Graphical Analysis and Revamping of Crude Distillation Units under Variable Operational Scenarios

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Case Report

Graphical analysis and revamping of crude distillation units under variable operational scenarios

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ABSTRACT

Energy cost represents a significant part of the total operating costs of many processing units. Crude distillation is an energy intensive process. Energy integration is a typical solution to reduce heating and cooling utilities through maximizing the target temperature of crude oil streams before entering the furnace. Over the past few decades, significant progress has been made in energy integration methods including pinch technology and mathematical programming approaches. Very recently, graphical techniques have been developed for revamping studies and energy analysis. Such diagrams are valuable in energy targeting to identity energy inefficiencies and are key to potential modifications for maximum energy integration. The current research applies the recent graphical revamping methodology on an existing crude atmospheric distillation unit. The unit is located in north of Egypt (Suez region) and is operated under two different operational modes; (1) without naphtha stabilizer; the process reformer is in operation to reform all naphtha streams without stabilization and (2) with naphtha stabilizer; LPG is separated from naphtha stream. A graphical-based revamping methodology is applied to retrofit the existing preheat train. The revamping procedure starts by simulating the existing HEN data, followed by validation against the real data. The current performance of the HEN is analyzed using the graphical axes of T_{hot}-T_{cold} diagrams. The graphical method is then used to identify exchangers across the pinch and recognize the potential modifications to improve the energy performance and reduce fuel consumption. Implementing the graphical identified modifications on the plant resulted in the following benefits: (1) when stabilizer is in operation, energy savings are achieved by 21.1% with additional capital investment of 0.81 MM$ and annual energy savings of 0.82 MM$, with a payback period of one year. (2) when reformer is in operation, the energy savings are 0.42 MM$ with capital investment of 0.33 MM$. The methodology results provide a flexibility in refineries operations.

1. Introduction

Nowadays, the oil refining industry is facing a large number of challenges. Among such challenges are the high increase in crude prices, continuous oscillation in product demand due to market fluctuations and strict environmental regulations on industrial processes [1]. Fig. 1 presents the world energy consumption by energy source with the predicted consumption up to the year 2040. It is clear that consumption of refinery products is expected to increase immensely.

Thus, refiners are forced to select more energy efficient methodologies and consequently they are exerting concerted efforts to improve energy efficiency for both existing and new units, which in-turn would help increase their profit and reduce their energy consumption cost [2].

The energy expenses make up a significant proportion of the overall operational expenditure for numerous processing facilities, including crude oil processing in refineries and energy intensive processes in

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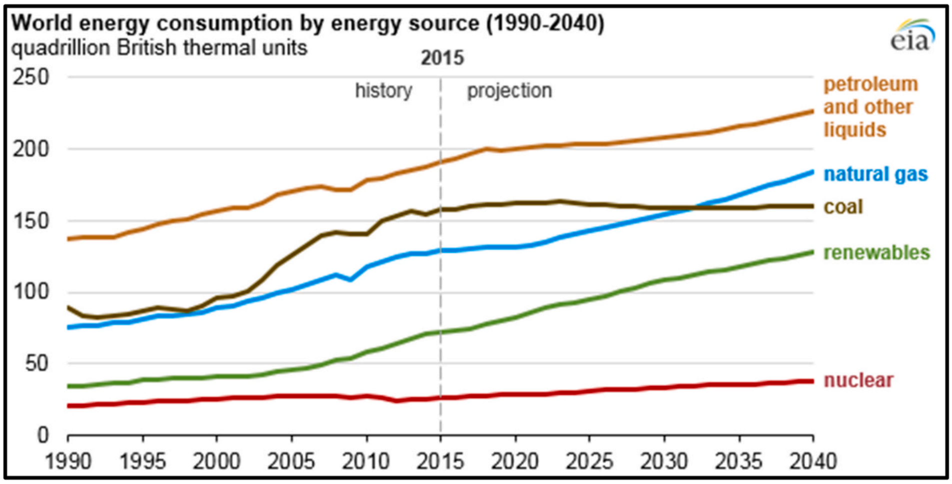

Fig. 1. World energy consumption by energy source (1990–2040) [3].

chemical plants. Among the process equipment and unit operations used, the most energy consuming unit is the distillation unit. The energy problems of crude distillation units in refinery plants were reviewed by Gadalla et al. [4] as the main energy-intensive unit and concentrated on the optimization of existing operating conditions to minimize energy requirements.

Smith [5]introduced the energy consumption fundamentals in the distillation industry, revamping of distillation units, distillation sequencing and optimization of its superstructure. He presented all principles of the Pinch Analysis in details. Pinch Analysis plays a crucial role in improving energy efficiency, reducing operating costs, and enhancing the environmental performance of industrial processes. It is an essential tool for sustainable process design and energy management in various industries, including chemical, petrochemical, refining, and manufacturing. Besides, El-Halwagi [6] utilized distillation units in many applications for energy integration and optimization and added an introduction to the conceptual design of bio-refining distillation as an alternative prospective.

Generally cooling and heating utilities consume a huge amount of energy in many chemical and petrochemical industries as shown in Tables 1 and 2. In separation processes and crude oil cracking fired heaters burn a huge amount of natural gas or fuel oil to supply energy required for crude oil fractionation [7]. In addition, steam used in stripping or heating, is produced by the combustion of fuel products or natural gas. On the other hand, cooling is provided for the removal of heat of reactions in a number of industrial applications.

Energy integration or heat recovery for processes is the minimization of energy consumption by recovering heat from hot streams or units which require cooling and heating cold streams or units that need heating. Hot process streams and units are known as heat sources while cold process streams and units are known as heat sinks [8,9]. Such integration is usually applied in heat exchanger networks and in the preheating train of processes. The overall energy consumption for a process is the energy amount provided by the external utilities. The more external requirements are needed by the process, the more is the process cost [10].

The present study concentrates on the revamping of heat exchanger networks for the crude oil distillation unit. Many times, operational optimization of distillation units is applied more than revamping. While implementing operational optimization is easy in both the distillation units and the HENs as the equipment structure doesn't change, it is more popular to revamp the HEN than the distillation tower [11,12]. Structural changes of the distillation unit are more complex because they require higher capital investment and more installation time than structural changes of the HEN, which usually require the relocation of existing heat exchangers or addition of ones and the installation of stream splitters [13].

