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Fuel saving due to pinch analysis and heat recovery in a petrochemical company

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Abstract:

Nowadays, decreasing the amount of natural resources and increasing the price of it, motivates to consider energy conservation as a main concern of many process industries, especially oil, refinery and petrochemical plants.

Pinch Analysis (PA) is a powerful method for identifying and selecting technical solution to improve efficiencies and provide an optimum procedure for energy saving.

This paper analyses, the effectiveness of applying PA to optimize energy consumption for a given set of process streams in a Petrochemical Company in Iran. In this study, firstly, the interested process streams have been selected, maximum heating and cooling load are computed, and then composite curves have been drawn - by Matlab code - which provides a visual profile of the availability of heating or cooling from the process streams. Secondly, the cost of recovered heat is computed in terms of fuel saving, which confirms applying PA could save significant amount of fuel expenses for the company. Finally, the corresponded Heat Exchanger Network (HEN) has been designed, and the investment costs for heat exchangers have been computed in order to find out payback time of the investment costs which is approximately 17 months for this case study.

Keywords:

Pinch analysis, Process integration, Heat recovery, Composite curve, energy optimization

1. Introduction

The efficient use of energy is a very important issue for the processing industries. Oil price has risen radically during past years and stays at high level. On the other hand, regulations about environment are getting more and more difficult to satisfy. Therefore, the issue is not just monetary incentives regarding to the efficient use of energy but also a growing challenge for a cleaner environment.

In order to have sustained growth in petrochemical and chemical industry, it is necessary to do many things such as energy saving and raising productivity simultaneously while satisfying many regulations in environmental and health issues.

Clearly energy cost rises sharply due to high oil price; therefore, reducing resource consumption becomes one of the prior challenges of the research in the field of energy.

Pinch Analysis PA is a family of methodologies for combining several parts of processes or whole processes to reduce the consumption of resources and consequently, harmful emissions into the environment. It refers to the thermal combinations of steady-state process streams for achieving heat recovery via heat exchange.[1]

Pinch analysis technique originally developed by Linnhoff and Flower In late 1978 with the key concept of setting energy targets[2]. The goal of PA is to recover energy from the process in the most economical way by matching hot and cold process streams. Any energy still needed is then supplied by external utilities [3]. In order to achieve the results obtained by PA, Heat Exchanger Network (HEN) design is needed. HEN could be seen a complement of PA: the PA determines the thermodynamic features of the heat exchanging process (so its energy efficiency), whereas HEN determines the physical structure of such system (so its economic cost). Thus, the goal of PA coupled with HEN design is to attain optimal thermodynamic or economic efficiencies of the analyzed system. [4, 5]

In every process with hot and cold streams like petrochemical industries, oil & gas or power plants there is a possibility to apply PA and then designing the HEN.

Developments of the mathematical modelling and process integration methods like PA and HEN design are one of the main interests of the research in the energy saving field[6]. There are plenty of applications on various energy systems and industries in order to show the effectiveness of the PA and HEN on energy saving and decreasing resource consumption.[3, 7-14]

The experience of the last three decades in the implementation of energy saving programs, has shown that it is possible to obtain up to 15% savings by energy conservation (protection from decay and destruction), avoiding wastes, effective maintenance, etc. However, going further in this effort, requires an additional investment. [15]

Since the oil refining industry is one of the major users of energy and is also highly heat integrated, it is therefore, a good candidate for applying PA.

