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Heat Transfer Intensified Techniques for Retrofitting Heat Exchanger Networks in Practical Implementation

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This paper addresses the implementation of heat transfer intensified techniques in practical heat exchanger networks (HENs). The issues considered in this paper not previously addressed include heat transfer intensification, changes in multiple tube passes and shell passes and temperature dependence of stream heat capacity (CP). These must be formulated into a new complex nonlinear model not reported previously in the existing literature. To solve such retrofit problems, an MILP-based iterative method has developed based on the work proposed by Pan et al. (2012a). A large scale example is presented to demonstrate the validity and efficiency of the proposed approach.

1. Introduction

Heat transfer intensification techniques have been widely studied, as intensification not only increases heat transfer (high potentiality of heat recovery) but also mitigates fouling deposition in the intensified exchangers (longer unit operating times), leading to greater benefit compared with conventional retrofit technologies.
Due to the nonlinearities in HENs, the HEN retrofit problem is usually formulated as an MINLP model or a combined NLP-MILP model. Yee and Grossmann (1991) used arithmetic mean temperature difference (AMTD) to replace LMTD. Ponce-Ortega et al. (2008) addressed HEN retrofit problems including isothermal process streams, and used Chen's approximation for LMTD computation. Nguyen et al. (2010) fixed the temperature intervals to obtain constant LMTD in each interval, changing MINLP problem to MILP problem. Pan et al. (2011) firstly proposed a novel MILP-based method to solve small scale HEN retrofit problems with intensified heat transfer techniques. After that, they developed an MILP-based iterative method for large scale problems (Pan et al., 2012a), and addressed HEN retrofit with different types of intensified techniques (Pan et al., 2013a), where suitable exchangers can be selected for enhancement by implementing one or more intensification techniques to increase the whole network energy recovery within very low retrofit cost. Besides constant network topology during retrofit, topology modifications can be also addressed based on the MILP-based iterative method. Pan et al. (2012b) developed the relevant optimization framework to facilitate the automated design of HEN retrofit with rigorous consideration of the conventional topology modification strategies (such as adding additional heat transfer area, installing new exchangers, and restructuring heat recovery matches). Recently, intensified heat transfer techniques are also considered to reduce fouling effect in enhanced exchangers (Pan et al., 2013b). In this work, the new retrofit approach can provide realistic and practical solutions for the industrial HEN retrofit problems as detailed performances of tube inserts (heat transfer enhancement and fouling mitigation) are systematically considered. This leads to substantial capital saving not only due to the significant energy reduction with low retrofit costs, but also due to longer exchanger operational times with less production losses. Based on the analysis of detailed performances for different intensification techniques, it is possible to consider HEN retrofit problems in most practical situations, such as multiple tube passes and shell passes (Pan et al., 2013c), exchanger pressure drops, and complex chemical process (Pan et al., 2013a).

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Thus, based on the research discussed above, this paper considers more practical issues for the implementation of heat transfer intensification in HEN retrofit problems. The MILP-based iterative method is upgraded for more complex retrofit scenarios, as detailed in the following sections.

2. MILP-based iterative method for practical HEN retrofit problems

The issues addressed for HEN retrofit problems in this paper include: heat transfer intensification, multiple tube passes and shell passes, logarithmic mean temperature difference (LMTD), LMTD correction factor (FT), and temperature dependence of stream heat capacity (CP). It is noted that LMTD, FT and temperature dependence of stream CP will lead to many nonlinear formulations in the retrofit model. Thus, the strategies of liberalizing these nonlinear terms are introduced first.

2.1 Initialization of LMTD (LMTD')

Logarithmic mean temperature difference (LMTD) is calculated based on stream temperatures, and described as a complex nonlinear term. To eliminate this nonlinearity, initial LMTD (*LMTD'*) is proposed in the new model, which can be obtained with initial stream temperatures, as shown in Eq(1).

$$LMTD'_{ex} = \frac{(HTI'_{ex} - CTO'_{ex}) - (HTO'_{ex} - CTI'_{ex})}{ln[(HTI'_{ex} - CTO'_{ex})/(HTO'_{ex} - CTI'_{ex})]}, \quad \forall ex \in EX \tag{1}$$

where *EX* is the set of all exchangers, HTI'_{ex}, HTO'_{ex}, CTI'_{ex} and CTO'_{ex} are inlet and outlet initial temperatures of hot and cold streams in exchanger *ex*.

