CHEMICAL ENGINEERING TRANSACTIONS

VOL. 72, 2019

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

Guest Editors: Jeng Shiun Lim, Azizul Azri Mustaffa, Nur Nabila Abdul Hamid, Jiří Jaromír Klemeš

ISBN 978-88-95608-69-3; **ISSN** 2283-9216

DOI: 10.3303/CET1972048

Heat Exchanger Network Synthesis Considering Different Minimum Approach Temperatures

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The minimum approach temperature (ΔT_{min}) has been used in the design of heat exchanger networks (HEN) and in energy targeting based on Pinch Analysis. It refers to the minimum allowable temperature difference between a heat source and a heat sink for designing an energy-efficient HEN. Smaller ΔT_{min} can improve process heat recovery but require large heat transfer area and may result in a higher capital cost. Capital-energy trade-off is typically performed to determine the cost-optimum ΔT_{min} during HEN synthesis (HENs). Conventionally, an entire process is analysed to obtain the optimum value of ΔT_{min}. In this work, the capital-energy trade-off is performed using the individual stream temperature versus enthalpy plot (STEP) to obtain an optimum ΔT_{min} for each identified STEP. First, simultaneous area and utility targeting of HEN is performed using the established STEP HEN targeting procedure. The capital-energy trade-off is then analysed separately for every identified STEP. The different values of ΔT_{min} obtained are then applied for the grassroots synthesis of HEN. Application of the proposed procedure on a literature case study shows that the total annualised cost is reduced by 7.03 % when the capital-energy trade-off is performed separately for every STEP as compared to trading-off ΔT_{min} for an entire process.

1. Introduction

Pinch Analysis was introduced for the design of heat exchanger network (HEN) to maximise process heat recovery and minimise utility requirements using the minimum temperature approach (ΔT_{min}) as a key decision variable (Linnhoff and Flower, 1978). Designers typically perform capital-energy trade-off from the relationship between ΔT_{min}, utility, and capital costs before selecting the optimum ΔT_{min} for grassroots HEN design (Heggs, 1989). Linnhoff and Ahmad (1990) demonstrated the combination of energy and area targeting by examining the effect of ΔT_{min} on the utility and capital costs over a range of ΔT_{min} using the conventional Composite Curves (CC). The accuracy of the optimum ΔT_{min} targeting method was improved by considering more detailed capital cost models (Ahmad et al., 1990), mixed materials of construction, pressure ratings and exchanger types (Hall et al., 1990), multiple utilities targeting instead of the highest quality utilities at the end of the CC (Shenoy et al., 1998), as well as including piping cost into the equipment capital cost (Akbarnia et al., 2009). As CC is made up of composite hot and cold curves, it does not represent an individual stream profile that is essential for accurate representation and calculation of capital cost. To overcome the problem, Sun et al. (2013) determined the optimum ΔT_{min} by using the individual stream temperature versus enthalpy plot (STEP) which represents continuous individual hot and cold stream on a shifted temperature-enthalpy diagram (Wan Alwi and Manan, 2010). In contrast to the conventional CC, STEP maintains the representation of individual streams profile to enable direct matching of individual process streams. As the temperature and enthalpy of every heat exchanger is clearly indicated in the STEP graphical tool, capital cost of every heat exchanger can be calculated accurately with consideration of multiple utilities.

Besides graphical approach, mathematical optimisation methods have also been proposed to accurately calculate the heat exchanger capital cost. Kravanja and Glavič (1997) performed simultaneous optimisation of process and HEN by including capital-energy trade-off. More recent work includes the total cost target for HEN synthesis (HENs) which incorporates the pumping power and area effects by Serna-González and Ponce-Ortega (2011). Bakar et al. (2016) selected optimum ΔT_{min} for HENs based on trade-off plot by considering the

Paper Received: 30 March 2018; Revised: 09 July 2018; Accepted: 31 July 2018

Please cite this article as: Lai Y.Q., Wan Alwi S.R., Manan Z.A., 2019, Heat exchanger network synthesis considering different minimum approach temperatures, Chemical Engineering Transactions, 72, 283-288 DOI:10.3303/CET1972048

aspects of design, controllability, and cost. The method was applied on a fatty acid fractionation plant (Bakar et al., 2017). Sun et al. (2017) introduced a superstructure model for optimal HENs to trade-off between the number of shells and tubes with energy consumption. Despite the fact that the development of the capital-energy trade-off methods is trending towards improving the accuracy of the cost calculation, it is realised that the determination and application of the optimum ΔT_{min} is made in the context of an entire process. This work proposes the use of multiple ΔT_{min} for HENs to further optimise the total cost calculation. ΔT_{min} can be obtained by analysing the HEN separately according to the STEPs resulted from the HEN targeting and design methodology by Wan Alwi and Manan (2010).

