Optimizing Design of Heat Exchanger Network Grassroots for Crude Oil Distillation Unit at Zawia Oil Refining Plant

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ABSTRACT:

As the oil prices keep increasing, the need for energy conservation becomes a real necessity in oil refinery plant especially in crude oil distillation unit in order to reduce both the operating cost and gases emissions. The important method that used for energy saving is the optimization of heat exchanger network (HEN) design, which can be applied using various methods. In this study, Pinch Technology (PT) is applied using real data, in order to obtain optimum energy savings in preheat exchanger network of the crude oil distillation unit at Zawia Oil Refining Plant. Applying such technique has shown how to save considerable energy during the heat exchanger network design. From the HINT results the optimal value of ΔT_{min} found to be equal to 20°C, and the pinch point was found to be 116 °C. It has been also found that 23831.5 KW minimum heat flow must be supplied from hot utilities and 10882.8 KW minimum heat flow must be removed by cold utilities. The operating cost for both hot and cold utilities was estimated to be $2.97*10^6$ \$/year. Furthermore the estimated total heat transfer area was found to be 14507.48 m^2 and the predicted annual capital cost was equal to $8.7*10^5$\$/year. The obtained results are considered to be extremely promising for achieving considerable improvement in energy savings for the investigating unit particularly when retrofit design will be applied in the following part of this work.

Keywords: Process Optimization, Pinch Technology, Heat Exchanger Network**,** Oil Refining, Hint Program.

الملخص:

في ظل تزايد الطلب على الطاقة واستمرار ارتفاع أسعار النفط، أصبح من اللازم الحفاظ على مستويات الطاقة في مصافي تكرير النفط، خاصة في وحدات الفصل من أجل تقليل تكلفة التشغيل والانبعاثات الغازية. تعتبر طريقة تحسين تصميم شبكة المبادلات الحرارية من أهم الطرق المستخدمة لتوفير الطاقة، حيث تم في هذه الدراسة استخدام تقنية المكاملة الحرارية (التحليل النقطي) وباستخدام بيانات حقيقية، للحصول على أفضل توفير للطاقة في شبكة المبادلات الحرارية لوحدة فصل النفط الخام في مصفاة الزاوية لتكرير النفط، حيث أظهر تطبيق هذه التقنية كيفية توفير قدر كبير من الطاقة أثناء تصميم شبكة المبادلات الحرارية. ومن أهم نتائج برنامج Hint وجد ان ΔT_{min}=20، و نقطة الاختناق =116C°. وقد وجد ايضا انه يجب توفير 23831.5 كيلو واط، وهو الحد الادنى من تدفق الحرارة في الخطوط الساخنة و يجب إزالة 10882.8 كيلو واط، وهو الحد الادنى من تدفق الحرارة في الخطوط الباردة. حيث قدرت تكلفة التشغيل لكل من الخطوط الباردة والساخنة بحوالي $2.97*10^6$ دولار في السنة لإجمالي مساحة انتقال الحرارة $14507.48m^2$، وتكلفة رأس المال السنوية المتوقعة تساوي $8.7*10^5$ دولار في السنة. والنتائج التي تم الحصول عليها في هذه الدراسة تعتبر مُبشّرة وواعدة للغاية لتحقيق أفضل توفير للطاقة، خاصة عندما يتم تطبيق تصميم التعديل التحديثي.

