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Simulation of Poly-Generation System for Municipal Solid Waste Disposal Using Aspen Plus

Xuemei Deng, Le Wu*

Xi'an Key Lab of Green Hydrogen Energy Production, Storage & Application Integration Technology, School of Chemical Engineering, Northwest University, 710069, Xi'an, PR China
lewu@nwu.edu.cn

With the rapid growth of population and urbanization, the amount of municipal solid waste (MSW) generated in China has increased significantly. However, existing MSW treatment methods are costly. To further reduce the treatment costs, a poly-generation system for MSW disposal integrating pyrolysis and incineration was proposed. The system provided the gasoline produced from pyrolysis as the auxiliary fuel for the incineration process. The poly-generation system with a feed rate of 50 t/h, a treatment capacity of 3.175 t/h for pyrolysis and 46.825 t/h for incineration, is simulated by Aspen platform based on our previous study. The sensitivity analysis shows that the feed rate of feedstocks, incineration temperature, and moisture content of MSW have a significant positive influence on power generation. The simulation results of the MSW poly-generation system provide a basis for the subsequent optimization analysis.

1. Introduction

With rapid urbanization and economic development, the amount of municipal solid waste (MSW) is increasing. Approximately 1.9 Gt of MSW is generated annually worldwide, of which about 30 % is still not collected by municipal waste management systems (Nanda and Berruti, 2021). The prolonged accumulation of waste has detrimental effects on the natural environment and poses a threat to human life and safety. It is an urgent problem to identify and develop technologies for harmless waste disposal. MSW treatment technologies mainly include landfill, incineration, composting and pyrolysis. Landfill is the longest developed treatment technology, but it covers a large area and causes pollution that cannot be easily controlled. Composting technology utilizes natural microorganisms to degrade waste to produce organic fertilizer. However, composting is prone to produce irritating odor gases and greenhouse gases. The incineration process occurs with excess oxygen and temperatures above 800 °C. The waste incinerator covers a small area and can effectively eliminate pathogenic bacteria and other harmful substances from waste under high temperature operating environment, and the heat energy generated by the incineration process can be recycled. Incineration has received increasing attention for its superior performance compared to landfill and composting (Zhang et al., 2022). Han et al. (2023) found that dry matter content of waste has a significant impact on greenhouse gas emissions from the incineration process. In addition, after classifying waste, the increase in plastic content leads to more greenhouse gas emissions. Sabeti et al. (2022) found that incineration has the greatest potential for energy generation compared to anaerobic digestion and landfill gas. However, incineration has the highest total investment cost and operation and maintenance cost and is not economically feasible. Chen et al. (2022) proposed a new medical-waste-to-energy system based on plasma gasification and integrated with MSW incineration. The project has a short dynamic payback period and is economically feasible. However, waste classification was not considered. Pyrolysis is a process of thermal degradation by destroying chemical bonds of organic materials in an oxygen-free environment at 300 ~ 1,000 °C. Pyrolysis products usually include pyrolysis oil, gas and char (Varjani et al., 2022). Yang et al. (2018) conducted a comprehensive study on the yield of pyrolysis products of the organic part of MSW and found that pyrolysis temperature has a large impact on product yield and energy content, while feedstock moisture content has a smaller impact. The addition of catalysts to the pyrolysis process can reduce the oxygen content of the pyrolysis oil and obtain higher quality pyrolysis oil (Ly et al., 2022). Abdulkhani et al. (2023) found that the water and oxygen contents of bio-oil obtained in the presence of H-ZSM-5 catalyst were

