CHEMICAL ENGINEERING TRANSACTIONS
VOL. 75, 2019
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Sauro Pierucci, Laura Piazza

ISBN 978-88-95608-72-3; **ISSN** 2283-9216
DOI: 10.3303/CET1975105

Retrofitting Design of Heat Exchanger Networks Using Supply-Target Diagram

Mohammad A. Taher Al-Mayyahi[a,*], Firas A. Albadran[a], Mohammad N. Fares[b]

[a]Department of Chemical and Petroleum Refining Engineering, College of Oil and Gas Engineering, Basra University for Oil and Gas, Basra, 61004, Iraq
[b]Department of Chemical Engineering, College of Engineering, Basra University, Basra, 61004, Iraq
moh1973may@gmail.com

Energy saving is an important issue in process industries due to the increasing cost of energy and associated environmental pollution. Retrofitting of existing Heat Exchanger Networks (HENs) is a key solution to maintain their energy efficiency and minimize utilities consumption. Several graphical methods have been developed for retrofitting design of HENs during the last few years. However, some of these methods are tedious and often leads to complex and uneconomic retrofit. This paper presents a simple graphical retrofit method to cut utility consumption of existing HENs. The new retrofitting method uses a single graph called Supply-Target Diagram (ST-D) to identify and represent potential modifications in existing HENs. A case study is used to illustrate the application of the new graphical method for a retrofitting design of an existing HEN. The addition of two exchangers using the new graphical method shows that heating and cooling utilities can be reduced by 18.75% and 40% respectively.

1. Introduction

Global demand for energy has been increasing considerably due to the continuous growth in the global economic. The increase in the energy consumption and its environmental, economic and societal effects has created escalating global concern regarding the efficiency of energy use of the energy-intensive industries. For the sake of efficient grassroots and retrofitting design of energy systems, many graphical and mathematical techniques have been developed. Process Integration, which was introduced by Linnhoff and Flower (1978) has been used extensively on increasing energy efficiency of processing systems. The technique which also called pinch analysis, was first introduced to analyse energy flows in process heat exchanger networks based on the second law of thermodynamics which states that heat can only flow from higher temperatures (sources) to lower temperatures (sinks), (Boland and Linnhoff, 1979). Pinch analysis uses graphics and tables to provide a good overview of processes to the designer. The most popular graphical and tabular tools are Composite curve (CC), grand composite curve (GCC), Problem Table Algorithms, and Grid diagram. The Composite Curve (CC) is formulated by plotting temperatures versus enthalpies of process streams to identify utilities targets and pinch temperature. Grand composite curve (GCC) is produced by plotting the net heat-flow of a process at different temperatures. The GCC helps in identifying regions where external heating and cooling utilities are required. Problem Table is used for algebraically setting heating and cooling targets.
For designing and analysing heat exchanger network (HEN), typical grid diagrams (GDs) was introduced by Linhoff and flower (1978). Since GDs was introduced, many graphical methods have been developed for synthesizing and retrofitting of HENs. Lakshmanan and Bañares-Alcántara (1996) introduced a graphical diagram called Thermodynamic Diagram (RTD) using both the driving forces and loads of streams to analyse and retrofit existing HENs. A graphical technique based on several curves was introduced by Nordman and Berntsson (2001) to determine the investment cost associated with the changes in heating and cooling of HEN. Osman et al. (2009) proposed a retrofitting graphical method based on the path analysis approaches that allow increasing the heat transfer area without any structural changes on the existing HEN. Wan Alwi and Abd Manan (2010) developed a graphical method based on the stream temperature versus enthalpy plot

Paper Received: 20 March 2018; Revised: 17 September 2018; Accepted: 14 February 2019

Please cite this article as: Al-Mayyahi M., Albadran F.A., Fares M.N., 2019, Retrofitting Design of Heat Exchanger Networks Using Supply-target Diagram, Chemical Engineering Transactions, 75, 625-630 DOI:10.3303/CET1975105

(STEP). The STEP used to determine energy targets, pinch points and optimal HEN design. Grid Diagram Table (GDT) was introduced by Abbood et al. (2012) for the retrofitting of HENs and determination of pinch points and utility targets. The GDT combines graphical and numerical tools into a single diagram. Gadalla et al. (2016) developed the temperature driving force (TDF) method for retrofitting of existing heat exchanger networks (HENs). Lai et. al. (2017) used the STEP technique for analysing and retrofitting of existing HENs. Recently, Yeo et. al. (2017) extended the application of STEP method to involve phase changes.
However, even though these graphical methods offer good visualization techniques for design and retrofitting of HENs, most of them are rather cumbersome to manually construct. Others such as GDs are sometimes tedious and hard to follow due to the lack of visualization regarding temperatures intervals of streams.
This paper presents a new and simple graphical approach for HEN retrofitting design. The new approach based on a single graph called Supply-Target Diagram (ST-D). The ST-D is formulated by plotting supply temperatures versus target temperatures of streams. Streams matching can easily be applied in the ST-D and stream splitting is clearly visualized and applied. A case study will be used to illustrate the application of the new graphical method for retrofitting design of HENs.

