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Efficient Solution Strategy for Stage-wise MINLP Model of Interplant Heat Integration using Heat Recovery Loop

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Interplant Heat Integration using Heat Recovery Loop (HRL) is very different from intra-plant Heat Integration. As the heat sources and sinks are always separated in different regions, some additional factors should be focused on, i.e. capital cost of heat exchangers, installation cost of pumps and pipelines for long distance, and operation cost of pumping power and heat loss during the transportation. Based on economic criteria, this paper presents a stage-wise MINLP model for HRL designs considering the factors aforementioned. Unlike traditional heat exchanger networks (HENS), the flow rate of intermediate-fluid is considered as an important variable which results in a large complex, non-convex model. An efficient strategy is proposed for the problem by sequentially solving an MILP, an MINLP and a NLP. The distance plays a significant role in the design of HRL and it significantly affects the investment of pipelines. The optimum results show that the influence of pumps is relatively less. An industry case study is demonstrated to illustrate the efficiency of the strategy.

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. Hui and Ahmad (1994) described indirect Heat Integration between separated plants. Their studies were all based on graphical targeting tools of Pinch Technology. Rodera and Bagajewicz (1999) found that a single plant can further improve energy efficiency by sharing energy with other plants. They developed an energy targeting procedure for interplant Heat Integration. Their studies showed that direct integration may achieve less energy savings than indirect integration using HRL, as there would be a large heat loss for process streams participated in direct Heat Integration across plants, so interplant Heat Integration using HRL is preferred. Rodera and Bagajewicz (2000) developed another procedure for interplant Heat Integration using HRL and developed an MILP model to determine the optimal location of the fluid circuits in interplant Heat Integration. Perry et al (2008) analysed heating and cooling requirements in an enlarged geographical area, which was referred as a Locally Integrated Energy Sector (LIES). Hot water was used as heat recovery loop (HRL) to reused industry waste energy for district heating in LIES. Their method showed that HRL can be successfully applied to integrate waste and renewable energy and consequently reduced the carbon footprint in an overall perspective. Walmsley and Atkins (2012) analysed interplant Heat Integration at a semi-continuous factory by the application of HRL. They examined the dynamic operation and variability of HRL in multi-plant site. Kapil et al (2012) suggested district heating to utilize this waste heat and alleviate the carbon footprint of the integrated energy system.
There are still some significant factors ignored in conventional HRL design, i.e. the investment of pipeline heat exchangers, installation cost of pumps and pipelines, operation cost of pumping power and heat loss. Bade and Bandyopadhyay (2014) proposed a linear programming (LP) formulation to minimizing the flow rate of hot oil used as intermediate fluid for multiple plant Heat Integration. However, the formulation just considered the minimum total utilities requirement for interplant Heat Integration as a constraint. As mathematical programming can consider multiple factors aforementioned, this work presents a MINLP model with economic objective for interplant Heat Integration using HRL. The flow rate of intermediate-fluid needs to be large enough to recover the heat from heat source plant to heat sink plant, but the increased

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flow rate will directly increase the diameter of pipe and pump power so that both investment and operation cost will increase. This important variable results in nonlinear constraints with bilinear terms and a large complex, non-convex model, for which even finding a feasible solution is a challenge. An efficient strategy is developed for the complex problem by sequentially solving a MILP, a MINLP and a NLP. As the work focus on low temperature range, hot water is used as the intermediate-fluid medium. The solved results can give the mass flow rate of intermediate-fluid, diameter of pipeline, temperature of the intermediate-fluid circuit and the matches of heat exchangers networks (HENS) automatically.

2. MINLP model for inter-plant Heat Integration using HRL

The superstructure of HRL in Figure 1 is modified from stage-wise MINLP model for heat exchanger networks (Yee, 1990). The model is fairly general and it allows both series and parallel decoupling of the exchangers, due to the stage-wise superstructure.

