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Pinch Analysis of Crude Distillation Unit using the HINT Software and Comparison with Nonlinear Programming Technique

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Abstract: In this study, the effectiveness of HINT was first verified by the application to a case study investigated for minimum area target and then applied to a Crude Distillation Unit (CDU) after obtaining a satisfactory solution which was within 1% when compared with existing solution for minimum area target. The HINT package accomplished the maximum heat recovery between the hot streams and the cold streams and later identified the utility required for the heat balance in the Heat Exchanger Networks (HENs). Pinch analysis of the CDU plant showed that both hot and cold utilities are still needed after the maximum energy recovery between all the hot streams and all the cold streams present in the HENs synthesized. The total hot utility required was found to be 4.99×10^8 kJ h^{-1} while that of cold utility was 5.08×10^8 kJ h^{-1}. The ΔT_{min} that gives the minimum total annual cost was found to be 2.95 K and the corresponding total annualized cost was $4.88 million/year. The findings also revealed that HINT is capable of returning solutions that are comparable with those of mathematical based techniques such as the Nonlinear Programming (NLP) technique used as a basis for comparison.

INTRODUCTION

Energy conservation remains the prime concern for many process industries considering the rising energy cost and environmental limitations[1]. In order to increase the profitability of the industries and reduce their environmental impacts, several methods for analyzing energy systems of new and existing plants have been developed[2]. Among the various process integration methods used to minimize excessive heat energy consumption in different industrial processes, pinch analysis is most commonly used[3]. Pinch technology has made possible the design of new plants with optimum energy and capital costs and performance improvement of existing processes[4]. The technique has been used globally to target hot and cold energy requirement for Crude Distillation Units (CDU) and other processes[4]. Based on pinch analysis, the heat exchanger network retrofitting is envisaged as one of the promising options for reducing energy consumption which could lead to enhanced economic and environmental sustainability[3].

Literature is rich on the various industrial application areas of the pinch analysis technique. For instance, its application for general heat integration of distillation columns has been reported by Mane and Jana[5] and for internally heat integrated distillation columns by Nakaiwa *et al.*[6]. Al-Riyami *et al.*[7] studied the effects of changing the pinch temperature of a fluid catalytic cracking plant on the hot and cold utilities and the area of the heat exchanger networks. Ajao and Akande[8] investigated the energy integration of the crude pre heat train of Kaduna refinery where they found out the optimum pinch temperature for the pre-heat train using pinch analysis techniques. Chegini *et al.*[9] used the Heat-Int software which is based on methods of pinch technology to design, optimize and improve the integrated heat exchanger network of crude oil preheating process in distillation unit in Arak refinery. With the aid of the heat-int software[4] also carried out energy integration of a heat exchanger network in a plant refinery plant using pinch analysis and investigated the effects of pinch temperature on changes in hot and cold utilities and on the area of heat exchangers. Revamping projects using pinch design method conducted for existing oil refineries to improve their operation and achieve more energy savings have been reported[10]. In addition, the stage model has been applied to many CDUs as in the work of Promvitak *et al.*[11].

A previous study conducted by Akande[12] indicated that several possibilities exist for energy saving in the Nigerian industrial sector such as the plant refineries. On heat Exchanger Network Synthesis (HENS), first described and formulated by Masso and Rudd[13], extensive reviews have been contributed by a number of workers such as Linhoff and Flower[14], Nishida *et al.*[15], Papoulias and Grossmann[16], Linhoff and Ahmad[17], Yee *et al.*[18], Furman and Sahinidis[19, 20], Morar and Agachi[21], Klemes and Kravanja[22] and Klemes *et al.*[23]. But, despite the advancement in methodologies and tools of process modelling and optimization, a major challenge in HENS problems is how to develop superior models and algorithms that can optimally obtain optimal Heat Exchanger Network (HEN) with lower total annualized cost.

Among the several design targets for HEN synthesis proposed previously by different workers are the findings of Hohmann[24], Raghavan[25], Linnhoff and Flower[14], Papoulias and Grossmann[16] and Cerda *et al.*[26] which demonstrated the prediction of either the minimum utilities required for a specified minimum temperature difference (ΔT_{min}) or the minimum number of units for specified utilities, independent of area. But, the study conducted by Colberg and Morari[27] developed a pair of transshipment Nonlinear Programs (NLP) to simultaneously calculate the area and capital cost targets for HEN synthesis, making it possible to evaluate the trade-off between the area and number of units before synthesis. Basically, Colberg and Morari[27] formulated the transhipment model of Papilias and Grossman[16] as a NLP for targeting the area on HENS. The NLP Model of Colberg and Morari[27] is able to target for both restricted matches and those that are not restricted.

