American Journal of Engineering Research (AJER)
e-ISSN : 2320-0847 p-ISSN : 2320-0936
Volume-02, Issue-05, pp-11-18
www.ajer.us

Research Paper Open Access

Heat Exchanger Network Retrofit Design by Eliminating Cross Pinch Heat Exchangers

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***Abstracts*:** The rising cost of energy and environmental concerns are leading the petrochemical industry to search for methods of reducing energy consumption in refinery operations. To address this issue the research presented in this paper explores retrofit design for increasing the energy efficiency of Crude Distillation Units (CDUs). The case study presented uses monitored plant data from the preheat section of the CDU in a Refinery in the Niger Delta region of Nigeria, West Africa. Aspen Energy Analyser® software developed by Aspen Technologies is used in the analysis of this data. The research findings suggest that a retrofit design eliminating all cross pinch heat exchangers is the best retrofit design in terms of improving the energy performance of CDUs. There was an 84.62% and 92.31% reduction in the number of the heat exchangers used and the number of shells respectively. There were 16.57%, 2.74%, and 13.98% reductions in the operating cost, capital cost, and total cost respectively. 3.68% of the area became available for heat transfer. These gains were achieved despite a 12.27% increase in the heating demand. This design is therefore recommended to be applied after additional cost consideration.

Keywords: *Aspen Energy Analyser®, Cross Pinch Heat Exchangers, Heat Exchanger Network, Retrofitting.*

I. INTRODUCTION

Retrofitting heat exchanger networks falls under the broad category of research known as process integration. Process integration started as heat integration. Interest in which initially arose due to energy crisis in the 1970's. Process integration now includes several methods of combining processes to reduce the consumption of energy or other resources or harmful emissions to the environment [1]. The beginning of research in process integration is traced to Hohmann [2]. However, Hohmann's research was not pursued until Linnhoff and Flower developed Hohmann's work and in 1977 developed Pinch technology – the technique on which most heat integration applications are performed today [1, 3]. In a comprehensive review of the subject matter from 1975 – 2008, Morar & Agachi [3] identified Linnhoff, Floudas, Grossmann, Morari, Yee, Ciric, Saboo, Mathisen, Asante, Smith, Aguilera, and Marcheti as the most significant contributors to heat integration research. This is because their works signifies a turning point in the heat integration research field – with them came the introduction of pinch technology, mathematical programming techniques, and insights into the dynamic behaviour of heat exchanger networks. Also, their works are mostly cited by other researchers in the field as they extend, improve and make practical application of their research. A review of the literature shows that the heat exchanger retrofitting problem could be solved using either of or a combination of the following techniques: Pinch analysis technique [4, 5, 6, 7, 8]; Mathematical Programming Technique [9, 10, 11, 12]; Combination of Pinch analysis & Mathematical programming technique [13, 14]; Simulated Annealing and Genetic Algorithm technique [15, 16, 17, 18, 19, 20, 21]; and Path analysis technique [22]. The reader may consult the cited authors for a full discussion of these techniques. This research uses monitored plant data from the preheat section of the Crude Distillation Unit (CDU) of a Refinery to demonstrate that a retrofit design eliminating all cross pinch heat exchangers is the best retrofit design for a heat exchanger network with gross pinch rule violation. The case study was taken from a refinery in the Niger Delta region of Nigeria, West Africa, and as pointed out by Ajao and Akande [23], almost all industrial equipment stock in Nigeria were imported during the era of cheap energy, hence they are energy inefficient. True to this statement, serious pinch rule violations were noticed during the analysis. Aspen Energy Analyser® of Aspen Technologies Limited was used for the analysis. The software combines pinch technology and mathematical programming to provide an automatic retrofit design for heat exchanger networks. Retrofitting was recommended after the analysis of the heat exchanger network. The retrofit design eliminates cross pinch heat exchangers.

