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Energy Integration of Kero Hydrotreating Unit, A Case Study of Nigerian Refinery

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Abstract

Kero hydrotreating unit being an integral part of the refinery system has been characterized by heat leaks, heat losses and inefficiencies in the heat transfer processes. This has necessitated the investigation into analysis of the current energy configuration to curb this menace and to proffer solution which would lead to efficient utilization of energy. Application of Pinch technology to kero hydrotreating unit heat exchanger network is presented with an optimum minimum approach temperature of 2.5°C to determine the energy target. This was achieved via the development of composite and grand composite curves for the kero hydrotreating unit process. The Pinch point temperature was found to be 544°C, with the utility targets for the minimum approach temperature being 7491.9 kW and 8259.62 kW for hot and cold utilities respectively, leading to energy savings of 34.33% and 32.17%. The percentage energy savings reported is as a result of the re-use of the cold or hot process streams before being sent back to the power plant or the trim coolers. Pinch analysis as an energy integration technique is proven to save more energy and utility cost than the traditional energy technique currently being used in the unit. The energy integration of the refinery kero hydrotreating unit using Pinch analysis did not only save energy and utility cost but showed significant improvement and exposed the inefficiencies of the traditional design approach.

Keywords: Pinch analysis; Kero hydrotreating unit; Energy target; Heat integration

Introduction

The ability of any Nation to survive economically depends on its capacity to produce and manage sufficient supplies of low cost, safe energy and raw materials [1]. Worldwide consumption of limited fossil fuel resources is increasing with projections in this trend signifying that unless an efficient strategy is put in place, the world will soon be short in supply of energy. On the strategic statement of the energy sector of Nigeria vision 2020, it is necessary for the country to embark on energy conservation and efficiency initiatives which will require industries to move to energy saving equipment and utilities for reduction in total power demand by using technologies which ensure optimum energy utilization and integration.

Pinch technology is a complete methodology derived from simple scientific principles. It allows the design of new plants with reduced energy and capital costs as well as where the existing processes require modification to improve performance [2]. More so, Pinch approach enables calculation of energy and utility targets by simple analysis of the process data, thus, an opportunity to design a new system or modification of existing system before embarking on actual implementation [3].

Pinch technology, when applied with imagination, can affect reactor design, separator design and the overall process optimization in any plant. But its application has proven that it can address problems beyond what energy conservation principles can resolve, as well as to solve problems as diverse as improving effluent quality, reducing emission, increasing product yield and debottlenecking, increasing throughput, flexibility and safety of the process [4].

The procedure involved prediction of minimum requirements of external energy prior to design, determination of network area, and the number of units for a given process at the pinch point and synthesis of a heat exchanger network that satisfies the targets. Finally, the network is optimized by comparing energy cost and the capital cost of the network so that the total annual cost is minimized [5].

Energy saving in the Nigerian refineries is not a matter of possibility but a necessity considering that almost all the refineries were built in an era of cheap energy, hence attaining maximum efficiency was not a matter of serious concern [6]. However, improvement of energy efficiency can provide substantial benefit in general as many plants are faced with heat integration problems.

Research in the area of energy integration is as old as the concept itself with several remarkable progress made in process industries. In Nigeria, integration of several process streams with regards to heat transfer has been implemented [4,7-10]. The refineries in some other studies have been reported to have suffered from inadequacy of the existing design, with the benefit of retrofitting explored in various sections leading to improved energy efficiency [11].

It is evident from the most recent studies reported on kero hydrotreating unit of Nigerian refineries, that the plant is faced with energy efficiency problems as heat leaks and heat losses top the list of problems giving rise to high operational cost and loses. Thus, the need to develop a methodology that will lead to more energy efficient system that would minimize utility fluid usage and maximize process-process heat transfer.

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Materials and Methods

Materials

Aspen Hysys, Aspen Energy Analyzer and HINT has been used as tools for this research, with computer specifications of 64-bit operating system, 4G RAM, 1.5 GHz processor and windows 8 operating system.