The HINT (Heat-Integration) is non-commercial software developed by Department of Chemical engineering and Environmental Technology, University of Valladolid, Spain that is capable of handling design of small heat exchanger network[28]. It is based on the principle of pinch analysis, a reliable method that has been used in the optimization of HENs. In the present study, the goal is to apply pinch analysis using HINT software in energy conservation and optimization of Crude Distillation Unit (CDU) of Kaduna Refining and Petrochemical Company(KRPC) Ltd. and compare results with the NLP technique of Colberg and Morari[27].

MATERIALS AND METHODS

The tool used in this study is the Heat-Integration (HINT) software. Process data of CDU I was obtained from Kaduna Refining and Petrochemicals Company (KRPC) Limited. It involved four cold process streams and ten hot process streams from the existing heat exchanger network.

This study is the analysis, design and optimization of Heat Exchanger Network (HEN) of CDU I pre-heat train of KRPC Ltd. The pinch procedure involved data extraction, process simulation, network design and pinch analysis of the process plant as illustrated in Fig. 1. The application of pinch analysis in the energy conservation of CDU I remains the focus of this study.

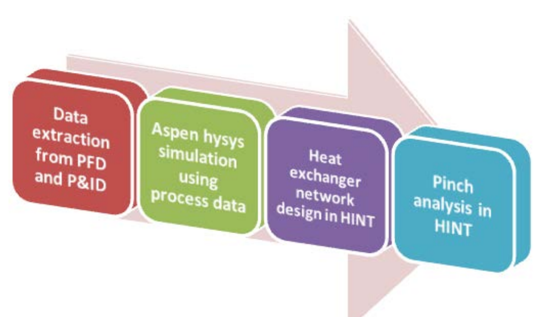

Fig. 1: Procedures involved in pinch analysis of the CDU pre-heat train

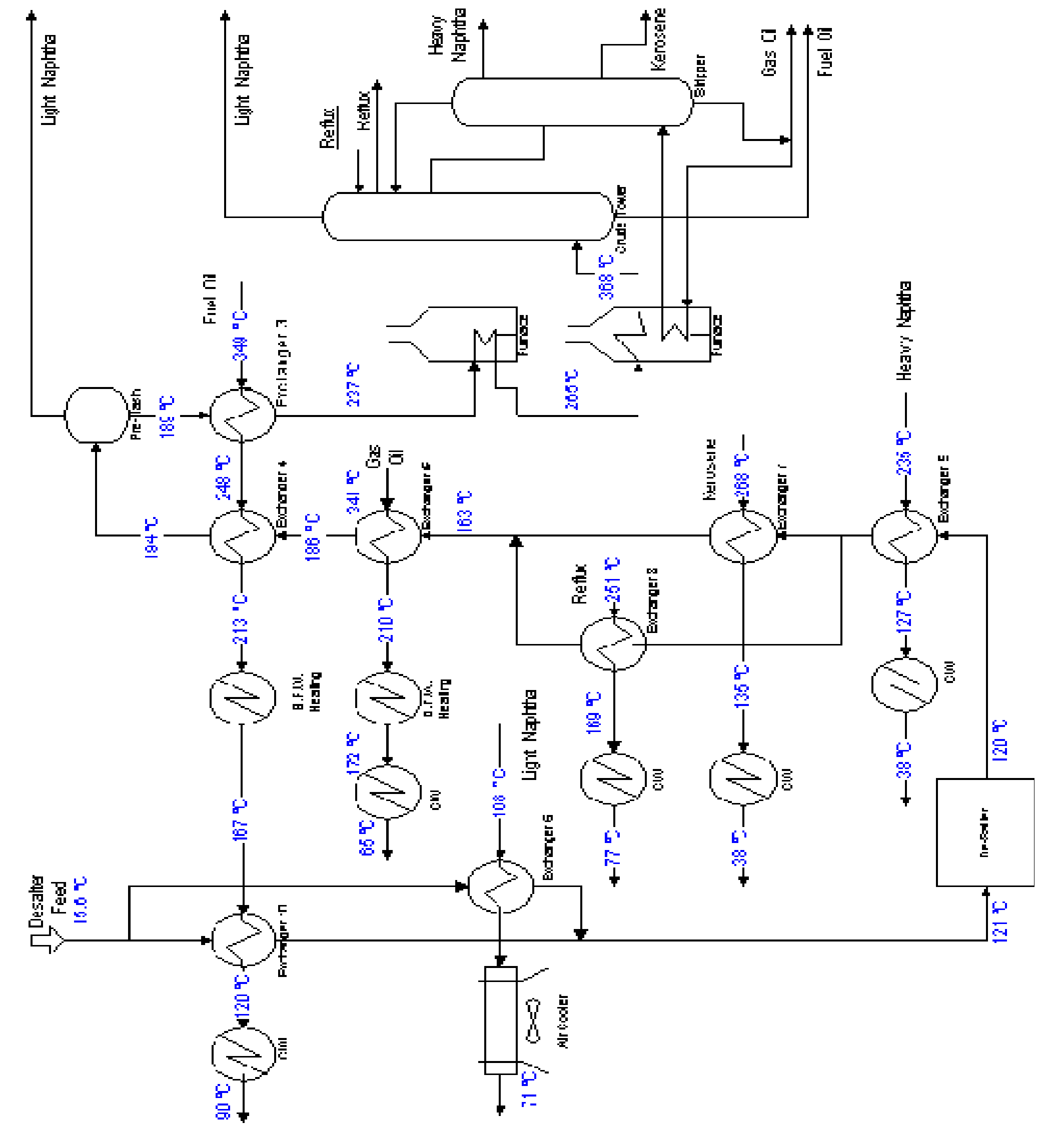

Fig. 2: Process flow diagram of CDU I, Kaduna Refining and Petrochemical Company Ltd.

The Process Flow Diagram (PFD) of the CDU I plant is presented in Fig. 2. The PFD shows that the CDU process involves four cold process streams and ten hot process streams from the existing heat exchanger network.

The process data and the PFD were used to carry out simulation of the CDU plant in Aspen HYSYS. Using the process simulation data of CDU I, the supply temperature (T_s), target Temperature (T_t), flow-rate and heat capacity of each stream in the heat exchangers network were extracted for carrying out the pinch analysis. Also, the areas of each heat exchanger in the network were extracted. The physical properties of the products from the