Prospective lifecycle design through process modeling of energy recovery from waste plastics

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Abstract

A novel energy recovery process for waste plastics has been proposed that combines measures to increase operating rates by thermal spraying on the surface of boiler tubes at waste incineration plants to reduce ash adhesion and deteriorated heat transfer coefficient, and to recover waste heat to generate cold heat. A prospective lifecycle assessment is needed to propose the optimal combination of technologies and provide feedback for technology development. A computer-aided process flow was used to evaluate the size and operating load of the equipment required for the process, and the environmental load of manufacturing and operation was evaluated. The results of the sensitivity analysis show that the thermal spray treatment has a significant effect on annual power generation amount. As for the generation of cold heat, it was found that the waste heat from waste plastics can be supplied as cold heat at off-site locations with reduced environmental impact by improving the performance of the ice maker, absorption chiller, and mobile thermal energy storage system.

**Keywords**: Circular economy, Waste incineration, Waste heat recovery

* 1. Introduction

Plastics recycling should be implemented in a cascade of advanced sorting, material recycling, chemical recycling, and energy recovery, and its optimization is important. From the perspective of resource circulation, energy recovery should be avoided as much as possible, but this may result in inefficient energy recovery as plastics with high heating value are reduced from existing waste incineration plants. Therefore, this study focused on a novel energy recovery process (NEDO, 2022) that combines 1) prevention of boiler tube fouling (Naganuma et al.,2022) and 2) waste heat recovery with cold heat generation (Kimura et al., 2022) to maintain energy recovery rates. For the process of waste heat recovery, steam is generated from the exhaust gas and used as a heat source for an absorption chiller, and ice slurry is generated in conjunction with an ice maker.

The purpose of this study is to simulate a process that can recover unused energy, and to conduct a lifecycle assessment (LCA) to identify hot spots and provide feedback for further technology development. In order to clarify the effectiveness of fouling prevention of boiler tubes and waste heat recovery in a computer aided process model simulating the material and energy balance of a waste incineration plant developed in a previous study (Fujii et al., 2023), a sensitivity analysis was conducted using heat transfer coefficient in the boiler, performance of absorption chiller, ice maker and mobile thermal energy storage system.

* 1. Materials and Method
     1. Process modeling

Figure 1 shows the combined process of waste incineration and energy recovery. To improve the efficiency of energy recovery from waste incineration plants, two measures are being considered: one is a high-temperature measure to prevent fouling by thermal spray treatment of the surface of boiler tubes to reduce ash adhesion and to improve power generation and operating rates (Naganuma *et al*., 2022), and the other is a low-temperature measure to recover waste heat and generate cold heat by combining a two-stage absorption chiller and an ice maker (Kimura *et al*., 2022). Two types of waste heat recovery are considered: on-site cold heat recovery and off-site cold heat recovery via mobile thermal energy storage systems using adsorbent.

A process flow model has already been developed (Fujii et al., 2023) to simulate the material and energy balance of a waste incineration plant with a 200 t/year class waste input as shown in Figure 1. As a base case, the heat transfer coefficient of the waste boiler was assumed to deteriorate 50% linearly after 8 months of operation. Since the UA value (Overall heat transfer coefficient) of the boiler changes with heat transfer degradation, the UA value after renewal was set as the target value, and the steam flow rate was adjusted until the calculated UA value reaches the target UA value. The calculations were performed for each month, and the total value was used as the annual result. By thermal spray treatment of the boiler tubes surface, the operation period is assumed to be extended by 1 month.

