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Analysis of Heat Exchanger Network of Distillation Unit of Shiraz Oil Refinery

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Abstract**—**The reduction of energy consumption through improvements in energy efficiency has become an important goal for all industries, in order to improve the efficiency of the economy, and to reduce the emissions of Co$_2$ caused by power generation. The objective of this paper is to investigate opportunities to increase process energy efficiency at the distillation unit of Shiraz oil refinery in south of Iran. The main aim of the project is to locate energy savings by use of pinch technology and to assess them. At first all the required data of hot and cold streams in preheating section of distillation unit has been extracted from the available flow sheets and then pinch analysis has been conducted. The present case study is a threshold one which does not need any utilities. After running range, targeting several heat exchanger networks were designed with respect to operating conditions and different ΔT_{min}. The optimal value of ΔT_{min} was calculated to be 22.3 °C. Based on this optimal value, there will be 5% reduction in annual total cost of heat exchanger network.

Keywords**—**Pinch technology, heat exchanger network, operating cost.

I. INTRODUCTION

PROCESS integration technology has been extensively used in the processing and power generating industry over the last 35 years and was pioneered by the Department of Process Integration, UMIST (now the Center for Process Integration, CEAS, The University of Manchester) in the late 1980's and 1990's. It has extended concepts and methodologies in the design of energy based systems from the established Pinch Technology. The term "Pinch Technology" was introduced by Linnhoff and Vredeveld [1] to represent a new set of thermodynamically based methods that guarantee minimum energy levels in design of heat exchanger networks.

Energy conservation remains the prime concern for many process industries while oil prices continue to increase and by attention to this issue will increase with rising energy costs and environmental constraints.

Most industrial processes involve heat transfer either from one process stream to another process stream (interchanging) or from a utility stream to a process stream. In the present energy crisis scenario in all over the world, the target of any industrial process design is to maximize the heat recovery process and to minimize the utility requirements.

To meet the goal of maximum energy recovery or minimum energy requirement (MER), an appropriate heat exchanger network (HEN) is required. The design of such a network is not an easy task considering the fact that most processes involve a large number of process and utility streams. The traditional design approach has resulted in networks with high capital and utility costs. With the advent of pinch analysis concepts, the network design has become very systematic and methodical [1], [2].

Pinch Technology is a methodology, comprising a set of structured techniques, for systematic application of the first and some aspects of second laws of thermodynamics. The application of these techniques enables process engineers to gain fundamental insight into the thermal interactions between chemical processes and the utility systems that surround them. Such knowledge facilitates the improvement of the overall utility consumption, and setting process and utility system configurations prior to final detailed simulation and optimization [3]–[5].

Three golden rules for the designer wishing to produce a design to achieve minimum utility targets:

- Don't transfer heat across the pinch.
- Don't use cold utilities above the pinch.
- Don't use hot utilities below the pinch [6].

Conversely, if a process is using more energy than its thermodynamic targets, it must be due to one or more of the golden rules being broken. As it is mentioned in following, this may be a deliberate compromise, but it is important to know that it happens. The decomposition of the problem at the pinch turns out to be very useful when it comes to network design [7]. The process needs external heating above the pinch and external cooling below the pinch. This tells us where to place furnaces, steam heaters, coolers, etc. It also tells us what steam site services should be used and how we should recover heat from the exhaust of steam and gas turbines.

In the present study, the HEN of the preheat train of the Shiraz refinery's distillation unit has been investigated. After PFD (process flow diagram) study of the unit, each stream specification was extracted. Then in the next section, the current HEN of the unit was evaluated. Composite curves were plotted and it was revealed that we had a "threshold problem" ahead. Eventually in the final part, different networks were designed based on different ΔT_{min}. Then, the optimal design was selected and it is shown that in this design we will have 5% reduction in the total cost.

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II. CASE STUDY

Distillation unit of Shiraz oil refinery, refines and distillates crude oil which is supplied from three oil tanks: T-2001, T-2002 and T-2003. This unit involves three subsections:

1) Crude distillation section
2) Stabilizer section
3) Vacuum section.

