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Analysis of Dynamic Characteristics for Self-Heat Recuperative Process

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Authors have recently developed an attractive technology; termed self-heat recuperation technology to reduce the energy consumption of chemical processes. In this technology, all of the self heat of the process stream is recirculated in the process without any heat addition. As a result, the energy consumption and exergy destruction of a process can be greatly reduced in the steady state. To apply and expand this technology to the industrial processes, it is necessary to design an operation system with investigation of their dynamics. For the first step to design the operation system, dynamic characteristics of self-heat recuperative processes has been investigated to achieve further energy saving and to investigate the stability of the process during operation by using dynamic simulation in this research.

1. Introduction

The combustion of fossil fuels for heating produces a large amount of carbon dioxide (CO_2), which is the main contributor to the global greenhouse gas effect. Energy saving technology has attracted increased interest in many countries as a means to suppress global warming and to reduce the use of fossil fuels. To date, to reduce the energy consumption, heat recovery technology (Eastop and Croft 1990, Kemp, 2007) has been applied to thermal processes, in which heat is exchanged between the hot and cold streams. To exchange the heat, an additional heat source may be required, depending on the available temperature difference between two streams for heat exchange. The additional heat may be provided by the combustion of fossil fuels, leading to exergy destruction during heat production. In addition, many energy saving technologies recently developed are only considered on the basis of the first law of thermodynamics. Hence, process design methods based on these technologies are distinguished by cascading heat utilization. Simultaneously, many researchers have paid attention to the analysis of process exergy and irreversibility through consideration of the second law of thermodynamics. However, many of these investigations show only the calculation results of exergy analysis and the possibility of the energy savings of some processes, and few clearly describe methods for reducing the energy consumption of processes (Lampinen and Heillinen, 1995; Aspelund et al., 2007; Grubbström, 2007).
Recently, an energy and exergy recuperative integrated gasification power generation system has been proposed and a design method for the system has been developed (Kuchonthara and Tsutsumi, 2003, 2006). By incorporating compressors and heat exchangers, the authors following on this concept have developed another attractive technology to reduce the energy consumption of chemical processes (Kansha et al., 2009a). In this technology, a process unit is divided into functions to analyze the process required heat and all of the self-heat of process stream is recirculated in the process

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without any external heat source. As a result, the energy consumption and exergy destruction of a process can be greatly reduced in the steady state. In fact, this technology has been applied to several chemical processes and its energy saving potential has been investigated (Kansha et al., 2009b, 2010a,b; Matsuda et al., 2010, 2011). Although this technology is proved to achieve reduction of energy consumption in the steady state, very few investigations of process dynamics and operation methods for the self-heat recuperative processes have been performed. Thus, to apply this technology to the industrial processes, it is necessary to design its operation system. There is a pilot self-heat recuperative distillation process for ethanol production in Japan (Nippon Steel Engineering, 2012). This process achieves drastic energy reduction in the steady state. However, operators are switching the operation mode when it reaches steady state condition.
Thus, we investigated the dynamic characteristics of the self-heat recuperative process to design the operation systems for the process to achieve further energy saving and to investigate the stability of the process during operation by using dynamic simulation in this research.

