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Heat Exchanger Network Retrofit Under Fouling Effects with Cleaning Schedule

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The energy conservation by heat exchanger network (HEN) is important in process design according to increase in energy costs and global environmental concerns. To minimize the energy consumption with positive net present value (NPV), the retrofitted HEN plays an important role in process energy systems. The HEN retrofit model is based on stage-wise superstructure by Yee and Grossmann (1990). In addition, fouling deposition on the surface area of heat exchangers causes extra energy consumption, production loss and maintenance costs. The new proposed model is retrofitting HEN with fouling effects. This method achieves HEN with the optimal trade-offs between energy savings, and investment over operating period. For cleaning schedule, retrofitted HEN shows better capable to recover heat and higher NPV than base-case considered from a lower number of cleaning requirement. In this study, the proposed model is combination of cleaning schedule strategy and HEN retrofitting with fouling effect to achieve greater profits.

1. Introduction

Most HEN synthesis methods rely on sequential or step-wise procedures (Gundersen and Naess, 1988) which decompose design problem for synthesized network targets. After that, Dolan et al. (1987, 1989) and Yee and Grossmann (1990) proposed HEN model accounting for all types of costs simultaneously. Dolan et al. proposed the method of simulated annealing as a synthesis technique, while Yee and Grossmann formulated the model as mixed integer nonlinear programming (MINLP) model for synthesis and retrofit design. Both methods approach optimal operating and capital cost network.

In addition, the main problem caused by fouling deposition has negative effects on thermal and hydraulic performance of heat exchangers. Fouling decreases overall heat transfer coefficient and thermal effectiveness of heat exchangers, resulting in extra hot and cold utilities consumption. In most of the cases, the cleaning schedule is applied for recovering heat exchanger efficiency as a systematic method to determine the optimal cleaning sequence in HENs under fouling. For predicting the fouling behaviours, the appropriate models are required. Ebert and Panchel (1995) was the first to give concept of fouling threshold. After that several modified models were proposed for improving the accuracy of crude oil fouling behaviour. In Polley's model (2002a), wall temperature and Reynold number were used instead of film temperature and shear stress term Polly's model is more accurate and easier to calculate comparing with Ebert and Panchel's model. In addition, Rangfak et al. (2017) proposed HEN retrofit with fouling effects which help save utility for crude preheat train operation and achieve high NPV in long period. The combination of cleaning schedule strategy and HEN retrofitting with fouling effect will save more utilities and gain more profits.

The purpose of this study is to retrofit HENs under fouling from oil refinery or petrochemical processes. The HENs with fouling effect model will be divided into sub-periods. The model of each period is formulated based on a stage-wise superstructure of Yee and Grossmann (1990). The HEN retrofitting under fouling effect model will be performed. And the cleaning schedule is applied to reduce energy consumption caused by fouling and get higher profit.

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2. The model of HEN retrofit

In this study, the model of HEN retrofit is MINLP based on stage-wise approach as shown in Figure1. In order to modify former stage-wise model to HEN retrofit model, the constraints for existing exchanger matches have to be added to the synthesis model. The objective function of HEN retrofit model is maximizing profit as a function of utilities saving revenue and total investment cost from additional area and new heat exchanger units. In HEN retrofit part, the main assumptions are shown, as follows.

- Constant heat capacities
- Constant specific heat capacities
- Counter current heat exchangers

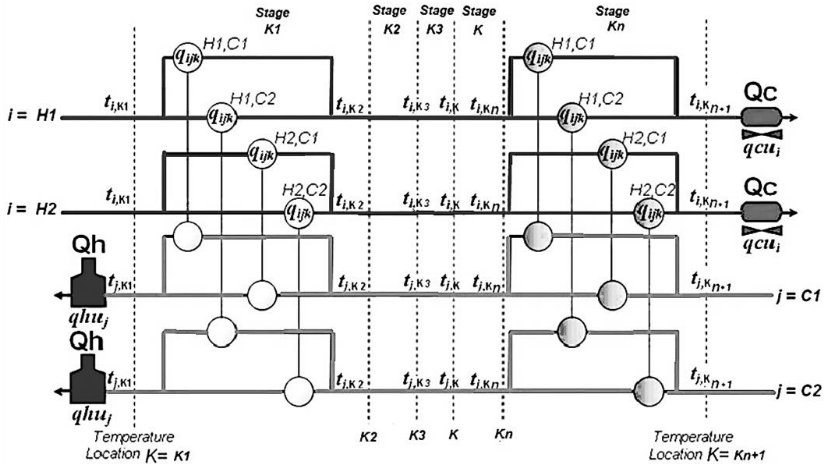

Figure 1: Stage-wise superstructure of HEN for two hot and two cold streams. (Yee and Grossmann, 1990)

