CHEMICAL ENGINEERING TRANSACTIONS
VOL. 61, 2017
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Petar S Varbanov, Rongxin Su, Hon Loong Lam, Xia Liu, Jiří J Klemeš

ISBN978-88-95608-51-8; **ISSN** 2283-9216
DOI: 10.3303/CET1761083

Synthesis of Flexible Heat Exchanger Networks Considering Fouling Resistance

Yiyuan Bai, Linlin Liu, Siwen Gu, Jian Du*

School of Chemical Engineering, Dalian University of Technology, 116012 Dalian, China
dujian@dlut.edu.cn

The conventional synthesis of heat exchanger network (HEN) is performed under nominal conditions with fixed operating parameters. However, it is inevitable for the network configuration to be disturbed by uncertain operating conditions (for example, feed temperatures, heat capacity flow rates, etc.). At the same time, fouling is a non-negligible factor, which will cause sustained decrease to the overall heat transfer coefficient due to the growth of deposit over the heat transfer surface of the heat exchange units. In practice, the fouling resistance is often fixed to its maximum value instead of considering its dynamic growth. In order to make the synthesis more controllable and operable, this paper presents a flexible synthesis method, in which uncertain operating conditions and the growth of the fouling resistances are considered simultaneously.
The methodology is sequentially implemented in two steps: the flexibility analysis and the flexible synthesis. By searching the critical directions, the improved flexibility analysis method for evaluating the flexibility index is proposed, which can reflect the simultaneous influence of uncertain operating conditions and fouling resistances. Then, the flexible HEN synthesis method based on the critical operating points identified by the aforementioned flexibility analysis method is presented, with the target of decreasing the complexity of the HEN to avoid over-synthesis and minimizing the total annual cost (TAC) simultaneously. The effectiveness of the methodology is demonstrated by a case study.

1. Introduction

HEN is intimately related to energy consumption, and its synthesis is vitally important in chemical process system. However, from a single unit to complex process system, they will inevitably be affected by uncertain operating conditions, which make the network deviate from the optimal operation. Therefore, the flexible HEN is needed to satisfy the design requirements of not only the nominal condition, but also arbitrary operating parameters in the range of uncertainties.
Flexibility analysis is the foundation and essential process of flexible synthesis research. In process industry, flexibility refers to the capability of a process to maintain feasible operation over a given range of uncertain operating conditions. Swaney and Grossmann (1985) first proposed a direct search method with the vertex assumption which searched all the vertices of the hyper-rectangle directly, and presented two improved methods: the heuristic vertex search and the branch-and-bound procedure. Li et al. (2015) exploited a novel method for flexibility analysis of the non-convex HEN, which introduced the direction matrix to describe the deviation direction of the uncertain parameters. Since the directions were not limited to the vertices, this method can be well adapted to the non-convex problems. For the flexible synthesis problem, Pintaric and Kravanja (2008) generated a synthesis method for flexible process based on the identification of critical points by using three algorithms: Karush-Kuhn-Tucher formulation, the two-level method and the approximate one-level method. All the three algorithms can be used to identify vertex, and even non-vertex critical points. Li et al. (2014) discussed a novel stage-wise method for the synthesis of flexible HEN by two main steps. The first step was structure synthesis which was initially synthesized at the nominal operating point and renewed by the topological union with the critical point. The second step was area optimization by developing an iterative approach with strong robustness.

Fouling occurs in most of the heat exchangers, which decreases heat transfer efficiency and causes fluctuation of the outlet temperatures of hot and cold streams. Researchers stated to pay much attention on the fouling problem, and they fixed the fouling resistance to its maximum value instead of considering its dynamic growth (Chen et al., 2013). Zhan et al. (2015) found redistribution of flow rates for the exchangers in the network is an efficient way to mitigate fouling. For the research of multi-period flexible problem, Xiao (2011) took the growth of fouling into account by dividing the fouling operation into four periods, and generated the flexibility-qualified HEN by combining the HEN topologies of all the selected operating periods and fouling periods. However, the complexity of the HEN structure grows exponentially with the scale of the problem.
From the investigation on the mentioned work, few studies focus on the simultaneous consideration of uncertain operating conditions and the growth of fouling resistance. Both adopting the topological union methodology for uncertain operating conditions, and the maximum fouling resistance for the influence of fouling can lead to the over-synthesis of the problem. To overcome this problem, this paper presents a superstructure-based flexible synthesis methodology for simultaneously considering uncertain operating conditions and the growth of fouling resistance with the target of qualified flexibility and minimum TAC. The methodology is demonstrated by a case study to show the efficiency.