2. Self-Heat Recuperative Process

Self-heat recuperation technology (Kansha et al., 2009a) facilitates recirculation of whole process heat, and helps to reduce the energy consumption of the process by using compressors and self-heat exchangers based on exergy recuperation. In this technology, i) a process unit is divided on the basis of functions to balance the heating and cooling loads by performing enthalpy and exergy analysis and ii) the cooling load is recuperated by compressors and exchanged with the heating load. As a result, the heat of the process stream is perfectly circulated without heat addition, and thus the energy consumption for the process can be greatly reduced.
Figure 1 (a) shows a flow diagram of a thermal process for gas stream with heat circulation using self-heat recuperation technology, respectively. In these processes, the feed stream is heated with a heat exchanger (1→2) from a standard temperature, T_0, to a set temperature, T_1. The effluent stream from the following process is pressurized with a compressor to recuperate the heat of the effluent stream (3→4) and the temperature of the stream exiting the compressor is raised through adiabatic compression. Stream 4 is cooled with a heat exchanger for self-heat exchange (4→5). The effluent stream is then decompressed with an expander to recover part of the work of the compressor for gas stream. This leads to perfect internal heat circulation through self-heat recuperation. The effluent stream is finally cooled to T_0 with a cooler (6→7). Note that the total heating duty is equal to the internal self-heat exchange load without any external heating load, as shown in Figure 1 (b). Thus, the net energy required of this process is equal to the cooling duty in the cooler (6→7). In the case of ideal adiabatic compression and expansion, the input work provided to the compressor performs a heat pumping role in which the effluent temperature can achieve perfect internal heat circulation without exergy destruction. Therefore, SHR can dramatically reduce energy consumption. Now the important thing when designing of the thermal process based on SHR is that the enthalpy of inlet and outlet streams to the system must be equal. In this case, the enthalpy of stream 1 and 7, stream 2 and 3 must be equal. Otherwise, the energy saving efficiency of SHR is reduced.
As well as a gas stream case, a thermal process based on SHR in vapor/liquid stream case can be developed as shown in Figure 1 (c). In this process, the feed stream is heated with a heat exchanger (1→2) from a standard temperature, T_0, to a set temperature, T_1. The effluent stream from the subsequent process is pressurized by a compressor (3→4). The latent heat can then be exchanged between feed and effluent streams because the boiling temperature of the effluent stream is raised by compression. Thus, the effluent stream is cooled through the heat exchanger for self-heat exchange (4→5) while recuperating its heat. The effluent stream is then depressurized by a valve (5→6) and finally cooled to T_1 with a cooler (6→7). This leads to perfect internal heat circulation based on SHR, similar to the above gas stream case. Note that the total heating duty is equal to the internal self-heat exchange load without an external heating load, as shown in Figure 1 (d). It is clear that the vapor and liquid sensible heat of the feed stream can be exchanged with the sensible heat of the corresponding effluent stream and the vaporization heat of the feed stream is exchanged with the condensation heat of the effluent stream. Similar to the thermal process for gas streams with heat circulation based on

SHR, as mentioned above, the net energy required of this process is equal to the cooling duty in the cooler (6→7) and the exergy destruction occurs only during heat transfer in the heat exchanger. In SHR, the hot stream line of heat exchange is shifted vertically by using the adiabatic compression for the hot stream. The shaft work of the compression is required to circulate the internal heat in the process and exhausted with the process stream.

Therefore, self-heat recuperation can dramatically reduce energy consumption. As a result, the energy required by the heat circulation module is reduced to 1/22–1/2 of the original by the self-heat exchange system in gas streams and/or vapour/liquid streams.

