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MATLAB MODEL FOR THE DESIGN OF HEAT EXCHANGER NETWORKS IN CHEMICAL PROCESSES

Mohammed Abou Hussein[1], Mamdouh Gadalla[1,2] and Dina Ahmed[1]
[1]Department of Chemical Engineering, Faculty of Engineering, The British University in Egypt, Egypt
[2]Port Said University, Egypt
E-Mail: Dina.Ahmed@bue.edu.eg

ABSTRACT

In chemical refineries and petrochemicals industries the energy consumptions is a very critical for both economic and environmental effects, the energy in chemical industries is mainly consumed through the heating and cooling processes. The efficient design of heat exchanger networks (HENs) has been studied by many researchers to reduce the energy consumption in chemical plants. Heat integration by pinch technology has been a unique method to design the HENs. In this paper a MATLAB code is developed to apply heat integration based on a graphical design approach using the temperature driving force between streams. The MATLAB model is explained in an educational way to introduce pinch analysis for students and young researchers in the field. The MATLAB code presented, intend to develop a useful toolbox for the synthesis of a heat exchanger network. The HEN is represented on a simple graph, where the cold stream temperatures are plotted on the X-axis, while the temperature driving forces for each exchanger are plotted on the Y-axis. This graphical technique describes the energy analysis problems in terms of temperature driving force (TDF) in a heat exchanger, this paper will study the design of two case studies through a developed MATLAB code.

Keywords: heat integration, pinch technology, heat exchanger network, MATLAB model, grassroot designs.

INTRODUCTION

A typical heat exchanger network is a group of heat exchangers utilized to reduce the use of external utilities by exchanging heat between accepted matches of hot and cold streams [1]. By studying the pinch technology on the chemical process, the minimum heating and cooling duties are calculated and are fulfilled by employing external utilities on the hot and cold streams [2], theses duties are also known as the energy targets which are found from the composite curve (CC), in which the temperature of the hot streams versus cumulative enthalpy and the temperature of the cold streams versus cumulative enthalpy are plotted [3]. The data obtained from the composite curve are used to set a heat exchanger network by dividing the network into two systems: one system with a temperature higher than hot pinch and another system with temperatures below cold pinch temperature [4]. The pinch technology states that no coolers should take place above the pinch, while no heaters should be placed below the pinch, this an economic wise to minimize the total costs, the proposed design should meet the energy targets and the minimum number of heat exchangers as well [5]. Also to provide a heat integrated design for a new proposed process and according to [5] the following stages should be applied and followed:

a) Data extraction: in this stages, the data of the available hot and cold streams presented in the process are collected regarding any condensation or vaporization that will take place, moreover, the available external utilities used for cooling and heating will be collected these data are known as utility data, the economics of the heat exchangers as well as the utilities should be also studied.
b) Performance targets: Based on the collected data, information regarding the number of heat exchangers to be used as well as the energy targets.
c) Process modifications: Using composite curves and plus/minus principles are used in converting the basic process into an integrated process.
d) Network design: By following the pinch design method rules and based on the calculated energy targets and the minimum number of heat exchangers a heat exchanger network (HEN) is proposed that includes maximum heat recovery for the process and requires the minimum use of external utilities.
e) Design evolution: in which energy relaxation will take, and it is the removal of small duty which will have relatively very high cost compared to the amount of heat transferred, this will also result in that the design will consume more utilities, this will produce less complex network as the removed heat exchanger can be based on a split stream as well as it can reduce the cost of the heat exchangers, this stage is achieved by energy paths or loops or by stream splitting technique.
f) Process simulation: Using computer software the proposed design will be tested to make sure that it is feasible and that it will provide the maximum heat recovery.

While for another case where a revamping of existing network will be required, this is totally different from the new designs of HENs, because the heat exchangers are already placed and purchased, therefore, they have to be maximized and reutilized to provide the highest performance possible [4]. One of main challenges

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in the revamping of HENs is that the heat exchangers used are designed based on the flowrates and the properties of the fluids flowing in the exchanger, another challenge is the capital investment set for the revamping of the HEN and this results in trying to keep the existing network structure and apply no changes to the structure [6].

Moreover, the actions taken in the revamping of HENs falls in the following modifications:

a) Addition of new heat exchangers.
b) Increase the heat transfer area.
c) Enhancing existing heat exchanger: this is achieved by changing the internals of the heat exchanger which will results in increasing the heat transfer coefficient as well as the heat transfer area.
d) Make changes to the piping connecting streams and heat exchangers: switch the heat exchange from parallel to series, change fluids on the hot and/or cold side of heat exchangers.

Furthermore, the retrofit of a typical existing HEN is done by studying the composite curve for the given process in order to calculate the energy targets that summarize the minimum heating and cooling duties in the process which will be compared with the existing targets, however, the main problem in the HEN revamping is that the improvement of the HEN should be bases on the minimum structural modification also the duties can be shifted using loops or utility paths can be used in case of dealing with misdirected heat exchanger and the addition of new exchanger can also be taken into considerations [6] Furthermore, some MATLAB codes were developed to participate in developing heat exchanger networks such that [7] have successfully developed a generalized MATLAB code for the calculations of pinch temperatures and energy targets.