2. Methodology

2.1 An improved method for flexibility analysis

Li et al. (2015) proposed an efficient method for flexibility analysis which introduced the direction matrix to represent the deviation direction. Both the flexibility index and the critical operating point that limits the flexibility of HEN could be identified. Compared to the inequalities of the method only related to feed temperature parameters and heat capacity flow rate parameters in Li's method, an improved method for flexibility analysis is proposed and proved to be effective when referring to the impact of fouling resistance on the overall heat transfer coefficient. The mathematical formula of the flexibility index F is obtained as follows, using Eq(1) with a non-negative scalar variable δ. It's obvious that the process would meet the feasible requirement if $F \geq 1$.

$$F = \min_{j} \delta^{\mathrm{D}_j} \tag{1}$$

$$\delta^{\mathrm{D}_j} = \max_{\delta, z} \delta \tag{2}$$

$$f(z, \theta) \leq 0 \tag{3}$$

$$a(z, r, \theta) - a^{\mathrm{N}} \leq 0 \tag{4}$$

$$\theta = \theta^{\mathrm{N}} + \delta \, \mathrm{D}_j \times \Delta\theta \quad \delta \geq 0 \tag{5}$$

$$\mathrm{D}_j = \begin{bmatrix} \mathrm{d}_1 & & & \\ & \mathrm{d}_2 & & \\ & & \cdots & \\ & & & \mathrm{d}_n \end{bmatrix} \tag{6}$$

Where vector z, r and θ denote the control variables, the fouling resistance variables and the uncertain operating variables such as feed temperatures and heat capacity flow rates, respectively. f is the vector of inequality constraints typically related to operation, and a is the vector of inequality constraints for exchanger areas. The direction matrix D_j is a diagonal matrix, where d_i ($1 \leq i \leq n$) represents the direction on the uncertain operating parameter, and n equals to the number of uncertain operating parameters. The deviation $\Delta\theta$ is defined as $\Delta\theta = (\Delta\theta_1, \Delta\theta_2, \ldots \Delta\theta_n)^{\mathrm{T}}$. δ^{Dj} represents the maximum deviation allowed in direction D_j. The superscript N represents the nominal operating condition.

2.2 Synthesis method of flexible HEN

Since the uncertain parameters vary at different operating points, the HEN structure of each operating point and the heat exchanger area for the same match are probably different. A stage-wise superstructure-based MINLP model is established which can express all the possible matches, to obtain a feasible HEN for simultaneous consideration of flexibility and minimum TAC. The network flexibility is satisfied by increasing areas of existing exchangers and involving new exchanger units. A brief review of the method is elaborated through a simple illustration displayed in Li's work (2014). Specific steps are as follows:
(1) Initially synthesis: The initial HEN structure is synthesized at the nominal operating condition, as is shown in Figure 1. EX(i, j, k) represents the match between hot stream i ($i \le N_H$) and cold stream j ($j \le N_C$) at stage k ($k \le N_K$). EX(2,2,1), EX(1,1,2), EX(2,1,2) and CU1 represent original units obtained through the initial synthesis.
(2) Flexibility analysis: Evaluate the flexibility index of the initial HEN. If it is less than 1, point out the critical operating point, then go to step (3), or else it indicates that the structure can satisfy the flexible requirement, and no further synthesis is needed.
(3) Flexible synthesis: Retain the obtained heat exchanger matches in the initial network with considering involvement of new possible heat exchangers indicated by the dotted line in Figure 2. Generate the new structure with the critical operating points.
The objective for synthesis under uncertainty can be generally expressed in the following formulation:

$$
\begin{aligned}
\min TAC = & \sum_i \sum_j \sum_k \left[C_f \cdot z(i,j,k) + C \cdot A(i,j,k)^B \cdot z(i,j,k) \right] \\
& + \sum_i \left[C_f \cdot zcu(i) + C \cdot Acu(i)^B \cdot zcu(i) + C_{cu} \cdot qcu(i) \right] \\
& + \sum_j \left[C_f \cdot zhu(j) + C \cdot Ahu(j)^B \cdot zhu(j) + C_{hu} \cdot qhu(j) \right]
\end{aligned} \tag{7}
$$

