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A Two Step Methodology for Inter-Plant Heat Integration Design

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HRL (heat recovery loop) is an indirect method for transferring heat from one plant to another plant using intermediate-fluid circles. Inter-plant heat integration using HRL is a very special approach for energy conservation, as there are some additional factors should be considered, such as the capital cost of additional heat exchangers, pumps and pipelines for long distance, operation cost of pumping power and heat loss during the transportation. Moreover, when the number of plants involved in Heat Integration is large, the connection between plants have to be considered. These factors simultaneously determine the possibility and performance of Heat Integration. In this work, graphical targeting and mathematical programming is combined, a generalized MINLP model with economic objection is proposed to minimize the total annual costs (TAC) for Inter-Plant Heat Integration using HRL. As this work concentrates on heat recovery in low temperature range, hot water is selected as the heat transfer medium. The solved results can give the mass flow rate of intermediate-fluids, diameter of pipeline, temperatures of the heat transfer medium and the configuration of heat exchanger networks (HENs). An industry case study with three plants is used to demonstrate the model.

1. Introduction

Heat recovery loop (HRL) is an Indirect Heat Integration method using intermediate-fluids and it has been considered as a viable energy saving method for processing plants. Bagajewicz and Rodera (1999) firstly studied Indirect Heat Integration using intermediate-fluid circles, i.e. dowtherms which needed not to be isothermal. They developed a systematic procedure to identify energy-saving target for inter-plant heat integration. Bagajewicz and Rodera (2000) developed another procedure for Inter-Plant Heat Integration and calculated targets for several industrial cases. An MILP problem was proposed to determine the optimal location of the fluid circuits. Bagajewicz and Rodera (2002) studied heat pumps system in multi-plant heat integration. Stijepović and Linke (2011) proposed an approach to enable the targeting of waste heat recovery potential in industry zone. Their study is concentrated on high temperature waste heat and the intermediate-fluid is steam. Atkins et al (2012) analysed Inter-Plant Heat Integration at a semi-continuous factory by the application of HRL. They developed a method to minimize the amount of heat exchanger area required for the HRL by optimizing the allocation of heat exchangers and the storage temperatures of the intermediate-fluid.

Inter-Plant Heat Integration is an important research area, while most researches above only focused on energy reused perspective. Wang et al (2013) pointed out that distance had a significant influence on the Inter-Plant Heat Integration, while it was not fully considered in the conventional design. Some additional factors such as installation cost of pumps and pipelines for long distance, operation cost of pumping power and heat loss during the transportation decupling with the capital cost of additional heat exchangers determine the performance of inter-plant heat integration synchronously. Nevertheless, their studies only simulated the HRL design based on graphical targeting tools, but the mass flow rate and temperatures of intermediate-fluid circuits are not optimized, which had a great impact on the performance of integration. Combining graphical targeting and mathematical programming method, for an overview see (Klemeš and Kravanja, 2013), this work presents an MINLP model based on economic criteria to minimizing the total annual cost (TAC). In addition, this work focus on low grate heat reused and hot water is selected as the

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heat transfer medium. The solved result can give the mass flow rate of intermediate-fluids, diameter of pipelines, temperatures of the intermediate-fluid circuits and the structure of heat exchanger networks (HENS) automatically.

2. Proposed method

2.1 Graphical targeting tool

The proposed method in this work included two steps for inter-plant heat integration using HRL. The first step is to determine the connection between plants through heuristic based graphical tools. It is known that when the number of plants is large, the possibility of connection between plants can be various. Using three plants as an example, based on the heat demand and heat required, there are three connection possibilities for the Inter-Plant Heat Integration (as shown in Figure 1). In this work, it is assumed that HENs within both plants are well established. Therefore, only the streams with cooler and streams with heater in the plants are considered to be integrated. All such streams are used for each plant to established Grand Composite Curves (Klemeš, 2013). Then based on the Grand Composite Curves for each plant, the connection between plants can be determined though the cascade utilization of energy.

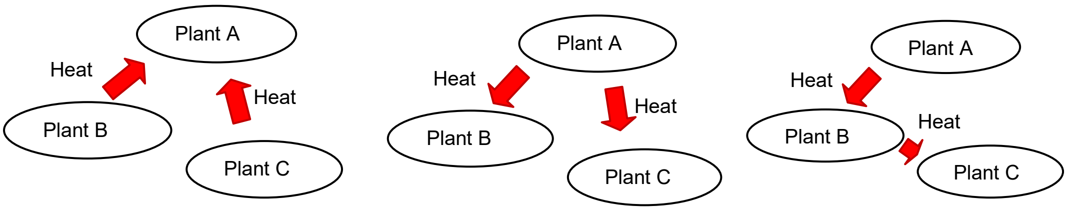

Figure 1: Connection possibilities for a three plants example

2.2 Mathematical programming model

Based on mathematical programming, an MINLP model is established to minimizing the TAC. The superstructure is modified from the generalized MINLP model for cooling water system. The configuration showed in Figure 2 encompasses both series and parallel for heat exchangers.