Methods

Kero hydrotreating unit heat exchanger network analysis, design and optimization is the core of this research, with the procedure involving data extraction, process simulation and pinch analysis as shown in Figure 1.

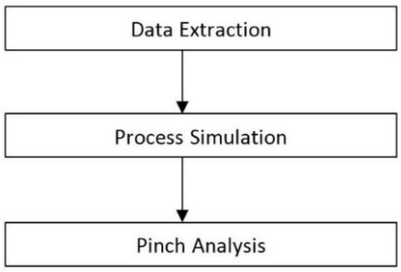

Figure 1: Steps involved in the energy integration of KHU.

Data extraction: Data extraction from the existing network as shown in Figure 2 using the available KHU process flow diagram (PFD), piping and instrumentation diagram (PID) was carried about as well as Laboratory analysis of the KHU feed and Products [12]. The stream temperatures, mass flow rates, pressures are parameters extracted for use in the analysis.

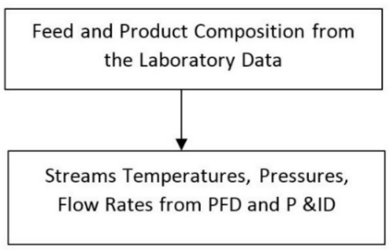

Figure 2: Data extraction steps.

Typical ranges of T_{min} values from experience were adopted and found to represent the trade-off for each class of the process used. Table 1 [3] shows values of T_{min} adopted based on experience in the process industry.

Type of Heat Transfer	Experience ΔT_{min} values (°C)	Selected ΔT_{min} values (°C)
Process stream against process stream	30-40	35
Process stream against steam	10-20	15
Process stream against cooling water	0-20	10
Process stream against cooling air	10-25	15

Table 1: Selected ΔT_{min} values.

Process simulation procedure: Process stream thermodynamic properties calculations is done using the Equation of State (EOS) selected. The various reactions involved were also fully defined, with all stream composition and conditions specified in order to develop a full process flow diagram ready for simulation as shown in Figure 3. The process simulation involved the use of the source and target temperatures, compositions and mass flow rate of all the streams (feed and products streams) in addition to the respective stream enthalpies and heat capacities.

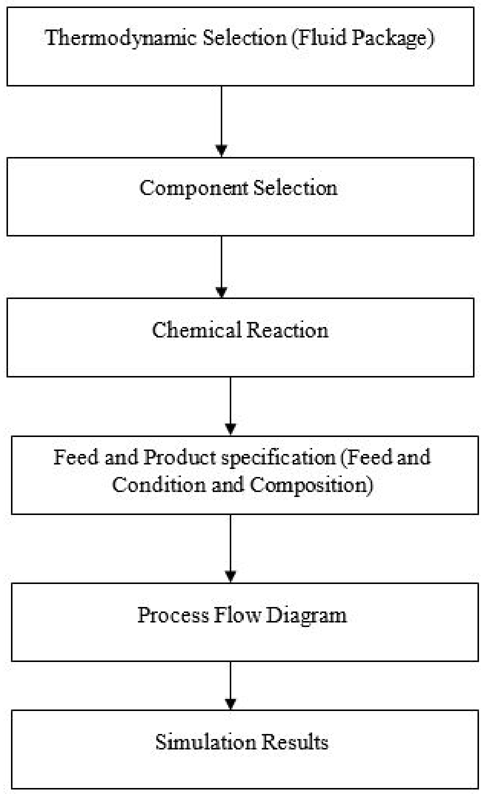

Figure 3: Process simulation step.