In order to formulate the MINLP model for the proposed superstructure described previously, the following definitions and equations are based on Yee and Grossmann (1990). And the modified model for retrofitting is proposed as follows.

$$\begin{aligned} \text{Maximize Profit} &= \text{utilities saving revenue} - \text{total investment cost} \\ &= + CCU\times(Qcu_{base}-\textstyle\sum_{i} qcu_i) + CHU\times(Qhu_{base}-\textstyle\sum_{j} qhu_j) \\ &\quad - cf\times \textstyle\sum_{i,j,k} (z_{i,j,k}-z_{base,i,j,k}) \\ &\quad - cfcu\times \textstyle\sum_{i} (zcu_i-zcu_{base,i}) - cfhu\times \textstyle\sum_{j} (zhu_j-zhu_{base,j}) \\ &\quad - CA\times \textstyle\sum_{i,j,k} (a_{i,j,k} - a_{base,i,j,k})^B \\ &\quad - CAC\times \textstyle\sum_{i} (acu_i - acu_{base,i})^B - CAH\times \textstyle\sum_{j} (ahu_j - ahu_{base,j})^B \end{aligned} \tag{1}$$

3. HEN retrofit under fouling effects strategy

As mention above, the main problem in energy handling in industry is extra energy consumption caused by fouling deposition. In order to recondition thermal efficiency of HEN, there are many fouling mitigation strategies. Most common strategy used to operate HEN with fouling deposition is design of cleaning schedule but this strategy have to shut-down some exchangers or add spare exchangers. Thus, the production loss problem and extra investment cost may involve. In this study, the new proposed model composed of three main steps is shown in Figure. 2. For first step, the model is divided into twelve one-month periods for one year and then base-case HEN is simulated for twelve months with fouling accumulation by GAMS software. Without any periodic cleaning, HEN has to consume more utility due to decreasing heat recovery and overall heat transfer coefficient of network. The fouling deposition is based on fouling threshold model. In this study the fouling threshold models refer to Polly et a. (2002a)

$$dRf/dt = \alpha Re^{-0.8}Pr^{-0.33}EXP(-E/RT_w)-\gamma Re^{0.8} \tag{2}$$

The idea is to retrofit HEN during the shut-down period around the end of twelfth month. Thus, the HEN consumes lower energy consumption and gets better heat recovery by the increased area of each existing exchanger. For second step, base-case HEN at twelfth month under fouling condition is retrofitted by MINLP model using GAMS. For the third step, the retrofitted HEN from second step is operated under fouling effects for twelve months and utilities usage is calculated. The equations of fouling deposition and HEN retrofit are shown below:

$$Rft = Rft\text{-}1 + Rf't \cdot \Delta t \quad (3)$$

$$1/U = 1/hh + 1/hc + Rf \quad (4)$$

Objective = Minimize total utilities cost for twelve month

$$= CCU \times \sum_{i,t} qcui,t + CHU \times \sum_{j,t} qhuj,t \quad (5)$$

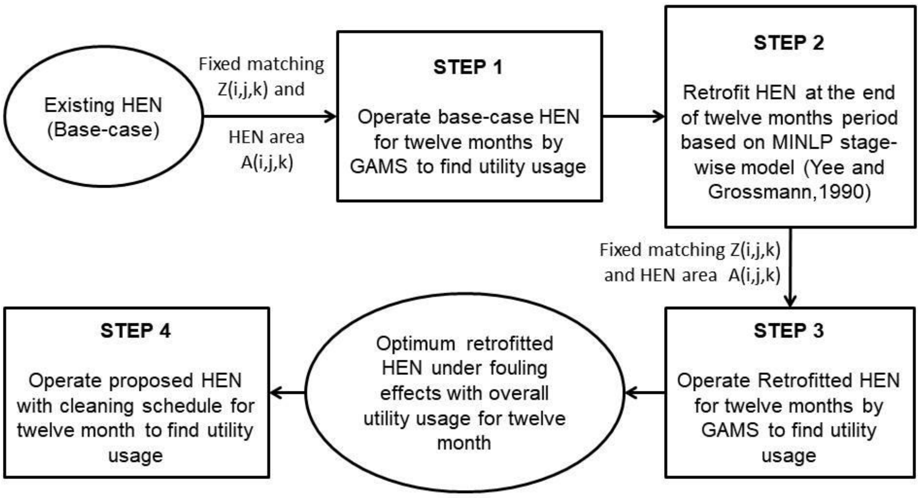

Figure 2: Scheme of HEN retrofit model under fouling effects with cleaning schedule

