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Cost Saving of the Explosive Waste Incineration Process via an Optimal Heat Exchanger Network

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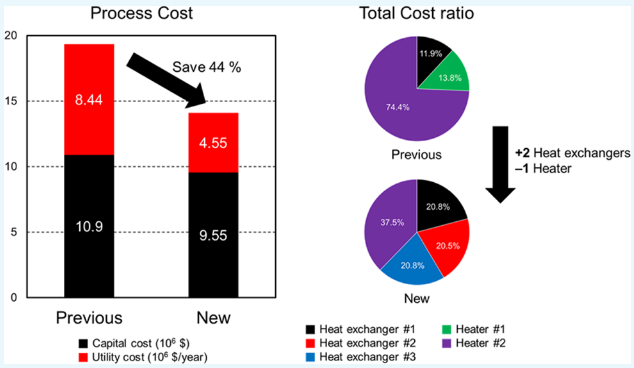

ABSTRACT: Explosive waste is very dangerous, and it should be incinerated under safe conditions. Currently, a rotary kiln is used to incinerate explosive waste; however, it creates air pollutants such as NO_x more than the government regulation (90 ppm). To this end, the fluidized bed was suggested, and previous study showed that it could be a new-generation incineration method since it creates NO_x less than regulation. Despite impressive results and many approaches to reduce NO_x emissions, it is still insufficient to apply the explosive waste incineration process. This is because this process has been studied only for NO_x emissions so far. Therefore, in this study, the heat exchanger network (HEN) was grafted and optimized to save the energy used in the process as much as possible based on the operating condition from previous study, which can emit the minimum NO_x. As a result, it was possible to save 44% of the total cost compared to the existing method without changing the operating conditions. This result is meaningful in that it is important not only to optimize the design condition of the reactor but also to apply the HEN which will be effective to save the process cost.

1. INTRODUCTION

To maintain national defense, the military always stocks up with sufficient military weapons. This process results in old weapons, which must be disposed of safely.[1] Explosive substances in old weapons, explosive wastes, are very difficult to incinerate because they are still explosive and sometimes react unpredictably.[2] In the past, primitive methods were used to incinerate them; however, a reactor called a rotary kiln is used currently.[3,4] Although the advantage of rotary kilns is that they can continuously process explosive waste, some problems are not solved yet.[5] In particular, it has a major disadvantage in that it emits more environmental pollutants such as NO_x than the government regulation (90 ppm) and requires the use of a purification process.[6] A huge amount of energy and cost is consumed in this process. In order to address this problem, a fluidized bed was suggested as a new type of incinerator.[7] As a result of the case study, it was found that the fluidized bed reactor could emit NO_x below the government regulation.[8] In addition, some approaches to reduce the NO_x emission concentration through optimization by using artificial intelligence were conducted.[9] As a result, it was shown that the explosive waste incineration process using a fluidized bed reactor can emit less pollutants than rotary kilns. Furthermore, the purification process was not required because of a lower NO_x emission concentration, and it was possible to save a lot of money for them. Despite the possibility to reduce the cost of disposing of explosive waste by eliminating the need for a purification process, previous studies have only focused on reducing the NO_x emission concentration.[10−12] As a result, the process cost increased exponentially as the NO_x emission concentration decreased.[13] In other words, NO_x emission concentrations and process costs were inversely related to each other. In this situation, it was judged that it is very difficult and time-consuming to perform multi-objective optimization considering both the NO_x emission concentration and the process cost. Therefore, a method was found to reduce the process cost without changing the process operating conditions, and it was determined that the energy and process cost could be saved by using the heat exchanger network (HEN).[14−16]

Of course, although the multi-objective optimization is valuable to reduce the process cost, it will take a lot of time to find optimal solution keeping NO_x regulation. Even though the multi-objective optimization will be conducted in the future after spending long time, the HEN can be applied in any cases because the HEN does not change the process condition. It