2. Supply-Target Diagram (ST-D)

The new graphical method uses a single diagram called supply-target diagram (ST-D) in the grassroots and retrofit design of HENs. The ST-D is produced by plotting supply temperatures versus target temperatures of streams on the Y-axis and X-axis respectively. Then, streams matching can be directly done in the ST-D by matching corresponding hot and cold streams. Matching constraints like cross-pinch and temperature feasibility can be easily observed. This makes the ST-D a powerful tool for HENs representation for both new and retrofit designs.
Process streams can be represented in ST-D as follows:
Consider a hot stream with supply and target temperatures equal to T_{SH} and T_{TH} respectively, and a cold stream with supply and target temperatures of T_{SC} and T_{TC} respectively,
Then,

$$Q_H = CP_H(T_{TH} - T_{SH}) \tag{1}$$

And,

$$Q_c = CP_H(T_{TC} - T_{SC}) \tag{2}$$

Where; Q_H is the heat load of the hot stream, CP_H is the heat capacity of the hot stream. Q_C is the heat load of the cold stream, and CP_C is the heat capacity of the cold stream, see Figure1a.
From equation (1) and (2) we can get,

$$T_{SH} = \left(\frac{Q_H}{CP_H}\right) + T_{TH} \tag{3}$$

$$T_{SC} = \left(\frac{Q_C}{CP_C}\right) + T_{TC} \tag{4}$$

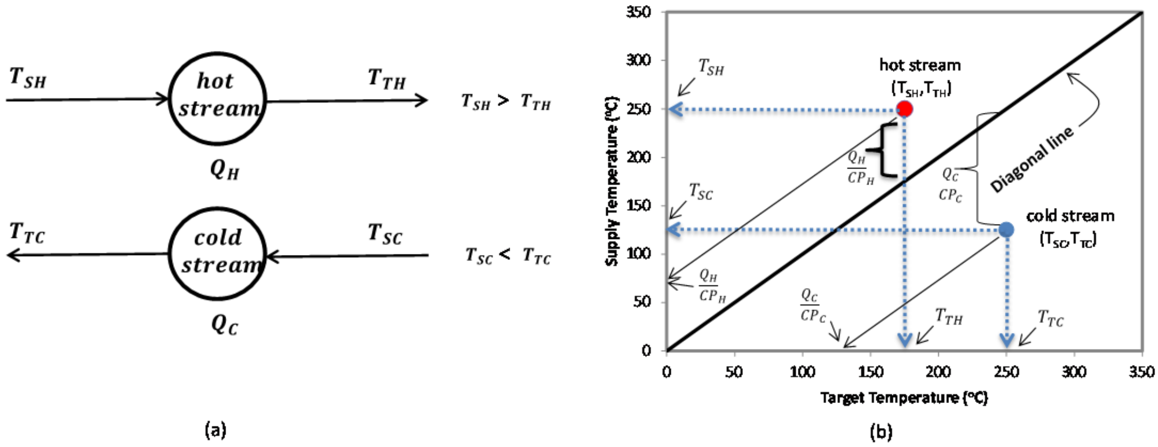

Figure 1: (a) hot and cold streams, (b) Representation of hot and cold streams on ST-D

As shown in Figure 1b, each hot and cold stream can be represented on Supply-Target Diagram (ST-D) as a point using supply (T_S) and target (T_T) temperatures of the stream as Y-coordinate and X-coordinate respectively.

It can be seen from Figure 1b that when drawing a line parallel to the main diagonal line starting from hot and cold streams, the line intercepts y-axis and x-axis at values equal to $\frac{Q_H}{CP_H}$ for hot stream and $\frac{Q_C}{CP_C}$ for cold streams. Alternatively, these values can be read from the vertical or horizontal distance between the stream and the diagonal line respectively, as it shown in Figure 1b. Furthermore, the ST-D shows that all hot streams are represented above the main diagonal line while cold streams are located below this line.