Based on Eq.(1), variables (*LMTD*) are converted to parameters (*LMTD'*) in the new model.

2.2 Initialization of FT (FT')

As the flow pattern is a mixture of counter-current and co-current flow in multi-pass shell and tube exchangers, the LMTD correction factor (FT) is required for calculating the mean temperature difference. Eq.(2) – Eq.(9) present the FT computation for any number of shell passes and any even number of tube passes, where FT is also initialized with stream initial temperatures, $FT'_{ex,n}$ is the initial FT value of exchanger *ex* with *n* shell passes, NSP'_{ex} is the initial number of shell passes in exchanger *ex*, R'_{ex}, P'_{ex}, $\alpha'_{ex,n}$ and $S'_{ex,n}$ are the factors used to calculate FT' in exchanger *ex* with *n* shell passes.

It is assumed that hot stream flows in shell side:

$$R'_{ex} = \frac{HTI'_{ex} - HTO'_{ex}}{CTO'_{ex} - CTI'_{ex}}, \quad \forall ex \in EX \tag{2}$$

$$P'_{ex} = \frac{CTO'_{ex} - CTI'_{ex}}{HTI'_{ex} - CTI'_{ex}}, \quad \forall ex \in EX \tag{3}$$

If $R_{ex} \neq 1$:

$$\alpha'_{ex,n} = \left(\frac{1 - R'_{ex} \times P'_{ex}}{1 - P'_{ex}} \right)^{1/NSP'_{ex}}, \quad \forall ex \in EX, \ n \in N \tag{4}$$

$$S'_{ex,n} = \frac{\alpha'_{ex,n} - 1}{\alpha'_{ex,n} - R'_{ex}}, \quad \forall ex \in EX, \ n \in N \tag{5}$$

$$FT'_{ex,n} = \frac{\sqrt{R'^2_{ex} + 1} \times ln\left(\frac{1 - S'_{ex,n}}{1 - R'_{ex} \times S'_{ex,n}} \right)}{(R'_{ex} - 1) \times ln\left[\frac{2 - S'_{ex,n} \times \left(R'_{ex} + 1 - \sqrt{R'^2_{ex} + 1} \right)}{2 - S'_{ex,n} \times \left(R'_{ex} + 1 + \sqrt{R'^2_{ex} + 1} \right)} \right]}, \quad \forall ex \in EX, \ n \in N \tag{6}$$

If $R_{ex} = 1$:

$$S'_{ex,n} = \frac{P'_{ex}}{NSP'_{ex} - (NSP'_{ex} - 1)P'_{ex}}, \quad \forall ex \in EX, \ n \in N \tag{7}$$

$$FT'_{ex,n} = \frac{\sqrt{2}S'_{ex,n}}{(1 - S'_{ex,n}) \times ln\left[\frac{2 - S'_{ex,n} \times (2 - \sqrt{2})}{2 - S'_{ex,n} \times (2 + \sqrt{2})}\right]}, \quad \forall ex \in EX, \ n \in N \tag{8}$$

2.3 Initialization of stream CP (CP')

It is unrealistic to always assume constant stream CP during the retrofit, as stream CP is commonly temperature-dependent. In this paper, stream CP is assumed to be a linear equation with temperature. Thus, the overall CP value between two temperature points can be expressed as their average value, as presented in Eq.(9), where *CP'* is initial value of CP, *IT'* and *OT'* are stream inlet and outlet initial temperatures, and $f_{cp}()$ is the function of CP.