This paper develops a MATLAB code using a simple algorithmic approach to design heat exchanger networks by employing a graphical approach. The model applies the pinch principles in an extension to the Temperature driving force (TDF) graphical design approach introduced by [8]. In the TDF the heat exchanger network (HEN) is represented in (T-T) graph.

TEMPERATURE DRIVING FORCE (TDF) APPROACH

This approach considers the temperature driving force (TDF) in every exchanger which is accounted for on the Y-axis versus the cold stream temperatures plotted on the abscissa. The new approach provides a visual representation for each heat exchanger, the position of inefficiencies, and temperature driving forces in each exchanger. This consequently provides a better visual indication for the area of heat transfer. The TDF graphical technique used in the revamping of existing networks can successfully tell if there any misallocated heat exchanger, coolers, or heater, and since it divides the HEN into 5 main regions, it can also provide information regarding the area of the heat exchanger which is very important in case of dealing with energy relaxation situations [8].

The hot end temperature difference is calculated as the temperature difference between the hot stream supply temperature and the cold stream target temperature while the cold end temperature difference is the difference between the hot stream target temperature and the cold stream supply temperature [9].

The cold streams are then represented on the x-axis (T_C) as two vertical lines ($T_C = T_{CS}$) and ($T_C = T_{Ct}$) while the hot streams will be presented as two inclined lines: the first line will consist of (0, T_{hs}) and (T_{hs},0) while the second line will consist of (0, T_{ht}) and (T_{ht},0), moreover, the hot pinch temperature will be added similar to the hot streams as an inclined stream (0, T_{hp}) and (T_{hp},0) and the cold pinch temperature similar to the cold streams as a vertical line (T_C=T_{CP}), and the minimum temperature difference is represented as a horizontal line starting at ($\Delta T = \Delta T_{min}$), also the hot end temperature difference will be represented as horizontal line (ΔT=ΔT_{he}) and the cold end temperature difference (ΔT=ΔT_{ce}). Moreover, any heat exchanger will start at ΔT_{he} and end at ΔT_{ce} [10] as presented in Figure-1.

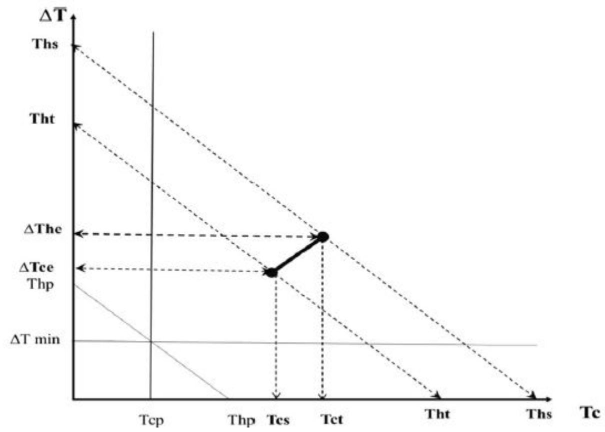

Figure-1. Drawn heat exchanger [11].

According to [10] the slope of the drawn line for the heat exchanger will have the following slope:

$$S = \frac{C_{pc}}{C_{ph}} - 1 \tag{1}$$

The length of the heat exchanger can be predicated by as a side of a 90-degree triangle and by applying Pythagoras theorem the following equation:

$$L = Q\sqrt{\left(\frac{2}{C_{pc}}\right)^2 + \left(\frac{1}{C_{ph}}\right)^2 + \left(\frac{2}{C_{ph}\,C_{pc}}\right)} \tag{2}$$

Equation (2) shows that the length of the heat exchanger is directly proportional to the amount of heat to be transferred.

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Moreover, Figure-2 shows the actual graphical representation of the important mentioned parameters:

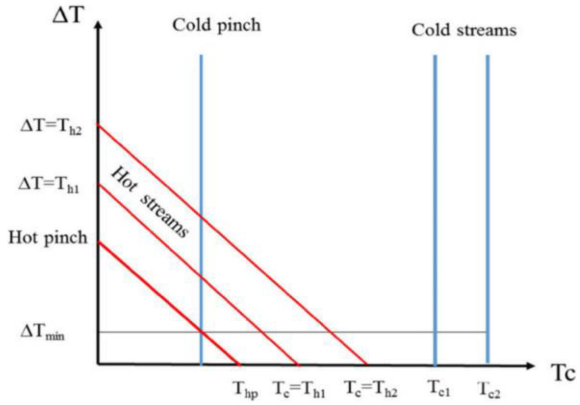

Figure-2. Main parameters used in the new graphical technique presented [9].

As already mentioned before the new graphical method divides the graph into five regions as shown in Figure-3.

