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A SYSTEMS DESIGN APPROACH FOR OVERCOMING HEAT EXCHANGER FOULING BOTTLENECKS – A STUDY ON A REFINERY PREHEAT TRAIN

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ABSTRACT

Process fouling and the penalties associated with it in petroleum refinery, particularly in the crude preheat train, have been the subject of extensive research over the last 30 years. Periodic cleaning and temperature drop due to fouling have resulted in productivity losses and increased energy consumption. A common approach to reduce cleaning downtime is the injection of effective antifoulants into crude oil stream. However, with the wide variation in crude oil composition and fouling mechanisms, the use of antifoulant alone can often be ineffective. Together with the use of antifoulant, a systems' design approach was proposed in this study to remove process bottlenecks due to heat exchanger fouling in a petroleum refinery preheat train. The method calls for retrofit by over-designing the non-fouled exchangers as opposed to the traditional practice of over-designing the fouled exchangers. Retrofit has managed to prevent drastic temperature drop due to severe heat exchanger fouling and also due to the removal of the fouled heat exchangers for cleaning. In addition, retrofit has enabled the plant authority to maintain the targeted nominal production rate throughout the year. The project can potentially result in a total savings of $0.6 million in utility costs and in productivity increase. Economic analysis shows that a reasonable pay back period of within two years for the retrofit is achievable; indicating that retrofit is technically and economically feasible.

INTRODUCTION

Heat exchanger fouling refers to the formation of deposits on heat transfer surfaces. Fouling impede the transfer of heat and increase the resistance to fluid flow (Bott, 1995; Somerscales and Knudsen, 1982). The growth of these deposits causes the thermal and hydrodynamic performance of heat transfer equipment to decline with time. The most serious heat exchanger fouling problem within oil refineries usually exist in the crude distillation unit (CDU) pre-heat train. About half of the financial penalties due to fouling in oil refineries are attributable to this unit in which all of the incoming crude oil is heated from ambient to elevated temperature in a network of shell and tube heat exchangers and furnaces (Van Nostrand *et al.*, 1981). Frequent cleaning of heat exchangers is to be avoided for several reasons. Cleaning of the hottest CDU preheat exchangers normally requires the unit to be shut down or the throughput to be reduced in the case where exchangers are in parallel banks. Heat exchanger cleaning may require a large maintenance effort and often lasts for several days for each exchanger.

A common approach to reduce cleaning downtime is the injection of effective antifoulants into crude oil stream before it enters the heat exchangers (Eyles and Wagner, 1978). However, with the wide variation in the crude oil composition and fouling mechanisms, proper control of an antifoulant program can be very difficult (Dickakian and Seay, 1988). Normally, antifoulants are added at a constant rate based on experience with enough antifoulant being added to reduce fouling to a tolerable level.

Together with the use of antifoulant, over-designing the fouled exchangers is commonly implemented to compensate for the fouling effects. However, putting additional heat transfer area on the fouled exchanger may increase the effect of fouling since a decrease in the fluid velocity tend to accelerate the fouling rate. Kotjabasakis and Linnhoff (1988) state that over-designing the fouled exchangers cannot effectively counteract the fouling problems. In this study, a technique which involves over-designing the non-fouled exchangers was implemented to overcome heat exchanger fouling bottlenecks in the preheat train of a refinery crude distillation unit (CDU). The main objective of retrofit is to find a cost effective solution in terms of energy and capital investment to overcome the fouling bottlenecks.

CASE STUDY DESCRIPTION

The relevant operation data for the plant shown in FIGURE 1 was acquired from an oil company in Malaysia. The plant under study has a nominal capacity of 100,000 Barrel Per Stream Day (BPSD). The crude oil is preheated to 130°C in the heat exchangers listed in TABLE 1 before entering the Desalter Unit (A-1101). After A-1101, the crude oil is further preheated to 234°C in the preheat exchangers listed in TABLE 2 before entering the Crude Preflash Drum (V-1101). In V-1101, the vapour generated is separated and routed to flash zone of the Crude Tower (C-1101).

