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MINLP model for simultaneous scheduling and retrofit of refinery preheat train

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Abstract
There is greater awareness today on the depleting fossil energy resources and the growing problem of atmospheric pollution. Engineers are developing practical techniques to ensure energy processes are designed and operated efficiently. Inefficient heat exchangers lead to higher fuel demand and higher carbon emission. This paper presents mixed-integer nonlinear programming (MINLP) model for simultaneous cleaning and retrofit of crude preheat train (CPT) in oil refinery plant. The formulation of the model is generated and coded in General Algebraic Modeling System (GAMS). The model minimizes the cost of energy and the cost of cleaning. The model takes into account the changes in fouling rates throughout time. There are two cases for this study. The cases are online cleaning (Case 1) and simultaneous online cleaning and retrofit (Case 2). The largest energy saving are found in Case 2. The installation of high efficiency heat exchangers improves furnace inlet temperature (FIT) from 215°C to 227°C. Furthermore, Case 2 results in the highest percentage of cost saving by about 59%. The payback period for investment in high efficiency heat exchangers is 5 months. Thus, Case 2 is the most cost effective option for reductions of energy consumption in Crude Distillation Unit (CDU).

Keywords: Fouling; Cleaning; Schedule; Retrofit; Heat exchanger.

1. Introduction

The presence of dissolved or suspended materials in heat exchanger may cause the accumulation of deposits on heat transfer surfaces. The formation of these deposits is known as fouling. Fouling not only deteriorates the heat transfer surface and decreases the heat transfer capacity of heat exchanger but also can cause large production losses due to planned or unplanned shutdowns of the entire unit [1].

In order to overcome this problem, heat exchangers are cleaned between shutdowns or during operations to restore its efficiencies. However, the most crucial factor for heat exchanger cleaning schedule is to determine which heat exchanger need to be cleaned and when during operation. The development of systematic techniques such as heuristic reduction methods, decomposition or aggregation techniques highlights the application of different optimization approaches. Many researchers have developed different strategies of modeling technique for optimal cleaning schedule in heat exchanger network [2-5].

In this paper, the set of equations are presented to simulate online cleaning schedule for CPT. The model minimizes the total operating cost by finding the balance point between fouling and the cleaning cost. The first model is optimum online cleaning of heat exchangers. The current study extends the first model to develop combined online cleaning with retrofit of high efficiency heat exchangers. Thus, the objective is to optimize the model for simultaneous scheduling and retrofit of CPT with reasonable payback period and contribute to the highest energy saving.

2. Methodology

2.1 Model formulation background

A heat exchanger network of a crude distillation unit (CDU) is known as CPT as shown in Figure 1. The crude oil in CPT is heated up by using heat recovered from distillation column products before entering furnace at operating temperature of FIT. The relevant process data are extracted from a refinery to establish performance benchmark of the system. The historical data is needed to obtain correlation and profiles of the respective parameters.

All the models are coded in the commercial optimization software, GAMS version 23.9 and solved by BONMIN solver. Mixed Integer Non Linear Programming (MINLP) cleaning schedule optimizer models are applied for all the cases. The model determines which heat exchanger needs to be cleaned in which period of time with some resource availability and constraints so that the total operating cost is minimized.

