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Heat Exchanger Network Design for the Optimization of Total Annual Cost of the Catalytic Reforming Unit

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ABSTRACT: This research involved the energy integration of the Catalytic Reforming Unit of a Refinery using Aspen Pinch 11.1 Software. The operating data of the unit was analyzed on composite and grand composite curves from the Software to obtain an optimum minimum temperature of 15ºC, pinch temperature of 149.5ºC and hot and cold utilities targets of 37094 kW and 22440 kW respectively. Problem table algorithm (PTA) was used as a sensitivity tool to test the accuracy of these values; the exact same values were obtained with less than 0.4% difference between the energy targets. This integration achieved a minimum heat recovery (Q_{REC}) of 55465.00 kW with an increase in the number of heat exchangers from eighteen (18) to twenty one (21) with total area of 1995.80m^2. Power law correlation was used for the heat exchanger costing to obtain a minimum Annual Capital Cost of $5,918.25/yr, Annual Energy Cost of $2,892.28/yr and Total Annual Cost (TAC) of $57,442.90/yr. By extension, these will certainly reduce the annual operating cost in terms of cost of utilities as well as minimize pollution emissions. Pinch analysis provides the best target for the minimum energy consumption as well as minimum total annualized cost.

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Pinch analysis is another very effectively means of improving energy efficiency either for a new plant or for the purpose of revamp. One of the highest sources of emission in chemical industries and other process industries is the energy industry of which refinery is prominent, this implies that adopting any effective energy efficiency methods will not only reduce pollution emissions but will do so at minimized operating cost (Worrell and Galitsky, 2005). Optimized energy efficiency has a positive economic impact on the entire process, as there is usually an expected reduction in utility need. Major areas for energy efficiency improvement include the utilities, fired heaters, process optimization, heat exchangers, motor and motor applications. Optimal use and design of heat exchangers is a key area for energy efficiency improvement (Anna and Carin, 2011). Heat exchanger network (HEN) is a system of several heat exchangers connected together which can be seen as networking. 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. 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 (Akpa and Okoroma, 2012). One of the most successful and generally useful techniques of HEN synthesis developed by Linnhoff *et al*., (1978) and subsequently other workers is known as pinch technology (Sinnot, 2005). It is a systematic method for energy integration in industrial processes. It involves minimizing the energy costs of a chemical process by utilizing the internal energy from the process streams rather than the use of external utilities for cooling or heating. It provides tools that allow for the investigation of the energy flows within a process and to identify the most economical ways of maximizing heat recovery and minimizing the demand for external utilities. Hence, the prime objective of pinch analysis is to achieve financial savings by better

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process-to-process heat integration (Barnes, 2013). There have been feasible and progressive successes in the industrial application of optimal heat exchanger network, which have also yielded financial gain by reduction in external energy consumption over the years (El-Temtamy *et al*., 2010). In this work, the Pinch Technology as available in Apen Pinch was used to synthesize and evaluate the heat exchanger network of the catalytic reforming unit of KRPC. 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.

MATERIALS AND METHODS

The materials required for carrying out this research work are Process Data of the Reforming Unit (KRPC manual, 2011); Aspen Pinch 11.1 software and A personal Computer

In any Pinch Analysis problem, whether a new project or a retrofit situation, a well-defined stepwise procedure. It should be noted that these steps were not necessarily performed on a once-through basis independent of one another. Additional activities such as re-simulation and data modification occurred as the analysis proceeds and some iteration between the various steps was required.
The analysis was carried out in three distinctive steps: viz-a-viz Data Collection; Evaluation of Targets and Design Procedure.

Data Collection includes:

i. Identification of the process hot, cold and the utility streams from the process flow diagram (PFD).
ii. Extraction of the thermal data for the process and utility streams from the PFD and the process plant.
iii. Selection of initial minimum temperature difference (ΔT) from literature.
iv. Determination of the optimal minimum temperature difference through several iteration methods.
v. Construction of composite and grand composite curves.

Evaluation of Targets:

i. Estimation of minimum energy targets.
ii. Estimation of heat exchanger network (HEN) capital target.
iii. Estimation of optimal minimum temperature difference (ΔT) value.
iv. Estimation of practical targets HEN design.

Design Procedure:

i. Design of heat exchanger network
ii. Retrofit simulation of the existing plant.