The application of revamping of projects and operational optimization is motivated by increasing of productivity, the changes in feedstock conditions and the increase of energy cost.

Nowadays, in any industrial design, one of the main targets is to maximize the heat recovery in the process and to minimize the energy requirement (utility consumption). To reach this target pinch analysis is used [14]. Graphical methodology (Composite Curves) is one of the methods that used to achieve the minimum heat requirements. In this method, temperature-enthalpy (T-H) profiles for both energies available in the process "hot composite curve" and energy demands "cold composite curve" are graphically represented [15]. Composite curves help determine the minimum energy target, minimum hot utility requirement "QH_{min}" and minimum cold utility requirement "QC_{min}" for a given ΔT_{min}.

Since composite curves do not indicate individual temperatures of the hot and cold streams, areas of heat exchangers and driving force between hot and cold streams, thus the heat load across the pinch and negative temperature difference exchangers cannot be fixed graphically within the existing HEN. As a result, it is not possible, using composite curves, to specify accurately the positions of heat exchangers. The grid diagram is a popular method to represent the existing HENs. This diagram is a simple representation of the existing HEN showing the outlet and inlet streams and their connections, but does not predict the presence of the network pinch, especially in very complicated networks [16].

A design method was presented by Nordman and Berntsson [17] by using pinch analysis with modified grand composite curve (GCC). The

Table 1
Heat exchangers modification cost [24].

Item	Value
Exchanger additional area ($)	1530*(additional area, m^2)$^{0.63}$
New heat exchanger ($)	6000 + A*200
Exchanger relocating & resequencing ($)	35,000

Table 2
The utility costs used in the calculations.

Item	Value
Fired heating (1000–400 °C) ($/MWH)	7.23
Cooling water (10–40 °C) ($/MWH)	3.38
Electricity ($/MWH)	9.35
HP steam (250–249 °C) ($/MWH)	70.05

disadvantage of the GCC is that it does not provide any information about the existing network, so changes implemented in the network to reach the optimal level are not indicated. To solve this problem, eight various curves have been drawn (four below the pinch and four above the pinch) for all measures. The four curves above pinch are; the extreme heat load curve (EHLC), theoretical heat load curve (THLC), actual heat load curve (AHLC), and hot utility curve (HUC). Those below the pinch are; the extreme cooling load curve (ECLC), theoretical cooling load curve (TCLC), actual cooling load curve (ACLC), and cooling utility curve (CUC). Using these curves, changes in complexity in heating and cooling could be fixed and evaluated. Nordman and Berntsson [17] noticed that the investment cost depended on where the AHLC curve is placed between the EHLC curve and the THLC curve. In a later study, Nordman and Berntsson [18] developed a graphical method for revamping HENs. The method included various scenarios (heating cross pinch, cooling above the pinch and heating below the pinch), as well as different revamp alternative solutions. They identified networks that minimize the problem size (for a fixed level of heat recovery) and evaluated their economic feasibility before detailed design. The overall external energy consumption was reduced by adjusting heat exchangers among process streams, preventing heating cross pinch, and correcting pinch violations (such as heat exchange cross pinch, above pinch cooling and below pinch heating). They used a comprehensive cost calculation which involved new exchangers cost, additional area cost and piping, valves and pumps costs. Thus there, graphical representation presented a very good insight for feasible solutions [19].

A pinch revamp method was developed by Li and Chang [20] that identifies heat transfer cross pinch and then eliminates, shifts or relocates them to below or above pinch depending on general design guidelines. When the heat exchange cross-pinch is eliminated, the heat load is divided and transferred to different process streams. To reduce heat exchangers numbers, the conventional tick-off tool is used with few changes. The modifications are: maximize heat duty of match above the pinch to relocate heat load on a hot stream; if this is not applicable, then the heat duty should equal the heat load of the cold stream and that for matches below the pinch. The networks were revamped by eliminating the heat transfer across the pinch at a moderately low capital cost.

Recently, Gadalla [21,22] developed a new graphical representation for the revamping of heat exchanger networks. Temperatures of hot energy sources were analyzed for an existing preheat train versus streams of cold energy sources. Y-axis represents the temperatures of all hot streams in the developed graphical representation, while the X-axis represents the corresponding temperatures of the cold streams. Each heat exchanger was plotted graphically and locations of the network inefficiencies were identified. However, the work did not take into consideration the driving force and the area of all heat exchangers in the analysis.

This paper proposes the T-T Graphical Analysis method compared with other applicable methodologies for HEN revamping. The aim is to ensure that the graphical presentation is better for performance enhancement and energy saving as it identifies the network pinch location and exchangers of heat cross pinch.

By using the T-T graphical approach, the Pinch Analysis Principles can be easily applied for more energy improvements. In this paper heat integration is applied to an existing heat exchanger network with two operational modes:

- with naphtha stabilizer when LPG is separated from naphtha stream, and
- without naphtha stabilizer when the process reformer is under run to reform all naphtha streams without stabilization to decrease the energy consumption.

Decreasing energy requirements leads to saving in operating costs due to the decrease in utilities consumption.

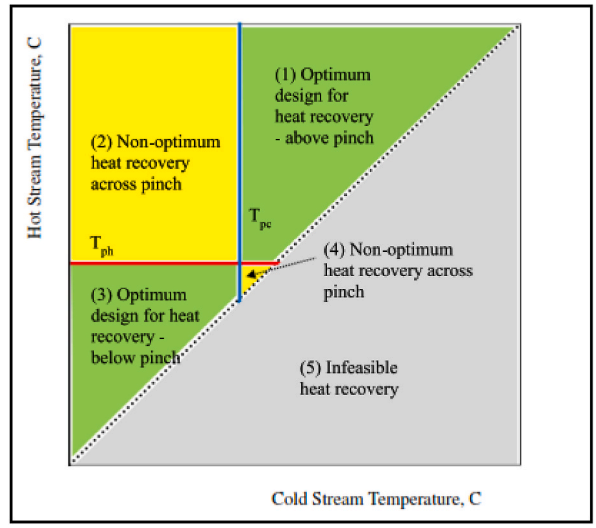

Fig. 2. Feasibility regions diagram for heat recovery [25].