Worrell E. and Galitsky C. suggest that given available resources and technology, there are opportunities to reduce energy consumption in the petroleum refining and petrochemical industry while maintaining the quality of the products. They stated that major areas for energy-efficiency improvement are utilities (30%), fired heaters (20%), process optimization (15%), heat exchangers (15%), motor and motor applications (10%), and other areas (10%) [10]. Spriggs H. et al., computed the energy saving due to the application of PA not only in the petrochemical and bulk chemical plants but in the wider range of industries, including food, pulp and paper, cement brewing and dairy product process. Results showed that energy consumption reduced in the range of 15-75%, capital requirements reduced for new designs, flexibility improved and plant capacities increased [16]. Yoon S-G et al. modified HEN for an industrial ethyl benzene plant by PA, which reduced the annual energy cost by 5.6% and demonstrated that the capital investment cost will be recovered less than one year. [17]

This study applies PA on the part of the Para-xylene Separation Unit of Petrochemical Company in order to be investigated in terms of heat recovery as well as reducing resource consumption. Six streams have been chosen in this unit according to the preference of the process department. However, this analysis could be performed for more streams according to the consideration of process department as well as possibility of modification in the site.

2. Methodology

2.1. Pinch Analysis

The concept of PA based on thermodynamic rules and offers a systematic approach to optimum energy integration in a process. The improvements in the process associated with this technique are not due to the use of advanced unit operations, but to the generation of a heat integration scheme. The principal objective is to match cold and hot process streams with a network of exchangers so that demands for externally supplied utilities are minimized. [18]

The first and the most important step in the PA is to understand the process well and to extract proper data. Necessary data are source and target temperatures, heat capacity and mass flow rate of each stream. Each process stream is classified either as a hot stream or a cold stream. By the data, it is possible to calculate the current energy situation for each stream in the whole process, which means computing required energy for each stream in order to reach from source to the target temperature. Heat energy has to be removed from hot streams and has to be supplied to cold streams. Energy recovery using the pinch method is achieved by matching the appropriate hot and cold streams. Afterwards during HEN design, heat capacity will be used again in order to compute inlet and outlet temperature of each heat exchanger which is needed to calculate heat transfer area.

Fig. 1 shows the practical steps of the PA and HEN design.

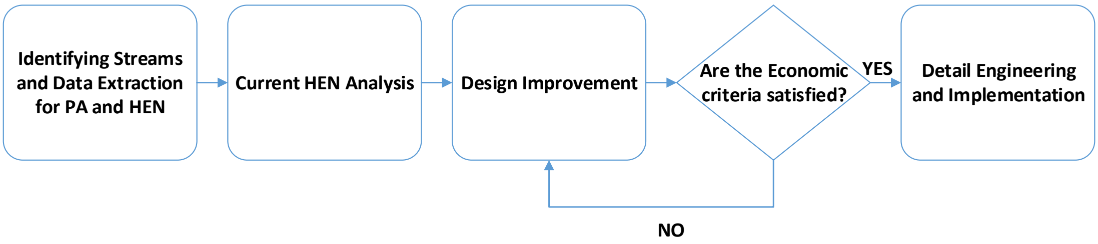

Fig. 1. Practical flow of pinch analysis (PA) and heat exchanger network (HEN)design

The energy required for each stream is obtained from below formula in which multiplication of mass flow rate convert it to the flux:

$$\Phi = G.C_p.\Delta T = CP.\Delta T \qquad (1)$$

Where Φ is the heat flux, G is the mass flow rate, C_p is the specific heat capacity, ΔT is the temperature difference between source and target temperature, and CP is the heat capacity rate which defined as $G.C_p$. Note that, this formula only can be used when there is no phase change. In case of phase change, each phase should consider as one stream.

Plotting temperature versus heat flux known as composite curve for both hot and cold streams (Fig. 2). The amount of heating and cooling load specified in this figure, represents the minimum required loads that should be provided by means of external utilities like heater and cooler. Fixing the location of the composite curves with respect to each other completes the composite diagram. The location of ΔT_{min} (pinch position) on the composite diagram is where the two curves most closely approach each other in temperature, when measured in vertical direction. The optimum value for ΔT_{min} is generally in the range of 3 to 40 °C for heat exchanger networks, but it is unique for each network and needs to be established before the PA is completed [18]. Detailed information regarding to the construction of composite curve can be found in [2]. On the first plotting of these curves, the vertical distance will rarely equal to the preselected ΔT_{min}. This deficiency will be solved by moving one of the two curves horizontally until the distance of closest vertical approach matches the preselected ΔT_{min}.

