OPTIMIZATION OF THERMAL SYSTEM OF NAPHTHA HYDRO-TREATING UNIT USING PINCH TECHNOLOGY

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ABSTRACT

Optimization of thermal system of the Naphtha hydro- treating unit (NHU) of Kaduna Refining and Petrochemical Company Kaduna, Nigeria was carried out using Pinch Technology. The pinch analysis was done using the Heat Integration Software "HINT".This methodology (Pinch Analysis) is a process integration technique for minimizing the energy costs of a chemical process by reusing the heat energy in the process streams rather than that from outside utilities.The process data which is represented as a set of streams were extracted from the process diagram (PD) of the NHU operating manual and tabulated. The Heat Integration Software was employed where these data were combined for all the streams in the plant to give the composite curves, one for all hot streams (releasing heat) and one for all cold streams (requiring heat). The point of closest approach between the two curves is the pinch point or just pinch and this is where the design is most constrained. For the selected minimum approach temperature of 30 K, the optimum minimum approach temperature was found to be 7.1 K. The pinch point temperature was 488 K. The utilities targets for the minimum approach temperature were found to be 18,246.1 kW and 15,408.4 kW for hot and cold utilities respectively compared to the traditional energy approach of 24,516.0 kW and 22,492.4 kW. There was reduction in operating cost by 31.3 % and total cost by 15 %. It was observed that the pinch analysis indicated a total energy savings of 28.41 % compared to the traditional design. The results showed that Pinch technology as an energy integration technique saves more energy and utilities cost than the traditional energy technique and based on this, the Nigerian National Petroleum Corporation (NNPC) should carryout retrofit of the NHU of Kaduna Refining and Petrochemicals Company (KRPC) in order to increase its output.

Keywords: Optimization, Naphtha hydro-treating unit, Pinch Technology, Heat Integration Software,

1 INTRODUCTION

1.1 Background of Study

Energy is central to sustainable development and poverty reduction. It is essential to our well-being and quality of life and a critical factor for the economic growth of any nation. The rapid drive for industrialization around the globe has consequently place the demand for energy on the high level. This manifested trend is more prominent in developing countries. Process and power industries are the consumers of about 45 to 50 % of total energy resources (Dayo,2000). One of the strategic priority statements for the energy sector of the Nigeria vision 20:2020 states that, "It is necessary for the country to embark on energy conservation and energy efficiency initiatives which will require industries to move to energy saving equipment and utilities for reduction in total power demand (Dayo, 2000). Process integration, is an efficient approach that allows industries to increase their profitability through reduction in energy, water and raw materials consumption, reduction in green house gas (GHG) emissions, and waste generation. Process integration, together with other tools such as process simulation, is a powerful approach that allows engineers to systematically analyze an industrial process and the interaction between its various parts (Mehta,2001). Nick (2002) explained that process integration has a far wider scope and touches every area of process design.

Thermal hydro de-alkylation unit of Kaduna Refining and Petrochemical Company (KRPC) is the most strategic unit for the production of benzene from reformate. The process involves thermal dealkylation of Xylene, Toluene and methylbenzene to produce benzene. This involves passing the feed (reformate) and product (benzene) through preheat trains of exchangers prior to the main distillation or fractionation of the products. The products are also cooled before sending to storage units. Fluid catalytic cracking operation is majorly a cracking process and mainly exothermic reaction. The catalytic reforming unit reactor of KRPC is a reforming operation and mainly endothermic reaction. Pinch Analysis is used to identify energy cost and heat exchanger network (HEN) capital cost targets for a process and recognizing the pinch point. The procedure first predicts, ahead of design, the minimum requirements of external energy, network area, and the number of units for a given process at the pinch point. Thereafter, a heat exchanger network design that satisfies these targets is synthesized. The network is then finally optimized by comparing energy cost and the capital cost of the network so that the total annual cost is minimized. Thus, the main objective of energy integration is to achieve financial savings by better process heat integration (maximizing process-to-process heat recovery and reducing the external utility loads) (Dayo,2000).