2. Methodology

Revamping the heat exchanger network is proposed to be carried out in three main steps to maximize the temperature of the crude oil stream before entering the furnace, thus reducing the furnace duty and energy consumption [23]. The first step involves creating a model of the existing plant using Aspen Hysys with different operational scenarios, the second step involves validating the model results against real plant data, and the final step involves applying revamping through T-T Graphical Analysis and Standard Pinch methods. A complete economic study is performed to evaluate the cost of different scenarios and select the optimal solution.

To calculate the total investment cost for the modified networks

Total investment cost = (additional area cost + relocation cost + cost of new exchangers) × 2019 cost index

2.1. T-T graphical analysis method

The T-T graph is constructed to represent the existing HENs. Each exchanger is represented by a straight line, the slope of which is proportional to the heat capacities ratio of its hot and cold streams and its length proportional to the heat load transferred.

That graphical representation could easily recognize heat exchangers across the pinch, the pinch of the network, pinching matches and suitable replacement for energy saving. Besides, such a graph could identify promising adjustments to improve the energy performance and lower the consumption of fuel and cooling water [25]. In Fig. 2, the feasibility regions for heat recovery could be identified and thus suitable modification of an existing HEN for energy saving could be recognized.

Fig. 2 shows that heat exchangers in regions (1) and (3) demonstrate an energy-efficient design with maximum heat recovery. In region (1) above the pinch, only external hot utilities are needed, while in region (3) below the pinch, only external cold utilities are needed. The steps of the graphical-based revamping method are presented in Fig. 3.

3. Case study and results

The methodology presented in Fig. 3 was applied to a case study of an atmospheric distillation unit for energy analysis. Actual industrial data were supplied by SOPC (Suez Oil Petroleum Company, Suez, Egypt). The existing unit is operated under two different operational modes; (1) without naphtha stabilizer when the process reformer is in

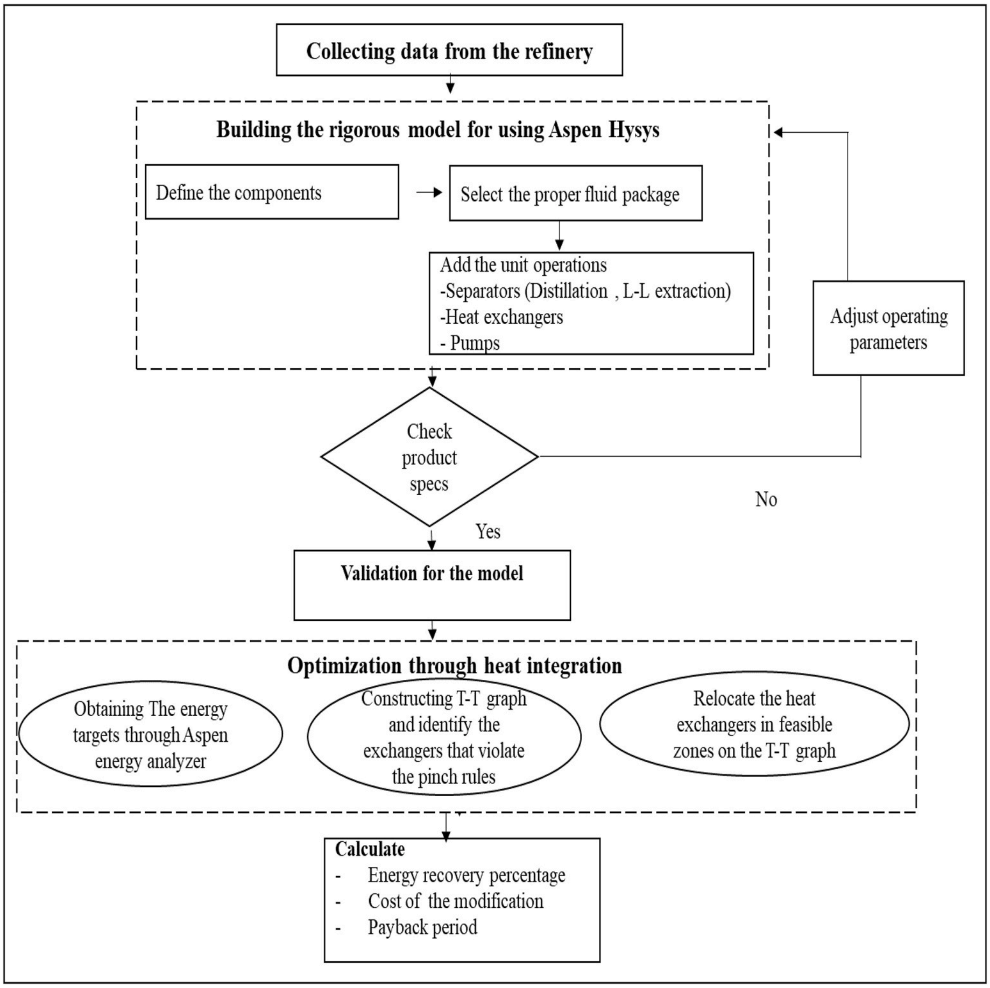

Fig. 3. The steps of the graphical-based revamping method.

operation to reform all naphtha streams without stabilization and (2) with naphtha stabilizer when LPG is separated from naphtha stream. The unit processes over 5000 tons per day of crude oil and is presented in Fig. S1.

3.1. First operational scenario

In this scenario the Atmospheric distillation unit (ADU) is operated without the presence of naphtha stabilizer when the process reformer is in operation to reform all naphtha streams without stabilization.

3.1.1. Energy analysis of the existing network

Relevant data for process streams is presented in supplementary data Table S1 including supply and target temperatures, stream heat duties, flow rates and stream specific heat capacities. It is noted that the minimum temperature driving force is approximately 25 °C for all exchanger units (i.e. $\Delta T_{min} = 25$ °C).

The overall energy consumption of this operational mode is estimated as follows:

Hot energy consumption of “fired heater” = 23.94 MW
Cold energy consumption of “water coolers” = 3.5081 MW
Cold energy consumption of “air coolers” = 22.586 MW
Total cold energy consumption = 26.09 MW
The temperature of crude oil feed before the fired heater = 253 °C

Fig. S2 displays the grid diagram for the 11 heat exchanger units in

Table 3
Results for the first operational mode.