2.1. Regions of Supply-Target Diagram (ST-D)

The ST-D is divided into 6 regions as it shown in Figure 2a:

Region 1: this region is for all hot streams that their supply and target temperatures are below the pinch temperature.

Region 2: this region is for all hot streams that their supply temperatures are above the pinch temperature but their target temperatures are below the pinch temperature. Hot streams at this region are located cross pinch temperature.

Region 3: this region is for all hot streams that their supply and target temperatures are above the pinch temperature.

Region 4: this region is for all cold streams that their supply and target temperatures are above the pinch temperature.

Region 5: this region is for all cold streams that their supply temperatures are below the pinch temperature but their target temperatures are above the pinch temperature. Cold streams at this region are located cross pinch temperature.

Region 6: this region is for all cold streams that their supply and target temperatures are below the pinch temperature.

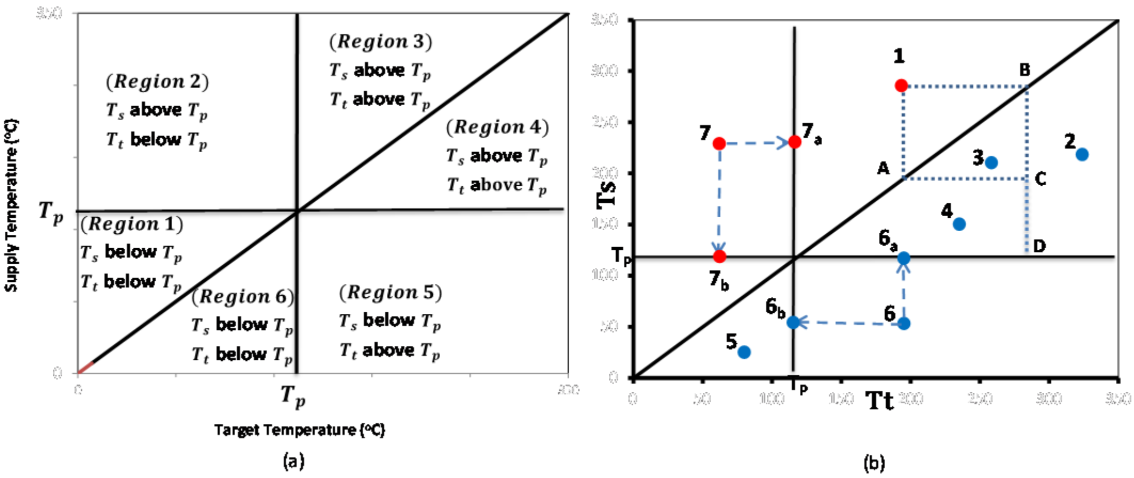

Figure 2: (a) ST-D Regions. (b) Streams matching rules

2.2. Streams Matching Rules

Each heat exchanger can be represented in the ST-D by a line connecting two streams, a hot and cold stream. These two streams must have the same heat load and their temperature differences must not violate minimum temperature approach. In order to minimize utilities consumption and meet minimum energy targets, heat exchanger should not be matched across the pinch line. For the purpose of illustration, Figure 2b shows seven streams, two hot and five cold. It can be seen that:

1. The hot stream 1 cannot be matched to any cold stream located to the right of the dotted line BD (such as stream 2) because it will violate the minimum temperature approach, i.e. supply and target temperatures of any cold stream are higher than target and supply temperatures of the hot stream 1 respectively.
2. Similarly, the hot stream 1 cannot be matched to any cold stream located above the dotted line AC (such as stream 3) because it will violate the minimum temperature approach, i.e. supply temperature of any cold stream is higher than target temperature of the hot stream 1.

3.The hot stream 1 can be matched to any cold stream, with same heat load, located below the dashed line AC, as shown in Figure 2b due to the minimum temperature satisfaction at both ends of any potential heat exchanger.
4.Both cold stream 6 and hot stream 7 are located cross pinch temperature, Tp. Therefore, they can be split into two streams (regions), below and above pinch point, (6a and 7a) and (6b and 7b) respectively, as shown in Figure 2b.

2.3. Representation of segmented streams in the ST-D

Often in the heat exchanger networks, streams have to be matched in a segmented way due to the large heat duty required by single steams or because of that the heat duty required can only be supplied by multiple streams. Figure 3 illustrates the representation of a segmented cold stream. Figure 3b shows that the segmented stream (**Sm**) can easily be represented in the ST-D following the path (blue arrows) shown in the Figure 3b and based on the heat duty of each segment or temperature difference as it sown in equations (5) and (6).