$$CP' = f_{cp}\left(\frac{IT' + OT'}{2}\right) \tag{9}$$

2.4 Heat transfer intensification

Regarding heat transfer intensification and shell pass number in exchangers, a set of binary variables is proposed: $EEX_{ex,j}$ =1, if the j^{th} type (intensification/non-intensification with *n* shell passes) of technique is implemented in exchanger *ex*; otherwise, it is 0. Thus, the heat transfer coefficients of intensified exchangers can be formulated as:

$$U_{ex} \geq MINU_{ex,j} \times (1 - EEX_{ex,j}), \ \forall ex \in EX, \ j \in J \tag{10}$$

$$U_{ex} \leq MAXU_{ex,j} \times (1 - EEX_{ex,j}), \ \forall ex \in EX, \ j \in J \tag{11}$$

where *J* is the set of types of intensification techniques, U_{ex} is the heat transfer coefficient of exchanger *ex*, $MAXU_{ex,j}$ and $MINU_{ex,j}$ are the upper and lower bounds of heat transfer coefficient when the j^{th} type of technique is implemented in exchanger *ex*.

2.5 Heat transfer differences

In Eq.(12) and Eq.(13), HBA_{ex} and HBB_{ex} are positive variables, and present the differences for energy exchange between streams and exchanger. For the energy balance between streams and exchangers, HBA_{ex} and HBB_{ex} should be small and the objective function has been formulated to minimize the sum of this infeasibility in energy balances. In addition, $HFCP'_{ex}$ is the initial heat-flow capacity (the multiplication between heat capacity and flow-rate) of hot stream in exchanger *ex*, and EXA_{ex} is area of exchanger *ex*.

$$HBA_{ex} \geq HFCP'_{ex} \times (HTI_{ex} - HTO_{ex}) - EXA_{ex} \times U_{ex} \times LMTD'_{ex}, \ \forall ex \in EX \tag{12}$$

$$HBB_{ex} \geq EXA_{ex} \times U_{ex} \times LMTD'_{ex} - HFCP'_{ex} \times (HTI_{ex} - HTO_{ex}), \ \forall ex \in EX \tag{13}$$

2.6 Energy balance differences

Due to the initial stream CP in heat exchangers, the heat duties of cold streams and hot streams might be different. Eq.(14) and Eq.(15) show these differences. The variables, AEB_{ex} and BEB_{ex}, are positive and should be small. $CFCP'_{ex}$ is initial heat-flow capacities of cold stream in exchanger *ex*.

$$AEB_{ex} \geq HFCP'_{ex} \times (HTI_{ex} - HTO_{ex}) - CFCP'_{ex} \times (CTI_{ex} - CTO_{ex}), \ \forall ex \in EX \tag{14}$$

$$BEB_{ex} \geq CFCP'_{ex} \times (CTI_{ex} - CTO_{ex}) - HFCP'_{ex} \times (HTI_{ex} - HTO_{ex}), \ \forall ex \in EX \tag{15}$$

2.7 Stream temperatures

Eq.(16) and Eq.(17) restrict the minimum temperature difference approach (ΔT_{min}) in each exchanger.

$$HTI_{ex} \geq CTO_{ex} + \Delta T_{\min}, \ \forall ex \in EX \tag{16}$$

$$HTO_{ex} \geq CTI_{ex} + \Delta T_{\min}, \ \forall ex \in EX \tag{17}$$

In the proposed MILP-based iterative method, initial stream temperatures are used to linearize nonlinear terms. When the energy consumption of the original HEN changes during the retrofit procedure, some differences will occur between initial stream temperatures and updated stream temperatures. These differences ($DAHTI_{ex}$, $DBHTI_{ex}$, $DAHTO_{ex}$, $DBHTO_{e}$, $DACTI_{ex}$, $DBCTI_{ex}$, $DACTO_{ex}$ and $DBCTO_{ex}$) are presented in Eq(18)-Eq(25).