Simulation of the KHU process was also carried out using HINT software as shown in Figure 4, with the energy targets being the minimum amount of utilities needed to satisfy the process stream requirements [13]. The utility load allocation method and pinch temperature are used to calculate the energy target values, with the pinch temperature also used in designing the optimal Heat Exchanger Network (HEN) by identifying the impossible heat transfers between streams when the temperature difference between streams is equal or less than the pinch temperature and unnecessary use of cold utility. This occur when a cold utility is used to cool hot streams in the region above the pinch and finally unnecessary use of hot utility, which

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usually occurs when a hot utility is used to heat cold streams in the region below the pinch. The calculation of heat requirement for each stream is based on stream grid which gives a visual representation of the heating and cooling requirement. The stream grid also provides a good tool for designing the heat exchanger network.

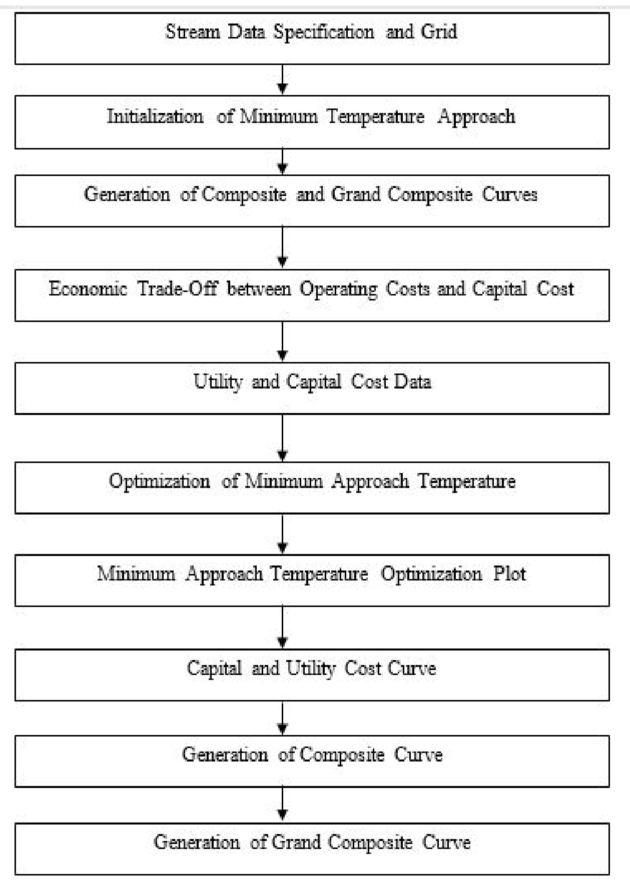

Figure 4: Pinch analysis simulation procedure.

Traditionally, composite curves were used to set energy targets, but the approach is not convenient because it is based on a graphical technique which necessitate the use of problem table algorithm. The problem table algorithm is a method of calculating energy targets directly by dividing the process into temperature intervals in the same way as for construction of the composite curve, aiding the determination of the minimum utility duties. This also involves the shifting of the stream temperatures e.g., the hot stream temperature is shifted by -½ ΔT_{min} and cold stream temperature by ½ ΔT_{min}. The hot and cold streams are then combined to give the hot and cold stream composite curves respectively.

In the design of heat exchanger equipment, ΔT_{min} value is critical and second law of thermodynamics that prohibits any temperature crossing between the hot and cold streams must be satisfied. Thus, the temperature of the cold and hot streams at any point in the exchanger must always have a minimum temperature difference (ΔT_{min}). The initial values of minimum approach temperature used were as reported [3] in Table 1. Finally, plots are generated that provide a visual analysis of key variables and trends for the heat integration in a given stream data.

Heat exchanger network optimization: The network design that maximized heat recovery and minimized the cost of hot and cold utility fluids may not be necessarily the optimum design for the network. The optimum design will be that which gives the lowest total annual cost; taking into account the capital cost of the system, in addition to the utility cost and operating costs. However, there is a scope for reducing the number of heat exchangers, but the heat loads of the coolers and heaters increases in order to bring some of the streams to their target temperatures. Whether the revised network would be better and more economical, depends on the relative capital cost and utilities. For any network, there will be an optimal design that gives the least annual cost, capital charges plus utility and other operating cost. So, for the optimal design, a plot of the capital cost, operating cost and the total annual cost is used to determine the minimum point of the annual cost chosen as the optimal point. The temperature at the point of minimum annual cost is regarded as the optimum minimum approach temperature for the network design.

