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Heat Integration Across Plants Considering Distance Factor

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Total site integration can provide an opportunity for energy saving across different individual plants and processes. Some design methods including direct integration using process streams and indirect integration using intermediate-fluid circuits have been proposed. Normally, from the view of control and security, indirect integration using intermediate-fluid circuits is preferred. The distance between plants is a very important factor which normally is not considered in conventional total site heat integration methodologies. The distance has a great impact on pressure drop and heat loss during transportation of intermediate-fluid. The investment of pipe can be high when the distance is long. This paper presents a novel total site design methodology allows the impact of distance related factors to be involved. In the case study, both direct and indirect Heat Integrations are studied considering the distance related problems. The application of our methodology is very practical and can bring a significant energy saving across plants.

1. Introduction

Heat Integration across plants can bring large energy saving and has been studied for many years. Total Site Heat Integration was first introduced by Dhole and Linnhoff (1993) to describe heat integration across plants. The site sink-source profiles they proposed in their work can be used to determine the different levels of steam that can be generated in order to indirect integrate heat through processes. Then Klemeš et al. (1997) further developed the Total Site Profile and the Site Utility Grand Composite Curve to evaluate total site potential heat recovery. Rodera and Bagajewicz (2001) introduced a mathematical methodology to compare the difference between indirect integration and direct integration. Moreover, they also analysed the factors like number of intermediate-fluid circuit, type of intermediate-fluid in terms of cost. More recently, Perry et al. (2008) extended the Total Site concept to a broader spectrum of processes in addition to the industrial process considering carbon footprint. Varbanov and Klemeš (2011) further developed Total Site Methodology to involve renewable energy sources and CO_2 emissions. Kapil et al. (2012) proposed a new methodology for estimating the cogeneration potential for a site utility system via bottom-up and top-down procedures. In their methodology, the low-grade heat is used through heat pumping, Organic Rankine cycles, energy recovery from exhaust gases, absorption refrigeration and boiler feed water heating. Nemet et al. (2012) proposed a total site integration methodology that can estimate the capital cost.

Although many efforts have been made in the study of Total Site, there are still some unexplored problems. First of all, the distance between plants was not considered. The distance between plants determines the quantity of heat loss during transportation of intermediate-fluid. A large heat loss will result in a large decline in the heat quality of intermediate-fluid so that the temperature may not be high enough to satisfy the heat sink. Secondly, the cost of intermediate-fluid circuits related pipe line and heat insulation material should be counted in. Thirdly, the pump power for transporting fluid and the thickness of insulation material for preventing heat loss during transportation should be considered.

Direct Heat Integration is normally not appropriate in practice due to safety and operation concerns, especially when the distance between plants is long. When heat loss is considered, every process stream participated in heat transfer across plants will lose heat when stream is transported from one plant to another. Therefore, the widely accepted statement that Direct Integration can achieve more energy

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savings than Indirect Integration in the Total Site may be not valid when heat loss is considered. In this work, both Direct Heat Integration and Indirect Heat Integration are analysed.

District heating systems has received increasing interest during the past two decades. Compare with industrial energy using system, residential heating system provide heat to a much larger area. Therefore, in district heating system, some aspects rather than those aspects in Total Site Heat Integration are emphasised, such as use of energy and exergy efficiency analysis, Exergoeconomic approach, district heating-on fuel demand and CO_2 emissions (Sanaei and Nakata, 2012). Geothermal district heating system is a typical heat system, Chuanshan (1997) and Hepbasli and Canakci (2003) studied geothermal district heating system with evaluating both energy and exergy losses of network. In our work, we analyse the heat loss during transportation according to the methodologies they proposed.

In this work, the methodologies of industrial Total Site Integration and district heating system are combined to consider energy saving in industrial total site and the heat loss in intermediate-fluid transportation. A Chinese chemical plant is studied as case study.

2. Considering distance in heat integration across plants

When the distance between plants are considered in heat integration across plants, heat loss is most important issue needs to be concerned. Without considering heat loss, the design will induce big errors. When heat loss is not considered, the energy balance is shown in Eq (1), where Q_s and Q_r are heat supplied from heat source plant and heat received by heat sink plant. In Eq (1), Q_s and Q_r can be represented as the form of Eq(2) and (3), where $T_{s,in}$, $T_{s,out}$, $T_{r,in}$ and $T_{r,out}$ are the intermediate-fluid inlet and outlet temperatures of heat source plant and heat sink plant. In the condition that heat loss is not considered, the heat source plant inlet temperature ($T_{s,in}$) is equal to heat sink plant outlet temperature($T_{r,out}$) and heat source plant outlet temperature ($T_{s,out}$) is equal to heat sink plant inlet temperature ($T_{r,in}$). Figure 1 shows the heat transportation between heat source plant and heat sink plant.