In this research, the process of pinch technology was used to carry out the design optimization of the Naphtha Hydro-treating Unit of KRPC (In terms of thermal energy).The refinery was built and commissioned in 1978. Then, the level of technological advancement; energy cost and even the global concern about environment were not as hash as they are presently. That is to say that the trade-off between energy and capital costs have changed drastically; it is, therefore, important to check the validity of this traditional configuration. It is therefore indispensable to carry out analysis of the naphtha hydro-treating units so as to redesign the heat exchanger network of the units using pinch technology.

2 LITERATUREREVIEW

2.1 Process Integration

The term "process integration" means a number of things to different people. It may be applied to a simple heat exchanger that recovers heat from a process product stream, to waste-heat recovery from a gas turbine, to the optimal scheduling of reactor usage, to the integration of a number of production units in an oil refinery, or to the complete integration of an industrial complex. Process Integration (PI) refers to the analysis and optimization of large and complex industrial processes. PI may therefore be defined as: "All improvements made to process systems, their constituent unit operations, and their interactions to maximize the effective use of energy, water, and raw materials".

2.2 Pinch Analysis

One of the most practical tools to emerge in the field of process integration has been pinch analysis, which may be used to improve the efficient use of energy, hydrogen and water in industrial processes. Pinch analysis is a recognized and well-proven method in each of the following industrial sectors:

i. Chemicals
ii. Petrochemicals
iii. Oil refining
iv. Pulp and paper
v. Food and drink
vi. Steel and metallurgy

The approach may be used to identify energy-saving projects within a process or utility systems.The ideal time to apply pinch analysis is during the planning of process modifications that will require major investments, and before the finalization of process design. Maximum improvements in energy efficiency, along with reduced investments can be obtained in a new plant design, since many plant-layout and -process constraints can be overcome by redesign (Hallale, 2002).

2.3 The Value of a Structured Approach

At any one time, site managers may be under pressure to meet new environmental limits, improve efficiency and increase plant capacity. Any of these, on its own, is likely to require project management and engineering time for its development, and capital investment for its implementation. Figure 1 shows some typical site issues.

Figure 1: Typical Site Issues. Source: www.nrcan.gc.ca, 16th October,2014

2.4 The Pinch Concept

Pinch analysis (or pinch technology) is a rigorous, structured approach that may be used to tackle a wide range of improvements related to process and site utility. It analyzes a commodity, principally energy (energy pinch), hydrogen (hydrogen pinch), or water (water pinch), in terms of its quality and quantity, recognizing the fact that the cost of using that commodity will be a function of both (Linnhoff,1983).

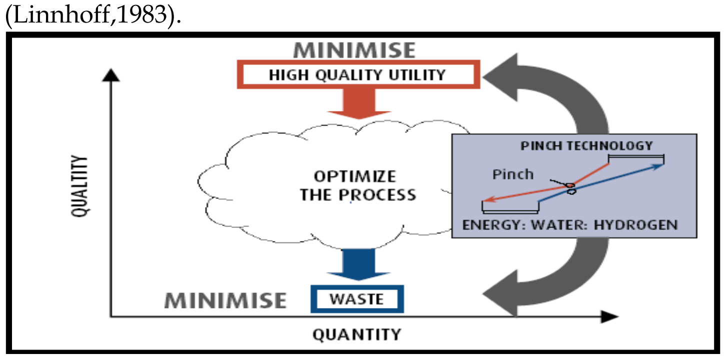

Figure 2: Minimization of Utility Use. Source: www.nrcan.gc.ca, 16th October,20

2.5 Building the composite curves

One of the principal tools of pinch analysis is the graphic representation of composite curves, the construction of which is simple but powerful. Composite curves are used to determine the minimum energy-consumption target for a given process. The curves are profiles of a process' heat availability (hot composite curve) and heat demands (cold composite curve). The degree to which the curves overlap is a measure of the potential for heat recovery. Constructing the curves requires only a complete and consistent heat and mass balance of the process in question. Data from the heat and mass balance are first used to define process streams in terms of their temperature and heating or cooling requirements. This data may be produced from one or all of the following:

i. Plant measurements.
ii. Design data.
iii. Simulation.

