CHEMICAL ENGINEERING TRANSACTIONS

VOL. 76, 2019

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

Guest Editors: Petar S. Varbanov, Timothy G. Walmsley, Jiří J. Klemeš, Panos Seferlis

ISBN 978-88-95608-73-0; **ISSN** 2283-9216

DOI: 10.3303/CET1976068

Cost Optimisation of a Flexible Heat Exchanger Network with Fluctuation Probability using Break-Even Analysis

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Heat exchanger network (HEN) which is designed to achieve the maximum energy recovery (MER) involves the integration and interactions of multiple process streams. Small disturbances on one stream can affect other connecting streams. In order to manage these disturbances, the process to process and utility heat exchangers with bypass streams installation are typically overdesigned. However, overdesign also means higher capital investment. This study presents the cost optimisation of flexible MER HEN design which considers the fluctuation probability using break-even analysis. Data were extracted for the Pinch study and assessment for flexibility and MER was performed. The MER heat exchanger maximum size (MER-HEM) is able to handle the most critical supply temperature fluctuations while minimising the utility consumption. The overdesign factor can affect the total annualised cost at a certain probability of fluctuation occurrence. Thus, the break-even analysis of the MER-HEM is performed to determine the probability that resulted in high savings of total annualised cost. Two Scenarios (A and B) with different fluctuation probabilities were used to demonstrate the methodology. Application of the proposed methodology on an Illustrative Case Study shows that, for the fluctuation at hot stream H1, the MER-HEM gives the optimum annualised total cost for Scenario A with additional savings of 10 %. For Scenario B, the MER heat exchanger original size (MER-HEO) is the optimum, giving an additional savings of 4 %. For cold stream C1, the MER-HEO is the optimum for Scenario A, giving an extra savings of 4 % whereas the MER-HEM is the optimum for Scenario B, yielding an extra savings of 9 %.

1. Introduction

Heat Integration has been a well-established energy saving technique for the chemical process industry since the global energy crisis in the 1970s (Klemeš and Kravanja, 2013). Savings on energy consumption in industrials sectors using heat integration techniques typically range between 10 and 35 % (Klemeš et al., 2013). However, additional savings of between 5 to 15 % can be obtained using conventional methods such as monitoring and process modifications (Klemeš et al., 2018). Most previous researchers work on the improvement of HEN synthesis focussing more on the utilisation of maximum energy recovery, minimum area, unit targets and minimum global total cost. In energy-intensive industries, HEN is very complex and can potentially cause operability issues. Lack of emphasis on operability and safety aspects may lead to undesired conditions including failure of heat exchanger operation. Supply temperature and heat capacity flowrate have high potential to deviate from the nominal values (Tellez et al., 2006). Recent developments in designing and controlling HEN under uncertainty such as synthesis of HEN with the consideration of safety and operability aspects using Pinch-based methodology (Hafizan et al., 2016), multi-period HEN under different operating conditions (Miranda et a., 2017), flexible HEN with bypass placement consideration and heat exchanger sizing based on the new heuristics (Hafizan et al., 2019), retrofit HEN under fixed and uncertain dynamic operating conditions of existing Total Sites (TS) (Čuček and Kravanja, 2016) and back-off approach using Power Series Expansions (PSE) (Rafiei-Shishavan et al., 2017) have yet to fully factor in fluctuation probability and process condition feasibility

Paper Received: 26/03/2019; Revised: 09/04/2019; Accepted: 09/04/2019
Please cite this article as: Hafizan A.M., Wan Alwi S.R., Manan Z.A., Klemes J.J., Hamid M.K.A., 2019, Cost Optimisation of a Flexible Heat Exchanger Network with Fluctuation Probability using Break-Even Analysis, Chemical Engineering Transactions, 76, 403-408 DOI:10.3303/CET1976068

into design even though they can be a significant influence on cost optimisation. Wechsung et al. (2010) proposed an approach with the application of relaxation-based dependability analysis to quantify the effect of uncertainty on process design. This approach enhanced the design by limiting the unnecessary process overdesign when it met unnecessary process conditions. However, the impact on the design cost is not included. Lal et al. (2018) presented the effect of variability in stream properties on the economic performance of a HEN retrofit by using Monte Carlo simulation. The Monte Carlo simulation takes variable inputs as probability distributions and randomly sample these distributions for model calculations.