Item	Base case	Graphical solution	Base case [simulated by ASPEN HYSYS]	Solution 1[by ASPEN HYSYS]
Hot utility (MW)	23.94	20.71	23.6	20.8
Cold utility (MW)	25.816	22.8	23.15	20.3
Crude oil feed temperature before fired heater (C)	253	266	253	268.9
Hot Energy saving (%)		13.5%		13.1%
Cold Energy saving (%)		12.3%		12.3%
Saving on hot utility cost ($)		185,257.48		179,657.28
Saving on cold utility cost ($)		239,095.25		248,280.01
New HE cost ($)		98,316.66		75482.2754
Additional area cost ($)		175,196.02		340,188.16
Repiping & Resequencing ($)		35,000		0
Total capital cost used ($)		337,989.83		455,386.07
Operating cost saving ($)		424,718.85		423,453.07
Payback period (year)		0.8		1.08

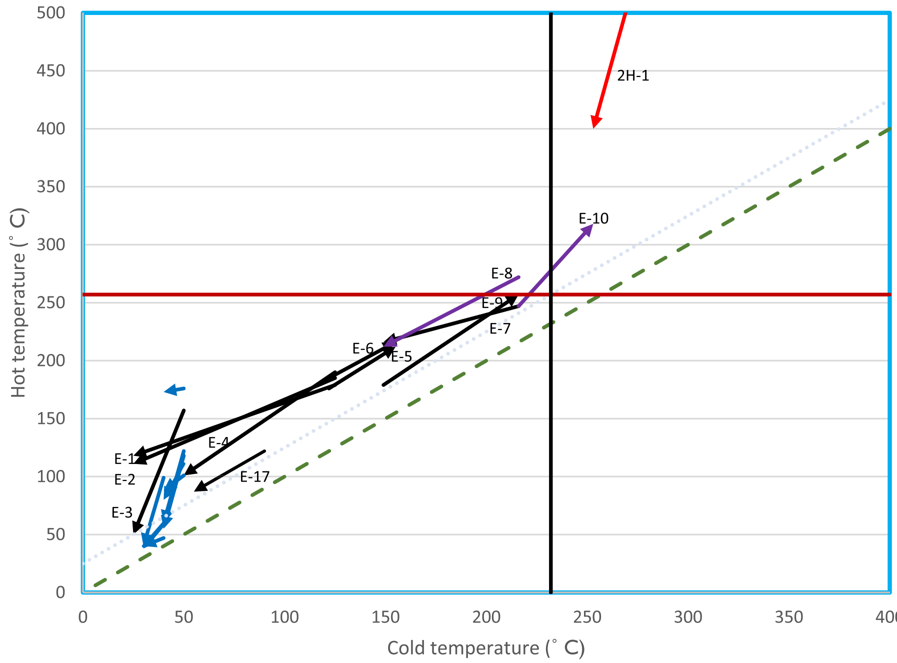

Fig. 4. First operational mode HEN graphical representation.

the First operational mode, based on data from Table 3. This existing network comprises of 9 hot streams and 2 cold streams, which are supplied by external utilities through 1 heater, 4 water coolers, and 5 air coolers. The energy targets for this operational mode HEN, set at a minimum temperature of 25 °C, are 20.71 MW for hot utility (fuel & HP steam), 22.86 MW for cold utility (Air & Water), with hot and cold pinch temperatures at 257 °C and 232 °C, respectively. The network performs below energy targets, with hot utility consumption 13.5% above the target and cold utility consumption 11.5% above target. These excessive consumptions in energy suggest potential for fuel and energy savings of 13.5% and 11.5% respectively.

The exchanger units on the main crude oil feed "cold stream C1" are represented as a sequence of exchanger lines, one after another. Crude oil feed stream starts its heating integration process at an exchanger units' series from E-1, E-2, E3 and E-4 (in parallel), to E-5, E-6(in parallel), E-7, E-8, E-9(in parallel), E-10, and finally through the fired heater "2H-1". Intermediate temperatures are also clear between successive exchangers. This layout matches with the HEN diagram represented in Fig. S2.

3.1.1.1. Graphical representation. The graphical method for the analysis of the energy performance of the First operational mode of the existing HEN at its ΔT_{min} of 25 °C is represented in Fig. 4.

The identification of every cross-pinch exchanger, using the graphical representation in Fig. 4, showed that the two exchangers E-8 and E-10 are placed in the left upper region, where heat integration takes place across the pinch and thus violating the principles of the Pinch Analysis. As a result, the existing network consumes at least 13% more energy than that necessary for heating and at least 11.5% for cooling.

3.1.1.2. Aspen HYSYS simulation of the base case. The assay data of the inlet crude was obtained from the RAS SHUKAIR crude oil with 33.7° API and the cumulative volume percent versus the true boiling point temperature data.

Flow rates and stream specifications of the distillation unit, required for HEN simulation, are presented in Table S2 through Table S4. The tray number, flow rate (kg/h) and conditions of the feed of the main distillation column 2C-1 and its products are presented in Table S2.

Table S3 summarizes the data of the side strippers 2C-3, 2C-4 namely; number of trays, draw and return stage for the product, product flow rate (kg/h) and flow rate of the steam in each stripper (kg/h). Table S4 represents the specifications of the two pump arounds namely; flow rate (kg/h), draw and return temperatures and draw stage/return stage for the pump around stream.

The heat exchanger network was simulated and the process flow sheet is presented in Fig. S3.

