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Pinch Analysis of Heat Exchanger Networks in the Crude Distillation Unit of Port-Harcourt Refinery

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Abstract

The pinch analysis of the heat exchanger networks in the crude distillation unit of the New Port-Harcourt refinery has been performed. This analysis is aimed at ascertaining the energy efficiency and operation of the heat exchangers used in preheating the crude. Process data of the heat exchanger networks (HEN) were collected to formulate a problem table and used in Aspen-Pinch ® software for pinch analysis of the networks. The software produced the composite and grand composite curves, the grid representation and target reports. From these, the minimum heating and cooling requirements of the entire network, the process streams not properly matched and the heat exchangers not properly placed were obtained. The analysis indicated that a total of 98916.1 KW hot utility, 8298.7 KW cold utility were not utilized within the network (poor process stream matching) and that ten heat exchangers were not properly placed. Hence the heat exchangers in the crude distillation unit need to be retrofitted to ensure adequate heat recovery, process to process integration and efficient energy utilization within the network.

Keywords: heat exchanger network, crude distillation unit, pinch analysis

INTRODUCTION

One of the most frequently encountered problems in industrial plants is the excessive energy consumption for production (Robin, 2009). It represents one of the highest contributions to the composition of global cost of industrial products. Most industrial processes require the consumption of energy at one temperature level and rejection at another level. The consumption is achieved by the use of utilities such as steam, hot water, flue gas etc. and the rejection by the use of cooling water, air and refrigerant. In most industrial processes also, there are streams that require heating and streams that require cooling; these are usually achieved using hot and cold utilities respectively. This heating and cooling process occur in heat transfer equipments. One of the most frequently used heat transfer equipment is the Heat exchanger (Woranee, 2009).

A Heat Exchanger Network (HEN) is a system of several heat exchangers connected together. It enables several streams to exchange sufficient amounts of thermal energy so that they can attain the respective temperature values (“targets”) specified by process requirements. Heat Exchanger Network (HEN) synthesis can be used to obtain process streams energy integration - using hot streams to heat cold streams and cold streams to cool hot streams. This reduces the amount of hot and cold utilities, the number of heat transfer equipment and decreases the fixed cost of the final network. Hence, Process integration can lead to substantial reduction in energy requirement (efficient heat recovery) and reduce utility cost of a process. Therefore the efficient and optimal design of heat transfer equipment and Heat exchanger network (HEN) to minimize energy consumption is imperative.

Gundersen and Naess (1998) and Furman and Sahinidis (2002) have published complete reviews on heat exchanger networks (HEN) synthesis. Methodologies for designing optimal Heat exchanger network (HEN) can be accomplished using Pinch Analysis or Mathematical Programming, (Ravagnani *et al.*, 2003, 2007). The use of Pinch Analysis as a tool for designing optimal Heat exchanger networks is investigated in this work.

One of the most successful technique for investigating energy integration and the efficient design of heat exchanger networks is pinch technology. Pinch Analysis uses thermodynamic concepts and heuristics, as can be seen in the works of Linnhoff and Flower (1978), Linnhoff et al. (1979, 1982), Linnhoff and Hindmarsh, (1983) and Linnhoff, (1993, 1994). Pinch technology is a complete methodology based on thermodynamic principles that can be used to design new plants with reduced energy and capital costs and for existing processes; to ascertain efficiency and provide potential design modifications to improve performance. A fundamental strength of pinch analysis is that it determines the most appropriate set of heat exchange stream matches. In doing so, minimizes energy loss, reduces the cost of hot and cold utilities and can be used to determine the minimum requirement for both hot and cold utilities in a process and thus, enhance process integration (Promvitak, 2001). Chemical plants have in the past been designed using the traditional design techniques, which involved mass and energy balances, heuristics or rules of thumb, good engineering judgment and creative ability of the designers. Such designs were neither optimal in terms of energy consumption nor in capital cost invested. A typical example of such deficiency in design is the Nigerian refineries as reported in the works of Anozie and Odejobi, (2007); resulting in frequent breakdown, excessive energy loss, minimum energy recovery, poor process network dynamics and control.

The refineries in Nigeria were designed and built before the advent of pinch technology, in this work therefore, the Pinch Technology was used to synthesize and evaluate the heat exchanger network in one of the Nigerian refineries viz; the heat exchanger network in the crude distillation unit of the New Port Harcourt Refinery (NPRC) in Port-Harcourt, Rivers State, Nigeria. The analysis will ascertain design efficiency of the existing heat exchangers; determine appropriate number of heat exchangers and identify improper stream matching within the selected network.

Process Description of the Crude Distillation Unit (CDU)

The atmospheric crude distillation unit (area 1) built in 1989 has a producing capacity of 150,000 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 vapours are removed from the top, condensed and sent to 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.

MATERILAS AND METHOD

Configurations of the Heat Exchangers and Streams

The preheating of the raw crude from the tank farm in crude distillation unit of the Port-Harcourt refinery is accomplished via twenty three (23) heat exchangers using hot streams from other units within the refinery complex. For the purpose of this evaluation the twenty three heat exchangers were sectioned into three Heat Exchanger Networks (HENs), HEN-1, HEN-2 and HEN-3. The configurations of the three networks obtained from the pipe flow diagram (PFD) are shown below.