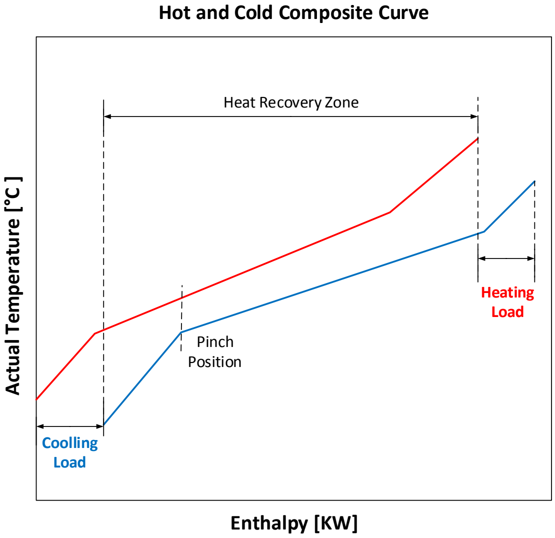

Fig. 2. Composite curves

Higher value of ΔT_{min} means higher heating and cooling loads while lower ΔT_{min} not only increases the heat recovery zone but also decreases heating and cooling loads. However, low temperature difference increases the cost of the heat exchangers due to the fact that for the same amount of heat flux, higher heat transfer area is needed. Therefore choosing an optimal ΔT_{min} is an important issue in this analysis. Heggs P.J. [19], discussed the relationship between minimum temperature difference and investment cost in detail. Fig. 3 shows the variation of energy and capital cost respect to the ΔT_{min}.

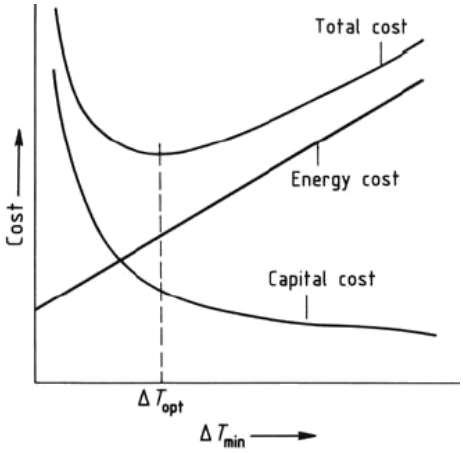

Fig. 3. Energy and capital cost versus ΔT_{min}

2.2. Heat Exchanger Network (HEN) design

HEN has progressed significantly during the last two decades, particularly following the development of the heat recovery pinch methods [20, 21]. It is a tool which has been utilized for executing the result of PA in order to increases heat recovery from industrial processes by matching hot and cold streams to exchange heat and reducing external utility consumption such as steam, fire heaters, etc [3].

HEN could be represented in two ways; grid diagram and mass-content diagram. The most common representation scheme is the grid diagram, in which each heat exchange unit is represented as a vertical line connecting two streams. In this study, the first representation has been presented, which consist of:

1. Solid horizontal lines which flow from the left (hot side) to the right (cold side) of the diagram represent hot streams (in this paper, they have been shown in red).
2. Solid horizontal lines which flow from the right (cold side) to the left (hot side) of the diagram represent cold streams (in this paper, they have been shown in blue).
3. Solid vertical lines with two circles represent heat-exchange unit. Each line can connect a hot and a cold stream.
4. Vertical dashed lines indicate the position of any pinch points for the system.

