



Energy Integration of Crude Distillation Unit of a Refining and Petrochemical Company in Northern Nigeria

HAMIDU, U; AHMED, SI; *HAMZA, UD

Department of Chemical Engineering, Faculty of Engineering and Engineering Technology, Abubakar Tafawa Balewa University, Bauchi, Nigeria

*Corresponding Author Email: dhusman@atbu.edu.ng
Co-Author Emails: umainhamidu@gmail.com; alsaeedng@yahoo.com

ABSTRACT: Most Nigerian refineries were constructed before pinch technology was developed, hence, the design were not optimal, leading to high energy loss. The objective of this work is to evaluate energy integration of crude distillation unit (CDU) of a refining and petrochemical company in Northern Nigeria using pinch analysis by utilising HINT software. Minimum heating and cooling demand of 32251.1 kW and 29637.9 kW at the pinch point of 506.5 K was evaluated from the composite curve, grand composite curve and the cascade diagram. The region of overlap in the composite curve indicates a total of 108,945 kW as the possible energy that can be recovered in the process. Existing utility demand of the unit was 96,873.5 kW, after heat integration it reduces to 61,889 kW, this showed 36.11 % energy saving with a total operating cost of US\$4,560,766.5 that could be saved (annually). Minimum approach temperature (DT_{min}) analysis results showed an optimum DT_{min} of 15 K which resulted in a total annual cost of US\$6,715,700. Furthermore, the analysis showed the effect of DT_{min} on energy, area, minimum number of units and cost targets. The design objective of the retrofit heat exchanger network (HEN) was set toward maximum energy recovery. A total of twenty (20) heat exchangers made up the new network, which comprises of twelve (12) process to process heat exchangers, two (2) heaters and six (6) coolers.

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Keyword: Cost; Crude Distillation; Energy integration; Heat Exchangers; Pinch analysis

Linnhoff, a key proponent of pinch technology or process integration, has developed a technique for reducing the energy requirements of process plants (Linnhoff and Turner 1981). Process plants, such as oil refineries or large chemical manufacturing plants, need that the feed stock be heated or cooled as the processes are carried out. Obviously, it would be advantageous to use the energy from a cooling stream to heat another that requires heating; this reduces the amount of energy that must be supplied from a high temperature source (or utility), and the amount of energy that must be rejected to a low temperature sink (or utility). Both of these external transfers add to the plant's operating costs. Pinch technology is a method for automating the design process while reducing external heat transfer (Linnhoff and Turner, 1981). Pinch technology has been used to tackle a wide range of issues; improving effluent quality, lowering

emissions, increasing product output, debottlenecking, increasing throughput, and improving process flexibility and safety (Akande, 2007). Multinational oil companies such as Shell, Exxon, and BP-Amoco, among others, revealed that this strategy saved roughly 25% on fuel and reduced emissions by millions of dollars every year (Mohammed and Sadiq, 2021). Energy saving in the Nigerian industrial sector has several possibilities, due to the fact that, almost all the industrial equipment stock in the country were imported during the era of cheap energy. The refineries in Nigeria were built before the advent of pinch technology, therefore, the design were not optimal with attendant issues of excessive energy loss. Hence pinch technology was introduced as a methodology that guarantees minimum energy levels in heat exchanger network (HEN) design (Linnhoff and Hindmarsh, 1983). The refinery's distillation

