CHEMICAL ENGINEERING TRANSACTIONS

VOL. 52, 2016

A publication of AIDIC

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

Guest Editors: Petar Sabev Varbanov, Peng-Yen Liew, Jun-Yow Yong, Jiří Jaromír Klemeš, Hon Loong Lam

ISBN 978-88-95608-42-6; **ISSN** 2283-9216

DOI: 10.3303/CET1652057

Revamping of Heat Exchanger Network of an Egyptian Refinery Plant using New Temperature Driving Force (TDF) Graphical Technique

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This paper introduces a new graphical approach for revamping of existing heat exchanger networks (HENs) based on pinch analysis rules. The HEN is represented on a simple graph, where the cold stream temperatures are plotted on the X-axis against the driving forces for each exchanger plotted on the Y-axis. This graphical technique can describe the energy analysis problems in term of temperature driving force inside the heat exchanger, which is an important factor in the revamping process as the differences in these driving forces are involved in calculating the area of heat exchangers, and consequently affecting the revamping cost. Also, each exchanger is represented in this graph as a straight line with a slope related to the heat capacity flows and length as function of the heat duty. An algorithm for revamping is also proposed.

The temperature driving force new representation is applied on an existing HEN in an Egyptian refinery (EORU) to boost its energy efficiency. The graphical revamping in application on the HEN shows savings of approximately 10 % in the energy demand with minor structural modifications.

1. Introduction

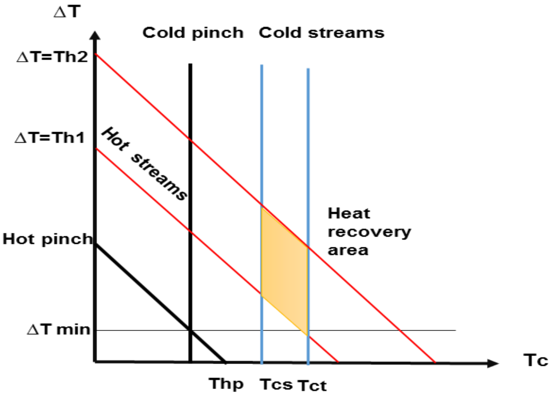
Process integration is an approach that considers the process as one unit, and exploits the interaction between the process units rather than optimizing them separately. Such integration takes place in the crude oil preheat train to reduce the energy consumption on the furnace. Pinch analysis is a very important method of process integration; it was developed in late seventies by of Hohman (1971), Linnhoff and Flower (1978), Linnhoff and Hindmarsh (1983) and Umeda (1983). The pinch analysis aims to identify the opportunities of heat recovery between different heat sources and heat sinks in the plant. For the last 40 years many researchers have worked on developing the techniques of revamping of existing HENs. Asante et al. (1997) were able to establish a new approach for revamping of HENs known as the network pinch approach. In this technique, the bottlenecks which are considered as the restrictions for heat integration are recognized and accordingly modifications are recommended to improve the integration within the existing HEN. This technique was adjusted by Bedard and Bakhtiari (2013) to take into consideration the effect of stream splitting and segmentation. Recently, Gadalla (2015) introduced a graphical approach for the revamping of HENs, the approach represents each heat exchanger graphically and provides the positions of the network inefficiencies. On the other hand, the work does not consider neither the driving force nor the individual areas of each heat exchanger.

This paper presents a new approach that provides a visual representation for each heat exchanger, indicating the position of inefficiencies, and temperature driving forces in every exchanger. This will consequently provide a visual indicative for the area of heat transfer. The approach is applied to an existing refinery in Egypt (EORU) to reduce the overall energy consumption.

Please cite this article as: Kamel D. A., Gadalla M. A., Ashour F. H., 2016, Revamping of heat exchanger network of an egyptian refinery plant using new temperature driving force (tdf) graphical technique, Chemical Engineering Transactions, 52, 337-342 DOI:10.3303/CET1652057

2. New graphical approach for HEN analysis

The new graphical technique uses the same principles of pinch analysis. In this approach, an existing HEN is described graphically as the driving force of the exchanger is plotted on the Y-axis and the cold temperature of the streams is plotted on the X-axis, as shown in Figure 1. The driving force of heat exchangers is divided into two parts: the hot end driving force (ΔThe) which is the difference between the supply hot temperature (Ths) and the target cold temperature (Tct), while the cold end driving force (ΔTce) is the difference between the target hot temperature (Tht) and the supply cold temperature (Tcs).



