CHEMICAL ENGINEERING TRANSACTIONS Volume 25, 2011
Editors Jiří. Jaromír Klemeš, Petar Sabev Varbanov, Hon Loong Lam
 ISBN 978-88-95608-16-7 ISSN 1974-9791
DOI: 10.3303/CET1125063

Improving energy recovery in heat exchanger network with intensified tube-side heat transfer

Ming Pan[1], Igor Bulatov[1], Robin Smith[1], Jin-Kuk Kim[2]
[1]Centre for Process Integration, The University of Manchester, Sackville Street, M13 9PL, Manchester, United Kingdom
[2]Department of Chemical Engineering, Hanyang University, 17, Haengdang-dong, Seongdong-gu, Seoul, Republic of Korea
igor.bulatov@manchester.ac.uk

Implementing tube-inserts, namely tube-side enhancement, is an efficient way to increase the heat transfer coefficients of shell and tube heat exchangers, which can achieve substantial energy saving in heat exchanger network (HEN) if suitable retrofit strategies are used (Pan et al., 2011). In this paper, a new optimization method is proposed to consider more details of tube-side enhancement for HEN retrofitting, such as multiple tube passes, logarithmic mean temperature difference (*LMTD*), *LMTD* correction factor (*FT*). Even though *LMTD* and *FT* will lead to complex nonlinear terms in mathematical programming, the proposed approach can deal with the relevant computational difficulties efficiently. The validity of new optimization approach is illustrated with solving a literature example (Li and Chang, 2010).

1. Introduction

Nowadays, heat transfer enhancement (HTE) techniques have been widely studied for retrofitting heat exchanger network (HEN) as low capital cost for network modifications is required to increase significant energy saving. To intensify heat transfer in shell and tube heat exchanger, there are several options available, for example, tube-side enhancements (twisted-tape inserts, coiled-wire inserts, hiTRAN®), and shell-side enhancements (helical baffles, EM baffles). Compared to shell-side enhancements, implementation of tube-inserts is a relative simple task that can be easily achieved within a normal maintenance period when physical size modifications of exchangers are avoided. It is very common to use mathematical programming methods for HEN retrofit. But with the nonlinear characteristics in heat transfer, logarithmic mean temperature difference (*LMTD*), and *LMTD* correction factor (*FT*), HEN retrofit must be formulated as a mixed integer nonlinear programming (MINLP) problem. Yee and Grossmann (1991) used arithmetic mean temperature difference (*AMTD*) to simplify nonlinear expression in heat transfer equations, which might overestimate the driving force if the temperature difference approach of one exchanger side is significantly different than the other side. Sorsak and Kravanja (2004), and Ponce-Ortega et al. (2008) used *LMTD* and *FT* approximate equations to avoid the numerical difficulties, thus will

Please cite this article as: Pan M. Bulatov I., Smith R.. and Kim J.K., 2011, Improving energy recovery in heat exchanger network with intensified tube-side heat transfer, Chemical Engineering Transactions, 25, 375-380
DOI: 10.3303/CET1125063

lead to infeasible solutions in some cases. Smith et al. (2009) further improved the network pinch method by considering multi-segmented stream data, and combined structural modifications and cost optimisation in a single step to achieve cost-effective design. Recently, Pan et al. (2011) proposed a novel MILP-based optimization method to solve HEN retrofit problems concerning exact *LMTD*. It is the first work to use *LMTD* exact equations for optimizing HEN retrofit, but the *FT* values of all exchanger are assumed to be fixed.
Based on the work of Pan et al. (2011), this paper presents an updated MILP-based optimization method for HEN retrofit with HTE, where more details of tube-side enhancement are considered, and the values of *LMTD* and *FT* for each exchanger can be calculated exactly.

