CHEMICAL ENGINEERING TRANSACTIONS Volume 25, 2011
Editors Jiří Jaromír Klemeš, Petar Sabev Varbanov, Hon Loong Lam
Copyright © 2011, AIDIC Servizi S.r.l., ISBN 978-88-95608-16-7 ISSN 1974-9791
DOI: 10.3303/CET1125113

Structure Optimization Based on Pseudo-temperature of Heat Exchanger Network for Batch Processes

Jian Du[1]*, Chunni Li[1], Li Chen[2]

[1]Institute of Chemical Systems Engineering, Dalian University of Technology, Dalian, 116012, Liaoning, China, dujian@dlut.edu.cn
[2]School of Environment & Chemical Engineering, Dalian University

The structure optimization of the heat exchanger network (HEN) for batch processes will be studied with the heat directly exchanged network (HDEN) for batch processes based on pseudo-T-H diagram approach (PTHDA), with related content of continuous processes. Heat load loops are determined within each time interval. According to three rules put forward in this paper, including two rules applicable to both continuous and batch processes and one rule applicable to batch processes only, these heat load loops can be disconnected. The structure optimization for batch processes can reduce the number of heat exchange units and meet the minimum annual total cost simultaneously. Two examples are used to show the reliability and validity of the proposed rules.

1. Introduction

Along with speeding up of market changes and high-speed developments of chemical products, batch processes share larger and larger proportion in chemical production with high flexibility in production. But compared with continuous processes, researches of batch processes started quite late, were comparatively rare, and were limited in the practical application.

The structure optimization of the HEN is the design proposal that the HEN synthesized to get the maximum heat recovery is tuned to make the structure of the HEN simplified. According to the different final goals, the structure optimization of the HEN may result in the followings: (1) taking the optimization structure of the HEN as the goal, total cost may be not the least; (2) taking the minimum total cost as the goal, the structure of the HEN becomes complex; (3) consideration of the structural complexity and the total cost of the HEN, the nearly optimal result can be obtained.

At present, most researchers synthesize the HEN of batch process by traditional pinch analysis, namely minimum heat transfer temperature difference, $\Delta T_{\min}$, to determine the position of the pinch. With a single $\Delta T_{\min}$, the synthesized HEN is not the optimal, or the economics of the system is not reduced.

Pseudo-temperature method is the method on the basis of the different heat transfer coefficient etc. physical parameters of streams of the network and the different price caused by the difference of the heat exchanger material structure etc., to determine the heat transfer temperature difference contribution value ΔT_{C} of each stream, to modify the start and the end temperature of each stream into the pseudo-temperature, adopting

Please cite this article as: Du J., Li C. and Chen L., 2011, Structure optimization based on pseudo-temperature of heat exchanger network for batch processes, Chemical Engineering Transactions, 25, 677-682
DOI: 10.3303/CET1125113

the pseudo-temperature to redistribute the energy of different temperature in the system, to regulate the distribution of temperature difference in the network, making the heat transfer temperature difference distribution of each heat interchanger more reasonable. In this paper, adopting this method is in order to reduce the network area and the total cost, and to get the network structure closer to the practicable target.

The traditional heat transfer temperature difference contribution value only considered the economic influence, but the thermodynamic influence is not considered. Then Equation (1) was proposed to value the heat transfer temperature difference contribution value Δ T_C. The influence of thermodynamic and economic factors is considered in the equation simultaneously.

$$\Delta T_C^p = \sqrt{\frac{a_p h_r}{a_r h_p}} \cdot \frac{T_p^2}{T_r^2} \cdot \Delta T_C^r = C \cdot a_p^{1/2} \cdot h_p^{-1/2} \cdot T_p^2 \tag{1}$$

In this equation, p represents object stream, r indicates reference stream, a, h, T, C are respectively cost coefficient per unit heat transfer area, heat transfer film coefficient, actual temperature, area cost coefficient, and they all can influence the value of Δ T_C. This approach can be applied to the HEN with unequal heat transfer film coefficients and different materials of construction.

2. Structure Optimization of HEN for Batch Processes

2.1 Minimum Unit Number

Foo et al (2005) apply the minimum unit number of the mass exchanger network for batch processes to the HEN for batch processes. In their paper, the number of the minimum heat exchange units of the HEN for batch processes, U is:

$$U = \sum_k U_k - \sum_l U_{AE,l} \tag{2}$$

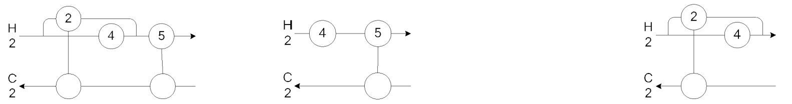
Where, $U_{AE,\ l}$ is the number of additional heat exchangers with l pairs of matching streams.