3.1.2. Revamping of the existing network

3.1.2.1. T.T graphical analysis method. The following modifications were performed with the aim of improving energy performance and reducing the consumption of heating and cooling utilities:

- Modification [1]: All matches with loads cross-pinch were disconnected and then their heat duties on the cold and hot streamside were split according to the pinch temperatures. Subsequently, at each side of or between the pinch temperatures, the split heat duties at either stream were merged and matched according to the Pinch Analysis principles.
- Modification [2]: For more realistic application of the modified HEN, a maximum of 60% additional heat transfer area was added to existing exchangers.
  1. For the implementation of modification [1] above the pinch for E-8, a new heat exchanger "NEW1" was installed above the pinch from the pinch points (232 °C, 257 °C) to intersect with the supply temperature of hot stream H5 (272 °C).At the intersection point (40 °C, 173.1 °C), the new location of air cooler [C-3] was plotted between the hot and cold ends to satisfy the cooling requirement of the hot stream of "0.023 MW" compared to that of the existing "1.3 MW" with savings in the cooling utilities of 4.9%.
  2. Above the pinch, an exchanger line was drawn from the pinch points (232 °C, 257 °C) to intersect with the supply temperature of hot stream H2 (318 °C), and represents the new location of E-10.

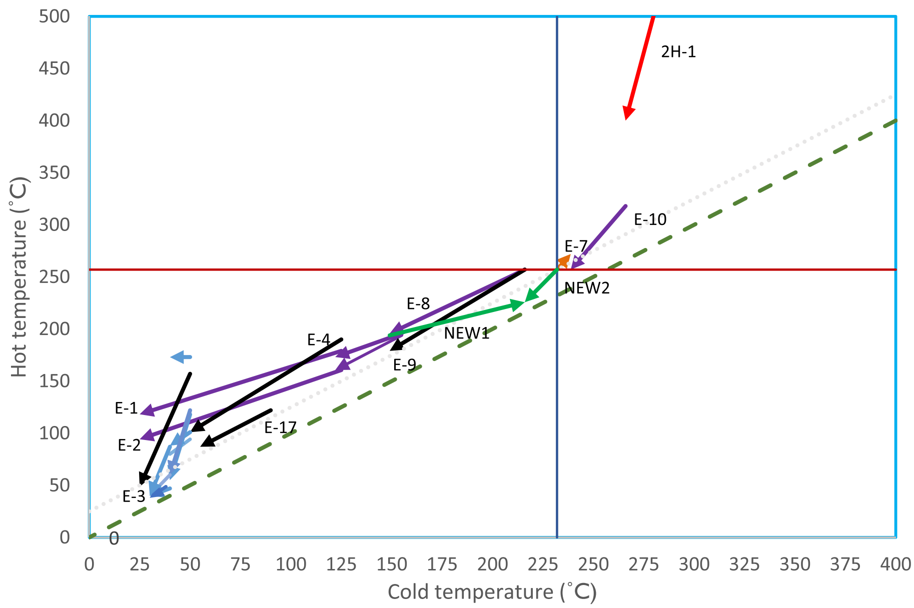

Fig. 5. The graphical representation of the modified HEN.

3. For the implementation of modification [1] below the pinch, for E-10, a new heat exchanger "NEW2" was installed on the main cold stream C1 to recover 2.935 MW from the hot stream H2 at the pinch points (232 °C, 257 °C). The remaining cooling requirement of hot stream H2 was provided by air cooler [C-1] "1.656 MW" compared to that of the existing "3.635 MW" with savings of 7.6%.
4. As a result of the above modifications, the crude inlet temperature to the fired heater 2H-1 increased from 253 °C to 266 °C with savings in heating utilities of 13.5%.

As a result, the heat load on the fired heater 2H-1 decreased to 20.7 MW, compared with 23.94 MW for the existing network. In addition, the temperature before the fired heater 2H-1 increased by 13 °C over the base case. On the other hand, the consumption of cooling utilities decreased by a 2.95 MW equivalence. This corresponds to a saving of 13.5% in the fuel requirement (or hot utility) and 11.5% for cooling utilities (air coolers) with the existing performance. Therefore, the distribution of the temperatures across the modified HEN changed.

It is obvious that heat exchanger E-10 is now placed within the heat integration region above the pinch and heat exchanger E-8 is now placed within the heat integration region below the pinch and so both no longer violate the principles of the Pinch Analysis. The heat transfer area of some of the existing heat exchangers of a very small temperature driving force, has been increased by more than 60%. Therefore, the location of E-7 will be exchanged with that of NEW1.

The modifications proposed by Fig. 5 were extracted using results in the HEN grid diagram presented in Fig. S4.

3.1.2.2. Aspen HYSYS and aspen energy analyzer. After building a process design in Aspen HYSYS [26], Activated Energy Analysis was initialized.

3.1.3. Results

3.1.3.1. T.T graphical analysis method. Data extracted from the graphical representation for the modified HEN of First operational mode after all the modifications are including terminal temperatures, duties and heat transfer areas for each exchanger unit.

These data show that the network requires 2047.189 m^2 of heat transfer area including two new heat exchangers to complete the required improvements, six of the existing heat exchangers require additional area after modifications.

There are 13.5% saving of hot energy and 12.3% saving of cold energy for the new modified HEN with respect to the actual case. Significant savings in energy demands are achieved with consumptions of fuel oil as Crude oil feed temperature before the fired heater is decreased to 266 °C and electricity (air coolers) by the new modified HEN.

The fuel oil consumption by the fired heater is minimized and its heat load after modifications is decreased by 3.24 MW. On the other hand, cold utilities as cooling water and air coolers are decreased from 26.09 MW to 22.861 MW. Data extracted from the modified HEN show that heat load on water coolers is the same as the actual case so the reduction in cold utilities is equal to 3.229 MW of air cooling.

3.1.3.2. Aspen HYSYS and aspen energy analyzer

3.1.3.2.1. Adding a new heat exchanger to the network [solution 1]. Data extracted from the heat integration project imported from Aspen HYSYS and are including terminal temperatures, duties and heat transfer areas for each exchanger unit.

2160.114 m^2 of heat transfer area are used by eight of the fifteen existing heat exchangers and a new heat exchanger after the modifications made by HYSYS to modify the network for better performance.

There are 13.1% saving of hot energy and 12.3% saving of cold energy for the new modified HEN with respect to the actual case. Significant savings in energy demands are achieved with consumptions of fuel oil as Crude oil feed temperature before the fired heater is decreased to 268.9 °C and electricity (air coolers) by the new modified HEN.

The fuel oil consumption by the fired heater is minimized and its heat load after modifications is decreased from 23.6 MW to 20.59 MW as the crude oil temperature before the fired heater reaches 268.9 °C instead of 253 °C. On the other hand, cold utilities as cooling water and air coolers are decreased from 23.15 MW to 20.14 MW. Data extracted from the modified HEN show that heat load reduction on water coolers is 0.034 MW while the reduction in heat load of air coolers is equal to 3.3 MW.