Economic analysis: The cost analysis is crucial to the economic evaluation of the existing KHU configuration, thus, a reference point for comparison with the developed models. The cost element is the total annual cost (profitability analysis) used to determine annual income, return rates and payback period among others. The total annual cost of a heat exchanger network comprises of two parts, the capital cost and the operating cost. The used cooling water and air costs are $21.04/kW and $12.75/kW, respectively. Meanwhile, the equipment cost is based on 2016 CEPCI cost index as in the approach reported [14].

The optimum selection of the ΔT_{min} value is as a result of the trade-off between operating costs and the installation cost of the network. The installation of the large heat exchangers can reduce operation costs for utilities but at the expense of a higher capital cost for the network.

Theoretical Background

The network temperature also referred to as Pinch Design Method (PDM) has for decades been outlined [15,16] and comprehensively described [17]. It represents a bottle neck to feasible heat recovery in a heat exchanger network and provides an opportunity for developing a network in a sequential manner, with heat exchangers treated one at a time.

Pinch analysis is a rigorous, structured approach that can be used on a wide range of process and site utility related problems such as lowering operating costs, de-bottlenecking processes, raising efficiency and reducing capital investment [4]. Its strength lies in its ability to set the best stream matches that maximize process-process heat exchange and minimizes the use of utility fluids. It is these two factors that attract the use of pinch technology to analyze and design the heat exchanger network of any system. Here, only the source temperature, target temperature, heat capacity and mass flow rates of the process streams are required to carry out the analysis and it works on certain established principles or concepts such as problem table calculation, composite curve, Grand composite curve, Grid representation etc.

Targets

Targets are values which theoretically represents the ideal or perfect situation. They serve as a bench mark for comparison to ascertain how close or far away the current design is from the optimal conditions.

Energy targets

Energy targets are the minimum amount of utilities needed to satisfy the process stream requirements [13]. In pinch software like Aspen Energy Analyzer, the energy target values are calculated depending on the Utility Load Allocation Method and pinch temperature. The hot and cold utility energy targets are both displayed in Table 2.

	Current Energy target for KHU (kW)	New Energy Target (kW)
Hot Utility	11409.03	7491.9
Cold Utility	12176.61	8259.62

Table 2: Energy target effect of pinch technology.

Pinch temperature

The pinch temperature is used in designing the optimal heat exchanger network (HEN) by identifying the following:

Impossible heat transfers between streams when the temperature difference between streams is equal or less than the pinch temperature.

Unnecessary use of cold utility, when a cold utility is used to cool hot streams in the region above the pinch.

Unnecessary use of hot utility, when a hot utility is used to heat cold streams in the region below the pinch.

Plots

The plots provide visual analysis of the variables and trends for the heat integration in a given stream data. There are a wide variety of plots available.

Composite curve

Composite curve is a plot of temperature against enthalpy for hot and cold streams which represents the sum of the energy changes for a given temperature range. The composite curve allows the designer to calculate hot and cold utility requirements ahead of design, to understand driving force for heat transfer. It also allows for the location of heat recovery pinch with the degree of overlap of the curves as a measure of potential for heat recovery [4].

The utility target shown in Figure 5 [4], depends on the value of ΔT_{min}. A small ΔT_{min} brings the curves closer together, reducing hot and cold utility demands and yielding lower operating lost. This is at the expense of the large heat exchange area and hence greater capital cost. The optimum choice of ΔT_{min} depends on the trade-off between capital and energy cost.