*Corresponding Author Email: dhusman@atbu.edu.ng

sector is a large energy consumer, accounting for 35 to 45 percent of the refinery's total consumption (Liuvia *et al.*, 2014). Pinch technology has demonstrated exceptional success in the works of Adnan *et al.* (2017), Ajao and Akande (2009), and Adejoh *et al.* (2013), in which considerable amounts of energy were recovered, resulting in a cost-effective design. In the works of Barambu *et al.* (2017) and Tibasiima and Okullo (2017), better energy recovery was accomplished in the food industry, indicating that wherever heating and cooling occurs, there is a potential opportunity. Several literatures were reviewed on pinch analysis of units in the refinery, Ajao and Akande (2009) worked on "Energy Integration of Crude Distillation Unit using Pinch Analysis." Pinch analysis methodology using Marple software was employed on the process streams of crude distillation unit of Kaduna refinery and petrochemical company, stream data was extracted as hot and cold streams according to analysis procedure and process heating and cooling duties were reviewed. As the result of the integration, the hot and cold utility requirements were found to be 1.112×10^8 kJ/hr and 1.018×10^8 kJ/hr respectively. A minimum temperature of 15°C was found to be optimal, with a pinch point of 220°C . Adejoh *et al.* (2013) worked on "Energy Integration of Vacuum Distillation plant using Pinch Technology (A case study of KRPC VDU Unit)" Energy integration and design approaches using pinch analysis methodology have been adopted to maximize heat recovery of VDU unit of Kaduna refinery and petrochemical company. All process heating and cooling duties were reviewed. The hot utility requirement of the process was obtained from the energy balance to be 0.32MW, due to the integration it was reduced to 0.24MW while the cold utility requirement for the traditional approach and pinch analysis were found to be 0.31MW and 0.19 MW respectively. The objective of this work is to evaluate the energy integration of the crude distillation units (CDU) of a refining and petrochemical company in Northern Nigeria.

MATERIALS AND METHODS

The materials used are: HINT software, process data of the crude distillation units (CDU) of the KRPC. The Heat Exchanger Network (HEN) of the CDU was analysed, designed, and optimized in this study. The technique entailed identifying process streams, extracting data, then simulating and designing the energy process systems using HINT software.

Stream Identification: In stream identification, the process was divided into hot, cold and utility streams. Hot Streams are those that can be cooled to meet a process requirement while cold Streams are those that

can be heated to meet a process requirement. Utility Streams are those that are used to heat or cool process streams when heat exchange between them is not practical or cost-effective.

Data Extraction: For each process stream identified, the following thermal data was extracted from the process flow diagram of the Kaduna Refinery:

Supply temperature (TS $^\circ\text{C}$): the temperature at which the stream is available.

Target temperature (TT $^\circ\text{C}$): the temperature the stream must be taken to.

Film heat transfer coefficient: ($\text{W}/\text{m}^2\text{C}$)

Heat capacity flow rate (CP $\text{kW}/^\circ\text{C}$): the product of flow rate (m) in kg/sec and specific heat (Cp $\text{kJ}/\text{kg}^\circ\text{C}$).

$$CP = m \times Cp \quad \dots 1$$

The specific heat capacity of petroleum can be calculated using empirical formula:

$$Cp = [0.402 + 0.00081t]/\sqrt{d} \quad \dots 2$$

Where d , is the specific gravity of the stream at 15°C , t is the mean temperature in $^\circ\text{C}$ and Cp is the specific heat in $\text{kcal}/\text{kg}^\circ\text{C}$ (Adnan *et al.* 2017).

Enthalpy change is given by:

$$H = CP \times (TS - TT) \quad \dots 3$$

Pinch Analysis Using HINT Software: The steps of carrying out pinch analysis is summarised in figure 1. Figure 1 shows the HINT software technique for doing pinch analysis. The HINT was used to create a grid diagram of the existing heat exchanger network from which composite curves were produced. The composite curves were used to determine cooling and heating requirements as well as to assess potential heat integration opportunities. A retrofit grid diagram was obtained by improving the existing one using minimum utilities and optimization of the minimum temperature difference.

Cost Targets: The cost data includes the operating or running cost for utilities and the capital cost for heat exchangers. The annualized cost data was calculated using a 5-year payback time and a 10% interest rate. The capital cost was calculated using Equation 4 below.

$$\text{Capital Cost}(\$) = a + b(\text{area})^c \quad (4)$$

Where *area* denotes area of heat exchanger (m²), *a* denotes the fixed cost of installation, *b* and *c* denotes the cost of area per unit which are both dependent on the material of construction of the heat exchanger. For a carbon steel shell and tube exchanger, *a* is 16000, *b* is 3200, *c* is 0.7. In present study, the same equation was assumed to hold for all types of heat exchangers in the network, process to process and utilities exchangers (Abubakar *et al.*, 2020).

