CHEMICAL ENGINEERING TRANSACTIONS

VOL. 29, 2012

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at: www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Hon Loong Lam, Jiří Jaromír Klemeš
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ISBN 978-88-95608-20-4; **ISSN** 1974-9791

DOI: 10.3303/CET1229238

Retrofit Procedure for Intensifying Heat Transfer in Heat Exchanger Networks Prone to Fouling Deposition

Ming Pan*, Igor Bulatov, Robin Smith

Centre for Process Integration, The University of Manchester, Sackville street, Manchester, M13 9PL, UK
ming.pan@manchester.ac.uk

This paper presents a novel optimization method of addressing fouling effects in heat exchanger network (HEN) retrofit with intensified heat transfer. In the new approach, the fouling deposition in each heat exchanger is taken into account when heat transfer intensification is regarded as a retrofit option in HENs, and the optimization procedure proposed by Pan et al. (2012b) is developed to solve the addressed problems efficiently. A practical industrial process is carried out to show that with the consideration of fouling influence. The benefit that can be derived from implementing intensified technologies is not only increasing heat recovery but also extending exchanger operating times with the mitigation of fouling deposition.

1. Introduction

A number of retrofit approaches have been reported for retrofitting heat exchanger network (HEN) in the last few decades. The existing approaches include implementing intensified heat transfer techniques, adding more exchanger area, installing new exchangers, moving exchangers and repiping streams (Ponce-Ortega et al., 2008; Nguyen et al., 2010; Pan et al., 2012a, 2012b). However, these conventional approaches are proposed based on the assumption of constant fouling resistances in exchangers during the whole operating period, which might suffer from the chronic operational problem caused by fouling, and thus compromises energy recovery and environmental welfare in the retrofitted HENs.

Fouling concerns the formation of unwanted material on heat transfer surfaces. Fouling problems manifest themselves as loss or reduction in production, increased energy consumption, increased pressure losses, antifouling chemical costs, cleaning costs, and so on. To reduce fouling effects in HENs, most researchers tried to increase exchanger area or modify operating conditions in the existing HENs. Brodowicz and Markowski (2003) proposed several control methods to increase exchanger area or increase the capacities of heaters and coolers. Rodriguez and Smith (2007) optimized the operating conditions (such as wall temperature and flow velocity) to mitigate fouling in HENs. Coletti et al. (2010) used a dynamic and distributed mathematical model for shell-and-tube heat exchangers undergoing crude oil fouling to simulate the existing HENs. Recently, Yang et al. (2011) found that, fouling of the heat exchanger depends on two major operational parameters, namely the wall shear stress and the surface temperature. The use of tube inserts (one type of enhancement techniques) has been shown to be effective in mitigating crude oil fouling whilst enhancing heat transfer at the same time, as there will be axial and radial distributions of local shear stress in tube side with the introduction of inserts (Ritchie and Droegemueller, 2008; Krueger and Pouponnot, 2009). Thus, in this paper, the fouling model of tube inserts proposed by Yang et al. (2009) is adopted, and afterward combined in the optimization approach of HEN retrofit proposed by Pan et al. (2012b). Finally, an industrial study is

Please cite this article as: Pan M., Bulatov I. and Smith R., (2012), Retrofit procedure for intensifying heat transfer in heat exchanger networks prone to fouling deposition, Chemical Engineering Transactions, 29, 1423-1428

presented to demonstrate the validity and efficiency of the enhancement techniques in HEN retrofit scenarios.