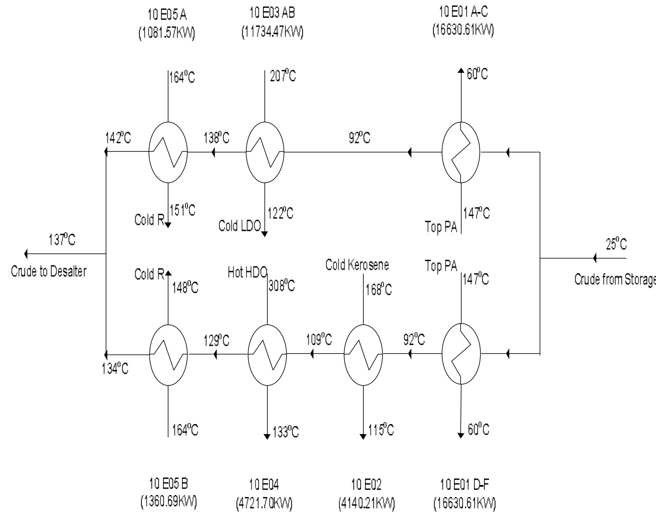

Figure 1: Heat exchangers configuration showing all streams in HEN-1

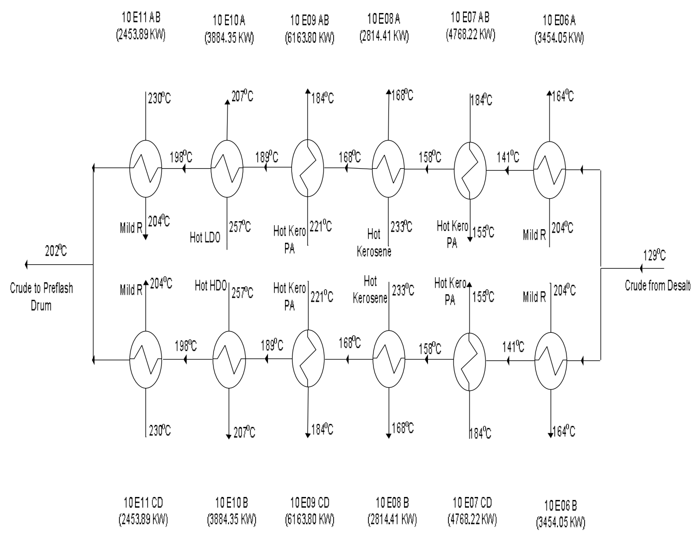

Figure 2: Heat exchangers configuration showing all streams in HEN-2

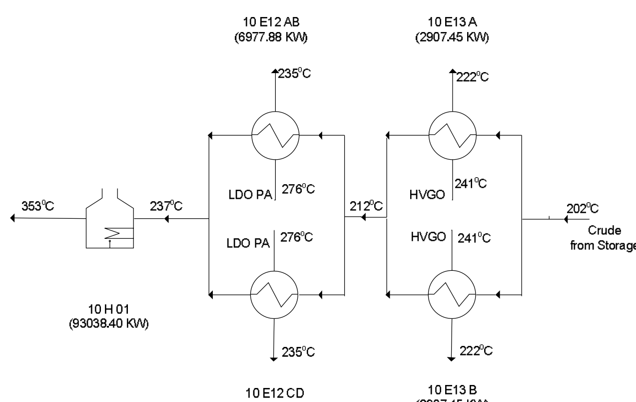

Figure 3: Heat exchangers configuration showing all streams in HEN-3

MATERIALS AND METHODS

The materials used include: process flow diagram (PFD) and plant data of the Crude Distillation Unit of the New Port Harcourt Refinery (PHRC Brochure, 2005); Aspen® Pinch 11.1 software (used to produce the composite curves and grid diagrams) and Microsoft® Office Visio.

METHODS

The Aspen Pinch 11.1 process tool was employed to perform a detailed and accurate pinch analysis of the three 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 grid diagram of all networks following the algorithm in figure 4. 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.

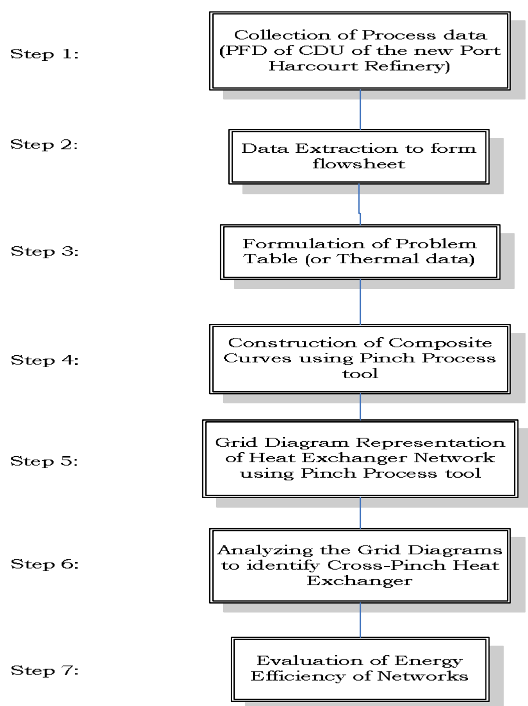

Figure 4: Flowchart for Pinch Analysis

Data Extraction

This involves the identification of process heating and cooling duties and extraction of information from a given process heat and material balance to form the thermal data.