4. HEN retrofit under fouling effects strategy with cleaning schedule

In order to maximize profit, the cleaning schedule is applied. Wang et al. (2016) apply cleaning schedule for mitigating fouling and get the lower the cost comparing with practical fouling mitigation. The time of operation is divided into 2 types; operation and cleaning sub-periods, shown in Figure 3. The logical constraint, as shown in equation 6, defines the logic that if the effectiveness of heat exchanger ($\frac{Q_t}{Q_{t0}}$) is less than cleaning criteria (C), then the cleaning operation will be occurred. The cleaning status is indicated by binary variable $X_{cl,t}$. Where $X_{cl,t}$ is one and zero referring to cleaning operation and non-cleaning, respectively. Equation 7 is used to indicate fouling resistance when cleaning operation is involved.

$$-\Omega \leq (C - Qt/Qt0) - (\Omega \times Xcl,t) \leq 0 \quad (6)$$

$$Rft = (Rft\text{-}1 + Rf't) \times (1 - Xcl,t) + (Rft0 \times Xcl,t) \quad (7)$$

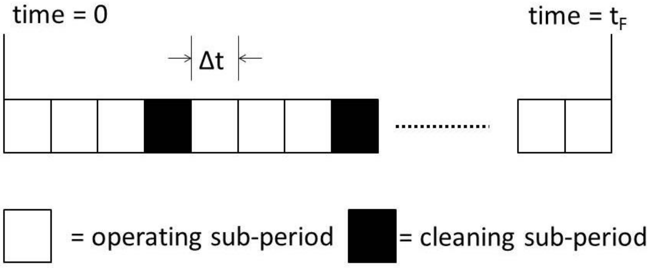

Figure 3: Time discretization for modelling cleaning in HEN.

5. Case study

This crude preheat train case is used to illustrate the HEN retrofit model under fouling effects. The problem is accomplished in GAMS 24.2.1 solved by DICOPT as an MINLP solver on notebook computer (ASUS A45V Series (Intel® Core™ i7-3610QM CPU @ 2.30GHz, 8GB of RAM, Windows 10 (64-bit Operating system)). Project life (n) is five years with 20% of annual interest rate. The stream data is represented in Table 1.

Crude preheat train HEN comprises of 10 hot and 3 cold process streams with 6 existing exchangers as presented in Figure 4a. At first, this base-case HEN requires hot and cold utility for 67,988 and 75,076 kW respectively. This base-case is improved to recover heat transfer efficiency using exchanger minimum approach temperature (EMAT) of 5 ˚C.

When crude preheat train is operated for twelve months in first step, the result shows that HEN consumes more utilities due to decreasing heat recovery of HEN as shown in Figure 4b. Total hot and cold utility consumptions are 70,162 and 77,250 kW respectively. After twelve months, this HEN is modified by retrofit model.

The HEN retrofit shows that there is one new exchanger needed as shown in Figure 4c. The area is increased from 3,913 to 8,424 m^2. At the start of run, retrofitted HEN requires hot utility of 53,354 kW and cold utility of 60,442 kW. And retrofitted HEN operated for twelve months shows that hot and cold utilities are 55,851 kW and 62,939 kW, respectively as shown in Figure 4d. For base-case HEN, fouling accumulation rate is increased in existing exchangers, resulting in increasing heat load and decreasing overall heat transfer coefficient during all of the operating periods as shown in Figure 5. For the retrofitted HEN, the result shows that it saves total hot and cold utility along twelve months and gets positive NPV as shown in Table 2.