crude distillation unit are shown in Table 1. Aspen HYSYS process simulator was used for the process simulation of the plant streams. The source and target temperatures of all the streams, mass flow rates, feed and product compositions of the feed and product of the plant were used for obtaining the specific heat capacities and enthalpies of the streams.

The data of Table 1 were converted to appropriate units suitable for input in HINT 2.2 software. Temperatures are required in Kelvin (K) and heat content in kW. Hence, for the enthalpy values in kJ h^{-1}, these were converted to kW by using Eq. 1:

$$\text{Enthalpy (kW)} = \frac{\text{Enthalpy}\left(\frac{\text{kJ}}{\text{h}}\right)}{3600} \quad (1)$$

Table 1: Data extracted from Aspen HYSYS simulation, showing the heating and cooling of the process streams[8]

Stream Name	Types	T_s (°C)	T_t (°C)	Enthalpy (kJ h^{-1})
Low temp crude_To_Preheat Crude	Cold	30	232.22	2.72E+08
PreFlashLiq_To_HotCrude	Cold	232.22	343.33	1.95E+08
KeroSS_ToReb@COL1_TO_Kerosene@COL1	Cold	226.16	231.77	7, 912, 951
TrimDuty@COL1	Cold	345.59	351.53	33, 391, 352
PA_3_Draw_To_PA_3_Return@COL1	Hot	319.41	244.09	36,926,963
Waste H_2O_To_Cooled Waste H_2O	Hot	73.24	40	819, 313.4
Residue_To_Cooled Residue	Hot	347.28	45	2.15E+08
PA_2_Draw_To_PA_2_Return@COL1	Hot	263.51	180.15	36, 926, 963
AGO_To_Cooled AGO	Hot	297.35	110	13, 977, 836
Diesel_To_Cooled Diesel	Hot	248.02	50	45, 034, 887
Naphtha_To_Cooled Naphtha	Hot	73.24	40	6, 903, 304
Kerosene_To_Cooled Kerosene	Hot	231.77	120	19, 522, 251
PA_1_Draw_To_PA_1_Return@COL1	Hot	167.06	69.55	58, 028, 085
To Condenser@COL1_TO_OffGas@COL1	Hot	146.67	73.24	65, 759, 664

Ts = Supply temperature; Tt = Target temperature

This study uses process simulation data of the plant streams generated by Ajao and Akande[8] carried out with Aspen HYSYS process simulator. The supply and target temperatures of all the process streams, mass flow rates, feed and product compositions of the feed and product of the plant were used for obtaining the specific heat capacities and enthalpies of the streams. For the purpose of the present study, the data was analyzed in the desired format that is suitable for use in HINT software.