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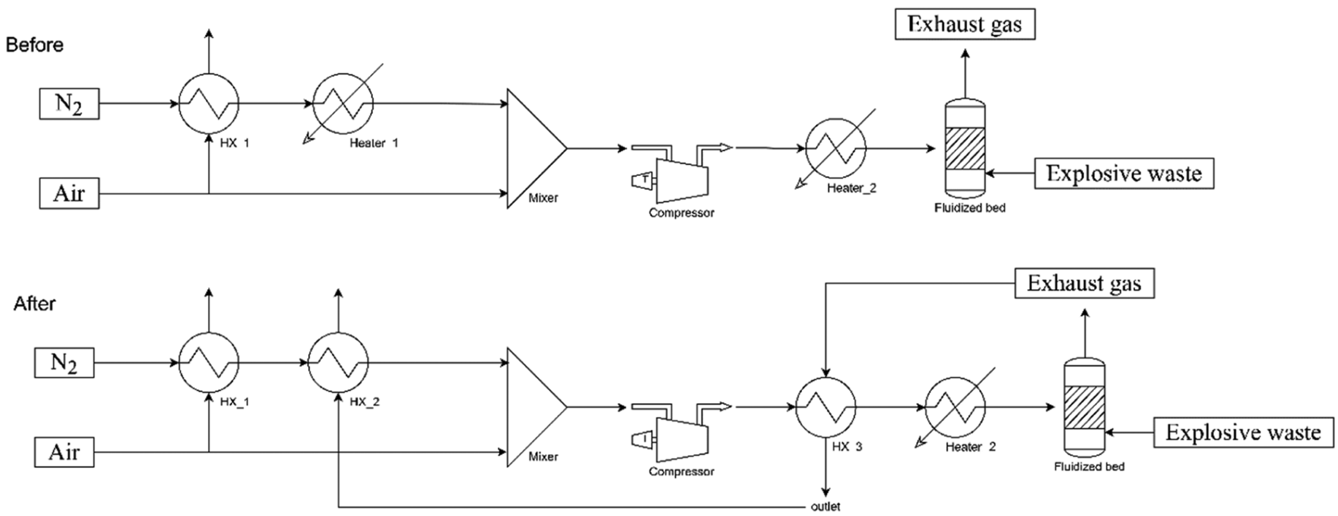

Figure 1. Previous process design (before) and new process design with a HEN (after).

shows that the multi-objective optimization and applying the HEN are different approaches to reduce the process cost. Additionally, despite the single-objective optimization, the latest study required 1800 h to find optimal solution. The computational time will be increased to obtain multi-objective optimization solution. On the other hand, applying and optimizing the HEN did not take long time.[17,18] This is because the computational fluid dynamics (CFD) simulation was used to find single-objective optimization solution, but the HEN did not use this.[19,20] Compared to the HEN which can reduce the process cost effectively in short time, multi-objective optimization is expected to spend a long time (double time compared to single-objective optimization) and reduce the process cost by approximately 20−50%.

Important points when applying a HEN are the capital cost incurred when installing the heat exchanger, how much utility cost can be saved through this, and how long is the payback time at this time.[21] First, the cost of a heat exchanger is determined by the type of heat exchanger, heat exchange area, and processing flow rate. In this study, heat exchange area was an important factor. A consideration was given to how much heat exchange had to be performed when cold flow and hot flow met for the most optimal result. The second is how much heating (or cooling) utility costs can be saved.[22] It is obvious that it would be nice to be able to save a lot of utility costs; however, in this case, it would be necessary to increase the heat exchanger performance excessively.[23] This leads to an increase in the capital cost of the heat exchanger. In the case of payback time, the total process cost was calculated and evaluated by adding the capital cost and 20 years of utility cost.[24] Moreover, rather than simply installing a HEN, a new explosive waste incineration process was designed and compared, and optimization was performed by using a process simulation program to find the optimal heat exchange system.[25] As a result, it was found that the process cost can be reduced by 44% compared to the conventional one. This is significant in that it was achieved by installing a HEN without changing the operating conditions of the explosive waste incineration process.[26] Even though this study just applied a heat exchanger network and optimized, the result was much better than that of the case study to change operating conditions to decrease the process cost. When optimization is carried out that considers not only the NO_x emission concentration but also the process cost, applying a HEN and optimization once again will be able to save more process cost than the existing results.[27−29]

2. MODELING

2.1. Process Design. The explosive waste incineration process was designed, and a new process with a heat exchanger network was also designed. Figure 1 shows the process designs.