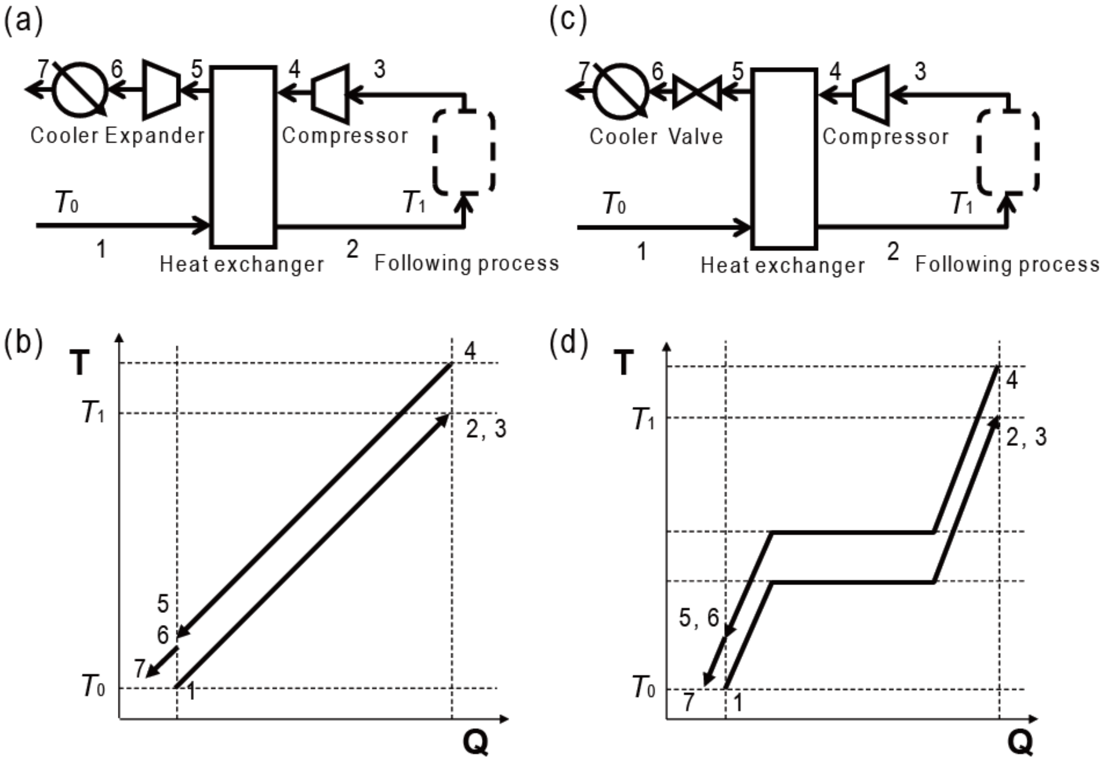

Figure 1: Self-Heat Recuperative Thermal Process a) Process Flow of Gas Streams, b) Temperature-Heat Diagram of Gas Streams, c) Process Flow of Vapor/Liquid Streams, d) Temperature-Entropy Diagram of Vapor/Liquid Streams

3. Dynamic Characteristics of Self-Heat Recuperative Process

To investigate the dynamic characteristics of a self-heat recuperative process, step response test was conducted by HYSYS Ver. 7.3 (ASPEN Tech.). The schematic flow diagram for gas stream is shown in Figure 1 (a). As a real fluid, butane was used for the gas stream. The stream 1 was heated from 25 ^{O}C to a set temperature 100 ^{O}C, and the flow rate of the stream was 100 kmol/h at the initial steady state and ±10 % step changes of the flow rate were introduced to investigate the dynamics. The Soave-Redlich-Kwong was used for the state equation. The minimum temperature difference for heat exchange was assumed to be 6 K. The efficiency of the heat exchanger was 100 % (i.e., no heat loss) and the adiabatic efficiency of the compressor was 80 %. Shell and tube is chosen as a heat exchanger of which TEMA type is AFL. Overall heat transfer (*UA*) in the heat exchanger was fixed to 1.216×105 kJ/K^{-1}h^{-1}. The pressure drops of both streams in this heat exchanger are 0.69 kPa. The stream pressures among the compressor are 100.6 and 120.8 kPa. Figure 2 shows the representative response curves of stream temperatures (stream 2 and 4) when the flow rate 10 % increase is introduced. It can be seen that the stream temperature of stream 2 cannot reached to the set temperature (100 ^{O}C) due to the increased flow rate. This means that in the case of gas streams, this process cannot naturally keep the equal enthalpy of the feed streams to that of the effluent streams in

the module without any adequate operation system under dynamic condition. In addition, the temperature of stream 4 decreased along with temperature decrease of stream 2.
As well as the case study with gas stream, the simulation using water as a vapour/liquid stream to close the distillation process was conducted. In this simulation, water must be liquid at standard condition. Thus, it is easy to understand that this process requires the heater to produce vapour initially. Although the heater to initially heat the process stream was introduced, the super heated steam cannot be produced and vapour/liquid mixture was produced in this dynamic simulation.
In the case of vapour/liquid stream, the feed water transforms from liquid to vapour in the heat exchanger in steady state simulation. However, the hold-up in the heat exchanger is required in the dynamic simulation and cannot transform the phase perfectly in this ordinal heat exchanger. Thus, it requires other suitable heat exchanger to produce the super heated steam.
To realize the ideal heat circulation module, it is required to balance the enthalpy of the feed streams to that of the effluent streams. However, this observed phenomena caused by hold-up in the heat exchanger seem to be preferable in respect of design of the heat circulation module in the self-heat recuperative distillation, because the void fraction and enthalpy of feed stream are possible to be controlled by regulating the hold-up level in the heat exchanger.