Heat exchangers network: The design of Heat Exchanger Network (HEN) was synthesized in HINT 2.2 software using the data previously presented in Table 1. Different HENs were designed based on minimum delta T bearing in mind the cost implications of the utilities and number of heat exchanger units. An optimum delta T minimum that gives the minimum total annualized cost was finally obtained.

Pinch analysis using the HINT software: HINT software procedure for carrying out pinch analysis has been summarized in Fig. 1. The HINT was used to create a grid diagram of the existing heat exchanger network from which composite curves were generated. The composite curves were used to identify cooling and heating requirements and to evaluate possible heat integration opportunities. A retrofit grid diagram was obtained by improving the grid diagram using utilities and optimization of the minimum delta T. The cost data comprises of the operating cost for utilities and the capital cost for heat exchangers. The annualized cost data was based on 86,000 h per year, pay-back period of 10 years with no interest rate. Utility cost data was taken from Azeez *et al.*[29, 30]. The capital cost used is that given by Eq. 2 which is found by Azeez *et al.*[29, 30] and Al-Mutairi and Elkawad[4]:

$$\text{Capital cost(\$)} = a+b(\text{Area})^c \tag{2}$$

Where:

Area = Area of heat exchangers
a = The fixed cost of installation
b and c = The cost of area per unit which both depend on the material of constructions of heat exchanger

In Eq. 2, a = 0, b = 1200, c = 0.6 and Area is area of exchangers (m^2). In this study, it was assumed that the same equation holds for all types of heat exchangers in the network, process to process and utilities exchangers.

The cost data used for utilities was that provided by Yee and Grossman[31] where the heat transfer coefficient, h = 1 kW/(m^2 K), hot utility (S1) cost = 140 \$/(kW year) and cold utility (W1) cost = 10 \$/(kW year). In their work, steam was used as the heating utility and cooling water as the cold utility in the popular magnets problem. Water was used as a coolant because it is cheap, non-hazardous and a good heat transfer medium. The thermodynamics data used in this work and as provided by Yee and Grossman[31] were as follows:

- Steam (S1); cost = 140 \$/kWa, h = 1, Ts = 700 K, Tt = 700 K
- Cooling water (W1); 10 \$/kWa, h = 1, Ts = 300 K, Tt = 320 K

The shifted composite curve was obtained by using the following Eq. 3 and 4 to calculate the shifted temperatures[8]:

$$\text{Shifted Hot Stream Temp.} = \text{Unshifted Hot Stream Temp.} - \frac{\Delta T_{min}}{2} \tag{3}$$

$$\text{Shifted Cold Stream Temp.} = \text{Unshifted Cold Stream Temp.} + \frac{\Delta T_{min}}{2} \tag{4}$$

Table 2: Stream data for example problem of Coldberg and Morari[27]

Stream	Supply temperature (K)	Target temperature (K)	Heat capacity flow rate (kW/K)	Film heat transfer coefficient (kW/m^{2}K)
HI	395	343	4	2.0
H2	405	288	6	0.2
C1	293	493	5	2.0
C2	353	383	10	0.2
Steam	520	520	-	2.0
Water	278	288	-	2.0

ΔT_{min} = 10 K. Cooling water was treated as a third cold stream with heat capacity flow rate of 23 kW/K, according to Colberg and Morari[27] who considered that necessary because cooling water is a nonisothermal (or "non-point") utility, whereas condensing steam is an isothermal (or "point") utility

In order to be sure that HINT software will produce a reliable result, the software was first applied to a problem that has been investigated by Colberg and Morari[27] where the authors targeted for minimum area using pinch technology. The example is presented below.

Example problem of Colberg and Morari[27] using the HINT: An example problem in the work of Colberg and Morari[27] was solved using HINT software which involved the determination of the Area targets for heat exchanger network synthesis with constrained matches and unequal heat transfer coefficients. A comparison was then made between their results and the result obtained in the present study. The stream data for this problem is shown in Table 2.