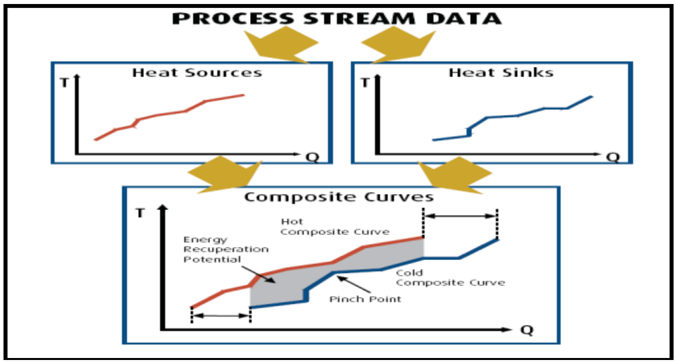

Figure 3: The Composite Curves. Source: www.nrcan.gc.ca, 16th October,2014.

2.6. Pinch design procedure

Without specifying the Heat Exchanger Network (HEN) we have been able to set targets for energy and area requirements of a network. We have to synthesize the network prior to its detailed design. The procedure is as follows:

1. Initiate the design by determining the optimum approach temperature.
2. Decompose the network at the pinch into two subsystems, above and below the pinch, and commence the synthesis at the pinch.
3. Just above the pinch the following conditions must be met to have a feasible match.

   $CP_{hot} \leq CP_{cold}$

   $N_{hot} \leq N_{cold}$

   On the other hand, just below the pinch

   $CP_{hot} \geq CP_{cold}$

   $N_{hot} \geq N_{cold}$

   If these conditions are not met at the pinch, the streams can be splited. However, these conditions are only necessary for pinch matches, as we move away from the pinch we need not consider these constrains.

   1. Maximize the heat load on each of the matches so as to reduce the stream population (heuristic tick).
   2. The two separate subsystems design; above and below the pinch can now be brought together for a complete design.

2.7 Naphtha hydro-treating unit

The Naphtha Hydro-treating Unit, NHU is designed to provide suitable feed, treated heavy Naphtha cut of sulfur content less than 1.00 ppm for the Catalytic Reforming Unit (CRU) (Chiyoda, 1980).

i. Catalytic treatment of whole naphtha for the removal of impurities by reaction with hydrogen
ii. Separation of whole naphtha into its fractions.

2.7.1 Process principle

The process is a sweetening process involving removal of impurities, like sulfur, nitrogen, oxygenetc, that constitute catalyst poison in the presence of a catalyst. Therefore major reactions include; desulphurization, denitrification and hydrogenation reactions. These are carried out in the reactor section. These reactions include;

2.7.2 Reactions to promote

Desulphurization

$R - SH + H_2 --- RH + H_2S$

Denitrification

$R - NH2 + H_2 --- R - H + NH_3$

These reactions occur at relatively elevated temperature between 315 °C – 370 °C and in the presence of hydrogen for the following:

1. Atomizing the feed
2. To provide required pressure
3. To provide hydrogen for reaction with Sulfur compounds and reduce coking.

While the work up section separates the whole naphtha into;

i. Liquefied Petroleum Gas
ii. Light naphtha
iii. Heavy naphtha

This involves the operation of two columns with reboiler assembly and reflux system.

2.7.3 Feed

The feed material to the unit is whole Naphtha from Area 1, CDU 1&2.Whole Naphtha is a crude oil fraction extracted from the two crude distillation units (CDU 1&2) and which contains hydrocarbons with boiling point up to 175 °C (Chiyoda, 1980).

2.7.4 Unit design capacity

The unit design capacity is 24,000 BPSD or 158 m^3/hr for a stream factor of 330 days operation per year.The unit is divided into; reactor section and work-up section.

2.7.5 The reactor section

The feed from CDU 1&2 comes to the surge drum 11D05 where it is de-watered and any excess pressure sent to flare. The feed is pumped using 11P01 to the preheater 11E01 where it is mixed with Hydrogen and Preheated. The feed is totally vaporized at 11H01 inlet before being introduced into 11 R0 1.