1. INTRODUCTION

Process integration or pinch technology refers to the exploitation of potential synergies that are inherent in any system that consist of multiple components working together. It is good knowing that almost all refinery plants need energy, for this a study of an optimum integration for supply and removal of heat among the process streams in the petroleum industry is required. As a matter of fact process integration applies to most sectors in the process industries including petroleum refining and chemical manufacturing [1].It can reduce the overall thermal energy consumption in industrial processes, and often lead to a reduction of both capital and operating cost. Most industrial plants have hot utilities for heating cold streams, and cold utilities for cooling hot streams. Some of the hot and cold streams can be matched using heat exchangers then the necessity for hot and cold utilities can be substantially reduced. The heat exchangers network is widely used to reduce the energy consumption in many process industries such as oil refineries, petrochemical and chemical industries. In these industries, saving in cost can be achieved if an optimal network design is used. A number of methods based on simulation and rigorous optimization techniques have been developed [2]. The energy optimization technique commonly used is related to pinch technology, proposed in 1979 by Linnhoff and Boland and the reuse of energy, based on the conservation of energy principles, which are associated with the first law of thermodynamics. The implementation of this procedure enables the structure of networks to be developed using thermal exchange and through energy integration this should result in energy reuse, to minimize the consumption and cost of energy [3].

The PT provides much graphical representation that is easy to use by the designer for analysis and better understanding of the problem. This technology was applied to many existing (retrofit design) and new processes grassroots design [2]. Furthermore, analysis of the literature during the nineteenth of the last century can shows that most of the studies published at reducing cost in the crude oil distillation process are associated in one or other way with some change in the process itself, such as Pre-flash design, Prefraction design and Stripping-Type of crude distillation design, which in turn will contribute in cost rising. However, for working refinery industries, it is interesting to solve another problem. This is a cost reduction in the crude oil distillation process without significant changes in the process itself, which led directly to heat process integration methods, and, in particular, the pinch technology[4], which has been successfully applied to reduce specific energy consumption and decrease emissions from processing industries. Papalexandri and Patsiatzis in 1998 studied a crude preheat system of crude distillation unit for energy reduction by carried out the balance between production of steam and consumption of fuel [5]. However, the integrated approach was developed in 1999 by Suphanit to reduce the energy consumption in the crude oil distillation system design [6]. On the other hand, Querzolila et al.

studied crude distillation and residue cracking units and found reducing the crude distillation unit requirement by 40% for new grassroots design [7]. Furthermore, in 2012 Yu-Lin studied crude distillation unit and carried out analysis of heat exchangers to investigate energy saving in the heat exchangers network using pinch analysis method [8]. The latest development of pinch analysis methods for performing the reconstruction of HEN in the presence of strict restrictions enabled to reduce energy consumption by 26% of the crude oil refining unit [9]. Wong et al. Have also examined the reliability of heat exchangers in crude oil, heating processes when developing new HEN [10], while Nianqi Li et al. examined the potential for the application of the target-evaluation method for HEN retrofit with the consideration of the thermal efficiency [11]. A detailed review of pinch analysis was performed by Klemeš et al. [12].

The aim of this article is to provide information about the feasibility study on the heat exchanger network of the atmospheric distillation unit at the Zawia Oil Refining Plant, using problem table algorithms and composite curves, as a first stage of applying pinch technology. The article also provides a description of the grassroots design for the heat exchanger network and their implementation features of the crude distillation unit. In the article context, the economic indicators of the heat integration will be presented, while re-designing the heat exchanger network of the atmospheric distillation unit according to the heat exchanger grassroots network optimum design. All pervious mentioned objectives, are achieved with the help of non-commercial software namely Hint program.

2 METHODOLOGY:

This section shows all the steps involved in analyzing, designing and optimizing of the Heat Exchangers Network for the crude distillation unit (CDU) at the Zawia Oil Refining Plant. The procedures that included here are; data extraction, process simulation and pinch analysis, which is shown Figure 1.

Step1: Collection of process data of CDU of the Zawiya Oil Refining Plant

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Step2: Data extraction

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Step3: Selection of initial ΔT_{min} value

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Step4: Construction of Composite Curves

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Step5: Grid Diagram Representation of Heat Exchanger Network using Pinch Process

The procedure involved analyzing the existing heat exchangers network of the unit Preheat train of the order to extract all the necessary information required for the analysis, using a process flow diagram of the crude distillation unit of the Zawia Oil Refining Plant, and the data obtained from the refinery plant [13]. The use of pinch technology in the energy conservation area remains the focus in this work.