RESULTS AND DISCUSSION

Prior to solving the CDU network synthesis problem, the reliability of the HINT software was first investigated by solving the example problem of Colberg and Morari[27] whose stream and cost data was presented in presented in Table 2. The goal was to predict the area target of the HEN in that study. A comparison was then made between their results and the results obtained in the present study which showed similar area targets thus confirming the reliability of HINT software. The grid diagram of the heat exchanger network and the composite curve as generated in the HINT for the problem adapted from Coldberg and Morari[27] is presented in Fig. 3 and 4, respectively. A total number of 6 exchangers and area target of 298.227 m^2 were obtained in this study. The area target obtained in this study is within 1% of the one obtained in simple area targeting of Colberg and Morrari[27]. This suggests that the HINT software employed in this study is an effective package for pinch analysis. It gives operating and capital cost of 31,000 and 34,215.5 \$/year, respectively. This amounts to total cost of 65,215.5 \$/year. The NLP of Colberg and Morari[27] could not target for the operating cost and the total cost.

Results were compared with that of Colberg and Morari[27] as shown in Table 3. Colberg and Morari[27] obtained with their NLP, a total area target of 259.7 m^2 as the starting point solution using MINOS 5.0 software with

Table 3: Results comparison

Methods	Area target (m^2)	Difference (%)
Colbberg and Morari[27]-No forbidden match	258.8	-
Coldberg and Morari[27]-Simple area targeting	295.6	14.22
Present study by the HINT	298.227	15.23

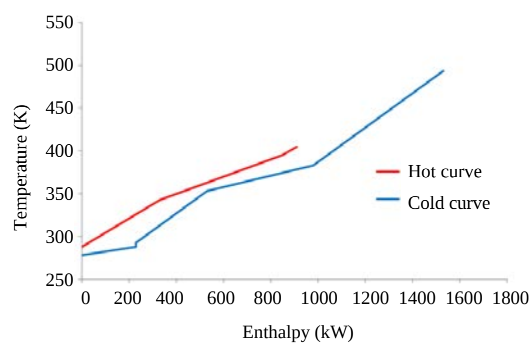

Fig. 3: Composite curve of example problem showing total heating and cooling targets of 620 and 230 kW, respectively

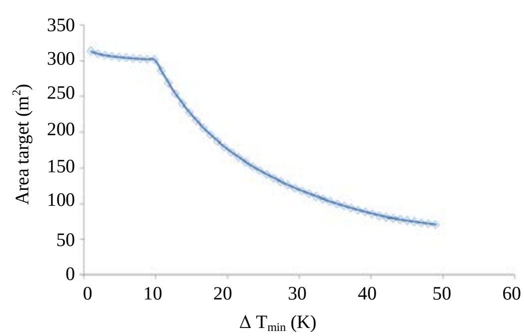

Fig. 4: Optimum ΔT_{min} of 8.84 K at area target of 301.88 m^2 obtained from HINT

a spaghetti structure. With no restriction in stream matching, the NLP yielded an area target of 258.8 m^2 but the author's simple area targeting method based on composite curves predicted a target of 295.6 m^2. They also observed that the optimal ΔT_{min} of 4.2 K was <ΔT_{min} (10 K) specified for utility targeting in that case study. A comparison of results revealed that the simple area

Table 4: Data extracted for the pinch analysis, showing hot and cold process streams, description, supply and target temperatures of the existing process

Stream description	Type	Supply Temp. Ts (K)	Target Temp. Tt (K)	Enthalpy (kW)
C1	Cold	303.15	505.37	75,555.56
C2	Cold	505.37	616.48	54,166.67
C3	Cold	499.31	504.92	2,198.04
C4	Cold	618.74	624.68	9,275.38
H1	Hot	592.56	517.24	-10,257.49
H2	Hot	346.39	313.15	-227.59
H3	Hot	620.43	318.15	-59,722.22
H4	Hot	536.66	453.30	-10,257.49
H5	Hot	570.50	383.15	-3,882.73
H6	Hot	521.17	323.15	-12,509.69
H7	Hot	346.39	313.15	-1,917.58
H8	Hot	504.92	393.15	-5,422.85
H9	Hot	440.21	342.70	-16,118.91
H10	Hot	419.82	346.39	-18,266.57

targeting method of Colberg and Morari[27] overestimated the area target by 14.22% while the matching used in the present study overestimated the target by 15.23% which is just about 1% different from the NLP solution of Colberg and Morari[27]. However, given the closeness of the areas between this study and that of Colberg and Morari[27], the HINT software is therefore, considered a reliable tool that can be used in the study of pinch technology.

Heat Exchanger Network (HEN) of CDU I, KRPC Ltd.: The first step in the application of pinch analysis involved data extraction. Data were extracted from the CDU I process and were represented in appropriate unit as given in Table 4.