The motivation of this paper is to present the cost optimisation of flexible HEN for grassroots design considering fluctuation probability, and its trade-off between MER and total cost. In the previous work by Hafizan et al., (2019), the MER heat exchanger maximum size (MER-HEM) was proposed to handle the most critical supply temperature fluctuations while minimising the utility consumption. However, the overdesign factor can affect the total annualised cost at a given probability of temperature fluctuation occurrence. The MER heat exchanger original size (MER-HEO) is sometimes preferred over the MER-HEM. This methodology allows the designers to design a flexible HEN which can cater to fluctuations with optimal cost. The methodology proposed is then tested by using Illustrative Case Study to show its practicality.

2. Maximum Energy Recovery Targeting with Disturbance on Supply Temperature (T_s)

The maximum energy recovery (MER) of HEN can be targeted by using Pinch Analysis method such as Problem Table Algorithm (PTA) or Composite Curves (CC) by Linnhoff and Flower (1978) or Streams Temperature vs Enthalpy Plot (STEP) by Wan Alwi and Manan (2010). The supply temperature disturbance in a HEN design considering the utility consumption, heat exchanger sizing, and bypass placement is managed by using the heuristics proposed in the prior work of Hafizan et al. (2019). A more detailed methodology is proposed in this work as an extension of the work by Hafizan et al. (2019) to determine the impact of fluctuation probability on maximum total annualised cost saving, and ultimately propose heat exchangers of suitable size to manage the fluctuations. Two HEN designs of MER-HEO and MER-HEM with the probability of fluctuation occurrence were compared. Table 1 shows the stream data involving 2 hot and 2 cold streams from an Illustrative Case Study used to demonstrate the approach. The supply temperature of streams H1 and C1 are assumed to fluctuate within $\pm$ 5 ℃.

Table 1: Stream data with a fluctuation supply temperature

Stream	Supply temperature, T_S (℃)	Target temperature, T_t (℃)	Heat capacity flowrate, FC_P (kW/℃)	Enthalpy, ΔH (kW)
Hot 1 (H1)	180 $\pm$ 5	40	2	-280
Hot 2 (H2)	150	40	4	-440
Cold 1 (C1)	60 $\pm$ 5	180	3	360
Cold 2 (C2)	30	130	2	200

Analysis on the effect of disturbances on streams H1 and C1 towards the HEN design for the MER-HEO (process to process heat exchanger size is based on MER) is summarised in Table 2 while for the MER-HEM (process to process heat exchanger size is based on MER when the disturbance gives lower cooling or heating utility duty) is shown in Table 3. The disturbances can result in either positive or negative impacts on the heating utility, Q_H, and cooling utility, Q_C of HEN.

Table 2: Analysis of utility requirements for the MER-HEO

Stream	Stream position	Disturbance at T_S (℃)	HE affected	HE nominal size (kW)	HE duty during disturbance (kW)	Q_H or Q_C affected	Max. size of Q_H or Q_C		Duty of Q_H or Q_C	
							Q_H (kW)	Q_C (kW)	Q_H (kW)	Q_C (kW)
H1	Across Pinch	+ 5	HE 1	60	60	CU 2	60	30	60	30
		Nominal	None		60	None			60	20
		- 5	HE 1		60	CU 2			60	10
C1	Across Pinch	+ 5	HE 2	240	240	HU 1	75	200	45	200
		Nominal	None		240	None			60	200
		- 5	HE 2		240	HU 1			75	200

Table 3: Analysis of utility requirements for the MER-HEM

Stream	Stream position	Disturbance at T_S (℃)	HE affected	HE max. size (kW)	HE duty during disturbance (kW)	Q_H or Q_C affected	Max. size of Q_H or Q_C		Duty of Q_H or Q_C	
							Q_H (kW)	Q_C (kW)	Q_H (kW)	Q_C (kW)
H1	Across	+ 5	HE 1	70	70	HU 1	60	20	50	20
	Pinch	Nominal	None		60	None			60	20
		- 5	HE 1		60	CU 2			60	10
C1	Across	+ 5	HE 2	255	240	HU 1	60	200	45	200
	Pinch	Nominal	None		240	None			60	200
		- 5	HE 2		255	CU 1			60	185