II. MATERIALS AND METHODS

A. Process mapping

The study is mainly concerned with the preheat section of the Crude Distillation Unit (CDU) of a refinery in Port Harcourt Nigeria. The heat exchangers and process streams involved in crude preheating as the crude flows from storage to the distillation column are shown in Fig. 1. The process consists of 11 streams – 3 cold streams and 8 hot process streams. The cold streams are heated by 24 heat exchangers from a temperature of about 29.9^{O}C to 344^{O}C before it enters the distillation column where the components are separated. The cold streams include the crude from storage stream, the desalted crude stream, and the pre-flashed crude stream. 8 hot process streams are used to preheat the cold streams, these includes atmospheric residue, stripped kerosene, stripped Light Diesel Oil (LDO), stripped Heavy Diesel Oil (HDO), Heavy Vacuum Gas Oil (HVGO), and the 3 Pump Around streams – Top Pump Around, Kerosene Pump Around, and LDO Pump Around [24].

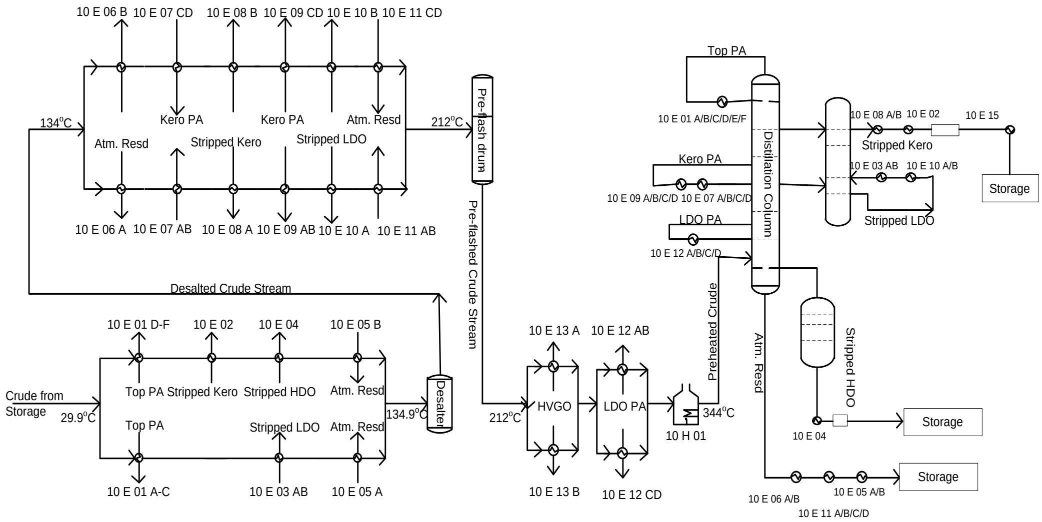

Fig. 1: rocess Map [24]

Table 1 and 2 show the process stream and utility stream data obtained from the process flow diagram and operating data of the Crude Distillation Unit obtained from the refinery.

Table 1 Extracted Process Streams Data [24]

Process Stream Data						
Name	Inlet Temp (^{O}C)	Outlet Temp (^{O}C)	Density (Kg/m^3)	Flow rate M^3/hr	Flow Rate Kg/H	Specific Heat Capacity (Kcal/Kg^{O}C)
Top Pump Around	152.4	96.7	788	747	588636	0.5919
Kerosene Pump Around	226.3	184	833	451	375683	0.6413
	184	154.9	833	451	375683	0.6038
LDO Pump Around	278.7	233.6	858	152	130416	0.6777
Stripped Kerosene	227.9	168	828	96	79488	0.6447
	168	35.6	828	96	79488	0.5913
Stripped LDO	280	207	863	158	136354	0.6769
	207	38.9	863	158	136354	0.6132
Stripped HDO	316	65.6	898	18	16164	0.6943
Atmospheric Residue	328	204	944	150	141600	0.6872
	204	164	944	150	141600	0.5838
	164	95.4	944	150	141600	0.5505
HVGO	241	222	927	10	9270	0.6203
Crude from Storage	29.9	134.9	841	310	260710	0.4648
Desalted Crude	134	212	841	306	257346	0.5567
Pre-flashed Crude	212	344	841	529	444889	0.6256