2. MILP-based approach of HEN retrofit with tube-side HTE

2.1 *LMTD* and *FT*

In this work, *LMTD* and *FT* are calculated based on the exact equations (Serth, 2007) which are shown respectively in the following formulations, where EX is the set of all exchangers, NS_{ex} is the number of shell-side passes in exchanger *ex*, HTI_{ex} and HTO_{ex} are inlet and outlet temperatures of hot stream in exchanger *ex*, while CTI_{ex} and CTO_{ex} are inlet and outlet temperatures of cold stream in exchanger *ex*.
For *LMTD*:

$$LMTD_{ex} = \frac{(HTI_{ex} - CTO_{ex}) - (HTO_{ex} - CTI_{ex})}{\ln[(HTI_{ex} - CTO_{ex})/(HTO_{ex} - CTI_{ex})]}, \quad \forall ex \in EX \tag{1}$$

For *FT* (assume that hot stream is located in shell side):

$$R_{ex} = \frac{HTI_{ex} - HTO_{ex}}{CTO_{ex} - CTI_{ex}}, \quad P_{ex} = \frac{CTO_{ex} - CTI_{ex}}{HTI_{ex} - CTI_{ex}}, \quad \forall ex \in EX \tag{2, 3}$$

If R_{ex} <>1:

$$\alpha_{ex} = \left(\frac{1 - R_{ex} \times P_{ex}}{1 - P_{ex}}\right)^{1/NS_{ex}}, \quad S_{ex} = \frac{\alpha_{ex} - 1}{\alpha_{ex} - R_{ex}}, \quad \forall ex \in EX \tag{4, 5}$$

$$FT_{ex} = \frac{\sqrt{R_{ex}^2 + 1} \times \ln((1 - S_{ex})/(1 - R_{ex} \times S_{ex}))}{(R_{ex} - 1) \times \ln\left[\dfrac{2 - S_{ex} \times \left(R_{ex} + 1 - \sqrt{R_{ex}^2 + 1}\right)}{2 - S_{ex} \times \left(R_{ex} + 1 + \sqrt{R_{ex}^2 + 1}\right)}\right]}, \quad \forall ex \in EX \tag{6}$$

If R_{ex} =1:

$$S_{ex} = \frac{P_{ex}}{NS_{ex} - (NS_{ex} - 1)P_{ex}}, \quad FT_{ex} = \frac{\sqrt{2}S_{ex}}{(1 - S_{ex}) \times \ln\left[\dfrac{2 - S_{ex} \times (2 - \sqrt{2})}{2 - S_{ex} \times (2 + \sqrt{2})}\right]}, \quad \forall ex \in EX \tag{7, 8}$$

2.2 Tube-side HTE

To select suitable tube-side enhancements for exchangers, one set of binary variables ($EEX_{ex,j}$) is used. $EEX_{ex,j}$ = 1, if the *j*th kind of tube geometry is implemented in exchanger *ex*; otherwise, it is 0. One exchanger only has one kind of tube geometry, as shown in Equation (9), where J is the set of all kinds of tube geometry (such as single/multiple tube passes, or single/multiple tube passes with tube inserts).

$$\sum_{i \in J} EEX_{ex,j} = 1, \quad \forall ex \in EX \tag{9}$$

The heat transfer coefficients of exchangers with different kinds of tube geometry can be formulated as:

$$U_{ex} \geq EEU_{ex,j} - M \times \left(1 - EEX_{ex,j}\right), \; U_{ex} \leq EEU_{ex,j} + M \times \left(1 - EEX_{ex,j}\right), \tag{10, 11}$$

$$EEU_{ex,j} \geq EEU_{ex,j}^{\min}, \quad EEU_{ex,j} \leq EEU_{ex,j}^{\max}, \quad \forall ex \in EX, \quad j \in J \tag{12, 13}$$

In Equations (10)-(13), M is a sufficiently large positive number, $EEU_{ex,j}$ is the heat transfer coefficient of exchanger ex if the jth kind of tube geometry is implemented, $EEU_{ex,j}^{\max}$ and $EEU_{ex,j}^{\min}$ are the upper and lower bounds of $EEU_{ex,j}$.