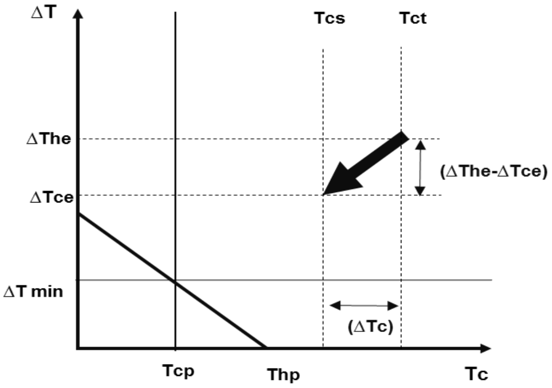


Figure 1: Streams graphical representation

Figure 2: Graphical representations of an exchanger

For an energy analysis problem, Figure 1 provides the representation of temperature driving forces in exchanger units versus temperature of cold streams flowing through these exchangers. Every point in the graph has two coordinates, one showing the temperature driving force across the exit or inlet of an exchanger versus the corresponding cold temperatures. Characterizations of the new graphs are summarized below:

1) The cold stream lines are represented as vertical lines starting at Tc on the X-axis, while the hot stream lines are represented as inclined straight lines starting from ΔT = Th on the Y-axis (Tc=zero) and ending at Tc=Th on the X-axis (ΔT = zero) as shown Figure 1.
2) The cold pinch temperature is represented as a vertical line at Tc = Tcp.
3) The hot pinch temperature is represented as an inclined line connected between the points (0, Thp) and (Thp, 0).
4) All hot streams are parallel to the hot pinch line, and at the same time all cold streams are parallel to the cold pinch line.
5) ΔTmin is represented as horizontal line starting at $\Delta T = \Delta T_{min}$.
6) Each point in the graph is the locus of the temperature driving force, the hot temperature and the cold temperature.
7) Assuming constant heat capacities for process streams, each exchanger can be represented by a straight line drawn between (Tcs, ΔTce) and (Tct, ΔThe) as shown in Figure 2.
8) The slope of the exchanger is determined as the ratio between the difference in the driving force and the difference in the cold temperature for a certain stream which is involved in the heat transfer process.

$$S=\frac{\Delta T_{he}-\Delta T_{ce}}{\Delta T_c} \tag{1}$$

By applying the above definition of temperature driving force in Eq(1);

$$S=\frac{\Delta T_h-\Delta T_c}{\Delta T_c} \tag{2}$$

Since the duties calculated for a certain exchanger, therefore Eq(3) represents a relation between the heat flow and the temperature difference;

$$\frac{CP_c}{CP_h}=\frac{\Delta T_h}{\Delta T_c} \tag{3}$$

Finally, the slope can be related with the ratio of heat flow as seen from Eq(4);

$$S=\frac{CP_c}{CP_h}-1 \tag{4}$$

Similarly, the length of the exchanger straight line, L, can be determined as follows from Eq(5):

$$L=Q\sqrt{(\frac{1}{CP_h})^2+\frac{2}{CP_h*CP_c}+(\frac{1}{CP_c})^2} \quad (5)$$

Since the heat capacity flows for certain hot and cold streams is assumed constant, the length of the heat exchanger line will be proportional to its heat duty.

9) The graph is divided into 5 regions according to the pinch analysis principals as shown in Figure 3:

- Region 1 is below both the hot and cold pinch temperatures; therefore it is the optimum region for heat exchangers and coolers.
- Region 2 is above the hot pinch temperature yet below the cold pinch temperature, therefore it is the non-optimum region for heat exchangers as it opposes the pinch rules (i.e. crossing the pinch).
- Region 3 is above both the hot and cold pinch temperatures; therefore it is the optimum region for heat exchangers and heaters.
- Region 4 is below the ΔT = Zero line so the presence of any heat exchanger in this region is infeasible.
- Region 5 is below the hot pinch temperature but above the cold pinch temperature, therefore it is the non-optimum region for heat integration.

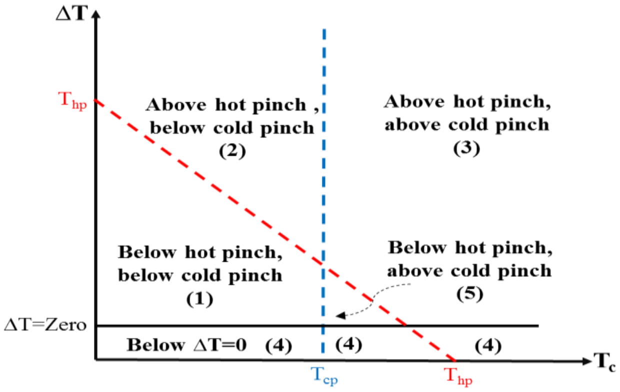


Figure 3: Graphical representation of feasible regions for heat integration.