A comparison of utility consumption for MER-HEM and MER-HEO is shown in Tables 2 and 3. The observations of the MER-HEM over the MER-HEO are:

1) Hot stream at across Pinch / above Pinch
    - If the supply temperature increased, the duty of HE 1 heat exchanger is increased and resulted in decreasing the HU 1 utility. The MER-HEM for HE 1 is contributed by the probability of increased temperature fluctuation.
    - For temperature fluctuation at stream H1, additional Q_H savings can be achieved if the HE 1 heat exchanger is sized at 70 kW instead of 60 kW (which occurred during temperature increase fluctuation).
    - However, if the supply temperature decreased, the CU 2 utility is decreased with maintaining the duty of HE 1 heat exchanger. That is similar to the result obtained by the MER-HEO. Thus, the MER-HEO for HE 1 is contributed by the probability of decrease temperature fluctuation to avoid the overdesign of HEN.
2) Cold stream at across Pinch / above Pinch
    - If the supply temperature decreased, the duty of HE 2 heat exchanger is increased and resulted in decreasing the CU 1 utility. The MER-HEM for HE 2 is contributed by the probability of increase temperature fluctuation.
    - For temperature fluctuation at stream C1, additional Q_C savings can be achieved if the HE 2 heat exchanger is sized at 255 kW instead of 240 kW (which occurred during temperature decrease fluctuation).
    - However, if the supply temperature increased, the CU 1 utility is decreasing with maintaining the duty of HE 2 heat exchanger. That is similar to the result obtained by the MER-HEO. Thus, the MER-HEO for HE 2 is contributed by the probability of decrease temperature fluctuation to avoid the overdesign of HEN.

Next, using break-even analysis, we assess the probability of favourable temperature increase or decrease that could potentially lead to more utility savings. This is done to determine if maximising the size of process-to-process heat exchanger is worth the investment as compared to buying a nominal size heat exchanger.

3. Break-even analysis of HEN

The break-even analysis graphically represents the relation between the fixed costs (annualised capital cost of MER-HEM), variable costs (annualised utility cost of MER-HEM) and annualised additional savings (the difference between annualised total cost of MER-HEM and MER-HEO). Break-even point indicates the exact fluctuation probability where the annualised total cost of MER-HEM and MER-HEO are the same, at which the net profit value (NPV) equals to zero (Zhang et al., 2017). Above the break-even point, the difference between the annualised total cost of MER-HEO and MER-HEM lines represented the additional savings if using the MER-HEM. However, below the break-even point, it represented a loss if using the MER-HEM. According to the observations in Section 2, the MER-HEM is preferred for the fluctuations that resulted in decreasing the utility. On the other hand, the MER-HEO is favoured for the fluctuations that resulted in increasing the utility. Thus, the break-even analysis considering the MER-HEM is performed to prevent the overdesign of HEN. The annualised capital cost is calculated using Eq(1) (Na et al., 2015). The annualised utility cost and the annualised total cost for both HEN design options with the assumption of 100 % fluctuation is listed in Table 4.

$$Annualised\ capital\ cost = Annualised\ factor\ \times (1{,}300 + 1{,}000\ A^{0.83}) \tag{1}$$

where the annualised factor is 0.298.

Table 4: Result comparisons of HEN design for fluctuation at stream H1 and C1

	MER-HEO	MER-HEM	MER-HEO	MER-HEM
Stream	Stream H1		Stream C1	
Stream temperature fluctuation	Increase		Decrease	
Probability	1.0		1.0	
Hot utility (kW)	60	50	75	60
Cold Utility (kW)	30	20	200	185
Total affected HE area (m^2)	16.090	19.575	48.217	54.048
Annualised capital cost ($/y)	4,367.10	5,229.20	12,313.40	13,755.50
Annualised utility cost ($/y)	16,186.60	13,281.30	26,977.60	22,619.70
Annualised total cost ($/y)	20,553.70	18,510.50	39.291.00	36,375.20