Formulation of the Problem Table (Thermal Data)

This is the collection of the process stream and equipment (heat exchangers and utilities) parameters and tabulated as shown in Table 1, Table 2 and Table 3. The heat load or heat duty of the heat exchangers were estimated using equation 2 and tabulated in Tables 1, 2 and 3.

$$Q = (Cp \times F) \times \Delta T \quad (1)$$

Where Cp = specific heat capacity of the stream (kJ/kg. ^{o}C), F = mass flow rate of the stream (kg/s), ΔT = temperature difference (^{o}C), Q = heat exchanger duty (KW)

Determination of the Specific Heat Capacities of Petroleum Fractions

The specific heat capacity of a petroleum product is determined using the empirical equation below.

$$Cp = {}^{1}/_{d}\,[0.402 + 0.00081T] \quad (2)$$

Where Cp = specific heat (kcal/kg.^{o}C), d = specific gravity at 15 ^{o}C, T = temperature (^{o}C). The specific gravity (at 15 ^{o}C) of the various petroleum fractions are obtained from the Process Flow Diagram of the refinery.

Determination of Optimal ΔT_{min}

The optimum value of ΔT_{min} for refinery processes has been determined by Linnhoff, (1998) to be in the range of 20 to 40^{o}C. Hence a value of 30^{o}C was used in this work.

Problem Table Analysis Results

Table 1: Problem Table for HEN – 1

Streams	Start/ supply temp	Target temp	Mass flow rate (kg/s)	Specific heat capacity (kJ/kg^{o}C)	Heat capacity flow rate (kW/^{o}C)	Heat duty (kW)
Top Pump Around (PA)	147	60	157.7365	2.7683	436.6619	33261.22
Hot HDO	308	133	10.8972	3.0375	33.1002	4721.70
Cold LDO	207	122	56.0000	2.7637	154.7672	11734.47
Cold kerosene	168	115	32.2333	2.7206	87.6939	4140.21
Cold Residue	164	150	72.4416	2.3722	171.8459	2442.26
Crude from Storage	25	137	232.2889	2.1022	488.3177	56299.86

Table 2: Problem Table for HEN – 2

Streams	Start/ supply temp	Target temp	Mass flow rate (kg/s)	Specific heat capacity (kJ/kg^{o}C)	Heat capacity flow rate (kW/^{o}C)	Heat duty (kW)
Mild Residue	230	164	72.4416	2.5158	182.2486	11815.88
Hot Kero PA	221	155	186.9444	2.9203	545.9337	21864.04
Hot LDO	257	207	56.0000	2.8449	159.3114	7768.7
Hot kerosene	233	168	32.2333	2.9869	96.2776	5628.82
Crude from Desalter	129	202	116.1444	2.5215	292.8581	47077.44

Table 3: Problem Table for HEN – 3

Streams	Start/ supply temp	Target temp	Mass flow rate (kg/s)	Specific heat capacity (kJ/kg°C)	Heat capacity flow rate (kW/°C)	Heat duty (kW)
LDO PA	276	253	120.8333	3.0529	368.8919	13955.76
HVGO	241	222	122.7000	2.6971	330.9342	5814.9
Crude from Pre-flash drum	202	353	212.9277	2.8158	599.5618	112809.06
(Fuel Oil)	353	350	108.6240	3.2362	351.5389	93038.40

Constructing the Composite Curves

This is a plot of the temperature-enthalpy profile of 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.

Representing the Heat Exchanger Network On A Grid Diagram

Each heat exchanger in the network was represented as a grid. 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 stream lines respectively. The diagram shows the heat exchangers that violate the pinch rule (that cross the pinch). The heat exchangers are represented by vertical lines linking a hot stream and a cold stream. Culprit heat exchangers are identified by an additional bar attached to the vertical line. A targeting report is also generated showing heat duties of all existing heat exchanger and cross pinch penalty (amount of heat energy not utilized) of culprit heat exchangers.

RESULTS AND DISCUSSIONS

Analysis of Heat Exchanger Network-1

The composite and grand composite curves and grid diagram for the seven (7) heat exchangers in HEN 1 are shown in figure 5, figure 6 and figure 7 respectively. The right end of the composite curves show that the hot and cold streams have the same enthalpy indicating proper stream matching, adequate and efficient process to process heat integration and utilization. Therefore there is zero excess hot utility. However, the left end of the curve shows that there is little excess cold utility (energy) not utilized for cooling.

The pinch location cuts across the end points of the hot and cold composite curves, implying that there should be no external hot utility (like heater) in this network. Although there is no heater in the HEN-1 of the CDU, the little excess cold utility revealed by the curve still indicates a heat imbalance due to the absence of a hot utility (stream requiring heating) to match the little excess cold utility.

In the Grand Composite Curve shown in figure 6, the area to the right of the dotted/pinch line shows the amount of heat energy efficiently utilized by the hot and cold streams, while the area to the left indicates the excess heat not utilized within the network. A targeting report of the HEN-1 pinch shows that HEN-1 requires a minimum cold utility of 2421.0kW (external heat requirement) and minimum hot utility of 0Kw (no heating requirement). The pinch location is at one far end of the grid diagram indicating improper stream matching. A typical grid diagram should contain a region above the pinch (LHS of pinch location) and a region below the pinch (RHS of pinch location) separated by a pinch location point, the grid diagram of HEN-1 only contains a region below the pinch. This implies that the HEN-1 of the CDU of Port Harcourt refinery is not properly placed on network grid diagram for design analysis using the pinch analysis. The grid diagram also showed that no heat exchanger crossed the pinch line, indicating all heat exchanger are properly placed.