The costs include capital costs for heat transfer units and operating costs for utility consumption. The general calculation formula for capital costs can be expressed as: $C_f + C \cdot A^B$. The first item represents fixed installation costs, and the second item represents area costs. C, A and B represent the heat transfer area coefficient, the heat transfer area and index, respectively. q represents the heat load. The subscript *hu* and *cu* represent the heating and cooling utility, respectively. Each unit is defined by a binary variable z where

$$
z = \begin{cases} 1 & \text{if a heat exchanger exists} \\ 0 & \text{if no exchanger exists} \end{cases} \tag{8}
$$

The binary variables for the obtained heat exchanger matches in the initial network take the value of 1, and for a new possible heat transfer unit, it will take the value of 0 or 1. The constraints consist of a series of equality constraints which represent the heat balances, and a number of inequality constraints for assessing feasibility and defining logical operations (Verheyen and Zhang, 2006). Moreover, this method proposes two additional important constraints.
(1) Area constraints:

$$A_{initial}(i,j,k) \ge A^{N}_{initial}(i,j,k) \tag{9}$$

$$Acu_{initial}(i) \ge Acu^{N}_{initial}(i) \tag{10}$$

$$Ahu_{initial}(j) \ge Ahu^{N}_{initial}(j) \tag{11}$$

Where optimization variable $A_{initial}$ represents the areas of original heat transfer units, and the superscript N denotes the nominal condition.
(2) To ensure the feasibility of HEN at critical operating point, the output temperature constraints for hot and cold streams can be expressed as follows:

$$\left| T_{iout} - T_{iout}^{N} \right| \le \zeta \tag{12}$$

$$\left| T_{jout} - T_{jout}^{N} \right| \le \zeta \tag{13}$$

Where ζ is a small value to ensure that the outlet temperature isn't deviated from the target.

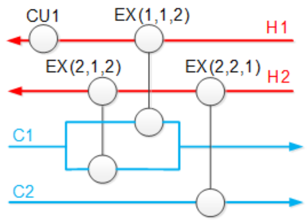

Figure 1: Initial HEN structure

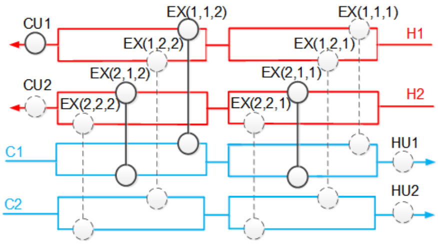

Figure 2: Further synthesis structure

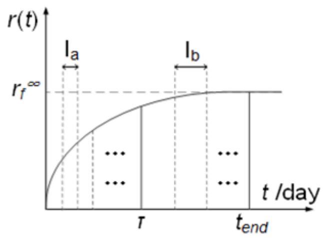

Figure 3: Time segmentation

3. Dynamic growth of fouling resistance

Fouling is a non-negligible factor for heat exchange operation. It will cause decrease to the overall heat transfer coefficient due to the growth of deposit over heat transfer surface of heat exchange units as Eq(14) shows. And it will also generate fluctuation of the outlet temperatures of hot and cold streams. In petrochemical process, as the deposits commonly grow asymptotically over time, a universal asymptotic fouling formation model (Zubair et al., 1992) is adopted to describe the growth of fouling, which is represented as Eq(15).

$$\frac{1}{U(t)} = \frac{1}{h_i} + \frac{1}{h_j} + r_i(t) + r_j(t) \tag{14}$$

$$r(t) = r_f^{\infty}\left(1 - e^{-t/\tau}\right) \tag{15}$$

Where r_f^{∞} and τ are empirical parameters obtained by experiments. The accumulated time t calculates from the clean condition. In order to investigate the influence of the dynamic growth of fouling resistance on the optimal design of the HEN structure, it is necessary to divide the operating time into N_p intervals according to time constant τ. As Figure 3 shows, the duration of each time interval before τ is shorter than that after τ because fouling grows faster before τ (Chen et al., 2013). To simplify the fouling process, the fouling resistance at terminal point of each interval p ($p \leq N_p$) is used for flexibility analysis and flexible synthesis throughout the whole interval.