The liquid crude from V-1101 is heated in the crude heater (F-1101) before entering the flash zone of C-1101. The crude feed is fractionated into

Atmospheric Gas Oil (AGO), Diesel Oil, Kerosene, Heavy Naphtha and Naphtha Lighters. C-1101 has four pump-arounds consisting of the top pump-around, Heavy Naphtha pump-around, diesel oil pump-around and AGO pump-around. Heat removal from C-1101 is accomplished by these four pump-arounds in such a manner that uniform vapour loadings exist throughout the column. These four pump-arounds are the main sources of recovered heat for the crude preheat train.

TABLE 1. Heat exchangers upstream of the desalter unit

Heat Exchangers	Hot Fluid
E-1101A/B	Top Pump-around
E-1102A/B	Cold Kerosene Product
E-1103A/B	Heavy Naphtha Pump-around
E-1104A/B/C/D	Cold Low Sulfur Wax Residual (LSWR)

TABLE 2. Heat exchangers downstream of the desalter unit

Heat Exchanger	Hot Fluid
E-1105A/D	Heavy Naphtha Pump-around
E-1106	Hot Kerosene Product
E-1107	AGO Product
E-1108A/D	Intermediate LSWR
E-1109	Diesel Pump-around
E-1110	AGO Pump-around
E-1111A/B	Hot LSWR

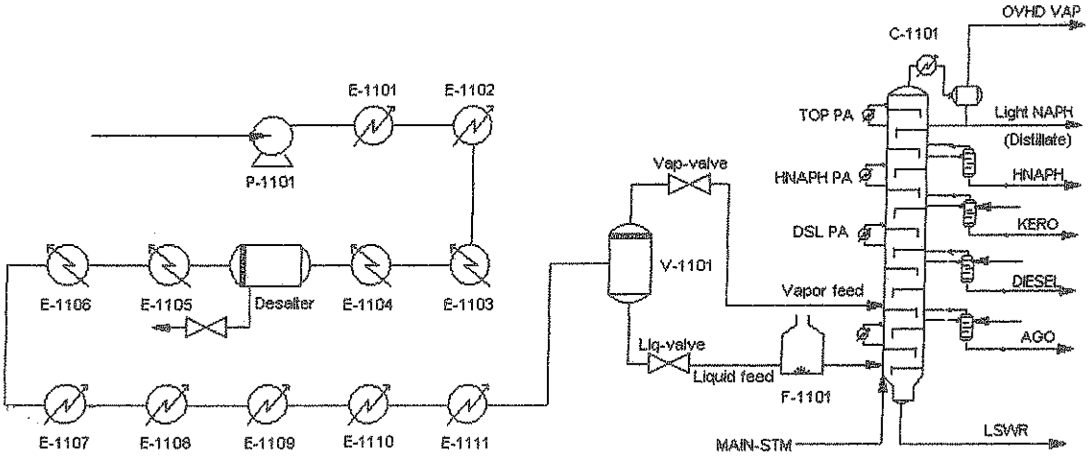

FIGURE 1. Process flow diagram of Crude Distillation Unit (CDU) and its preheat train

Current operation

Increased throughput into the preheat train and severe fouling problems on heat exchangers E-1102A/D and E-1103A/D causes the utility firing in the crude heater (F-1101) to increase. When both E-1102A/D and E-1103A/D of the existing plant were severely fouled, both heat exchangers were by-passed and cleaned simultaneously for 7 days. The production rate was decreased to as low as 80% of the design throughput in order to maintain column C-1101 inlet temperature and fractionation efficiency, and prevent a loss in the product quality. Decreased throughput resulted in a 25% productivity loss for a period of 7 days for every 10 months.

