile matter	46.15	C	30.77
Fixed carbon	7.70	H	4.62
Ash	46.15	O	17.30
Moisture	48 wt.%	N	0.77
		S	0.39
		Cl	-
		Ash	46.15

2. Model assumptions

Modeling of the chemical looping gasification was based on a chemical equilibrium approached and performed by using Aspen Plus simulator. The following assumptions were made; (1) this process was operated under steady state and isothermal conditions; (2) all reactions were considered at equilibrium; (3) the product gases contained H_2, CO, CO_2, CH_4, H_2O, N_2, NH_3, H_2S and HCl only; (4) char was only assumed as carbon; (5) ash was inert and does not participate in the reactions; (6) tar formation is neglected; (7) heat losses and pressure drop were not considered; (8) the influence of the particle size distribution of solid particle was neglected; (9) all the reactions were divided into two parts as follows [7-9]

Table 2 Main reactions in the direct chemical looping gasification

Reactions in the fuel reactor				**Reactions in the air reactor**	
Reaction		Reaction		Reaction	
$C + CO_2 \leftrightarrow 2CO$	(R1)	$CuO + H_2 \rightarrow Cu + H_2O$	(R9)	$Cu + 0.5O_2 \rightarrow CuO$	(R16)
$C + H_2O \rightarrow CO + H_2$	(R2)	$2CuO + C \rightarrow 2Cu + CO_2$	(R10)	$2Cu_2O + O_2 \rightarrow 4CuO$	(R17)
$CH_4 + H_2O \leftrightarrow CO + 3H_2$	(R3)	$2Cu_2O + C \rightarrow 4Cu + CO_2$	(R11)		
$CuO \rightarrow 0.5Cu_2O + 0.25O_2$	(R4)	$4CuO + CH_4 \rightarrow 4Cu + CO_2 + H_2O$	(R12)		
$C + 0.5O_2 \rightarrow CO$	(R5)	$S + 2H_2 \rightarrow H_2S$	(R13)		
$C + 2H_2 \leftrightarrow CH_4$	(R6)	$0.5N_2 + 1.5H_2 \rightarrow NH_3$	(R14)		
$CO + H_2O \leftrightarrow CO_2 + H_2$	(R7)	$Cl_2 + H_2 \rightarrow 2HCl$	(R15)		
$CuO + CO \rightarrow Cu + CO_2$	(R8)				

In the fuel reactor, the reactions (R1)-(R4) are highly endothermic. The reactions (R8)-(R12) in the fuel reactor and the oxidation reaction in the air reactor generate a large amount of heat for the endothermic reactions.

3. Process simulation

The municipal solid waste was defined as a non-conventional in the simulation and the Peng-Robinson with Boston-Mathias function (PR-BM) was used to calculate the thermodynamic properties [9]. In this study, an equilibrium reactor model based on the minimization of Gibbs free energy was used to simulate the gasification process. Figure 1 shows the simulation flowchart of the process and the description of the unit block in the flowsheet is given in Table 3. The MSW with the flow rate of 100 kg/h was fed to the reactor DECOM where the non-conventional components in biomass is converted into the conventional components. Because of kinetic limit, it is difficult to keep the complete char conversion. Therefore, the char provided to the fuel reactor was set to 0.9 and the remaining char was burned in the air reactor using the SEP block [7]. After splitting char, the stream was fed into