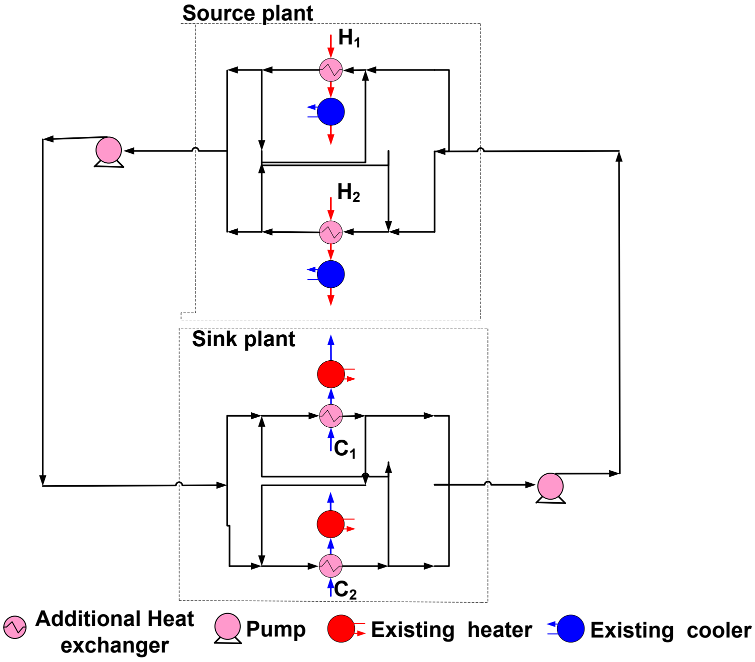

Figure 2: Superstructure of Inter-Plant Heat Integration using HRL

In the mathematical model, energy balance around each heat exchanger is expressed as:

$$F_w = \sum_{i\in HP} f_i^{in} \qquad i \in HPS \tag{1}$$

$$f_i = \sum_{i'\in HP} f_{ii'}^{out} \qquad i \in HPS \tag{2}$$

$$F_w = \sum_{j\in CP} f_j^{in} \qquad j \in CPS \tag{3}$$

$$f_j = \sum_{j'\in CP} f_{jj'}^{out} \qquad j \in CPS \tag{4}$$

Mass and heat balances for mixers:

$$F_w = \sum_{i\in HP} \sum_{i'\in HP} f_{ii'}^{out} \qquad i = i' \tag{5}$$

$$F_w \cdot T_{supply} = \sum_{i\in HP} \sum_{i'\in HP} f_{ii'}^{out} \cdot t_i^{out} \qquad i = i' \tag{6}$$

$$F_w = \sum_{j\in CP} \sum_{j'\in CP} f_{jj'}^{out} \qquad j = j' \tag{7}$$

$$F_w \cdot T_{return} = \sum_{j\in CP} \sum_{j'\in CP} f_{jj'}^{out} \cdot t_j^{out} \qquad j = j' \tag{8}$$

$$f_i = \sum_{\substack{i''\in HP\\ i''\neq i}} \sum_{\substack{i'\in HP\\ i'=i,}} f_{i''i'}^{out} + f_i^{in} \qquad i \in HPS \tag{9}$$

$$f_i \cdot t_i^{in} = \sum_{\substack{i''\in HP\\ i''\neq i}} \sum_{\substack{i'\in HP\\ i'=i,}} f_{i''i'}^{out} \cdot t_{i''}^{out} + f_i^{in} \cdot T_{return} \qquad i \in HPS \tag{10}$$

$$f_j = \sum_{\substack{j''\in CP\\ j''\neq j}} \sum_{\substack{j'\in CP\\ j'=j,}} f_{j''j'}^{out} + f_j^{in} \qquad j \in CPS \tag{11}$$

$$f_j \cdot t_j^{in} = \sum_{\substack{j''\in CP\\ j''\neq j}} \sum_{\substack{j'\in CP\\ j'=j,}} f_{j''j'}^{out} \cdot t_{j''}^{out} + f_j^{in} \cdot T_{supply} \qquad j \in CPS \tag{12}$$