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significantly reduced, and the heating values of catalytic pyrolysis bio-oil sample were increased. In the catalytic pyrolysis process, biomass feedstock, catalyst type, pyrolysis temperature and residence time significantly affect the yield and quality of bio-oil (Wang et al., 2022). Classifying waste before disposal can effectively reduce greenhouse gas emissions and promote the recycling of resources (Bian et al., 2022). A single treatment process has high investment cost and low benefit. In previous studies, few people have linked these treatment technologies to establish an integrated system and considered the classification of waste. The novelty and relevance of this study lies in first classifying MSW according to its formation, and then integrating incineration and pyrolysis technology to establish a poly-generation system for waste treatment and discussing the factors influencing the product yield of the system.
Integrating the waste incineration power generation section, pyrolysis section and fuel upgrading section to establish a poly-generation system can effectively reduce the treatment cost and increase the benefit. MSW is classified into plant waste, plastic waste, cloth waste and kitchen waste according to the formation of the MSW. Plant waste is pyrolyzed to produce bio-oil and bio-gas. The bio-oil is hydrocracked with excess hydrogen to produce gasoline and diesel. Gasoline is delivered to MSW incineration section for power generation as auxiliary fuel, and bio-gas and diesel can be sold as a by-product.
In this study, taking the MSW as feedstock, the Aspen Plus is used to simulate MSW poly-generation system, and the results of sensitivity analysis are discussed.

2. Aspen simulation

Aspen Plus is a chemical process simulation software based on steady-state simulation, optimization, sensitivity analysis and economic evaluation. It can be used to simulate various operational processes and from a single operating unit to an entire process. It is widely used in scientific research due to its complete database and accurate results in process modeling. Aspen Plus is used to simulate MSW poly-generation system in this study. MSW is classified into plant waste, plastic waste, cloth waste and kitchen waste. Based on our previous study (Lei et al., 2022), at a feed rate of 50 t/h of MSW, 3.175 t/h of plant waste for pyrolysis and the remaining MSW (including plant waste, plastic waste, cloth waste and kitchen waste) for incineration is the optimal configuration. The process flow diagram of the simulated MSW poly-generation system using Aspen Plus is presented in Figure 1. The purple lines represent feedstocks and the blue lines represent products.

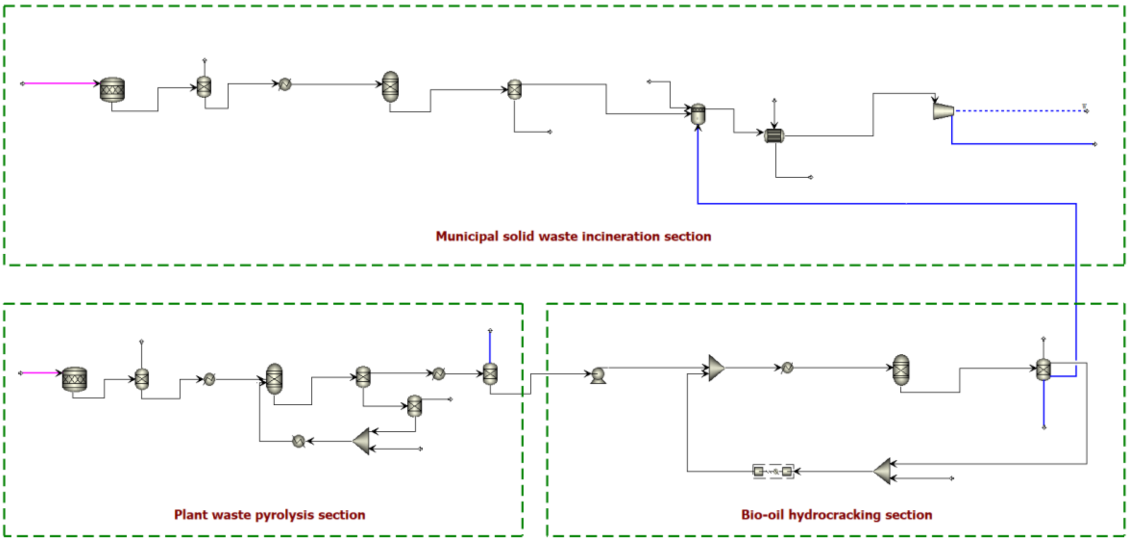

Figure 1: Diagram of the Aspen Plus flowsheet for MSW poly-generation system

2.1 Model assumption

The following assumptions are made for the whole simulation process: (1) all reactors operate stably and equipment parameters do not change with time, (2) the ash in feedstock is an inert component, (3) bio-char contains only solid carbon and ash, (4) there is no heat loss in the whole system, (5) pressure and gas loss and leakage are not considered.