* + 1. Setting for lifecycle assessment

The objective of the LCA in this study was to verify whether the novel energy recovery process can replace the conventional power generation recovery process at waste incineration plants with less environmental impact, and to provide feedback for further technology development for each component by conducting sensitivity analysis of system variation parameters. Manufacturing and operating environmental loads of equipment required for the novel process were considered as lifecycle environmental impacts as shown in Figure 2. The waste incineration plant was assumed to operate 24 hours per day, 300 days per year. The functional unit was defined as the operation of a waste incineration plant with a 200 t/year of municipal solid waste applying around 2,300 kW power generation. Material and energy balance results of waste incineration plant from the developed process flow model (Fujii et al., 2023) were used to identify foreground data such as heat exchanger size and required auxiliary power of various equipment, and background data were obtained from an existing database (AIST, 2019, ecoinvent v3.8, 2021). LCA using LIME2 (Itsubo and Inaba, 2012) considered climate change as an intermediate impact item. For the high-temperature side of the process, heat transfer area was calculated from the UA value of the boiler calculated in the developed process flow model, assuming 35 W/(m2·K) of heat transfer coefficient, and the required amount was calculated assuming the thermal spraying is done at a density of 8.0 kg/m2, and the manufacturing environmental load was calculated assuming the thermal spraying is done every 2 years. For the waste heat recovery process, a heat exchanger for waste heat recovery, a two-stage absorption chiller, an ice maker, a heat charging and discharging units for off-site mobile thermal energy storage system and adsorbent as heat storage material are required. For the heat exchanger for waste heat recovery, UA value was calculated in the process flow model, and the heat transfer area was calculated assuming 35 W/(m2·K) of heat transfer coefficient, and the manufacturing environmental load was calculated. For the absorption chiller, background data was used (ecoinvent v3.8, 2021). For the ice maker, a combination of heat exchangers, pumps, and tanks was assumed, and the capacity and heat transfer area of each were calculated from the process flow model, and the manufacturing environmental load was calculated. Reported inventory data were used for the heat charging and discharging devices (Fujii et al., 2022). The adsorbent was assumed to be zeolite 4A and manufacturing environmental load was calculated from the existing database (AIST, 2019). Each device was assumed to have a durability of 15 years. The operating load was calculated assuming the COP (Coefficient of performance) of the absorption chiller to be 0.23 (Kimura et al., 2022) and the auxiliary power of the ice maker to be 20%. For the mobile thermal energy storage system, the heat storage density was calculated by equilibrium adsorption water uptake before (4%) and after adsorption (23%) calculated using adsorption isotherms (Miyahara et al., 2020) and the amount of air introduced into the heat charging and discharging devices was calculated, and the blower power was calculated. The number of transports was calculated assuming a truck capacity of 10 t, and fuel consumption was calculated.

For the sensitivity analysis, the heat transfer coefficient of the boiler for the high temperature side, and the COP of the absorption chiller, the auxiliary power of the ice maker, and the heat storage density for the low temperature side were targeted.



Figure 1 Process flow of waste incineration plant with energy recovery process combined with high-temp. measure and low-temp. measure



Figure 2 Lifecycle boundary of energy recovery process

* 1. Result and discussion

The results of the heat transfer sensitivity analysis of monthly and accumulated power generation are shown in Figure 3. Cases in which the heat transfer deterioration can be suppressed by 100% (100% case in Figure 3) and 50% (50% case in Figure 3) due to the thermal spraying treatment after 9 months compared to the heat transfer coefficient in the 8th month of the base case were estimated.

When the operation period is extended by one month due to the thermal spraying treatment, the monthly power generation decreases with the decrease in hourly waste input, but the accumulated power generation increases over the base case due to the extended operation hours.



Figure 3 Annual and monthly power generation of base case, case of 50% and 100% heat transfer deterioration prevention (50% case/100% case)

Figure 4 shows the breakdown of lifecycle GHG (Greenhouse gas) emissions both on- and off-site cases, including cold heat generation, when heat transfer degradation is completely suppressed by thermal spray treatment. The deduction for electricity generation is large, indicating that the suppression of heat transfer deterioration is highly effective.

Figure 5 shows the results of the sensitivity analysis of lifecycle GHG emissions on the cold side. In both cases, absorption chillers, ice makers, and heat storage density all had almost similar sensitivity, indicating that improving the performance of either has a significant impact on lifecycle GHGs. Since off-site transportation is not expected to significantly reduce GHGs due to the large airflow and blower power requirements of the heat charging and discharging device and the large environmental impact of adsorbent manufacturing, performance improvement is mandatory.



Figure 4 Breakdown of lifecycle GHG emissions both on- and off-site cold energy recovery ((M) and (O) mean Manufacturing and Operating, respectively)



Figure 5 Results of sensitivity analysis for waste heat recovery side

* 1. Conclusions

The lifecycle assessment was conducted using a process flow that combines the power generation and operation rate improvement by thermal spraying with waste heat recovery and cold heat generation, which is being considered as the novel energy recovery process for the incineration of waste plastics. If the thermal spraying process can prevent the deterioration of heat transfer, it can be expected to improve annual power generation and reduce GHG emissions. It was found that cold heat generation is highly effective onsite, but when implemented offsite, the efficiency of the component equipment needs to be improved. In particular, since small-scale incineration plants and cold heat demand are often separated by distance, the energy recovery of waste plastics through improved performance of ice makers, absorption chillers, and mobile thermal energy storage systems is expected to be highly effective.

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