Energy balance around each heat exchanger:

$$q_i = F_i \cdot \left(T_i^{in} - T_i^{H}\right) \qquad i \in HPS \tag{13}$$

$$q_i = f_i \cdot \left(t_i^{out} - t_i^{in}\right) \qquad i \in HPS \tag{14}$$

$$q_j = F_j \cdot \left(T_j^{C} - T_j^{in}\right) \qquad j \in CPS \tag{15}$$

$$q_j = f_j \cdot \left(t_j^{in} - t_j^{out}\right) \qquad j \in CPS \tag{16}$$

The temperature difference:

$$dt_i^{in} \le T_i^{H} - t_i^{in} + \Gamma_i \cdot \left(1 - z_i\right) \qquad i \in HPS \tag{17}$$

$$dt_i^{out} \le T_i^{in} - t_i^{out} + \Gamma_i \cdot \left(1 - z_i\right) \qquad i \in HPS \tag{18}$$

$$dt_j^{in} \le t_j^{out} - T_j^{in} + \Gamma_j \cdot \left(1 - z_j\right) \qquad j \in CPS \tag{19}$$

$$dt_j^{out} \le t_j^{in} - T_j^{C} + \Gamma_j \cdot \left(1 - z_j\right) \qquad j \in CPS \tag{20}$$

Finally, the objective function for the total annual cost (TAC) and the complete model are as follows:

$$
\begin{aligned}
TAC = Min\ CCU \cdot \sum_{i \in HPS} qcu_i + CHU \cdot \sum_{j \in CPS} qhu_j + Pumping + \frac{I \cdot (1+I)^n}{(1+I)^n - 1} \cdot (Costpipe + Costpump) \\
\alpha \cdot \sum_{i \in HPS} z_i + \beta \cdot \sum_{i \in HPS} \left(\frac{\left(h_i^{-1} + h^{-1}\right) \cdot q_i}{\left(dt_i^{in} \cdot dt_i^{out} \cdot 0.5 \cdot \left(dt_i^{in} + dt_i^{out}\right) + \delta\right)^{0.3333}} \right)^{\gamma} + \\
\alpha \cdot \sum_{j \in CPS} z_j + \beta \cdot \sum_{j \in CPS} \left(\frac{\left(h_j^{-1} + h^{-1}\right) \cdot q_j}{\left(dt_j^{in} \cdot dt_j^{out} \cdot 0.5 \cdot \left(dt_j^{in} + dt_j^{out}\right) + \delta\right)^{0.3333}} \right)^{\gamma}
\end{aligned} \tag{21}
$$

3. Case Study and result

This case is a heat integration project for three existing plants: a Styrene plant, a Solvent plant and a Methanol plant. The cost data are shown in Table 1. In the table, D_{out} and D_{in} are the outer and inner diameter of pipe, Wt_{pipe} is the weight of pipe and P_{cul} is the cost of pipe.

Table 1: Cost data for case study

Items	Value
Electric cost	0.12 ($\$ \cdot kW^{-1} \cdot h^{-1}$)
Capital cost of heat exchanger	$4{,}000+200 \cdot Area^{0.83}$ ($\$ \cdot y^{-1}$)
Capital cost of pump	$450(q \cdot H^{0.5})^{0.2}$ ($\$ \cdot y^{-1}$)
40sch pipeline	D_{out}(m) = $1.052D_{in}+0.005251$ Wt_{pipe}(kg/(m) = $644.3D_{in}^2+72.5D_{in}+0.4611$ P_{cul}(\$/m) = $0.82Wt_{pipe}+185D_{out}^{0.48}+6.8+265D_{out}$

I = 10 % n = 4 y   Heat loss: 60 W/m

Stream data is analysed by using the Grand Composite Curve shown in Figure 3. From the figure, it can be seen that the surplus heat of Styrene plant can be used as the heat source for Solvent plant, and the surplus heat of Styrene plant is not enough for the heat demand of both Solvent plant and Methanol plant, so the surplus heat of Solvent plant is used as heat source for the Methanol plant. Therefore, in this case, Solvent plant is not only a heat source plant, but also a heat sink plant.

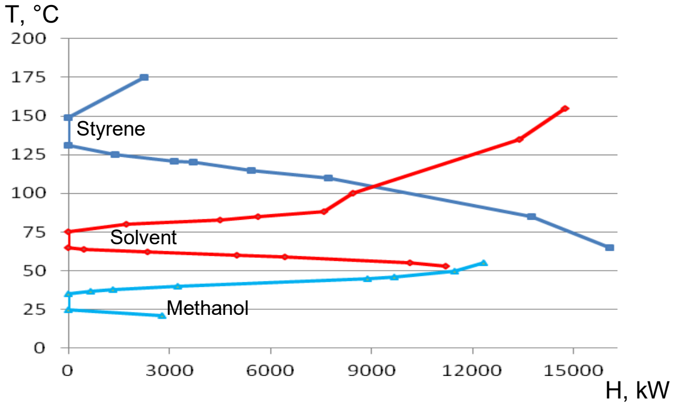

Figure 3: The Grand Composite Curve each plant

By using Grand Composite curve, the connection between plants is obtained, as shown in Figure 4. The distance between plants is also shown in the figure.