The Aspen Pinch 11.1 process tool was used to perform a detailed pinch analysis of the Catalytic Reforming Unit of the refinery. To do this, the thermal data obtained from the process flow diagram were fed as input to the software to construct the composite curves and grid diagram of all networks at different values of ΔT_{min} to obtain the optimum ΔT_{min}value. Problem Table Algorithm was used to calculate targets and the pinch point, which were compared with that obtained from the software to ensure accuracy. Then the heat exchanger network was designed using the grid diagram of the process streams on the software, Aspen Pinch 11.1. The following pinch rules were employed to ensure the use of the minimum energy targets; no heat was transferred across the pinch, there was no external cooling above the pinch and no external heating below the pinch (heaters were placed above and coolers below the pinch).

RESULTS AND DISCUSSION

Data Extraction: The data extracted are as shown in Table 1 below. The Unit contains eight (8) cold streams and ten (10) hot streams. The other required parameters were calculated by the software in Table 1.

Table 1: Process Data for Catalytic Reforming Unit (CRU) of the Refinery

S/N	Type	Ts (ºC)	Tt (ºC)	MCP (kW/ ºC)	Enthalpy (kW)
1	Cold	142	449	157.02	48206.35
2	Cold	449	500	141.38	7210.60
3	Cold	414	500	141.99	12211.50
4	Cold	449	500	143.66	7326.90
5	Cold	466	500	143.66	4884.60
6	Cold	40	108	17.79	1209.52
7	Cold	40	188	51.08	7559.50
8	Cold	235	254	214.88	4082.13
9	Hot	500	133	131.35	48206.35
10	Hot	133	48	172.17	14677.06
11	Hot	48	40	138.11	1104.85
12	Hot	56	40	60.33	965.29
13	Hot	108	40	20.52	1395.60
14	Hot	235	92	52.86	7559.50
15	Hot	92	48	42.29	1860.80
16	Hot	48	40	39.25	314.01
17	Hot	76	48	62.30	1744.50
18	Hot	48	40	26.17	209.35

Selection of Optimum ΔT_{min} Value: Using the process of Supertargeting to compare targets obtained at various minimum approach temperatures ΔT_{min} as shown in Table 2, 15ºC was obtained as the optimum approach temperature between two streams in a heat exchanger. This minimum temperature can be seen at the pinch point in the composite curve of the process (Figure 2). The value of 15 ºC obtained is also in line with Linnhoff's ΔT_{min} estimate for Petrochemical processes; between 10 – 20 C and 20-40 C for Oil Refining (Linnhoff et al., 1978).

Table 2: Results of Minimum Approach Temperature (ΔT_{min}) Selection

Description	**Minimum Approach Temperature (ºC)**				
	10	**15**	**20**	**25**	**30**
Minimum Hot Utility (kW)	36173.3	37094.4	38015.5	38936.6	39276.8
Minimum Cold Utility (kW)	21519.5	22440.6	23361.7	24282.8	25203.9
Number of Exchangers	19	21	22	23	24
Number of Shells	34	35	36	42	54
Pinch Temperature (ºC)	147.0	149.5	152.0	154.5	157.0
Target Report/Remark	Utility Load Used Is Greater Than The Minimum Requirements	The Streams And Utilities Are In Heat Balance	The Streams And Utilities Are Not In Heat Balance. Utility Load Used Is Less Than The Minimum Requirements	The Streams And Utilities Are Not In Heat Balance. Utility Load Used Is Less Than The Minimum Requirements	The Streams And Utilities Are Not In Heat Balance. Utility Load Used Is Less Than The Minimum Requirements