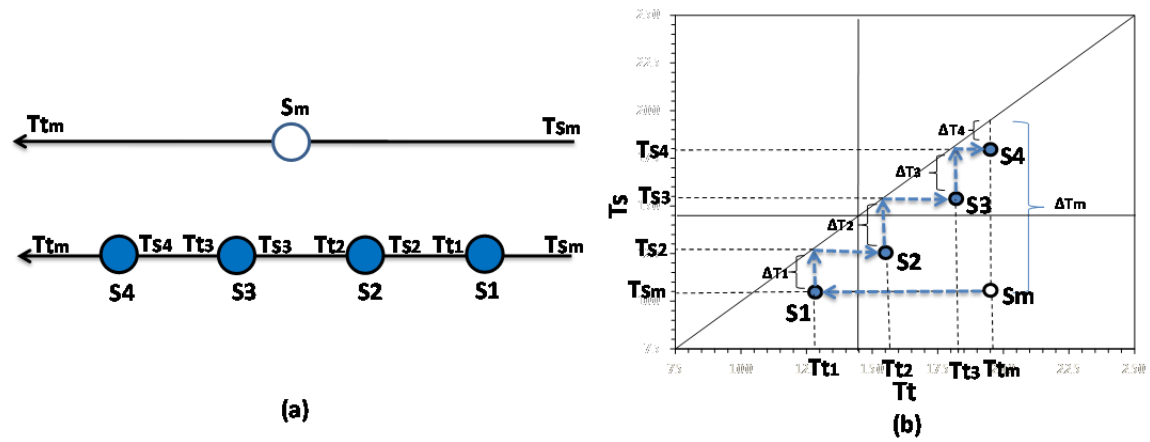

Figure 3: Segmented streams (a) Grid diagram representation (b) ST-D Representation

$$\Delta T_m = \Delta T_1 + \Delta T_2 + \Delta T_3 + \Delta T_4 \quad (5)$$

$$\frac{Q_m}{CP} = \frac{Q_1}{CP} + \frac{Q_2}{CP} + \frac{Q_3}{CP} + \frac{Q_4}{CP} \quad (6)$$

3. Illustrative Case study

The ST-D can be used to identify and represent potential modifications in existing HENs. Pinching matches and network pinch are easy to locate using the ST-D. In order to maximize heat recovery of an existing network at given conditions, topology modification can be conducted to eliminated pinch matches and reduce requirement for heating and cooling utilities. Topology modification could include rearrangement of existing exchangers to re-sequence exchangers in parallel or in series, introducing new exchangers between streams that have not been matched and elimination of exchangers. An existing HEN given by Asante and Zhu (1997) is considered as a case study for the purpose of illustration of the new graphical approach.

Figure 3a is the grid diagram representation of the HEN. The latter consists of three heat exchangers, two coolers and a heater. Figure 4b is the ST-D representation of the network. The ST-D is plotted using shifted temperatures with a minimum temperature difference of 10 ^{o}C. The hot pinch temperature is obtained by a horizontal line at 145 ^{o}C and the cold pinch temperature is represented by a vertical line at 145 ^{o}C. The hot stream of each heat exchanger is represented as a sold circle (red) above the diagonal line using supply and target temperatures of hot streams, T_{SH} and T_{TH}, respectively. On the other hand, the cold streams are represented as sold circles (blue) below the diagonal line using supply and target temperatures of cold streams, T_{SC} and T_{TC} respectively. Heat exchangers, HE1, HE2, and HE3 are represented as lines match between the corresponding hot and cold streams. The heater, H1 (160MW) is represented by a sold circle (blue) whilst the two coolers, C1 (20MW) and C2 (30MW), are represented as solid circles (red).