Table 1: Stream data for real crude oil preheat train for base case

Stream	T_{IN} (˚C)	T_{OUT} (˚C)	FCP (kW.˚C^{-1})	h (kW.m^{-2}.˚C^{-1})
H1	319.4	244.1	136.186	1.293
H2	73.24	30	6.842	5.063
H3	347.3	45	197.495	0.892
H4	263.5	180.2	123.06	1.361
H5	297.4	110	20.722	1.299
H6	248	50	63.166	1.344
H7	73.24	40	57.687	1.28
H8	231.8	120	48.526	1.396
H9	167.1	69.55	165.278	1.388
H10	146.7	73.24	253.551	0.505
C1	30	232.2	373.238	0.5165
C2	232.2	343.3	488.127	0.788
C3	226.2	231.8	392.55	3.328
Hot utility	120 ($/kW·y)	120 ($/kW·y)	-	2
Cold utility	20 ($/kW·y)	20 ($/kW·y)		2

Heat exchanger cost = 26460 + 389×[area (m^2)]$^{0.83}$

Cleaning cost = 500 $

Cleaning criteria (C) = 70% of thermal effectiveness

Table2: Comparison between base-case and retrofit case

	Without cleaning		With Cleaning	
	Base-case for 12 months	Retrofit case for 12 months	Base-case for 12 months	Retrofit case for 12 months
NPV	-	$639,165	-	$660,038
Hot utility saving	-	20.40%	3.11%	22.23%
Cold utility saving	-	18.53%	2.82%	20.17%
Utility cost	$1,751,709	$1,388,799	$1,751,709	$1,381,134
Additional area cost	-	$419,755	-	$419,755
Cleaning cost			$3500	$2000

The last step, the cleaning schedule is applied by using cleaning criteria of 70 % of thermal effectiveness ($\frac{Q_t}{Q_{to}}$) for comparing between a number of cleaning operations of base-case HEN and retrofitted HEN. The result shows that there are seven cleaning operations for base-case HEN while retrofitted HEN has four cleaning operations as shown in Figure 6. The comparison result of cleaning schedule is shown in Table 2. When cleaning schedule is applied with retrofitted case, HEN gets higher utility saving and NPV.

