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Pinch Analysis of Vacuum Distillation Unit of Kaduna Refinery and Petrochemical Company

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Abstract: Excessive energy demand in the unit under study leads to high operating cost and suboptimal design. This is because the unit was design using traditional design energy (TDE) methods prior to the advent of pinch technology. Thus, making it imperative to carry out energy assessment of the unit. The aim of this study is to investigate the energy consumption of the unit via pinch analysis. The methodology includes; data extraction from the process flow diagram (PFD) of the unit, selection of initial value of ΔT_{min}, targeting (energy and cost), determination of $optimum\,\Delta T_{min}$ (tradeoff between energy and capital cost) and determination of utilities requirement via composite curves (CCs) and grand composite curves (GCC). The results of the analysis showed that, the optimum ΔT_{min} is 25 ^{o}C which results to total annual cost (TAC) of 1.663×10^6 $\$/year$, contrary to the TAC of 1.69×10^6 $\$/year$ obtained when ΔT_{min} of 10 ^{o}C was selected. This achieved financial saving of 27,000 \$/year. Furthermore, the minimum hot and cold utilities demands of the unit are $4.962 \times 10^7 kj/h$ and $2.644 \times 10^7 kj/h$ respectively. In contrast to the traditional method which requires huge amount of hot and cold utilities of $7.762 \times 10^7 kj/h$ and $10.082 \times 10^7 kj/h$ respectively. Therefore, the pinch method achieved hot and coldutility saving of 2.8×10^7 KJ/hand 7.44×10^7 KJ/hrespectively, and better cost saving.

Keywords: pinch technology, maximum energy recovery/minimum energy requirement (MER), minimum approach temperature difference (ΔT_{min}), tradeoff (optimumΔT_{min}), composite curves (CCs) and grand composite curves (GCC).

I. INTRODUCTION

Most petroleum refineries and petrochemical companies consumed significant amount of energy. This has been an issue of great concern in most chemical processing industry (Robin, 2009). Because the plants were built during the era of cheap energy using traditional design energy (TDE) methods such as mass and energy balances, rules of thumb, good engineering judgment and creative ability of the designers which are not economical. Nowadays, with increased in energy cost, the plants cannot operate optimally (Linnhoff et al., 1982). Kaduna refinery and petrochemical company (KRPC) as well as other refineries in Nigeria were also built using those concept without recourse to energy efficiency. Thus, leading to substantial amount of fuel consumption, emission of CO_2 to the environment and high operating cost. This raises serious concerned toward a better process design known as Process Integration.

Process Integration is a fairly new term that emerged in the 80's and has been extensively used in the 90's to describe certain Systems oriented activities related primarily to Process Design. Integration of any process is all about saving energy, minimizing resources consumption towards achieving better economy. This is the main target of any industrial process (Khorshidi et al., 2016). Many effort have been made in the past to define process integration. Raskovic (2007) unveiled that describing the fundamental principles behind PI is a difficult task. However, El-Halwagi (1997) revealed that PI is a holistic approach to process design, retrofitting, and operation of industrial plants, with applications focused on resource conservation, pollution prevention and energy management. Also Friedler (2010) sees it as a family of methodologies for combining several processes to reduce consumption of resources or harmful emissions to the environment. The most complete definition of PI was given by International Energy Agency (IEA) which considered it to a systematic and general methods for designing integrated production systems, ranging from individual processes to total sites, with special emphasis on the efficient use of energy and reducing environmental effects (IEA, 2007). This comprises several techniques that allow engineers to evaluate the entire processes or sites rather than focusing on individual unit operation (Rossister, 2010).

Among the techniques of process integration, pinch technology is the most widely used methods in industries. This is because of its simplicity, physical insight and achievement recorded in the past project around the globe. Hence, it is considered as industrial favorites. Multinational Oil Companies, such as Shell, Exxon, and BP-Amoco, etc. unveiled that this technique achieved fuel savings of about 25% and similar emissions reductions that worth millions of dollars per year. Pinch technology was introduced by Linnhoff in 1979 as a methodology that guarantee minimum energy levels in HENs design (Linnhoff et al., 1982). It is a systematic approach based on thermodynamic principles to achieve utility savings by better process heat integration, maximizing heat recovery and reducing the external utility loads (cooling water and heating steam). Therefore, Pinch Design Method (PDM) leads to maximum energy recovery (MER), minimum utilities requirement, and achieving optimum HEN design.