Analysis of Heat Exchanger Network-2

The composite and grand composite curves and grid diagram of the twelve (12) heat exchangers in HEN 2 are shown in figure 8, figure 9 and figure 10 respectively. The right and left end of the composite curve shows that the hot and cold streams have varying enthalpy, indicating excesses in both hot and cold utilities (energy) not utilized for heating and cooling, a heat imbalance between the streams and utilities, improper stream matching, inadequate and inefficient process to process heat integration and utilization. Hence the streams in HEN-2 are not fully utilizing all heat generated by the network. The pinch location cuts in-between the end-points of the hot and cold composite curves, implying that the HEN-2 is properly represented on the grid diagram for analysis. Once again, the heat imbalance in the network is clearly evident as the curve reveals little excess hot utility below the pinch and excess cold utility above the pinch.

The Grand Composite Curve in figure 9 shows an irregular curve with scattered enclosures. The summation of areas to the right of the dotted lines gives the amount of heat energy efficiently utilized by the hot and cold streams, while the areas to the left collectively indicate the excess heat not utilized within the network. Comparing, this shows a relatively fair process-to-process stream matching in the network. In addition, the targeting report reveals that there is a minimum hot utility of 2817.20kW and minimum cold utility of -2817.20kW. Although the network grid diagram on figure 10 shows a good representation and clarity of pinch location, a cross pinch effect is observed as there are 8 heat exchangers violating the pinch rule and resulting in pinch penalty of -2817.20kW, these culprit heat exchangers are clearly identified by the vertical lines attached to horizontal bars running (crossing) from left to right of the pinch location.