The explosive waste incineration process was basically designed with an air inlet, a nitrogen inlet, a compressor, a heater, and a fluidized bed. The inlet flows are compressed and heated to optimal conditions to emit minimum NO_x.[9] The flowrates of air and nitrogen are 0.892 and 0.918 kg/s, respectively, and the pressure of air and nitrogen gas is increased to 2.0 bar by the compressor, and the temperature is increased to 523 K. In the case of heat exchanger 1 (HX_1), the temperature of nitrogen is increased to 273 K by heat exchanging with excessive air. This is because the source of nitrogen is liquid nitrogen, and the initial temperature of nitrogen is 77 K. The nitrogen is heated again to 293 K in order to mix with air. In the case of the previous process (before), the heater (Heater_1) is used to increase the temperature, but the new process (after) uses a heat exchanger (HX_2). The hot flow of the exchanger is exhaust gas from the fluidized bed. Another difference between the previous and new process is using a heat exchanger for mixture gas. The previous process uses only a heater (heater_2) for heating to target temperature (523 K); on the other hand, the new process uses both a heat exchanger (HX_3) and heater (Heater_2). Table 1 shows the detailed conditions of two processes.

The fluidized bed was designed to incinerate explosive waste, which consists of trinitrotoluene and water. The target incineration rate of explosive waste is 20,000 kg/year. The fluidized bed reactor is cylindrical in shape and has a diameter of 0.5 m and a height of 2.0 m. The gas mixture enters the fluidized bed reactor at a velocity of 2.605 m/s, a pressure of 2.0 bar, and a temperature of 523 K.

2.2. Heat Exchanger Design. In this study, a heat exchanger was basically designed to counterflow a double pipe exchanger. The temperature of flows was decided by Table 1, and the heat transfer surface was calculated by using the condition of each flow.

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Table 1. Detailed Information about Previous and New Processes

equipment	flowrate (kg/s)	temperature (K)	pressure (bar)
nitrogen inlet	0.892	77	1.0
air inlet	0.918	298	1.0
Heater_1	0.892	298	1.0
compressor	1.810	298 to 333[a]	2.0
Heater_2	1.810	523	2.0
fluidized bed (exhaust gas)	1.898	523	2.0

[a]Effects of pressure increase.

The heat exchanger is determined by using the following equations

$$\dot{m}C_p\Delta T = \dot{Q} = UAT_{lm} \tag{1}$$

where $\dot{m}$ is the mass flowrate (kg/s), C_p is the specific heat capacity (J/kg·K), T is the temperature (K), $\dot{Q}$ is the heat transfer rate (J/s), U is the overall heat transfer coefficient (J/s·m^2·K), A is the heat transfer surface area (m^2), and $T_{\rm lm}$ is the logarithmic mean temperature difference (K). The logarithmic mean temperature difference is defined by using the following equation

$$T_{\rm lm} = \frac{(T_{\rm hot\_in} - T_{\rm cold\_out}) - (T_{\rm hot\_out} - T_{\rm cold\_in})}{\ln[(T_{\rm hot\_in} - T_{\rm cold\_out}) / (T_{\rm hot\_out} - T_{\rm cold\_in})]} \tag{2}$$

When the inlet and outlet target temperatures of the cold stream are fixed and the overall heat transfer coefficient is constant, the heat transfer surface area is determined according to the hot flow temperature. This means that the state of hot flow is an important value because if the temperature of the hot flow inlet is low, the $T_{\rm lm}$ will be decreased and heat transfer surface area will be increased. The heat transfer surface area and cost are proportional.

The following equations show the conditions considered in the design aspect. Equation 3 is the constraint of heat exchanger 1. It means that pinch temperature is 15 K because the hot flow (air) is 298 K. Equation 4 means that the nitrogen flow should be heated to 298 K before being mixed with air. Similar to eqs 3 and 5, the pinch temperature is 15 K as well. 508 K of eq 5 is calculated by using the hot flow of heat exchanger 3, exhaust gas, from the fluidized bed.