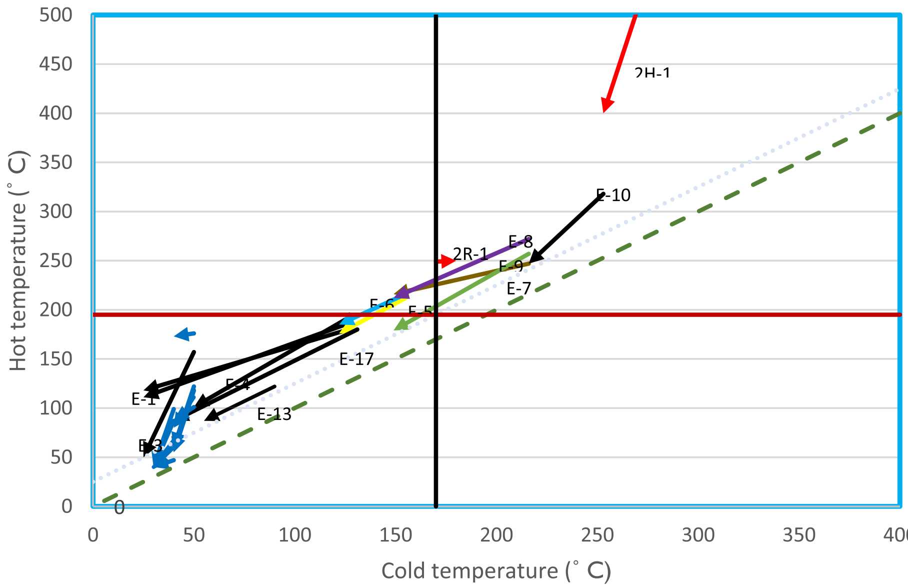

Fig. 6. Graphical representation of the Second operational mode existing network.

3.2. Second operational mode

When the unit is operated with naphtha stabilizer when LPG is separated from naphtha stream.

3.2.1. Energy analysis of the existing network

Data for process streams is presented in Table S5 including supply and target temperatures, heat duty, flow rates and specific heat capacities. It is noted that the minimum temperature driving force is approximately 25 °C for all exchanger units (i.e. $\Delta T_{min} = 25$ °C).

The actual network is presented in the diagram shown in Fig. S5 using the collected data in Table S5. The diagram shows the details of all heat exchange between hot and cold process streams. The crude oil enters the fired heater at a temperature of 253 °C and exits at a temperature of 349 °C to enter the atmospheric tower. On the other hand, the naphtha leaving the stabilizer, enters the reboiler at a temperature of 170 °C and exits at a temperature of 180 °C.

The energy consumption for the Second operational mode is estimated as follows:

Hot energy consumption of "fired heater" = 23.94 MW
Hot energy consumption of "boiler" = 4.3 MW
Total hot energy consumption = 28.24 MW
Cold energy consumption for "water coolers" = 7.8081 MW
Cold energy consumption for "air coolers" = 22.586 MW
Total cold energy consumption = 30.3941 MW
The temperature of crude oil feed before fired heater = 253 °C
The temperature of crude oil feed before reboiler = 170 °C

The HEN energy consumption targets for this operational mode, at its minimum temperature of $\Delta T_{min} = 25$ °C, are hot utility (fuel & HP steam) equals 22.2 MW, cold utility (Air & Water) equals 24.35 MW and hot and cold pinch temperatures are 195 °C and 170 °C respectively.

It is obvious that the performance of the existing network is not up to the required standard. Hot utilities consumption is 21% higher than the targeted consumption, which indicates that fuel oil and natural gas are excessively consumed.

On the other hand, cold utilities consumption is higher by 19.8% than the targeted consumption which indicates excessive consumption of air and water used in cooling.

Therefore, potential savings in heating and cooling mediums of 21% and 19.8% respectively are possible.

3.2.1.1. Graphical representation. The graphical method was employed to analyze the energy performance of the actual network. The first operational mode of the existing (HEN) is represented by the graphical method in Fig. 6 for its existing ΔT_{min} of 25 °C.

All exchanger units are represented by straight lines and the following features are noticed:

(1) The following heat exchangers perform in accordance to the Pinch Analysis rules:
   i. Exchangers E-1 to E-4, E-13, and E-17 are integrating heat below the pinch.
   ii. Exchanger E-10 is integrating energy above the pinch.
   iii. The heaters including fired heater and reboiler heat cold process streams above the pinch.
   iv. All water and air coolers are cooling the process hot streams below the pinch.
(2) Heat exchangers from E-5 to E-9 do not perform in accordance with the Pinch Analysis rules and are integrating energy across the pinch.

3.2.2. Revamping of the existing network

3.2.2.1. Graphical analysis method. From above it is clear that the energy performance of the existing HEN is quite poor and that the heating medium, whether fuel oil or natural gas, is excessively consumed.

The following modifications are suggested to improve the energy performance of the HEN and thus minimize fuel and cooling water requirements.

- Modification [1]: Relocation of E-4 and addition of a new heat exchanger [NEW2] to the crude oil stream after the preflash drum, thus exchangers E-7, E-8 and E-9 will be shifted above the pinch.
- Modification [2]: Addition of a new heat exchanger [NEW1] to recover more heat to the crude oil stream below the pinch.
- Modification [3]: Addition of a new heat exchanger [NEW3] to replace part of the heating duty of the reboiler 2R-1 on the cold stream C4 '4.2 MW' and utilize this energy to preheat the crude stream before the reboiler.