2. Fouling deposition in tube side

Based on the work presented by Yang et al. (2009), fouling on a heat exchanger surface can be described as two steps. In the first step (induction period), the active fouling species adhere to the heat transfer surface and gradually cover it from a fractional coverage of θ = 0 to total coverage at θ_{max}. This pre-conditioning layer is very thin, where the increase in fouling resistance R_f can be negligible, thus, changes in surface roughness are ignored. In the second step (fouling period), the fouling layer may start to grow immediately on the covered/pre-conditioned surface when it may be assumed that the growth rate is proportional to θ. The overall rate of fouling resistance growth can therefore be expressed as:

$$\frac{dR_f}{dt} = \theta R'_f \tag{1}$$

where, R'_f is the form of established fouling rate expression, and the simple threshold model (Polley et al., 2007) is utilized in this paper:

$$R'_f = \alpha\, Re^{-0.8}\, Pr^{-0.33}\, exp\left(\frac{-E}{R \cdot T_w}\right) - \gamma\, Re^{0.8} \tag{2}$$

$$Re_e = 1.8526\, Re - 0.3945 \tag{3}$$

In Equations (2) and (3), α and γ are constants, Re and Re_e are Reynolds numbers before and after the implementation of tube inserts, Pr is Prandlt number, E is activation energy, R is universal gas constant, and T_w is tube wall temperature.

Yang et al. (2009) also proposed second order growth rate (θ_g) and one order removal rate (θ_r) on fractional surface coverage (θ). Equation (4) describes that in the early stage of surface pre-conditioning, active species can be captured and adhered to the surface; meanwhile, the particles that stick to the surface act as seeds, attracting more foulant around them, such that fouling proceeds in a micro-growth manner.

$$\frac{d\theta_g}{dt} = k_1\theta(1-\theta) \tag{4}$$

Based on the concept of removal or release from the surface as in adsorption science, the removal rate (θ_r) of the surface coverage is assumed to be proportional to the surface coverage, as shown in Equation (5).

$$\frac{d\theta_r}{dt} = k_2\theta \tag{5}$$

Thus, the net growth rate of θ is obtained with combining Equations (4) and (5):

$$\frac{d\theta}{dt} = k_1\theta(1-\theta) - k_2\theta \tag{6}$$

Integrating Equation (7) gives the fractional surface coverage (θ):

$$\theta = \frac{k_1 - k_2}{k_1} \times \frac{1}{1 + c \times e^{-(k_1-k_2)t}} \tag{7}$$

where c is constant, t presents time, k_1 and k_2 are lumped growth rate and removal rate constants.

$$k_1 = A_i \, exp\left(\frac{-E}{R \cdot T_w}\right) \tag{8}$$

$$k_2 = r \times u^{0.8} \tag{9}$$

In Equations (8) and (9), A_i and r are constants, T_w is tube wall temperature, R is universal gas constant, E is activation energy, and u is flow velocity.

Compared with the induction time (when the growth of θ reaches its maximum at $0.5\theta_{max}$), the fouling time is much longer (normally several months vs. several days). Thus, the induction time may be negligible in the whole operational period, and the overall rate of fouling resistance growth in Equation (1) can be simplified as:

$$\frac{dR_f}{dt} = \theta_{max} R'_f \tag{10}$$

According to Equation (7), θ_{max} is given by:

$$\theta_{max} = \frac{k_1 - k_2}{k_1} \tag{11}$$

The fouling resistance at *t* operational time can be estimated based on the integration of Equation (10):

$$R_f = \theta_{max} \times R'_f \times t \tag{12}$$

The procedure of HEN retrofit addressed in this paper is to change the heat transfer coefficients of heat exchangers in tube side by implementing tube inserts under constant heat transfer area, which provides energy saving without any topology modifications. In addition, heat transfer area, stream flowrates and heat capacities in each exchanger maintain constant during HEN retrofit. Therefore, the fouling resistance formulations can be combined in the optimization approach proposed by Pan et al. (2012b) for HEN retrofit, and only two types of nonlinear terms are generated in the proposed model, namely, logarithmic mean temperature difference (*LMTD*) and fouling resistance (R_f).