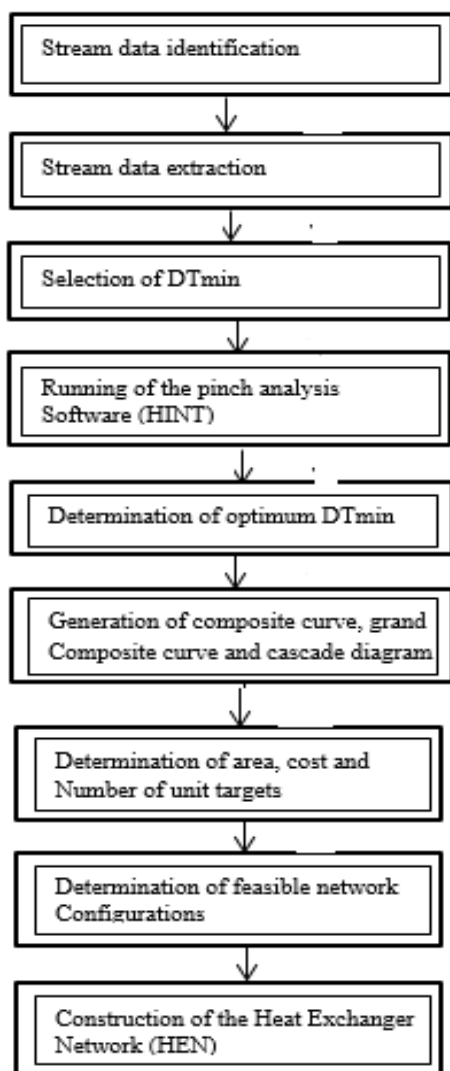


Fig 1: Steps of Pinch Analysis Using HINT Software

The cost data used for utilities as provided by Abubakar *et al.* (2020), where hot utility costing US\$140 / (kW yr), and cold utility costing US\$10 / (kW yr). The following are the thermodynamics data that were used: Steam; heat transfer coefficient, *h* is 1(kW/m² K), *T*_s is 700 K, *T*_t is 700 K. Cooling water; heat transfer coefficient, *h* is 1(kW/m² K), *T*_s is 300 K, and *T*_t is 320 K.

Number of Units Target: The total number of process streams (hot denoted *N_h* and cold denoted *N_c*) and utility streams (*N_u*) in the heat exchanger network determines the minimum number of units (*N_{min}*). Equation 5 was used to define a target for the minimum number of heat exchangers (Adnan *et al.* 2017).

$$N_{min} = (N_h + N_c + N_u - 1)_{above\ pinch} + (N_h + N_c + N_u - 1)_{below\ pinch} \quad \dots (5)$$

Feasible Network Configuration: The grid diagram of process streams of the crude distillation unit is divided into two sections: hot end design (above pinch) and cold end design (below pinch). As a result, the design of the heat exchanger network becomes easier than the original single-task problem. Apart from avoiding heat transfer across the pinch, the following conditions must be met when designing heat exchanger network using pinch analysis:

Above the pinch; number of hot streams ≤ number of cold streams, *mC_p* of hot stream ≤ *mC_p* of cold stream.

Below the pinch; number of hot streams ≥ number of cold streams, *mC_p* of hot stream ≥ *mC_p* of cold stream.

RESULTS AND DISCUSSION

Pinch Analysis of Crude Distillation Unit (CDU): The plant data of the crude distillation unit of KRPC is shown in Table 1.

The graphical technique was used to implement pinch analysis with the aid of HINT software. The Composite Curve (CC) and Grand Composite Curve (GCC) of the CDU were produced and their key features highlighted and discussed. Determination of area, cost and minimum number of unit targets was performed to get the optimum minimum temperature difference otherwise called the pinch point. Then, heat exchanger network of the process was redesigned using the remaining problem analysis with the goal of maintaining the minimum area target of the process for maximum energy recovery.

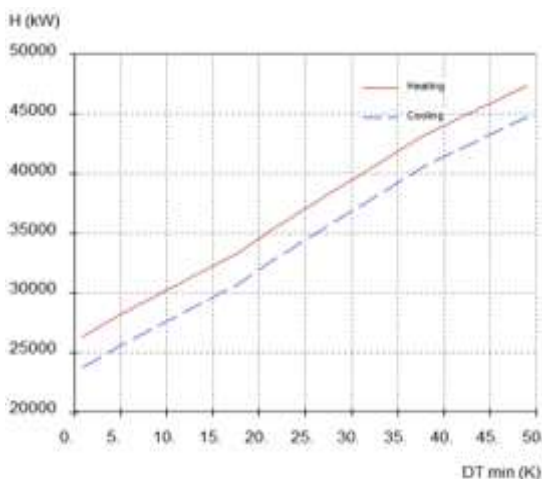
Data Extraction: Extraction of data is the initial step in pinch analysis. Data was collected from the CDU process flow diagram and converted to suitable unit for use in the HINT software, as shown in Table 1. Ten hot streams with a total enthalpy of 138,583.129 kW, and four cold streams with a total enthalpy of 141,195.641 kW made up the existing network.