2.1 Process Description of the Crude Distillation Unit at the Zawia Oil Refining Plant

The atmospheric crude distillation unit built in 1974 has a producing capacity of 120,000 BPD. Raw, crude oil is pumped to the CDU after settling and dewatering at the tank farm. It passes through a heat exchanger train, the desalter (for removal of salt and sediments), the pre-flash column (for removal of lighter ends) and the crude heater where it is heated up, then to the fractionating column where the crude is separated into its components. The vapors are removed from the top, condensed and sent to the saturated gas concentration unit (SGCU) for further separation and production of LPG or cooking gas while the liquids are withdrawn from the sides, based on the boiling point range.

2.2 Description of the HINT program process:

The materials used include: process flow diagram (PFD) and plant data of the Crude Distillation Unit of the Zawia Oil Refining Plant; the Hint program (Heat integration program) used to produce the composite curves and grid diagrams. In fact HINT is essentially a pinch based package that utilizes the heuristics and cost data available in the literatures [14].

The Hint program (Heat integration program) process tool was employed to perform a detailed and accurate pinch analysis of the heat exchanger networks. To do this, the thermal data obtained by data extraction were fed as input to the software to construct the composite curves and a grid diagram of network the algorithm. The following pinch rules were employed in order to achieve the minimum energy targets for the crude preheating process. Heat must not be transferred across the pinch, there must be no external cooling above the pinch and no external heating below the pinch (heaters must be placed above and coolers below the pinch). Violating any of these rules will lead to cross-pinch heat transfer resulting in an increase in the energy requirement beyond the target. Any heat transfer across the pinch is excess heat, which is wasted, and expressed as a pinch penalty.

2.3 Thermal Data Extraction

A central part of data extraction is the identification of heating and cooling requirements in the process. Heat loads and temperatures for all the streams in the process are required for the heat integration carried out in this work. The Target and supply temperatures for the streams involved were identified as shown in Table 1. For each hot, cold and utility stream identified, the following thermal data are extracted from the process material and heat balance flow sheet:

- Supply temperature (T_S °C): the temperature at which the stream is available.

- Target temperature (T_T°C): the temperature to which the stream must be taken to.
- Heat capacity flow rate of the stream CP (KW/ °C): the product of the mass flow rate
- (ṁ) in (kg/sec) and specific heat (Cp) in (kJ/kg °C), (CP =ṁ*Cp)
- Enthalpy Change: ΔH) KW): $\Delta H = CP\ (T_S - T_T)$.

A furnace provides utility heating in the Crude Pre-Heat Train of CDU Unit. The furnace design which was represented for fire heaters for the Pinch analysis as a heat sources as a single temperature that is hot enough to satisfy any anticipated heat load in the Unit. The air-cooling and water-cooling likewise can each be represented as heat sinks at a single temperature.

Table 1: Thermal data extraction for pinch analysis.

Stream type	Stream No	Tin at source (°C)	Tout at target (°C)	CP (KW/°C)	ΔH (KW)
Residue\hot	H-1	319	80	68.711	-16421.8
HGO\hot	H-2	298	47	27.347	-6864.16
BPA\hot	H-3	261	192	95.13	-6564.07
LGO\hot	H-4	231	47	34.421	-6333.44
Kerosene\hot	H-5	173	34	41.29	-5739.63
TPA\hot	H-6	126	53	229.595	-16760.4
Crude 1\cold	C-1	20	116	201.126	17296.8
Crude 2\cold	C-2	116	332	238.563	53915.2
Water\cold	C-3	80	99	22.097	419.8

2.4 Selection of initial ΔT_{min} value and ΔT_{min} Optimization in HINT program

The design of any heat transfer equipment must always adhere to the second law of thermodynamics that prohibits any temperature crossover between the hot and the cold stream, i.e. a minimum heat transfer driving force must always be allowed for a feasible heat transfer design [15]. In general the optimum value of ΔT_{min} for petroleum refinery processes has been determined by Linnhoff, (1998) to be in the range of 20 to 40°C[16]. Hence an initial value of $\Delta T_{min}$was selected to be 20°C in this work, and then the actual optimal ΔT_{min} identified using HINT software, which achieved based on the cost target versus ΔT_{min} diagram, in which the result of the total annual cost was minimum at the optimum ΔT_{min}.