Fig. 1 shows the flow sheet of preheat section of distillation unit of Shiraz oil refinery. The HEN includes six heat exchangers E101, E102, E103, E104, E105, and E129 as shown in Fig. 1. The crude oil feed stream at 20 °C is preheated in three sections by hot streams of distillation products including Kerosene, Kerosene product, Light gas oil, heavy gas oil and vacuum column bottoms to around 200 °C. Then it is heated to 369 °C by two heaters (H101 and H102).

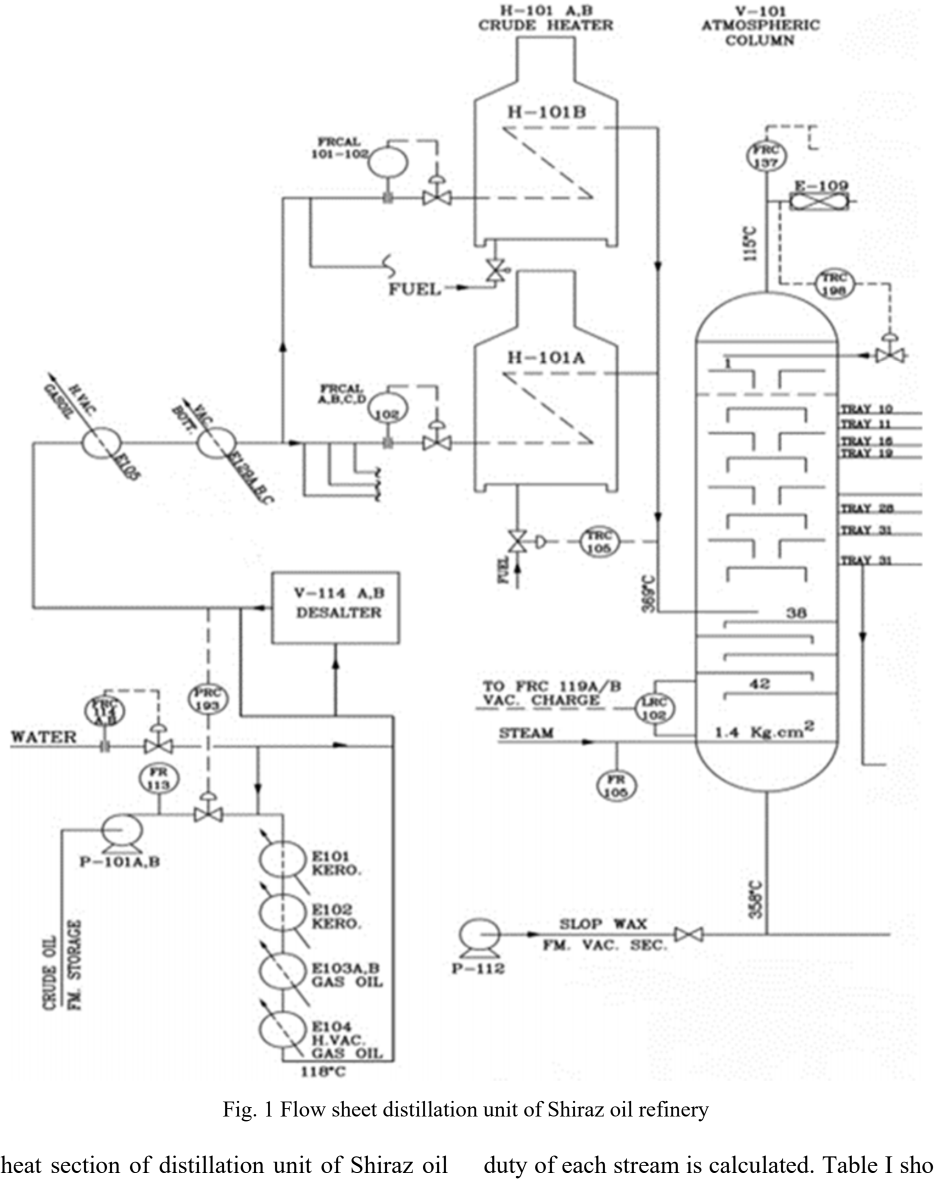

Fig. 1 Flow sheet distillation unit of Shiraz oil refinery

Streams of preheat section of distillation unit of Shiraz oil refinery are shown in Fig. 2. After the inspection of flow sheets and data files of the distillation unit, the HEN of the current process section can be extracted. The necessary data are temperatures, heat duty, heat capacity of each stream and available utility data. The cost data is also necessary to estimate energy cost and capital investment.