2.3 HEN retrofit

The model of HEN retrofit includes energy balance, temperature constraints and energy assumptions. Equation (14) presents the energy balance for each exchanger, where $HFCP_{ex}$ and $CFCP_{ex}$ are heat-flow capacities (the multiplication between heat capacity and flow-rate) of hot stream and cold stream in exchanger ex.

$$HFCP_{ex} \times \left(HTI_{ex} - HTO_{ex}\right) = CFCP_{ex} \times \left(CTI_{ex} - CTO_{ex}\right), \quad \forall ex \in EX \tag{14}$$

The temperatures constraints of processing streams are shown in Equations (15)-(18), where CS and HS are the set of all cold streams and hot streams, respectively; EX^{i}_{cs}, EX^{o}_{cs}, EX^{i}_{hs} and EX^{o}_{hs} describe the set of all exchangers located in the stream inlet or outlet; CMF_{ex} and HMF_{ex} are flow fraction of cold and hot streams in exchanger ex; $CSTI_{cs}$ and $CSTO_{cs}$ are inlet and outlet temperatures of cold stream cs, while $HSTI_{hs}$ and $HSTO_{hs}$ are inlet and outlet temperatures of hot stream hs.

$$CTI_{ex} = CSTI_{cs}, \quad \sum_{ex \in EX^{o}_{cs}} \left(CMF_{ex} \times CTO_{ex}\right) = CSTO_{cs}, \quad \forall ex \in EX^{i}_{cs}, \; cs \in CS \tag{15, 16}$$

$$HTI_{ex} = HSTI_{hs}, \quad \sum_{ex \in EX^{o}_{hs}} \left(HMF_{ex} \times HTO_{ex}\right) = HSTO_{hs}, \quad \forall ex \in EX^{i}_{hs}, \; hs \in HS \tag{17, 18}$$

In addition, the minimum temperature difference approach (ΔT_{min}) in each exchanger is restricted in equations (19) and (20).

$$HTI_{ex} \geq CTO_{ex} + \Delta T_{\min}, \quad HTO_{ex} \geq CTI_{ex} + \Delta T_{\min}, \quad \forall ex \in EX \tag{19, 20}$$

Equation (21) presents the increased energy saving (QS) in HEN, where EX_{hu} and EX_{cu} are the set of all exchangers consuming hot and cold utility, CTI'_{ex} and HTI'_{ex} are the initial inlet temperatures of cold stream and hot stream in exchanger ex before retrofit.

$$QS = \sum_{ex \in EX_{hu}} \left[CFCP_{ex} \times \left(CTI_{ex} - CTI'_{ex}\right)\right] + \sum_{ex \in EX_{cu}} \left[HFCP_{ex} \times \left(HTI'_{ex} - HTI_{ex}\right)\right] \tag{21}$$

In Equations (22) and (23), the heat transfer in each exchanger is estimated based on the initial $LMTD'_{ex}$ and FT'_{ex} which can be calculated with the stream initial temperatures (HTI'_{ex}, HTO'_{ex}, CTI'_{ex} and CTO'_{ex}) in Equations (1)-(8). HBA_{ex} and HBB_{ex} are positive variables, and present the difference of energy exchange between streams and exchangers. For energy balance between streams and exchangers, HBA_{ex} and HBB_{ex} should be small and the objective function has been formulated to minimize infeasible energy balances.

$$HBA_{ex} \geq HFCP_{ex} \times \left(HTI_{ex} - HTO_{ex}\right) - EXA_{ex} \times U_{ex} \times LMTD'_{ex} \times FT'_{ex}, \quad \forall ex \in EX \quad (22)$$

$$HBB_{ex} \geq EXA_{ex} \times U_{ex} \times LMTD'_{ex} \times FT'_{ex} - HFCP_{ex} \times \left(HTI_{ex} - HTO_{ex}\right), \quad \forall ex \in EX \quad (23)$$

Since the tube geometry of some exchangers change, there might be some differences between initial stream temperatures and updated stream temperatures, which are formulated in Equations (24) and (25).

$$DAHTI_{ex} \geq HTI_{ex} - HTI'_{ex}, \quad DBHTI_{ex} \geq HTI'_{ex} - HTI_{ex}, \quad \forall ex \in EX \quad (24, 25)$$