Table 2 Utility Streams Data [24]

Utility Stream Data					
Name	Inlet Temp (°C)	Outlet Temp (°C)	Heat Transfer Coeff. (Kj/hm² °C)	Flow Rate Kg/H	Specific Heat Capacity (Kcal/Kg°C)
Air	25	30	399.60	43074232.05	0.5919
Cooling Water	20	25	13500.00	84786.75	0.6777
Fuel Oil	400	350	720.00	479529.21	0.6256

The basic information needed for the simulation includes the inlet and outlet temperature of the process and utility streams, and the enthalpy or heat capacity value of the streams. The data was extracted correctly taking into consideration basic data extraction principles such as – avoiding mixing of the streams at different temperatures; extracting streams on the safe side; segmenting streams with varying enthalpies; and not extracting true utility streams that can be replaced by other streams [25]. The specific heat capacity of petroleum products were calculated using the empirical formula:

$$C_p = \frac{1}{\sqrt{d}}[0.402 + 0.00081t] \tag{1}$$

where d is the specific gravity of the petroleum product at $15°C$, t is the temperature in $°C$, and C_p is the specific heat $(Kcal/Kg°C)$.

The extracted data was later imputed into Aspen Energy Analyser® for the analysis of the design and retrofitting of the existing design.

B. Heat Exchanger Network Analysis

The heat exchanger network is represented using a grid diagram as shown in Fig. 2. In order to avoid the error of solving the wrong problem, care was taken to represent the heat exchanger network as it appears on the case studies' process flow diagram as shown in Fig. 1. The heat exchangers network was fully solved with all process streams satisfied. This is necessary to enter the retrofit design mode of the simulation software.