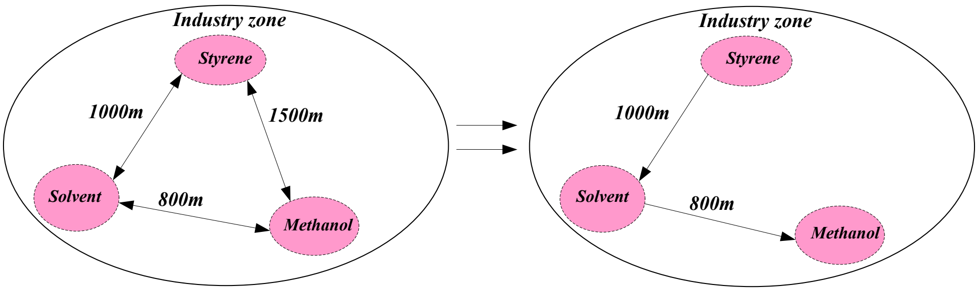

Figure4: The location and connection of the plants

The detailed connections between plants are showed in Figure 5. The detailed economic performance is shown in Table 2. The minimized total annual cost is 2,004,939 $ and the heat recovered is 17,822 kW. The flow rate of intermediate-fluid is 221 t/h and 257 t/h for the two HRLs. From Table 2, it can be known that the investment for the pipeline and heat exchangers are the major part of the investment, because the distance between plants is relatively long, and the number of new heat exchangers is large, about 16 new heat exchangers.

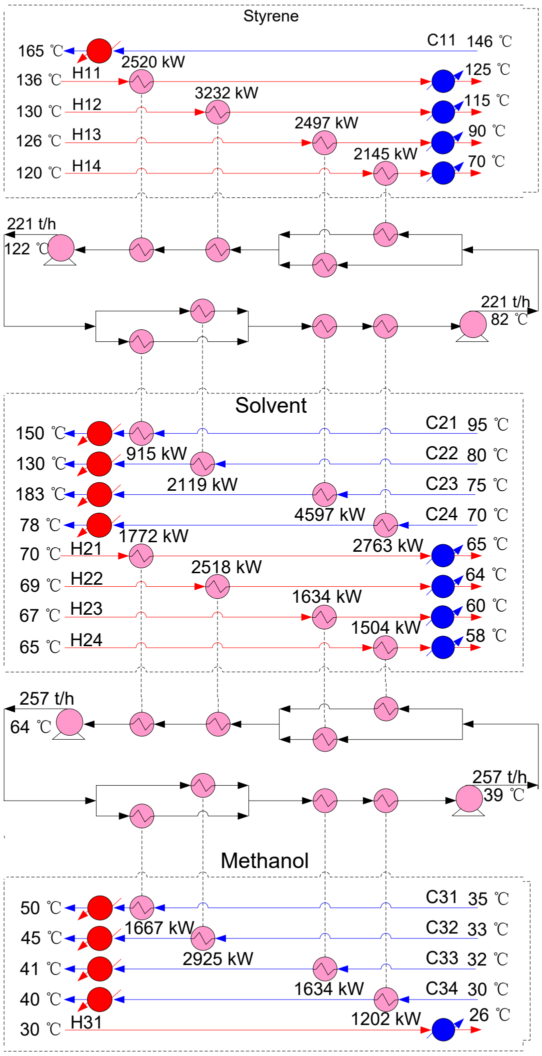

Figure 5: The HENs of each plant

Table 2: Annualized cost and profit of the project

Items	Solved results
Annualized pipe cost	288,238 $\$\cdot y^{-1}$
Annualized pumps cost	24,342 $\$\cdot y^{-1}$
Heat loss	520 kW
Pump power cost	8,286 $\$\cdot y^{-1}$
Annualized heat exchanger cost	883,293 $\$\cdot y^{-1}$
Energy saving benefit	17,822 kW

4. Conclusions

Inter-plant heat integration using HRL can improve energy and economic efficiencies in an overall prospective. A two-step Inter-Plant Heat Integration methodology including a graphic tool and generalized MINLP model is established for HRL designs. By using the new methodology, the connection between plants and the detailed design for HRL can be obtained. From the results of case study, the investment for the pipeline and heat exchangers are the major part of the investment, and the total annual cost is 2,004,939 $. The heat recovery obtained in the case is also very promising, which is 17,822 kW.

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