This study uses real operating data of the plant to extract the temperature and flow data of the process streams and the heat duty of each stream is calculated. Table I shows extracted data from the distillation unit process. It involves stream numbers and names, type of streams (of cold or hot), supply temperature (T_s), target temperature (T_t), heat capacity flow rate (*FCP*) and convective heat transfer coefficient (*h*). There are 5 hot streams and 2 cold streams in the process.

TABLE I
STREAMS DATA

Stream Number	Stream's Name	Initial Temperature T_s (∘C)	Target Temperature T_t (∘C)	Type	*FCP* (kw/∘c)	*Q* (kw)	*h* (kw/m^2∘c)
1	C1	26.6	121	Cold	133.20	12574.2	765
2	C2	118.3	204.4	Cold	153.76	13239.2	765
3	H1	182.2	48.9	Hot	22.63	3016.9	221.42
4	H2	193.3	157.2	Hot	81.14	2929.0	1141.98
5	H3	251.6	126.6	Hot	21.39	2674.2	595.61
6	H4	273.9	141.7	Hot	80.98	10705.4	382.7
7	H5	398.9	254.4	Hot	44.90	6487.7	76.09

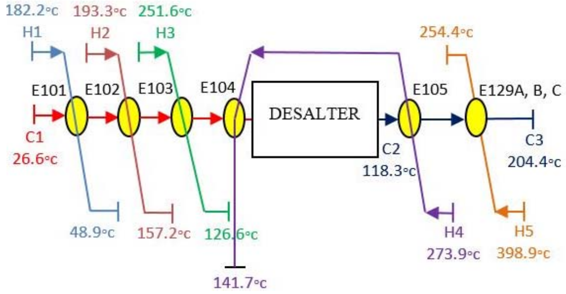

Fig. 2 Streams of preheat section of distillation unit of Shiraz oil refine

Table II shows cost data which is used to estimate economic efficiency [8]. Design by pinch technology is a trade-off problem between energy saving and capital investment. Outcomes are assessed by the relative amount of the cost saved and investment required. Therefore, the precise cost data are very important in real design problems since the results are influenced directly by the cost data. Utility cost and heat exchanger parameters in Table II are needed to calculate the energy cost saving and investment cost.

TABLE II
COST DATA TO CALCULATE ECONOMICAL EFFICIENCY

Utility Cost	C_U ($/KJ.year)
Steam	140
Cooling Water	18.2
Heat Exchanger Cost	$
Carbon Steel	33,422 + 814 × [Area (m^2)]$^{0.81}$

III. EXISTING HEN ANALYSIS

The existing HEN is drawn by the previous data extracted. Fig. 3 is a diagram of the existing HEN of the process. As mentioned before the process consists of 5 hot streams and 2 cold streams. Hot streams are located in the upper side of the diagram and cold streams are in the lower side. The existing HEN has six heat exchangers between process streams. Utility has not been used. From the HEN diagram and cost data, capital cost of the existing process is calculated and shown in Table III.

Fig. 3 shows that the existing HEN is operated rather efficiently and recovers a lot of heat energy from hot streams. However, there is always a possibility to improve things further. In this study composite curves are employed to investigate this possibility. Fig. 4 is the composite curve of the process. The composite curve has two curves, which are a hot composite curve and a cold composite curve. Each curve shows composited hot streams and cold streams [9]. The composite curve represents that no heating and cooling is required.

The distance which is pointed in Fig. 4 is the ΔT_{min} (minimum temperature difference), which means the minimum driving force for heat exchange. Temperature differences of the two curves have to be over ΔT_{min} in all temperature range. At the pinch point, two curves approach closest and the temperature difference of two composite curves is ΔT_{min} [2].

The ΔT_{min} is related to economic efficiency of heat exchangers because the quantity and the area of heat exchanger are directly affected by ΔT_{min}. The value of ΔT_{min} varies by the characteristic of a process. In a heuristic pinch problem, a process with vapor phase and high temperatures over 300 °C uses over 20 °C of ΔT_{min}. A process with very low temperatures about 0 °C uses under 5 °C of ΔT_{min}. And a process between previous two characteristics uses about 10 °C of ΔT_{min} [10].