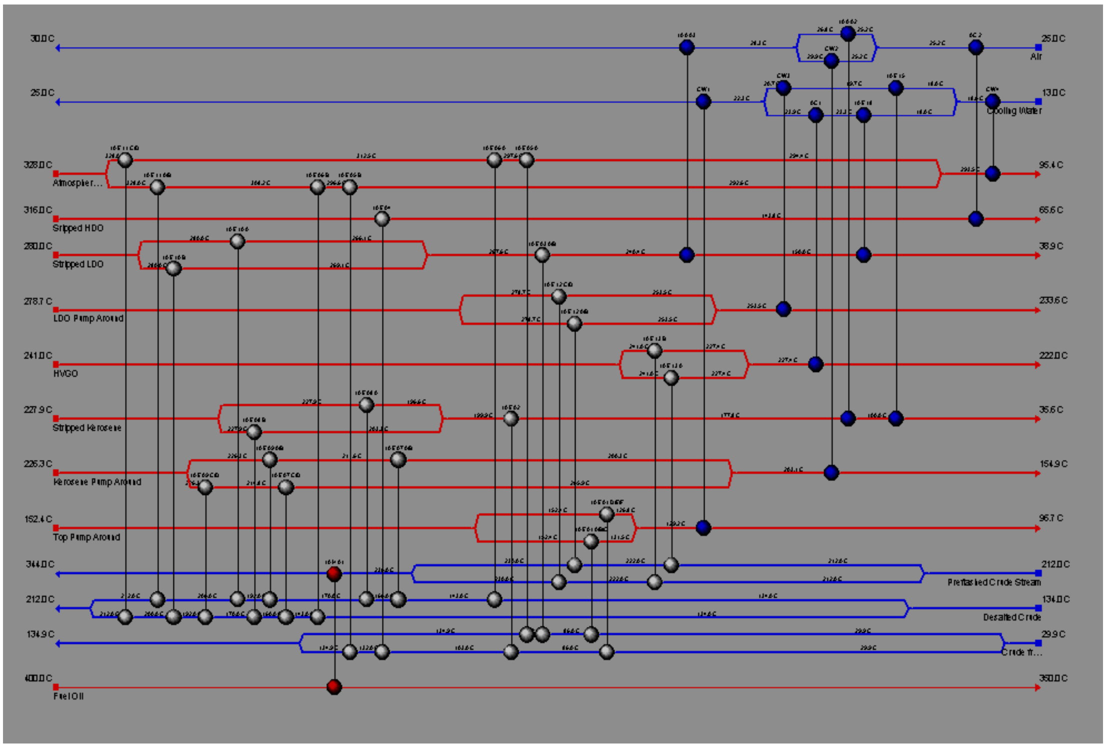

Fig. 2 Grid Diagram Representations of the Heat Exchangers

The analysis of the heat exchanger network determines the targets - energy requirement, area requirement, Pinch temperature, number of design units, and the cost index targets - based on the imputed process and utility stream data. The targets were generated based on the composite curves and minimum approach temperature, ΔT_{min}. Targeting provides the optimal operating condition for an ideal heat exchanger network based on the imputed process and utility streams. The range targeting feature of the software was used to determine the optimal minimum approach temperature ΔT_{min} for the design. The minimum approach temperature provided a balance between the capital and operating costs. Figs. 3 and 4 show the composite and grand composite curves used for energy and utility targeting, while Table 3 shows the generated targets.