The heat capacity flow rate is given by CP (kW/K) = FCp(T-To). The heat exchanger network featured four cold streams with combined enthalpy of 141,195.65 kW and 10 hot streams having total enthalpy of 138,583.12 kW. It is clear from the capacity of hot and cold streams presented in Table 4 that the load available in all hot streams is more than those available in the cold streams.

In order to generate targets for minimum energy targets, the ΔT_{min} value was set for the problem with an initial value of 10°C. The ΔT_{min} or minimum temperature approach 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 reflects the trade-off between capital investment (which increases as the ΔT_{min} value gets smaller) and energy cost (which goes down as the ΔT_{min} value gets smaller). For the purpose of this study, typical ranges of ΔT_{min} values that have been found to represent the trade-off for each class of process have been used.

The retrofitted HEN grid diagram for the base case design is shown in Fig. 5. It can be observed from the CDU network that there is little restriction on heat exchange between the cold process and the large hot process streams. This results in wastage of useful heat energy which is also unsafe for the environment and the plant operators. Hence, in the retrofitted network, cold utility (Cooling Water-CW) was introduced in order to make up for the deficient heat sink (cold process streams) to exchange heat with the heat source (hot process streams). The temperature versus enthalpy plot or composite curve is shown in Fig. 6.

Figure 6 and 7 show the composite curves and the grand composite curves for the heat exchanger network presented in Fig. 5. The temperature-enthalpy diagram is a graphical tool that depicts the heat transfer between any two hot and cold streams. It is an alternative technique that gives useful insights into the temperature-driving force for heat transfer between the streams. It is a plot of temperature on the y-axis versus enthalpy or heat transferred on the x-axis for the same heat-exchanger units in the network. As shown in Fig. 6 and 7, the hot stream (red line) enters the heat exchanger from the right side 620.42 K and leaves at the left side at 313.14 K. As a counter current heat transfer, the cold stream (blue line) enters the exchanger from the left side at 303.14 K and exits at the right side at 624.67 K. The horizontal distance between the red and blue lines corresponds to the heat-transfer rate from the hot stream, Q_H, to the cold stream, Q_C. The slope of the hot or cold stream line is inversely proportional to the ability of the stream to give off or accept heat. The total heat transferred from the hot stream H_H is given by Eq. 5 or to the cold stream H_C is given by Eq. 6:

$$\Delta H_H\,(kW) = \left(MC_p\right)_H \left(\frac{kW}{K}\right)\left(T_H^{supply} - T_H^{target}\right)(K) \tag{5}$$

$$\Delta H_C\,(kW) = \left(MC_p\right)_C \left(\frac{kW}{K}\right)\left(T_C^{target} - T_C^{supply}\right)(K) \tag{6}$$

where, the capacity flow rate, $(MC_p)_i$ refers to the product of the mass flow rate, M_i and the heat capacity, $C_{p,\,i}$, of each stream i.

As shown in Fig. 6, the composite curves are graphical representation of the heating and cooling