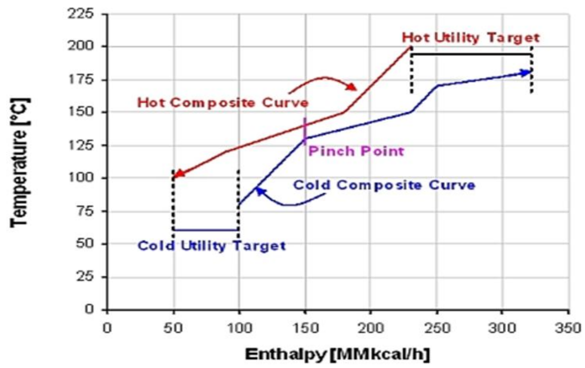

Figure 5: Composite curve.

Grand composite curve

The Grand composite curve shown in Figure 5, is a plot of shifted temperature versus the cascade heat between each temperature interval [17]. It is derived from the same process data as the composite curve and shows the net heat flow through the process. It highlights the process/utility interface and guides in the selection of different utilities source.

Area targets

The area targets are the minimum amount of heat transfer area required for the hot and cold streams in a heat exchange network to achieve their specified temperature values. Heat exchange total area can be estimated by summing the differential heat exchange area in different temperature intervals as expressed by equation 1. Equation 1 is also known as the uniform BATH formula.

$$A = \sum\left(\frac{1}{F_l \times \Delta T_{LM}}\right)_i \sum_j \left[\left(dT_h \times \sum_{jh}\left(\frac{MC_p}{h}\right)_{jh} + (dT_c)_i \sum_{jc}\left(\frac{MC_p}{h}\right)_{jc}\right)\right] \quad (1)$$

Minimum number of heat exchanger

In order to facilitate capital cost estimation prior to detailed design; the minimum number of heat exchangers required for a process must be known in addition to the total surface area. This can be evaluated by applying the Euler terrain. "It states that the minimum number of connections (N_{min}) required in a network is one less than the number of streams, N, including the utilities. Thus. Equation 2 shows the number of exchangers in the Process.

Number of Heat Exchengers=No.of Streams+No.of Utilities-1 (2)

$N=N_s+N_u-1$ (3)

Results and Discussion

The results of the data extracted is presented in Table 3, with the heat load and temperatures of all streams used for the energy integration calculations. The target and supply temperatures for the

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streams involved were identified, with the furnace providing the utility heating. The furnace was modeled as fired heaters in the pinch analysis which served as a heat source with a single temperature that is hot enough to satisfy any anticipated heat load in the unit. The air-cooling and water-cooling likewise were represented as heat sinks at a single temperature. The Minimum Temperature Approach (T_{min}) values required to generate targets for the minimum energy were set for the problem to be 10°C and 35°C for process-cooling water and process to process, respectively. The T_{min}, is the smallest temperature difference that is allowed between the hot and cold streams in the heat exchanger where counter-current flow was assumed. This parameter reflected the trade-off between capital investment (which increases as the T_{min} value gets smaller) and energy cost (which decreases as the T_{min} value gets smaller).

No.	Stream Name	Supply Temperature (K)	Target Temperature (K)	Heat Load (kW)
1	13E01A-C FEED	316	591	21070
2	13H01 FEED	591	628	5280
3	13R01 PRODUCT	633	409	21070
4	13E06 FEED	439	313	34.89
5	13A01 FEED	409	333	4838
6	13E02 FEED	333	313	1196
7	13E03 FEED	313	489	10870
8	13C01 FEED	539	377	10870
9	13A03 FEED	377	333	2477
10	13E05 FEED	333	313	1082
11	13H02 FEED	539	552	6129
12	13A02 FEED	405	333	2070
13	13E04 FEED	333	313	476.83

Table 3: Data extraction results of kero hydrotreating unit of the selected refinery.