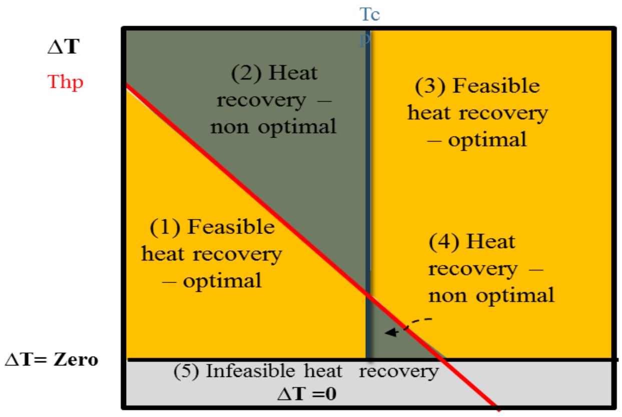

Figure-3. The main regions in the new graphical methods [11].

a) **Region 1:** below the hot pinch and cold pinch temperature which provides the optimum and most feasible area for cooler and heat exchangers [11].
b) **Region 2:** above the hot pinch but below the cold pinch which can result in having a heat transfer across the pinch and break the pinch rules, therefore, this area is infeasible for any heat transfer [11].
c) **Region 3:** above the hot pinch and the cold pinch which provides the finest and most feasible area for heaters and heat exchangers [11].
d) **Region 4:** below the (ΔT = zero) line, considered to be an infeasible region [11].
e) **Region 5:** above the hot pinch and below the cold pinch which can result in having a heat transfer across the pinch and break the pinch rules, therefore, this area is infeasible for any heat transfer [11].

$$Q = U \times A \times LMTD$$

Another feature of this technique is the cases that include steam and reboiler as they are represented differently, for example when dealing with saturated steam it will raise the temperature of the cold stream by losing the latent heat which means that for the steam no temperature change will occur but phase change will take place, therefore, the supply and a target temperature of the steam will be the same [10]. However, when dealing with evaporative steam it is different will take place at the cold stream temperature as a vertical line having similar target and supply temperature which will results in an infinity slope as in Figure-4.

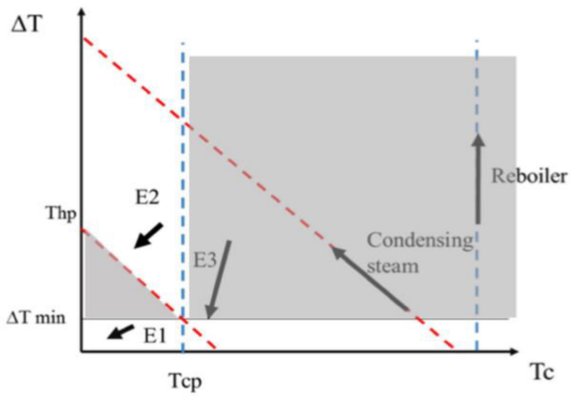

Figure-4. Presenting saturated and evaporative steam [10].

Steps for the Grassroots Design of HENs Using the TDF Approach

A. The first step for any typical design is to plot all of the given supply and target temperature for all the given hot and cold streams, and also plot the minimum temperature difference line, hot pinch line, and the cold pinch line as already shown in the literature section.
B. Identify the optimum regions for the design of the network and divide the plot into two systems: above and below the pinch.
C. For above the pinch systems:

a) Begin matching with the hot stream having the lowest target temperature (T_{ht})
b) The beginning of the design and the first point will be the intersection of the hot stream target temperature (T_{ht}) line and the cold stream supply temperature line (T_{cs}).
c) If the hot stream target temperature (T_{ht}) is below the pinch, then the intersection will be between the hot pinch line (T_{hp}) and the cold stream supply temperature (T_{cs}) line.
d) If the cold stream supply temperature is below the pinch, then the intersection will be between the hot stream target temperature (T_{ht}) line and the cold pinch line (T_{cp}).

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e) If both the hot stream target temperature (T_{ht}) and the cold stream supply temperature (T_{cs}) are below the pinch, then the design will begin at the intersection of the hot pinch temperature and cold pinch temperature lines.
f) If the intersection is at the pinch point, then the golden rule must be checked and applied while if not then the intersection must be above the minimum temperature line.
g) A line with the following slope will be drawn:

$$S = \frac{C_{pc}}{C_{ph}} - 1$$

h) If the drawn line intersects the supply temperature of the hot stream, then this means that the hot stream is satisfied while the cold stream will reach intermediate temperature.
i) If the drawn line intersects the target temperature of the cold stream, then this means that the cold stream is satisfied while the hot stream will reach intermediate temperature.
j) Another scenario that could happen is that they both reach intermediate temperatures as they intersect the pinch.
k) Then the next hot stream will be matched with cold streams until and this will be done until no more hot streams available to be matched with the cold streams and in this case, a heater for each unsatisfied cold stream will be added.