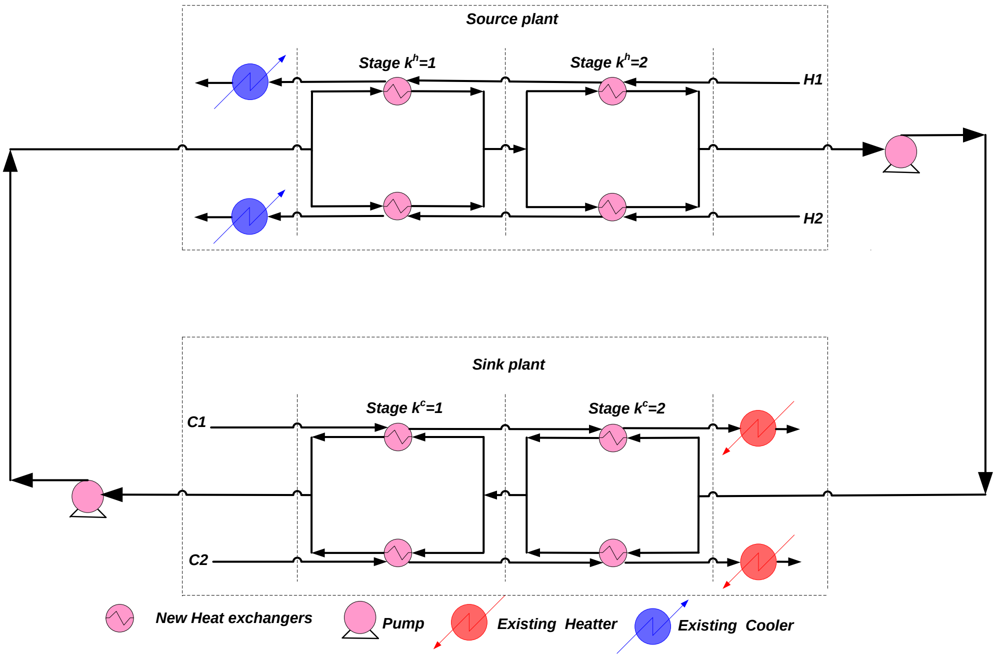

Figure 1: Superstructure of interplant Heat Integration using HRL

Energy balance of each additional heat exchanger is performed in order to define the outlet temperatures of heat exchanger, which leads to equations with bilinear terms:

$$q^H_{ik^h} = F^H_i \cdot \left(th_{ik^h} - th_{ik^h+1}\right) \qquad i \in HPS,\; k^h \in Sth \tag{1}$$

$$q^H_{ik^h} = f^H_{ik^h} \cdot \left(t^H_{ik^h} - t_{k^h+1}\right) \qquad i \in HPS,\; k^h \in Sth \tag{2}$$

$$q^C_{jk^c} = f^C_{ik^c} \cdot \left(t_{k^c} - t^C_{jk^c}\right) \qquad j \in CPS,\; k^c \in Stc \tag{3}$$

$$q^C_{jk^c} = F^C_j \cdot \left(tc_{jk^c} - tc_{jk^c+1}\right) \qquad j \in CPS,\; k^c \in Stc \tag{4}$$

Energy balance of each mixer defines the inlet temperatures of stages, which also leads to equations with bilinear terms:

$$\sum_{i \in HP} f^H_{ik^h} \cdot t^H_{ik^h} = Fcp \cdot t_{k^h} \qquad k^h \in Sth \tag{5}$$

$$\sum_{j \in CP} f^C_{jk^c} \cdot t^C_{jk^c} = Fcp \cdot t_{k^c+1} \qquad k^c \in Stc \tag{6}$$

Energy balances for final utility units define the utility loads:

$$qcu_i = F^H_i \cdot \left(th_{ik^h} - Th_i^{out}\right) \qquad i \in HPS,\; k^h \in Lasth \tag{7}$$

$$qhu_j = F_j^C \cdot \left(Tc_j^{out} - tc_{jk^c}\right) \qquad j \in CPS,\ k^c \in Firstc \tag{8}$$

In addition, big-M constrains are needed to ensure that the temperature approach if the heat exchangers exist. The parameter Γ is an upper bound for the temperature difference.