$$DAHTI_{ex} \geq HTI_{ex} - HTI'_{ex}, \ \forall ex \in EX \tag{18}$$

$$DBHTI_{ex} \geq HTI'_{ex} - HTI_{ex}, \ \forall ex \in EX \tag{19}$$

$$DAHTO_{ex} \geq HTO_{ex} - HTO'_{ex}, \ \forall ex \in EX \tag{20}$$

$$DBHTO_{ex} \geq HTO'_{ex} - HTO_{ex}, \ \forall ex \in EX \tag{21}$$

$$DACTI_{ex} \geq CTI_{ex} - CTI'_{ex}, \ \forall ex \in EX \tag{22}$$

$$DBCTI_{ex} \geq CTI'_{ex} - CTI_{ex}, \ \forall ex \in EX \tag{23}$$

$$DACTO_{ex} \geq CTO_{ex} - CTO'_{ex}, \ \forall ex \in EX \tag{24}$$

$$DBCTO_{ex} \geq CTO'_{ex} - CTO_{ex}, \ \forall ex \in EX \tag{25}$$

2.8 Energy saving

Eq.(26) presents energy saving (QS) achieved in the retrofitted HEN, where EX_{hu} and EX_{cu} are the set of all exchangers consuming hot and cold utilities; $OCTI_{ex}$ and $OHTI_{ex}$ are the original inlet temperatures of cold stream and hot stream in exchanger *ex* before retrofit.

$$QS = \sum_{ex \in EX_{hu}} \left[CFCP'_{ex} \times \left(CTI_{ex} - OCTI_{ex} \right) \right] + \sum_{ex \in EX_{cu}} \left[HFCP'_{ex} \times \left(OHTI_{ex} - HTI_{ex} \right) \right] \tag{26}$$

2.9 Objective function

The objective of the new MILP-based method is to minimize the summation of differences in energy balances, heat transfer and stream temperatures with the restrictions of an estimated energy saving value (QS'), as shown in Eq.(27) and Eq.(28).

$$QS \geq QS' \tag{27}$$

$$\begin{aligned} Obj = & \left[\sum_{ex \in EX} \left(DACTI_{ex} + DBCTI_{ex} + DACTO_{ex} + DBCTO_{ex} \right) + \sum_{ex \in EX} \left(HBA_{ex} + HBB_{ex} \right) \right] \\ & + \left[\sum_{ex \in EX} \left(DAHTI_{ex} + DBHTI_{ex} + DAHTO_{ex} + DBHTO_{ex} \right) + \sum_{ex \in EX} \left(AEB_{ex} + BEB_{ex} \right) \right] \end{aligned} \tag{28}$$

The new MILP optimization framework model for maximum energy saving consists of an objective function given in Eq.(28) and model constraints given from Eq.(1)-Eq.(27).

2.10 Iteration algorithm

A similar iteration algorithm (two iteration loops) proposed by Pan et al. (2012a) is used to find the optimal solution for the retrofit problems addressed. In the first loop, the MILP model is solved repeatedly to obtain a feasible solution for HEN retrofit with certain energy saving, namely updating the values of LMTD, FT and stream CP until the addressed differences in the MILP model are small enough. While in the second loop, the maximum value of energy saving is searched, and its retrofit solution can be found by using the procedure in the first loop.

3. Case study

The example investigated in this paper is a literature case used by Pan et al. (2012a). However, different from the existing work, this paper considers more practical issues including heat transfer intensification, multiple tube passes and shell passes, logarithmic mean temperature difference (LMTD), LMTD correction factor (FT), and temperature dependence of stream heat capacity (CP). The original HEN includes three hot streams (S1-S3), two cold streams (S4 and S5), and seven exchangers (Figure 1). The heat-flow capacity of each stream depends on stream temperature, as shown in Table 1. Table 2 presents the range of heat transfer coefficients in different exchanger geometries.

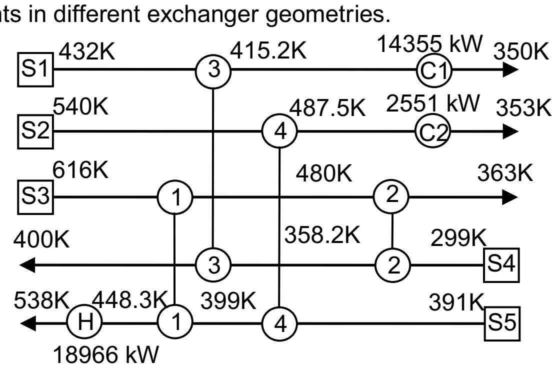

Figure 1: A HEN for the case study

Table 1: The heat-flow capacity of each stream

Parameter	Stream heat-flow capacity *FCP* (kW/K) = A × Stream Temperature + B				
	Stream 1 (S1)	Stream 2 (S1)	Stream 3 (S1)	Stream 4 (S1)	Stream 5 (S1)
A	0.9756	0.0535	0.1581	0.3960	0.5442
B	-152.96	-3.477	-23.591	-45.116	-56.689