3. Procedure of HEN revamping

The new approach together with its valuable features will allow the graphical revamping of a HEN by visual identification of the misallocated coolers, exchangers, paths and loops for the existing HEN, and suggesting appropriate steps for the revamping procedure. A systematic procedure for revamping existing heat exchanger networks train is presented in the form of algorithm in Figure 4.

4. Case study

An existing crude atmospheric unit is considered for the application of the new revamping approach. The atmospheric unit belongs to an Egyptian Oil Refinery Unit (EORU). The objective of the case study is to increase the energy efficiency of the existing preheat train with minimum structural modifications.

The crude oil is heated from 25 °C to 261 °C by heat exchange using process hot streams. The overall energy consumption for heating purposes is 66.8 MW.

4.1 Graphical energy analysis of EORU HEN

The existing HEN of the base case is represented graphically in Figure 5 by the new approach using the data for the supply and target temperatures. The energy targets, the hot pinch temperature, and the cold pinch temperature are calculated using Aspen energy analyzer (2011), for a minimum temperature difference of 20 °C; the target hot utility is 54.96 MW and that for cold utility is zero. Also the hot pinch and the cold pinch temperatures are 40 °C and 20 °C, respectively.

The existing hot utility needed for the HEN is calculated graphically using the relationship between the length of the heater and the duty in Eq(5) which is 66.8 MW. Thus an excess of fuel oil of approximately 21.5 % is consumed. Similarly, the cold utility required for this HEN is 11.97 MW.

As shown in Figure 5, the coolers are obviously misallocated because all the coolers are present above the hot pinch line and below the cold pinch line. This is translated to region 2 in Figure 3. The optimum location of the coolers in an existing HEN should be within region 1; between the supply and target temperature of the cold utility. On the other hand, all the heat exchangers exist in the 3rd region which fulfils the pinch rules.

4.2 Graphical conceptual revamping of existing HEN

The revamping of this HEN will be focusing on moving the misallocated coolers to an appropriate position. This will be achieved by applying the graphical revamping methodology presented in Figure 4. The first step is HEN revamping without structural modification. This case takes an advantage of the presence of utility paths in the HEN to decrease the energies consumed by the coolers and consequently decrease the overall energy consumption in the HEN.