$$T_{\rm HX\_1\_cold\_out} < 283\ {\rm K} \tag{3}$$

$$T_{\rm Heater\_1\_out} = T_{\rm HX\_2\_cold\_out} = 298\ {\rm K} \tag{4}$$

$$T_{\rm HX\_3\_cold\_out} < 508\ {\rm K} \tag{5}$$

2.3. Cost Calculation. In order to estimate the process cost, the Aspen Plus simulation program (10.0 version) was used. This program is widely used for process design and cost estimation. In addition, cost optimization can be performed. The cost of each equipment piece is calculated by using eq 6. The total cost of the new process was estimated by using eq 7, and it was minimized by using an optimizer.

$$\text{Cost (\$)} = \text{Capital cost (\$)} + \text{Utility cost (\$/yr)} \times 20\ \text{yr} \tag{6}$$

$$\text{Cost}_{\rm Total} = \text{Cost}_{\rm HX\_1} + \text{Cost}_{\rm HX\_2} + \text{Cost}_{\rm HX\_2} + \text{Cost}_{\rm Heater\_2} \tag{7}$$

There are two reasons the period of 20 years was assumed. First, in this study, 20 years was considered enough time to compare previous and new process cost. This is because the capital cost of the new suggested process is more expensive than that of the previous one, and more than 10 years are needed to check the effect of decreased utility cost. The second reason is that related study to consider the process cost has been set to 20 years to estimate the total process cost. In order to combine this and related study, it was judged that it would be better to unify the period of the two studies. In the case of the compressor, the condition between the previous and new process is the same. Therefore, the cost calculation of the compressor was neglected.[30,31]

In addition, in order to reliably determine the profitability of an investment, an index analysis should be carried out. Therefore, the net present value NPV of the investment should be in accordance with the following equation.

$$\text{NPV} = \sum_{t=0}^{n} \frac{\text{NCF}_t}{(1+r)^t} \tag{8}$$

where NCF_t is the net cash flow in period t, r is the discount rate, t is the time index, and n is the number of years of investment.

When the NPV has a positive value, it means that this investment is profitable. The following equation is another step to calculate the investment's PI (modified profitability index) profitability ratio.

$$\text{PI} = \frac{\sum_{t=m+1}^{n} \frac{\text{NCF}_t^+}{(1+r)^t}}{\left|\sum_{t=0}^{m} \frac{\text{NCF}_t^-}{(1+r)^t}\right|} \tag{9}$$

where NCF_t^- is the negative cash flow and period 0 to m is for the negative cash flow; NCF_t^+ is the positive cash flow and period $m + 1$ to n is for the positive cash flow.

If a PI value is bigger than 1, it means that the investment will pay for itself within the planned lifetime.

The last step is to determine the value of the investment's modified profitability index (MPI) profitability ratio, which considers the reinvestment rate. MPI is calculated by using the following equation.

$$\text{MPI} = \frac{\sum_{t=m+1}^{n} \frac{\text{NCF}_t^+ \cdot (1+r_{\rm ri})^{n-t}}{(1+r)^t}}{\left|\sum_{t=0}^{m} \frac{\text{NCF}_t^-}{(1+r)^t}\right|} \tag{10}$$

where $r_{\rm ri}$ is the reinvestment rate and usually is 0.01.

Similar to PI, if an MPI value is bigger than 1, it means that the investment will pay for itself within the planned lifetime. The PI and MPI indices can be used interchangeably or supplementarily.

3. RESULTS AND DISCUSSION

A rigorous simulation was performed based on Section 2, and the results were obtained. In order to compare the previous and new process, cost estimation of the previous process was performed first. Next, the HEN optimization of the new process was performed. The important point to be considered was how much heat was exchanged for each heat exchanger. As mentioned above, when heat exchange is carried out too much, the capital cost of the heat exchanger increases excessively. Therefore, optimal heat exchange distribution is required.

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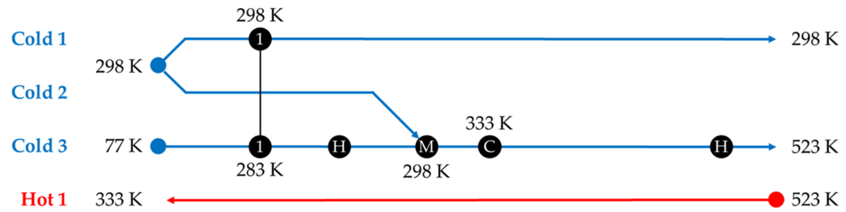

Figure 2. Simple flow map of the previous process. The number means the heat exchanger number, M means the mixer, C means the compressor, left H means Heater_1, and right H means Heater_2.