Most importantly, this paper considers more details for calculating overall heat transfer coefficient (*U*) rather than simply calculation of *U* in the previous work (Pan et al., 2012b):

$$\frac{AD_{ex}}{A_{ex}} DUD_{ex} = \frac{OD_{ex}}{ID_{ex}} DTUD_{ex} + \frac{OD_{ex} \, ln(OD_{ex}/ID_{ex})}{2k_{tube}} + DSUD_{ex} + TRF_{ex} + SRF_{ex} \tag{13}$$

where $DTUD_{ex}$, $DSUD_{ex}$ and DUD_{ex} are the reciprocal values of tube-side, shell-side and overall designed heat transfer coefficients for exchanger *ex*, AD_{ex} and A_{ex} are designed and required area of exchanger *ex*, OD_{ex} and ID_{ex} are outer and inner tube diameters of exchanger *ex*, k_{tube} is tube conductivity, TRF_{ex} and SRF_{ex} are tube side and shell side fouling resistances.

To resolve the computational difficulties related to those nonlinear terms, the iterative procedures developed by Pan et al. (2012b) are utilized to find the optimal solutions of implementing tube inserts in HEN retrofit with fouling consideration.

3. Case study

A HEN of existing preheat train for a crude oil distillation column in a refinery plant is carried out to evaluate the proposed optimization approach. As shown in Figure 1, the retrofit objective is to reduce the hot utility (HU) consumption, namely, reduce the heat duty of heat exchanger 30 (target exchanger). The stream data and initial exchanger data can be found in Tables 1 and 2. Moreover, the heat-flow capacities of hot utility and cold utility are 93 kW/ °C and 9652.5 kW/ °C, the inlet temperatures of hot utility and cold utility are 1500 °C and 12.45 °C, the minimum temperature difference approaches (ΔT_{min}) before and after heat transfer intensification are 19 ºC and 5 ºC, and the minimum operating time of exchanger in the original HEN is 3.1 months (exchanger 28).

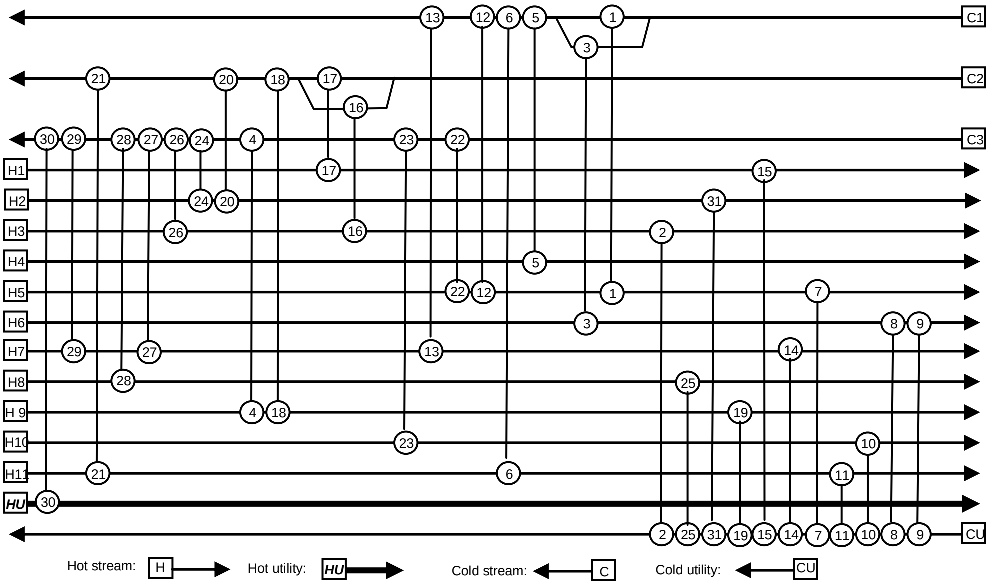

Figure 1: A HEN for the case study

Table 1: Stream details in case study

Stream	C1	C2	C3	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11
FCP (kW/ ºC)	323	358.5	474	14.2	181.5	113	100	22.2	39.5	28.0	176	24.5	25.0	69.6
T_{in} (ºC)	33.5	91.34	151	335	253.2	294	212	213	174	364	290	284	240	179
T_{out} (ºC)	95.6	157.3	352	69.4	116.1	130	156	61.7	43.3	65.6	211	65.6	57.8	69.3