The reactor effluent leaving the reactor bottom is used to preheat the feed charge. The effluent is completely cooled using the air fin cooler 11A01 and the trim cooler 11E02 (Chiyoda, 1980).

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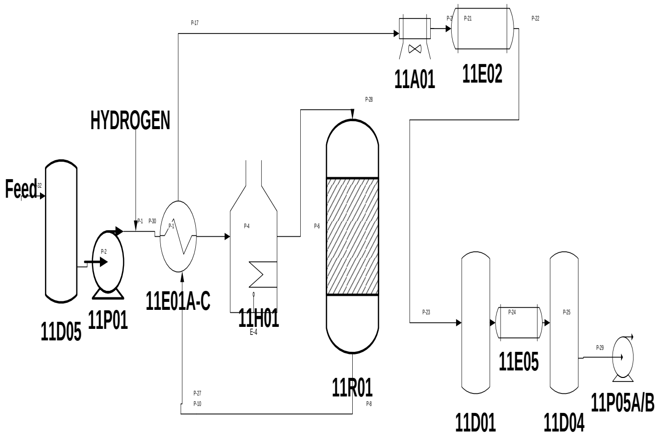

Figure 4: The Reactor Section. Source: PFD of the NHU of KRPC.

2.7.6 Catalyst

The process of Hydro-treating is a catalyzed reaction. The catalyst aids the reaction. It drives it in the forward direction and favors required reaction which occurs on the catalyst bed. The catalyst is high purity alumina extricates impregnated with cobalt and molybdenum oxides. As a result of safety hazard in its handling, the catalyst it is delivered in oxide form. To activate it is necessary to transform the oxides into sulphides. Sulphiding in NHU involves heating a stream of hydrogen and Whole naphtha feed such that the hydrogensulphide produced reacts with the oxides to form sulphides (Chiyoda, 1980).

2.7.7 Hydro-treating process

Two kinds of reactions take place in the NHU reactor

1. Hydrorefining reactions
2. Hydrogenation reactions

2.7.8 Hydro-refining reactions

Desulphurization; Mercaptans, sulphides and disulphides react leading to corresponding hydrocarbons (Chiyoda, 1980).

$R - SH + H_2 \text{---} RH + H_2S$ 1

Denitrification; It is the more important reaction besides the desulphurization.

$R - NH_2 + H_2 \text{---} R - H + NH_3$ 2

These reactions occur at relatively elevated temperature between 315 ^oC – 370 ^oC and in the presence of hydrogen for the following

i. Atomizing the feed
ii. To provide required pressure
iii. To provide hydrogen for reaction both with sulfur/nitrogen compounds and reduce coking.

2.7.9 Hydrogenation reactions

This result in Aromatic hydrocarbon saturation will increase the work load on CRU. Hydrogeneration reactions should be carried out at a temperature which depends on the state of the Catalyst, the severity, and the feed flow rate.A high hydrogen partial pressure will reduce coke deposit (Chiyoda, 1980).

2.7.10 Regeneration

The catalyst with time loses its activity due to foulant oxide and needs to be regenerated to restore it. The process of regeneration involves burning off of these laid down foulant. During regeneration the oxide of these metals are formed (Chiyoda, 1980).

2.7.11 Work-up section

Work-up section separates the whole naphtha into;

i. Liquefied Petroleum Gas
ii. Light naphtha
iii. Heavy naphtha

This involves the operation of two columns with reboiler assembly and reflux system. Figure 6 shows the work up section.