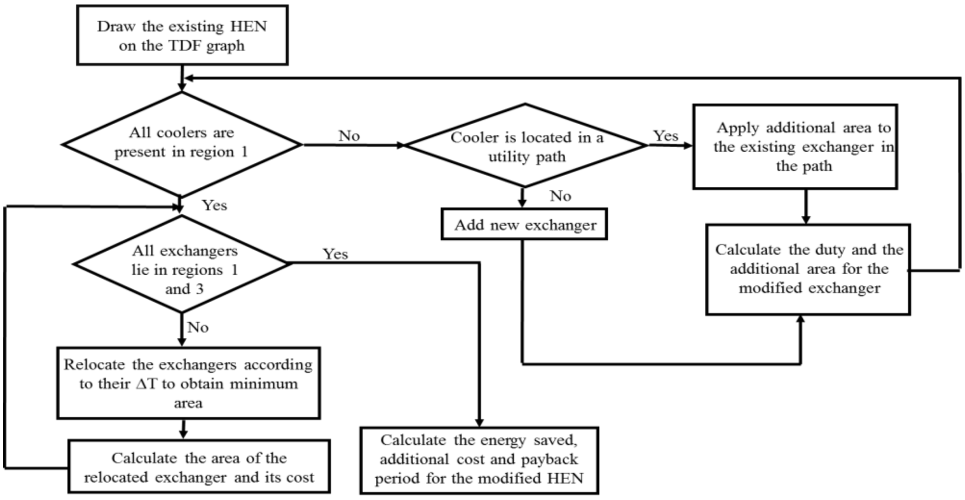


Figure 4: Algorithm for the complete steps of graphical revamping

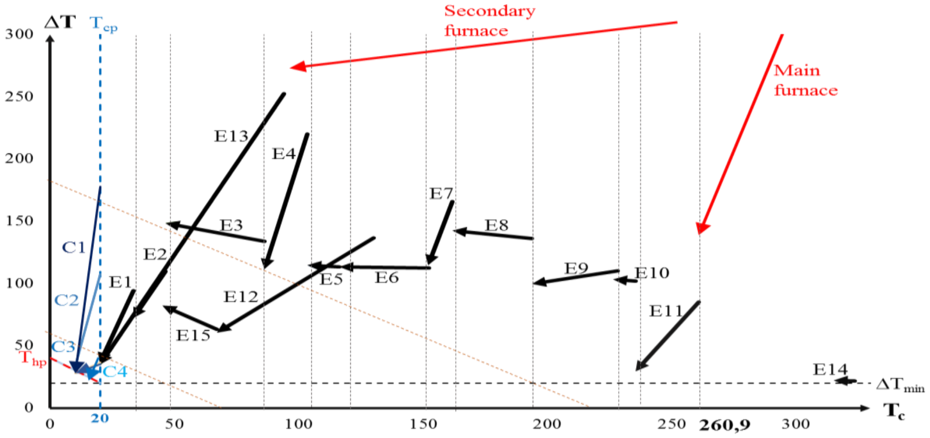


Figure 5: TDF of the existing HEN

This HEN has 3 utility paths as illustrated in Figure 5. The first path connects the cooler C4 and the main crude furnace through the exchanger E1. Similarly, the second path connects exchanger E4, cooler C1 and main crude furnace. The last path connects exchanger E13, cooler C3 and secondary furnace.

The revamping of coolers within a utility path is done graphically by the following steps: obtaining the maximum target hot temperature, which lies at the intersection between the supply cold temperature and the ΔTmin line as shown in Figure 6. Then mark the new starting point of the modified exchanger at the intersection of the maximum target hot temperature and the supply cold temperature. The modified exchanger is plotted using the starting point and the slope from Eq(4) till it intersects the hot supply temperature (Ths) line. Finally, obtain the new target cold temperature by drawing a vertical line at the intersection of the exchanger and the initial hot supply temperature of the exchanger E1. This presented procedure is applied on the above mentioned utility paths. This will conquer an additional area for the three exchangers E1, E4 and E13, and results of an overall energy recovery of 5.33 MW.

On the other hand, this new revamping technique is applied on the cooler C2 which has a duty of 4.817 MW and does not exist within a utility path. Therefore, a new exchanger will be introduced to the HEN in order to recover part or all of the cooler's duty.
The position of the new exchanger in the HEN is investigated graphically. Since the new exchanger is intended to replace the cooler C2, the supply and target hot temperatures boundaries for the new exchanger are the hot supply temperature and hot target temperature of the existing cooler.