The grid diagram is divided into two sub problems defined by the pinch points (above and below the pinch). Within these regions, simple design rules should apply to achieve the minimum heating and cooling utility duties as well as maximum heat recovery;

1. Start at the pinch; The pinch is the most constrained region of the problem and ΔT_{min} exists between all hot and cold streams.
2. Individual heat exchangers should have a temperature difference not smaller than the ΔT_{min} between the composite curves.
3. T The CP inequality for individual matches should be considered for each region (CP is equal to G.Cp for each stream);

$$CP_H \leq CP_C \quad \text{(Above pinch)}$$

$$CP_H \,/\, CP_C \quad \text{(Below pinch)}$$

Note that the CP inequalities given by above Equations are only applied at the pinch and as far as getting far from the pinch, they can be violated.

Number of streams should follow these rules:

$N_H \le N_C$ (Above pinch)

N_H / N_C (Below pinch)

Where:

NH = number of hot streams and NC = number of cold streams

In case of violation of rules related to number of the streams and CP inequalities, the problem should be solved by splitting one stream. A more detailed description of the HEN design procedure under the PA can be found in the literature.[22]

3. Case study

3.1. Unit description

The problem is stated as follows:

Small section of the Para-xylene separation unit (Fig. 4) of the Company has been considered to be analysed according to the preference of the process department. The description of the process is the following; Part of the bottom product of the distillation column which is the pure Para-xylene should be cooled down through the air fan cooler in order to be stored in the storage tank (Stream number 3), and the rest should be heated up in the reboiler in order to come back to the column (Stream number 5). In addition, there are other hot and cold streams, which are involved in the analysis that comes from other units of the plant which are;

Stream number one is recirculation solvent in Eluxy process unit, Stream number two is the feed of Eluxy unit, which comes from Reformate & Aromatic separation unit, stream number six, which is Para-xylene for purification and removing Toluene, and finally stream number four, which is again Para-xylene. In Fig. 4 each stream specified by a number and after cooling or heating process their names changes by adding an “A” character after the aforementioned numbers. “H” and “C” also represents heater and cooler respectively.

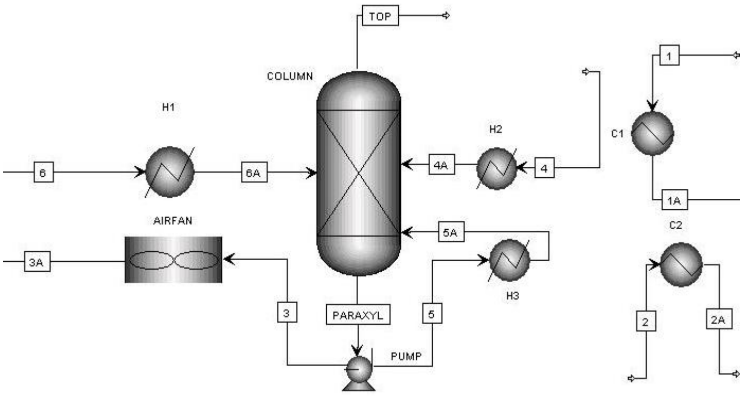

Fig. 4. Schematic view of the considered unite

To summarize; there are three hot process streams “NH” to be cooled down and three cold process streams “NC” to be heated up. In Table 1 which based on the stream’s properties of the existing case, all required data for starting the analysis has been listed.

Table 1. Streams table for existing case

No.	G [kg/s]	C_p [kJ/kgK]	T_{in} [°C]	T_{out} [°C]
1	193.4	2.36	192	175
2	119.6	2.36	208	182
3	26.2	2.2	169	47
4	93.5	2.21	138	175.5
5	91	2.21	155	191.5
6	26.7	2.08	134	152

3.2. PA application

As it mentioned before, the first step for applying PA is to list all considered hot and cold streams with their properties, then computing the energy (flux) requirements for each stream by means of (1). Hot streams should be cooled down therefore, computed flux via (1) is called maximum cooling load "$Q_{max,C}$" which is equal to 22.12 MW according to the streams properties which have been listed in Table 1. In a contrary, cold streams should be heated up and same computation is called maximum heating load "$Q_{max,H}$" which is equal to 16 MW.