METHODOLOGY

The main objective for the retrofit study is to find a cost effective solution in terms of energy and capital investment to overcome fouling problems in the CDU preheat train. The proposed solution should allow the retrofitted plant to maintain its production rate throughout the year, while, at the same time, reduce the extra firing utility required in the crude heater (F-1101) as a result of fouling problems in the preheat train. The main challenge of this retrofit study is the unique feedstock and locations of fouled exchangers. For this refinery, fouling occurs before the Desalter Unit and not before the Crude Heater as is usually the case in other refineries.

The methodology for retrofit began with the base case steady-state process simulation of the existing CDU using ASPEN PLUS simulator (version 10.1). This was followed by the construction of a grid diagram (FIGURE 2) representing the heat exchanger network (HEN) for the entire crude preheat train. The grid diagram depicts the counter-current heat interchange between hot and cold process streams. Hot process streams are represented by arrowed lines shown from left to right (high temperature end to low temperature end) whereas cold process streams are shown from right to left.

The grid diagram enables a designer to analyse the interactions among heat exchangers along a "downstream path". FIGURE 2 shows the downstream paths through the fouling exchangers E-1102A/D and E-1103A/D. Note for example, that, any disturbance occurring in the KERO stream will propagate downstream and affect parameters across exchangers lying along downstream path 1. The affected exchangers include E-1106 (and all exchangers downstream E-1106), the fouling exchanger E-1102A/D, and the two coolers E-1119 and E-1120. Thus, it is possible to install additional area (over-design) on E-1106, E-1119 and E-1120 in order to compensate for the loss in heat transfer area when E-1102A/D is taken offline for cleaning.

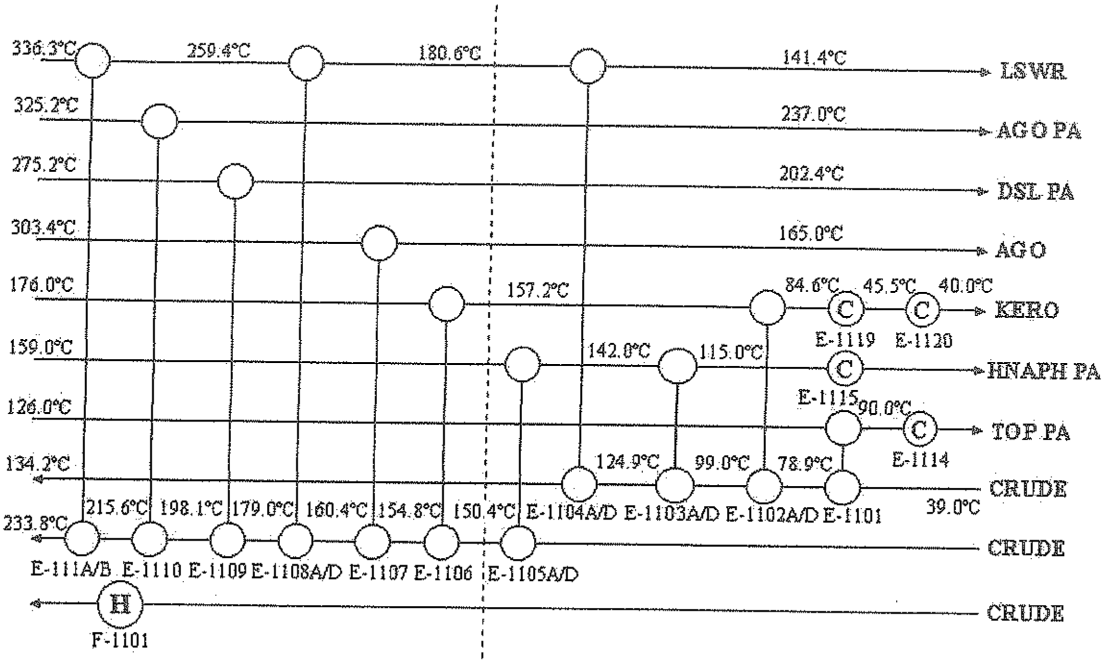

FIGURE 2. Grid diagram for preheat train to C-1101

Similarly, interactions of E-1105A/D and E-1115 with the fouling exchanger E-1103A/D can also be exploited to overcome the fouling bottlenecks. In order to prevent the drop in temperature due to fouling during both normal and cleaning operations, one may over-design the non-fouled or less fouled exchangers instead of over-designing the severely fouled E-1102A/D and E-1103A/D exchangers.