TABLE III
EXISTING HEAT EXCHANGERS TABLE

Heat Exchanger	Th_i °C	Th_e °C	Tc_i °C	Tc_e °C	*U* w/m^2∘C	*Q* kW	AREA m^2	cost $
E101	182.2	48.9	26.6	48.9	171.7	3016.9	283	112230.2
E102	193.3	157.2	48.9	72.2	458.1	2929.0	55.8	54576.27
E103	251.6	126.6	72.2	100	334.9	2674.2	84.2	62942.74
E104	193.3	141.7	100	121	249.9	3954.1	284.6	112590.9
E105	273.9	193.3	118.3	164.4	260.2	6751.3	284.6	112590.9
E129	398.9	254.4	164	204.4	69.2	6487.7	690	300134.9
						capital cost		755065.9

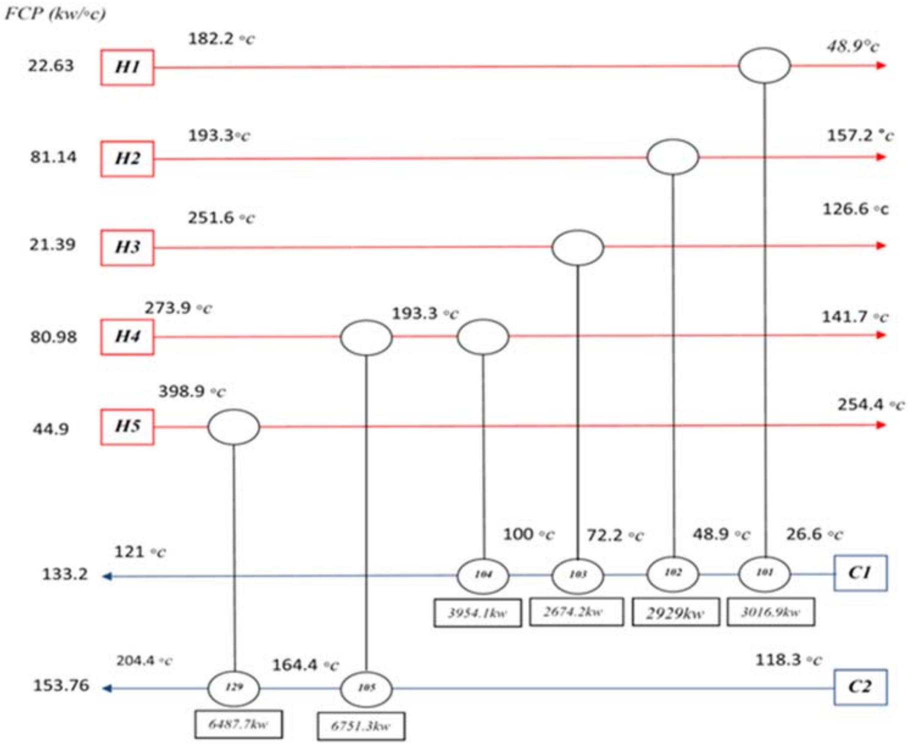

Fig. 3 Existing HEN diagram

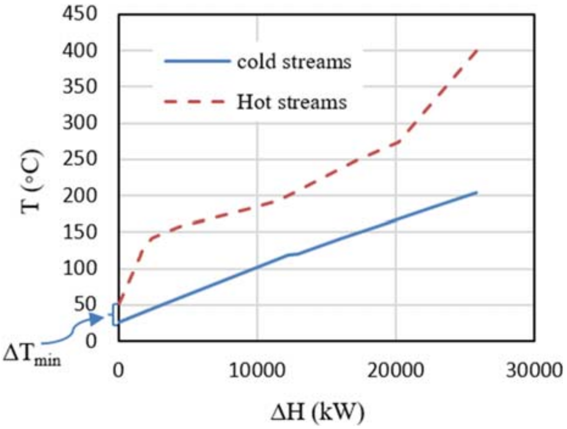

Fig. 4 Composite curve of the existing HEN

After investigating composite curves and tables for different streams, it was concluded that the optimal value of minimum temperature difference is ΔT_{min} = 22.3°C. In Fig. 4, it can be clearly seen that this is a threshold problem because no utility is used and pinch point situated in the left side of composite curves.