Table 1: Stream Data of Crude Distillation Unit (CDU) of Kaduna Refinery

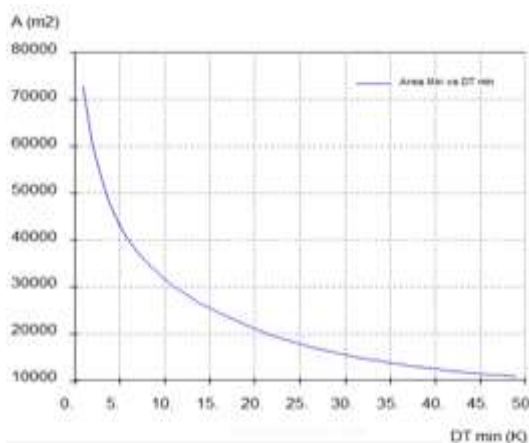
Stream no	Stream type	Stream Code	Supply temperature(K)	Target temperature (K)	Film heat transfer coefficient (kW/m ² K)	Enthalpy (kW)
1	Hot	H1	592	517	0.045	10257.490
2	Hot	H2	346	313	0.680	227.587
3	Hot	H3	620	318	0.643	59722.222
4	Hot	H4	537	453	0.648	10257.490
5	Hot	H5	570	383	0.652	3882.732
6	Hot	H6	521	323	0.596	12509.690
7	Hot	H7	346	313	0.589	1917.584
8	Hot	H8	505	393	0.646	5422.848
9	Hot	H9	440	343	0.700	16118.913
10	Hot	H10	420	346	0.420	18266.573
11	Cold	C1	505	616	0.752	54166.667
12	Cold	C2	619	625	0.810	9275.376
13	Cold	C3	303	505	0.740	75555.556
14	Cold	C4	499	505	0.784	2198.042

DTmin Analysis: The DTmin analysis of the problem was carried out with an initial value of 1 K and final value of 50 K. The DTmin is the smallest temperature difference that was allowed between hot and cold streams in the heat exchanger where counter-current flow was assumed. This parameter represents the trade-off between capital cost (which increases as the DTmin value decreases) and energy cost (which increases as the DTmin value increases). Hence an optimum DTmin which gives a minimized annualized total cost was evaluated from the analysis and used in the design of the new network for the process.

Energy targets: The plot of energy targets versus DTmin shows a direct relationship between the energy target of the process and the minimum allowable temperature difference, as DTmin increases the demand for external utility increases and the heat recovery in the exchanger decreases, thus DTmin has implication for energy cost (Figure 2).

**Fig 2:** Energy Target vs DTmin for CDU

Area target: The plot of area target versus DTmin shows an inverse relationship (Figure 3), as DTmin increases the area target decreases. For a given value of heat transfer load (Q), if smaller values of DTmin are chosen the area requirements rise, thus DTmin has implication for capital cost. The area target based on the optimum DTmin (15K) was found to be 17151.6 m² which is more economical than the 30380.8 m² target obtained when DTmin was 30K (Linhoff, 1998).

**Fig 3:** Area Target vs DTmin for CDU

Number of units target: The plot of minimum number of heat exchangers (HEmin) versus DTmin shows the effects of DTmin on the minimum number of heat exchangers (Figure 4). The figure shows that when DTmin increases from 6 to 18 K, the number of heat exchangers is 22. HEmin rise to 23 when the value of DTmin changes from 19 to 22 K and return to 22 when DTmin becomes 23 K, between 38-50 K, the number of HEmin reduces to 21.