By carefully observing the interactions among the heat exchangers and by examining how a disturbance in the feed affects the parameters of the exchangers downstream the crude feed, we have proposed the following specific steps to overcome the problems due to E-1102A/D and E-1103A/D fouling:

1) *E-1102A/D and E-1103A/D should be cleaned one by one as opposed to simultaneously as practiced by the plant.* This has been suggested since both exchangers are the key exchangers in the crude preheat train that have significant effect on the operation. Cleaning both exchangers simultaneously will significantly reduce the heat exchange between process streams, drastically increasing the heater firing duty and ultimately the fuel consumption. In fact, for the plant under study, fouling has caused the firing duty to increase beyond the maximum heater capacity such that the plant production rate has to be reduced to 80% of the nominal throughput.
2) *Over-design E1106 to overcome fouling problems on E1102A/D (see Figure 3).* E1102A/D allows the excess heat from hot kerosene product (KERO) to be transferred to the crude feed stream (CRUDE). When E-1102 is removed for cleaning due to severe fouling, reduced heat transfer causes the

temperature of the hot kerosene product to be higher than its target temperature. Removal of E-1102A/D also prevents the crude feed from attaining the specified inlet temperature of the crude heater (F-1101). E-1106 has been chosen for over-design since it is the only non-fouling heat exchanger on the hot kerosene product stream that has an effect on the fouled exchanger, E1102.

3) *Over-design E1105A/D to overcome fouling problems on E1103A/D (see Figure 4).* The hot heavy naphtha pump around stream (HNAPH PA) supplies heat to the crude feed stream via E1103A/D. When E-1103A/D is removed for cleaning due to severe fouling, reduced heat transfer causes the temperature of heavy naphtha pump around to be higher than its target temperature. Removal of E-1103A/D also prevents the crude feed from attaining the specified inlet temperature of F-1101. E-1105A/D has been chosen for over-design since it is the only exchanger on the heavy naphtha pump around product stream that is less fouling and has an effect on the fouling exchanger, E1103A/D.
4) *Maintain E-1104, E-1107, E-1108A/D, E-1109, E-1110 and E-1111A/B.* These exchangers have been excluded as candidates for over-design since there are no coolers on the product streams downstream of these exchangers. The coolers are crucial to remove any extra heat when E-1102A/D or E-1103A/D is taken offline for cleaning. Besides, E-1104, E-1108 and E-1111 are also prone to fouling.
5) *Also maintain E-1101.* Over-designing E-1101 is also infeasible. Since E-1101 is not linked to the hot side of either E-1102A/D or E-1103A/D, clearly, over-designing E-1101 cannot solve the required cooling task of both hot kerosene and heavy naphtha pump around streams when E-1102A/D or E-1103A/D is removed.

In general, over-designing E-1105A/D and E-1106 are able to remove the fouling bottlenecks. The next task is to determine the additional heat transfer area required for both heat exchangers. **(Eq. 1)** is used to calculate the required heat transfer area for the heat exchangers to be over-designed based on the heat exchangers' specifications made available by the plant:

$$Q = UA\Delta T_{\mathrm{lm}} \tag{1}$$

where

$$\Delta T_{\mathrm{lm}} = \frac{\left[(T_1 - t_2) - (T_2 - t_1)\right]}{Ln\dfrac{(T_1 - t_2)}{(T_2 - t_1)}}$$