Next step will be drawing two composite curves by means of Matlab code for hot and cold streams, which is shown in Fig. 5. For the beginning ΔT_{min} considered equal to 30 degrees but as stated before, it is rare to have the same amount of preselected value for the first plot of composite curves. Aforementioned Matlab code provides a useful tool to perform pinch analysis and draw composite curves for more streams which only needs few properties as input.

In Fig. 5, $Q_{min,h}$ and $Q_{min,c}$ are stands for minimum loads. Variation of ΔT_{min} will change the amount of recovered heat as well as external utilities loads. If the difference between minimum and maximum load is significant, it is worth applying PA. In the first attempt, the idea is shifting cold composite curve to the left in order to recover more heat and decrease an external heat load as much as possible (Case 1).

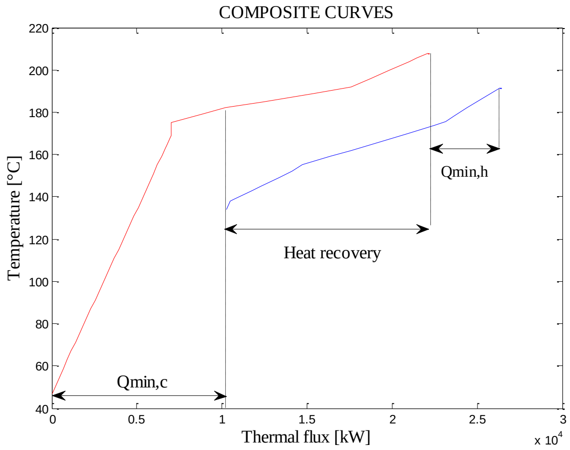

Fig. 5.Composite curves

By choosing ΔT_{min} equal to 16.5 °C which can be obtain either by calculation or graphically, the heating duty of the external utilities are becoming zero, cooling load decreases and heat recovery zone increases (Fig. 6) . Therefore, with this ΔT_{min}, maximum heating load (16 MW) required for heating up cold streams have been recovered from the heat available of hot streams.

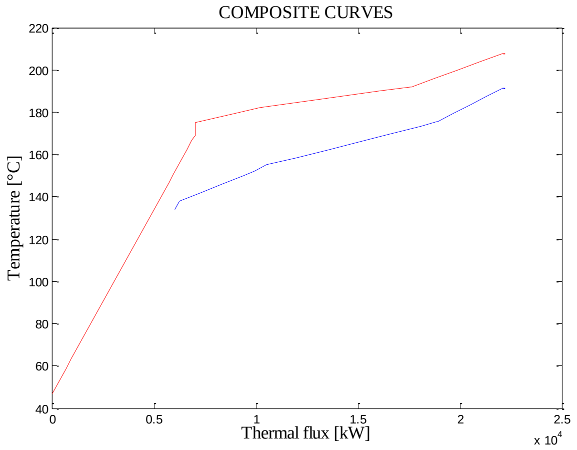

Fig. 6. Composite curve with modified $\Delta Tmin$ (case 1)

An interesting question is how much natural resources are needed to produce this much (16 MW = 504576 GJ/year = 12051.59 toe) of heat load? By considering natural gas as a fuel and taking into account the heating value of natural gas in Iran equal to 8600 Kcal/m^3, it is possible to compute how many cubic meters per hour of gas is needed in order to produce 504576 GJ/year heat flux ;

The result shows that, 14×10^6 m^3/year (1600 m^3/h) of natural gas is needed to produce such amount of heat flux. Considering the price of natural gas equal to 2650 Iranian Rial (IRR) for each m^3 , the amount of annual cost saving will be 3.71×10^{10} (IRR). This amount is equal to 1.4 million dollars according to the exchange rate of Iranian central bank.

In section 3.3, another stream will be added to the existing case in order to recover more available heat inside the system.