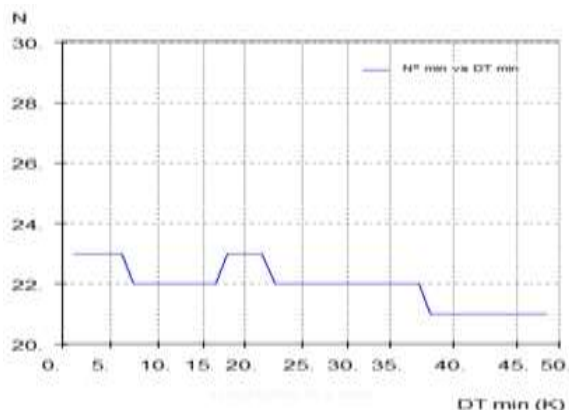


Fig 4: Minimum Number of Heat Exchangers vs DTmin for CDU

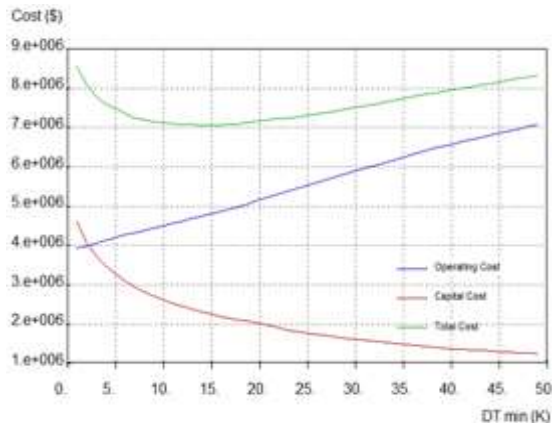


Fig 5: Operating-Capital Cost Trade off (Optimum DTmin) for CDU

Cost targets: The cost targets consist of both the operating, capital and total cost targeting. The plot of operating cost versus DTmin shows that as DTmin increases, the operating cost becomes higher hence an increase in demand for external utilities, while plot of capital cost versus DTmin shows that as DTmin increases, the capital cost which depends on number of heat exchangers, overall network area and the distribution of area between the exchangers decreases (Figure 5). The DTmin represent the trade-off between capital cost (which decreases as the DTmin increases) and energy or operating cost (which increases as DTmin increases). The total cost plot (Figure 5) provides information that corresponds to the optimization of minimum approach temperature (DTmin). It was evaluated by minimizing the total annual cost. The overall aim of the plot is to find the best compromise between the heat exchange area, utility requirements and unit shell number. Optimum DTmin was found to be 15 K, with an operating cost of US\$4,811,540/yr and capital cost of US\$1,904,160/yr leading to a total cost of US\$6,715,700/yr, contrary to the total annual cost of US\$8,662,880/yr obtained when DTmin of 30 K was selected in reference to the typical values of DTmin of CDU (30-40 °C) provided by Linnhoff (1998). The optimum DTmin value (15 K) is similar to that obtained in the work of Ajao and Akande (2009).

Composite Curve: A composite curve (CC) is a graphical combination (or composite) of all hot or cold process streams in a heat exchange network (Figure 6). The Temperature - enthalpy (T - H) plot have been use to set energy targets prior to network design. It consists of heat availability in the process (the hot composite curve) and heat demands in the process (the cold composite curve) combined in a single plot. At optimum DTmin of 15 K, the hot and cold pinch temperatures were found to be 514 K and 499 K respectively.

The CC shows that the minimum heating demand (QHmin) was 32251.1 kW while the minimum cooling demand (QCmin) was 29637.9 kW. From Figure 6, the region of overlap (of hot and cold curve) indicates a total of 108,945 kW as possible energy that can be recovered in the process. Table 2 shows 34,984.55 kW of energy saved, this presents a potential reduction of 36.11 % in the utility requirement of the unit. This percentage saving is in accordance to that provided by Linnhoff (1998) that energy costs could be reduced by 15-40% for retrofit design.

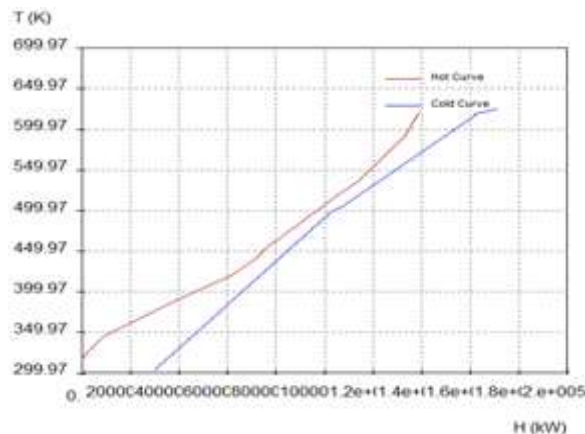


Fig 6: Composite Curve of Crude Distillation Unit of KRPC

Table 2: Possible Utility Requirement Saving of Crude Distillation Unit

Utility	Current (kW)	Minimum (kW)	Saved (kW)
Heating	64,642.80	32,251.10	32,391.70
Cooling	32,230.75	29,637.90	2,592.85
Total	96,873.55	61,889.00	34,984.55