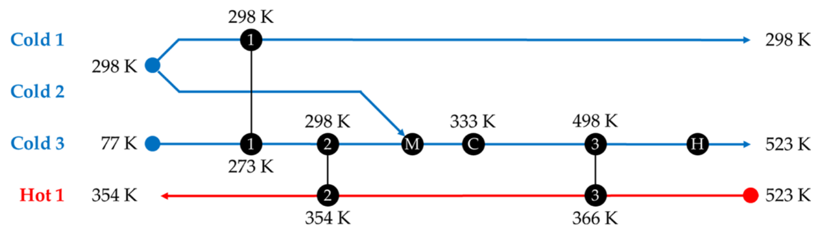

Figure 3. HEN of the new process. The number means the heat exchanger number, M means the mixer, C means the compressor, and H means Heater_2.

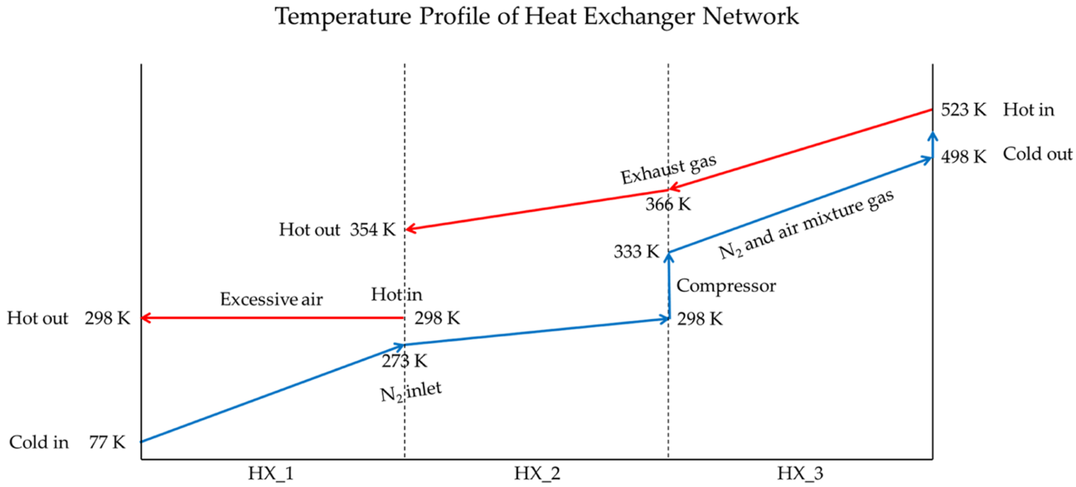

Figure 4. Temperature profile of the HEN.

Above all, the degree of heat exchange in each heat exchanger must be carefully considered because it affects the flow temperature of the other heat exchangers. Figure 2 shows a flow map of the previous process, and Figure 3 shows the heat exchanger network of the new process.

The previous process increased the temperature of cold flow 3 from 77 to 283 K using a heat exchanger (HX_1). On the other hand, the new process increased the temperature of cold flow 3 to 273 K. This is to reduce the capital cost consumed in the heat exchanger. While the previous process used a heater (Heater_1) to increase the temperature of cold flow 3 to 298 K, the new process uses a heat exchanger (HX_2). In addition, the new process uses one more heat exchanger (HX_3). Figure 4 summarizes the temperature profile of the new process.

When the specification of heat exchangers was calculated based on eqs 1 and 2, the result is in Table 2.

In the case of HX_1, the heat transfer surface area was 16.85 m^2, and it is much bigger than in the case of HX_2 because it needs more heat transfer than HX_2. The inlet and outlet temperature of hot flow of HX_1 is the same; it means that excessive flow (air) was provided for heating cold flow and to help reduce the heat transfer surface area. If the excessive air was not provided and the heat exchange was performed only using the same amount of air, the heat transfer surface area would be 66.05 m^2. In the case of HX_3, a large amount of heat exchange was performed, and the flowrate was twice compared to the case of HX_1 and HX_2. Therefore, it required more heat transfer surface area, and it became 88.27 m^2.