3.3. Improvement

As it is evidence from Fig. 6, the amount of cooling load that should be rejected to the extern is equal to 6 MW which could be still useful for heating purposes. The possible suggested option was heating up an additional water stream which is used in desulfurization unit. The source and target temperature of this stream and other properties which needed to perform PA have been written in the last row of Table 2. By adding this new stream, number of cold streams increases to 4 but number of hot streams remain fixed (case 2).

Table 2. Streams table with additional water fluid (case 2)

No.	G [kg/s]	C_p [kJ/kgK]	T_{in} [°C]	T_{out} [°C]
1	193.4	2.36	192	175
2	119.6	2.36	208	182
3	26.2	2.2	169	47
4	93.5	2.21	138	175.5
5	91	2.21	155	191.5
6	26.7	2.08	134	152
7	1.4	4.34	48	85

Fig. 7 shows the upgraded composite curve according to streams that have been listed in Table 2. By simply looking to the composite curves, it is clear that there is still possibility to recover more heat by increasing the mass flow rate of last stream.

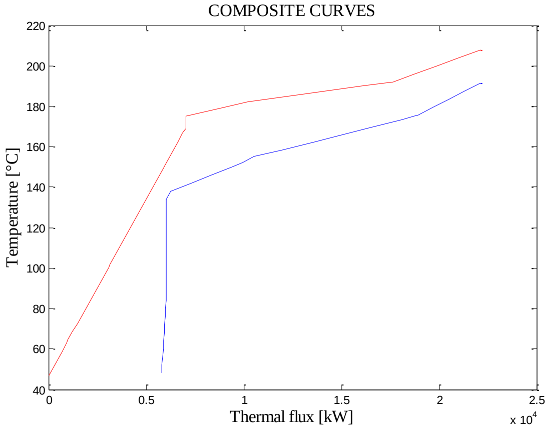

Fig. 7. Upgraded composite curves (case 2)

The idea is increasing mass flow rate gradually, up to the point that heating load starts to change from being zero; Therefore, the corresponded mass flow rate will be the upper bound. By following the procedure, maximum mass flow rate of water, which keeps the heating load equal to zero, will be equal to 57.9 kg/s. By updating last row of Table 2 with new value of mass flow rate, final composite curve for this improved case (case 3), can be drawn (Fig. 8). In this case, the minimum cooling load has reached to 3.9 MW.

In Table 3 one can see the amount of minimum cooling load, the recovered heat in each modification and the corresponded cost saving due to heat recovery in million dollars per year.

Table 3. Summary of modifications

	$Q_{min,c}$ [MW]	Recovered Heat[MW]	Cost of Recovered Heat [10^6 \$ / Y]
Case 1	6	16.12	1.39
Case 2	5.8	16.32	1.42
Case 3	3.9	18.22	1.58

Note that for all cases ΔT_{min} is equal to 16.5 °C and minimum heating load according to the composite curves is equal to zero.

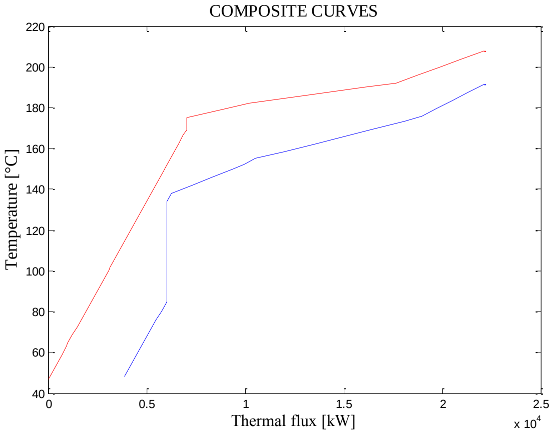

Fig. 8. Final composite curves (case 3)

4. HEN design and investment cost computation

4.1. HEN Design

The primary goal of HEN is to devise an efficient (economically or thermodynamically) heat exchanger network to optimize the exchange of heat between hot and cold process streams with known initial and final temperatures , heat capacities, and flow rates [4, 5].