IV. IMPROVEMENT AND HEN DESIGNS BASED ON DIFFERENT ΔT_{MIN}

It is well established that in threshold problems, as long as we have $\Delta T_{min} < \Delta T_{Threshold}$, the operating cost will be constant. Therefore, 5 HENs have been designed for the interval of 22.3 °C< ΔT_{min} <30 °C by the step of 2 °C as shown in Figs. 5-9. On the diagrams, utility use is represented by capital letters in a square. C is cooler and H is steam heater. Higher driving forces mean lower heat exchanging area. Characteristics of these HENs are compared in Table IV.

Now, optimization of the system viewed must be done. Optimization means determination of optimal ΔT_{min} for the case through determination of the minimum heat exchange area, optimal number of heat exchanger units, and minimum costs (operational and capital costs).

The minimum number of heat exchanger units is determined by (1):

$$N_{min} = (NA - 1) + (NB - 1) \quad (1)$$

where NA and NB are count stream numbers (including utilities) above and below the pinch, respectively. Table IV shows capital costs and heat exchange area for different values of ΔT_{min}. The capital cost is based on (2) and (3),

$$\text{Capital Cost} = N_{shell}\left[a + b\left(\frac{A_{exchanger}}{N_{shell}}\right)\right]^{c} \quad (2)$$

where A is a heat exchange area, a, b and c are cost parameters and N is number of shell units in network.