The robustness of this method can be seen in the works Bumbac and Ud-din (2015), Rezaei et al. (2013), Ulyev et al. (2018), Li et al. (2019), Al-Mutairi and Babaqi (2014), and Ajao and Akande (2009) in which significant amount of energy was recovered in their work, thus leading to economical design. It also shows a remarkable success in fluid catalytic cracking unit (FCCU) in the study conducted by Al-Riyami et al. (2001). It further achieved better energy recovery in power sector and food industry as reported in the works of Girei et al. (2013) and Klemes et al. (1999) respectively. Therefore, pinch technology is applicable to every process that requires heating and cooling for improving energy efficiency of industrial process.

Several literatures were reviewed extensively on pinch analysis, it was gathered that, most of the research works were on CDU with a very limited work on VDU of the KRPC. The only research on energy integration of VDU of the refinery was conducted by Adejoh et al. (2013) using Maple software where optimum ΔT_{min} of 10 ^{o}C was obtained which led to minimum heating and cooling utilities requirement of 0.24 MW and 0.19 MW respectively. According to Linnhoff, the standard values of optimum ΔT_{min} for VDU of a refinery ranges from 20 ^{o}C to 40 ^{o}C. A value of optimum ΔT_{min} for VDU that is below or above this specified ranges will leads to high cost. Therefore, the needs arise to revisit the unit under study with a view of checkmating the study conducted by the previous author using maple software. The novel contribution of this study is to evaluate the trade-offs between energy and capital cost, and the utilities consumptions of the unit via Aspen energy analyzer (AEA) package. Because the AEA software had achieved remarkable success in several studies. This can be attest in the work of Bayome et al. (2019) and Li et al. (2019).

II. MATERIAL AND METHODS

Material

The Material used for the analysis includes: Process Flow Diagram (PFD) of the unit, operating data, laboratory data, Aspen HYSYS, Aspen Energy Analyzer (AEA), and Microsoft Excel.

Methods

The method used for assessing the minimum utilities requirement of the unit can be summarize into five (5) stages as shown in figure 1.

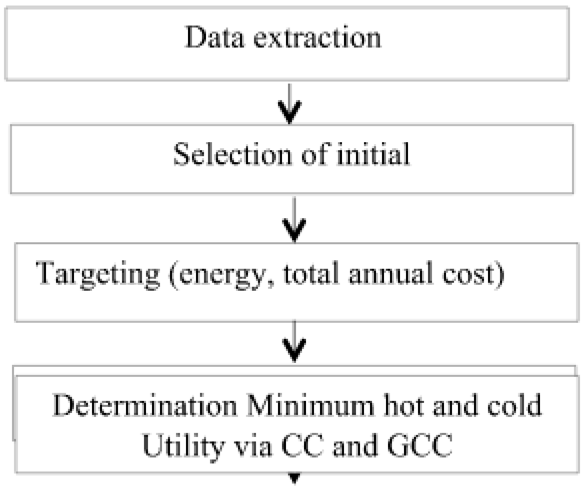

Figure 1 Steps for Pinch Design Method (PDM)

Data Extraction

This is the first step of the analysis. It involves extraction of thermodynamic data from the PFD of the unit. This process led to the specification of 4 hot and 4 cold streams with each stream having supply and target temperatures, heat capacity flow rate, and estimated heat duty as shown in Table 1

Table 1 Extracted Data from the PFD

Streams ID	T_s(°C)	T_t(°C)	T_s^*(°C)	T_s^*(°C)	CP (10^6 KJ/h°C)	ΔH (10^6 KJ/h)
Cold 1	287.6	289	292.6	294	32.84	45.97
Cold 2	151	293	156	298	0.323	45.97
Cold 3	289	306	294	311	0.261	4.44
Cold 4	293	309	298	314	0.278	4.44
Hot 1	309	175	304	170	0.258	34.62
Hot 2	309	210	304	205	0.350	34.62
Hot 3	354	306	349	301	0.087	4.19
Hot 4	354	309	349	304	0.093	4.19