2.5 Representing the Heat Exchanger Network

To represent heat exchanger network, the cold utility and hot utility are estimated using the composite curves for all streams in a network. The plot gives the minimum heating requirement (hot utility) for the cold streams and cooling requirement (cold utility) for the hot streams, the amount of heat utilized between the process streams and the minimum temperature change that should exist between the hot and cold streams (the pinch value). The area enclosed within the cold and hot composite curves accounts for the potential process-to-process heat recovery (minimum energy requirements) while the area not enclosed at the extreme left is the excess cold utility been wasted by the network.

After the all the utilities has been known on the grid diagram, each heat exchanger in the network was represented as follows;

- The process streams are drawn as horizontal lines with hot streams drawn at the top of the grid from left to right while cold streams are drawn at the bottom from right to left.
- The stream numbers and heat capacities are shown on and at the end of the streamlines respectively.
- The heat exchangers are represented by vertical lines linking a hot stream and a cold stream.

The design of heat exchanger network (HEN) was achieved in HINT software using the data presented in Table 1. The design started at the pinch then moved away on both sides above and below the pinch, and the stream matching carried out on the grid in HINT environment, mainly using the CP rule and other feasibility criteria obtainable in pinch technology [17].

3. Area and Cost Estimation

To estimate (calculate) the approximate heat exchanger first we have to calculate the surface area. The heat exchanger area, (A.m^2), can be calculate from the following equation:

$$Q = U.A.\ \Delta T_{LMTD}$$

The construction material of heat exchangers are assumed (carbon steel). Hence, the heat exchanger cost can be calculated from this equation [18]:

Heat exchanger cost ($) = a + b (Area) ^{c}

Where a: is represents a fixed cost of installation independent of the area, b the exchanger cost per unit area and which also accounts for different materials of construction.

Heat exchanger cost ($) = 34854 + 849 (Area) $^{0.81}$

Cost of fuel oil consumed for new design [14]:

Fuel oil Cost = R (kg/hr) * Cost ($/ton)

$$R = \frac{Q}{H * \varepsilon} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Heater efficiency (ε) = 0.77%, and net heating value of fuel oil

(H) =9600Kcal/hr

Cost of fuel /month = R * Fuel oil price ($ /ton)

Where: Fuel oil price ($ /ton) = 574.34

4. Results and Discussions by using HINT program

4.1 Optimal Value of ΔT_{min}

The best design for an energy efficient heat exchange network will often result in a trade-off between the equipment and operating costs. Thus, using HINT software Figure.2 is obtained.