NSCL. The FR block was used to simulate the reactions ((R1)-(R12)) in the fuel reactor. Due to the thermodynamic equilibrium, the formation of CO_2 and CH_4 were underestimated while the formation of H_2 and CO were overestimated. For this reason, the equilibrium temperatures of the reaction (R3) and (R7) were restricted at a temperature of 335 ºC below the gasification temperature and 300 ºC above the gasification temperature, respectively [9]. In the FR block, the calculation option was set by using 'Restrict chemical equilibrium – specify temperature approach [6]. Oxygen carriers separated by CYCLONE1 was sent to the air reactor (AR block) where the reactions (R16)-(R17) were occurred. In this study, the impact of the moisture content in MSW (from 0 to 48 wt.%), the gasification temperature in fuel reactor (from 750 to 950 ºC) and the oxygen carrier-to-carbon in MSW feed molar ratio (from 0 to 1), on the composition of the syngas product is analyzed. The oxygen carrier-to-carbon in MSW feed moles ratio is defined by Eq. (1) [7]

$$\Omega = \frac{\text{moles of CuO}}{\text{moles of carbon in MSW}} \quad (1)$$

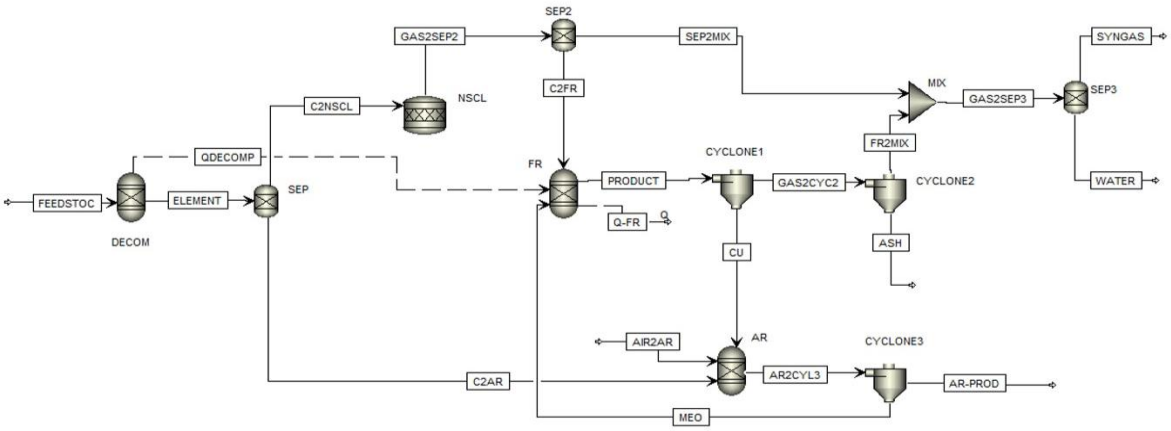

Figure 1 Simulation flowsheet of the direct chemical looping gasification process.

Table 3 Description of the unit block used in the simulation.

Block name	Block type	Description
DECOM	RYIELD	The conversion of non-conventional component into conventional components using calculator block
SEP	SEPARATOR	Separator of char and unconverted carbon
NSCL	RSTOIC	Reactor used for the simulation of NH_3, H_2S and HCl formation
SEP2	SEPARATOR	Separator of NH_3, H_2S and HCl
FR, AR	RGIBBS	Equilibrium model based on minimizing Gibbs free energy.
CYCLONE 1	CYCLONE	Separator of oxygen carriers which were reduced and product gas
CYCLONE 2	CYCLONE	Separator of ash and product gas
MIX	MIXER	Integrate NH_3, H_2S and HCl with product gas
SEP3	SEPARATOR	Separator of water and syngas
CYCLONE 3	CYCLONE	Separator of oxygen carriers which were regenerated and flue gas

Results and discussion

1. Model validation

The model of the direct chemical looping gasification was developed from a conventional fluidized bed gasifier. However, the experimental data of the direct chemical looping gasification in the fluidized bed gasifier is quite limited. Thus, the developed model of the direct chemical looping gasification is validated with the conventional gasification. A comparison of the gas composition predicted by the developed model and real plant data in Güssing [9] is made. This plant is based on the gasification of wood chips with steam at 850 ºC. Table 4 shows the gas composition obtained from real plant data and simulation model used in this work under the same operation conditions. The results show the prediction error of 5% and 7% in estimating the H_2 and CO compositions, compared with real plant data.