Energy Targets

Energy targets of the unit was carried out immediately after the data extraction have been extracted and the initial ΔT_{min} was selected. This involves the determination of minimum hot and cold utilities requirement via composite curves (CCs) and grand composites curves (GCC). The composite curves is a graph of streams temperatures (°C) against enthalpies (KJ/h) of the streams. It comprises the hot and cold composite curves. Also, the GCC is a plot of shifted temperature of the streams versus its enthalpies. The enthalpy change and the shifted temperatures were obtained via equation 1 and 2 respectively.

$$\Delta H = Q = CP(T_t - T_s) \quad 1$$

Where ΔH = Enthalpy change, Q = quantity of heat required, T_t = Target temperature, T_s= supply temperature and CP = heat capacity flow rate.

$$T^*_{hot\ stream} = T_{hot\ stream} - \frac{\Delta T_{min}}{2} \quad 2a$$

$$T^*_{cold\ stream} = T_{cold\ stream} + \frac{\Delta T_{min}}{2} \quad 2b$$

Where $T^*_{hot\ stream}$ = Shifted hot streams temperature, $T^*_{cold\ stream}$ = Shifted cold steams temperature, $T_{hot\ stream}$ = hot streams temperature, $T_{cold\ stream}$ = cold steams temperature and ΔT_{min} = Minimum temperature approach which was selected to be 10 °C.

Operating Cost (OC)

The operating cost is a function of utilities demands and the cost of the utilities as presented in equation 2. It was determined immediately after obtaining the minimum hot and cold utilities requirement and if the cost of these utilities were defined as shown in Table 2.

$$OC = (HU \times Cost\ of\ heating) + (CU \times Cost\ of\ cooling) \quad 2$$

Where; HU = Hot utility and CU = Cool utility

Table 2 Cost data

Utilities	Type	Amount ($/KJ)
Air coolant	Cooling	1.0×10^{-9}
HP steam	Heating	2.750×10^{-6}

Capital Cost (CC)

The capital cost of a Heat Exchanger Network (HEN) is expressed a functions of number of unit, shells and area of heat transfer as shown in equation 3. These parameters were obtained in the AEA software. A useful life period of 5 years at an annual interest rate of 10 % and plant operating time of 8765.76 h/year was used in this study (Aspen Energy Analyzer V8.8, 2015).

$$CC = a(no.of\ unit\ for\ MER) + b\left({Area}/{Shells}\right)^{C*Shells} \quad 3$$

Where A= area; a, b, and c, are cost law constants that vary from materials of constructions, pressure rating and types of exchanger.

$$TAC = OC + CC \quad 4$$

Capital- Energy Trade-off Targeting

The driving force (ΔTmin) has influenced on both costs (operating and capital cost). As the ΔTmin increases, the utilities requirement also increases, thus increasing the operating cost but the capital cost decreases due to decrease in area of heat transfer. Conversely, a decrease in ΔTmin will decrease the operating cost but increase the capital cost as shown in figure 2. Hence, resulting to uneconomical HEN design. Therefore, determination of optimum ΔTmin is necessary for cost effective design of HEN. This is obtained by plotting a graph of total annual cost (TAC) against ΔTmin. The value of the driving force that corresponds to lowest TAC value is the optimum ΔTmin. In this study, the optimum ΔT_{min} is 25 ^oC which corresponds to the lowest TAC value of $1.662 \times 10^6\ \$/year$. This value is inconformity with the optimum value of ΔTmin for VDU of a refinery processes which was predicted in the range of 20 to 40 ^oC by Linnhoff and Hindmarsh (1983). As it can be seen in figure 4, when the ΔT_{min} is set at 25 ^oC, the desired economic trade-off between capital and energy cost can be achieved. A further increase in ΔT_{min} would lead to decrease in capital cost. On the other hand, decreasing the value of ΔT_{min} below the trade-off would cause an increase in capital cost whereas the energy cost decreases.