Table 2: Exchanger details in original HEN

EXs	h_i (kW/m$^2\cdot$ ºC)		h_0 (kW/m$^2\cdot$ ºC)		U (kW/m$^2\cdot$ ºC)		Area (m^2)		Operating Time (month)
	Designed	Required	Designed	Required	Designed	Required	Designed	Required	
1	0.263	0.263	0.375	0.375	0.125	0.125	192.5	175.0	9.4
2	0.208	0.208	0.304	0.304	0.101	0.101	12.8	11.7	7.1
3	0.521	0.521	0.671	0.671	0.224	0.224	256.7	233.3	11.9
4	0.703	0.703	0.847	0.847	0.282	0.282	192.5	175.0	3.5
5	0.453	0.453	0.898	0.898	0.224	0.224	220.0	200.0	5.4
6	0.479	0.479	0.627	0.627	0.209	0.209	715.0	650.0	5.2
7	0.211	0.211	0.307	0.307	0.102	0.102	22.0	20.0	8.8
8	0.893	0.893	1.008	1.008	0.336	0.336	33.0	30.0	5.7
9	0.903	0.903	1.017	1.017	0.339	0.339	61.1	55.6	4.5
10	0.235	0.235	0.339	0.339	0.113	0.113	305.6	277.8	15.3
11	0.832	0.832	0.959	0.959	0.320	0.320	61.1	55.6	9.6
12	0.204	0.204	0.298	0.298	0.099	0.099	244.5	222.2	7.2
13	0.411	0.411	0.552	0.552	0.184	0.184	141.4	128.6	12.7
14	0.786	0.786	0.920	0.920	0.307	0.307	94.3	85.7	6.0
15	0.392	0.392	0.530	0.530	0.177	0.177	47.1	42.9	8.0
16	0.927	0.927	1.035	1.035	0.345	0.345	471.5	428.6	7.9
17	0.422	0.422	0.564	0.564	0.188	0.188	228.5	207.7	9.9
18	0.275	0.275	0.390	0.390	0.130	0.130	228.5	207.7	12.1

Table 2: Exchanger details in original HEN (Continued)

19	0.340	0.340	0.469	0.469	0.156	0.156	152.3	138.5	13.2
20	0.663	0.663	0.810	0.810	0.270	0.270	1523.1	1384.6	5.4
21	0.504	0.504	0.653	0.653	0.218	0.218	76.2	69.2	4.9
22	0.658	0.658	0.805	0.805	0.268	0.268	114.2	103.8	3.6
23	0.736	0.736	0.876	0.876	0.292	0.292	152.3	138.5	4.7
24	0.308	0.308	0.431	0.431	0.144	0.144	1142.3	1038.5	3.4
25	0.335	0.335	0.463	0.463	0.154	0.154	73.3	66.7	10.0
26	0.984	0.984	1.079	1.079	0.360	0.360	733.3	666.6	4.3
27	0.239	0.239	0.344	0.344	0.115	0.115	256.6	233.3	4.3
28	0.881	0.881	0.998	0.998	0.333	0.333	1122.0	1020.0	3.1
29	0.556	0.556	0.706	0.706	0.235	0.235	264.0	240.0	4.2
30	0.910	0.910	1.022	1.022	0.341	0.341	198.0	180.0	15.7
31	0.290	0.290	0.408	0.408	0.136	0.136	330.0	300.0	5.3