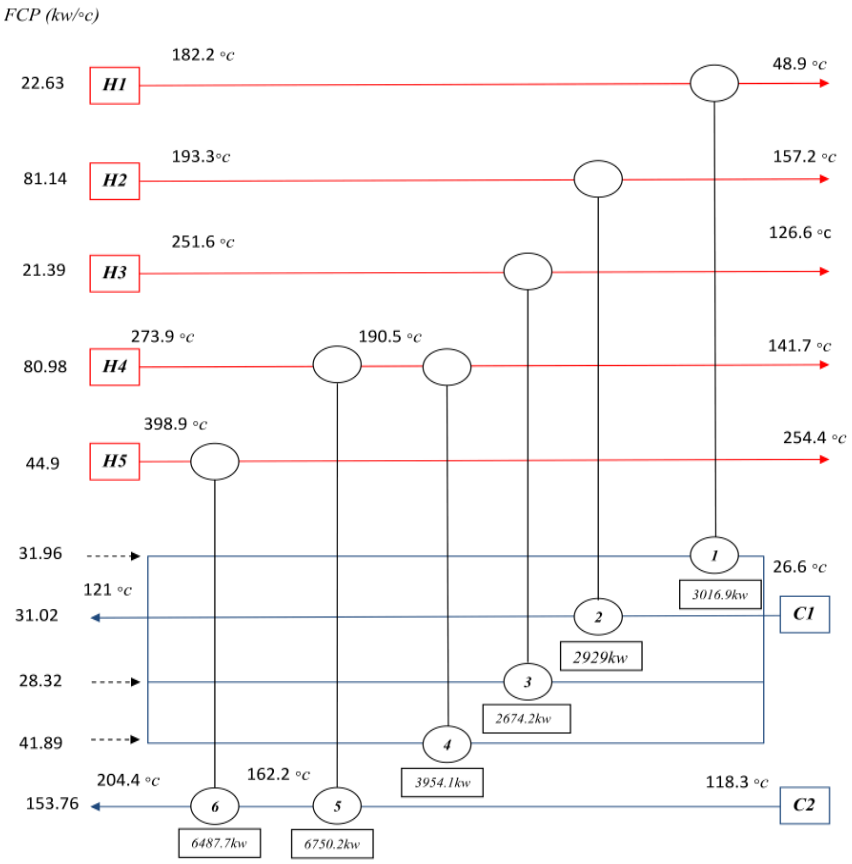

Fig. 5 Diagram of HEN for ΔT_{min}=22.3 °C

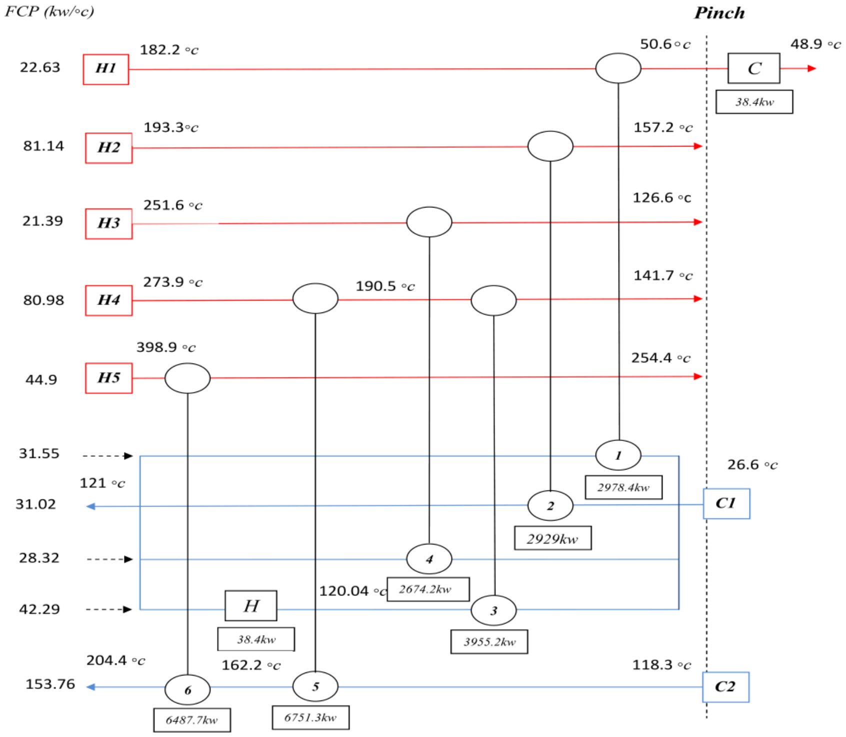

Fig. 6 Diagram of HEN for ΔT_{min}=24 °C

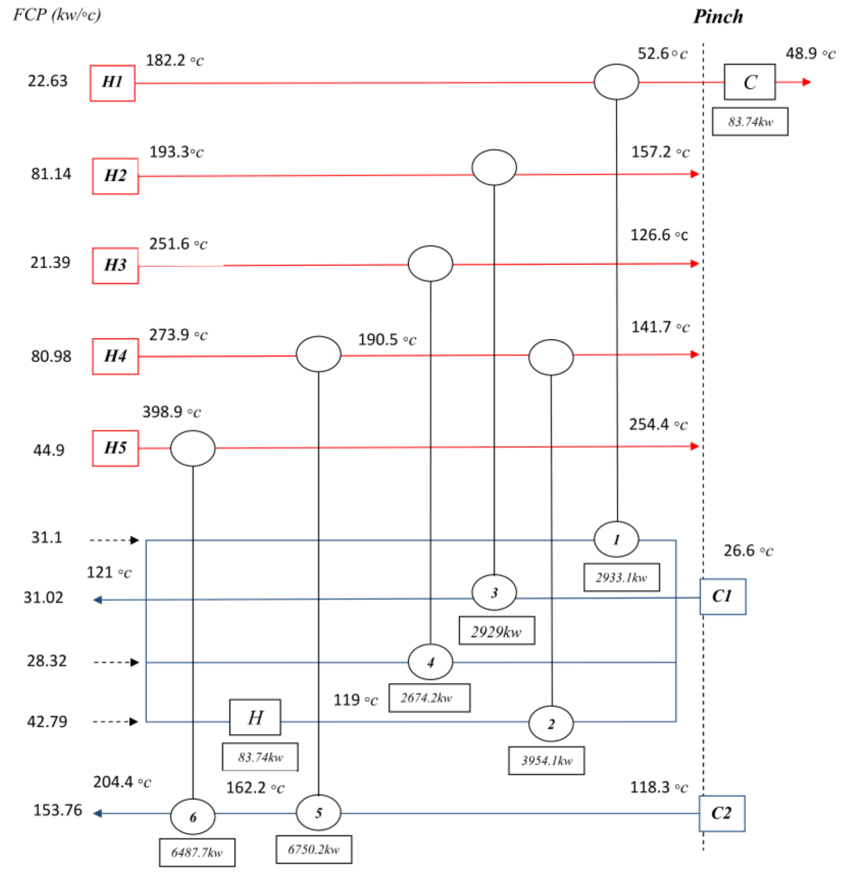

Fig. 7 Diagram of HEN for ΔT_{min}=26 °C

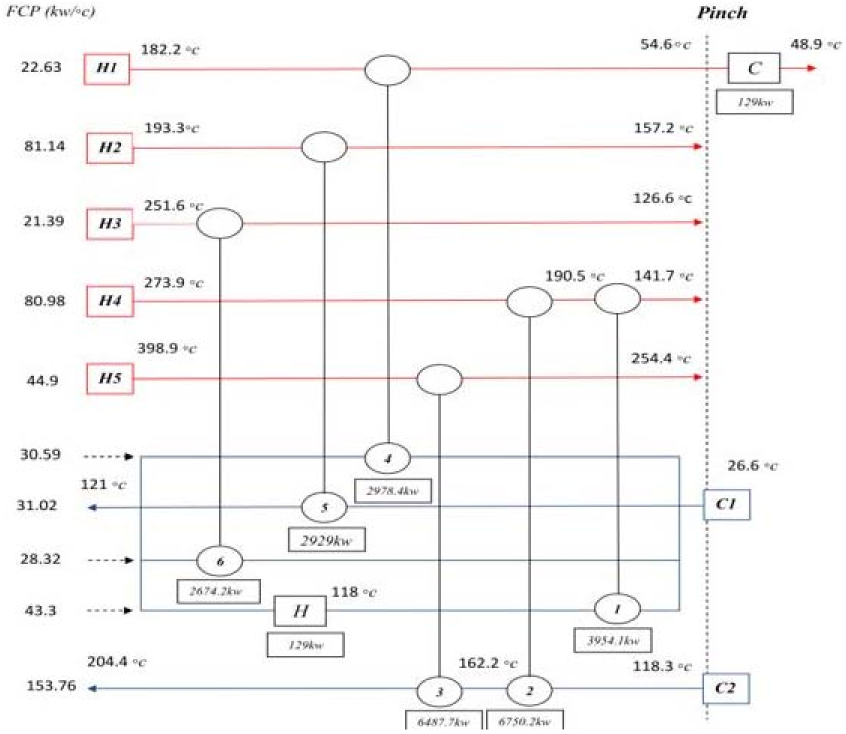

Fig. 8 Diagram of HEN for ΔT_{min}=28 °C

$$\text{Annualized Factor} = \frac{i(i+1)^n}{(i+1)^n-1} \tag{3}$$

where i is rate of return and n is plant life. For this study, *i* is 4 percent and n is equal to 12 years. Operating costs represent cost for utility using, and they are calculated with (4), as well as total annual costs, (5).

$$\text{Operating Cost} = \sum_{U=1}^{n} C_{u.min} \cdot Q_{u.min} \tag{4}$$

where Q_U is duty of utility (U / kW), C_U is unit cost of utility (U / \$/kW or year) and *U* is total number of utility used.

$$\text{Total Cost} = AF \times OC + CC \tag{5}$$

where *AF* is Annualized Factor, *OC* is Operating Cost and *CC* is Capital Cost.

All heat exchangers are of shell and tube type, and due to the Shiraz refinery's process restrictions only one material is available, and the cost is determined by temperature and heat exchanging area.

Using pinch technology rules for HEN design, the designer can make many alternatives for different combinations of connecting heat exchanger units. Table IV shows summarized data of the candidate HENs. In essence, the heat exchanger area is roughly inversely proportional to the temperature difference.