$$Q_s = Q_r \tag{1}$$

$$Q_s = CP_i \cdot (T_{s,out} - T_{s,in}) \tag{2}$$

$$Q_r = CP_i \cdot (T_{r,in} - T_{r,out}) \tag{3}$$

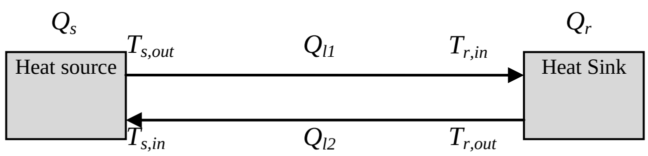

Figure 1: Heat transportation with and without considering heat loss

When heat loss is considered, the energy balance is re-written in the form of Eq (4), where Q_{l1} and Q_{l2} is the heat loss on the ways to heat sink plant and back to heat source plant, respectively. Due to heat loss, $T_{s,out}$ and $T_{r,in}$ as well as $T_{s,in}$ and $T_{r,out}$ are no longer equal. It is obvious that in practice, when heat loss cannot be ignored, the design generated by conventional methodologies will result in a large deviation from real number.

$$Q_s = Q_r + Q_{l1} + Q_{l2} \tag{4}$$

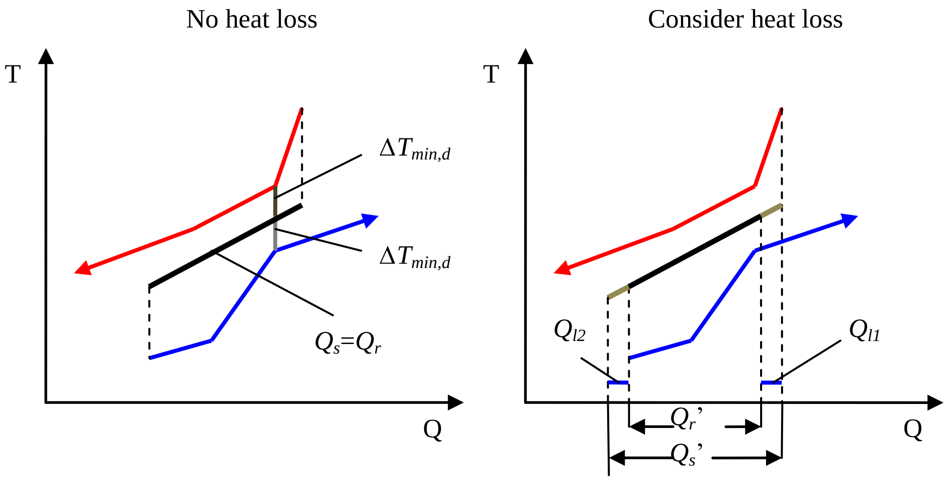

Figure 2: Composite Curves for Heat Integration across plants

To consider intermediate-fluid and heat loss in heat integration across plants, the composite curves (Linnhoff and Hindmarsh, 1983) for both heat sink plant and heat source plant are applied, as shown in Figure 2. In the Figure 2, the upper curve is Heat Source Curve, the lower curve is Heat Sink Curve and the curve in middle is Intermediate-Fluid Curve. To determine the position of Intermediate-Fluid Curve in the Figure 2, firstly, the minimum temperature approach ($\Delta T_{min,i}$) in Indirect Heat Integration between Heat Source Plant Curve and Heat Sink Plant Curve needs to be doubled as it in Direct Heat Integration ($\Delta T_{min,d}$). The Intermediate-Fluid Curve should transfer heat with heat sink/source without violating minimum temperature approach. Therefore, in the Figure 2, the distance between Intermediate-Fluid Curve and Heat Sink/Source Curve has to be larger than $\Delta T_{min,d}$ anywhere. The heat taken from Heat Source can be determine by Composite Curves through the distance between the point with highest temperature in heat source and the point with lowest temperature in heat sink, as shown in Figure 2. The heat capacity flow rate (*CP*) value (the gradient of curve in the figure) of intermediate-fluid can be adjusted but the minimum temperature approach has to be kept larger than $\Delta T_{min,d}$. The change in *CP* value has not make any change in energy consumption, but it affects the operation cost and investment, which is mentioned in the next section.
When heat loss is accounted in the Heat Integration across plants, from Figure 2, more heat (Q_s'=Q_s+Q_{l1}+Q_{l2}) is required to be taken from heat source plant, and Less heat (Q_s'=Q_s-Q_{l1}) is recovered by heat sink plant.