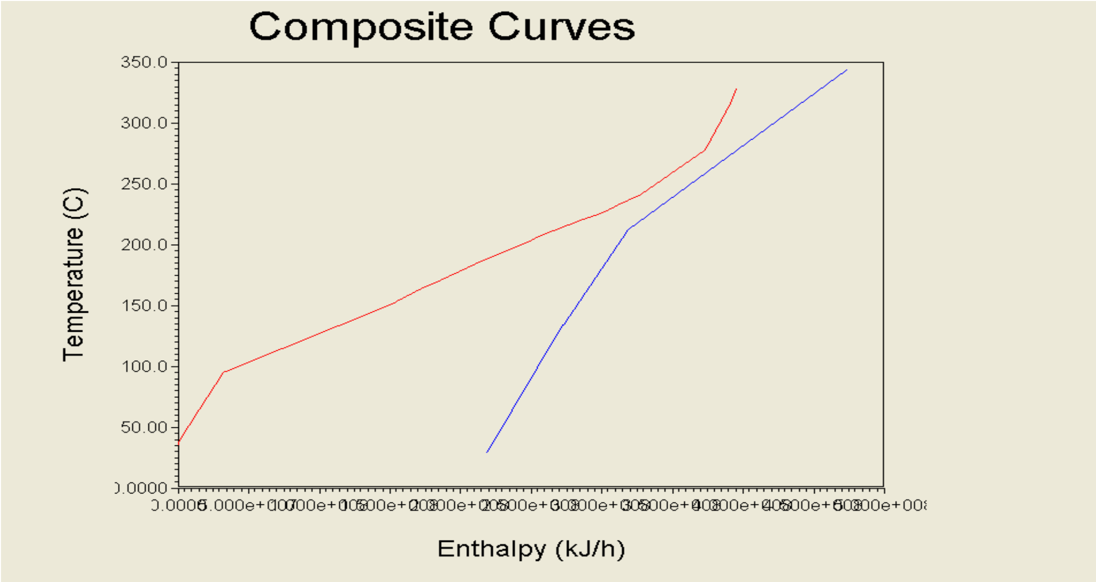

Fig. 3 Composite Curve showing Temperature – Enthalpy Relationship

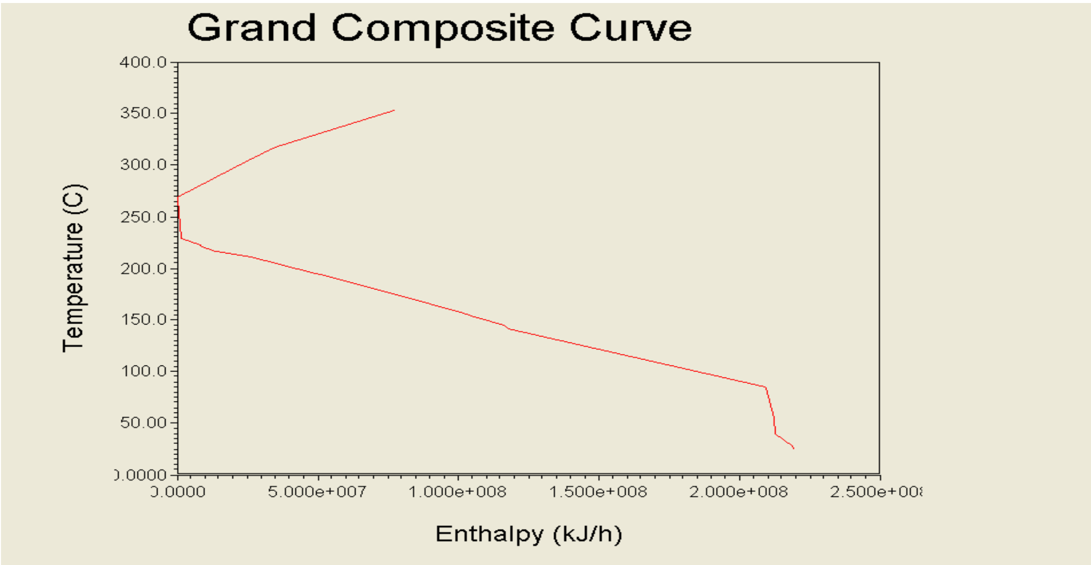

Fig. 4 Grand Composite Curve used for Utility Targeting

Table 3 Targets based on the Case Study Data

Target Summary		
Energy Target (Kj/h)	**Area Target (m^2)**	**Pinch Temp**
Heating $7.759*10^7$ Cooling $2.196*10^8$	Counter Current $2.601*10^4$ 1-2 Shell & Tube $3.223*10^4$	Hot Cold 278.7 258.2 45.5 25.0
Number of Units	**Cost Index Targets**	
Total Minimum 13 Minimum MER 4 Shells 26	Capital (Cost) $7.759*10^7$ Operating (cost/s) 0.2581 Total Annual (cost/s) 0.3187	

The energy targets are calculated using composite curves. The composite curve provides a counter current picture of heat transfer, and can be used to determine the minimum energy target for the process. From Table 3 the energy target for the process is $7.759*10^7$ Kj/h and $2.196*10^7$ Kj/h for the heating and cooling respectively, while the area target is $3.223*10^4$ m^2 for the shell and tube heat exchanger.

The calculation also show that a minimum of 13 units is required to build the heat exchanger network, but from the process flow diagram about 24 process to process heat exchangers are used in the network showing that the network is above the unit targets. The cost index targets are based on Aspen Energy Analyser® default cost and economic parameters, since cost and operations information could not be obtained for the case study.

III. RESULTS AND DISCUSSION

A Heat Exchanger Network Performance

The heat exchanger network performance was evaluated based on the targets in Table 3. The comparison of the targets and the performance of the heat exchanger network are depicted in Table 5. It can be seen that the heat exchanger performance differs greatly from the target values.