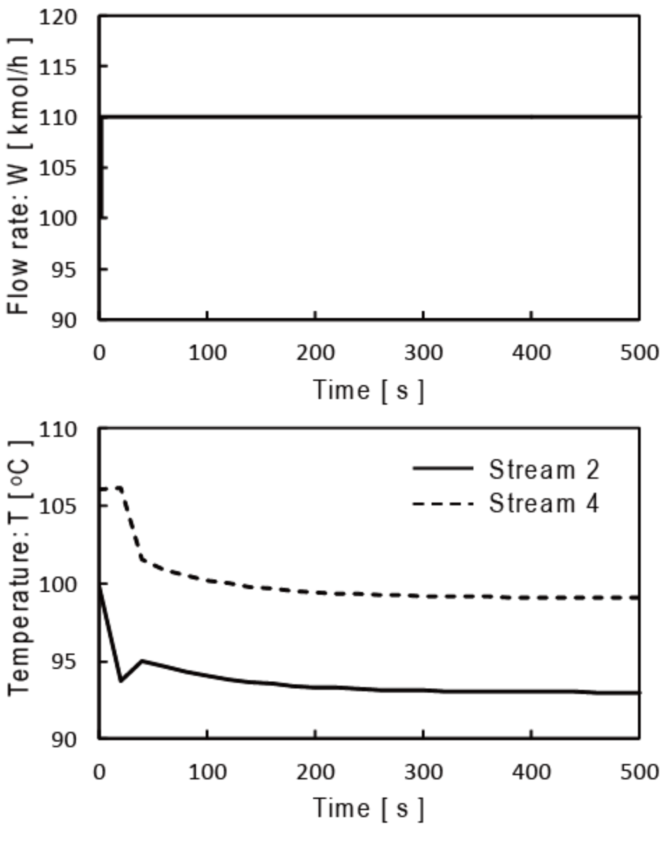

Figure 2: Step Change of Flow Rate from 100 to 110 kmol/h and Response of Stream Temperature

4. Discussion

In general, energy balance during heat transfer of a simple tubular heat exchanger shown in Figure 3 is represented by the following differential equations;
For hot stream (inner stream)

$$dT_h / dz = -U\pi D_h (T_h - T_c) / W_h C_{Ph} \tag{1}$$

For cold stream (outer stream)

$$dT_{\mathrm{c}} / dz = -U\pi D_{\mathrm{h}} (T_{\mathrm{h}} - T_{\mathrm{c}}) / W_{\mathrm{c}} C_{\mathrm{Pc}} \tag{2}$$

where T_h and T_c are temperatures, W_h and W_C are flow rates, and C_{Ph} and C_{Pc} are heat capacities of hot and cold streams, respectively, U is an overall heat transfer coefficient between hot and cold streams, D is a diameter of inner tube, and z is a position of differential equation in heat exchanger. From these two equations, the following equation can be derived;

$$\ln[(T_{\mathrm{h1}} - T_{\mathrm{c1}})/(T_{\mathrm{h2}} - T_{\mathrm{c2}})] = U[(1/W_{\mathrm{h}} C_{\mathrm{Ph}}) - (1/W_{\mathrm{c}} C_{\mathrm{Pc}})](\pi D_{\mathrm{h}} L) \tag{3}$$

where the length of tubular heat exchanger is L and temperatures of streams are T_{h1} and T_{c1} at z=0 and T_{h2} and T_{c2} at z=0, and hot and cold streams flows as counter current in the heat exchanger. This equation is a well-known equation to design a tubular heat exchanger.
At the same time, the flow rates can be expressed by;