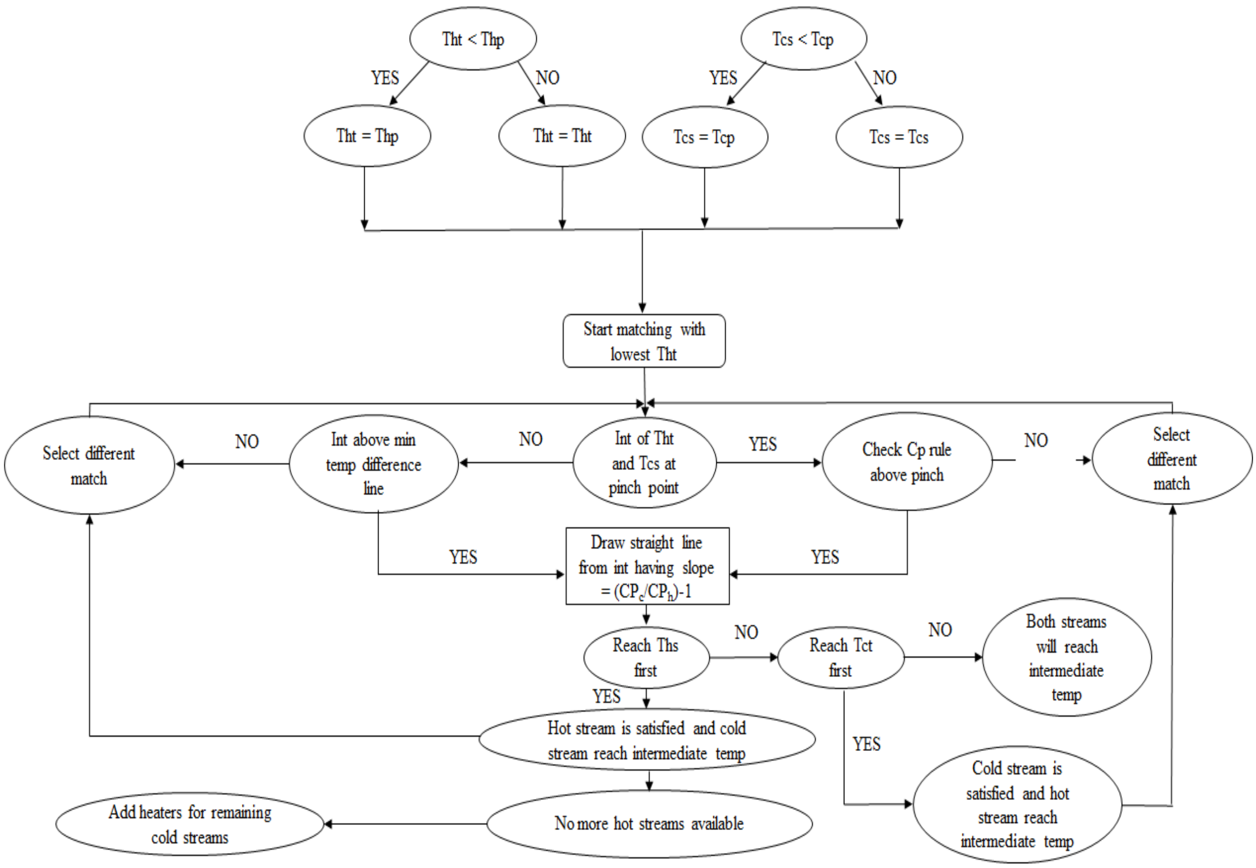

Figure-5. Procedures for the design above the pinch.

D. For below the pinch systems:
a) Begin with the cold stream having the highest target temperature (T_{ct}).
b) The beginning of the design and the first point will be the intersection of the cold stream target temperature (T_{ct}) line and the hot stream supply temperature (T_{hs}) line.
c) If the cold stream target temperature (T_{ct}) is above the pinch then the intersection will be between the cold pinch temperature line (T_{cp}) and the hot stream supply temperature (T_{hs}) line.
d) If the hot stream supply temperature is above the pinch then the intersection will be between the cold stream target temperature (T_{ct}) line and the hot pinch temperature line (T_{hp}).
e) If both the cold stream target temperature (T_{ct}) and the hot stream supply temperature (T_{hs}) are above the pinch, then the design will begin at the intersection of the hot and cold pinch temperatures lines.
f) If the intersection is at the pinch point, then the golden rule must be checked and applied while if not then the intersection must be above the minimum temperature line.

g) A line with the following slope will be drawn:

$$S = \frac{C_{pc}}{C_{ph}} - 1$$

h) If the drawn line intersects the supply temperature of the cold stream, then this means that the cold stream is satisfied while the hot stream will reach intermediate temperature.

i) If the drawn line intersects the target temperature of the hot stream, then this means that the hot stream is satisfied while the cold stream will reach intermediate temperature.

j) Another scenario that could happen is that they both reach intermediate temperatures as they intersect the pinch.

k) Then remaining cold streams will be matched with hot streams until no more cold streams are available to be matched with the hot streams and in this case, a cooler for each unsatisfied hot stream will be added.