Grand Composite Curve: The grand composite curve (GCC) is a plot of shifted temperatures versus the cascaded heat between each temperature interval (Figure 7). It shows the variation of heat supply and demand within the process. Using this diagram the

designer can find which utilities are to be used so as to maximize the use of cheaper utility levels and minimize the use of the expensive utility levels. The pinch point indicates zero heat transfer ($H=0$). The pinch of the process is found at 506.5 K, this means that cooling should be avoided above 506.5 K and heating should be avoided below this temperature in order not to violate pinch rules.

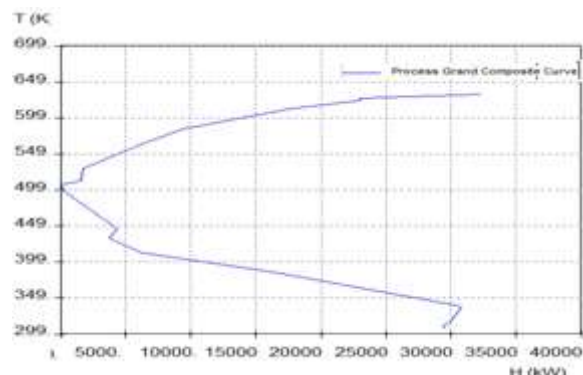


Fig 7: Grand Composite Curve of Crude Distillation Unit of KRPC

Heat Exchanger Network of Crude Distillation Unit (CDU): The design objective of the retrofit heat exchanger network (HEN) is set toward maximum energy recovery. A total of 20 heat exchangers made up the new network, which comprises of 12 process to process heat exchangers, 2 heaters and 6 coolers. The HEN was studied for possible matches and stream splitting to satisfy the pinch rules while saving energy. The vertical line in the grid diagram (Figure 10) divides the network into two; above the pinch and below the pinch. The hot pinch temperature is 514 K and the cold pinch temperature is 499 K, this means that hot stream temperature above 514 K lies above the pinch and cold stream temperature below 499 K lies below the pinch.

Heat Exchanger Network (above pinch): The criteria for matching streams near the pinch for above pinch is that the number of hot streams should be less than or equal to number of cold streams, so also the heat capacity of the hot streams should be less than or equal to that of the cold streams. Cold stream with a heat capacity of 374.038 and 366.34 kw/K (Figure 10) is split in to two each having a heat capacity of 215.001(stream 14) and 159.037 kw/K (stream 15) and 183.17(stream 18) and 183.17 kw/K (stream 19) respectively to meet up the matching criteria, see Figure 8 . Table 3 shows feasible stream matches, stream 4 can be matched with either stream 14, 15, 18 and 19 while stream 3 can only be matched with 14. The pinch heat exchangers was placed appropriately using the remaining problem analysis which helps in

making sure that the heat exchangers did not task the minimum area target.

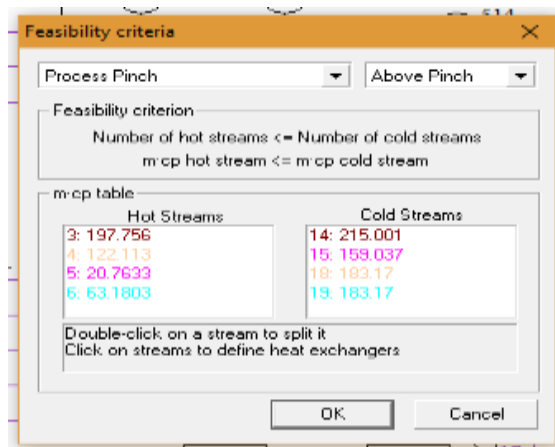


Fig 8: Feasibility Criteria for Matching Above Pinch Showing Split Cold Streams

Table 3: Feasible Matches Table (above pinch)

	3	4	5	6
14	*	*	*	*
15		*	*	*
18		*	*	*
19		*	*	*

Heat Exchanger Network (below pinch): The criteria for matching streams near the pinch for below the pinch is that the number of hot streams should be greater than or equal to number of cold streams, so also the heat capacity of the hot streams should be greater than or equal to that of the cold streams. In Figure 9, stream 3 can only be matched with split cold stream 15. Note that if a stream crosses the pinch, the pinch rule of heat capacity cannot be violated even for non-pinch heat exchangers. Table 6 shows feasible stream matches, the only feasible match is between cold stream 15 and hot stream 3.