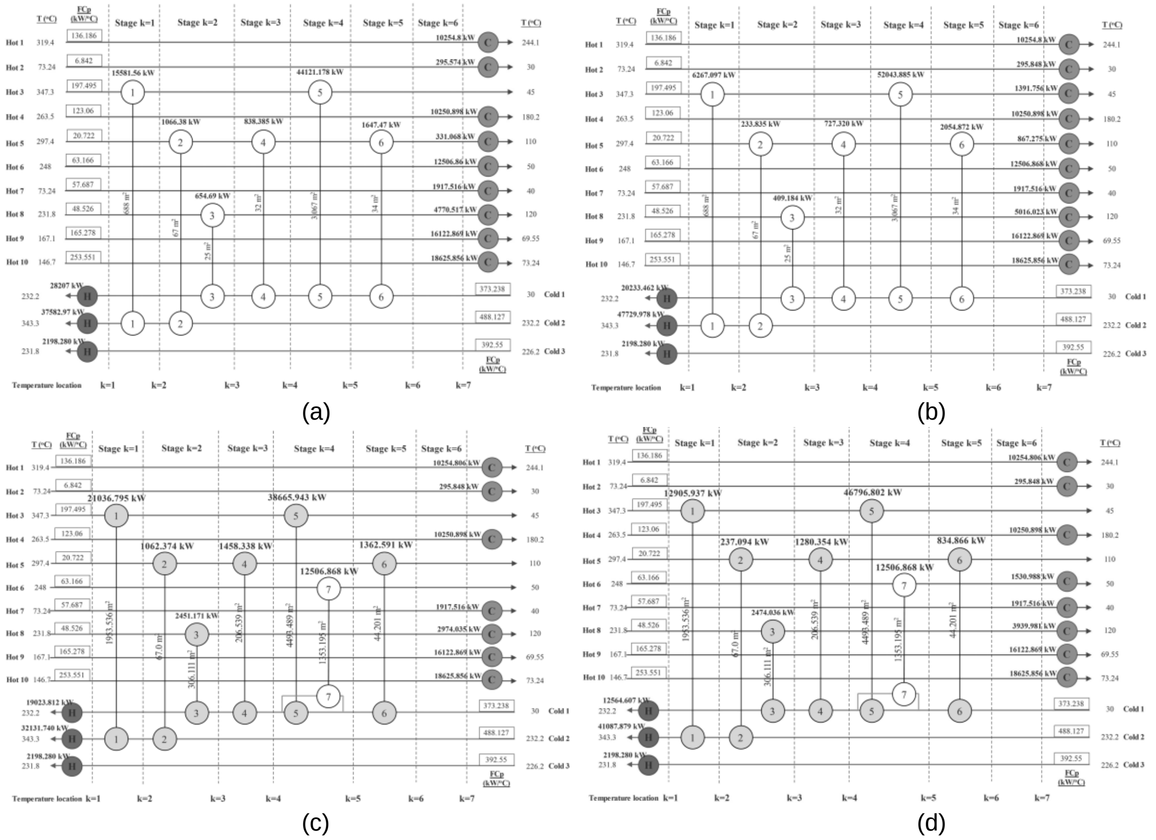

Figure 4: (a) Existing HEN of crude preheat train (0-month). (b) Existing HEN of crude preheat train (12-month). (c) Retrofitted HEN of crude preheat train (0-month). (d) Retrofitted HEN of crude preheat train (12-month)

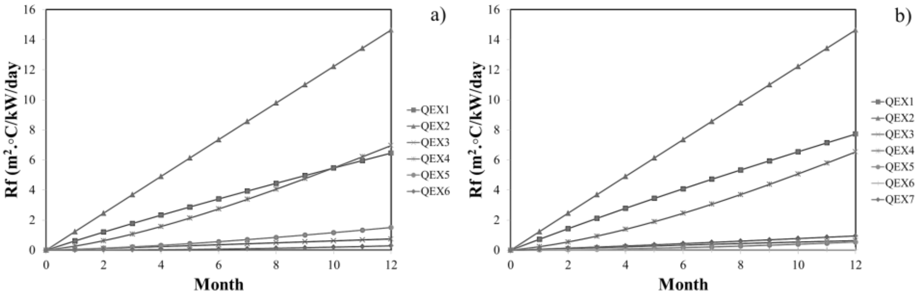

Figure 5: Cumulative fouling rate of exchangers (a) Base-case and (b) Retrofitted case

(a)

	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
HX1				■				■				
HX2		■		■			■			■		
HX3												
HX4							■					
HX5												
HX6												

(b)

	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
HX1												
HX2		■			■			■			■	
HX3												
HX4												
HX5												
HX6												
HX7												

Figure 6: Optimal cleaning schedule of (a) Base-case and (b) Retrofitted case

6. Conclusion

In this study, the proposed HEN retrofit under fouling effects helps save total utility cost. The strategy is HEN retrofit model where network is designed involving additional area to recover more energy. Therefore the model achieve the best trade-offs between investment cost due to addition of area and exchanger and utility cost which is caused by fouling. Comparison between base-case HEN and retrofitted HEN, the retrofitted HEN with cleaning schedule overcomes the base-case one with lower number of cleaning operation. When the cleaning schedule is applied, the model shows that combination of HEN retrofit under fouling effects and cleaning schedule achieve lower energy consumption and higher NPV.

Nomenclature

Indices

i	hot process stream
j	cold process stream
k	index for stage 1 ... k
t	time interval

Parameters

Ω	upper bound for heat exchanges
hh	film coefficient of hot stream (kw/°c.m^2)
hc	film coefficient of cold stream (kw/°c.m^2)
CF	fixed charge for exchangers ($)
CHU	per unit cost for hot utility ($/kW.year)
CCU	per unit cost for cold utility ($/kW.year)
CA	area cost coefficient ($/$m^2$)
B	exponent for area cost
α,β,γ	dimensional parameters that vary for different substances (m^2.°C/kW)
C	lower bound for thermal effectiveness

Binary variables

z	existence of matching
zcu	cold utility exchanging
zhu	hot utility exchanging
X_{cl}	cleaning status

Variables

Q	heat exchanged in heat exchanger (kW)
Qhu	heat exchanged in hot utility (kW)
Qcu	heat exchanged in cold utility (kW)
a	heat exchangers area (m^2)
U	overall heat transfer coefficient (℃·m^2/kW)
Rf	fouling resistance (℃ ·m^2/kW)
Rf'	fouling rate (℃ ·m^2/kW·month)
Re	Reynolds number
Pr	Prandltr number
Tw	wall temperature of process stream (°C)
R	gas constant

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