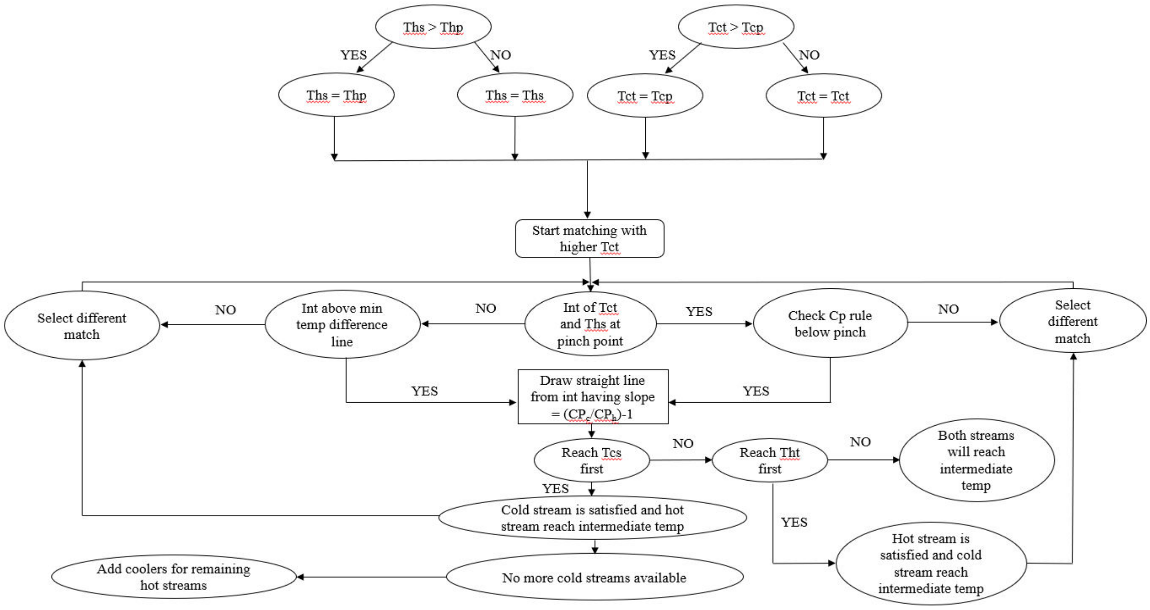

Figure-6. Procedures for the design below the pinch.

MATLAB CODE FOR THE DESIGN OF HEAT EXCHANGER NETWORKS USING GRAPHICAL APPROACH

In this section the code will be summarized in an algorithm and is going to be discussed briefly. Figure-7 shows the algorithm:

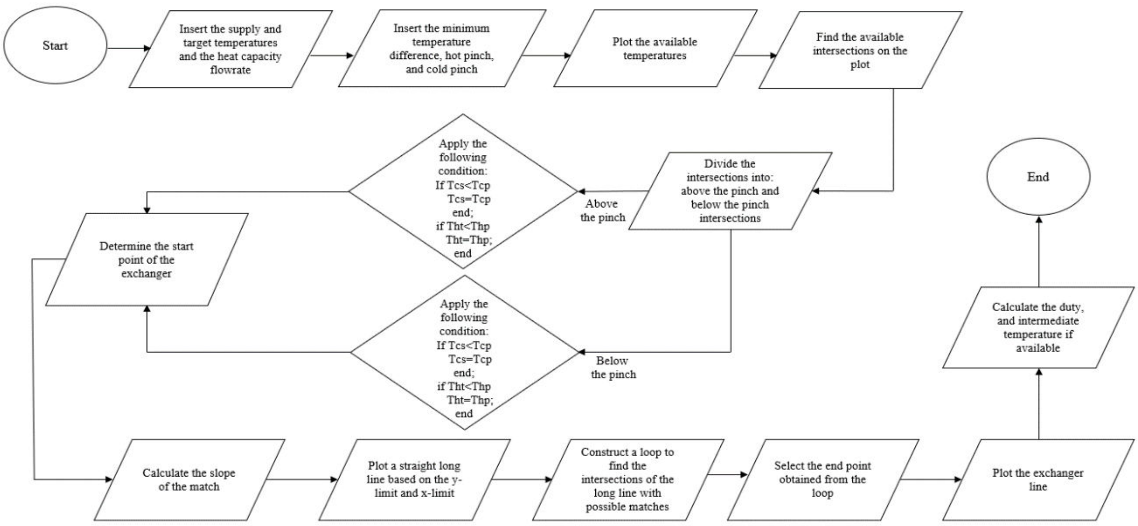

Figure-7. MATLAB code algorithm.

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The following steps are the summary of the code:

a) The available temperatures and heat capacity must be introduced, this includes the pinch temperatures and minimum temperature difference value.
b) All the available temperatures will be plotted.
c) The MATLAB will calculate every possible intersection for the plotted lines.
d) The intersections will be divided into intersection above the pinch, and intersections below the pinch.
e) If condition is introduced to make sure that all the temperatures introduced above the pinch are higher than the pinch temperatures (above the pinch).
f) Another If condition is introduced to make sure that all the temperatures introduced above the pinch are lower than the pinch temperatures.
g) The start point of the exchanger is identified in the form of a solution obtained from the MATLAB.
h) The slope equation is introduced and then the slope will be calculated.
i) Plot a straight long line based on the y-limit and x-limit, and solve for the possible intersections with this line.
j) Select the proper endpoint, and plot the exchanger line and calculate the duty and intermediate temperature if there are any.