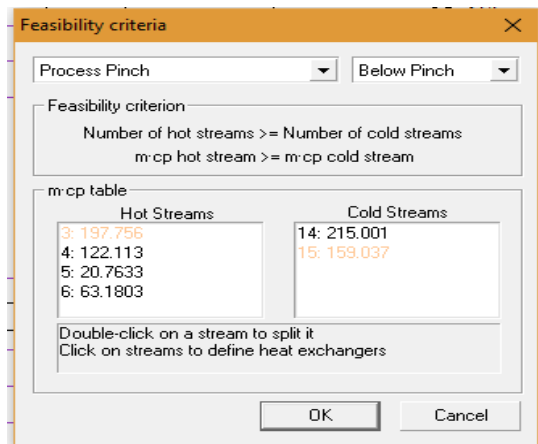


Fig 9: Feasibility Criteria for Matching Below Pinch Showing Split Cold Stream

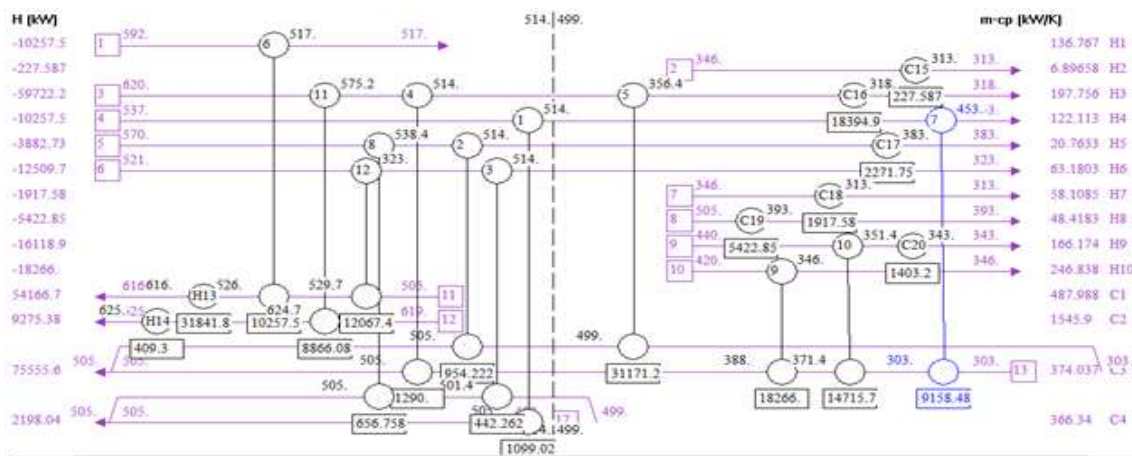


Fig 10: Retrofit Grid Diagram of the Heat Exchanger Network of Crude Distillation Unit of KRPC

Table 4: Feasible Matches Table (below pinch)

	14	15
3		*
4		
5		
6		

Figure 10 shows HEN for maximum energy recovery of the existing network. Above the pinch, stream 3 can only be matched with stream 14, stream 4 was matched with 18 in preference to 14, 15 and 19 due to minimum area target consideration. HE 11 (8866.08 kW) raises the temperature of stream 12 from 619 K to 624.7 K which is less than the targeted temperature of 625 K hence heater H14 (409.3 kW) was installed to reach the targeted temperature and thus satisfying stream 12. Below the pinch, stream 3 was matched with 14 with HE5 (31171.2 kW) raising the temperature of stream 14 from 303 K to 499 K while cooling the temperature of stream 3 from 514 K to 356.4 K. A cooler C16 (18394.9 kW) was then placed to cool the stream to its targeted temperature of 318 K. Finally, the total duty of heat exchangers on each stream was calculated to make sure the network is balanced appropriately. Installation of heaters and coolers requires approximately accurate calculation of the heating/cooling duty to avoid run time error from the software. Hence, the heat capacity (mcp) values were used to multiply the temperature difference to obtain a reasonable but approximate estimate of the heating/cooling duties of heaters and coolers (Akpa *et al.* 2018).