2.2 Loops Disconnecting Rules

With the pseudo-temperature method, the following three rules on the structure optimization of the HEN are summarized. Application of these rules to disconnect heat load loops, firstly, the stage number should be judged before disconnecting. If the first stage loop, whether there are common heat exchangers should be determined; if above secondary (including secondary) stage loops, the heat exchanger with the minimum heat load should be decided whether to remove or not.

2.2.1 Loop Disconnecting Rules Applied to both Continuous and Batch Processes

Rule 1: In the HEN with branches, on the condition that the heat load is non-negative and temperature constraints are met, loops should be disconnected with branches preferentially; or loops should be disconnected without branches.



(a) the initial network structure (b) disconnecting loop without branch (c) disconnecting loop with branchy

Figure 1. Disconnecting loop with and without branch

Rule 2: In above secondary (including secondary) stage loops of HEN for batch processes, the heat exchanger with the minimum heat load is given priority to removing. When it can't be removed, other heat exchangers with less heat load are considered.

If the temperature difference of import and export of heat exchangers are not very big, the change of other heat exchangers is the smallest in case of removing the heat exchanger with the minimum heat load first. In that way, the change of heat load and the increased area of the rest heat exchangers is less, so the total cost is less.

2.2.2. Only applicable to batch process rule

Rule 3: In the first stage loop with two non-common heat exchangers of batch processes, no matter which heat exchanger is removed, the structure, total expenses and area of the HEN are the same. If there is a common heat exchanger in the first stage loop, the non-common heat exchanger should be given the priority to removing. If both common heat exchangers in the first stage loop, removing which heat exchanger depends on whether the area of the common heat exchanger is the biggest area in the various time intervals.

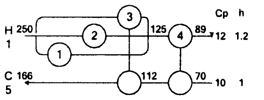


Figure 2: Initial network structure

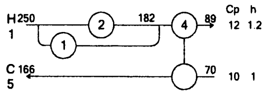


Figure 3: HEN of removing the heat exchanger 3

(a) *(b)*

Figure 4: HEN of removing the heat exchanger 4

Table1 Comparison of different methods to disconnect loop of the HEN

Heat exchanger code	Initial network structure			Removing the heat exchanger 14			Removing the heat exchanger 17		
	Heat /kW	Area /m^2	Cost /($\$\cdot y^{-1}$)	Heat /kW	Area /m^2	Cost /($\$\cdot y^{-1}$)	Heat /kW	Area /m^2	Cost /($\$\cdot y^{-1}$)
1	3178.3	63.0	30020.8	3178.3	55.7	27955.8	3178.3	55.7	27955.8
2	183.2	2.3	9596.9	183.2	1.2	8936.7	183.2	1.21	8936.7
3	1891.8	26.1	18894.5	0	0	0	3363.7	100.9	40085.5
4	1471.8	47.8	25657.1	3363.7	100.9	40085.5	0	0	0
total	6725.3	139.4	84169.4	6725.3	157.8	76978.0	6725.3	157.9	76978.0

It shows some heat exchangers in the network for a batch process in Figure 2. In the HEN, both heat exchangers in the first stage loop (3, 4) are non-common heat exchangers. The HEN is shown in Figure 3 removing the heat interchanger 3. The HEN should be Figure 4(a) removing the heat interchanger 4. But because the heat exchanger 2 doesn't meet the requirement of the temperature difference, Figure 4(b) is gotten by Rule 1. From Table 1, the results of removing the heat exchanger 3 and 4 are the same.

In batch processes, if there is a non-common heat exchanger, it should be given priority to removing, because the non-common heat exchanger is removed from the HEN thoroughly, reducing total cost, including both capital cost and operation cost.

The condition that heat exchangers in heat load loops mentioned in Rule 3 are both common heat exchangers is unusual and complex, which will not be analyzed in detail.

3. Examples

3.1 Example 1

The data of this example are shown in Table 2, including 4 heat streams, 3 cold streams, 1 hot utility and 1 cold utility.