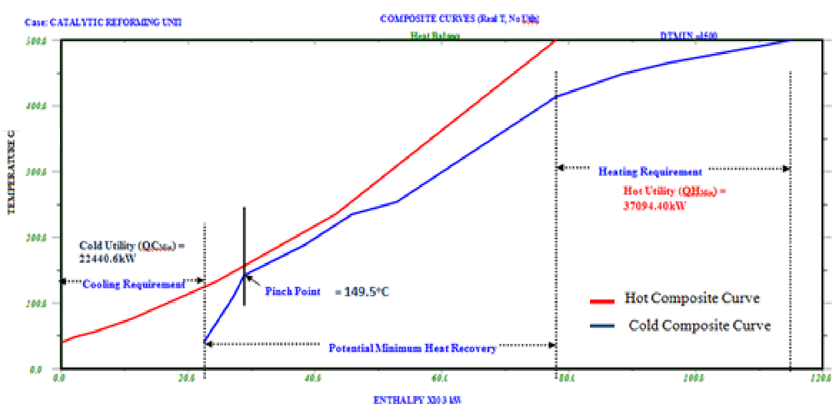

Fig 1: Composite Curves for CRU

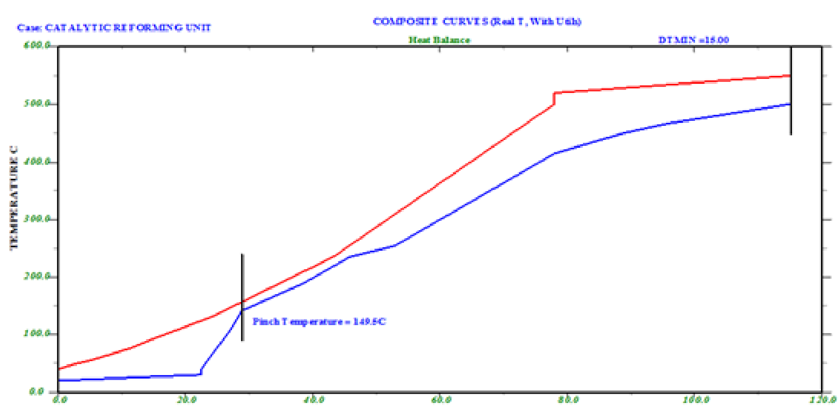

Fig 3: Balanced Composite Curves for CRU

Plotting of Curves (Targeting): From the Composite Curves in Figure1, using a minimum temperature difference (ΔTmin) of 15ºC, the region of overlap between the two curves (hot and cold composite curves), determines the amount of heat recovery possible (for ΔTmin = 15ºC). The end of the cold composite curve that extends beyond the line of the hot curve in Figure 2 cannot be heated by recovery hence requires steam. This is the minimum hot utility or energy target (QH_{MIN}) which is 37094.40 kW. While the end of the hot composite curve that extends beyond the start of the cold curve cannot be cooled by heat recovery and requires cooling water. This is the minimum cold utiltiy (QC_{MIN}) which for this work is 22440.60 kW

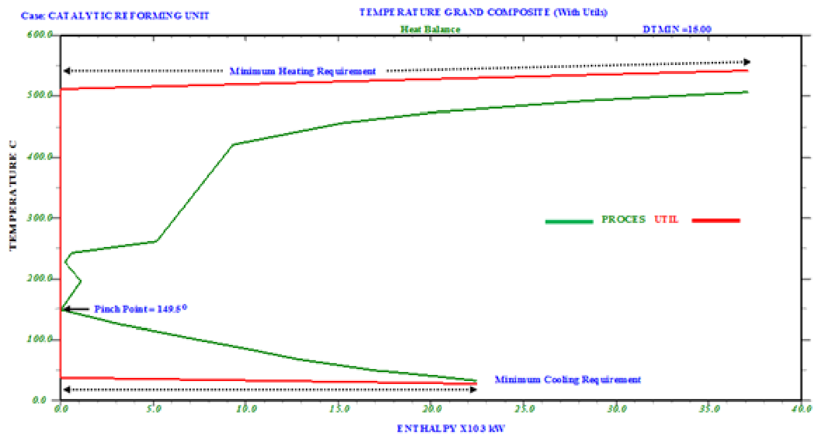

Fig 3: Balanced Grand Composite Curve with Utility in Place for CRU

Problem Table Algorithm: The software was used to generate the composite and the grand composite curves, however, a numerical approach called "Problem Table Algorithm" (PTA) (Linnhoff and Flower, 1978) was also used to determine the utility needs of the process as well as the location of the process Pinch as some sort of sensitivity test for accuracy. Figure 3 shows the temperature interval heat balance of the PTA using the shifted temperatures to create intervals, the heat capacity flow rate of each interval, CP_{net} is calculated with using the individual CPs of the streams in each interval, this value is used with the temperature difference that makes the interval to calculate the enthalpy in each interval $[\Delta H_i = (\sum CP_{hot} - \sum CP_{cold})(T_i - T_{i+1})]$ as shown in table 3. The Problem table Cascade is also shown in the table, where the highest energy need gotten from the enthalpy calculations, 36980.74 KW (Hot utility need) was cascaded down the intervals to locate the pinch point at 149.5 C and also obtain the Cold utility need as 22375.70 KW.