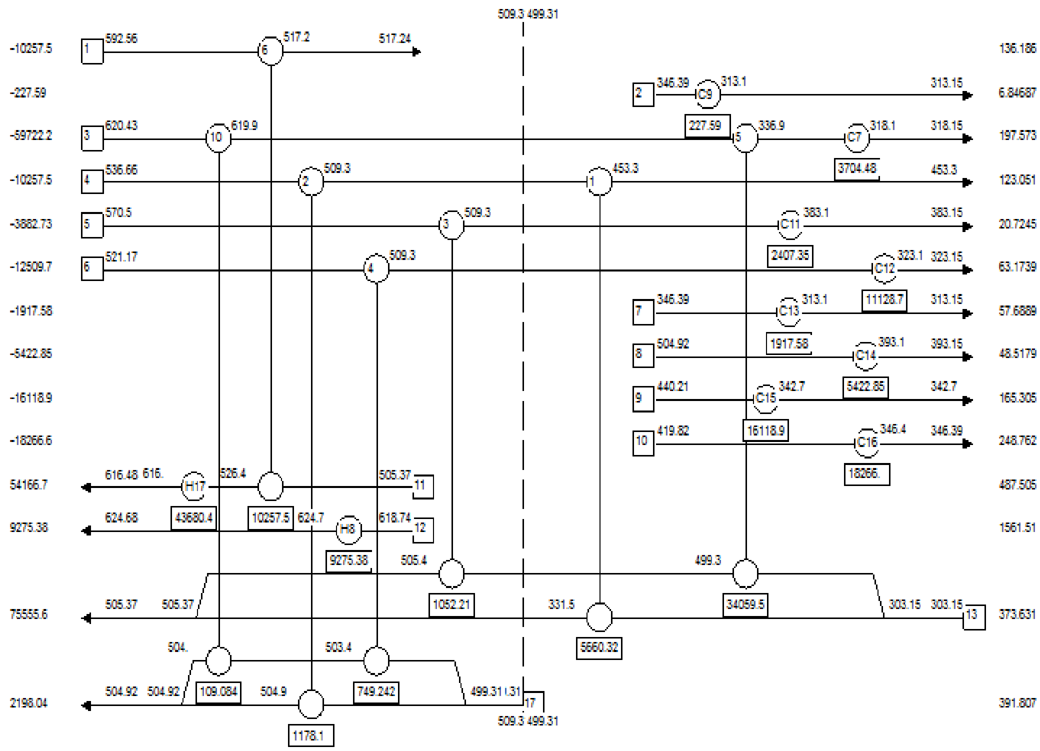

Fig. 5: Grid diagram of CDU heat exchanger network

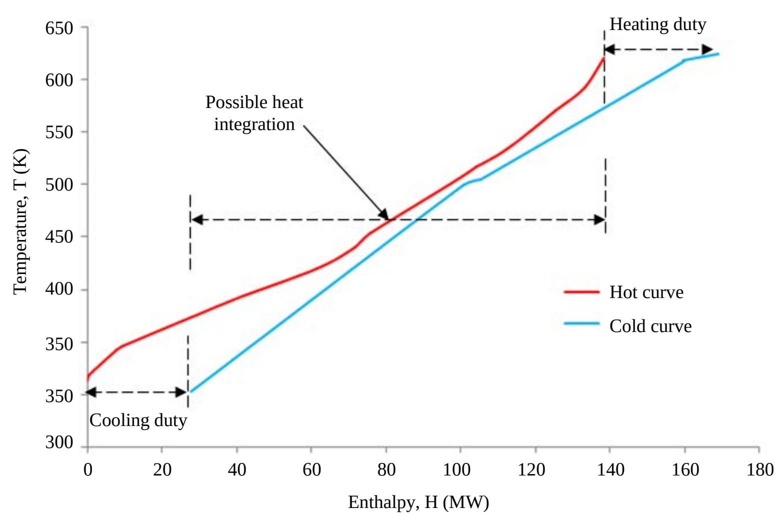

Fig. 6: Composite curves

demands of the entire system. It is used in identifying the minimum utility requirements. The construction of composite curves is an essential step in process integration by pinch analysis. Individual hot and cold streams are represented on a single diagram in order to determine the minimum utility duties for the entire system. The vertical overlap represents possible heat integration in the system of heat exchanger network. The composite curves also showed where to apply heating and cooling utilities to the cold and hot streams, respectively.

The composite curves give the energy targets before the design. Energy targets from the composite curve are heating 138.58 MW and cooling load 141.196 MW. The Grand Composite Curve (GCC) which is a plot of shifted temperatures against the cascaded heat between each