To determine the minimum targets for energy requirement, temperature against enthalpy values for KHU hot and cold streams were represented by the composite curve. Figure 6 [4] shows the composite curve of heat availability in the process (the "hot composite curve") and heat demand in the process (the "cold composite curve"). The KHU composite curve shown in Figure 7 is for counter current heat exchanger. The hot composite curve is indicated as the red curve while the blue curve represents the cold composite curve. The overlap between the cold and the hot composite curves gives the maximum heat recovery possible. The figure showed that the curves are closer to each other at the hot stream temperature of 549 K and cold stream temperature of 539 K. This also revealed the minimum external heating and cooling requirement of the process.

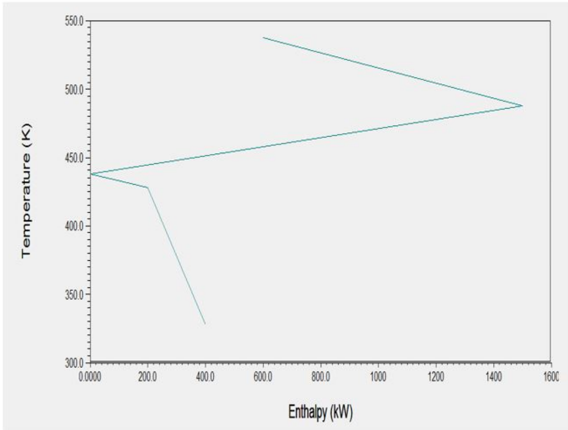

Figure 6: Grand Composite Curve.

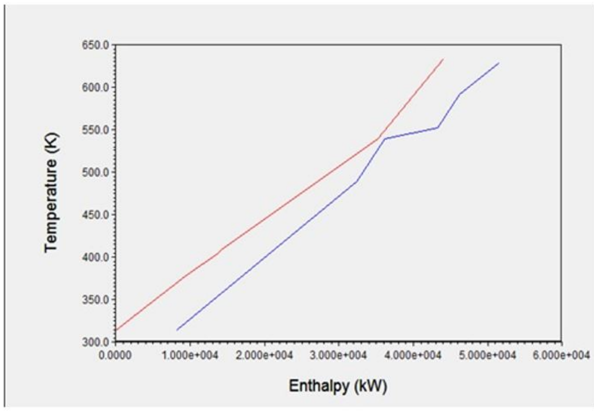

Figure 7: Shifted composite curve of KHU.

From Table 4, the heat available and heat demand within the process are 7491.9 kW and 8259.62 Kw, respectively. This shows that more heat was removed from the process in excess of what was supplied to the system. The heat demand in the process was very high resulting from high energy requirement in the removal of impurities [18]. Therefore, any utility for heating supplied to the process below the pinch temperature cannot be absorbed and will be rejected by the process to the cooling utility thereby increasing the amount of cooling utility required, hence, resulting to the wastage of energy (cold utilities) by the KHU process and consequently reducing its energy efficiency.

Minimum Hot Utility (kW)	Minimum Cold Utility (kW)	Minimum temperature approach (ΔT_{min}) (K)	No. of Heat Exchangers
7491.9	8259.62	544	15

Table 4: Energy targets of KHU.

Table 5 shows that the minimum temperatures approach (MTA) required for the KHU plant is 2.5 K. This is the closest approach

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temperature that is allowable between two streams exchanging heat. However, the optimum value of 2.5 K of this parameter is significantly affected by the relative costs of energy and heat exchange area, and this is the primary parameter that was optimized in the pinch design program. The value of 2.5 K means that the hot streams approached the temperature of the cold streams more closely, with the cold stream absorbing more heat from the hot stream. This in turn, reduced the utility heating required for the cold stream and also the utility cooling required for the hot stream, as the hot stream exits at a lower temperature after it has exchanged heat with the cold stream. This also reduced the operating costs by lowering the utility costs.