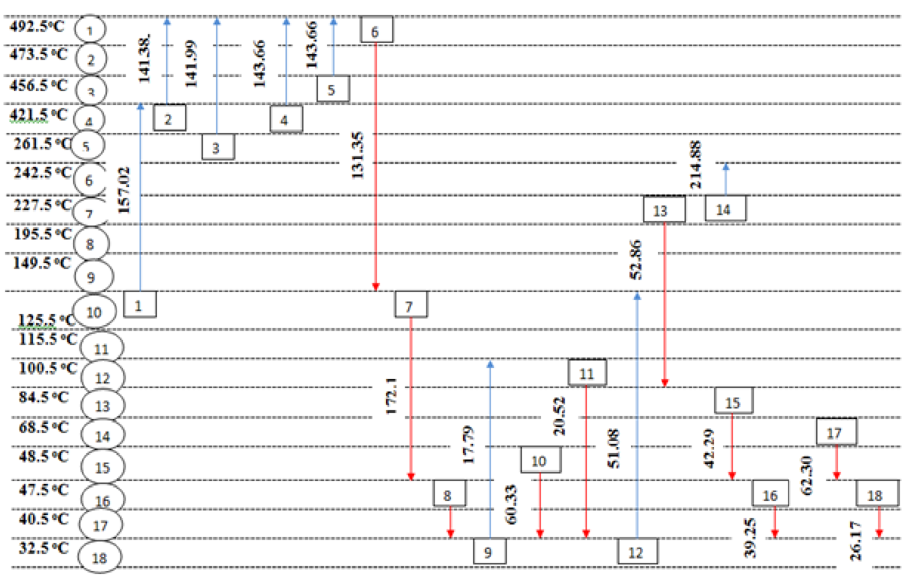

Fig 5: Schematic Representation of the Problem Table Algorithm

Table 3: Problem Table Cascade

Interval	**Interval Temp (ºC)**	**ΔT (ºC)**	**$\sum CP_C - \sum CP_H$ (KW /ºC)**	**ΔH (kW)**	**Surplus or Deficit**	**Cascade**	
	507.5					0	36980.74
1	492.5	15	439.34	6590.1	Deficit	6590.1	30390.64
2	473.5	19	439.34	8347.46	Deficit	14937.56	22043.18
3	456.5	17	295.68	5026.56	Deficit	19963.66	17017.08
4	421.5	35	167.66	5868.10	Deficit	25831.76	11148.98
5	261.5	160	25.67	4107.20	Deficit	29938.96	7041.78
6	242.5	19	150.87	2866.45	Deficit	32805.41	4175.33
7	227.5	15	-27.19	-407.85	Surplus	-32397.56	4583.188
8	195.5	32	-27.19	-870.08	Surplus	-31527.48	5453.26
9	149.5	46	-118.55	-5453.26	Surplus	-36980.74	0
10	125.5	24	-173.95	-4174.80	Surplus	-32805.94	4174.80
11	115.5	10	-173.95	-1739.50	Surplus	-31066.44	5914.30
12	100.5	15	-176.68	-2650.20	Surplus	-28416.24	8564.50
13	84.5	16	-166.11	-2657.76	Surplus	-25758.48	11222.26
14	68.5	16	-228.41	-3654.56	Surplus	-22103.92	14876.82
15	48.5	20	-288.74	-5774.80	Surplus	-16329.12	20651.62
16	47.5	1	-215.51	-215.51	Surplus	-16113.61	20867.13
17	40.5	7	-215.51	-1508.57	Surplus	-14605.04	22375.70
18	32.5	8	0	0		-14605.04	22375.70

Catalytic Reforming Unit Heat Exchanger Network Design: The heat exchanger network for the catalytic reforming unit in Figure 4 was designed using the grid diagram as obtained in Aspen Pinch 11.1. The descriptive summary of this network is as shown in Table 4, it made use of 21 heat exchanger units. There was no cross pinch transfer in the network as its design was carried out whilst adhering strictly to the pinch design rules.