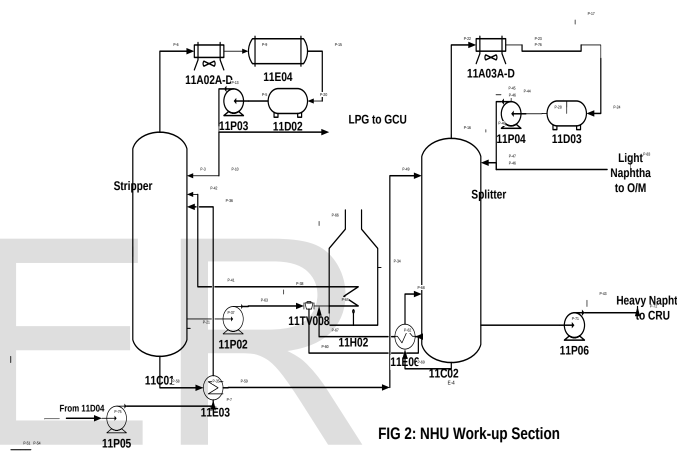

Figure 5: NHU Work-up Section. Source: (PFD of the NHU).

2.7.12 Products

The products leaving the stripper are as follows,

i. Raw (LPG) Liquefied Petroleum Gas
ii. Light Naphtha
iii. Heavy Naphtha (Treated)

3 MATERIALS AND METHODS

3.1 Materials

Heat integration software "Hint", was employed in carrying out the analysis and optimization of Naphtha Hydro-treating Unit (NHU) of Kaduna Refining and Petrochemical Company (KRPC). The materials used are shown in Table 3.

3.2 Stream Definition

The stream table was generated by Hint through the stream definition. Streams were defined by introducing the thermal data shown in Table 2 for each stream into the dialogue "Add Stream" using the command stream/add stream. Thesedata include:A description which identifies the stream (optional), the heat load (enthalpy) in kW or

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heat capacity flow rate (mcp) in kW/K, the source temperature in °K, and the target temperature in °K, the program calculates the remaining data. For stream one, the data input are "NHU REACTOR FEED", 28098.08 kW, 312 K, and 566 K. The procedure is repeated for the streams 2 to 17.

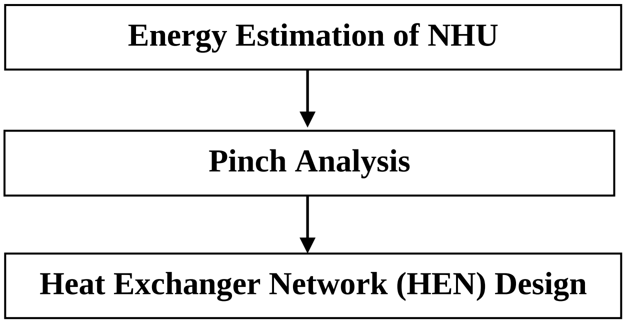

Figure 6: Steps Involved in the Energy Integration of NHU of KRPC

3.3 Pinch Analysis

The procedure for carrying out pinch analysis is shown in the Figure 8.