2. Methodology

A more detailed methodology is proposed to determine the values of ΔT_{min} using STEP. The STEP graphical tool contains information such as the Pinch points, energy targets, shifted temperature, enthalpy, and heat capacity flowrate (FC_p). STEP overcomes the limitation of conventional CC and Grid Diagram which requires iterative calculations to check for enthalpy and temperature feasibility. An example of STEP diagram is as shown in Figure 1. The black curve indicates continuous individual hot streams while the grey curve indicates continuous individual cold streams. Similar to CC, heat is transferred vertically downward from the hot streams to the cold streams, but with the exchanger pairs shown in the diagram. The minimum heating requirement ($Q_{h,min}$) and minimum cooling requirement ($Q_{c,min}$) is shown at the end of the STEPs. As STEP provides clear insight of streams profile, it is further used for area and multiple utility targeting (Sun et al., 2013). This work extends the use of STEP to determine different ΔT_{min} for HENs.

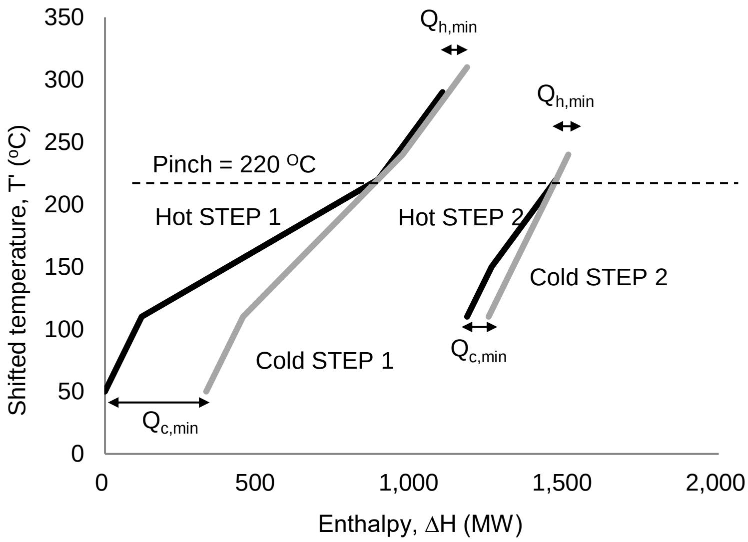

Figure 1: STEP diagram for simultaneous targeting and design (Wan Alwi and Manan, 2010)

Step 1: Perform simultaneous utility and capital cost targeting using the established STEP targeting procedure (Wan Alwi and Manan, 2010)
The first step involves performing multiple utility targeting, calculating the utility and capital costs using the temperature and enthalpy data obtained from the STEP diagram. Detailed procedure is presented in an earlier work (Sun et al., 2013).

Step 2: Construct trade-off diagram to determine optimum ΔT_{min} for each STEP ($\Delta T_{min,STEPi}$) identified from the STEP diagram
Next, a trade-off diagram is constructed to determine the optimum ΔT_{min} for each STEP ($\Delta T_{min,STEPi}$), generated using the targeting methodology by Wan Alwi and Manan (2010). Let i be the number of STEPs. The number of ΔT_{min} values therefore equals the number of STEPs generated. The trade-off diagram can be constructed by plotting the annualised capital and utility costs against a range of ΔT_{min} set for the study. ΔT_{min} which gives the lowest total annualised cost (sum of annualised capital and utility costs) is identified as $\Delta T_{min,STEPi}$. The range of ΔT_{min} differs for every study. The minimum ΔT_{min} can be set by the user and shall be

greater than 0 °C as ΔT_{min} is needed for heat transfer to occur. The maximum ΔT_{min} can be set at a value where further increasing the ΔT_{min} will not decrease the total annualised cost.