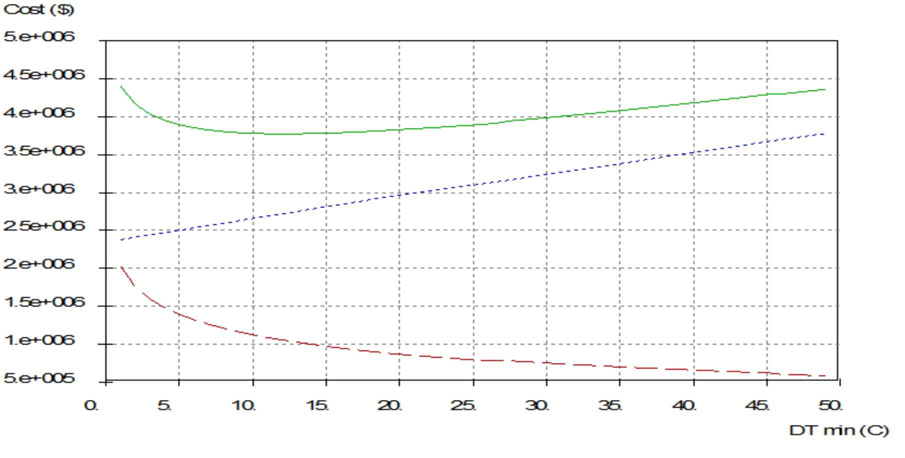

Figure 2. Capital and operating costs trade-off

Figure 2 shows the cost target versus ΔT_{min} graphs, in which the result of the total annual cost was optimized in respect to ΔT_{min}. One can see the lower the ΔT_{min} chosen, the lower the energy costs, and the higher the heat exchanger capital costs, as lower temperature diving forces in the network will result in the need for greater area. On the other hand a large ΔT_{min}, will lead to increase in energy costs as there will lead to less overall heat recovery, and the required capital costs will also be less. From the capital cost and operating (energy) cost trade-off (Figure 2) the optimal value of ΔT_{min} of the Crude Distillation Unit of the Zawia Oil Refinery identified in HINT to be in the range from approximately 5 °C to 20°C.

4.2 Pinch Analysis Target Results

Energy targets were set based on Composite Curves and minimum temperature, ΔT_{min}. After determining the optimal value of ΔT_{min}, the hot and cold Composite Curves are combined and represented in a graph of temperature-enthalpy, in the form of the complex Composite Curve. The Composite Curve (CC) provides aggregate energy targets (minimum demand for hot and cold utilities) and pinch temperature, but the graphical representation is inappropriate for determining appropriate utility levels and loads. The Grand Composite Curve (GCC) shows the interaction between process and the utility flow. Therefore, a GCC was generated from Problem Table Algorithm (PTA) method by using a simulator. To visualize a file correspondence between CC and GCC, these are placed next to each other in Figures 3and 4. From both figures the minimum amount of heat must be supplied from hot utilities is equal to 23831.5 KW, while the minimum amount of heat must be removed by cold utilities is equal to 10882.8 KW.