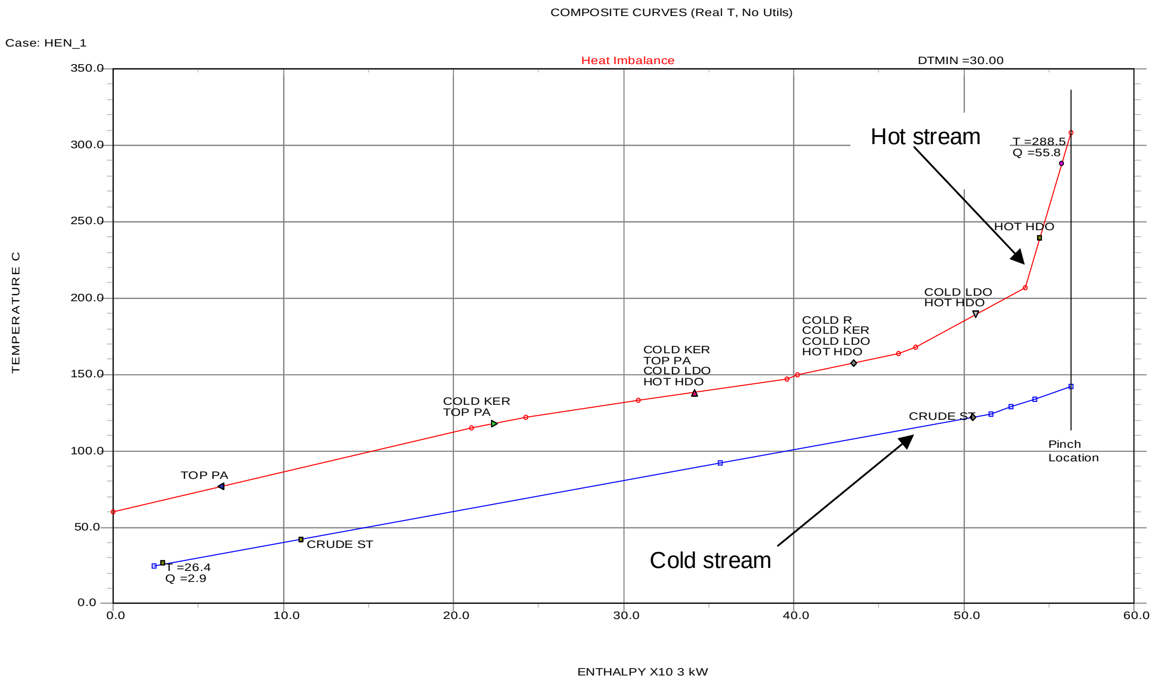

Figure 5: Composite Curve of HEN-1

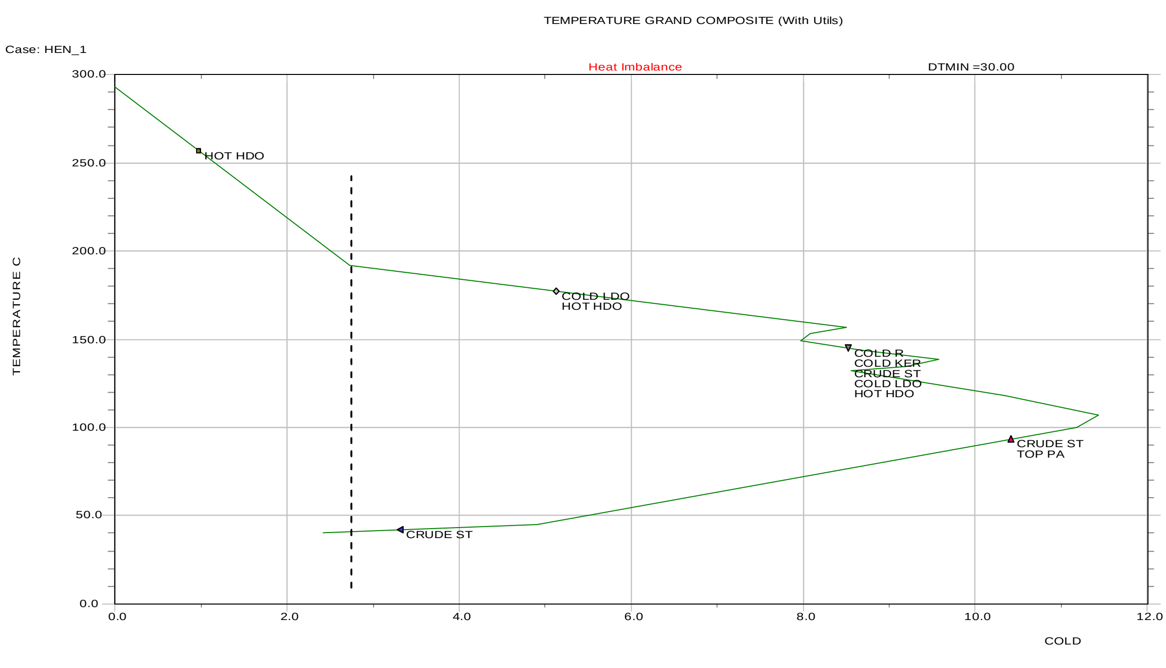

Figure 6: Grand Composite Curve for HEN-1

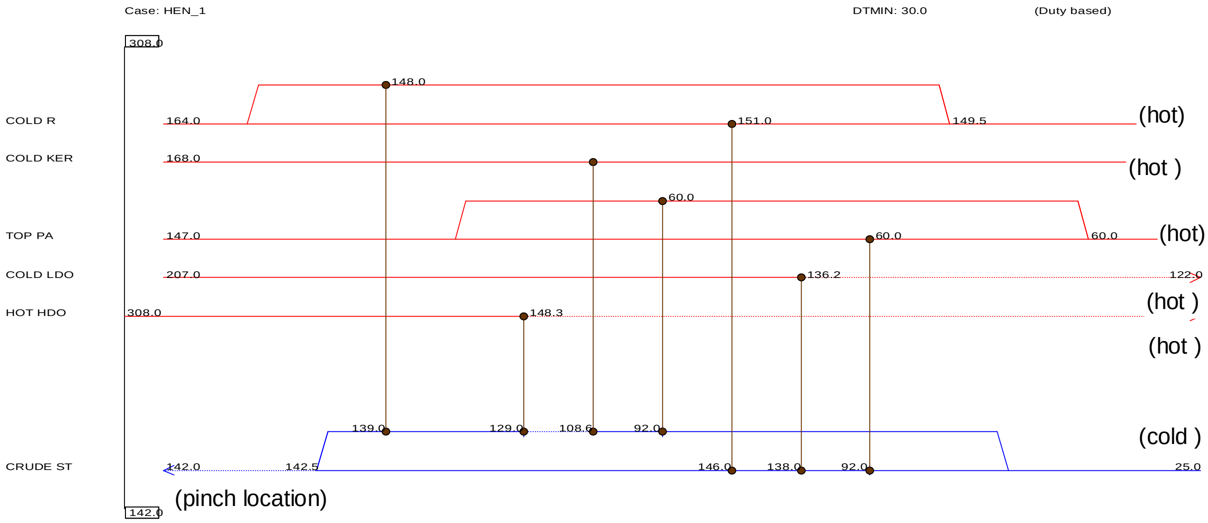

Figure 7: Grid Representation of HEN-1

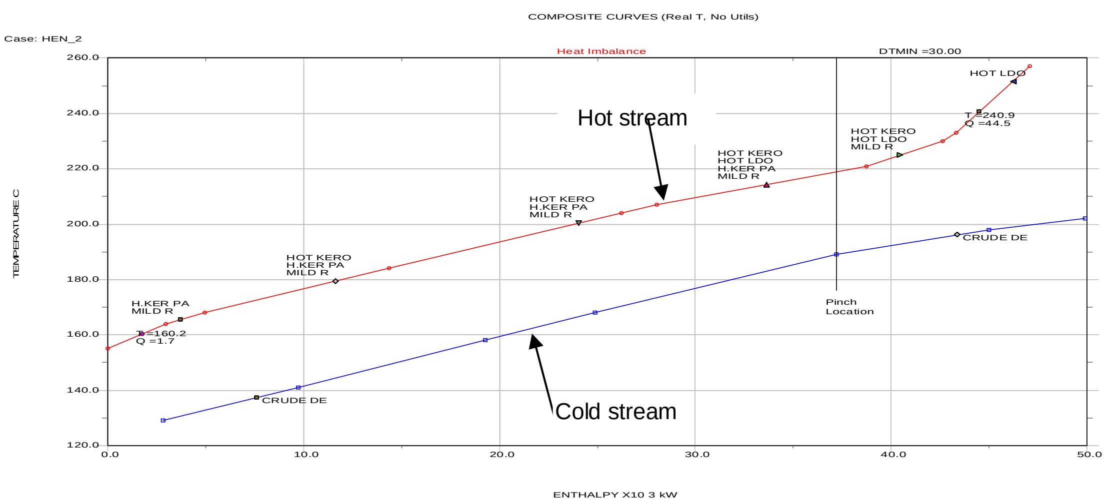

Figure 8: Composite Curve of HEN-2

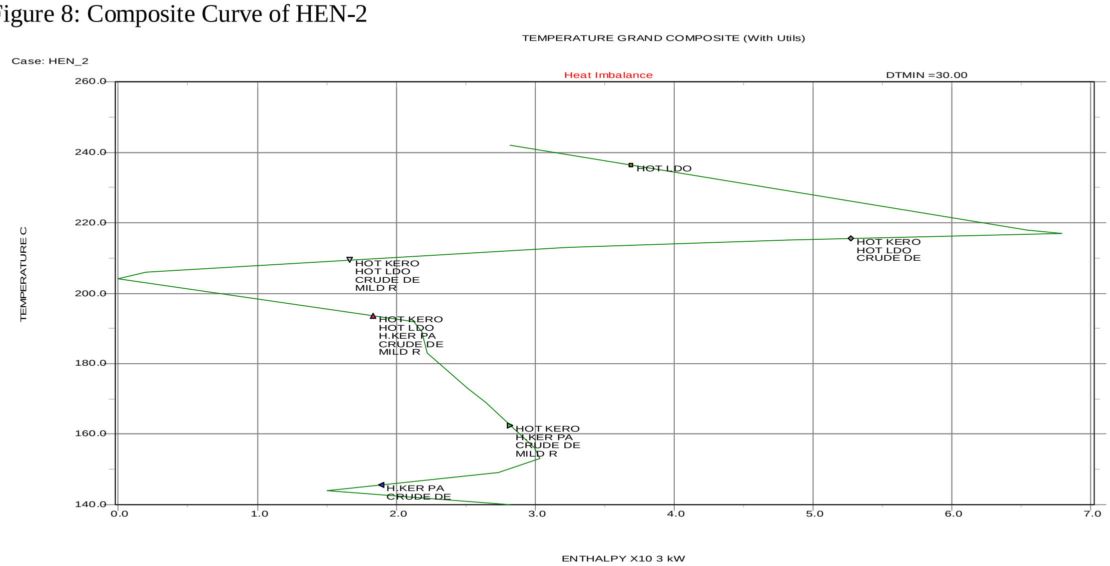

Figure 9: Grand Composite Curve of HEN-2

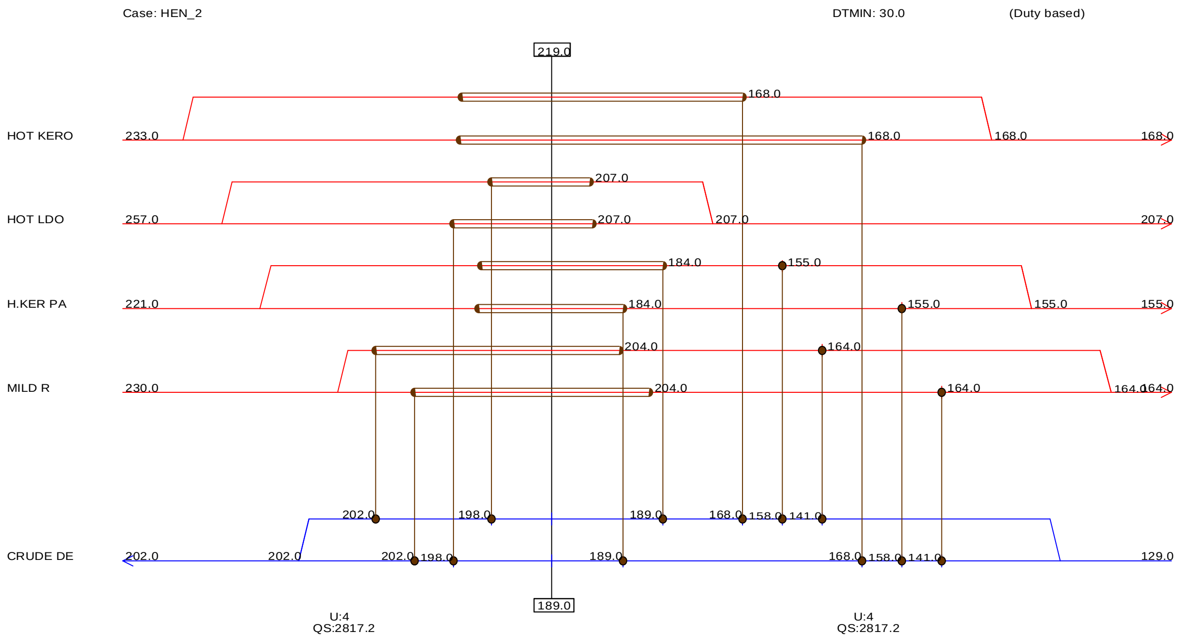

Figure 10: Grid Representation of HEN-2

Analysis of Heat Exchanger Network-3

The composite and grand composite curves and grid diagram of the four (4) heat exchangers in HEN 3 are shown in figure 11, figure 12 and figure 13 respectively. The right end of the composite curve shows a large hot utility (a large cold stream requiring heating) while the left end shows very little cold utility (very little hot stream require cooling). This indicates a large heat imbalance between the streams and utilities, improper stream matching, inadequate and inefficient process to process heat integration and utilization. There is also very little potential for process-to-process heat recovery as indicated by the small area enclosed by the cold and hot composite curves. These results are further confirmed as the HEN-3 of the CDU contains more cold process streams requiring heating. The targeting report further shows a minimum hot utility of 96098.90kW and minimum cold utility of 3060.50kW**.**

Figure 13 shows the pinch location positioned at the extreme right on the grid diagram indicating improper stream matching and grid diagram of HEN-3 only contains a region above the pinch (LHS of pinch location). This implies that the HEN-3 of the CDU of Port Harcourt refinery is not properly placed on network grid diagram for design analysis. A cross pinch effect was also observed as there are 2 out of 4 heat exchangers violating the pinch rule(not properly placed) resulting in a pinch penalty of -3060.47kW. These culprit heat exchangers are clearly identified by the vertical lines attached to horizontal bars running (crossing) from left to right of the pinch location.