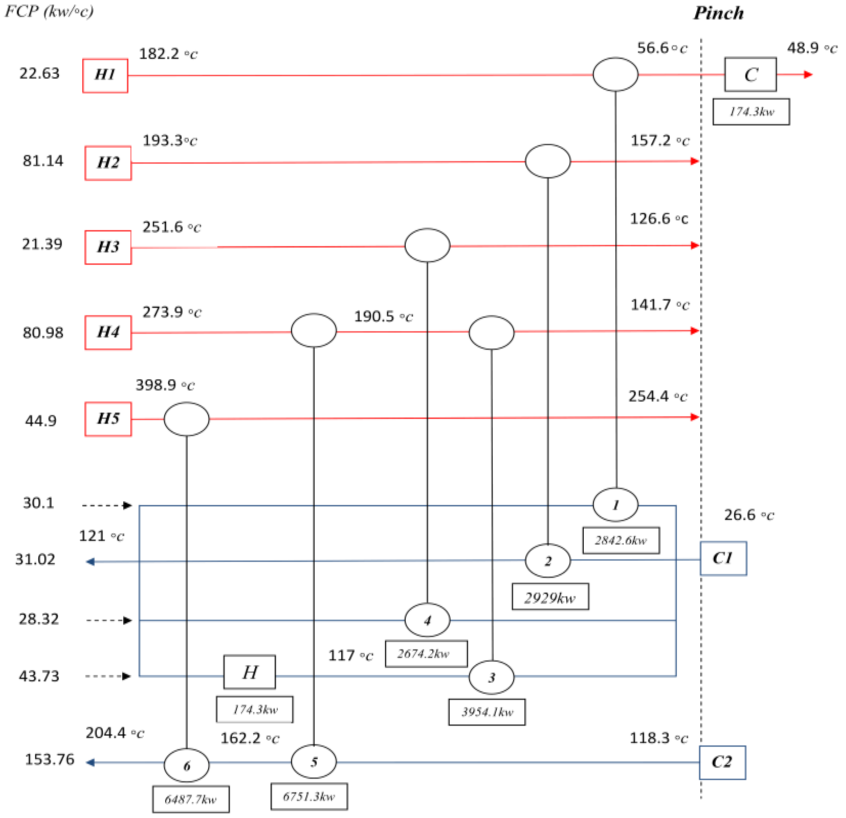

Fig. 9 Diagram of HEN for ΔT_{min}=30 °C

TABLE IV
COST OF HENS

HEN Number	ΔT_{min} °C	$A_{network}$ m^2	Capital Cost \$	Operating Cost \$	Total Cost \$	% of changing respect to existing HEN
Existing HEN	22	1682.2	80453	0	80453	-
1	22.3	1738.3	76326	0	76326	5% Decreasing
2	24	1717.8	75869	6075	81944	2% Increasing
3	26	1695.6	75369	13248	88617	10% Increasing
4	28	1675.2	74907	20408	95315	18% Increasing
5	30	1656.3	74477	27574	102051	27% Increasing

As it is demonstrated in Fig. 10, low values of ΔT_{min} can lead to very large and costly exchangers, as capital cost is closely related to area. Therefore, utility use rises linearly with ΔT_{min}, whereas exchanger area rises very sharply (asymptotically) for low ΔT_{min} values. We can see that there is an optimum for ΔT_{min} in this case, about 22°C. Clearly, it will be important to choose the right value of ΔT_{min} for our targeting and network design.

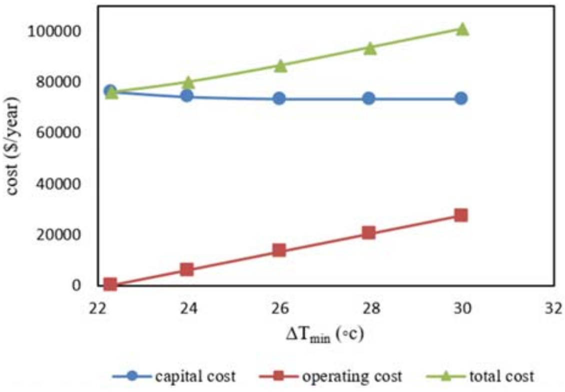

Fig. 10 Costs diagram based on ΔT_{min}

V. CONCLUSION

The purpose of present study was to investigate opportunities to increase process energy efficiency at the distillation unit of Shiraz oil refinery by the use of the pinch technology. Another considerable parameter was changing the material of the heat exchanger which could reduce the capital cost; but, in the case of our study and due to the refinery's restrictions changing the material was not an applicable, whereas the pinch analysis is more flexible. By extracting all the required data from the refinery's flow sheets we realized that in our study we would deal with a threshold problem which did not need any utilities. Then by conducting the pinch analysis and range targeting several new HENs were designed with respect to operating conditions and various ΔT_{min}. According to Fig. 10 and Table IV, by increasing ΔT_{min} capital cost decreases and operating cost increased. In the regions where energy prices are rather low, ΔT_{min} could be set higher since by doing so capital cost declines. However, in our investigation the optimal value of ΔT_{min} is 22.3 °C and based on energy consumption this design is affordable. There will be 5 percent reduction in annual total cost of HEN. Today by instantaneously increasing prices of energy saving, 5 percent of the total cost makes a lot of difference and shows how powerful and effective the pinch analysis could be.

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