The probability at which the break-even point occurred can be determined by using Eq(2). The plant is assumed to operate 8,760 h/y. Figure 1 shows the break-even analysis results for the stream H1. The probability at the break-even point for stream H1 is at 0.2691. The probability occurrence of supply temperature stream H1 increased has to be higher than this value if the MER-HEM is to be selected instead of the MER-HEO. Figure 2 shows the break-even analysis results for the stream C1. The probability at the break-even point for stream C1 is at 0.3309. The probability occurrence of supply temperature stream C1 decreased has to be higher than the value and increased fluctuation to gain high savings of annualised utility cost and resulted in a minimum total annualised cost.

$$Probability\ at\ the\ break-even\ point = \frac{Difference\ of\ annualised\ capital\ cost\ between\ MER-HEM\ and\ MER-HEO}{Difference\ of\ annualised\ utility\ cost\ between\ MER-HEM\ and\ MER-HEO} \tag{2}$$

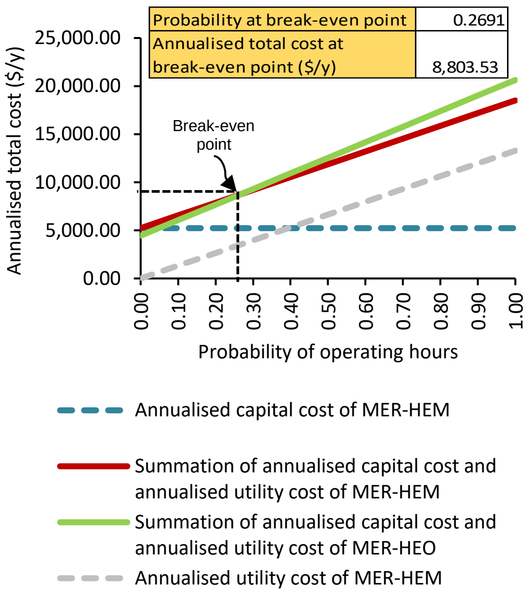

Figure 1: Break-even analysis for stream H1

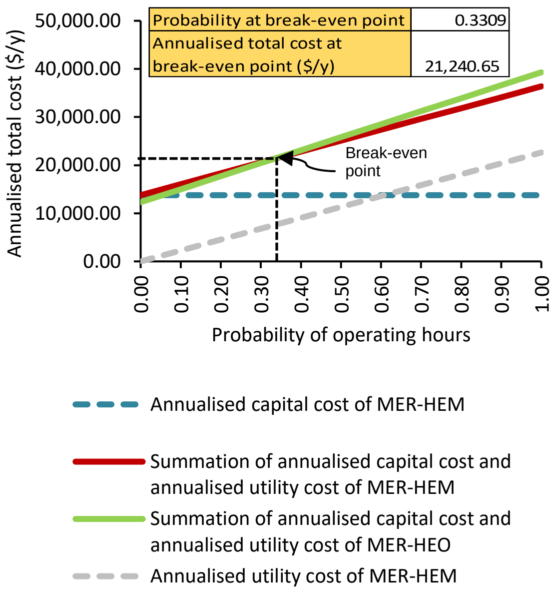

Figure 2: Break-even analysis for stream C1

4. Results and discussion

Two scenarios have been proposed in this work to validate the effect of fluctuation probability on the total annualised cost and the HEN design based on the break-even analysis obtained in Section 3. The probability of either increased or decreased fluctuations of supply temperature at different types and positions of the stream can affect the selection of the optimum HEN design. The plant is assumed to operate at 8,760 h/y and maintained the probability 0.60 of the nominal supply temperature. Two scenarios with the probability occurrence of supply temperature fluctuations are presented below:

- Scenario A: The probability occurrence of supply temperature increased is higher than the probability occurrence of supply temperature decreased.
- Scenario B: The probability occurrence of supply temperature decreased is higher than the probability occurrence of supply temperature increased.