Table 2. Detailed Information of Heat Exchangers

equipment	hot flow temperature (K) in	hot flow temperature (K) out	cold flow temperature (K) in	cold flow temperature (K) out	flowrate (kg/s)	heat transfer surface area (m^2)
HX_1	298	298	77	273	0.892	16.85
HX_2	366	354	273	298	0.892	2.60
HX_3	523	366	333	498	1.810	88.27

Tables 1 and 4 show the detailed cost information of both processes. Capital cost includes equipment cost and total installed cost. In the case of utility cost, the utility is hot oil, and its cost is 79.42 kW h/$

Table 3. Detailed Cost Information of the Previous Process

equipment	capital cost ($)	utility cost ($/year)	total cost (20 years)
HX_1	2.31×10^6	9.54×10^5	2.14×10^7
Heater_1	1.61×10^6	1.15×10^6	2.46×10^7
Heater_2	6.97×10^6	6.34×10^6	1.34×10^8
total cost	1.09×10^7	8.44×10^6	1.80×10^8

Table 4. Detailed Cost Information of the Optimized New Process

equipment	capital cost ($)	utility cost ($/year)	total cost (20 years)
HX_1	1.88×10^6	9.54×10^5	2.10×10^7
HX_2	1.66×10^6	9.50×10^5	2.07×10^7
HX_3	1.91×10^6	9.55×10^5	2.10×10^7
Heater_2	4.10×10^6	1.69×10^6	3.79×10^7
total cost	9.55×10^6	4.55×10^6	1.01×10^8

Upon comparing the cost of HX_1 of the two processes, it appears that the new process saves about 400,000 $ compared to the previous process. In addition, when comparing Heater_1 and HX_2, the capital cost of HX_2 is about 50,000 $ higher, but the utility cost can be saved by 200,000 $ per year. Next, upon comparing Heater_2 of the previous process with HX_3 and Heater_2 of the new process, the new process was able to reduce the capital cost by 990,000 $ and utility cost by 3,695,000 $ per year. Furthermore, when comparing the total cost of the two processes, it was estimated that the cost savings of 44% over 20 years can be achieved by installing a HEN.

Moreover, as eq 8, the NPV was calculated for checking the profitability of the HEN. The discount rate is 0.2, the number of years of investment is 20, and NCF_t is calculated based on Tables 3 and 4. The result of the NPV was 24.18, and it means that this HEN is reasonable. The second step was to estimate the PI by using eq 9, and its value was also 24.18 because there is no negative cash flow. In the case of MPI, it was calculated by using eq 10. When the r_{ri} is assumed 0.01, the MPI was 28.30. Since the PI and MPI value was bigger than 1, it was proved that the HEN is meaningful from an investment point of view.

In the case of heat exchanger 2, there is a constraint that the outlet temperature of the cold flow should be 298 K; however, in the case of heat exchangers 1 and 3, there is not a special constraint except that the pinch temperature is 15 K. In order to analyze the optimization results of heat exchangers 1 and 3, the cost change for each outlet temperature of cold flow was calculated. Figure 5 shows the sum of the total costs of HX_1 and HX_2 for each temperature.

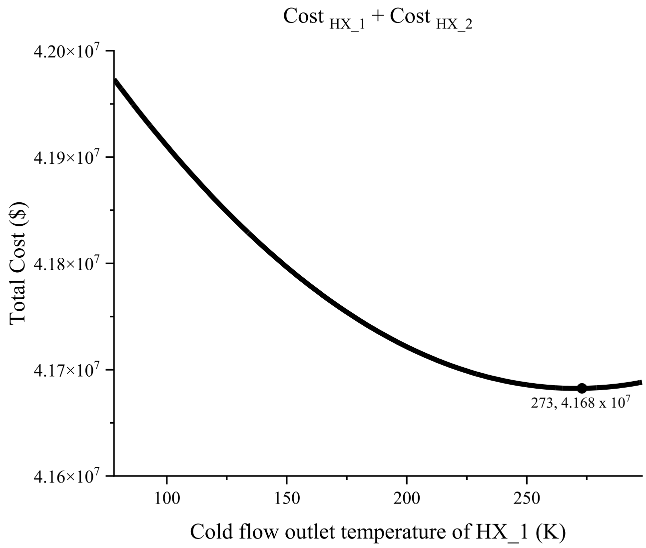

Figure 5. Sum of the total costs of HX_1 and HX_2 by cold flow outlet temperature of HX_1.