3. Economic Analysis for heat integration across plants considering distance

The distance related cost in heat integration can be large in both operation cost and investment.
Firstly, the *CP* value of intermediate-fluid is depended on the flow rate of the fluid. The relation between *CP* value and mass flow rate (*F*) of fluid is shown in Eq (5), where *Cp* is Specific heat capacity. The flow rate of hot water needs to be large enough to recover the heat from heat source plant in order to match the heat requirement of heat sink plant. But the increased flow rate directly increases the diameter of pipe and pump power so that both investment and operation cost increase. The diameter of pipe can be calculated through Eq (6), where *d* is pipe diameter, ρ is the density of intermediate-fluid, and *u* is flow velocity. In the equation, it is assumed that the density of intermediate-fluid does not change with temperature. The pump power required to transport water from plant to plant can be calculated through Eq (7). It is assumed that all the pump power is used to drive water against power loss during transportation. In Eq (7), ω_f is power loss due to friction, λ is friction factor and *l* is pipe length.

$$CP = Cp \cdot F \tag{5}$$

$$d = \sqrt{\frac{4F}{\pi u \rho}} \tag{6}$$

$$\omega_f = \lambda \cdot \frac{l}{d} \cdot \frac{u^2}{2} \quad (7)$$

Secondly, in the view of heat transfer, *CP* value also affects the temperature difference in heat exchanger as well as *FT* value to further affect the heat exchangers investment. Eq (8) and (9) can be used to determine the change in temperature caused by change in *CP*, where $T_{c,out}$, $T_{c,in}$, $T_{h,out}$ and $T_{h,in}$ are cold and hot outlet and inlet temperature, Q is heat duty of the exchanger and CP_c and CP_h are cold and hot heat capacity flow rate. *FT* is a value to describe heat transfer efficiency in multiple tube pass heat exchangers, a larger *CP* of hot water makes *FT* larger so that the heat transfer efficiency is higher.

$$T_{c,out} = T_{c,in} + Q / CP_c \quad (8)$$

$$T_{h,out} = T_{h,in} - Q / CP_h \quad (9)$$

Thirdly, good and thick insulation layer can prevent fluid from losing large quantities of heat, but it boosts investment. The models for heat loss in pipe are taken from Stubblefield et al.'s work (1996). In this work, the heat loss model is simplified by only considering heat transfer resistance in insulation layer, because it is much larger than other resistance, especially when the insulation layer is thick. The simplified models are shown in Eq (10), where T_w is hot water temperature, T_e is environmental temperature, R is heat transfer resistance and L is the distance between plants. The heat transfer resistance can be calculated by Eq(11), where r_T is pipe radius including insulation layer, r_p is bare tube radius and k is thermal conductivity of insulation. The optimal thickness of insulation layer can be determined through a trade-off between insulation layer cost and energy cost due to heat loss.

$$Q_{loss} = \frac{T_w - T_e}{R} \times L \quad (10)$$

$$R = \left(\frac{1}{2\pi k} \ln\left(r_T / \mathrm{r_p} \right) \right) \quad (11)$$

4. Case Study

The case is a Heat Integration project for two existing plants: a refinery and a rubber plant. The distance between two plants is 2 km. It is assumed that the heat exchanger networks within both plants are well established. In this case, refinery is considered as a heat source plant and the rubber plant is as a heat sink plant. Therefore, only the streams with exchangers using cold utility in refinery and with exchangers using hot utility in rubber plant are considered to be integrated. The data of streams using utilities are shown in Table 1.

Table 1: streams data for case study

Stream number	supply temperature (°C)	target temperature(°C)	duty (kW)
H1 (refinery)	170	90	10,000
H2 (refinery)	130	70	6,000
H3 (refinery)	110	60	8,000
C1 (rubber plant)	90	90.1	6,000
C2 (rubber plant)	130	130.1	3,000
C3 (rubber plant)	110	110.1	2,000
C4 (rubber plant)	100	100.1	2,000

In this case, because the temperature of recovered heat is not very high, hot water is selected as intermediate-fluid. The minimum temperature approach is set to be 10 °C in Direct Heat Integration. In Indirect Heat Integration, because heat needs to be transferred twice from hot streams to hot water and from hot water to cold streams, the minimum temperature approach is 20 °C. The flow velocity of hot water is set to be 2 m/s. From the composite curves, as shown in Figure 3, the *CP* value of hot water can be estimated to be 211 kW/°C, so that the flow rate of hot water can be determine from Eq (5). The diameter of pipe can be calculated through Eq (6).