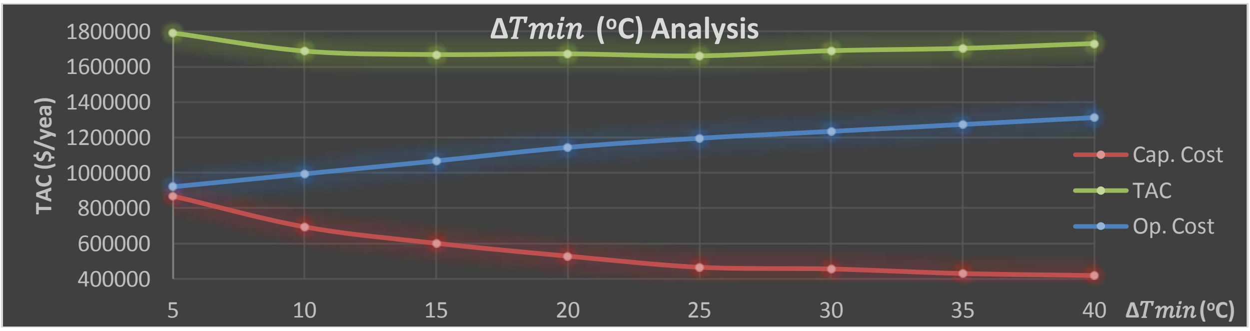

Figure 2 Capital-Energy Trade-off (Optimum ΔTmin)

III. EVALUATION OF RESULTS

The CCs presents the results of the energy consumption of the unit. It showed that the minimum hot and cold utilities requirement at the initial ΔT_{min} (10 ^oC) are $4.126 \times 10^7 kj/h$ and $1.808 \times 10^7 kj/h$ respectively as shown in figure 3. Also, the hot and cold pinch temperatures are 297.6 ^oC and 287.6 ^oC.

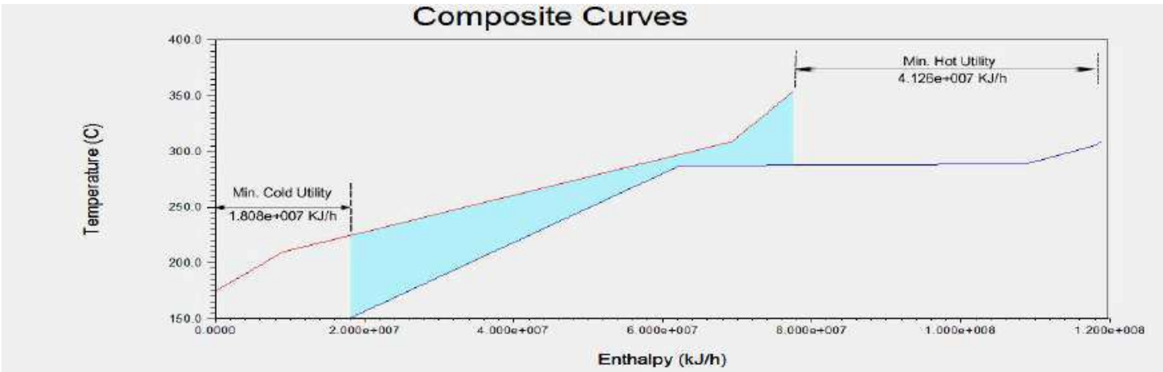

Figure 3 Composite curves at initial $\Delta T_{min} = 10\ ^oC$

At the optimumΔTmin, the minimum heating and cooling utilities requirement are $4.962 \times 10^7 kj/h$ and $2.644 \times 10^7 kj/h$ respectively as shown in figure 4. This shows that the hot and cold utilities have increased as the driving force (ΔTmin) increases from 10 ^oC to 25 ^oC. Because the area of the heat transfer decreases. Hence, increasing the pinch point to 296.5 ^oC and the hot and cold pinch temperatures to 309 ^oC and 284 ^oC respectively.