U = Overall heat transfer coefficient, W/m^{2}K
A = Area, m^2

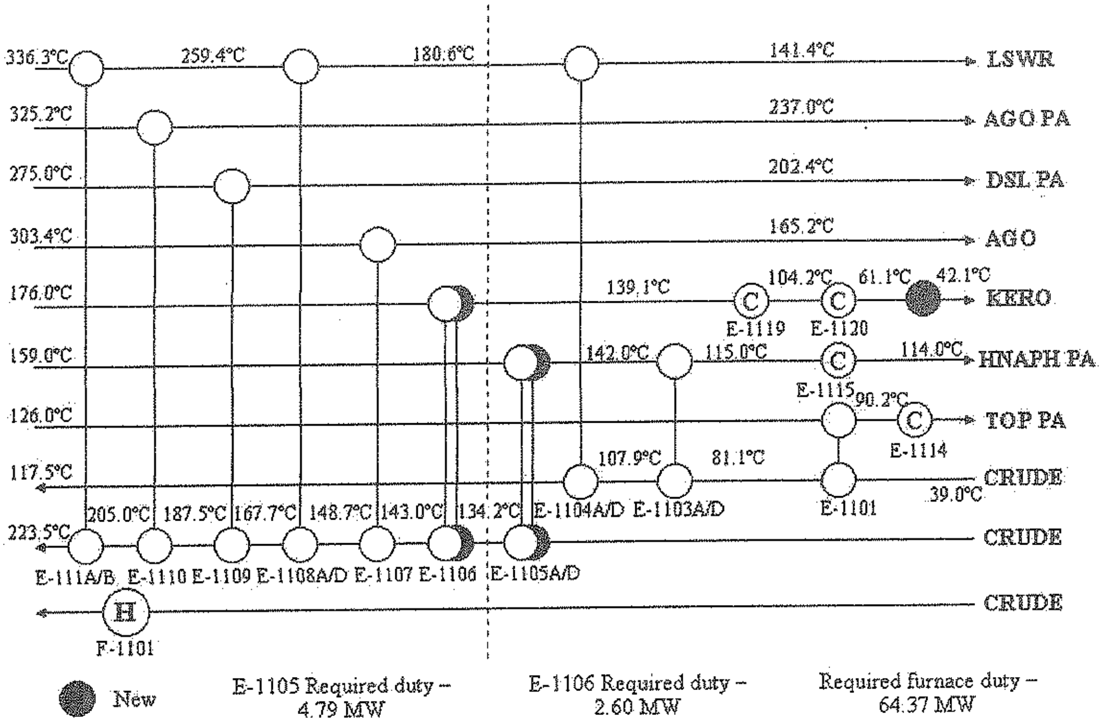

FIGURE 3. Temperature changes after retrofit when E-1102 is removed cleaning

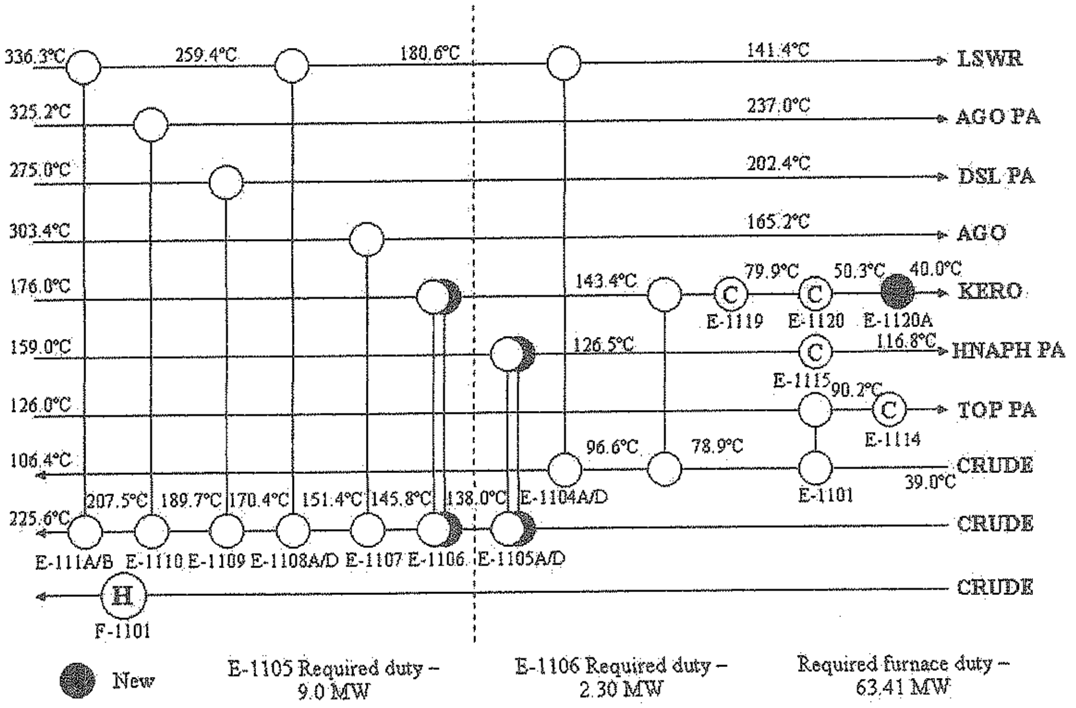

FIGURE 4. Temperature changes after retrofit when E-1103 is removed cleaning

RESULTS AND DISCUSSIONS

The results generated from the analysis of heat exchangers' interactions and ASPEN PLUS simulation are summarised in Figures 3, 4, 5 and in Tables 3, 4 and 5. The results of the proposed modifications to overcome fouling problems are divided into two parts: Performance of retrofitted plant during cleaning operation, and performance of retrofitted plant during normal operation.

Performance of Retrofitted Plant During Cleaning

TABLE 3 shows that when E-1102A/D is removed for cleaning, the heat duty of E-1105A/D is maintained. Both the duties of E-1106 and E-1120 are increased by approximately 1.3 MW to compensate for the temperature drop in the preheat train due to the removal of E-1102A/D. In addition, the newly installed E-1120A contributes 1.1 MW of the total required duty. The crude heater (F-1101) now requires only 64.4 MW, a reduction of 2.5% from the 66.0 MW total duty required before retrofit.