Table 5: Scenario A: High probability occurrence of supply temperature increased

Supply temperature fluctuation	Fluctuation frequency (h)	Probability
Increase	3,495	0.399
Normal	5,256	0.600
Decrease	9	0.001

Table 6: Scenario B: High probability occurrence of supply temperature decreased

Supply temperature fluctuation	Fluctuation frequency (h)	Probability
Increase	9	0.001
Normal	5,256	0.600
Decrease	3,495	0.399

Table 7 summarised the comparisons of stream H1 fluctuation between the MER-HEO and MER-HEM for both Scenarios A and B. For Scenario A, as the probability of increased fluctuation is higher than the probability at the break-even point and the decreased fluctuation, thus, the MER-HEM is the most preferred and optimum. On the other hand, for Scenario B, as the probability of increased fluctuation is lower than the probability at the break-even point and the decreased fluctuation and the MER-HEO would be the best design.

Table 7: Result comparisons with fluctuation probability of HEN design at stream H1

	MER-HEO		MER-HEM	
	Scenario A	Scenario B	Scenario A	Scenario B
Hot utility (kW)	60	60	56.10	59.99
Cold utility (kW)	23.98	16.02	19.99	16.01
Total disturbed HE area (m^2)	16.414		19.575	
Annualised capital cost ($/y)	4,447.30		5,229.20	
Annualised utility cost ($/y)	15,936.70	15,606.30	14,777.50	15,603.40
Annualised total cost ($/y)	20,384.00	20,053.60	20,006.70	20,832.60

On the contrary, for the cold stream, both Scenarios A and B presented opposite results as compared to the hot stream. For Scenario A, the probability of decreased fluctuation at stream C1 is lower than the probability at the break-even point and increased fluctuation. MER-HEO would give the optimum result. However, for Scenario B, the probability of decreased fluctuation is higher than the probability at the break-even point and increased fluctuation. COnsequently, MER-HEM would be the best design. Table 8 compares stream C1 fluctuation between the MER-HEO and MER-HEM for both Scenarios A and B.

Table 8: Results comparisons with fluctuation probability of HEN design at stream C1

	MER-HEO		MER-HEM	
	Scenario A	Scenario B	Scenario A	Scenario B
Hot utility (kW)	54.03	65.97	54.02	59.99
Cold utility (kW)	200	200	199.99	194.02
Total disturbed HE area (m^2)	48.217		54.048	
Annualised capital cost ($/y)	12,313.40		13,755.50	
Annualised utility cost ($/y)	21,755.60	24,728.90	21,751.20	22,990.10
Annualised total cost ($/y)	34,069.00	37,042.35	35,506.70	36,745.60

5. Conclusions

A detailed methodology for the cost optimisation of a flexible HEN design considering the MER and fluctuation probability using break-even analysis is proposed. The break-even analysis (BEA) can directly provide users with the probability of fluctuation occurrence that resulted in a minimum total annualised cost. The BEA can consequently identify the best HEN design of either MER-HEO or MER-HEM at a certain probability of fluctuation occurrence. It can be concluded that the MER-HEM is preferred when the probability occurrence of supply temperature at the hot stream increased or probability occurrence of supply temperature at cold stream decreased is higher than the probability at the break-even point. From the Illustrative Case Study, for the fluctuation at hot stream H1, it shows that MER-HEM is the optimum for Scenario A with the additional savings of 10 % while the MER-HEO is the optimum for Scenario B with the additional savings of 4 %. On the other hand, for cold stream C1, the MER-HEO is the optimum for Scenario A with additional savings of 4 % while the MER-HEM is the optimum for Scenario B with additional savings of 9 %. This proposed method can prevent the overdesign of HEN as well as obtained a flexible HEN with MER.

Acknowledgements

The authors thank Universiti Teknologi Malaysia (UTM) for funding the research presented in this paper via grant Q.J130000.3509.05G96, Q.J130000.2509.19H34, and the Ministry of Education of Malaysia for providing the Fundamental Research Grant Scheme R.J130000.7809.4F918. The authors also acknolwedge the support of EC project for Sustainable Process Integration Laboratory-SPIL (Project No. CZ.02.1.01/0.0/0.0/15_003/0000456) funded by Czech Republic Operational Program Research and Development, Education, Priority 1: Strengthening capacity for quality research in collaboration agreement with Universiti Teknologi Malaysia (UTM).

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