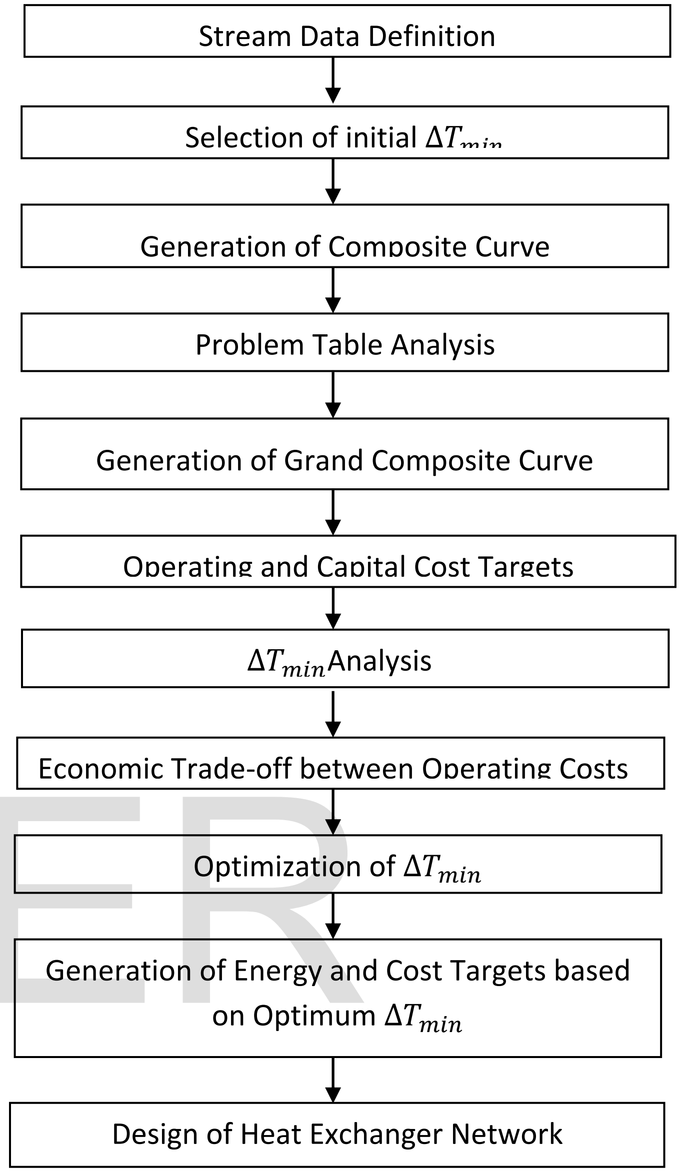

Figure 7: Steps of Pinch Analysis

3.3.1 Selection of initial ΔT_{min}

The initial ΔT_{min}value of 30 K was selected. This value was based on experience ΔT_{min} in literature.(Agrawal and Shenoy, 2006).

3.3.2 Energy targets

The problem table algorithm calculates heating and cooling energy requirement as well as the pinch point. NHU composite curve and the grand composite curve were plotted from adequate command of diagram menu to obtained energy as well as utility levels requirement of the unit, Pinch temperature and the minimum number of heat exchangers were also obtained using pinch analysis software Hint.

3.3.3 Cost targets

From Stream/Area Target command the streams total area target and the minimum number of heat exchangers were obtained. capital, operating and total cost targets were also calculated from the command stream/cost target of Hint software.

3.3.4 ΔT_{min} Analysis

At the initial ΔT_{min} **of 30 K**, plots of the relationship between ΔT_{min} and optimization parameters such as energy, area, minimum number of exchangers, Pinch temperature were obtained.

3.3.5 Economic trade-off between operating and capital costs

The target values obtained were translated into capital and energy cost for the network. The targets are then evaluated atdifferent values of ΔT_{min} by trading off energy and capital costs to obtain optimal valueofΔT_{min}

3.3.6 Optimization of ΔT_{min}

From the command tool/optimization of ΔT_{min} , the optimum ΔT_{min} value was obtained**.**

As the separation between hot and cold composite curves (ΔT_{min}) increases, the overlap between hot and cold curves is reduced, thereby decreasing the opportunities for heat recovery from hot streams to cold streams, and, consequently, increasing the utility demand

3.3.7 Pinch analysis based on optimum ΔT_{min}

This was done based on optimum ΔT_{min} value to obtained optimum energy and cost targets for heat exchanger network design.

3.4 Design of Heat Exchanger Network

Targets obtained from the pinch analysis based on optimum ΔT_{min} were used for the design of heat exchanger network (HEN). The NHU grid diagram was obtained from the command diagram/grid diagram. The grid was split into two thermally independent region, above and below by the pinch temperature(vertical dashed line) for maximum energy recovery (MER)

4 RESULTS

4.1 Results

The results of data extracted from the process flow diagram of NHU of KRPC, cost data, NHU pinch analysis and heat exchanger network investigated is presented in this section.

4.1.1 Data extraction

The stream data obtained from Process Flow Diagram (PFD) were introduced into the program and the result obtained was shown in Table 4.