$$W_{\mathrm{h}} = A_{\mathrm{h}} \frac{dz}{dt} \tag{4}$$

$$W_{\mathrm{c}} = A_{\mathrm{c}} \frac{dz}{dt} \tag{5}$$

where, A_h and A_c are the cross section of tubes, thus $A_h = \pi D_h^2/4$, $A_C = \pi(D_c^2 - D_h^2)/4$.
The relation between temperature and time can be written by the following equation;

$$\ln[(T_{\mathrm{h,t}} - T_{\mathrm{c,t}})/(T_{\mathrm{h,0}} - T_{\mathrm{c,0}})] = U[(1/A_{\mathrm{h}} C_{\mathrm{Ph}}) - (1/A_{\mathrm{c}} C_{\mathrm{Pc}})](\pi D_{\mathrm{h}} t) \tag{6}$$

where $T_{h,0}$ and $T_{c,0}$ are the temperature of the initial steady state at $0<z<L$, $T_{h,t}$ and $T_{c,t}$ are the temperatures at t.
To simplify the above mentioned self-heat recuperative thermal process simulation, the heat exchanger is assumed as a tubular type. Equation (6) can be adapted to the simulation results. However, the temperature profile of stream 2 is oscillated as shown in Figure 2. This is because the step change effect of flow rate reached to stream 4 after W_c/A_c seconds. At W_c/A_c+ W_h/A_h the effect reached to stream 5 and then the temperature gradually reached to the new steady state. Thus, the temperature profile of the stream 2 seems to be oscillated twice. In this simulation, we did not define anything as the following process of the self-heat recuperative thermal process. However, in a real process, the residence time of the following process must be assumed and the step response effect of the flow rate will occur after additional residence time. Note that $W_h = W_c = W$ in the simulation.
In the case of vapour liquid stream, we should assume the vessel type heat exchanger to add liquid hold-up in this vessel. Thus, the liquid level controller is required for maintaining the steady state condition. In addition, the temperature in the vessel would be uniform and is calculated by a concurrent flow.
Thus, self-heat recuperative processes have their own characteristics due to the recirculation of whole heat of the process stream. To apply the self-heat recuperation to thermal process, further investigation about the characteristics of the dynamics and development of the appropriate operation system are required.

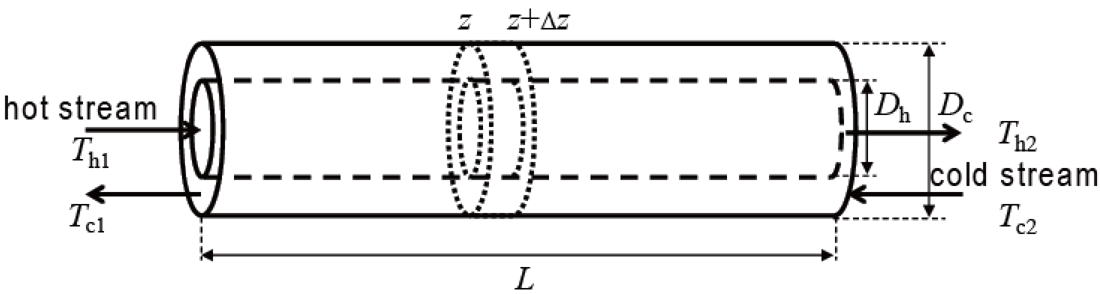

Figure 3: Schematic Diagram of Tubular Heat Exchanger

5. Conclusion

The dynamic characteristics of the self-heat recuperative process to design the operation systems for the process to achieve further energy saving and to investigate the stability of the process during operation are investigated in this paper. To realize the self-heat recuperative process it requires balancing the enthalpy of the feed streams to that of the effluent streams. According to these simulations, it is necessary to design the suitable operation system with further investigation to automatic operation. However, it can also be seen that this process has some potential for further energy saving.

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