Table 4 Composition of the product gas (% vol. dry basis) from simulation model and Güssing plant data

Product gas	Güssing plant	Model
H_2	35-45	50
CO	22-25	17
CO_2	20-25	22
CH_4	~10	11

2. Influence of moisture content in MSW

The effect of moisture content (MC) in the MSW on the gasification process was investigated. The fuel reactor is operated under the temperature of 850 ºC, atmosphere pressure and the oxygen carrier-to-carbon in MSW feed molar ratio of 0.25. Figure 2 shows the variation in the gas compositions depending on the moisture content (0 wt.% to 48 wt.%). When the moisture content increased, the H_2 production also increased from 12.5 mol% to 41.9 mol% while the production of CO and CH_4 were decreased due to the reactions (R2), (R3) and (R7). The reduction of CO was caused by the use of CO as a substrate in the reaction (R7), thus decreasing the CO production while the CO_2 increased. In Figure 3, when moisture content is increased, high energy is required to operate the gasifier and less heat is released from the process (from -212 to -2.42 MJ/h).

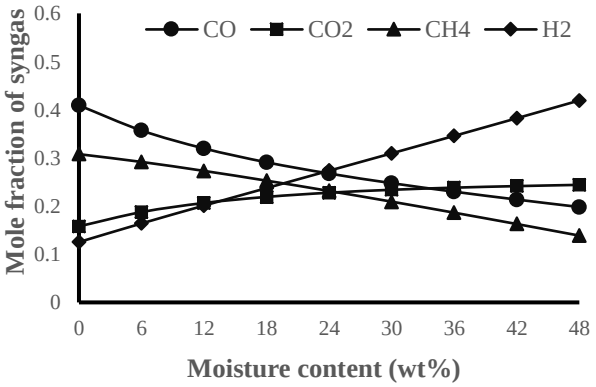

Figure 2 Effect of MC on syngas composition

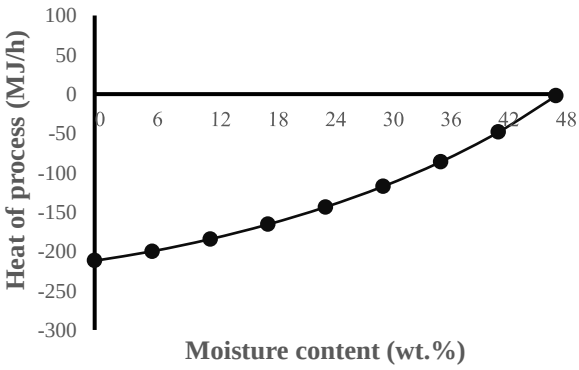

Figure 3 Effect of MC on heat of process

3. Influence of temperature in fuel reactor

Figure 4 shows the variation of gas composition as a function of temperature. The temperature of the fuel reactor was varied from 750 ºC to 950 ºC. When the temperature of fuel reactor was increased, the production of H_2 and CO were increased because the boudouard reaction (R1), steam gasification reaction (R2) and steam methane reforming reaction (R3) were endothermic and these reactions favored high temperatures. However, the increase in the temperature of the fuel reactor results in increased heat input. Figure 5 shows that when the temperature of fuel reactor was above 850 ºC, the external heat was required to the process.

