

Numerical Investigation of Energy Saving Potential for Self-Heat Recuperation

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Recently, energy saving technology has attracted increased interest in many countries for suppressing global warming and reducing the use of fossil fuels.

Self-heat recuperation technology has recently been developed for energy saving of chemical processes. It has the characteristics whereby total process heat can be recirculated within the process, leading to a marked reduction in energy consumption. The authors have developed a simple calculation technique for the minimum energy required for thermal processes that was derived numerically from the view point of irreversibility and exergy loss for heat transfer. In addition, the authors reported that the actual energy required for a self-heat recuperative thermal process is almost the same as the value derived from this calculation technique.

In this paper, the authors examined the minimum energy required for thermal processes with/without heat recovery or based on self-heat recuperation using the cold process stream properties and also evaluated the energy saving potential of these processes using process simulation. Since the results obtained from the calculation method can be used as target values of heat recovery technology, this investigation supports process intensification and is promising for industries to examine the energy saving potential when designing a thermal process.

1. Introduction

The reduction of CO₂ emission has become a major target in efforts to suppress global warming. The combustion of fossil fuel for heating produces a large amount of CO₂. For this reason, energy saving technology has attracted increased interest in many countries. So far, to reduce the energy consumption, heat recovery technology – Pinch Analysis, which exchanges heat between the hot and cold streams in a process, has been applied to thermal processes from 1980s (Linnhoff and Hindmarsh, 1983). Although this technology is a powerful technology for energy saving of the chemical process, an additional heat source may be required depending on the minimum temperature difference between hot and cold streams for heat exchange (Linnhoff, 1993). This additional heat is often produced by fuel combustion, leading to CO₂ production. Wechsung et al. (2010) developed a heat integration technology with pressure changes at sub-ambient temperature and successfully reduced the energy consumption of LNG plant. To expand this technology, Fu and Gundersen (2013) developed a vapour recompression process for the cryogenic air separation.

Recently, the authors have developed a self-heat recuperation technology based on exergy destruction minimization to reduce the energy consumption of thermal processes from different aspects (Kansha et al. 2009). Applying the self-heat recuperation technology to thermal processes, not only the latent heat but also the sensible heat of the process stream, i.e. all process heat, can be circulated into the processes without any heat addition. 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 processes as case

studies and shows large energy saving potentials in these processes such as azeotropic distillation (Kansha et al., 2010) and hydro-desulfurization reaction process (Matsuda et al., 2010b). Moreover, the authors have developed a simple calculation technique for the minimum energy required for thermal processes that was derived numerically from the point of view of irreversibility (Kansha et al., 2013a). The authors reported that the energy required for a self-heat recuperative thermal process is almost the same as the derived value.

In this paper, we examined the minimum energy required for thermal processes with/without heat recovery or based on self-heat recuperation using the process stream properties. Furthermore, we showed that the results obtained from our calculation method can be fixed as target values of heat recovery technology to evaluate the energy saving potential of these processes using process simulation.

2. Energy required for thermal processes

A process stream is heated in a thermal process to satisfy the condition of the following process, as shown in Figure 1(a). T_{in} and T_{out} are the input and output temperatures of the process stream to the heater. F is the flow rate of the process stream. By using heat capacity ($C_p(T)$) of the process stream, the received heat amount (Q) of the process stream is expressed by the following equation Eq(1):

$$Q = \int_{T_{in}}^{T_{out}} FC_p(T)dT \quad (1)$$

This equation can be simply rewritten when C_p is constant during temperature change;

$$Q = FC_p(T_{out} - T_{in}) \quad (2)$$

This heat amount (Q) is the required heat amount to increase temperature from T_{in} to T_{out} . Figure 1(b) shows the temperature–heat diagram which shows this relationship.

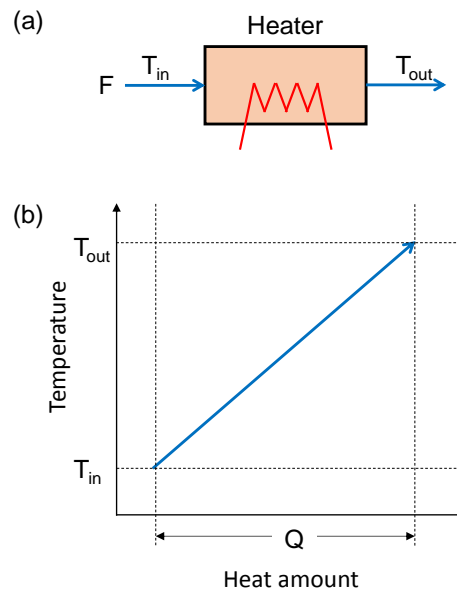


Figure 1: Conventional thermal process: a) flow diagram; b) temperature–heat diagram