CASE STUDY 1: CHEMICAL FERTILIZER

The studied fertilizer industry is located in Chennai and it consists of six process streams and they could be summarized as stated by [12] in Table-1.

Table-1. Stream summary table for case study 1.

Stream	Supply temperature (°C)	Target temperature (°C)	Heat Capacity Flow (KW/°C)
Hot	280	193	151.18
Hot	20	1	259.97
Hot	403	280	151.18
Cold	-12	10	224.52
Cold	214	258	422.62
Cold	149	214	196.68

Also in this case the minimum temperature difference was found to be 15 °C while the hot pinch to be 20 °C and the cold pinch to be 5 °C. The minimum cooling required by external utilities, in this case, is 112.2.5 KW while the minimum heating required by external utilities is 1123.1 KW. Figure 8 shows the suggested heat exchanger network developed by [12]:

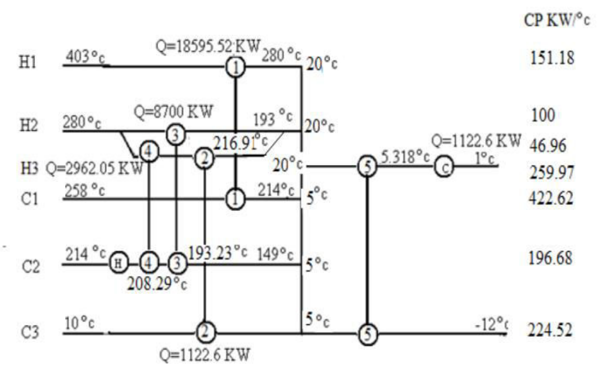

Figure-8. Existing exchanger for case study 1.

RESULTS AND DISCUSSION FOR 1ST CASE STUDY

At the beginning the available temperatures must be presented in the T-T diagram using the MATLAB as presented in Figure-9.

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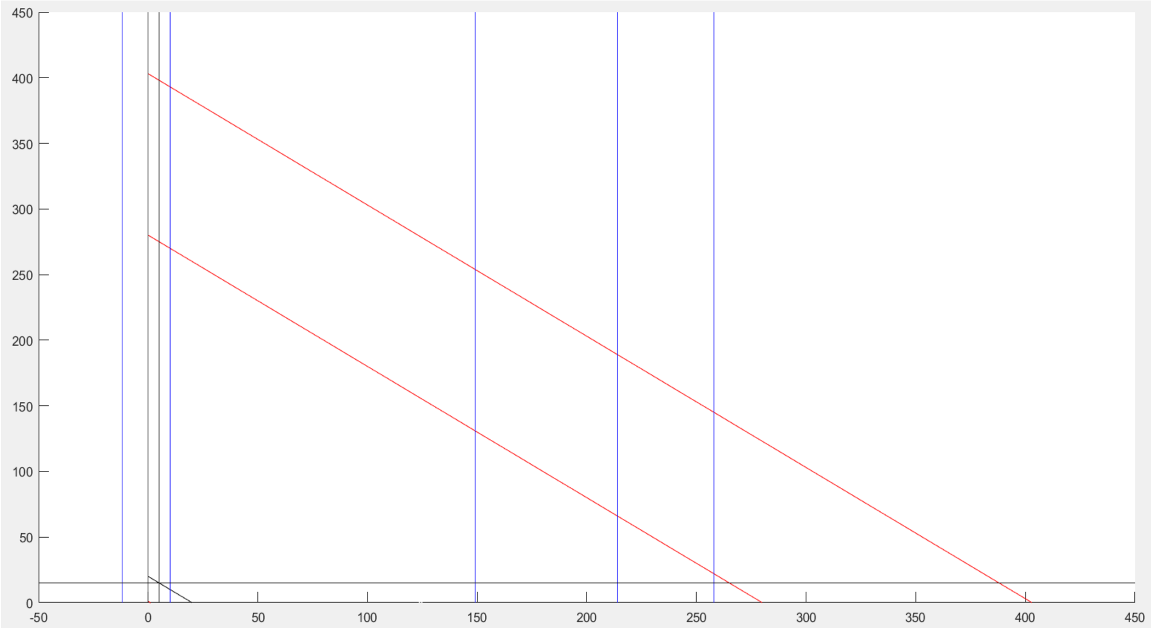

Figure-9. T-T diagram for case study 1 reported by MATLAB.