4. Methodology for flexible HEN synthesis considering fouling resistance

The methodology for flexible HEN synthesis with the simultaneous consideration of uncertain operating conditions and fouling growth is listed as follows:

(1) Divide the operation time into N_p intervals based on the growth profile of fouling resistance, and determine the fouling resistance of each interval.

(2) Design and obtain the initial HEN structure respecting to the nominal operating condition.

(3) Calculate the flexibility index F of the initial network with considering the uncertain operating conditions and fouling resistances for the first interval. If F<1, the existing network has to be improved using the method proposed in section 2.2, otherwise, keep the network unchanged. After these measurements, the network will meet the flexibility requirements of interval 1, and it's set as the initial network of interval 2.

(4) Follow the procedures stated in step (3) for each of the following intervals until interval N_p, then the final network is competent respecting the flexibility requirements throughout the whole process.

5. Case study

An example adapted from the work of Xiao (2011) is used to demonstrate the efficiency of the proposed strategy. The parameters for the case study are presented in Table 1. The uncertain operating parameters are feed temperatures of each stream, which are listed in Table 2. And the system operating period lasts for 720 d. As the time constants τ of each stream are all around 300 d, it is acceptable to set t = 300 as the boundary. Between 0 and 300 d, the operation is divided into 10 intervals equally. And between 300 and 720 d, the operation is divided into 5 intervals equally. The total operation is divided into 15 intervals to reflect the fouling resistance growth of each stream.

Table 1: Parameters for Case Study

process streams	T_{in} / K	T_{out} / K	FCp / (kW·K^{-1})	h / (kW·m^{-2}·K^{-1})	r_f^{∞} / (m^2·K·kW^{-1})	τ / d
hot stream 1 (H1)	512	393	7.032	1.40	0.348	220
hot stream 2 (H2)	512	421	8.440	1.25	0.201	300
cold stream 1 (C1)	379	423	6.096	1.50	0.333	200
cold stream 2 (C2)	399	523	10.000	1.20	0.351	350
hot utility (HU)	850	850	---	2.80	0.083	380
cold utility (CU)	293	313	---	3.00	0.059	230
COST = 8,000 + 1,000 $A^{0.6}$ \$·y^{-1}			DT$_{min}$ = 10 K			
C_{hu} = 80 \$·kW^{-1}·y^{-1}			C_{cu}=20 \$·kW^{-1}·y^{-1}			

Table.2: Range of variations for uncertain parameters

uncertain parameter	Nominal value / K	Lower value / K	Upper value / K
inlet temperature of H1	512	502	522
inlet temperature of H2	512	502	522
inlet temperature of C1	379	369	389
inlet temperature of C2	399	389	409

The initial HEN is synthesized at nominal operating condition (t=0) as shown in Figure 4, and then the improved method for flexibility analysis is employed to evaluate the flexibility index of the initial HEN structure, to judge whether it can withstand the fouling resistances and the uncertain operating parameters of interval 1. The flexibility index value is 0.376, implying that the initial HEN is infeasible for some possible conditions within the disturbance range. With the sequence ($Ti_{in}(1), Ti_{in}(2), Tj_{in}(1), Tj_{in}(2)$), the critical direction obtained is (502,522,369,409), (522,522,369,409) along with (522,522,389,409). The proposed flexible synthesis method is used to obtain the flexible HEN structure for interval 1. The iteration of the process isn't terminated until the retrofitted network can satisfy the fouling resistances and the fluctuations of temperatures from different intervals (until N_p=15). The results are displayed in Table 3 and Table 4, and the final qualified flexible HEN structure shown in Figure 6 is feasible to satisfy all the fluctuations in disturbance range with the flexibility index F=1. The TAC in this work is 109,100 \$·y^{-1}, which is decreased by 18.44 % comparing to Xiao' s method adopting the topological union method shown in Figure 5. At the same time, the complexity of the HEN structure in this work is reduced obviously. Although the number of utilities is equal to the literature, the number of heat exchangers is reduced from 5 to 3 heat exchangers. The effectiveness of the method can be demonstrated.