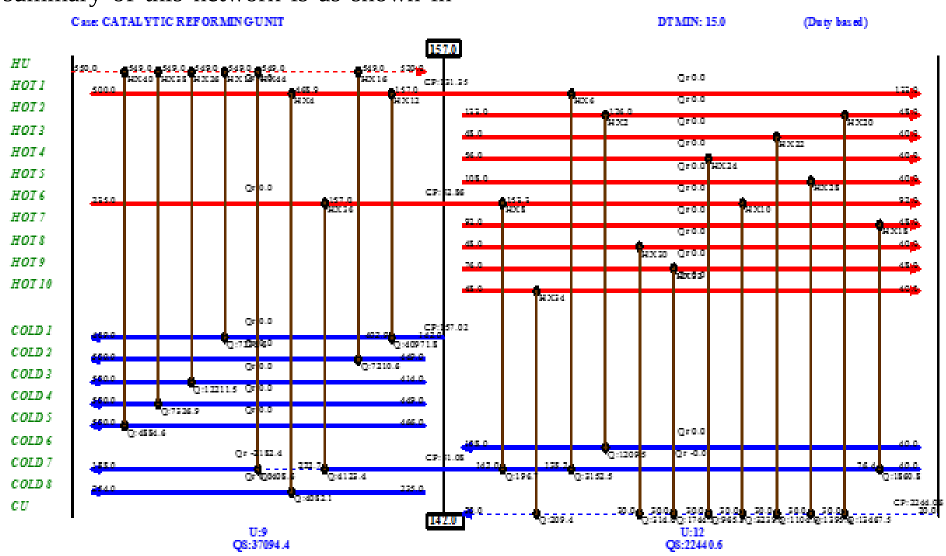

Fig 6: HEN design for Catalytic Reforming Unit of KPRC using Aspen Pinch 11.1

Table 4: Summary of Results obtained from the Pinch Analysis of CRU

Description	**Value**
ΔTmin	15.00ºC
Pinch Temperature	149.50ºC
Total Number of Exchangers	21
Total Area	1995.80 m^2
Total Installed Cost	29,591.26 US$
Total Hot Energy Usage	37094.40Kw
Total Hot Energy Cost	2596.59 US$/yr
Total Cold Energy Usage	22440.60 kW
Total Cold Energy Cost	263.90 US$/yr
Annual Capital Cost	5,918.25 US$/yr
Annual Energy Cost	2,892.28 US$/yr
Total Annual Cost (TAC)	57,448.90 US$/yr

Conclusion: The problem table and ASPEN Pinch Software were used to construct the composite curves, shifted composite curves, grand composite curves and an optimum heat exchanger network design from which the pinch temperature, utility requirements and the total annual cost were determined. In order to upgrade the Catalytic Reforming Unit of KRPC to a fully "Heat Integrated Plant", a retrofit heat exchanger network design with three additional heat exchangers is required.

REFERENCES

Akpa, JG; Okoroma, JU (2012). Pinch Analysis of Heat Exchanger Networks in the Crude Distillation Unit of Port-Harcourt Refinery. *J. Emerging Trends in Eng. Appl. Sci.* 477-484.

Anna, G; Carin, M (2011). Pinch Analysis of Nynas Refinery- An Energy Efficiency Study. Chalmers University of Technology, Goteborg, Sweden, p. 4-24.

Aspen Pinch Software Version 11.1 (Software)

Barnes, S (2013). Using Pinch Analysis to Optimize the Heat Exchanger Network of a Regenerative Rankine Cycle for an Existing Modern Nuclear Power Plant. Rensselaer Polytechnic Institute, Hartford, p. 12-41.

El-Temtamy, S; Hamid, I; Gabr, E; El-Rahman, AS (2010). The Use of Pinch Technology to Reduce Utility Consumption in a Natural Gas Processing Plant. *J. Petroleum Sci. Tech.*: 1316-1330.

Linnhoff, B; Flower, JR (1978). Synthesis of Heat Exchanger Networks: Systematic Generation of Network with Various Criteria of Optimality. *AIChE Journal:* 642-654.

Sinnot, RK, (2005). Chemical Engineering Design, Fourth Edition, Volume 6. Elsevier Butterworth-Heinemann, New York, Pp. 111-127.

Ukpo EM. (2017). Heat Exchanger Network Design for Minimum Total Annual Cost Using Pinch Analysis - - Case Study of Catalytic Reforming Unit of a Nigerian Refinery **(**Published Master's Thesis), Federal University of Technology, Minna, Niger State, Nigeria.

Worrell .E; Galitsky .C (2005). Energy Efficiency Improvement and Cost Saving Opportunities for Petroleum Refineries. Environmental Energy Technologies Division, University of California, Berkely, p. 1-56.