By studying the optimum matches above and below the pinch and by calculating the slope of all possible matches achieved using the MATLAB, a comparison between them resulted in the network presented in Figure-10:

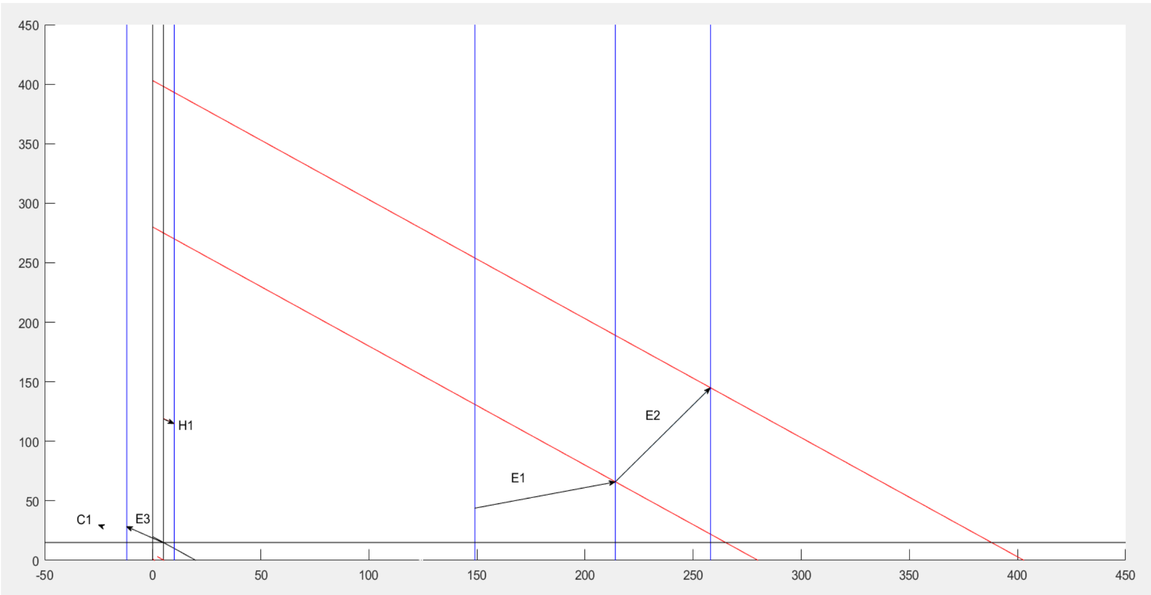

Figure-10. Heat exchanger network for case study 1 reported by MATLAB.

Table-2. Heat exchanger network summary.

Exchanger	T_{hs} (°C)	T_{ht} (°C)	T_{cs} (°C)	T_{ct} (°C)	Q (KW)
E1	280	193	149	214	12784
E2	40	280	214	258	18595.14
H1	5	10	125	124	1122.6
E3	20	5.3182	-12	10	3816.84
C1	5.3182	1	-25	-24	1122.59

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ARPN Journal of Engineering and Applied Sciences

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The proposed design involves 3 process heat exchanger, a heater, and a cooler, the minimum amount of heat required for cooling was reported in the HEN to be 1122.59 KW which agrees with the amount reported from the composite curves, while the minimum amount of heat required for heating in the HEN was reported to be 1122.6 KW which also agrees with the amount reported using the composite curves and showed less number of units involved in the network.

CASE STUDY 2: INDUSTRIAL CHEMICAL PROCESS

The second case which will be studied is obtained from [13], and it consists of eight process streams as summarized in Table-3:

Table-3. Stream summary table for case study 2.

Stream	Supply temperature (°C)	Target temperature (°C)	Heat Capacity Flow (KW/°C)
1	150	40	0.1
2	140	30	0.15
3	130	25	0.15
4	150	30	0.2
5	20	140	0.1
6	15	130	0.15
7	25	145	0.25
8	80	140	0.3

Also in this case the minimum temperature difference was found to be 10 °C while the hot pinch to be 90 °C and the cold pinch to be 80 °C. The minimum cooling required by external utilities, in this case, is 6.25 KW while the minimum heating required by external utilities is 16.25 KW. It is required to find an optimum heat exchanger network and compare it with the existing network. Figure 11 shows the suggested heat exchanger network developed by [13]:

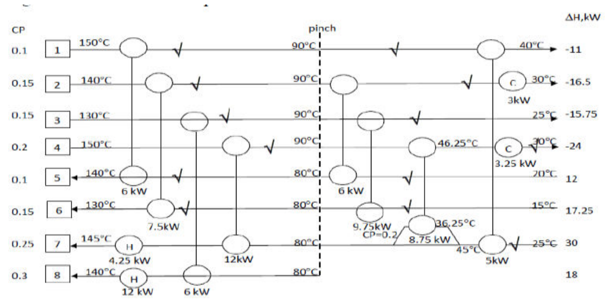

Figure-11. Existing heat exchanger network for case study 2.

RESULTS AND DISCUSSION FOR 2^ND^ CASE STUDY

Similarly, initially the available temperatures must be presented in the T-T diagram using the MATLAB as presented in Figure-12.