$$dt^H_{ik^h} \le th_{ik^h} - t^H_{ik^h} + \Gamma^H_{ik^h} \cdot \left(1 - z^H_{ik^h}\right) \qquad i \in HPS,\ k^h \in Sth \tag{9}$$

$$dt^H_{ik^h+1} \le th_{ik^h+1} - t_{k^h+1} + \Gamma^H_{ik^h} \cdot \left(1 - z^H_{ik^h}\right) \qquad i \in HPS,\ k^h \in Sth \tag{10}$$

$$dt^C_{jk^c+1} \le t^C_{jk^c} - tc_{jk^c+1} + \Gamma^C_{jk^c} \cdot \left(1 - z^C_{jk^c}\right) \qquad j \in CPS,\ k^c \in Stc \tag{11}$$

$$dt^H_{ik^h} \le th_{ik^h} - t^H_{ik^h} + \Gamma^H_{ik^h} \cdot \left(1 - z^H_{ik^h}\right) \qquad j \in CPS,\ k^c \in Stc \tag{12}$$

$$TAC = Min\ CCU \cdot \sum_{i \in HPS} qcu_i + CHU \cdot \sum_{j \in CPS} qhu_j + Pumping + \frac{I \cdot (1+I)^n}{(1+I)^n - 1} \cdot (Costpipe + Costpump) \tag{13}$$

$$\alpha \cdot \sum_{i \in HPS} \sum_{k^h \in Sth} z^H_{ik^h} + \beta \cdot \sum_{i \in HPS} \sum_{k^h \in Sth} \left(\frac{\left(h_i^{-1} + h^{-1}\right) \cdot q^H_{ik^h}}{\left(dt^H_{ik^h} \cdot dt^H_{ik^h+1} \cdot 0.5 \cdot \left(dt^H_{ik^h} + dt^H_{ik^h+1}\right) + \delta\right)^{0.3333}} \right)^{\gamma} +$$

$$\alpha \cdot \sum_{j \in CPS} \sum_{k^c \in Stc} z^C_{jk^c} + \beta \cdot \sum_{j \in CPS} \sum_{k^c \in Stc} \left(\frac{\left(h_j^{-1} + h^{-1}\right) \cdot q^C_{jk^c}}{\left(dt^C_{jk^c} \cdot dt^C_{jk^c+1} \cdot 0.5 \cdot \left(dt^C_{jk^c} + dt^C_{jk^c+1}\right) + \delta\right)^{0.3333}} \right)^{\gamma}$$

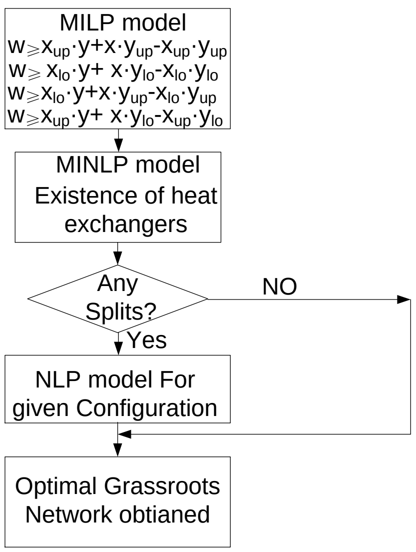

Figure 2: Solution strategy for interplant Heat Integration using HRL

3. Efficient solution strategy for the problem

The model described here consists of a general straightforward formulation for a given stage-wise superstructure. It is a non-convex problem because of some equation constraints involving bilinear terms, and also the Eq.(13) is nonlinear. The flow rate of intermediate-fluid is considered as a variable which results in non-convex constraints Eq(2) and (3). In addition, energy balance around each mixer defines the inlet temperatures of stages, which also leads to Eq(5) and (6) with bilinear terms or non-convex constraints. To conquer the difficult, an efficient solution strategy is present in Figure 2. By assuming isothermal mixing of streams for stage-wise superstructure, which significantly simplifies the model formulation, the nonlinear heat balances around mixer can be eliminated. For each streams and intermediate-fluids, only an overall heat balance must be performed within each stage and variables $f^H_{ik^h}$,

$f^{C}_{jk^c}$, $t^{H}_{ik^h}$ and $t^{C}_{jk^c}$ are no longer needed in the model. The first step is a MILP problem with the McCormick convex envelope. The objection in this step encompasses operation cost of utility, fixed capital cost, number of heat exchanger and pipeline. The flow rate of intermediate-fluid is optimised through the trade-off between pipeline cost and energy recovery in this step. The second step is a MINLP problem and the result can offer the network configuration with the existence of each heat exchangers. If steams splits are needed, an additional NLP model with fixed structure can be solved to remove the isothermal mixing assumption and perform further optimisation of heat exchangers area.