Table 5 Heat Exchanger Network Performance Data

Network Performance				
Parameter	Network Value	Target Value	Deviation	% Deviation
Heating Value (KJ/h)	$1.328*10^8$	$7.759*10^7$	$5.521*10^7$	71.15
Cooling Value (KJ/h)	$2.748*10^8$	$2.196*10^8$	$5.52*10^7$	25.14
Number of Units	24	13	11	84.62
Number of Shells	50	26	24	92.31
Total Area (m^2)	$1.735*10^4$	$3.223*10^4$	$-1.488*10^4$	-46.17

The heating and cooling value are above the target by 71.15% and 25.14% respectively. This is due to gross pinch rule violation as shown in the cross-pinch heat exchangers of Table 4. The consequence of a cross-pinch heat transfer is that both the cold and hot utility will increase by the cross-pinch duty. This results in an increase in the heat exchanger network size beyond the target [4, 24]. For the $278.70^{O}C/258.20^{O}C$ pinch temperature, there is cross pinch load of $5.517*10^7$ KJ/h, while for the $45.5^{O}C/25^{O}C$ pinch temperature, the cross pinch load is $1.717*10^8$ KJ/h.

Table 4 Cross Pinch Table

HEN Design Cross Pinch		
Heat Exchanger	278.70/ 258.20	45.50/25.00
E-249 (KJ/h)	$3.284*10^7$	
10 E 11 A-D (KJ/h)	$7.193*10^6$	
10 E 18 A/B	$6.013*10^6$	$7.263*10^7$
10 E 06 A/B (KJ/h)	$5.395*10^6$	
10 E 04 (KJ/h)	$1.752*10^6$	
E- 248 (KJ/h)	$1.470*10^6$	
10 E 10 A-B (KJ/h)	$5.020*10^5$	
10 E 16 (KJ/h)		$3.656*10^7$
CW 2 (KJ/h)		$4.675*10^6$
CW 1 (KJ/h)		$3.972*10^7$
CW 3 (KJ/h)		$7.361*10^6$
10 E 15 (KJ/h)		$1.072*10^7$
Total (KJ/h)	$5.517*10^7$	$1.717*10^8$

The number of heat exchanger units and number of shells is above the target value by 84.62% and 92.31% respectively. While the target value generated by the software suggest that at least 13 heat exchangers having 26 shells can be used to accomplish the crude heating demand, the network actually uses 24 heat exchangers having 50 shells. The network design however uses less area than the target area. While this is good, area optimisation is not enough. The equipment cost also needs to be optimised.

From the network performance it can be seen that the operational network design is far above target. The cross load is quite high supporting the fact that the heat exchanger network was designed during the cheap energy era. It also shows that pinch technology was not applied during the design of the heat exchanger network. Thus a retrofit is needed. This will help to eliminate the cross loads and optimise energy utilisation during crude preheating.

B Retrofit Design

To ensure that the software performs the retrofit efficiently, the following approach was used. The scope of the problem was reduced by minimising stream segmentation, and reducing the number of heat exchangers in the network. This simplifies the network and increases the efficiency of the model. The process to process heat exchangers were in pairs, in the retrofit design one of the two heat exchangers is used. This does not alter the design since one is always in use while the other is on standby. The simplified network design for retrofit purpose is shown in Fig. 5.