Step 3: Apply the $\Delta T_{min,STEPi}$ identified for HENs
After values of $\Delta T_{min,STEPi}$ are identified, the results can be applied in the HEN design. Applying different ΔT_{min} values at each STEP may result in the change of Pinch temperature for the overall process, notably if the value of $\Delta T_{min,STEPi}$ is smaller than the optimum ΔT_{min} for the overall process. Using different ΔT_{min} values for HENs redefines the Pinch temperature and energy targets to result in lower utility and capital costs requirement. The overall methodology proposed in this work is as shown in Figure 2.

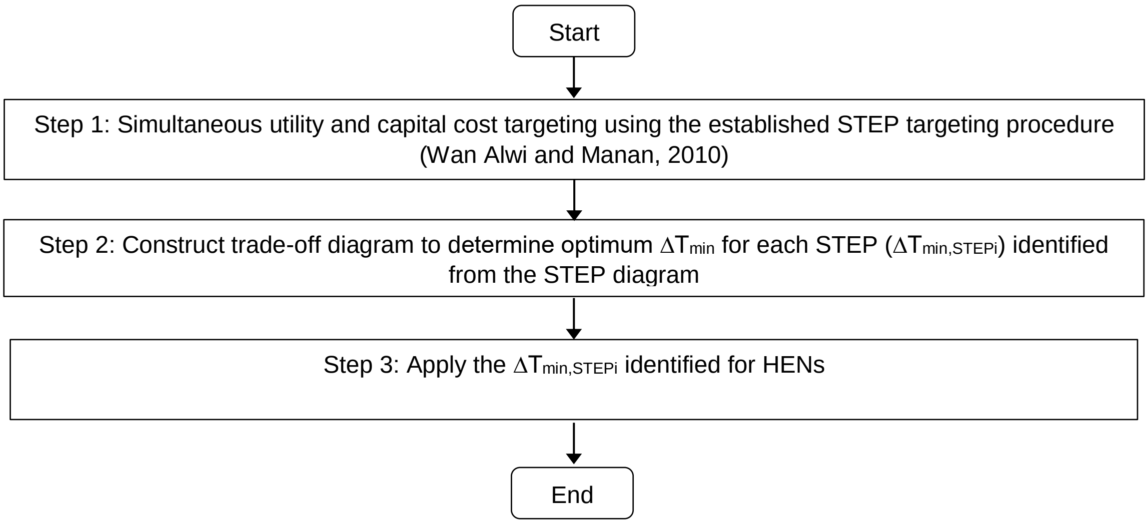

Figure 2: Methodology to identify ΔT_{min} values using STEP

3. Case Study

A literature case study from Wan Alwi and Manan (2010) is used as an illustrative example. The stream data is as shown in Table 1 while the utility data is shown in Table 2. The initial ΔT_{min} given is at 20 °C. Figure 1 shows the constructed STEP diagram. There are two STEPs identified for this process. The utility cost is calculated by using the cheapest utility possible listed in Table 2. For the calculation of capital cost, Eq(1) is applied by assuming that only one construction material is used for the heat exchangers with annualisation factor of 0.322 (Lukman et al., 2016).

$$Annualised\ capital\ cost = Annualisation\ factor \times (1300 + 1000A^{0.83}) \quad (1)$$

where A is the heat exchanger area.

Table 1: Stream data (Wan Alwi and Manan, 2010)

Stream	Supply temperature, T_s (°C)	Target temperature, T_t (°C)	Heat capacity flowrate, FC_p (kW/°C)	Enthalpy, ΔH (kW)
H1	300	160	2.5	-350
H2	230	100	6	-780
H3	160	60	2	-200
C1	40	230	2	380
C2	100	230	4	520
C3	200	230	2	60

After that, trade-off diagram is constructed for STEP 1 and STEP 2 using the capital and utility costs calculated. ΔT_{min} which gives the lowest total annualised cost at each STEP is identified as $\Delta T_{min,STEPi}$. The minimum ΔT_{min} for this study is set at 5 °C. Figure 3a and 3b show the trade-off diagram for STEP 1 and STEP 2. For STEP 1, the maximum value of ΔT_{min} is set at 50 °C after the lowest total annualised cost is identified at $\Delta T_{min,STEP1}$ of 30 °C. For STEP 2, the total annualised cost shows an increasing trend with increasing ΔT_{min}. The maximum ΔT_{min} value is set at the initial ΔT_{min} value of 20 °C since further increasing the ΔT_{min} will not result in lower total annualised cost. The lowest total annualised cost for STEP 2 is identified at $\Delta T_{min,STEP2}$ of 5 °C. After determining $\Delta T_{min,STEPi}$, the values are applied for the HEN design.