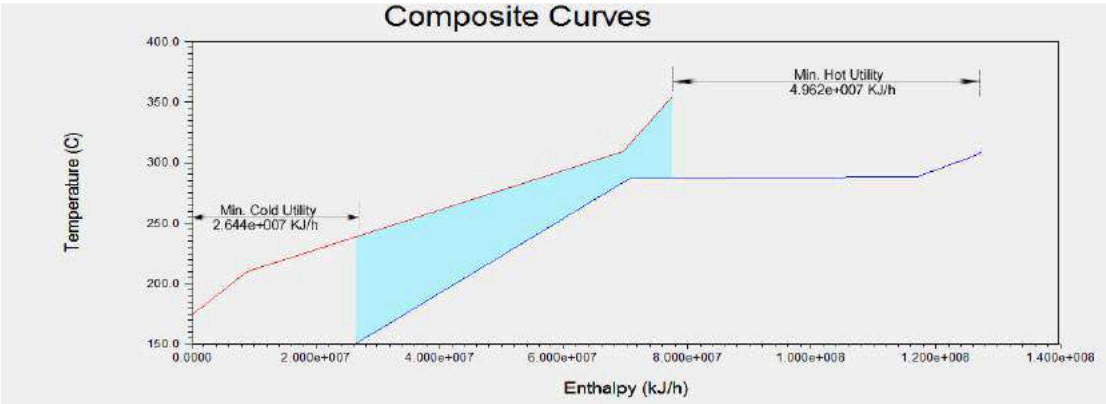

Figure 4 Composite Curves at Optimum ΔT_{min}

The overall results of the PA at the initial value of ΔT_{min} is presented in figure 5. It present the results of the targeting in terms of energy, number of unit, shells, area and cost. These parameters determined the TAC target which is 1.690×10^6 $/year.

Energy Targets	
Heating [kJ/h]	4.126e+007
Cooling [kJ/h]	1.808e+007

Number of Units Targets	
Total Minimum	9
Minimum for MER	11
Shells	27

Area Targets	
Counter Current [m2]	7100
1-2 Shell & Tube [m2]	7976

Cost Index Targets	
Capital [Cost]	2.155e+006
Operating [Cost/year]	9.948e+005
Total Annual [Cost/year]	1.690e+006

Pinch Temperatures	
Hot	Cold
297.6 C	287.6 C

Figure 5 Results Extracted from AEA for PA at $\Delta T_{min} = 10\ ^oC$

As the ΔT_{min} changes from its initial value of 10 ^{o}C to its optimum value of 25 ^{o}C, the TAC decreased to 1.663×10^6 $/year as shown in figure 6. This is because the capital cost has reduced as a result of decreased in number of unit from 11 to 10, decreased in number of shells from 27 to 20 and decreased in area from 7976 m^2 to 5099 m^2. The parameters have great impact on the capital cost, since they are all functions of the capital. Thus, decreasing the capital cost and the TAC.

Energy Targets	
Heating [kJ/h]	4.962e+007
Cooling [kJ/h]	2.644e+007

Number of Units Targets	
Total Minimum	9
Minimum for MER	10
Shells	20

Area Targets	
Counter Current [m2]	4602
1-2 Shell & Tube [m2]	5099

Cost Index Targets	
Capital [Cost]	1.447e+006
Operating [Cost/year]	1.196e+006
Total Annual [Cost/year]	1.663e+006

Pinch Temperatures	
Hot	Cold
309.0 C	284.0 C

Figure 6 Results Extracted from AEA for PA at $\Delta T_{min} = 25\ ^oC$

In addition to the determination of utilities requirement, the GCC enables the selection of the most appropriate utilities that will satisfy the process conditions. It also specifies the temperature intervals and the amount of the utilities to be used at a particular temperature interval. In this study, the HP steam was applied at temperature ranges from 355 ^{o}C to 354 ^{o}C and the air coolant was used at temperature ranges from 151 ^{o}C to 130 ^{o}C as shown in figure 7. This satisfied the process condition and achieved the target.