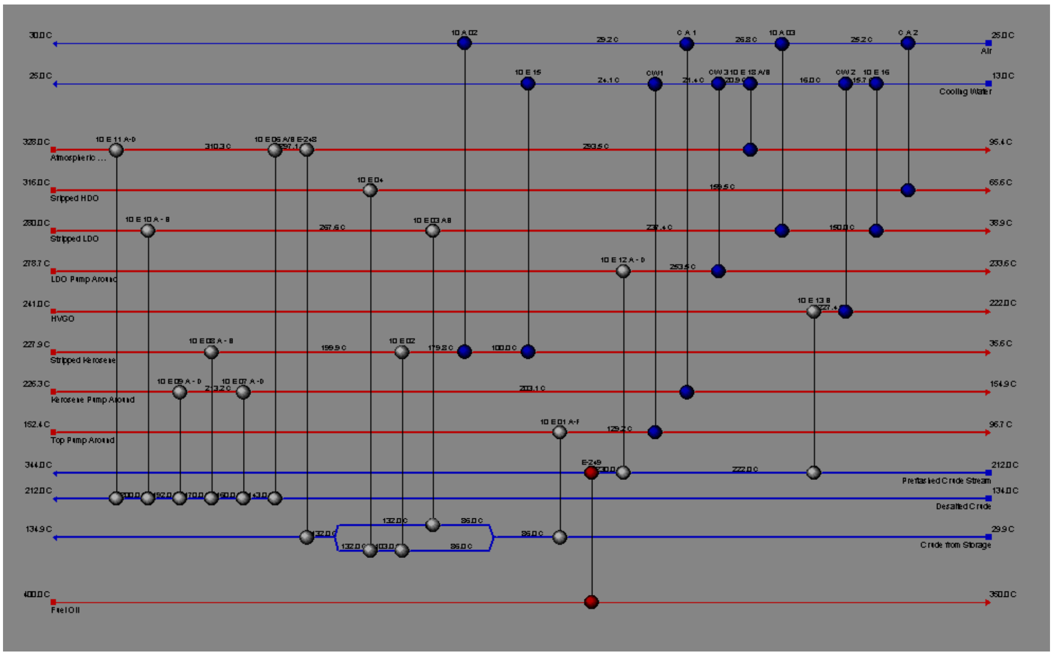

Fig. 5: Retrofit Design Grid Diagram

The retrofit design with no cross pinch violation is shown in Fig. 6. The same number of heat exchangers is used to accomplish the heating of the crude but some of the process stream temperatures are altered to avoid transferring heat across the pinch. The modifications made to the process streams to achieve this are shown in Piagbo [26]. Other retrofit designs such as modifying utility heat exchangers; re-sequencing heat exchangers; re-piping heat exchangers; addition of new heat exchangers; and addition of new area, did not provide an economically viable option as the design eliminating cross pinch heat exchangers [27]

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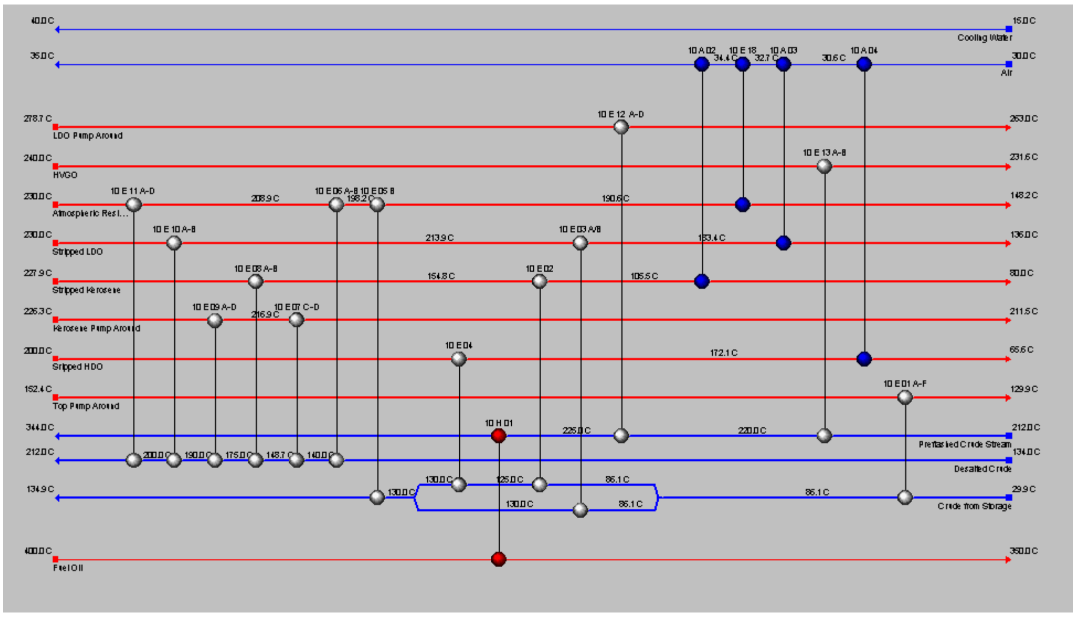