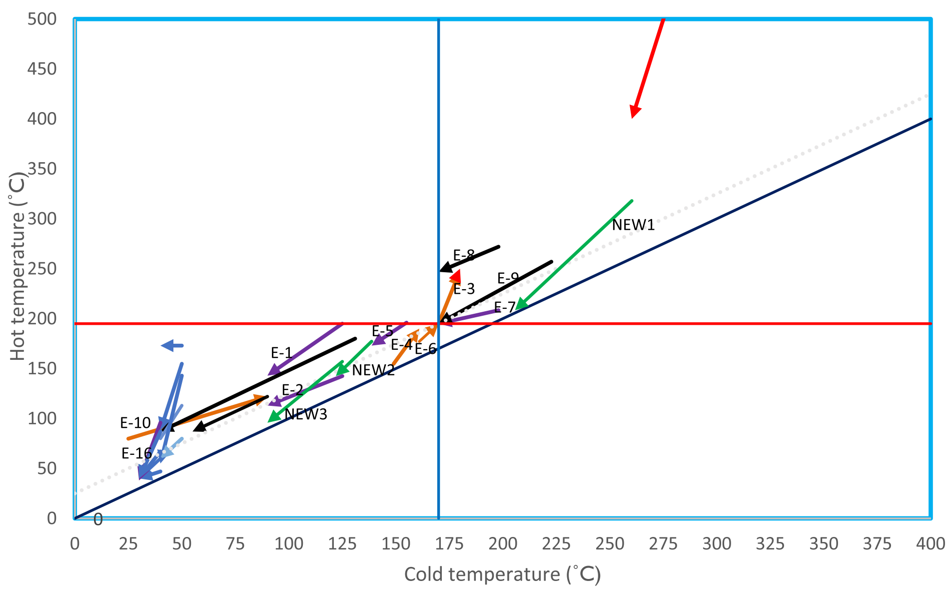

Fig. 7. The graphical representation of the modified HEN.

- Modification [4]: Replacement of the exchangers E-10 with NEW1, E-6 with NEW2 and E-3 with NEW3 according to additional area limitation which is that the existing exchanger unit should not increase more than 60%.

The HEN modifications were implemented using Aspen Energy Analyzer, according to the following steps with exchangers.

1. Relocation of E-4 at the intersection point (161 °C, 190 °C) with the supply temperature of the crude oil after the preflash drum of 149 °C. This was followed by the installation of a new heat exchanger (NEW2) located at the pinch temperatures (170 °C, 195 °C) to recover 1.525 MW from the hot stream (H2) which leaves (NEW2) at a temperature of 177.2 °C. As a result of the above modifications, heat exchangers E-7, E-8 and E-9 are shifted above the pinch at the cold streamside and E-6 below the pinch at both sides.
2. Above the pinch, on the hot streamside, an exchanger line is drawn from the pinch points (170 °C, 195 °C) to intersect with the supply temperature of the hot stream (H1) (257 °C). This exchanger line represents the new location of E-9. With the same procedure, heat exchanger E-7 is located from the pinch temperatures (170 °C, 195 °C) to recover 1.205 MW from the hot stream (H2). The heat load on heat exchanger E-8, which is located with the supply temperature of the hot stream (H5) (272 °C), is decreased from 5.021 MW to 2.098 MW. All such modifications above the pinch lead to an increase in the heat load on heat exchanger E-10 from 6.787 MW to 10.35 MW with a very small driving force and a large heat transfer area. As a result, the heat required by the fired heater decreases from 23.9 MW to 22.1 MW with a saving in the heating utility demand by 6.37%.
3. The new location of heat exchanger E-8 results in an outlet intermediate temperature of the hot stream (H5) of 246.9 °C. Above the pinch, a new heat exchanger (NEW3) is installed to recover 4.234MW from the cold stream (C4) at its supply temperature of (170 °C) and inlet intermediate temperature of the hot stream (H5) of (246.9 °C). After this modification, the temperature of the hot stream (H5) leaving exchanger NEW3 is determined to be 195 °C which leads to shifting the location of E-5 below the pinch on the hot streamside. To perform the below pinch modifications, splitting of the crude oil stream, after desalter, is omitted and E-5 and E-6 are relocated below the pinch. Since the temperature of the hot stream (H5) of E-5 is higher than (H2) of E-6 thus E-6 is relocated first with the supply temperature of crude oil stream after desalter (122 °C) and E-5 is relocated to recover 2.744 MW from hot stream H5 to reach the required temperature of the crude oil before preflash drum (155 °C). As a result, the heat load on the reboiler 2R-1 decreases from 4.3 MW to 0.1 MW with a corresponding saving in heating utility demand by 14.2% and the heat load of air cooler [A -3] decreases to zero MW.
4. A new heat exchanger (NEW1) is installed at the supply temperature of crude oil stream (C1) (25 °C) to recover 9.66 MW from the hot stream (H8), at its supply temperature 122 °C. This is required to heat the crude oil stream to the required temperature before the desalter (125 °C). At the intersection point (50 °C, 79.8 °C), the cooler line [C-5] is plotted between the hot and the cold end to satisfy the cooling requirement of the hot stream which is equivalent to 4.519 MW (previously 14.18 MW) with a saving in cooling utility (air) demand by 31.8%. The heat recovery of heat exchanger E-3 decreases from 1.548 MW to 0.864 MW resulting in an outlet intermediate temperature of the hot stream (H3) leaving E-3 of 95.8 °C. The remaining cooling demand of hot stream (H3), which is provided by cooling water in E-16, increases from 0.3 MW to 0.99 MW with an increase in water cooling demand by 2.27%. A grid diagram for the HEN was extracted from these the data and represented in Fig. S6.

As a result of all the above modifications, the heat transfer area for some of the existing heat exchangers isn't required to be increased by more than 60% of its original value. For more realistic modification of the HEN, additional area of the existing heat exchangers should be limited. To solve such a problem, the locations of such exchangers should be exchanged with the locations of the new ones. Therefore, the location of E-3 will be exchanged with that of NEW3, and E-6 with NEW2 and E-10 with NEW1. The new representation of the modified HEN is shown in Fig. 7. Repiping in shown in orange, new heat exchangers in green and heat exchangers with the additional area in purple.

The following savings could be achieved by the implementation of the suggested modifications in the HEN:

- The crude oil temperature increased by 7.3 °C to reach 260.3 °C while the heat load of the fired heater 2H-1 decreased from 23.94

Table 4
Results of the second operational mode.