4. Case Study

The case is a Heat Integration project for two existing plants: an aromatic and a butadiene plant. The distance between two plants is 1.5 km. It is assumed that HENS within both plants are well established. Only the streams with cooler in aromatic and streams with heater in butadiene plant are considered to be integrated across plant. In this case, the aromatic is a heat source plant and the butadiene plant is a heat sink plant. The stream and cost data are shown in Table 1 and Table 2. In the table, D_{out} is the outer diameter of pipe, D_{in} is the inner diameter of pipe, Wt_{pipe} is the weight of pipe, P_{cul} is the cost of pipe.
The HENS in each plant are showed in Figure 3. The Composite Curve of T-H profile of Heat Integration is showed as Figure 4. The minimised total annual cost is 772,613 $ and the heat recovered is 12,564 kW. The flow rate of intermediate-fluid is 143 t/h. In Table 3, the capital and operation cost of pump is about 12,172 $\$•y^{-1}$ and 4,246 $\$•y^{-1}$ and the heat loss is 200 kW, while the annualized pipe and additional heat exchanger cost is about 193,141 $\$•y^{-1}$ and 286,105 $\$•y^{-1}$.
The case study contains 164 continuous variables, 37 integer variables and 285 constraints. The problem is solved less than 1 min of CPU time on a desktop PC (Inter (R) Core (TM) i5 CPU 3.33 GHz, with 4.00 GB of RAM) using the GAMS 24.21. Table 4 is the computational performance of the model with different solvers. From the results, for Baron and Scip Solvers, without using the proposed strategy, no feasible solution can be obtained. And for Knitro and Dicopt Solvers, the solutions obtained by the proposed strategy are much better.

Table 1: Streams data for case study

Stream number	Tin(℃)	Tout(℃)	ΔH(kW)	h ($W•m^{-2}•℃^{-1}$)
H1 (aromatic)	165	120	3,045	711
H2 (aromatic)	150	115	3,192	731
H3 (aromatic)	136	65	2,110	742
H4 (aromatic)	120	58	3,671	851
H5 (aromatic)	115	50	3,184	954
C1 (butadiene)	70	145	4,807	808
C2 (butadiene)	65	140	3,734	723
C3 (butadiene)	43	120	4,597	718
C4 (butadiene)	42	110	2,763	831

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

Table 2: Cost data for case study

Items	Value
HU	80,000 $\$•MW^{-1}•y^{-1}$
CU	10,000 $\$•MW^{-1}•y^{-1}$
Electric cost	120 $\$•MW^{-1}•h^{-1}$
Capital cost of heat exchanger	$4,000+200•Area^{0.83}$ $\$•y^{-1}$
Capital cost of pump	$450(q•H^{0.5})^{0.2}$ $\$•y^{-1}$
Cost of pipeline:	$D_{out}(m)=1.052\ D_{in}+0.005251$ $Wt_{pipe}(kg•m^{-1})=644.3\ D_{in}^2+72.5\ D_{in}+0.4611$ $P_{cul}(\$•m^{-1})= 0.82\ Wt_{pipe}+185\ D_{out}^{0.48}+6.8+265\ D_{out}$

Table 3: Annual cost and profit of the project

Items	Solved result
Annualized pipe cost	193,141 $\$•y^{-1}$
Annualized pumps	12,172 $\$•y^{-1}$
Heat loss	200 kW
Pump power cost	4,246 $\$•y^{-1}$
Annualized heat exchanger cost	286,105 $\$•y^{-1}$
Energy saving benefit	12,564 kW

Table 4: Computational result of the model without and with the strategy

Solver	Model without the strategy		Model with the strategy	
	Obj. Function ($\$•y^{-1}$)	TAC ($\$•y^{-1}$)	Obj. Function ($\$•y^{-1}$)	TAC ($\$•y^{-1}$)
Baron	*	*	776,650	773,624
Scip	*	*	*	*
Knitro	100,269	99,869	777,636	774,629
Dicopt	97,542	93,269	775,642	772,613