So far, the PA for computing the amount of recovered heat has been performed, and it's the time for designing a proper heat exchanger network according to the rules which mentioned in section 2.2.

Fig. 9 is the designed heat exchanger network corresponds to the last modification of this case study (case 3).

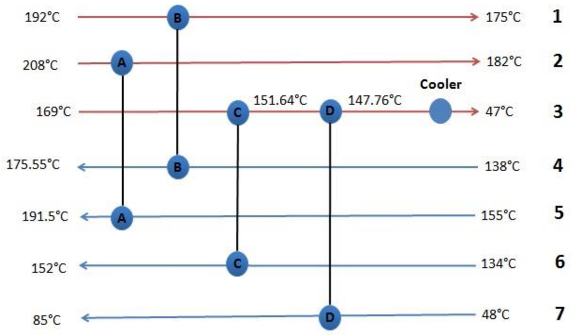

Fig. 9. Heat exchanger network

As it was expected from composite curves, there is no external heat utility in the HEN since heating load was equal to zero, and there is only one cooler that should reject 3.9 MW of flux to the environment. Heat duty, inlet and outlet temperature of each heat exchanger can be computed by performing heat and obtaining heat transfer area.

Next section is devoted to perform investment cost calculation of the HEN and computing payback time due to the saving of the resource consumption.

4.2. Cost computation

For any heat exchanger with a hot and cold stream, the heat requirement is calculated as:

$$Q = G.C_p.\Delta T \tag{2}$$

In addition, the overall heat transfer equation for the exchanger must be solved simultaneously:

$$Q = U.A.\Delta T_{LM} \tag{3}$$

Where U is the overall heat transfer coefficient which is a function of the flow geometry, fluid properties and material composition of the heat exchanger, A is the heat transfer area, and ΔT_{LM} is the log-mean temperature difference which is computed as follows:

$$\Delta T_{LM} = \left(\Delta T_1 - \Delta T_2\right) \;/\; ln\; \left(\Delta T_1 \,/\, \Delta T_2\right) \tag{4}$$

In which; $\Delta T_1 = (T_{hot,in} - T_{cold,out})$ and $\Delta T_2 = (T_{hot,out} - T_{cold,in})$

The log-mean temperature difference between the fluids is in general a function of the fluid properties and flow geometry as well. Heat exchanger design requires consideration of each of these factors. Since in both shell and tube side hydrocarbon passes, the typical overall heat transfer coefficient value for shell and tube heat exchanger could be estimated in a range of 50 to 300 [W/m2K][23]. Equation (4) implies that, the higher the amount of U is, the lower the heat transfer area [24]. However, high value of "U" requires higher investment cost due to its dependency to the material composition of the heat exchanger. By considering the value of overall heat transfer coefficient equal to 175 [W/m2K] and solving(2), (3) and(4), computation of heat transfer area will be straight forward. It is also possible to find out an investment cost of equipment according to the computed heat transfer area by means of curves and tables so called cost curves and installation's cost table which gives quick and rough estimation for investment costs. Fig. 10 shows cost curve related to the sell and tube heat exchanger.[25]

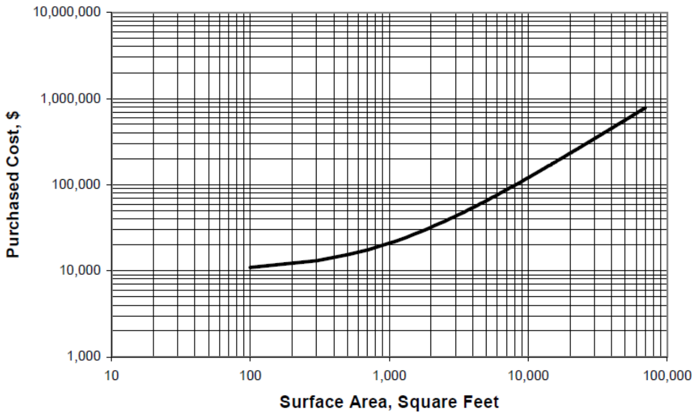

Fig. 10. Cost curve for purchasing shell and tube Heat Exchanger

Table 4 shows calculated heat duties, heat transfer area and investment costs (purchasing plus installation) related to each heat exchanger according to the last improvement (case 3). Note that investment costs have been computed according to the table of price which constructed at 1998.[25]