Table 2: Heat transfer coefficients of exchangers in different tube geometries (kW/m^2·K)

EXs	Tube passes (no tube-side enhancement)				Tube passes (tube-side enhancement)			
	1 (N)	2 (N)	4 (N)	6 (N)	1 (E)	2 (E)	4 (E)	6 (E)
1	0 ~ 0.51	0 ~ 1.00	0 ~ 2.00	0 ~ 3.00	0.60 ~ 1.00	0.80 ~ 2.00	1.80 ~ 4.00	3.60 ~ 5.00
2	0 ~ 0.10	0 ~ 0.20	0 ~ 0.42	0 ~ 0.60	0.12 ~ 0.20	0.15 ~ 0.40	0.35 ~ 0.90	0.80 ~ 1.20
3	0 ~ 0.15	0 ~ 0.30	0 ~ 0.61	0 ~ 0.72	0.20 ~ 0.30	0.28 ~ 0.60	0.58 ~ 1.20	0.90 ~ 2.00
4	0 ~ 0.08	0 ~ 0.16	0 ~ 0.32	0 ~ 0.50	0.08 ~ 0.16	0.16 ~ 0.35	0.34 ~ 0.60	0.53 ~ 1.00

Table 3: Exchanger details in the original HEN

EXs	HTI (K)	HTO (K)	CTI (K)	CTO (K)	LMTD (K)	Shell passes	Tube passes	Intensified	FT	Area (m^2)	U (kW/m^2·K)	Duty (kW)
1	616.00	479.97	398.97	448.30	119.14	1	2	No	0.913	200	0.394	8570.2
2	479.97	363.00	299.00	358.22	89.80	1	6	No	0.831	150	0.450	5034.8
3	432.00	415.15	358.22	400.00	43.27	1	4	No	0.933	200	0.544	4390.6
4	540.00	487.46	391.00	398.97	117.34	1	2	No	0.995	150	0.072	1260.8

The details for exchangers in the original and retrofitted HEN are given in Tables 3 and 4. In the retrofit solution, three exchangers (Exchangers 1, 3 and 4) are intensified, the tube passes in Exchanger 1 must be reduced to one as it's FT is infeasible after retrofit, and the tube passes in Exchanger 4 must increase with intensification associated with the requirement of very high heat transfer coefficient. The new method can save up to 22.8 % (reducing 18,966 kW to 14,639 kW) utility consumptions in this case. This case study shows that the new approach considering the exact LMTD, FT and stream CP can find optimal solutions for practical HEN retrofit and increase energy saving without a significant number of topology modifications.

Table 4: Exchanger details in the retrofitted HEN

EXs	HTI (K)	HTO (K)	CTI (K)	CTO (K)	LMTD (K)	Shell passes	Tube passes	Intensified	FT	Area (m^2)	U ($kW/m^2 \cdot K$)	Duty (kW)
1	616.00	423.28	409.01	470.79	56.44	1	1	Yes	-	200	1.000	11288.6
2	423.28	363.00	299.00	328.39	78.44	1	6	No	0.950	150	0.208	2323.8
3	432.00	404.16	328.39	400.00	50.78	1	4	Yes	0.847	200	0.825	7097.3
4	540.00	407.39	391.00	409.01	55.14	1	4	Yes	0.800	150	0.438	2899.8

4. Conclusions

Practical HEN retrofit problems are usually required to consider exchanger performance details, such as heat transfer intensification, multiple tube passes and shell passes, logarithmic mean temperature difference (LMTD), LMTD correction factor (FT), and temperature dependence of stream heat capacity (CP). To validate the implementation of heat transfer intensification for retrofitting HEN, this paper has developed a novel optimization framework (based on MILP-based iteration method) to facilitate the automated design of HEN retrofit. A case study shows that the new method can achieve significantly energy saving in the practical scenarios.

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