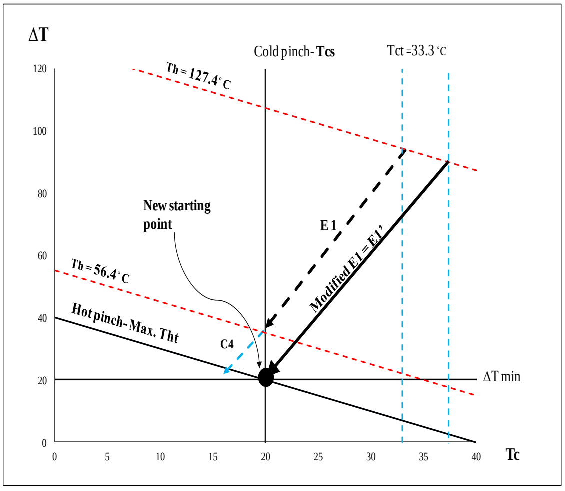


Figure 6: modified E1 within a path

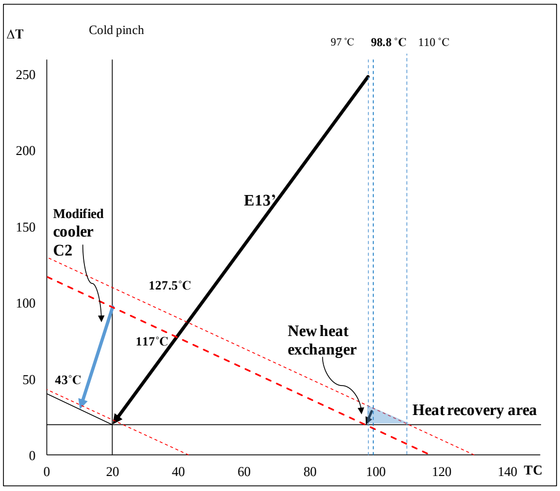


Figure 7: New exchanger after E13

As for the cold streams, there are two cold streams in this HEN that require external heating; the crude oil stream and the main steam stream. The crude oil stream already has 11 heat exchangers integrating heat with different hot streams in the plant, while the main steam stream has only one heat exchanger. Therefore, it is more convenient to add the new exchanger to the main steam line. The position of the new exchanger relative to exchanger E13' is investigated graphically. As shown in Figure 7, the new heat exchanger has to be introduced after exchanger E13' with a cold supply temperature equal to the cold target temperature of exchanger E13' which is 97 °C. The maximum achieved cold target temperature for the new exchanger exists at the intersection between the hot supply temperature line (127.5 °C) and the ΔT_{min} line. The minimum hot target temperature of the new exchanger exists at the intersection between the cold supply temperature line (97 °C) and the ΔT_{min} line. Figure 7 presents the available heat recovery area bounded between cold supply and maximum target temperature and the hot supply and minimum target temperature.
The new heat exchanger is drawn using the starting point and the slope. The duty recovered by the new exchanger is only 1.68 MW, due to the ΔT_{min} constraints.
Figure 8 shows the TDF graphical representation of the modified HEN. The final HEN requires the presence of 2 coolers only with duties of 6.81 MW instead of 4 coolers with duties of 11.9 MW. The revamping of coolers using the utility paths technique shifted all exchangers after E1 to the right. So the crude oil temperature before entering the main furnace is increased from 260.9 °C to 270.3 °C. A new exchanger E16 is added after exchanger E13 to recover part of the duty of cooler C2.

5. Results and discussion

The data show that a number of heat exchanger units after modification require additional heat transfer area, and the crude oil temperature before entering the furnace is increased by approximately 10 °C.
Table (1) compares the results of energy savings, costs, additional areas, payback periods, for the base case and modified HENs. The table reveals significant savings in energy demands and fuel oil consumption, versus the cost of the modifications and payback period. It is clearly seen that the proposed modifications by the new graphical representation improve the heat integration of the existing refinery.

6. Conclusions

A new graphical technique has been developed based on temperature driving forces across exchangers to revamp and analyze existing heat exchanger networks. This graphical technique is based on pinch analysis principles. The existing HEN is represented graphically as the temperature driving forces of an exchanger is plotted on the Y-axis versus the cold temperature of the streams on the X-axis. The new technique completely follows the pinch analysis rule, with the added advantage of being simple since each exchanger is represented by a straight line. This visual technique is indicative as both the length of the line and its slope have important physical implications. Exchangers' position in the HEN provides an insight on the relative areas of exchanger matches. Also the feasible regions for heat integration are easily identified visually.

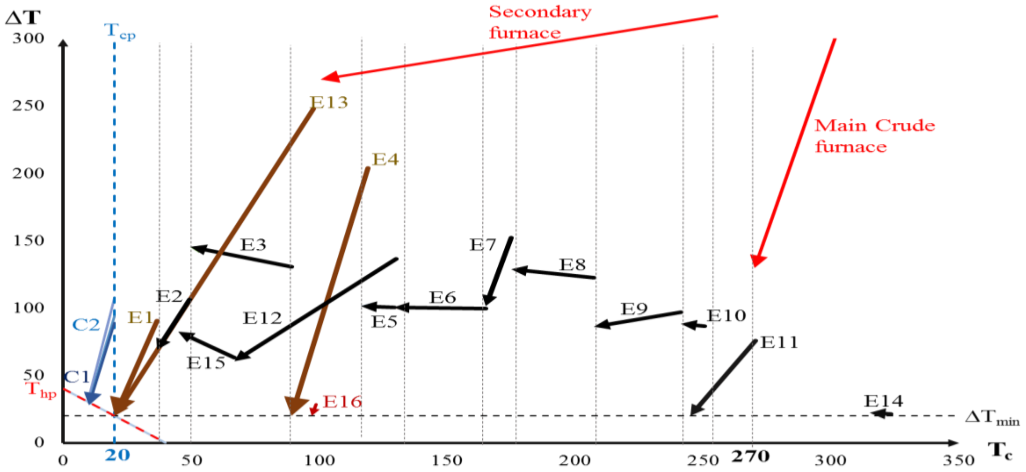


Figure 8: TDF for the modified HEN

Table 1: Summary of the results for the HEN revamping

Case	Duty of the furnaces (MW)	Add. area of HEN (m^2)	Energy cost ($/y)	Energy saved (%)	Cost of modification ($)	Payback period (y)
Base case	66.8	-	3,437,580	-	-	-
With additional area only	61.5	957.5	3,163,356	8	114,718	0.41
With add. area and new exchanger	59.8	1,208	3,077,435	10.5	224,105.8	0.62

A case study applied the graphical methodology in the revamping of an existing HEN, by both structural and non-structural methods and the results showed significant savings in energy consumption with minor capital costs and less payback periods. The potential for further energy recovery is still possible provided that the existing structure of the HEN is to be changed. This will incur substantial modification costs that may lead to an uneconomical solution. However, the distillation process is still a key factor for further savings; this study is under way using this new TDF graphical methodology and will be considered in further publications.

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