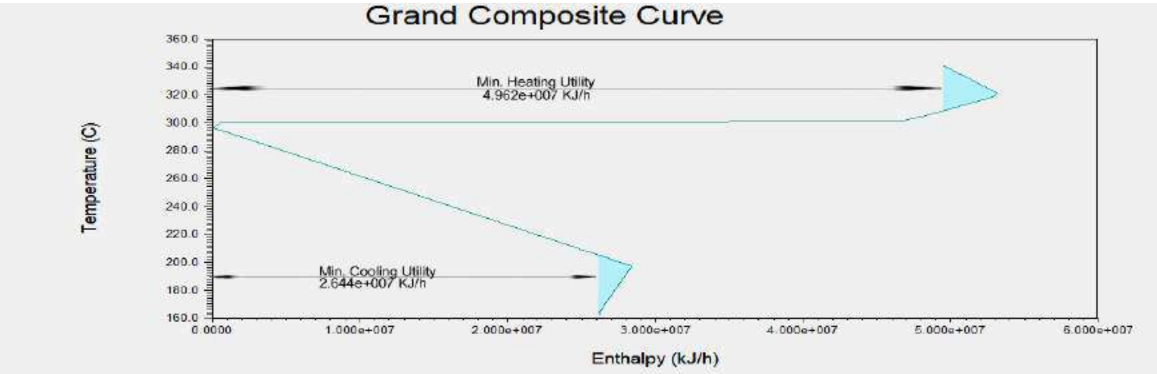

Figure 7 GCC at optimum $\Delta T_{min} = 25\,^oC$

Table 3 Utilities Requirement of the unit via PDM and TDE

	PDM at $\Delta \mathbf{T_{min}} = \mathbf{25\,^oC}$	TDE
Hot Utility Demand ($\mathbf{10^6}$KJ/h)	49.62	77.62
Cold Utility Demand ($\mathbf{10^6}$KJ/h)	26.44	100.82

Table 3 revealed that instead utilizing huge amount of hot and cold utilities of 7.76×10^7 KJ/h and 10.08×10^7 KJ/h respectively to satisfy the process via TDE method, minimum amount of hot and cold utilities of 4.96×10^7 KJ/h and 2.64×10^7 KJ/h were used via the PDM hence, satisfying the process requirement. Thus, saving 2.8×10^7 KJ/h of hot utility and 7.44×10^7 KJ/h of cold utility.

IV. CONCLUSION

Pinch Technology was adopted in this study to assess the energy requirement of the unit studied as the unit was built using TDE method which leads to significant consumption of energy, thus causing high operating cost and uneconomical HEN design. Therefore, it can be deduced that, theoptimum ΔT_{min} (tradeoff) result to lowest TAC (1.69×10^6 $/year$). Hence,saving 27, 000 \$/year over the initial$\Delta T_{min.}$ The pinch method utilized minimum amount of hot and cold utilities which reduces the operating cost. Hence, leading to cost effective HEN design.

Future work

HENs of the unit studied should be design based on the optimum ΔT_{min} value of 25 ^oC obtained.

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Nomenclature

VDU	Vacuum Distillation Unit
HEN	Heat Exchanger Network
KRPC	Kaduna Refinery and Petrochemical Company
ΔT_{min}	Minimum Temperature Difference (^oC)
TAC	Total Annual Cost ($/year)
CDU	Crude Distillation Unit
PFD	Process Flow Diagram
MER	Maximum Energy Recovery Design/ Minimum Energy Requirement (KJ/h)
AEA	Aspen Energy Analyzer
PT	Pinch Technology
PDM	Pinch Design Method
TDE	Traditional Design Energy
GCC	Grand Composite Curves
CCs	Composite Curves
OC	Operating Cost
CC	Capital Cost
T_s	Supply Temperature (^oC)
T_t	Target Temperature (^oC)
$\boldsymbol{T_s^*}$	Shifted Supply Temperature (^oC)
$\boldsymbol{T_t^*}$	Shifted Target Temperature (^oC)
CP	Heat Capacity Flow rate (KJ/h^{o}C)
ΔH	Enthalpy Change (KJ/h)
HP steam	High Pressure Steam
FCCU	Fluid Catalytic Cracking Unit

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