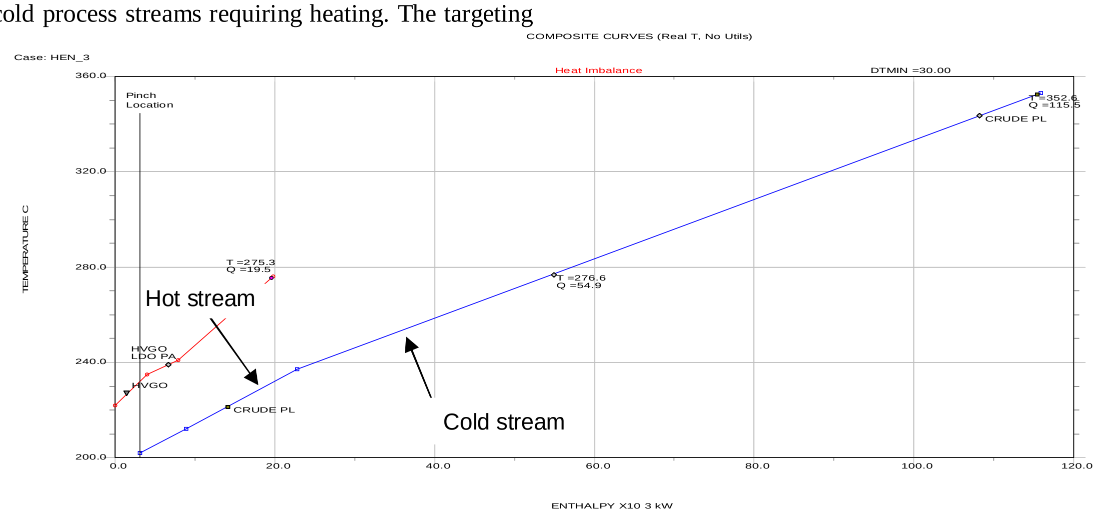

Figure 11: Composite Curves of HEN-3

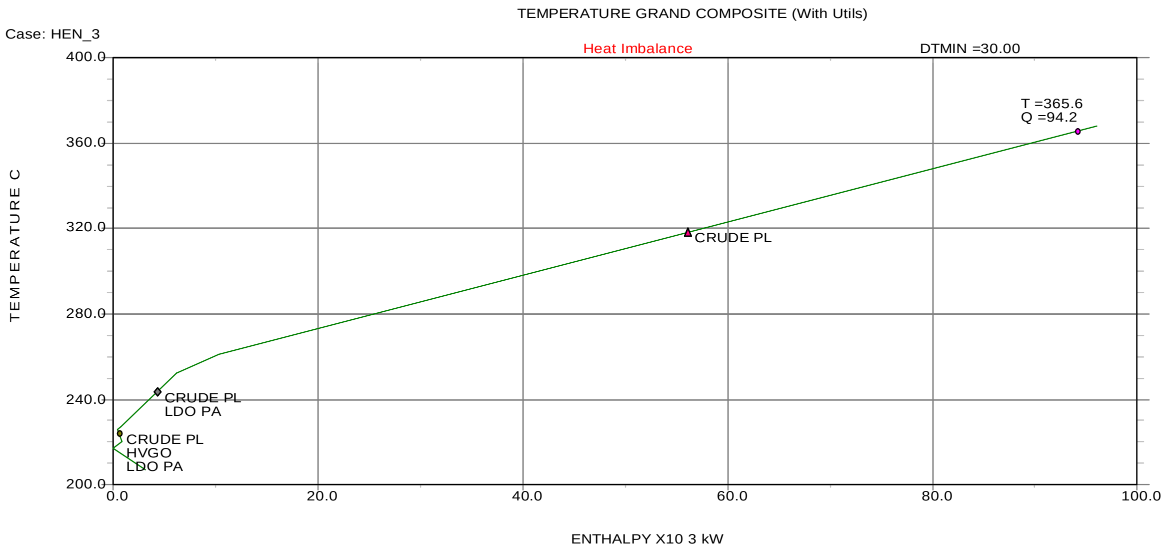

Figure 12: Grand Composite Curve of HEN- 3

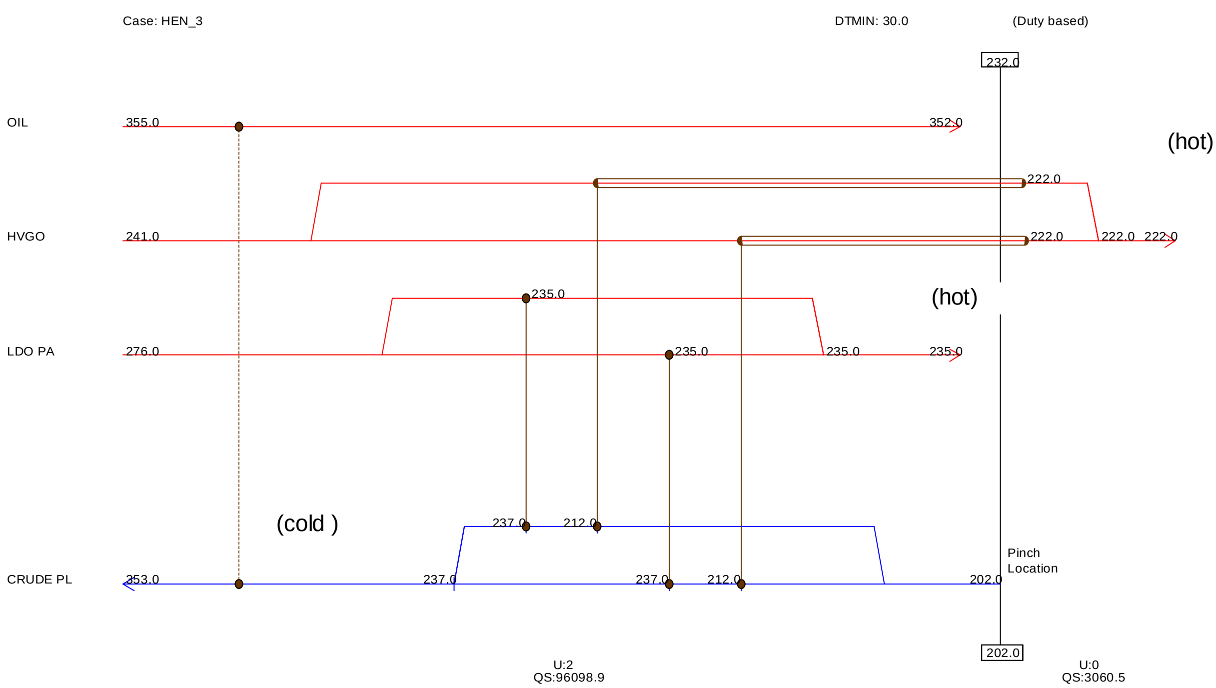

Figure 13: Grid Representation of HEN-3

A summary of results obtained from these analysis are presented in Table 4.

Table 4: Summary of Pinch Analysis on all HEN

Features of HEN	HEN -1	HEN -2	HEN -3
Clarity of Pinch location	Poor	Good	Good
$Q_{H,min}$ (kW) (Required external heating)	0.00	2817.20	96098.90
$Q_{C,min}$ (kW) (Required external cooling)	2421.00	2817.20	3060.50
Process-to-process heat recovery potential	High	Medium	Fairly low
Heat balance	No	No	No
Hot and cold stream matching	Poor	Fair	Fair
Cross pinch	Nil	Yes	Yes
Representation on Grid diagram	Poor	Good	Good
Number of heat exchanger violating pinch rule	Nil	8	2
Pinch penalty (kW)	Nil	-2817.20	-3060.47

CONCLUSION

Pinch Technology has been used to perform an analysis of the energy requirements and efficiency of the heat exchanger network of the crude distillation unit of the Port-Harcourt refinery. The minimum heating and cooling requirements of the process streams in each network were determined from the composite and grand composite curves while the grid diagrams showed the process streams not properly matched and the heat exchangers not properly placed. The results from these graphs showed that; HEN-1 had an excess cold utility (energy not utilized) of 2421 KW while all the heat exchangers were properly placed; HEN-2 had an excess hot and cold utility of 2817.2 KW each while eight heat exchangers were not properly placed; HEN-3 had an excess hot utility of 96098.9 KW and an excess cold utility of 3060.5 KW while two heat exchangers were not properly placed. Hence in the entire network, the pinch analysis indicated that a total of 98916.1 KW hot utility, 8298.7 KW cold utility were not utilized within the network (poor process stream matching) and ten heat exchangers were not properly placed.