Table :2 The data of example 1

The code of streams	Inlet temperature /K	Outlet temperature /K	Start time /min	End time /min	CP /(kW·K^{-1})	Heat load /kWh	Film coefficient of heat transfer /(kW·m^{-2}·K^{-1})	Cost /($·kW^{-1}· y^{-1})
H1	135	15	9	102	1.2	204.6	1	/
H2	100	95	48	102	20	90	1	/
H3	165	125	39	48	3.5	21	1	/
H4	165	125	102	120	3.5	42	1	/
C1	25	100	0	102	1	127.5	1	/
C2	130	180	48	120	3	180	1	/
C3	80	105	39	120	5	168.75	1	/
H	191	190	0	120	/	/	1	160
C	10	11	0	120	/	/	1	10

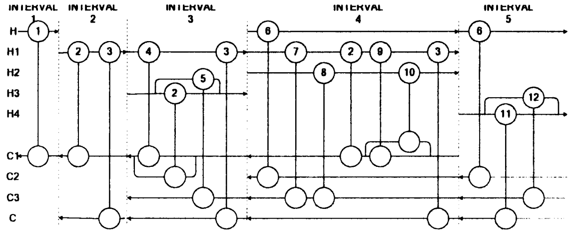


Figure 5: Initial structure of example 1

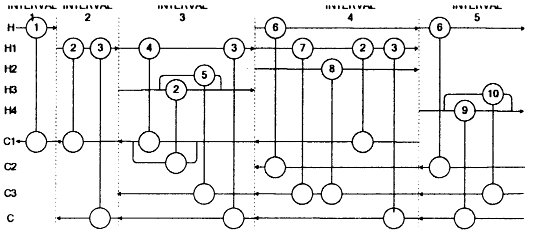


Figure 6: Final structure of example 1

Table 3: Comparison of before and after the optimization of the HEN for example 1

before optimization			after optimization		
code	area/m^2	investment cost/($·y^{-1})	code	area/m^2	investment cost/($·y^{-1})
1	1.21	458.11	1	1.21	458.11
2	6.13	1452.85	2	7.64	1698.97
3	0.37	197.65	3	6.56	1524.57
4	4.79	1220.35	4	0.37	197.65
5	3.06	886.35	5	4.79	1220.35
6	38.24	5330.06	6	10.39	2112.69
7	3.19	913.12	7	2.39	744.9
8	0.25	148.07	8	39.91	5493.96
9	10.38	2112.19			
10	9.88	2038.45			
11	4.79	1220.35	9	4.79	1220.35
12	171.43	15464.77	10	171.43	15464.77
total	253.72	31442.32	total	249.48	30136.32

The formula of the annual cost of heat exchangers is 401[area(m^2)]$^{0.71}$ \$·y^{-1}.The first initial network can be obtained by the pseudo-temperature method, as shown in Figure 5. The number of the minimum heat exchange equipments is U=15−5 =10. According to the rules proposed above, the final network structure can be obtained as Figure 6. It is easy to see that, in Table 3, after optimizing, the number of the heat transfer units is reduced by 2, and the total cost is reduced by 3.78%.

3.2 Example 2

This example is selected from the literature of Liu et al (2009), consisting of 6 heat streams, 5 cold streams, 1 cold utility and 1 hot utility. The formula of calculating the total annual cost of the HEN is [8000 + 800 area (m^2)] $^{0.8}$ \$·y^{-1}.

The initial HEN with the pseudo-temperature method is shown in Figure 7. The minimum heat exchange equipment number U=26-16=10. According to the rules proposed above, the final network structure can be obtained as Figure 8. It can be seen in Table 4 that the structure optimization of the HEN reduces total heat exchange equipment by 7, and reduces the total cost by 6.97%.