Figure 2(a) shows the flow diagram of feed–effluent heat exchange system as an example of conventional heat recovery. We assumed that the following process after this system does not have any enthalpy change for clear explanation. Hence, hot stream is perfectly the same as the cold stream. In this case, heat exchange duty in the heat exchanger is maximized. The received heat amount (Q) of the process stream to increase temperature from T_{in} to T_{out} can be represented by Eq(1). However, all of the heat cannot be exchanged with effluent stream due to the second law of thermodynamics. The heat amount supplied by the additional heater (q) is expressed by the following equation;

$$q = \int_{T_{\text{mid},1}}^{T_{\text{out}}} FC_p(T) dT \quad (3)$$

This amount is same as the cooling amount at cooler in Figure 2(a) due to the energy conservation law. According to the above mentioned assumptions, ΔT_{ht} which means the temperature difference between hot and cold (process stream) streams equals $T_{\text{out}} - T_{\text{mid},1}$ and $T_{\text{mid},2} - T_{\text{in}}$. This means that feed (cold) and effluent (hot) curve in the temperature–heat diagram as shown in Figure 2(b) are in parallel with ΔT_{ht} . Using ΔT_{ht} , Eq(3) can be simply rewritten as;

$$q = FC_p \Delta T_{\text{ht}} \quad (4)$$

In addition, ΔT_{ht} is defined by the heat exchanger properties.

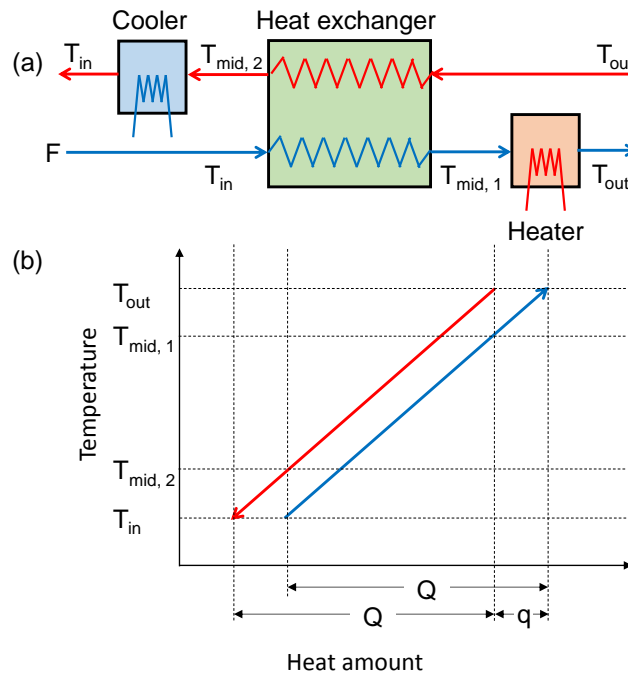


Figure 2: Conventional thermal process with heat recovery: a) flow diagram; b) temperature–heat diagram

Kansha et al. (2013a) reported the required energy for thermal process based on self-heat recuperation as shown in Figure 3 is almost same as the exergy destruction for heat transfer. This exergy destruction (EX_{dest}) for heat transfer can be represented by;

$$dEX_{\text{dest}} = \frac{F \Delta T_{\text{ht at } T} dS}{(T/T_0) + (\Delta T_{\text{ht at } T} / T_0)} \quad (5)$$

where S is entropy of the process stream, T_0 is the standard temperature and $\Delta T_{\text{ht at } T}$ is the temperature difference between process (hot and cold) streams at process stream temperature T ($T_{\text{in}} < T < T_{\text{out}}$).

Kansha et al. (2013a) also reported that temperature difference between process (hot and cold) streams during heat exchange in the thermal process based on self-heat recuperation using compression does not change significantly. This means that heat capacity is not significantly affected by compression. If we assume that the heat exchanger type of this thermal process is the same as the thermal process with feed-effluent heat exchanger, $\Delta T_{\text{ht at } T}$ can be set to ΔT_{ht} .