Table 4 , Exchanger's heat duty, heat transfer area and investment cost

Exchanger	Heat Duty [MW]	Heat Transfer Area [m^2]	investment cost at 1998 [$]
A	7.35	1970	675400
B	7.76	1750	636416
C	0.99	326	170842.5
D	0.224	15.6	66872
Total	16.324	4061.6	1.55×10^6

In order to adjust process plant construction costs from one period to another, Chemical Engineering Plant Cost Index (CEPCI) has been used [26], to correct the past price;

$$\left(\frac{C_2}{C_1}\right)=\left(\frac{I_2}{I_1}\right) \qquad (5)$$

Where; C_1 and C_2 are the prices, I_1 and I_2 are price indexes for past and present respectively. Since this study deals with HEN which includes heat exchangers, piping, valves, etc., it can be considered small part of the plant and composite index can be used to perform the computation ;

From Table 4, total cost of the network is equal to $C_1 = 1.55 \times 10^6$ $ and from CEPCI, annual average price index for past and present year can be extracted; $I_{1,\,(1998)} = 389.5$, $I_{2,(2013)} = 566.4$

The amount of updated total cost can be computed via (5) and it is equal to $C_2 = 2.25 \times 10^6$ $.

Now by looking to Table 3 and considering cost of recovered heat for case 3 which is actually resource saving due to PA application, it is possible to compute payback time of the investment cost(C_2) in order to construct HEN. Result shows the payback time of the investment is approximately equal to 17 months.

5. Conclusion

One of the most important roles in many industrial processes is reducing energy consumptions. Saving and optimizing the energy usage is a promise to meet the goal of an optimum energy cost and to gain more profitability.

In this paper, a very small scale of a real condition in a petrochemical plant has been analysed from the heat recovery point of view as well as economic aspect of the modification.

The result of first evaluation in terms of composite curve shows that by reducing the value of minimum temperature difference, the amount of recovered heat increases and on the other hand, external utilities duty decreases (Fig. 5 and Fig. 6 with 30 °C and 16.5 °C ΔT_{min} respectively).

The idea was to add another stream in order to recover more heat inside the system. For this purpose, the 48 °C water stream has been selected to be heated up. Next step was increasing the mass flow rate of water stream while minimum heating load remains zero. Then with the new mass flow rate of additional stream (case 3), HEN has been designed and heat transfer area is calculated. Finally, the investment and payback time have been computed, which is almost 17 months in this case.

In the next study, it is possible to draw a curve like Fig. 3 specifically for this case study, which shows the relationship between variation of energy and utility cost with different ΔT_{min} .

Numenclature

A	Heat transfer area, m^2
C	Cost, $
CEPCI	Chemical Engineering Plant Cost Index
C_p	Specific heat capacity, KJ/ (Kg K)
G	Mass flow rate, Kg/s
HEN	Heat Exchanger Network
I	Cost index
IRR	Iranian Rial
NC	Number of cold streams
NH	Number of hot streams
PA	Pinch Analysis
Q max,C	Maximum cooling load, MW
Q max,H	Maximum heating load, MW
Tin	Source temperature, °C
Tout	Target temperature, °C
toe	Tonnes of Oil Equivalent
U	Overall heat transfer coefficient, W/(m^2 K)
ΔT	Temperature difference
$\Delta Tmin$	Minimum temperature difference
ΔT *LM*	log-mean temperature difference
Φ	Heat Flux, MW

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