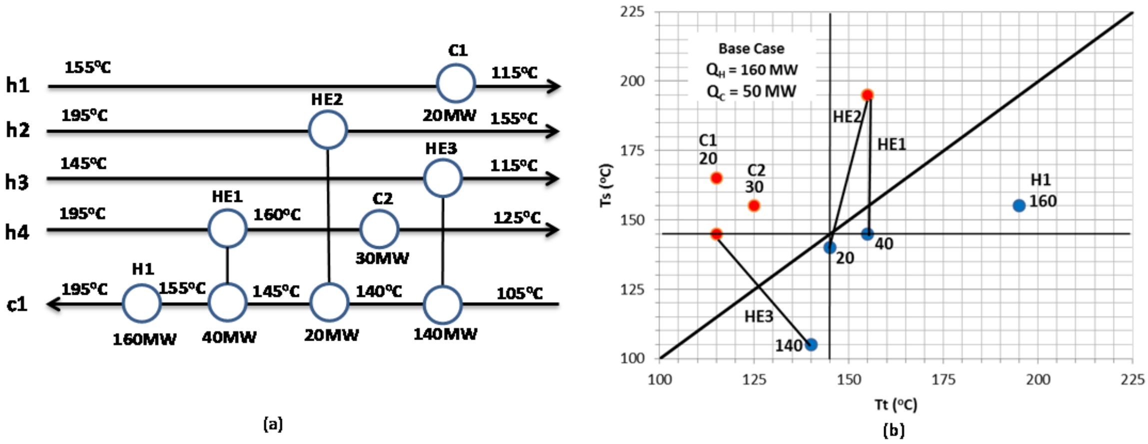

Figure 4: (a) Grid diagram representation (b) ST-D Representation

The application of pinch analysis principles shows that minimum hot and cold energy targets are 125 and 15MW respectively (Asante and Zhu, 1997). It is clear that the heat exchanger network is below the optimum design where the existing hot and cold utilities are 28% and 233% respectively higher than the optimum.

The investigation of Figure 4b shows that there is a cross pinching match at HE2 as it crosses the hot pinch line. Furthermore, possibility for adding new heat exchangers can be easily determined from Figure 4b. It can be seen that HE1 (140MW) can be shifted up by 20MW as shown in Figure 4b. This provides heating duty equal to 20MW below HE1 which can be matched with hot stream C1 (20MW). The new heat exchanger obtained is called HE4. Consequently, HE2 and HE3 have to be shifted up by 20MW as it shown in Figure 5a. Finally, the heater H1 is shifted up by 20MW with remaining heating load of 140MW, Figure 5a. The addition of HE4 reduces both heating and cooling duties by 20MW. Furthermore, by shifting HE2 up by 20MW, the pinching match has been avoided, see Figure 5a.

Further investigation of the network in Figure 5a shows that there is a possibility to provide 20MW by shifting HE2 and HE3 up. However, maximum heat load can be withdrawn from the hot stream of C2 (30MW) is 10MW as it shown in Figure5b. Therefore, the heating load of C2 (30MW) is split into two streams, 20 and 10 MW as it shown in Figure 5b. Then, another exchanger with heat load of 10MW is added between HE1 and HE2 as it presented in Figure 5b. The new exchanger is called HE5. Consequently, HE2 and HE3 are shifted up by 10MW as it shown in Figure 5b. The remaining heat load of H1 is reduced to 130MW which is also shifted up by 10MW, see Figure 5b.

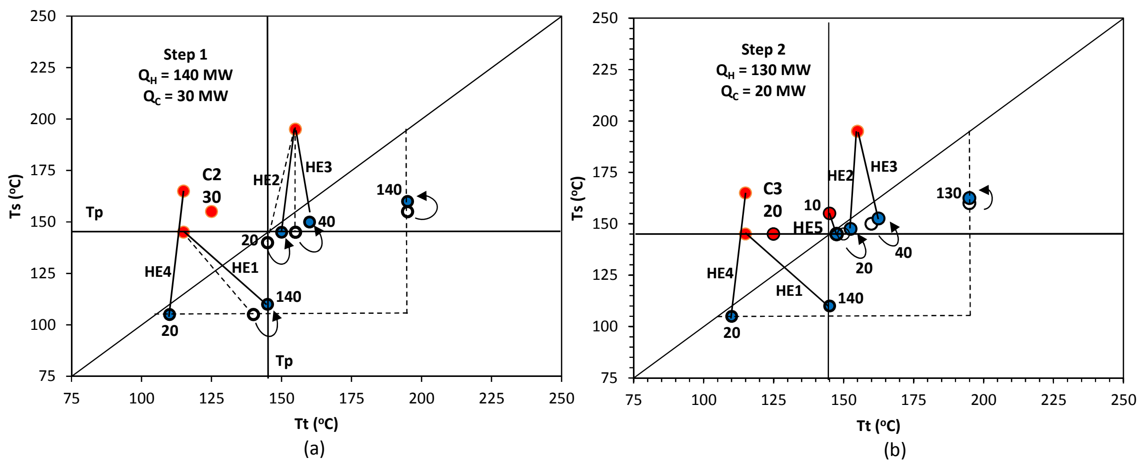

Figure 5: (a) The addition of HE4 (b) The addition of HE5

Figure 6a shows the grid diagram representation of the retrofitted network whilst Figure 6b is the ST-D representation of the HEN. The final form of the network consists of five heat exchangers, one heater and one cooler. The heating duty is 130MW and cooling duty is 20MW.