The sum of costs decreases before the cold flow outlet temperature of HX_1 is 273 K, and it increases after that point. This is because the capital cost of HX_1 is increased rapidly as it approaches the pinch temperature. Therefore, 273 K, which is a temperature that can efficiently perform heat exchange slightly away from the pinch temperature, was calculated as the optimum temperature.

In the case of HX_3, Figure 6 shows the total cost trend.

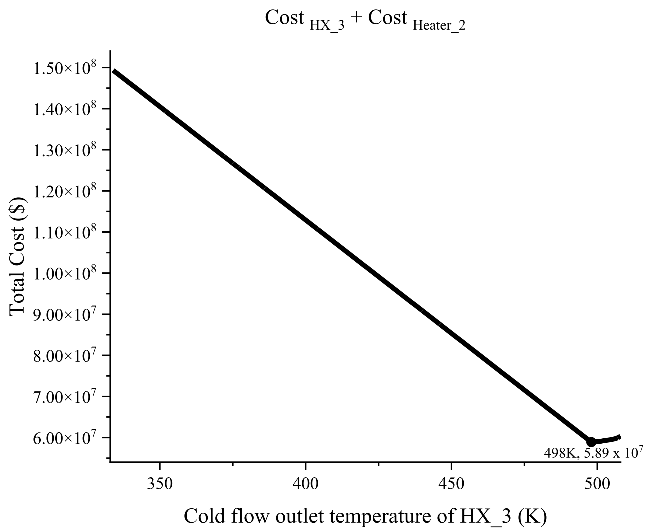

Figure 6. Sum of the total costs of HX_3 and Heater_2 by the cold flow outlet temperature of HX_3.

Contrary to Figure 5, the total cost decreases sharply up to the optimum temperature. This is because the utility cost consumed by the heater is drastically reduced. The total cost shows the minimum value when the temperature is 498 K, and this is also because the capital cost of the heat exchanger increases as the temperature coming out of the heat exchanger increases from 498 K. Furthermore, Figure 6 shows once again that installing a heat exchanger can save the half level of total cost. The maximum value of the total cost is approximately 1.55×10^8, and the minimum value is 5.89×10^7, which is less than half.

Based on the above-mentioned results, it is shown that the installation of a HEN in the explosive waste incineration process can bring very significant cost savings. In addition, the HEN was also well optimized when price analysis was performed for each device related to each other. Moreover, apart from the multi-objective optimization mentioned above, the results of this study can more effectively reduce the process cost and be validated by the process simulation program. Installing a HEN is another method to reduce the process cost; it is meaningful as it can be performed in parallel with multi-objective optimization simultaneously.

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4. CONCLUSIONS

This study aimed to apply the HEN to the previous process to lower the cost of the explosive waste incineration process. The explosive waste incineration process through a fluidized bed reactor was focused on reducing the emission concentration of NO_x, and the cost of the process was not taken into account. As process costs increase at the expense of lower NO_x emission concentrations, the need to consider both conditions in process design has emerged. However, multi-objective optimization that considers both NO_x emission concentrations and process costs should consider too many variables and spends long time. Therefore, a heat exchange network is applied as a way to reduce the process cost without significantly changing the process conditions. As a result of installing a heat exchanger where necessary based on the previous process, it became possible not to use one heater, and the load on another heater was greatly reduced. In addition, performing optimization of the HEN helped select appropriate temperature that considers the pinch temperature of the heat exchangers. Moreover, it was achieved to reduce 44% the total process cost compared to the previous process. This result proves how useful the application of the HEN is for the explosive waste incineration process. Furthermore, when the multi-objective optimization is performed in the future, the HEN will be a very significant method to reduce the cost compared to the present. This study could be performed more effectively than the optimization of the process conditions, and the result is expected to be of the same level as the saving effect by multi-objective optimization. In addition, it is assumed that when both HEN and multi-objective optimization are applied, the process cost will be decreased by less than half. After the multi-objective optimization is finished in the future, HEN is applied at the same time, and the explosive waste incineration process can save a lot of money or reduce NO_x emissions.

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Notes

The authors declare no competing financial interest.

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