2.2 Physical property method

The PR-BM method is used to estimate the physical properties of conventional components, considering that the MSW poly-generation system involves weakly polar mixtures. This method is based on the Boston-Mathiasα function and the Peng-Robinson cubic equation of state to determine the physical properties of compounds in the system. Plant waste, MSW and ash are considered nonconventional components, and their enthalpy and density are calculated using HCOALGEN and DCOALIGT in Aspen Plus, respectively. These unconventional compounds are modeled by proximate and ultimate analysis. The component attributes of plant waste (Lyu et al., 2020) and MSW (Sun et al., 2021) are shown in Table 1. Bio-oil, gasoline and diesel are considered to be pseudocomponents whose properties are defined by molecular weight, average normal boiling point and specific gravity.

Table 1: Component attributes of plant waste and MSW

	Proximate Analysis (dry basis)				Ultimate Analysis (dry basis)						
	Moisture (wet basis)	Fixed carbon	Volatile matter	Ash	C	H	O	N	S	Cl	Ash
Plant waste (wt.%)	10.20	17.28	78.59	4.13	45.99	6.33	42.91	0.11	0.53	0	4.13
MSW (wt.%)	44.00	6.13	63.05	30.82	37.36	5.21	25.27	0.95	0.18	0.21	30.82

2.3 Model description

The whole poly-generation system consists of three sections: plant waste pyrolysis, bio-oil hydrocracking and MSW incineration power generation. The blocks involved in the whole simulation process are shown in Table 2.

Table 2: Simulation flowsheet blocks

Equipment	Block type
Drier	RStioc
Separator	Sep
Heater	Heater
Pyrolyzer	RYield
Condenser	Heater
Mixer	Mixer
Pump	Pump
Compressor	MCompr
Hydrocracker	RYield
Decomposer	RYield
Burner	RGibbs
	RStioc
Boiler	HeatX
Generator	Compr

2.3.1 Plant waste pyrolysis

Plant waste pyrolysis consists of four processes: drying, pyrolysis, condensation and separation. The feedstock is dried from 10.2 wt% to 4 wt% moisture content using RStioc reactor as a drier. The drying operation is controlled by writing FORTRAN statement in the calculator block. The evaporated water is separated from the dry plant waste by a Sep block. The dry plant waste is first heated to 500 °C by a heater at atmospheric pressure. It is then converted into a mixture of fluids and solids in the RYield reactor together with sand used as a heat carrier. The pyrolysis mixture is separated by a separator. The solids comprise of bio-char and sand, of which the sand is recycled. The fluids enter the condenser and separator for condensation and separation to obtain bio-oil and bio-gas. The bio-oil is placed into the next section for hydrocracking and the bio-gas can be sold as a by-product. The yield of bio-oil during pyrolysis is 30 %, bio-gas is 27 % and bio-char is 43 %.

2.3.2 Bio-oil hydrocracking

Bio-oil is pressurized to 89 bar by pump. Hydrogen fed at normal temperature and pressure is compressed to 89 bar by a multi-stage compressor. The bio-oil is mixed with compressed hydrogen and fed to a heater and then into a cracker for cracking to produce gasoline and diesel. The excess hydrogen is recycled, and the resulting gasoline is used as an auxiliary fuel to enter the MSW burner. The diesel is sold as a by-product. The consumption of hydrogen during the hydrocracking of bio-oil is 200 Nm^3/t(bio-oil). The yields of gasoline and diesel are 42 % and 20 %, respectively.