Economic Analysis: This analysis entails the capital and operating costs of CDU of the refinery. Using the cost correlation in Figure 11, for an optimum minimum temperature difference ($DT_{min, optimum}$) of 15 K, the capital cost was obtained to be US\$1,904,160/yr and an operating cost of US\$4,811,540/yr which gives a total annual cost of US\$6,715,700.

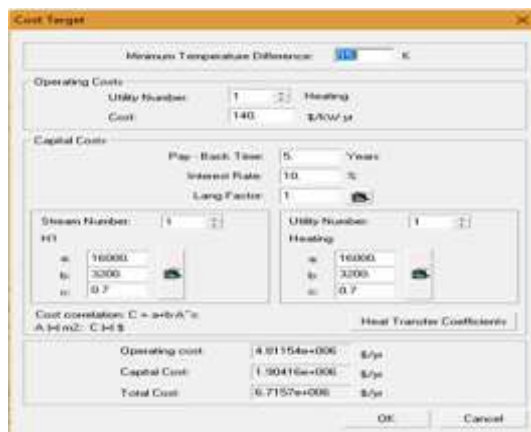


Fig 11: Cost Target of Crude Distillation Unit of KRPC

Utility Cost Target of Crude Distillation Unit: Figure 12 shows that the heating utility (32,251.1 kW) required by the CDU cost US\$4,515,150/yr and the cooling utility (29,638 kW) amounting to US\$296,380/yr.

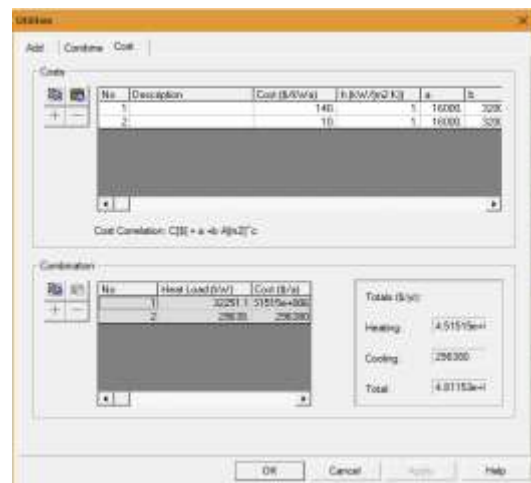


Fig 12: Utilities Cost Target of Crude Distillation Unit

The total cost of utility saved (A) could be calculated as follows: First we obtained the amount of heating utility saved (B) as

$$B = \text{current heating utility} \\ - \text{minimum heating utility}$$

Hence

$$B = 64,642.80 \text{ kW} - 32,251.10 \text{ kW}$$

$$B = 32,391.7 \text{ kW}$$

$$\text{hot utility (S1) cost} = 140 \text{ \$/ (kW yr)}$$

Then cost of heating utility saved (C) is

$$C = 32,391.7 \text{ kW} \times \frac{140\$}{\text{kW yr}} \\ C = 4,534,838 \text{ \$/yr}$$

Then we evaluate the amount of cooling utility saved (D) as

$$D = \text{current cooling utility} \\ - \text{minimum cooling utility}$$

$$D = 32,230.75 \text{ kW} - 29,637.90 \text{ kW}$$

$$D = 2,592.85 \text{ kW}$$

$$\text{cold utility (W1) cost} = 10 \text{ \$/ (kW yr)}$$

The cost of cooling utility saved (E) could be evaluated as

$$E = 2,592.85 \text{ kW} \times \frac{10\$}{\text{kW yr}} \\ E = 25,928.5 \text{ \$/yr}$$

$$A = C + E$$

$$A = 4,560,766.5 \text{ \$/yr}$$

Conclusions: HINT software was used in the analysis and showed reliable application in carrying out all the necessary analysis required for pinch design method. DTmin analysis was also carried out on the process and targeted energy, area and cost were obtained. Optimum retrofit design of the heat exchanger network of the distillation unit was obtained. The pinch analysis with HINT software proved to be valuable in retrofit of the existing HENs of crude distillation of KRPC with enormous potential for energy and cost savings.

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