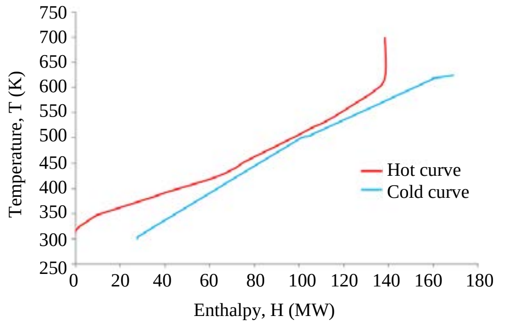

Fig. 7: Composite curves with utilities

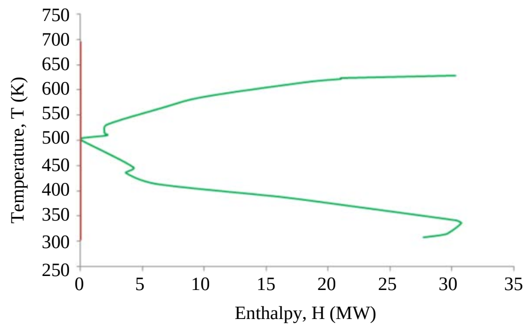

Fig. 8: Grand composite curve

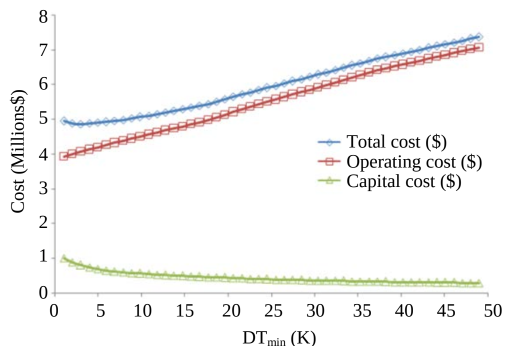

Fig. 9: Plot of DT_{min} against total annual cost for the crude pre-heat train

temperature interval is shown in Fig. 8. This was obtained at DT_{min} of 10°C. The range targets plot for this problem is shown in Fig. 9. It provides information that corresponds to the optimization of minimum approach temperature (DT_{min}). It was calculated 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.

Results as presented in Fig. 9 show the plot of total cost index against minimum temperature approach for Crude Pre-Heat Train of CDU I Unit, KRPC. Capital cost decreases with increasing minimum temperature difference while operating cost increases with the minimum delta T. Along with variation in the minimum

Table 5: Results comparison between the present study and Ajao and Akande[8]

Pinch analysis targets	Ajao and Akande[8]	Present study
Energy targets		
Heating (kJ h^{-1})	1.11×10^8	4.99×10^8
Cooling (kJ h^{-1})	1.02×10^8	5.08×10^8
Number of unit targets		
Total minimum	19	17
Minimum for max. Recovery	38	-
Cost targets		
Capital cost ($)	60,363.35	8.05E+05
Operating cost ($/year)	22,355.63	4.07E+06
Total annual cost ($/year)	41,798.77	4.88E+06

approach temperature, the corresponding total annualized cost of the HEN was calculated in order to find a ΔT_{min} that yields the minimum total annual cost. The plot shows that optimum minimum temperature approach desired is 2.95 K which is similar to the one obtained in one of the examples solved by Yee and Grossmann[31]. This value of minimum temperature approach was determined by parametric optimization. Here, the least total annual cost of $4.88 million/year was attained at ΔT_{min} of 2.95 K with a total of seventeen heat exchanger units to achieve maximum energy recovery. The DT_{min} that gives the minimum total annual cost was found to be 2.95 K and the corresponding total annualized cost was $4.88 million/year.

The minimum temperature approach (ΔT_{min}) was found to affect the pinch location, minimum number of heat exchangers and the heat exchanger area. In the plot of pinch temperature against minimum delta T, the pinch point of 519.96 K occurred at minimum temperature difference of 38°C. The dependence of number of heat exchangers on the Delta minimum is shown in the minimum number of heat exchangers vs. DT_{min} plot. The plot revealed that the minimum number of heat exchangers of 21 was obtained at minimum temperature approach of 38°C. Also, the area target plot showed that there is an exponential relationship between the total heat exchange area and the minimum temperature difference.

Result comparison with previous study: Table 5 compares the results obtained in the present study with that of Ajao and Akande[8] for the Crude Pre-heat train CDU I.

It is observed that there are differences in the cost reported in the work of Ajao and Akande[8] and this study. This can be due to the fact that Ajao and Akande[8] obtained their operating cost, capital cost and total cost in Naira. As at year 2009, dollar conversion to naira exchange rate was between ₦145 and ₦171 to $1, hence, an average value of ₦158 per $1 was used to convert the results of Ajao and Akande[8] from naira to dollar equivalence. It was nevertheless not clear, the conversion factor used by the authors to convert from dollars to

Naira. Another possible reason for the difference in cost obtained is that the authors did not state the number of hot streams and the number of cold streams identified in the process flow sheet. Moreover, the network structure of the optimized CDU was not shown in the study of Ajao and Akande[8].

CONCLUSION

Appropriate software packages will continue to be relevant in process optimization and in the pinch analysis of complex processes because of the mathematical and computing requirements involved. It has been shown in this study that HINT software is a reliable package for HENs optimization since it gives a result that is within 1% of that of NLP technique for minimum area targeting in the case study investigated. For the case of CDU I of KRPC Ltd., the pinch analysis showed that eight coolers and two heaters are required as utilities for the energy balance and heat conservation in the CDU unit. In this case, the ΔT_{min} that gives the minimum total annual cost was found to be 2.95 K and the corresponding total annualized cost was $4.88 million/year. However, further studies are suggested such as the application of the HINT in the HENs design by pinch technique for other process units of the plant refinery and its comparison with multi objective optimization approach.

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