Table 3: Exchanger details in retrofitted HEN

EXs	h_i (kW/m^{2}· ºC)		h_0 (kW/m^{2}· ºC)		U (kW/m^{2}· ºC)		Area (m^2)		Operating Time (month)
	Designed	Required	Designed	Required	Designed	Required	Designed	Required	
1	0.263	0.253	0.375	0.375	0.125	0.122	192.5	175.0	12.0
2	0.208	0.124	0.304	0.304	0.101	0.071	12.8	11.7	40.1
3	0.521	0.521	0.671	0.671	0.224	0.224	256.7	233.3	11.9
4	0.703	0.561	0.847	0.847	0.282	0.251	192.5	175.0	8.0
5	0.455	0.452	0.898	0.898	0.225	0.224	220.0	200.0	9.2
6	0.588	0.555	0.627	0.627	0.232	0.226	715.0	650.0	9.3
7	0.211	0.214	0.307	0.307	0.102	0.103	22.0	20.0	8.0
8	1.227	1.155	1.008	1.008	0.386	0.376	33.0	30.0	8.2
9	0.903	0.789	1.017	1.017	0.339	0.317	61.1	55.6	8.0
10	0.236	0.219	0.339	0.339	0.113	0.108	305.6	277.8	25.3
11	0.832	0.634	0.959	0.959	0.320	0.278	61.1	55.6	26.3
12	0.204	0.194	0.298	0.298	0.099	0.096	244.5	222.2	10.4
13	0.452	0.445	0.552	0.552	0.194	0.192	141.4	128.6	21.5
14	0.786	0.733	0.920	0.920	0.307	0.296	94.3	85.7	8.8
15	0.392	0.304	0.530	0.530	0.177	0.152	47.1	42.9	24.4
16	1.335	0.858	1.035	1.035	0.402	0.333	471.5	428.6	33.4
17	0.698	0.593	0.564	0.564	0.241	0.224	228.5	207.7	15.0
18	1.667	1.376	0.390	0.390	0.257	0.246	228.5	207.7	9.7
19	0.340	0.282	0.469	0.469	0.156	0.140	152.3	138.5	34.4
20	3.311	2.356	0.810	0.810	0.456	0.426	1523.1	1384.6	8.0
21	0.504	0.454	0.653	0.653	0.218	0.205	76.2	69.2	8.0
22	3.289	1.509	0.805	0.805	0.453	0.377	114.2	103.8	8.0
23	3.676	1.901	0.876	0.876	0.484	0.420	152.3	138.5	8.0
24	1.541	0.636	0.431	0.431	0.269	0.205	1142.3	1038.5	8.0
25	0.335	0.274	0.463	0.463	0.154	0.137	73.3	66.7	24.5
26	4.926	2.283	1.079	1.079	0.567	0.486	733.3	666.6	8.1
27	1.193	0.705	0.344	0.344	0.220	0.190	256.6	233.3	8.0
28	4.405	1.725	0.998	0.998	0.535	0.433	1122.0	1020.0	8.0
29	2.762	1.263	0.706	0.706	0.408	0.334	264.0	240.0	8.0
30	0.910	0.785	1.022	1.022	0.341	0.317	198.0	180.0	26.7
31	0.290	0.149	0.408	0.408	0.136	0.088	330.0	300.0	41.5

Bold exchanger number presents intensified exchanger.

In case study, tube side fouling deposition and intensification are considered simultaneously to improve energy saving in the whole network. In addition, shell side heat transfer coefficient and fouling resistance are assumed constant in exchangers during HEN retrofit, as only tube-side intensified techniques are considered. From Table 3, it can be noted that to increase the operational time of the whole process, the proposed method is utilized to obtain the optimal solutions under the constraint of operating times ≥ 8 months. In the retrofit solution, the implementation of tube inserts not only increases the heat transfer coefficients in enhanced exchangers, but also prolongs their operating times significantly, which might save substantial capital investment because of potential production losses during cleaning process.

4. Conclusions

Implementation of intensified heat transfer is an efficient way to increase energy recovery and overcome fouling deposition in retrofitting HEN. In order to solve large scale HEN retrofit problems efficiently, a new optimization method has been proposed. The proposed design approach is able to give realistic and practical solutions for the debottlenecking of HEN as detailed intensified techniques are systematically applied. This leads substantial capital saving as no structural modification in heat recovery system configuration is considered. The case study shows that, based on the new approach, more energy saving is achieved (5.35%) under long operating times (3.1 months to 8 months).

Acknowledgement

The financial support is gratefully acknowledged from the EC FP7 project “Intensified Heat Transfer Technologies for Enhanced Heat Recovery – INTHEAT”, Grant Agreement No. 262205.

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