These results show the inefficiency within the network, the large prospect for process to process heat recovery and a possible reduction in number of heat exchangers. A complete overhauling of the entire network is necessary. A first step in this regard is the retrofitting of the network. This is imperative and recommended as a basis to taken of a holistic decision on upgrade and improvements in design. This work has shown the inaccuracy in the design of the heat exchanger network of the crude distillation unit of the Port Harcourt refinery designed without the application of pinch design methods.

The use of Pinch technology in design ensures maximum heat recovery and minimum energy consumption resulting in minimum cost of hot and cold utilities. This might not necessarily give the optimum design for the network. The optimum design will be that which gives the lowest total annual costs: taking into account the capital cost of the system, in addition to utility and other operating costs. As recommendation therefore, the first step at solving inefficiency of the Port Harcourt refinery is the proper retrofitting or revamping of the refinery.

NOMENCLATURE

F	-	Mass flow rate of the stream (kg/s)
ΔT_{min}	-	Minimum temperature difference (°C)
CPF	-	Heat capacity flow rate (kW/°C)
Cp	-	Specific heat capacity of the stream (kJ/kg. °C)
ΔH	-	Enthalpy change (KW)
Q	-	Heat exchanger duty (KW)
T	-	Temperature (°C)
$Q_{H,min}$	-	Minimum energy required by network (kW)
$Q_{C,min}$	-	Minimum cooling requirement by network (kW)
$Q_{H, op}$	-	Minimum energy required by network (kW)
BPD	-	Barrels Per Day
FCCU	-	Fluid Catalytic Cracking Unit
HDO	-	Heavy Diesel Oil
HVGO	-	Heavy Vacuum Gas Oil
LDO	-	Light Diesel Oil
LVGO	-	Light Vacuum Gas Oil
NPHR	-	New Port Harcourt Refinery
OPEC	-	Organization of the Petroleum Exporting Countries

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