Table 3: Stream Table for NHU Pinch Analysis

Stream	Description	Type	Heat type	T1 (K)	T2 (K)	H (kW)	mcp (kW/K)
1	NHU REACTOR FEED	Cold		312.	566.	28098.08	110.6224
2	NHU REACTOR EFFLUENT	Hot	Sensible	643.	398.	-28098.08	114.686
3	NHU REACTOR CHARGE HEATI	Cold	Sensible	566.	643.	7419.94	96.36286
4	NHU REACTOR EFF. COOLER	Hot	Sensible	398.	321.	-6896.59	89.5661
5	NHU RXTOR EFF. TRM COOLEF	Hot	Sensible	321.	313.	-604.76	75.595
6	NHU LP SEP. CHARGE COOLER	Cold	Sensible	288.	313.	407.05	16.282
7	NHU STRIPPER FEED	Hot	Sensible	510.	406.	-7454.83	71.68106
8	NHU BOTTOM EXCHANGER	Cold	Sensible	313.	406.	7454.83	80.15946
9	NHU STRIPPER OH CONDENSE	Hot	Sensible	350.	321.	-5105.57	176.0541
10	NHU STRP OH TRM CONDENSI	Hot	Sensible	321.	313.	-651.28	81.41
11	NHU STRIPPER REB HEATER	Cold	Sensible	473.	510.	17096.1	462.0568
12	NHU SPLITTER REBOILER	Hot	Sensible	494.	463.	-4977.64	160.569
13	NHU SPLITTER REBOILER B	Cold	Sensible	387.	410.	4977.64	216.4191
14	NHU SPLITTER OH CONDENSE	Hot	Sensible	345.	328.	-5919.67	348.2159
15	NHU LIGHT NAPHTHA COOLER	Hot	Sensible	328.	308.	-267.49	13.3745
16	NHU HEAVY NAPHTHA COOLEF	Hot	Sensible	410.	321.	-2442.3	27.44157
17	NHU H-NAPHTHA TRIM COOLEI	Hot	Sensible	321.	313.	-197.71	24.71375

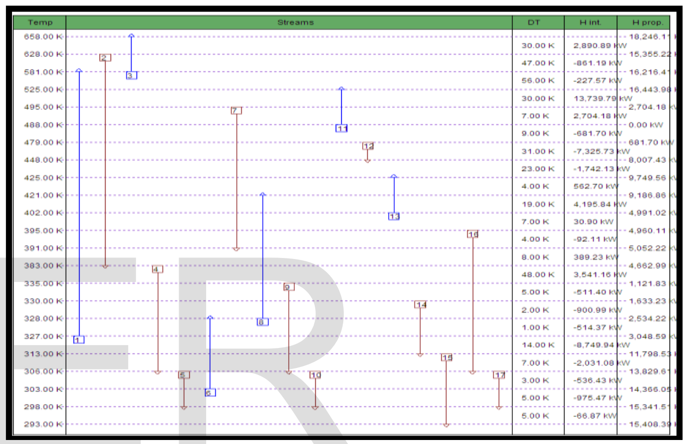

Figure 8: Process Streams

4.1.3 NHU energy requirement results

Tables 4 and 5 showed the computed traditional energy requirement of NHU.

Table 4 : Estimated Traditional Hot Utility Energy Requirement of NHU

Stream	Description	H (kW)
1	NHU Reactor Charge Heater	7419.94
2	NHU Stripper Reboiler Heater	17096.1
	Total Heating Duty	**24516**

Table 5: Estimated Traditional Cold Utility Energy Requirement of NHU

Stream	Description	H (kW)
1	NHU Reactor Effluent Cooler	6896.59
2	NHU ReactorEffluent Trim Cooler	604.76
3	NHU LP Sep Charge Cooler	407.05
4	NHU Stripper OH Condenser	5105.57
5	NHU Stripper OH Trim Condenser	651.28
6	NHU Splitter OH Condenser	5919.67
7	NHU Light Naphtha Cooler	267.49

8	NHU Heavy Naphtha Cooler	2442.3
9	NHU Heavy Naphtha Trim Cooler	197.71
	Total Cooling Duty	**22492.4**

Table 6: Comparison between Energy Requirement for Traditional Energy Approach and Pinch Analysis

	Traditional Energy Requirement (kW)	Pinch Analysis (kW)	Saving (%)
Energy Target (Heating) Energy Target (Cooling)	24516.0 22492.4	18246.1 15408.4	25.57 31.50
Total Energy	47008.4	33654.5	28.41

5 DISCUSSION

5.1 Data Extraction

Table 3 showed the stream table of NHU extracted from the unit's Process Flow Diagram (PFD). From the table the unit consist of 11 hot streams and 6 cold streams, indicated along with each stream is the source and target temperatures, enthalpy and heat capacity flow rate. These design values represent the amount of information available from the plant measurement. The implication of these is that it captures the relevant sources that are the hot streams and the sinks which are the cold streams and their interaction with the overall process.