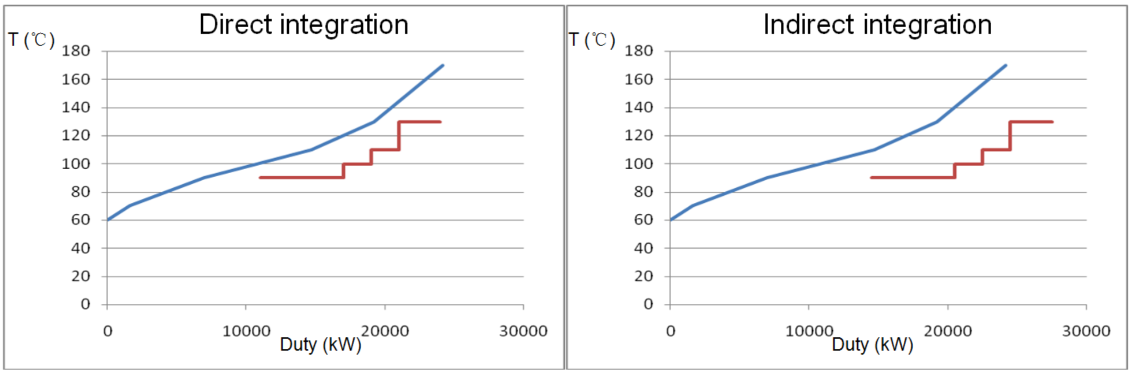

Figure 2: Composite Curves for Direct Integration and Indirect Integration in case study

When heat loss is not considered, the energy recovery target for Direct and Indirect Integration can be achieved by conventional Total Site Integration methodology. The energy recovery targets for Direct and Indirect Integration are 13,000 kW and 9,500 kW. When the heat loss is considered, the change in energy recovery quantity for Direct and Indirect Integration is different, because each hot stream in Direct Integration is transported through a separated pipe line so that the heat loss is high. The number of pipe line in Direct Integration in this case is 3. Because of this reason, the pipe line of Direct Heat Integration is much longer than Indirect Integration, results in a very high pipe cost, which is shown in the first row in Table 2.

Table 2: Results for direct and indirect integration under difference considerations

Integration schemes	Direct heat integration	Indirect heat integration
Annualized pipe cost	284,901 $/y	84,415 $/y
optimal insulation layer thickness	0.07 m, 0.05 m, 0.05 m	0.05 m
Annualized insulation material cost	38,790 $/y	6,668 $/y
Heat loss on the way to heat sink	941.5 kW	277.2 kW
Pump power cost	79,531 $/y	42,297 $/y
Annualized heat exchanger cost	41,926 $/y	63,085 $/ y
Energy saving benefit	633,796 $/y	485,473 $/y
Profit	188,648 $/y	289,008 $/y

Wool glass is selected as the insulation material in this work. The thermal conductivity is 0.065 W/m·℃. After the trade-off between heat loss cost and insulation material cost, the optimal insulation layer thickness can be achieved, as shown in Table 2. The reason for a higher insulation cost is due to the larger length of pipe line in Direct Integration. The pump power of both Direct Heat Integration and Indirect Integration are calculated through Eq (7). In Direct Integration, the fluid transported to the other plant is process stream, and in Indirect Integration, the fluid is water. The process streams in refinery normally have larger viscosity than water, so that the required pump power for those streams is much larger. When Indirect Heat Integration is considered, the heat is firstly transfer from heat source to hot water, and then transfer from hot water to sink. Therefore, more heat exchangers are required in Indirect Heat Integration than Direct Heat Integration, so that the heat exchangers cost is higher.
From the results shown in Table 2, Indirect Heat Integration is more economic than Direct Heat Integration when the distance factors are counted in.

5. Conclusions

Heat Integration across plants can bring large energy saving. When the distance between plants is considered, the distance related factors such as heat loss, pump power and pipe cost affects the economic performance of Heat Integration significantly, especially when the distance is very long. Heat loss can reduce the supply temperature to heat sink plant, and without considering heat loss, the exchangers in heat sink plant may be invalid due to the violation of minimum temperature approach. The thickness of insulation layer can be achieved from the trade-off between energy cost due to heat loss and insulation material cost. Both Direct and Indirect Heat Integration are studied in case study, from the results, Direct Heat Integration is not appropriate not only because the control and security problems, but also for the very high investment. In the case study, the cost of pipe line is the largest expense in the integration across plants, when the distance is long, the high cost of pipe line makes the integration uneconomic. This new methodology for Heat Integration across plants considering distance can make the design more practical. The future work is going to establish an optimisation procedure to consider the value of *CP* and the cost of additional area.

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