Hence, entropy and heat capacity has the following relationship;

$$dS = \frac{C_p(T)}{T} dT \quad (6)$$

The energy required (W) for the thermal process based on self-heat recuperation can be derived by the following equation when process stream temperature is close to T_0 and ΔT is much smaller than T_0 .

$$W = \int_{T_{in}}^{T_{out}} FC_P \Delta T_{ht} \frac{dT}{T} = FC_P \Delta T_{ht} \ln \left(\frac{T_{out}}{T_{in}} \right) \quad (7)$$

This energy required (W) is supplied to the system by work as the net energy required for compression. To compare the values (Q , q , W) from Eqs(2), (4) and (7), we can simply estimate the energy required amount for the thermal processes with/without heat recovery or based on self-heat recuperation using process stream properties.

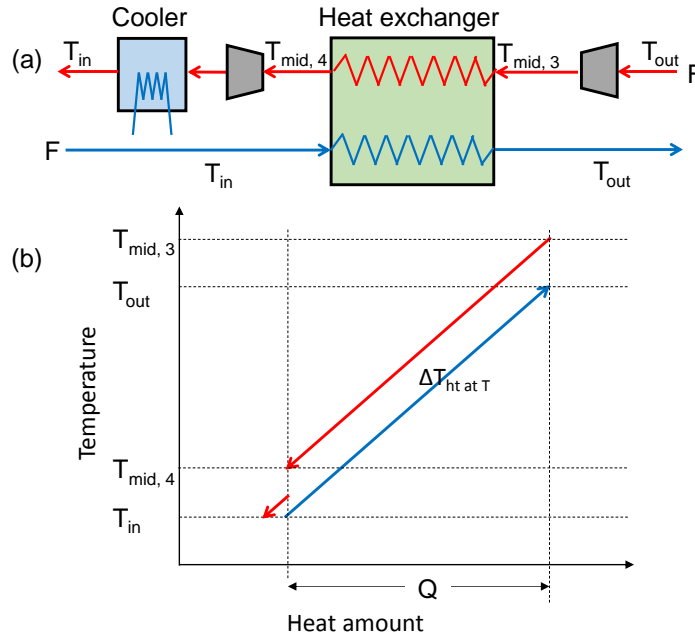


Figure 3: Thermal process based on self-heat recuperation: a) flow diagram; b) temperature–heat diagram

3. Simulations

3.1 Thermal process for gas stream

Kansha et al. (2009) reported comparisons between the energy required for self-heat recuperative processes and the conventional counterparts. According to the above-mentioned paper, the process simulation was conducted using PRO/II Ver. 8.1. As a real fluid, butane was used for the gas stream. In the calculations for all cases, the streams were heated from 300 K to a set temperature T_{in} , and the flow rate of the stream, F , was 100 kmol/h (= 5,812 kg/h). The Soave–Redlich–Kwong equation of state was used considering the real gas stream. The minimum temperature difference for heat exchange was assumed to be 10 K. The pressure ratio in the compressor was set to maintain a constant temperature increase of 10 K owing to compression. The efficiency of the heat exchanger was 100 % (i.e. no heat loss), and the adiabatic efficiencies of the compressor and expander were 100 %. C_P of butane at standard condition was $1.72 \text{ kJ kg}^{-1} \text{ K}^{-1}$.

A comparison between the energy required (Q , q , W) for the thermal processes calculated from Eqs(2), (4) and (7) as shown in Table 1, and the energy required for the thermal processes calculated by the simulation as shown in Table 2 was conducted.

It can be seen from Tables 1 and 2 that the energy required for the thermal processes by the above-mentioned simple calculations are almost consistent with the simulation results. In simple calculations, increase in Q was proportional to increase in T_{out} and q was kept at a constant value of 27.7 kW because C_P was assumed to be constant for simple calculations, and hot and cold streams were the same stream.

It can be estimated that the difference of values mainly came from temperature dependence of heat capacity (C_P). This effect can be understood by the fact that the increase of q depends on T_{out} . At the same

time, it can be observed that the difference of W between calculation and simulation becomes larger with the increase in temperature. This is because the denominator of Eq(5) becomes larger at higher temperatures.