TABLE 4 shows that when E-1103A/D is removed for cleaning, E-1105A/D duty is increased by 4.21 MW while E-1106 duty is increased by 0.96 MW. These changes enable the system to achieve the target temperature of fractionator C-1101. In addition, the cooling duty of E-1120 has to be increased from 0.3 MW to 0.9 MW. There is no utility (cooling water) required in E-1120A during this operation. The crude heater (F-1101) firing duty dropped to 63.4 MW, a reduction of 8.5% from the pre-retrofit duty of 69.3 MW.

TABLE 3. Comparison of utility consumption before and after retrofit (with E-1102 removed during cleaning operation)

	Temp. Before Retrofit (°C)		Temp. After Retrofit (°C)		Duty Before Retrofit	Duty After Retrofit	(%)
	Inlet	Outlet	Inlet	Outlet	MW	MW	
E-1105 (Hot Side)	159.0	142.0	159.0	142.0	4.8	Maintain	-
(Cold Side)	117.5	134.2	117.5	134.2			
E-1106 (Hot Side)	176	157.2	176.0	155.4	1.3	2.6	(+) 100
(Cold Side)	134.2	138.8	143.0	143.0			
E-1120 (Hot Side)	45.5	40.0	61.1	61.1	0.3	2.6	(+) 722
(Cold Side)	-	-	88.9	88.9			
E-1120A (Hot Side)	-	-	42.1	42.1	-	1.1	(+)
(Cold Side)	-	-	50.9	50.9			
F-1101	219.9	358.0	223.5	358.0	66.0	64.4	(–) 2.5