$DAHTI_{ex}$ and $DBHTI_{ex}$ are positive variables, and present the difference between initial and updated temperatures of hot stream inlet. Meanwhile, the differences between initial and updated temperatures for hot stream outlet ($DAHTO_{ex}$ and $DBHTO_{ex}$), cold stream inlet and outlet ($DACTI_{ex}$, $DBCTI_{ex}$, $DACTO_{ex}$ and $DBCTO_{ex}$) are formulated in the same way.
Equation (26) restricts that FT_{ex} has to be considered if multiple tube passes are implemented, where J_m is the set of all kinds of tube geometry with multiple tube passes, and MT_{ex} is a set of 0-1 parameters that describes whether multiple tube passes are used in exchanger *ex*.

$$MT_{ex} = \sum_{j \in J_m} EEX_{ex,j}, \quad \forall ex \in EX \quad (26)$$

In practice, it is inefficient if FT_{ex} is less than 0.8 in counter-flow exchanger, which means that when multiple tube passes are used in an exchanger, its *FT* value has to be larger than 0.8 and less than 1, while *FT* is equal to 1 only in one-tube-pass exchanger.
The objective of the new MILP-based method is to minimize the differences of heat transfers and stream temperatures under the restriction of an estimated energy saving value (*QS'*), as shown in Equations (27) and (28).

$$QS \geq QS' \quad (27)$$

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

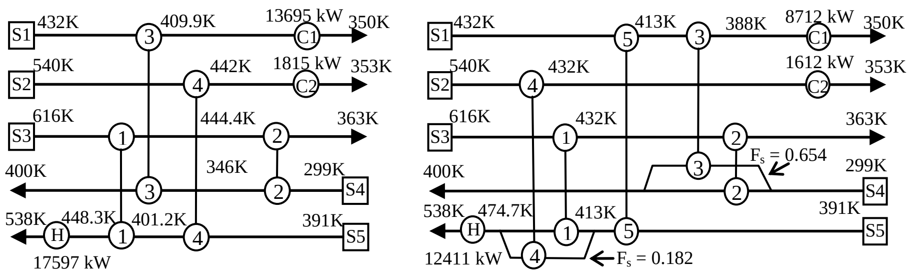
The new MILP optimization framework model consists of objective function given in Equation (28) and other model constraints given from Equations (9)-(27). The iteration algorithm is mainly based on the work proposed by Pan et al. (2011), where two iteration loops are proposed to find the optimal solution for HEN retrofit based on the MILP model. The first iteration loop is to find the solution for HEN retrofit under certain energy saving, while the second iteration loop is to find the maximum energy saving for HEN retrofit.

3. A case study

An example presented by Li and Chang (2010) is used for a case study. In this section, the techniques of multiple tube passes and tube inserts are implemented in existing HEN to improve energy recovery. The existing HEN includes three hot streams (S1-S3) and two cold streams (S4 and S5). The heat-flow capacity of each stream is 228.5 kW/K (S1), 20.4 kW/K (S2), 53.8 kW/K (S3), 93.3 kW/K (S4), and 196.1 kW/K (S5), respectively. Table 1 shows the heat transfer limits of exchangers in different tube geometries. The original and retrofitted HENs proposed by Li and Chang (2010) are presented in Figure 1. Figure 2 presents the original and retrofitted HENs optimized with the new approach. By comparing Figures 1 and 2, the new method can save up to 12% and 9.3% utility consumptions for Cases 1 and 2, respectively. The details for exchangers in each case are given in Tables 2. The case study shows that the new approach considering exact *LMTD* and *FT* can find optimal solutions for practical HEN retrofit and increase energy saving without heavy topology modifications.