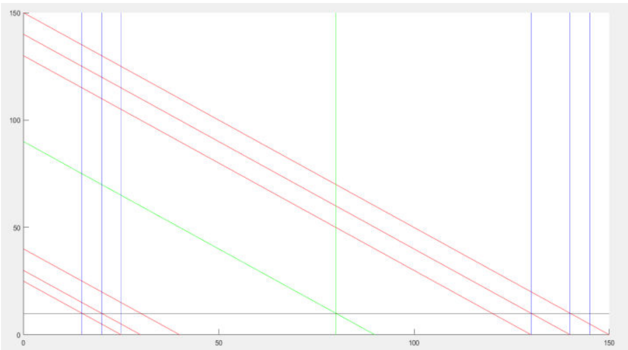

Figure-12. T-T diagram for case study 2 reported by MATLAB.

By studying the optimum matches above and below the pinch and by calculating the slope of all possible matches, this achieved using the MATLAB, then a comparison between the available matches was done which resulted in the network presented in Figure-13 was developed.

VOL. 17, NO. 1, JANUARY 2022 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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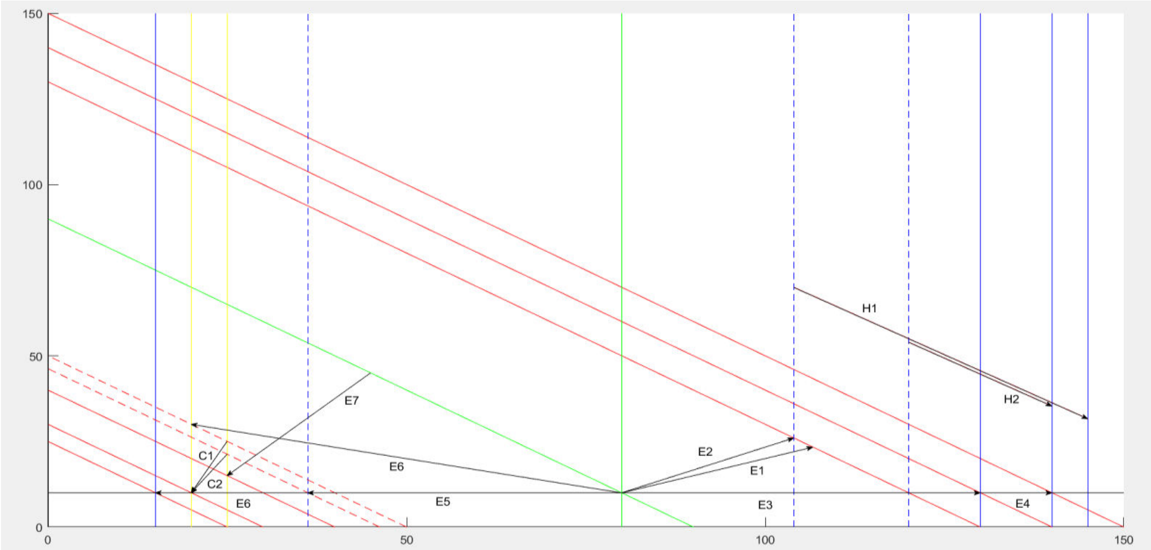

Figure-13. Heat exchanger network for case study 2 reported by the MATLAB.

Table-4. Summary of the available exchangers in case study.

Exchanger	T_{hs} (°C)	T_{ht} (°C)	T_{cs} (°C)	T_{ct} (°C)	Q (KW)	Area (m^2)
E1	130	90	80	104	6	350
E2	140	90	80	130	7.5	750
E3	150	90	80	120	12	660
E4	150	90	80	140	6	600
E5	90	46.25	36.25	80	8.75	875
E6	90	25	15	80	9.75	975
E7	90	50	20	80	6	330
E8	90	40	25	45	5	184

The proposed network is summarized in table 4 and involves 8 process exchangers, 2 heaters, and 3 coolers, the obtained network agrees with the targets obtained using the Energy Analyzer and the value obtained using the original design.

CONCLUSIONS

In consequence, the objective of this project was to develop a MATLAB code for the graphical approach based on the temperature driving forces in the exchangers presented in the heat exchanger network. The graphical approach could be used for the revamping of existing heat exchanger networks, grassroots design of the network, and for the analysis of the existing network.

The graphical approach follow the pinch analysis guidelines, the temperature difference which is the driving forces is plotted on the y-axis is plotted against the cold temperatures on the x-axis. Unlike the traditional design of the heat exchanger network, the graphical approach is concerned by the temperature differences as this parameter is used in the calculations of the area of heat transfer which is used to find the cost of the exchanger: higher areas result in higher costs. The main benefit of the developed MATLAB code are:

a) No need for complex or commercial simulation or software packages.
b) Instantaneous determination of the value of the driving force for each exchanger to avoid the presence of network pinch.
c) Good selection of accepted and excluded matches regarding the driving force.
d) Visualization in design especially for low-temperature applications.

The code has successfully provided the proper tools for the use of a graphical approach, as it avoids any human error calculations as all of the calculations and intersections are reported using the MATLAB with less time-consuming.

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