The minimum approach temperature also increased the capital costs, and this was as a result of the fact that the lower approach temperature between the hot and cold streams reduced the Log Mean Temperature Difference (LMTD) in the heat exchanger. The lowered driving force and higher duty of individual heat exchangers resulted in larger heat exchanger areas being required, which increased the capital costs. Similarly, a large value of the minimum approach temperature resulted in lower capital costs and higher utility (operating) costs. The minimum number of heat exchangers at this optimum minimum approach temperature of 2.5 K was 15.

Optimum Minimum temperature approach (Optimum ΔT_{min}) (K)	Minimum No. of heat exchangers to target
2.5	15

Table 5: Optimization results.

Table 6 shows the calculated minimum heating and cooling requirement for both the traditional design and the pinch analysis. This also shows that the two requirements when compared shows significant energy requirement savings of 34.33% (from 11409.03 kW to 7491.90 kW) for heating and 32.17% (from 12176.61 kW to 8259.62 kW) for cooling, with 33.22% savings of the total energy requirement achieved. This was consistent with the reported energy savings in similar refineries [4,7] on naphtha hydrotreating unit (NHU) and Hydro desulphurization units (HDU) of the refinery. The energy savings achieved were as a result of proper utilization of the wasted heat in the new integrated heat transfer process of KHU which the traditional design could not efficiently utilize. These inefficiencies have been addressed by the new design thereby leading to a maximum process to process heat exchange and minimization of the process utility requirement. The area and cost target also achieved are presented in Table 7. The minimum possible number of heat exchangers was identified to be fifteen (15) with area target of 1299 m^2 and total cost of about $409,206 /Yr. However, it is interesting to see that in Figure 8, the decrease in ΔT minimum results into increase in operating cost and vice versa. This is because the higher the minimum approach temperature, the more the energy (cost) is required to overcome the resistance of energy transfer. This means in heat transfer devices, increase in the heat transfer surface area implies a reduction in utility requirement thereby causing a decrease in operating cost and an increase in physical configuration cost. The optimal ΔT minimum gave the lowest total cost.

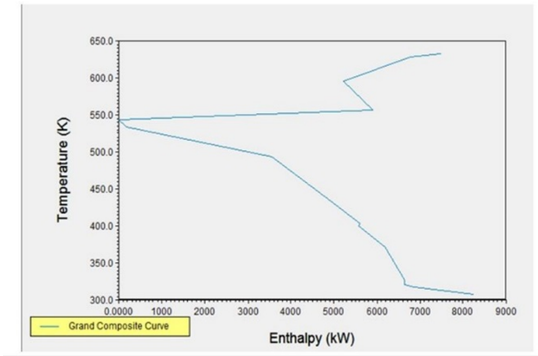

Figure 8: Grand composite curve.

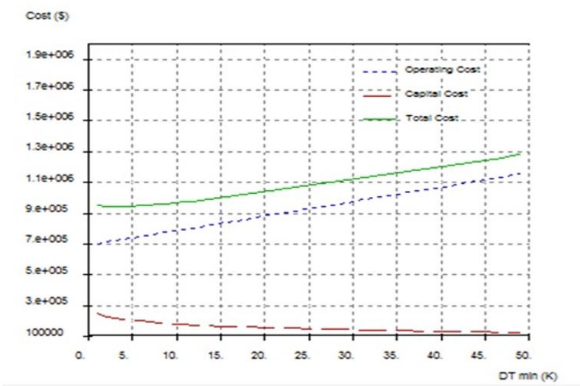

Figure 9: Minimum temperature approach against total cost index.

Figure 9 shows that as MTA increases, the capital consumption cost decreases. There was a steady value in the capital cost as the MTA increased from 17 to 19 K. The capital cost, then gradually continued to drop as shown on the plot.

	Traditional Energy requirement (kW)	Pinch Analysis (kW)	Savings (%)
Energy Target (QHMIN)	11409.03	7491.90	34.33
Energy Target (QCMIN)	12176.61	8259.62	32.17
Total Energy	23585.64	15751.52	33.22

Table 6: Pinch analysis targets of KHU.