TABLE 4. Comparison of utility consumption before and after retrofit (with E-1103 removed during cleaning operation)

		Temp. Before Retrofit (°C)		Temp. After Retrofit (°C)		Duty Before Retrofit	Duty After Retrofit	(%)
		Inlet	Outlet	Inlet	Outlet	MW	MW	
E-1105	(Hot Side)	159.0	142.0	159.0	126.5	4.8	9.0	(+) 88
	(Cold Side)	108.8	125.8	108.8	138.0			
E-1106	(Hot Side)	176	157.2	176.0	155.4	1.3	2.3	(+) 77
	(Cold Side)	134.2	138.8	143.0	143.0			
E-1120	(Hot Side)	45.5	40.0	61.1	61.1	0.3	0.9	(+) 200
	(Cold Side)	-	-	88.9	88.9			
E-1120A	(Hot Side)	-	-	42.1	42.1	-	-	-
	(Cold Side)	-	-	50.9	50.9			
F-1101		212.6	358.0	225.6	358.0	69.0	63.0	(–) 8.7

Performance of Retrofitted Plant During Normal Operation

Due to $\Delta T_{\min}$ constraint in the network, only an additional 14% heat recovery by E-1106 can be achieved from the retrofitted network during normal operation (TABLE 5). Part of the flowrate going through the over-designed E-1105A/D and E-1106 is by-passed during normal operation (see FIGURE 5). The retrofitted network also results in a reduction of half of the cold utility (cooling water) required for E-1120 and 0.3% of the firing utility (fuel gas) for crude heater (F-1101). The flowrate through E-1105A/D and E-1106 are gradually increased as fouling worsens.

TABLE 5. Comparison of utility consumption before and after retrofit (during normal operation)

		Temp. Before Retrofit (°C)		Temp. After Retrofit (°C)		Duty Before Retrofit	Duty After Retrofit	(%)
		Inlet	Outlet	Inlet	Outlet	MW	MW	
E-1105	(Hot Side)	159.0	142.0	159.0	126.5	4.8	Maintain	-
	(Cold Side)	134.2	150.4	134.2	150.4			
E-1106	(Hot Side)	176.0	157.1	176.0	155.4	1.3	1.5	(+) 15
	(Cold Side)	150.4	154.8	150.4	155.3			
E-1120	(Hot Side)	45.5	40.0	42.8	40.0	0.3	0.2	(-) 50
	(Cold Side)	35.0	44.5	35.0	41.8			
E-1120A	(Hot Side)	-	-	-	-	-	-	-
	(Cold Side)	-	-	-	-			
F-1101		233.8	358.0	234.2	358.0	59.6	59.0	(–) 1.0

The retrofitted flowsheet was re-simulated using ASPEN PLUS. Finally, a simple economic analysis was carried out to determine the project feasibility.