Table 2: Utility data

Utility	Supply temperature, T_s (°C)	Target temperature, T_t (°C)	Annualised cost (USD/y.kW)
Hot oil	330	300	10
High pressure steam	255	254	70
Medium pressure steam	205	204	50
Chilled water	20	25	20
Cold water	30	40	10
Cooling air	40	65	5

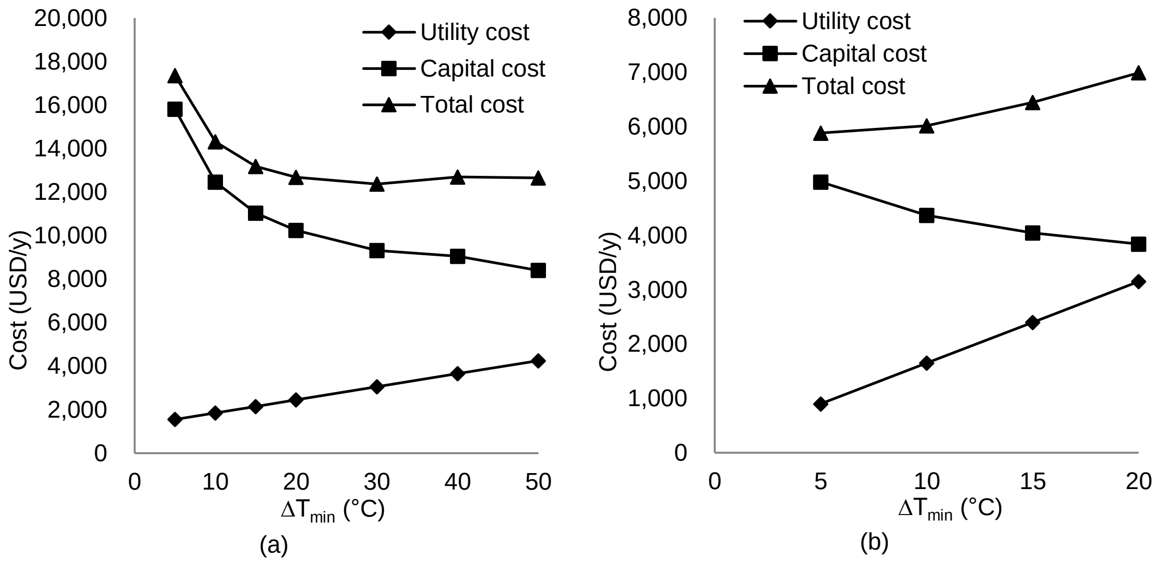

Figure 3: Trade-off diagram for (a) STEP 1 and (b) STEP 2

4. Results and Discussion

The total annualised cost for the HEN design using the two $\Delta T_{min,STEPi}$ determined is calculated by adding the total annualised cost needed at STEP 1 using $\Delta T_{min,STEP1}$ of 30 °C (refer Table 3), and $\Delta T_{min,STEP2}$ of 5 °C at STEP 2 (refer Table 4).

Table 3: Annualised cost for STEP 1

ΔT_{min} (°C)	Utility cost (USD/y)	Capital cost (USD/y)	Total cost (USD/y)
5	1,550	15,807	17,357
10	1,850	12,461	14,310
15	2,150	11,030	13,180
20	2,450	10,234	12,684
30	3,050	9,316	12,366
40	3,650	9,046	12,696
50	4,250	8,397	12,647

The optimum ΔT_{min} value for the overall process is determined for the purpose of comparison. The trade-off diagram for the overall process in Figure 4 shows the optimum ΔT_{min} at 15 °C. The total annualised cost needed when different ΔT_{min} is applied for HENs is then compared with the total annualised cost needed when only one ΔT_{min} is applied for HEN design (refer Table 5). In this case study, the total annualised cost is reduced by 7.03 % when two values of ΔT_{min} are applied for HENs.