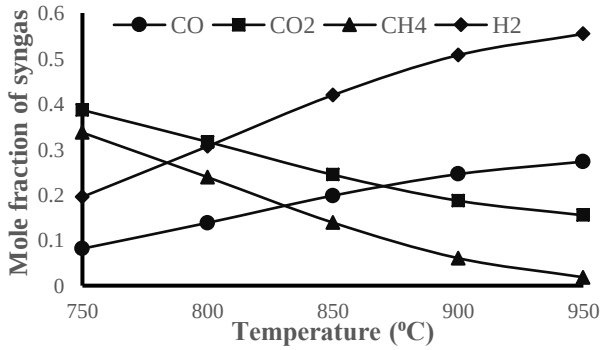

Figure 4 Effect of temperature on syngas composition

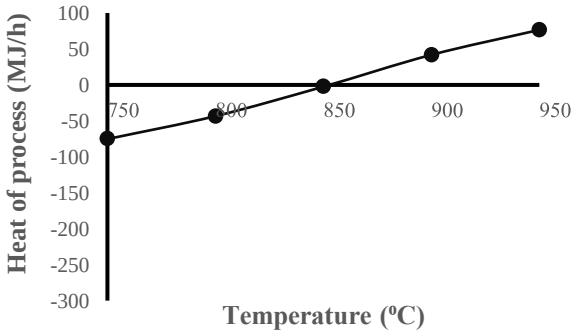

Figure 5 Effect of temperature on heat of process

4. Influence of oxygen carriers

In this study, the amount of oxygen carriers was considered in term of the ratio of oxygen carrier-to-carbon in MSW feed molar ratio (**Ω**) which was varied from 0 to 1. Figure 6 shows the variation of gas composition as a

function of the amount of oxygen carriers. It was found that the production of CO_2 was increased as **Ω** increased; the concentration of CO_2 increased from 18.3 mol% at **Ω** was 0 to 59.1 mol% at **Ω** was 1. Due to the increasing of oxygen carriers, the amount of oxygen in the process increased, resulting in the complete oxidation reaction with the product gas in the process. Increased **Ω** increases the heat of the process as shown in Figure 7. However, the amount of oxygen added to the process results in increased carbon dioxide. Therefore, limiting the amount of oxygen entering the process must be properly considered.

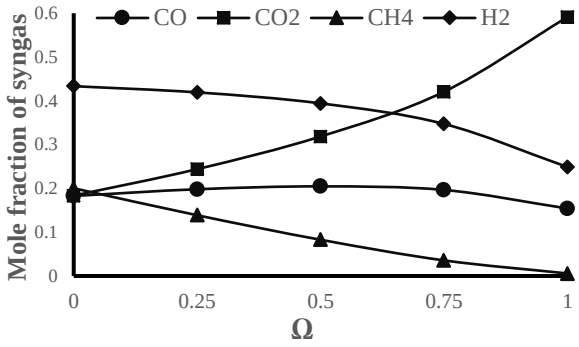

Figure 6 Effect of **Ω** on syngas composition

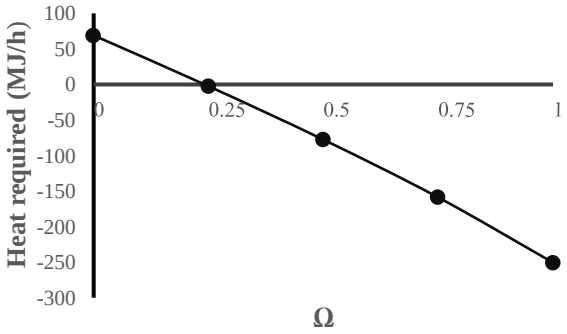

Figure 7 Effect of **Ω** on heat of process

Conclusion

In this study, the direct chemical looping gasification for converting a municipal solid waste (MSW) into a synthesis gas was investigated. Modeling the gasification process based on the thermodynamic approach was performed by using Aspen Plus simulator. The effects of moisture content in MSW, temperature of fuel reactor and oxygen carrier-to-carbon in MSW feed molar ratio, on the gas composition and heat requirement of the DCLG were evaluated. The simulation results showed that increasing moisture content can enhance the production of H_2 whereas heat required in process was increased. However, the heat from the air reactor can supply to the fuel reactor via the oxygen carriers. It was also found that the amount of oxygen carriers affects the generation of CO_2. For this reason, it was important to consider the suitability of the amount of oxygen carriers. In addition, when increasing the fuel reactor temperature, the composition of syngas were increased because the reactions of syngas production (the boudouard reaction, steam gasification reaction and steam methane reforming reaction) were endothermic reactions and favored high-temperature operation.

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