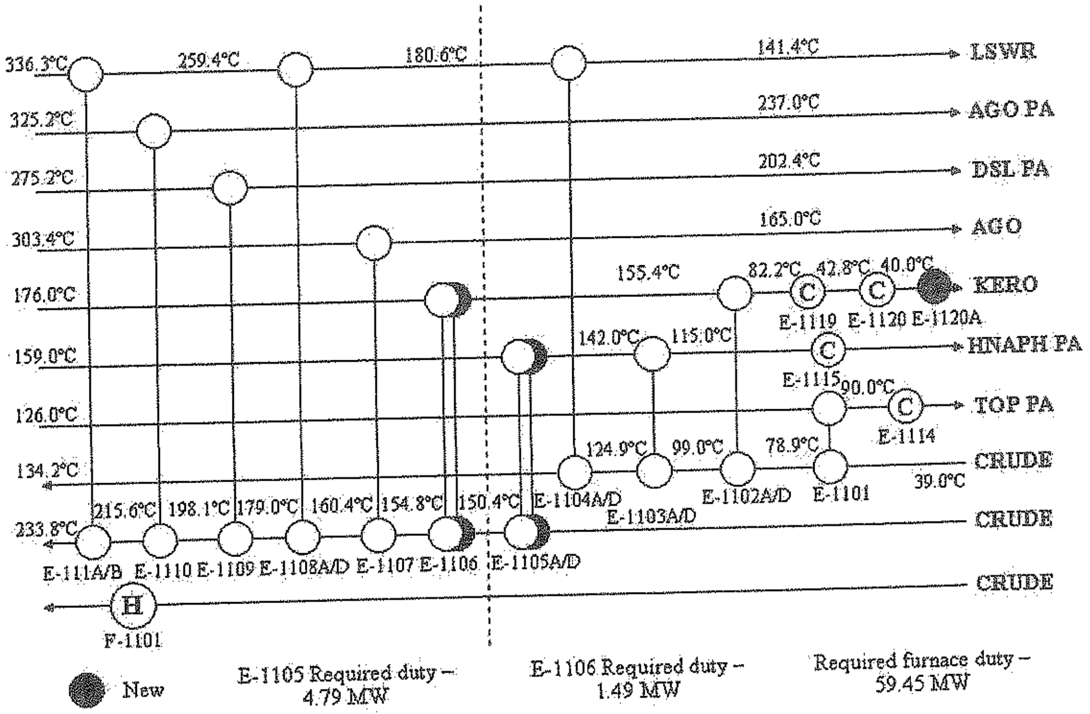

FIGURE 5. Temperature changes after retrofit during normal operation

ECONOMIC EVALUATION

From the results of the proposed changes during normal and fouled conditions, it was possible to determine the additional area of the heat exchangers required, the over-productivity loss due to cleaning operation and the utilities saved from the over-design of the non-fouled heat exchangers. With this information, the pay back period for the proposed retrofit project was calculated. Equipment cost was estimated based on the procedure outlined in Biegler *et al.* (1997) and updated to March 2000 using the Chemical Engineering Plant Index (Chemical Engineering, 2000). TABLE 6 and 7 show the estimated investment costs incurred and the total potential savings for the proposed retrofit project.

For a projected annual savings of 0.6 million in terms of productivity increase and utility savings, a total of RM (Ringgit Malaysia) 1.2 million needed to be invested in additional area. The pay back period is 2 years. From the management perspective, the pay back period of up to 4-5 years is acceptable. Therefore, the pay back period of 2 years for this retrofit project is considered feasible and economical. For the detailed economic calculations, readers are referred to Ling, 2000.

TABLE 6. Summary of heat exchangers' sizes and costs

	Additional Area (m^2)	Capital Cost ($)
E-1105	2,543	829,450
E-1106	337	223,069
E-1120A	150	131,761

TABLE 7. Summary of cost savings and investment after retrofit

	Saving ($/yr)	Additional Investment ($)
Production Loss	35.3×10^4	-
Fuel Gas	0.2×10^6	-
Cooling Water	35.1×10^3	-
Equipment Expenses	-	1.2×10^6
Total	0.6×10^6	1.2×10^6

CONCLUSIONS

Over-designing the non-fouled heat exchangers not only enabled the production rate to be maintained throughout the year, but also allows savings in utilities. Simple economic analysis shows that, for a projected annual savings of 0.6 million in terms of productivity increase and utility savings, a total of RM (Ringgit Malaysia) 1.2 million needed to be invested in additional area. The pay back period was calculated at 2 years. Therefore, this retrofit to overcome the fouling problems can be considered as a worthwhile investment.

NOMENCLATURE

AGO	Atmospheric Gas Oil
LSWR	Low Sulfur Wax Residue
Q	Energy (MW)
U	Overall heat transfer coefficient (W/m^2K)
A	Area (m^2)
ΔT_{lm}	log min temperature different (K)

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