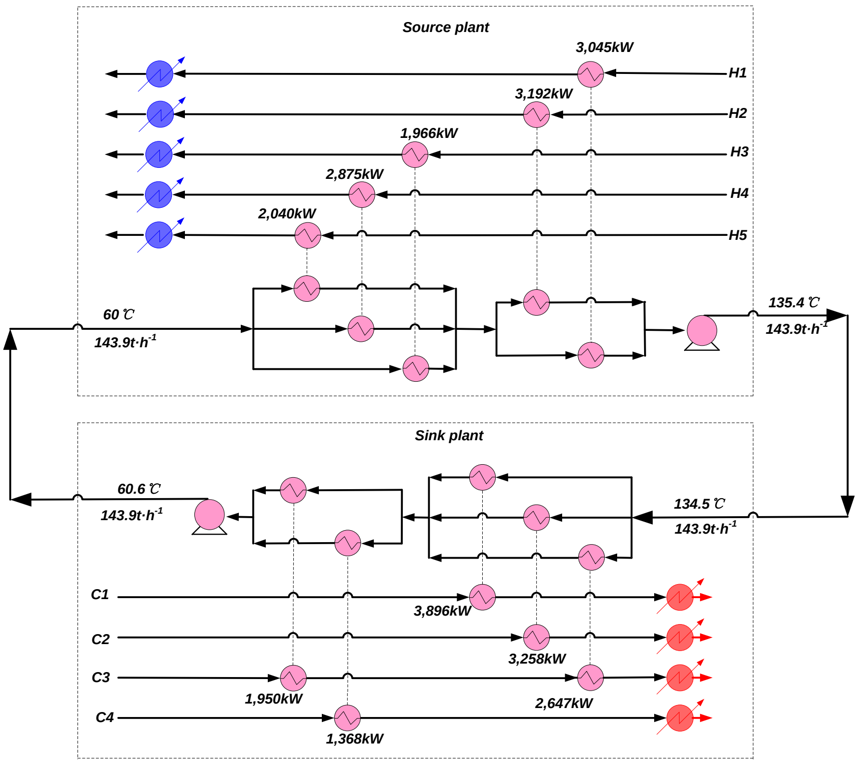

Figure 3: The heat exchanger networks in source and sink plants

5. Conclusions

Interplant Heat Integration using HRL is an efficient way to improve energy and economic efficiencies. An MINLP model based on economic objective is established for HRL designs. The flow rate of intermediate-fluid is an important variable and this results in a large complex, non-convex model, for which even finding feasible solution is a challenge. An efficient strategy is developed for the complex problem by solving a MILP, a MINLP and a NLP sequentially. The solved results can give the mass flow rate of intermediate-fluids, diameter of pipeline, temperatures of the intermediate-fluid circuits and the matches of HENS automatically. The proposed methodology can be used by industrial clusters to explore energy and cost savings opportunities. The solved results give the mass flow rate of intermediate-fluid, diameter of pipeline, temperature of intermediate-fluid circuits and matches of HENS automatically. The solution strategy has been illustrated with a case study for two plants within one industrial cluster.

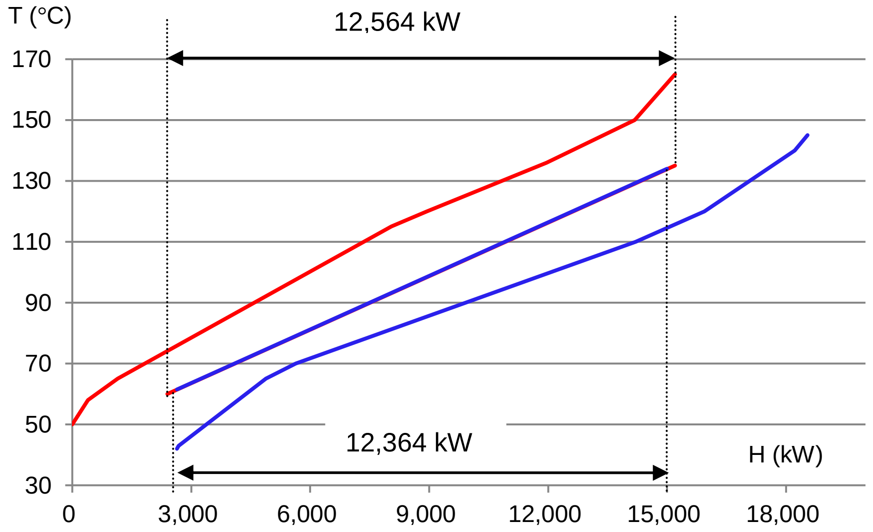

Figure 4: Composite Curve and intermediate fluid T-H profiles of Heat Integration

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