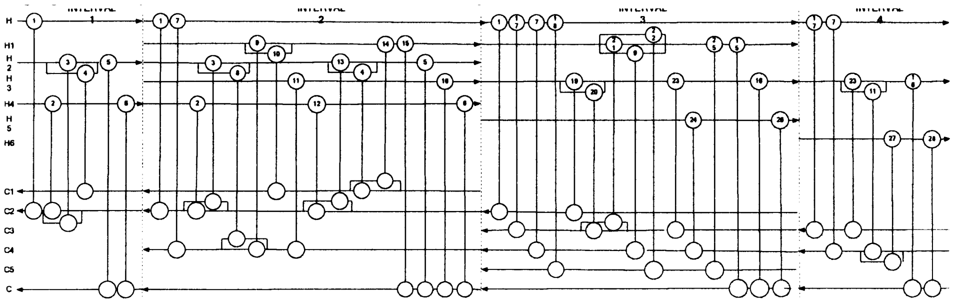


Figure 7. The initial network structure for the example

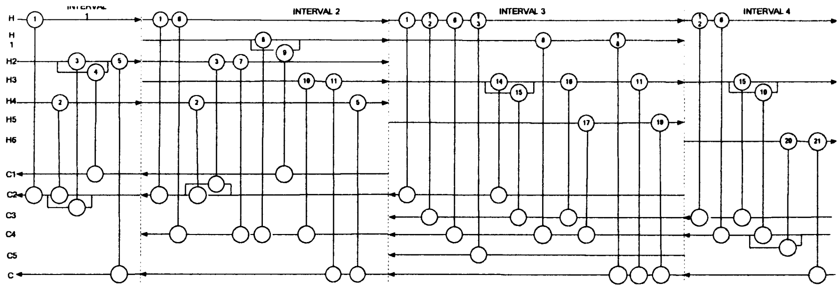


Figure 8. The final network structure for the example

4. Conclusions

Researching the total cost of the HEN for batch processes as the object, giving consideration to the complexity and the total annual cost of the HEN, nearly optimal result can be obtained. Based on the Time Slot Model, with pseudo-temperature method, taking example by the structure optimization of the HEN for continuous processes, the rules of the structure optimization of the HEN for batch processes are put forward. Adopting proposed structure optimization rules to optimize the structure of examples, the number of heat exchange equipments and the total cost of the HEN are reduced, reaching the goals of both simplifying the network structure and reducing the total annual cost, proving the reliability and validity of proposed rules.

Table 4. Comparison of before and after the optimization of the HEN for the example

before optimization			after optimization			before optimization			after optimization		
code	area $/\mathrm{m}^2$	investment cost $/(\$\cdot \mathrm{y}^{-1})$	code	area $/\mathrm{m}^2$	investment cost $/(\$\cdot \mathrm{y}^{-1})$	code	area $/\mathrm{m}^2$	investment cost $/(\$\cdot \mathrm{y}^{-1})$	code	area $/\mathrm{m}^2$	investment cost $/(\$\cdot \mathrm{y}^{-1})$
1	15.89	15310.03	1	14.11	14648.92	15	13.31	14343.56	11	26.81	19109.31
2	325.15	89800.80	2	5.94	11329.44	16	49.22	26064.06	12	91.70	37715.02
3	26.58	19032.66	3	32.24	20875.40	17	4.38	10608.29	13	125.66	46234.30
4	69.92	31920.49	4	6.44	11550.60	18	5.18	10981.58	14	89.62	37175.00
5	12.72	14118.72				19	92.44	37906.65	15	286.62	81950.17
6	53.90	27424.22	5	180.75	59138.80	20	139.70	49615.52	16	10.96	13433.60
7	28.91	19800.87	6	782.93	173222.11	21	2.37	9596.92			
8	72.66	32668.41	7	81.65	35079.41	22	26.16	18894.55			
9	63.05	30020.88	8	32.04	20813.09	23	170.71	56853.25	17	6.61	11624.79
10	67.92	31372.27	9	86.57	36378.35	24	287.17	82063.26	18	57.78	28537.07
11	153.21	52805.02	10	128.27	46867.20	25	47.84	25657.13			
12	82.59	35330.71				26	500.58	123522.74	19	85.46	36086.33
13	15.86	15299.06				27	107.71	41798.80	20	522.11	127481.24
14	32.07	20822.46				28	26.71	19077.14	21	50.15	26337.46

	before optimization			after optimization		
total	amount	area$/\mathrm{m}^2$	investment cost$/(\$\cdot \mathrm{y}^{-1})$	amount	area$/\mathrm{m}^2$	investment cost$/(\$\cdot \mathrm{y}^{-1})$
	28	2493.91	962710.06	21	2704.43	895587.60

5. Acknowledgement

Supported by the National Natural Science Foundation of China (No.20976022) and Dalian University of Technology for Constructing Interdiscipline 'Energy + X'.

References

Foo C.Y., Manan Z.A., Yunus R.M. and Aziz R.A., 2005, Synthesis of mass exchange network for batch processes – Part II: minimum units target and batch network design. Chemical Engineering Science, 60 (5):1349–1362.

Foo C.Y., Chew Y.H. and Lee C.T., 2008, Minimum units targeting and network evolution for batch heat exchanger network. Applied Thermal Engineering, 28: 2089–2099.

Krummenacher P. and Favrat D., 2001, Indirect and mixed direct-indirect heat integration of batch processes based on pinch analysis. International Journal of Thermodynamics, 4(3):135-143.

Liu L.L., Du J., Xiao F., Chen L. and Yao P.J., 2009, Heat exchanger network synthesis based on the pseudo-temperature for batch process. Computers and Applied Chemistry, 26(8):1018-1020.

Xiao W., Dong H.G., Li X.Q., Yao P.J., Luo X. and Wilfried R., 2006, Synthesis of large-scale multistream heat exchanger networks based on stream pseudo temperature. Chinese Journal of Chemical Engineering, 14(5):574-583.