Table 4: Annualised cost for STEP 2

ΔT_{min} (°C)	Utility cost (USD/y)	Capital cost (USD/y)	Total cost (USD/y)
5	900	4,982	5,882
10	1,650	4,366	6,016
15	2,400	4,047	6,447
20	3,150	3,839	6,989

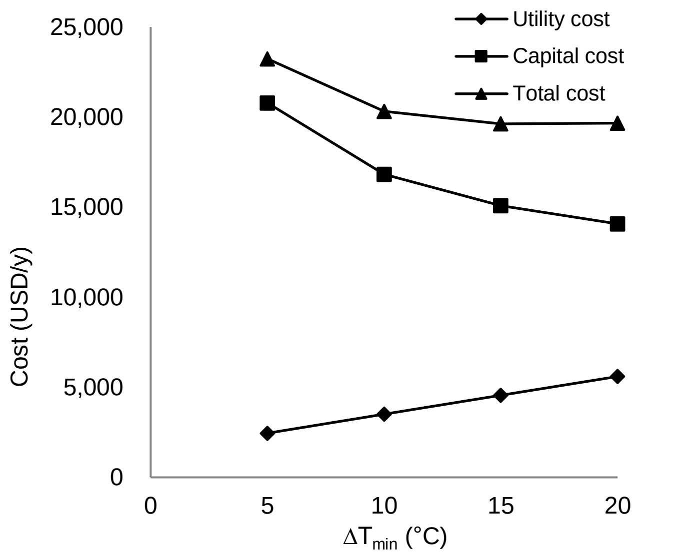

Figure 4: Trade-off diagram for overall process

Table 5: Comparison of results

ΔT_{min}	Total annualised cost (USD/y)
Using only 15 °C	19,627
Using 30 °C for STEP 1 + 5 °C for STEP 2	18,248

The results obtained from this work show the ability of STEP to be used for more detailed energy and area targeting. There is the possibility that the total annualised cost can be reduced when the process is analysed in a segmented way as compared to performing capital-energy trade-off for the entire process. When a given process is analysed separately according to the different STEPs identified, multiple values of ΔT_{min} can be obtained. The result can be more precise when the different ΔT_{min} are applied for HENs. The proposed method recommends the use of larger ΔT_{min} values at some parts of the HEN so that bigger driving force can result in smaller area requirement while maintaining energy target at an acceptable level. The possibility of using different ΔT_{min} values is hindered when the entire process is analysed. Detailed representation of STEP diagram enables a given process to be divided into a few CC-like STEPs. Capital-energy trade-off can be performed by analysing the STEPs individually. It is suggested that future research can be done to determine ΔT_{min} for every heat exchanger using STEP to further improve the accuracy of the energy and area targeting methods.

The cost reduction for using STEP for capital-energy trade-off differs from case to case. There is also the possibility that no reduction can be achieved after analysing the process separately. However, the benefit of STEP over the conventional methods is that STEP enables the use of different ΔT_{min} at some parts of the HEN, which may reduce the total annualised cost required to implement the design. In terms of the complexity of the method, although multiple trade-off diagrams are needed to determine $\Delta T_{min,STEPi}$, the process of calculating the capital and utility costs remains the same. The multiple trade-off diagrams are constructed by just plotting the graphs separately according to the STEPs generated.

5. Conclusions

An improved methodology for energy and area targeting using STEP has been proposed to determine unique ΔT_{min} values for HENs. Optimum ΔT_{min} is determined for every STEP identified from the STEP diagram, generated from the STEP HEN design procedure. This is done by constructing the trade-off diagram separately for each STEP. Application of the unique ΔT_{min} values yields improved overall HEN performance. This new methodology enables a given process to be analysed more accurately, provides the process more flexibility and further reduces the total annualised HEN cost. This work can be the basis for future work to explore on the effect of using different ΔT_{min} on the performance of HEN.

Acknowledgments

The authors gratefully acknowledge the financial support from the Universiti Teknologi Malaysia (UTM) Research University Grant under Vote No. Q.J130000.2508.17H16.

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