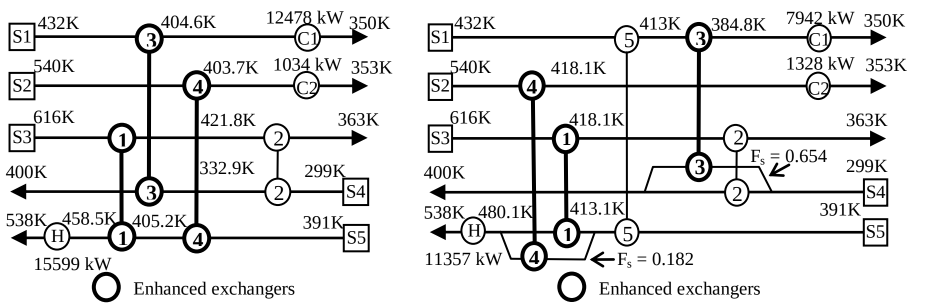
Table 1: Heat transfer coefficients of exchangers in different tube geometries ($kW/m^2{\cdot}K$)

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
5	0 ~ 0.20	0 ~ 0.40	0 ~ 0.89	0 ~ 1.00	0.20 ~ 0.70	0.40 ~ 0.80	0.89 ~ 1.00	1.00 ~ 2.00



(a) Case 1: Original HEN (base case) (b) Case 2: Retrofitted HEN (Li and Chang, 2010)

Figure 1: The base case and retrofitted HENs proposed by Li and Chang (2010)



(a) Case 3: HTE-based retrofit of base case HEN (b) Case 4: HTE-based retrofit of Case 2

Figure 2: The optimal solutions with tube-side HTE

Table 2: The details for exchangers in each case

Case	Exchanger 1			Exchanger 2			Exchanger 3			Exchanger 4			Exchanger 5		
	A	U	TP	A	U	TP	A	U	TP	A	U	TP	A	U	TP
1	200	0.50	1(N)	150	0.41	4(N)	200	0.61	4(N)	150	0.16	2(N)			
2	200	**0.83**	**1(E)**	150	0.30	4(N)	200	**0.75**	**4(E)**	150	**0.45**	**6(N)**			
3	323	0.50	1(N)	962	0.10	1(N)	840	0.15	1(N)	753	0.08	1(N)	300	0.88	4(N)
4	323	**0.83**	**1(E)**	962	0.07	1(N)	840	**0.25**	**1(E)**	753	**0.15**	**1(E)**	300	0.88	4(N)

A: area (m^2), **U:** overall heat transfer coefficient ($kW/m^2{\cdot}K$), **TP:** tube passes.

4. Conclusions

Nonlinear terms in *LMTD* and *FT* usually lead to a complex MINLP model for HEN retrofit. To reduce the corresponding computational difficulties, a new MILP model has been built up, and an iteration algorithm is utilized to guarantee the global optimization. Unlike existing design methods, the new method can maintain its practicability and reliability for HEN retrofitting as *LMTD* and *FT* are both from exact calculations.

Acknowledgement

Financial support from Research Councils UK Energy Programme (EP/G060274/1 Intensified Heat Transfer for Energy Saving in Process Industries) and EC Project INTHEAT (FP7-SME-2010-1-262205-INTHEAT) are gratefully acknowledged.

References

Li B.H. and Chang C.T., 2010, Retrofitting heat exchanger networks based on simple pinch analysis, Industry and Engineering Chemistry Research, 49, 3967-3971.

Pan M., Bulatov I., Smith R. and Kim J.K., 2011, Novel optimization method for retrofitting heat exchanger networks with intensified heat transfer, 21st European Symposium on Computer Aided Process Engineering – ESCAPE 21 (Submitted).

Ponce-Ortega J.M., Jiménez-Gutiérrez A. and Grossmann I.E., 2008, Optimal synthesis of heat exchanger networks involving isothermal process streams, Computers and Chemical Engineering, 32, 1918-1942.

Serth R.W., Eds., 2007, Process Heat Transfer Principles and Applications. Elsevier, Amsterdam.

Smith R., Jobson M. and Chen L., 2009, Recent development in the retrofit of heat exchanger networks, Chemical Engineering Transactions, 18, 27-32.

Sorsak A. and Kravanja Z., 2004, MINLP retrofit of heat exchanger networks comprising different exchanger types. Computers and Chemical Engineering, 28, 235-251.

Yee T.F. and Grossmann I.E., 1991, A screening and optimization approach for the retrofit of heat exchanger networks, Industry and Engineering Chemistry Research, 30 (1), 146-162.