5.2 Composite Curves

The NHU composite curve at a ΔTmin of 30 K. The change in the slope of the connected straight lines represents the change in the heat capacity flowrate (Cp). For heat exchange to occur from the hot stream to the cold stream, the hot stream cooling curve must lie above the cold stream heating curve. The kinked nature of the curves makes them approach each other most closely at one point defined as the minimum approach temperature (ΔTmin) which for this analysis is 30 K before the final optimized temperature. This point is referred to as the pinch. The hot end and cold end over shoots indicates the minimum hot utility requirement (QHmin) and minimum cold utility requirement (QCmin) of the process.It was observed that the curves are pinched at a temperature of 488 K. The curves also reveal the minimum external heating requirement (the overshoot of the cold composite curve) to be 18246.1 kW while the minimum quantity of external cooling required (overshoot of the hot composite curve) is 15408.4 kW as shown in Table 8.

5.2.1 The grand composite curve

The NHU grand composite curve is constructed by plotting the heat load difference between hot and cold composite curves, as a function of temperature. It provides a graphical representation of the heat flow through the process from the hot utility to those parts of the process above the pinch point, and from the process below the pinch point to the cold utility. This is because the grand composite curve represents heat flows in an ideal process, there is no heat flow through the pinch point which accounts for the general shape of the curve (Robin, 2010). The pinch point is where the curve touches the T-axis. As shown in the figure, the pinch occurs where the curve touches the T-axis at 488 K, while the horizontal distance between the first and last points of the plot and y-axis represents the minimum heating and cooling utility duties, respectively.

5.2.2 Targeted energy savings for NHU.

Table 8 showed the calculated minimum heating and cooling requirement for the traditional design and the requirement for pinch analysis. The hot utility requirement of the traditional design of NHU and pinch analysis are 24516.0 kW and 18246.1 kW. This indicates a significant energy requirement savings of 25.57 %. The cold utility requirement for the traditional design and pinch analysis are 22492.4 kW and 15408 kW respectively. This shows energy savings of 31.50%.Pinch analysis saves more utilities cost than the traditional approach. This statement is in agreement with literature (Bassey, 1995).

5.2.3 Targeting for area and cost

The targeted area, minimum number of heat exchangers and the cost values for NHU for the initial ΔT_{min} of 30 K is showed in Table 9. These values were compared with the values obtained based on the optimum ΔT_{min} of 7.1 K and as shown in Table 9, the heating and cooling energy requirement were reduced by 30.1 % and 35.6 %, respectively as well as a reduction in operating cost by 31.3 % and total cost by 15 %. Based on the pinch principle this leads to increase in area requirement of the heat exchanger, number of heat exchangers and the capital cost by 36.1, 5, and 20.8 %, respectively (Dayo,2000).

6.0 CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The following conclusion may be drawn from the result of the analysis.

1 For the selected minimum approach temperature of 30 K the optimum approach temperature was found to be 7.1 K
2 The utilities targets for the traditional design method were found to 24516.0 kW and 22492.4 kW for hot and cold utilities, respectively.
3 Within the range of minimum approach temperature 10 – 50 ^oC analyzed the best minimum approach temperature was found to be 10 ^oC.
4 The utilities targets for the minimum approach temperature were found to be 18246.1 kW and 15408.4 kW for hot and cold utilities respectively.
5 The utility and capital cost for optimum MTA of 10 ^oC are \$1.2 x $10^6$and \$ 0.26 x 10^6, respectively.
6 The pinch analysis indicates possible energy and utilities cost savings at NHU. KRPC

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