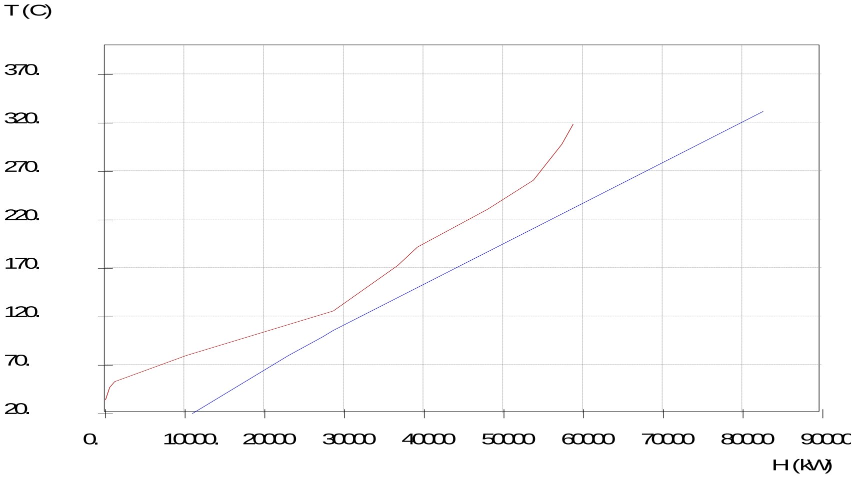

Figure 3. Composite Curve (CC) of HEN

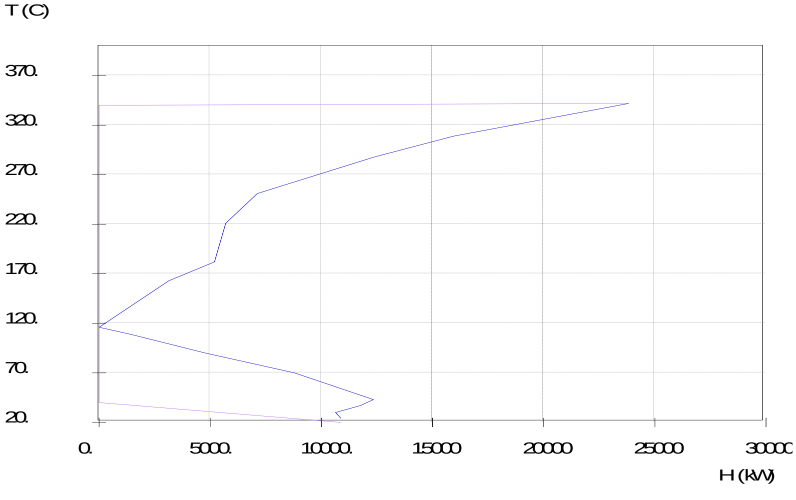

Figure 4. Grand Composite Curve (GCC) of HEN.

In Figure 3, the upper curve represents the hot Composite Curve while the lower curve represents the Cold it represents Composite Curve and the overlapping area between the hot and the cold Composite Curves. Heat exchange process to process. The minimum distance between the curves shows minimum approach temperature (ΔT_{min}), this point is known as Pinch Point. The area above the heat sink Pinch, like there bypass the Cold Composite Curve, which required hot utility, and the part under the pinch is the heat source, where there is an excess of heat it must be rejected by using cold utilities. From Figure 4, it is observed that the total energy targets and process to process heat exchange. In Figure 4, the point at which the assignment is zero is called the Pinch Point.

4.3 Heat Exchanger Network analysis

The process flows and utility flow data were used to design a Heat Exchanger Network. The Heat Exchanger Network design obtained is represented using a Network diagram and is shown in Figure 5. All the heating and the cooling requirements of the process are combined together, and the result is shown in the Network Diagram. The direction of current when placing the heat exchangers on the Network diagram. The process flows are shown as horizontal lines, with hot streams flowing from left to right, while cold streams flowing from right to left. This is a very important parameter when placing heat exchangers before or after another heat exchanger on currents. Simply Network diagram is an overview of all heating/cooling requirements of the process.

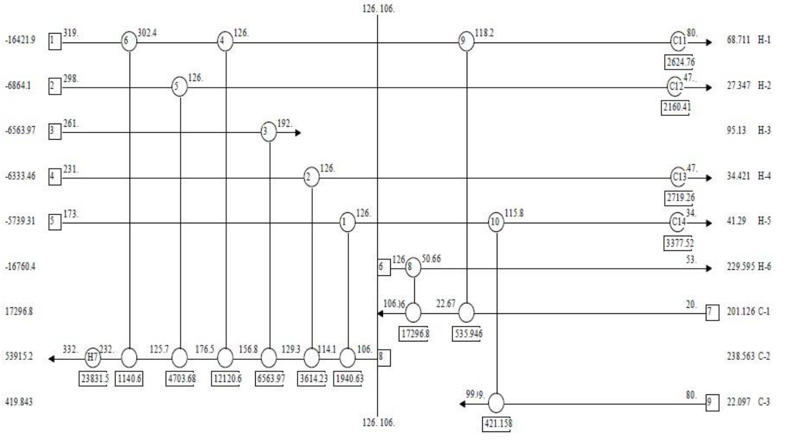

Figure 5. Grid Representation of HEN.

Figure 3is the composite curve (temperature-enthalpy) profile of heat availability in the process (the “hot composite curve”) and heat demands of the process (the “cold composite curve”) together in a graphical representation. Figure 3and Table 2 shows that the heat available in the process is 23831.5kw, while the heat demand with the process is 10882.8kw this shows that more heat is to be removed from the process than heat to be supplied to the system. Figure 3 (Grand composite Curve) shows that the Pinch temperature of the in investigated process is 116 °C.