Minimum Number of Heat Exchangers	Area Target (m^2)	Operating Cost ($/yr)	Capital Cost ($/yr)	Total Cost ($/yr)
15	1298.95	338,841	70,110	407,742

Table 7: Area and cost target at optimum ΔT_{min}.

Figures 10 and 11 shows the new design and the traditional integration design of KHU respectively. The new integration design shows a more complex configuration, but it ensured maximum heat transfer between the process streams compared to the traditional design which has some streams with energy potentials to be reused by other equipment but returned to the power plant without fully harnessing its exergy. Thus, the traditional design in its present form is inefficient in maximizing process to process heat transfer.

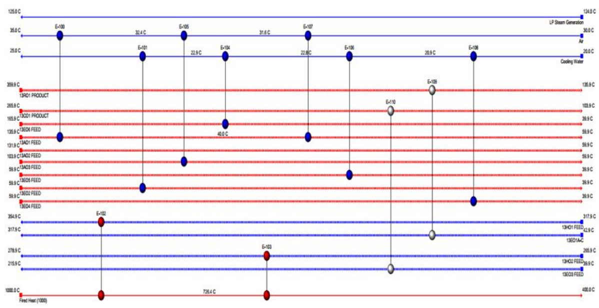

Figure 10: Traditional heat exchanger network of KHU.

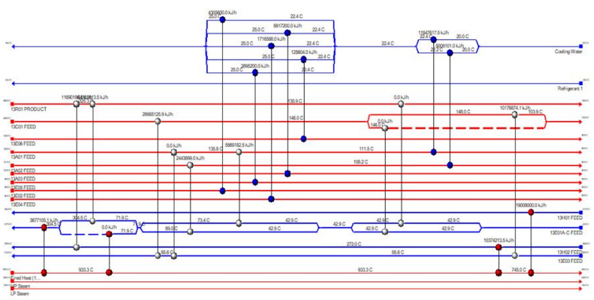

Figure 11: Proposed heat exchanger network of KHU.

The optimum design for an energy efficient heat exchange network is presented in Figure 11. It is dependent on the choice of the ΔT_{min} for the process. The lower the ΔT_{min} chosen, the lower the energy costs, but conversely the higher the heat exchanger capital costs, as lower temperature driving forces in the network will result in the need for greater area. A large ΔT_{min}, which was the case with the traditional design shown in Figure 8, on the other hand, will mean increased energy costs as there will be less overall heat recovery, but the required capital costs will be less. One of the draw backs of the proposed HEN design using pinch method is that it leads to a complex network configuration which could lead to controllability problems, but the aim is to achieve a network that operates with the minimum energy requirements and in which all heat exchangers operates at the least minimum approach temperature. For certain types of applications such as refinery crude preheat trains, where there are few matching constraints between hot and cold streams; it is possible to set capital cost targets in addition to the energy targets [19]. This allows the consideration of the trade-offs between capital and energy in order to obtain an optimum value of ΔT_{min} ahead of network design.

Conclusion

The energy integration of the kero hydrotreating unit of the existing refinery has shown that the initial design is characterized by energy wastage that could be utilized, thus, the need for the process energy efficiency improvement. The search for optimal energy integration technique has been examined and has proven to save more energy than the traditional energy utilization approach leading to an overall energy savings of 33.22% (34.33% and 32.17% for hot and cold utility, respectively). This indicates that the design of the heat exchanger network in this unit was done in the era of cheap energy. The use of pinch analysis provide means of modifying the heat exchangers network to eliminate cross pinch exchangers via process streams temperature modification to avoid violation of pinch principle and heat transfer beyond that at the desired minimum temperature. Therefore, the result of the present study shows that KHU like other units of the refinery investigated using pinch technology is not efficient and has greater potentials for improvement. Retrofit of the current energy configuration is recommended to be carried out so as to utilize already existing equipment to maximize the utility usage as against a new design which may lead to further reduction in the overall cost of the unit.

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