Fig. 6 Retrofit Designs Eliminating Cross Pinch Heat Exchangers

Table 6 Comparison of Retrofit Design Eliminating Cross Pinch Heat Exchangers with Base Case

Eliminating Cross Pinch Exchangers				
Network Cost Indexes				
Parameter	Retrofit Design	Base Case	Deviation	% Deviation
Heating (Cost/sec)	0.1313	0.1169	0.0144	12.32
Cooling (Cost/sec)	$3.887*10^2$	$8.709*10^2$	-482.2	-55.37
Operating (Cost/sec)	0.1702	0.2040	-0.0338	-16.57
Capital (Cost)	$4.554*10^6$	$4.682*10^6$	-128000	-2.74
Total Cost (Cost/sec)	0.2166	0.2518	-0.0352	-13.98
Network Performance				
Parameter	Retrofit Design	Base Case	Deviation	% Deviation
Heating Value (KJ/h)	$1.491*10^8$	$1.328*10^8$	$1.63*10^7$	12.27
Cooling Value (KJ/h)	$2.413*10^7$	$2.748*10^8$	$2.5067*10^8$	-91.22
Number of Units	18	24	-6	-25
Number of Shells	47	50	-3	-6
Total Area (m^2)	$1.805*10^4$	$1.735*10^4$	700	4.04

Table 6 compares the network cost indices and the network performance of the retrofit design eliminating all cross pinch exchangers and the original case study design. From the table, the value of the retrofit design eliminating all cross pinch exchangers is clearly seen. Despite the 12.3% increase in heating cost and heating value respectively, the retrofit design operates at about 14% reduced total cost compared with the case study design. There is significant reduction in the cooling cost and cooling duty by 55.37% and 91.22% respectively. The 18.97% reduction in the number of shells and 47.1% reduction in the number of exchanger units translate into a 16.57% and 2.74% reduction in operating cost and capital cost respectively. The 4.04% increase in total area of the retrofit design over the original design is understandable because pinch principle violation and misapplication of the driving force principle leads to reduced area in the network design [14].

The retrofit design ‘eliminating cross pinch exchangers’ provides huge energy and cost savings as can be seen in the reduction in cooling value, operating cost, capital cost and total cost. There is a 16.57% reduction in the operating cost. This confirms the fact that for HEN with gross cross pinch violation or misapplication of the ΔT_{min} driving force principle, providing a retrofit design that eliminates the cross pinch and proper application of the minimum driving force provides viable retrofitting option [4, 14, 25]. This design is promising, however, the cost implication involved in the modification of the process temperatures and areas of the heat exchanger network have to considered in implementing this design.

IV. CONCLUSION

Process integration has assumed an unusual dimension in process industries due to globalisation and the need for business concerns to remain economically viable in a stiff competitive economic environment. Process integration ensures that energy is conserved and properly utilised in the industry. Aspen Energy Analyser® software of Aspen Technologies was used for the retrofit operation. The software combines pinch technology and mathematical programming in providing automatic retrofit designs to existing heat exchanger networks. Besides retrofitting, the software also has capabilities for automatic heat exchanger network designs and simulation of individual heat exchangers. The analytical capability of the software was also useful in determining targets and minimum approach temperature requirement for a given set of process and utility data. The manually generated retrofit design which eliminates all cross pinch exchangers required some modification to the temperatures of the process streams to avoid violation of pinch principle and exchanging heat beyond the allowed minimum temperature requirement. The costs of these modifications need to be evaluated and compared with the operational cost savings to ascertain the economic viability of the design.

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