Item	Base case	Manual solution		Graphical solution	
		Without steam [fired heater]	With HP steam	Without steam [fired heater]	With HP steam
Hot utility (MW)	28.24	23.207		22.2743	
Cold utility (MW)	30.3941	25.347		24.412	
Crude oil feed temperature before fired heater (°C)	253	261		260.3	
Crude oil feed temperature before reboiler (°C)	170	177.1		179.8	
Hot Energy saving (%)		17.8%		21.1%	
Cold Energy saving (%)		16.6%		19.6%	
Saving on hot utility cost ($)		303,070.64	1,828,187.47	346,039.07	2,452,746.48
Saving on cold utility cost ($)		374,469.13		479,891.31	
New HE cost ($)		374,311.5977		382,686.4092	
Additional area cost ($)		299,112.59		217,145.72	
Repiping & Resequencing ($)		105,000		140,000	
Total capital cost used ($)		852,799.49		810,520.12	
Operating cost saving ($)		677,539.77	2,202,656.60	825,930.38	2,932,637.79
Payback period (year)		1.26	0.39	0.98	0.28

MW in the actual HEN to 22.13 MW. In addition, crude oil temperature, before entering reboiler '2R-1', increased by 9.8 °C to reach 179.8 °C and its total load decreased from 4.3 MW for the actual HEN to 0.07 MW. Thus, a total 21% energy savings in heating could be achieved.

- The corresponding consumption of cooling water reached 8.49 MW (loads of E-11, E-12, E-14, E-15, E-16, and E-18), compared with 7.81MW with an increase of 8.7%. On the other hand, the corresponding consumption of electricity by air coolers is equivalent to 15.85MW (load of A-1, A-2, A-3, A-4, and A-5), compared with 22.58 MW with savings of 29.8%. Thus, one of the suggested HEN modifications is replacing some of the air HEN modifications is replacing some of the air coolers with water coolers because the electricity used in air coolers is much more expensive than cooling water. This replacement leads to a decrease in the total cost of the cooling utilities and thus saving in the total operating costs.

3.2.2.2. Standard PINCH method. Many trials have been made, using Aspen Energy Analyzer, in order to reach the modified network presented in Fig. S7. The relocated exchangers are shown in yellow, new ones in green and those with additional heat transfer in purple.

3.2.3. Results

3.2.3.1. Graphical methodology. Data extracted from the graphical representation for the modified HEN are including terminal temperatures, duties and heat transfer areas for each exchanger unit.

Data show that the network requires 4506.63 m^2 of heat transfer area including 3 new heat exchangers to complete the required improvements and a number of the existing heat exchangers require an additional area after modifications.

There are 21.3% saving of hot energy and 19.8% saving of cold energy for the new modified HEN with respect to the actual case. Significant savings in energy demands are achieved with consumptions of fuel oil as Crude oil feed temperature before the fired heater is decreased to 260.3 °C and Crude oil feed temperature before reboiler is decreased to 179.8 °C.

The results show a decrease in the heat load of the fired heater and reboiler and a decrease in the cold utilities namely cooling water and air coolers. It is worth noting that additional cooling water is used instead of air cooling to increase the total energy saving costs, since cost of electricity required in air coolers is higher than that of cooling water. This resulted in an increase in the heat load of water coolers and a decrease in the heat load of air coolers.

3.2.3.2. Standard PINCH method. HEN modifications are including terminal temperatures, duties and heat transfer areas for each exchanger unit. 3647.92 m^2 of heat transfer area mentioned in appendix (F) including 4 new heat exchangers and the additional area required for a number of heat exchangers.

The network requires, there are 18.7% saving of hot energy and 16.6% saving of cold energy for the new modified HEN with respect to the actual case. Significant savings in energy demands are achieved with consumptions of fuel oil as Crude oil feed temperature before the fired heater is decreased to 261 °C and Crude oil feed temperature before reboiler is decreased to 177.2 °C.

The grid diagram and the data presented before show the following:

- Crude oil reached a temperature of 261 °C before the fired heater 2H-1 with an increase of 8 °C
- Heat load on 2H-1 decreased by 2.25 MW compared to the actual HEN "23.94 MW".
- Crude oil reached a temperature of 177.1 °C before entering the reboiler '2R-1' with an increase of 7.1 °C.

Therefore, the total heating utilities for the modified HEN are then 22.937 MW, compared with 28.24 MW for the base case. The energy savings achieved for heating are of approximately 18.7%. While the corresponding consumption by cooling water is equivalent to 7.497 MW (load of E-11, E-12, E-14, E-15, and E-18), compared with 7.81MW with a decrease of 4%. On the other hand, the corresponding consumption by air coolers "electricity" is equivalent to 17.851 MW (load of C-1, C-2, C-3, C-4, and C-5), compared with 22.58 MW with savings of 20.9%.

4. Conclusion

The results showed the following:

- The hot pinch temperatures for first and second operational modes are 257 °C and 195 °C, while the cold pinch temperatures are 232 °C and 170 °C respectively.

For the first operational mode, the minimum energy target obtained was 20.71 MW for the hot energy (fired heater) and 22.86 MW for cold energy (water and air coolers). Since the energy consumption of the existing HEN is equal to 23.94 MW, thus a 13.5% energy savings could be attained. Three scenarios were generated by ASPEN HYSYS software to reach the same energy target. One scenario was studied which resulted in 13.1% savings in energy. Applying the graphical method, more profit was achieved with lower energy consumption than that obtained by the retrofit tool of the Aspen HYSYS as presented in Table 4 with a payback period of 0.8 years.

For the Second ooperational mode, the minimum energy target was 22.2 MW for hot utility (fired heater and HP steam) and 24.35 MW for cold utility (water and air coolers). Since the energy consumption of the existing HEN is equal to 28.28 MW, thus a 21% energy savings could be attained. The savings in hot utilities depend on whether a fired heater is used or a boiler for the production of HP steam, this will also affect the savings in operational cost and payback period. The graphical approach achieved maximum profit with lower energy consumption compared to that obtained from the manual solution as shown in Table 4.

Based on the results presented in Tables 3 and 4, applying the systematic T-T graphical methodology for the revamping of the HEN on two different operational scenarios, achieved higher percentage of energy saving and consequently higher profit with payback periods of 0.8 and 0.28 years for first and second modes respectively.

Declaration of competing interest

There is no conflict of interest.

Data availability

The data that has been used is confidential.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cscee.2023.100490.

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