Table 1: Energy required for the thermal processes (Calculation)

T_{out} [K]	Q [kW]	q [kW]	W [kW]
350	138.6	27.7	4.3
400	277.2	27.7	8.0
450	415.8	27.7	11.2

Table 2: Energy required for the thermal processes (Simulation), Kansha et al. (2009)

T_{out} [K]	Q [kW]	q [kW]	W [kW]
350	147.7	31.0	4.4
400	313.7	34.6	8.6
450	497.0	38.0	12.5

3.2 Methanol production

In a methanol production process (LPMEOH™ Demonstration Unit, Heydom et al., 2003) as a case study, we compared the energy required (Q , q , W) for the thermal processes calculated from Eq(2), Eq(4) and Eq(7) with the energy required for the thermal processes calculated by the simulation using PRO/II Ver. 9.0 (Invensys, SimSci) (Kansha et al., 2013b). The feed stream (CO, H₂, etc.) was provided from reformer, this stream was mixed with recycle stream and converted to methanol as shown in Figure 4 (Kansha et al., 2014). In this simulation, the Soave–Redlich–Kwong equation was selected for the thermodynamics data and 100 % adiabatic efficiency was assumed for the compressors. The reactor was assumed to be an isothermal reactor. In addition, the minimum temperature difference for the heat exchangers was fixed at 10 K for all the heat exchangers, and the heat and pressure losses from the system were assumed to be negligible. To ensure the effect of self-heat recuperation and heat recovery, the flow diagram was modified and the feed and reactor conditions were fixed at 313.7 K and 5.07 MPa, and 478.7 K and 5.07 MPa. Flow rate to the reactor was 43,700 kg/h and C_p of this stream was 2.22 kJ kg⁻¹ K⁻¹. By using stream number in Figure 4, stream 1 was feed stream to the heater at 313.7 K and stream 2 was feed stream to the reactor at 478.7 K. Because of the isothermal reactor, stream 3 was the effluent stream from reactor at 478.7 K and stream 4 was output stream from cooler at 313.7 K.

Heater duty (Q) of the thermal process without heat recovery was calculated to be 4.4 MW. At the same time, the energy required for the thermal process with heat recovery (q) and that based on self-heat recuperation (W) were numerically calculated to be 0.27 MW and 0.11 MW. According to the simulation results, these three values (Q , q , W) were 4.5, 0.48, and 0.10 MW, as summarized in Table 3. From this comparison, it can be seen that the energy required (Q , q , W) for the thermal processes calculated from Eq(2), Eq(4) and Eq(7) followed the tendency of the simulation results. However, the energy required for the thermal process with heat recovery (q) calculated from Eq(4) was not fitted well to the simulation values. The reason for this difference is that feed stream (1→2) did not receive enough heat from effluent stream (3→4) due to a pinch point in the heat exchanger. The effluent stream contains much methanol, in which its sensible and latent heats has to be exchanged with sensible heat of feed stream. Thus, the composite curves of feed and effluent stream in the heat exchanger are not in parallel. In fact, the temperature of the exited feed stream from the heat exchanger was 18 K lower than the reaction temperature (478.7 K).

Table 3: Comparison of Energy required for the thermal processes in the methanol production

	Q [MW]	q [MW]	W [MW]
Calculation	4.4	0.27	0.11
Simulation	4.5	0.48	0.10

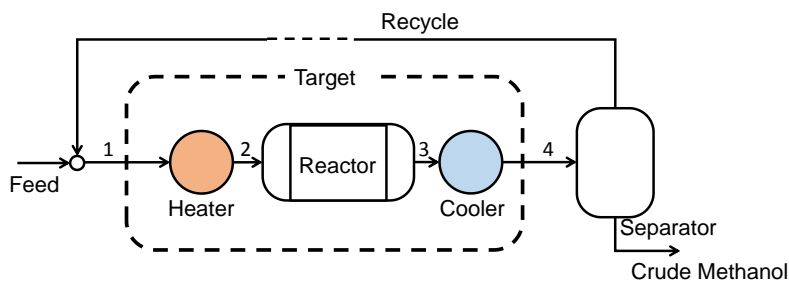


Figure 4: Simple flow diagram for methanol production

4. Conclusions

In this paper, we proposed a simple calculation method to obtain the energy required for the thermal processes with/without heat recovery or based on self-heat recuperation using the process stream properties. The results obtained from this simple calculation method were well-fitted to the simulation results. Therefore, this method can estimate the energy saving potential of heat recovery and self-heat recuperation without simulation and the obtained results can be used as target values for energy saving. This investigation supports process intensification and is promising for industries to examine the energy saving potential when designing a thermal process.

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