2.3.3 MSW incineration

The drying process of waste is the same as that of plant waste. The wet MSW enters the RStioc reactor for drying with moisture content from 44 wt% to 10 wt%. The dry waste is heated and enters the RYield reactor for decomposition. Decomposition is one of the main steps of the combustion process, where each feedstock entering the decomposer is decomposed into its constituting components. The yield distribution is set according to the ultimate analysis of the MSW, in which the waste is decomposed into carbon, hydrogen, oxygen, nitrogen, chlorine, sulfur and ash. The decomposed products are separated from the ash by the separator, and the remaining products enter the burner for combustion with excess air. The combustion process is simulated using the Hierarchy block. The Hierarchy block contains two reactors: the RGibbs reactor and the RStioc reactor. The MSW combustion reaction occurs in the RGibbs reactor. The RGibbs reactor calculates the multiphase chemical equilibrium by minimizing the Gibbs free energy, without considering the specific reaction process and mechanism. This is because the heat released when gasoline and MSW are burned together in the RGibbs reactor cannot be fully utilized. Therefore, gasoline from the bio-oil hydrocracking process is combusted in the RStioc reactor under adiabatic conditions. The hot combusted gas from combustion enters the boiler for heat exchange with water. The water is heated into steam and enters the turbine to convert the heat energy of steam into electric energy, so as to realize the MSW incineration process for power generation.

3. Results and discussion

MSW poly-generation system was first simulated using Aspen Plus, and then sensitivity analysis of the poly-generation system was conducted to examine the factors influencing the products.

3.1 Simulation results

The final results of the simulation are shown in Table 3. When the feed rates of plant waste and MSW are 3.175 t/h and 46.825 t/h, respectively, and the incineration temperature is 850 °C, 1.20 t/h of bio-gas, 3.22 t/h of gasoline, 1.53 t/h of diesel, 239.50 t/h of steam and 36.09 MW of electricity can be obtained.

Table 3 Simulation results of MSW poly-generation system

Products	Values
Bio-gas/t·h^{-1}	1.20
Gasoline/t·h^{-1}	3.22
Diesel/t·h^{-1}	1.53
Steam/t·h^{-1}	239.50
Electricity/MW	36.09

3.2 Sensitivity analysis

In this study, the effects of different feed rates, incineration temperature and moisture content of waste on the production of electricity were investigated, and the results are shown in Figure 2. Figure 2(a)-(c) depict the effect of varying plant waste feed (0, ± 10 %, ± 20 %), MSW feed (same as plant waste) and total feedstock on electrical power generation. The result shows a positive correlation between feedstock and electricity production, as the RYield reactor used in the study regulates yield based on the set yield. Therefore, increasing feedstock results in increased product output, more heat released by combustion and eventually more power generated. Figure 2(d) shows the linear relationship between combustion temperature and electric quantity when the feed rates of plant waste and waste are 3.175 t/h and 46.825 t/h, respectively. Higher combustion temperatures lead to more thorough waste burning, longer burning times, and more heat released. Figure 2(e) shows the effects of moisture content of waste on power generation, with the variation range of moisture content ranging from 4 wt% to 44 wt%. The waste drying process was simulated by RStioc reactor and the conversion rate is controlled by a calculator. The figure illustrates a correlation between moisture content of MSW and power generation. A decrease in moisture content results in a reduction in the flow of dry material feed, and a decrease in power generation.