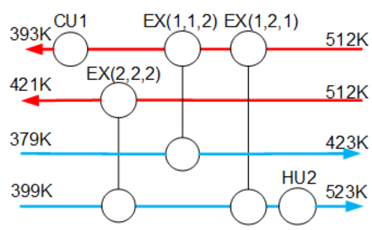

Figure 4: The initial HEN structure

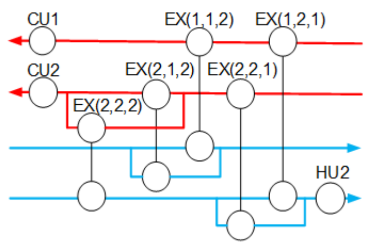

Figure 5: The final HEN structure in Xiao's work (2011)

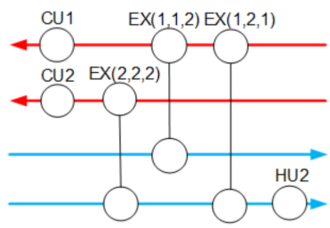

Figure 6: The final HEN structure in this work

Table 3: Comparison of unit areas

Item / Area (m^2)	EX(1,2,1)	EX(2,2,1)	EX(1,1,2)	EX(2,1,2)	EX(2,2,2)	CU1	CU2	HU2
nominal condition	17.99	---	5.45	---	39.51	3.26	---	0.86
Xiao's result	28.89	35.57	10.71	3.29	13.26	3.69	1.41	7.25
this work result	20.07	---	12.21	---	42.88	5.71	1.84	1.83

Table 4: Comparison of total annual cost

Item	fixed installation cost ($ • y^{-1})	area cost ($ • y^{-1})	operating cost ($ • y^{-1})	TAC ($ • y^{-1})
Xiao's work	64,000	33,655	36,114	133,769
this work	48,000	25,792	35,308	109,100

6. Conclusions

This paper presents a flexible HEN synthesis methodology that simultaneously considers uncertain operating conditions and the growth of fouling resistance. It is efficient to get the final feasible HEN structure with the target of qualified flexibility demonstrated by a case study, which not only reduces the complexity of the HEN structure from 5 to 3 heat exchangers, but also brings down the TAC with 18.44 % comparing to the literature obviously.

Acknowledgments

The authors would like to gratefully thank Natural Science Foundation of China (No.21576036 and No.21406026) for providing the research fund for this project.

References

Chen P.P., Li J.L., Fan J., Hong S.H., Du J., 2013, Synthesis of Flexible Heat Exchanger Network with Fouling Growth, Journal of East China University of Science and Technology (Natural Sci Edition), 39(1), 51-54

Li J.L., Du J., Zhao Z.C., Yao P.J., 2014, Structure and Area Optimization of Flexible Heat Exchanger Networks, Industrial & Engineering Chemistry Research, 53(29), 11779-11793

Li J.L., Du J., Zhao Z.C., Yao P.J., 2015, An Efficient Method for Flexibility Analysis of Large-scale Nonconvex Heat Exchanger Networks, Industrial & Engineering Chemistry Research, 54(43), 10757–10767

Pintarič Z.N., Kravanja Z., 2008, Identification of critical points for the design and synthesis of flexible processes, Computers & Chemical Engineering, 32(7), 1603-1624

Swaney R.E., Grossmann I.E., 1985, An index for operational flexibility in chemical process design Part II: Computational algorithms, AIChE Journal, 31(4), 631-641

Verheyen W., Zhang N., 2006, Design of flexible heat exchanger network for multi-period operation, Chemical Engineering Science, 61(23), 7730-7753

Xiao F., 2011, Simultaneous optimization of synthesis and cleaning schedule in flexible heat exchanger networks (Chinese). PhD Thesis, DUT, Dalian, China

Yee T.F., Grossmann I.E., 1990, Simultaneous Optimization Models for Heat Integration-II. Heat Exchanger Network Synthesis, Computers & Chemical Engineering, 14(10), 1165 – 1184

Zhan S., Wang Y., Feng X., 2015, Optimization of velocity in heat exchanger networks for fouling mitigation, Chemical Engineering Transactions, 45, 61-66

Zubair S.M., Sheikh A.K., Shaik M.N., 1992, A probabilistic approach to the maintenance of heat-transfer equipment subject to fouling, Energy, 17(8), 769–776.