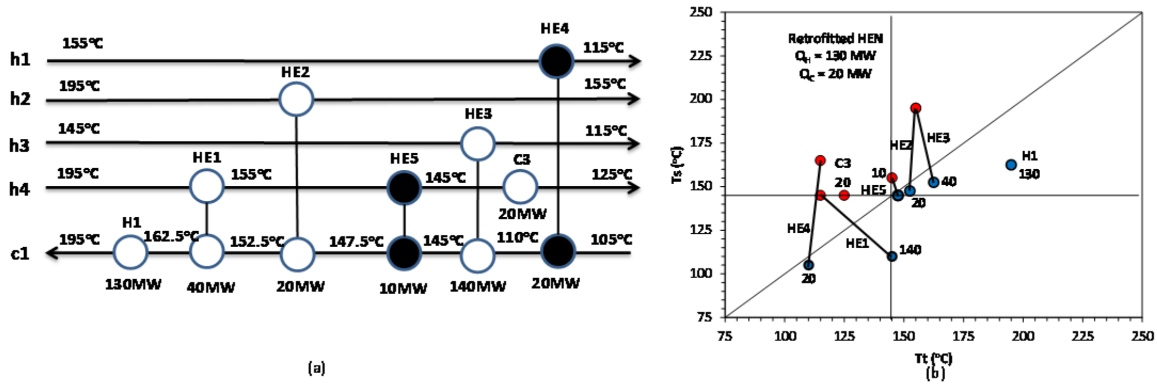

Figure 6: Retrofitted HEN (a) Grid diagram representation (b) ST-D representation

4. Conclusions

A new graphical method is presented in this paper for retrofitting design of HENs using a single diagram called Supply-Target Diagram (ST-D). The ST-D is formulated by plotting supply versus target temperatures of streams. Potential retrofitting steps can be easily investigated and represented in the ST-D. Possible retrofitting strategies include streams' splitting, exchangers re-sequencing, addition and elimination of exchangers. A case study is used to illustrate the application of the new graphical method for retrofitting design of HENs. The application of the new graphical method shows that it is possible to cut 18.75% and 40% of heating and cooling utilities respectively by adding two exchangers to the existing HEN.

References

Abbood NK, Manan ZA, Wan Alwi SR., 2012, A combined numerical and visualization tool for utility targeting and heat exchanger network retrofitting, Journal of Cleaner Production, 23, 1-7

Asante NDK, Zhu XX. 1997, An automated and interactive approach for heat exchanger network retrofit, Trans IChemE, 75, 349

Boland D, Linnhoff B., 1979, The preliminary design of networks for heat exchange by systematic methods. Chem. Eng. 222.

Gadalla MA., 2015, A New Graphical Method for Pinch Analysis and Energy Integration, Chemical Engineering Transactions, 43, 1291-1296.

Lai YQ, Manan ZA, Wan Alwi SR., 2017, Heat Exchanger Network Retrofit Using Individual Stream Temperature vs Enthalpy Plot, Chemical Engineering Transactions, 61, 1651-1656.

Lakshmanan R, Bañares-Alcántara R., 1992, A Novel Visualization Tool for Heat Exchanger Network Retrofit, Ind. Eng. Chem. Res., 35, 4507-4522.

Linnhoff, B., Flower, J.R., 1978, Synthesis of heat exchanger networks - 1. Systematic generation of energy optimal networks. AIChE Journal 24 (4), 633-642.

Nordman R, Berntsson T., 2001, New Pinch Technology Based HEN Analysis Methodologies for Cost-Effective Retrofitting, Can. J. Chem. Eng., 79(4), 655-662.

Osman A, Abdul Mutalib MI, Shuhaimi M, Amminudin KA., 2009, Paths combination for HENs retrofit, Applied Thermal Engineering, 29(14–15), 3103-3109.

Wan Alwi SR, Abd Manan Z., 2010, STEP—A new graphical tool for simultaneous targeting and design of a heat exchanger network, Chemical Engineering Journal,162, 106-121.

Yeo Y.S., Wan Alwi S.R., Ahmad S., Abd Manan Z., Zamzuri N.H., 2017, A new graphical method for heat exchanger network design involving phase changes, Chemical Engineering Transactions, 56, 1249-1254.