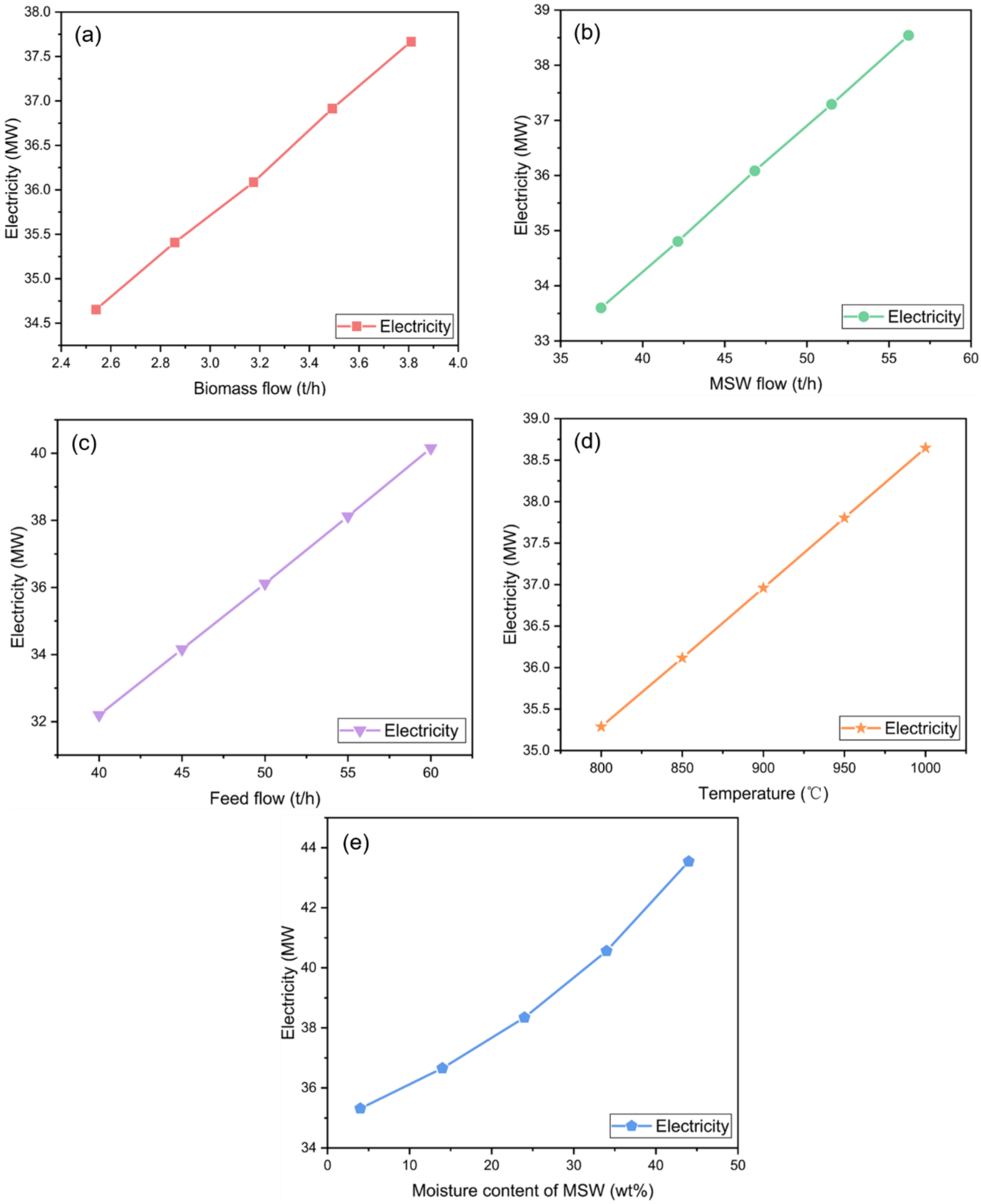

Figure 2: Impact of different influencing factors on power generation

4. Conclusion

In this study, the simulation of MSW poly-generation system is established by using Aspen Plus software, and the model development and simulation process of MSW poly-generation are introduced in detail. The influence of different feed rates, combustion temperatures and moisture content of waste on power generation is studied. Feed rate, combustion temperature and moisture content of MSW are positive correlation with power generation of MSW incineration. The model can be used to predict the performance of poly-generation systems in a wide range of operating conditions. This research provides valuable insights for enhancing the efficiency and sustainability of MSW poly-generation system. Further work can be addressed to estimate economic performance of poly-generation system.

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