The results show that the utility heating of the plant is slightly higher than the utility cooling of the plant. Therefore, any utility cooling supplied to the process above the pinch temperature cannot be absorbed and will be rejected from the process to the heating utility, increasing the amount of heating utility required, hence a waste of energy (hot utilities) by the Crude of CDU of the Crude Distillation Unit of the Zawia Oil Refining Plant. A summary of results obtained from these analysis are presented in Table 2.

Table 2: Pinch Analysis Targets

Energy Targets	Values
Hot Utility, KW	23831.5
Cold Utility, KW	10882.8
Total Utility, KW	34340
Pinch Temp (°C)	-
Hot (°C) Cold (°C) Pinch Temp (°C)	126 106 116
Number of Unit Targets	-
Number of Heat Exchanger	9
Number of Cooler	4
Number of Heater	1
Number of units	14
Heat inlet temperature to heater(°C) Cost of fuel($/month)	232 1146334.243
Total Area target for Heat exchangers(m^2)	14507.48
Cost Index Targets	Values
Exchanger cost C.C,$/year	8.7*10^5

CONCLUSIONS

Pinch analysis as an energy integration method saves more energy and utility costs than traditional energy technology, this technology has been used in this work to perform an analysis of the energy and area requirements of the heat exchanger network of the atmospheric distillation unit at the Zawia Oil Refining Plant. At ΔT_{min}=20°C, minimum heating and cooling requirements for the process, are determined by problem table algorithm and composite curves during the network pre synthesis stage, they found to be 23831.5 KW and 10882.8 KW respectively. These values was confirmed during the actual grassroots heat exchanger network design stage, which indicates that the process streams were correctly matched and the heat exchangers placed correctly. In the designed new HEN the total number of units was found to be 14 units and the total area of 14507.48m^2 with an external hot utility of 23831.5 KW and the external cold utility of 10882.8 KW. The operating cost for both external utilities was determined to be \$/year $2.97*10^6$, while the estimated annual capital cost was equal to \$/year $8.7*10^5$.

Recommendation

From the obtained results, the pinch techniques is recommended to be applied to the atmospheric distillation unit at the oil refineries, which gives heat exchanger network more economical than the exits one and will achieve considerable improvement in energy savings, particularly when retrofit design will be applied in the following part of this work. The work presented here, also demonstrated the accuracy of the design using HINT software and thus it is recommended software to design the network of heat exchanger for crude oil refining plants.

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NOMENCLATURE

Symbols	Definition
$\dot{m}$	Mass flow rate of the stream (kg/s)
ΔT_{min}	Minimum temperature difference (°C)
CP	CP - Heat capacity flow rate (kW/°C)
Cps	Cp - Specific heat capacity of the stream (kJ/kg. °C)
ΔH	ΔH - Enthalpy change (kW)
Q	Q - Heat exchanger duty (kW)
T	T - Temperature (°C)
T_S	T_S– Supply Temperature (°C)
T_T	T_T – Target Temperature (°C)
$Q_{H,min}$	$Q_{H,min}$ - Minimum energy required by network (kW)
$Q_{C,min}$	$Q_{C,min}$ - Minimum cooling requirement by network (kW)
A	A – Heat Exchanger Area (m^2)
U	U – Overall Heat Transfer Coefficient (kW /m^2. °C)
Q	Q – Heat Duty
ΔT_{LMTD}	ΔT_{LMTD} – Log Mean Temperature Difference (°C)
R	R- Fuel Oil Consumed (kg/hr)
ε	ε - Heater Efficiency
H	H – Net Heating Value of Fuel Oil (kcal/kg)
BPD	BPD - Barrels Per Day
RS	RS - Residual
HGO	HGO - Heavy Gas Oil
BPA	BPA – Bottom Pump Around
LGO	LGO - Light Gas Oil
KERO	KERO - Kerosene
TPA	TPA – Top Pump Around