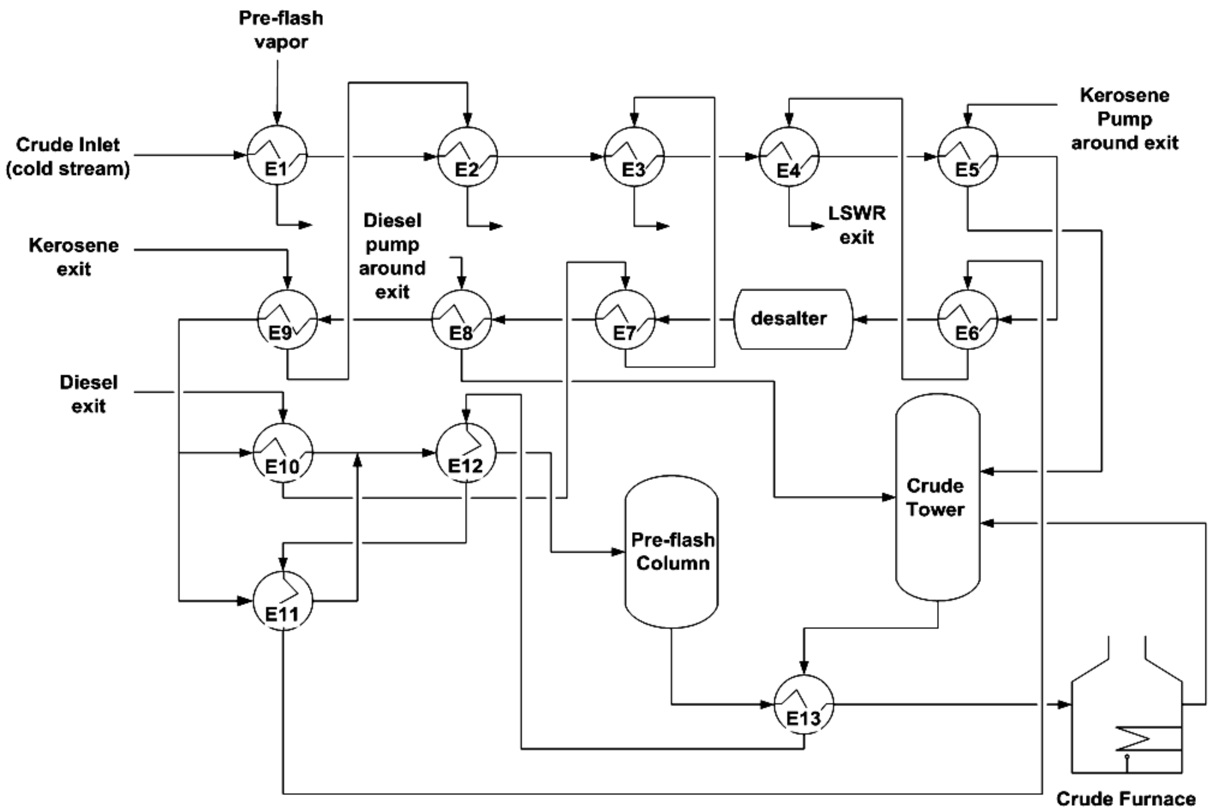

Figure 1. CDU crude preheat train flow scheme

3. Results and discussion

3.1 Development of model formulation

The objective function minimizes cost that includes furnace's extra fuel cost and cleaning cost. Equation (1) represents the objective function for Case 1 and Case 2.

$$Cost = \alpha \sum_{t} (FG_t - FG_{t=0}) C_{fl} + \sum_{t} \sum_{i} y_{i,t}^{cl} C_{cl} \quad (1)$$

where FG_t (m^3/h) is the fuel gas consumption at time t, $FG_{t=0}$ is the fuel gas consumption at clean condition when period t equal to zero, C_{fl} (RM/GJ) is the furnace's fuel cost, C_{cl} is the cleaning cost. Symbol α is the conversion factor with unit of GJ.h/month.m^3.

The binary variable y_{it}^{cl} is defined to identify when and which heat exchanger is cleaned.

$$y_{i,t}^{cl} = \begin{cases} 1 & \text{if the } i^{th} \text{ heat exchanger is cleaed in period } t \\ 0 & \text{otherwise} \end{cases}$$

The historical data for fuel gas flow rate and furnace inlet temperature (FIT) are collected for 10 months. FIT is the crude oil exit temperature of crude preheat train before additional heating is provided by furnace. From Figure 1, FIT in this case is outlet cold stream temperature for heat exchanger E13, $Tc2_{E13}$. As the time of operation increases, the value of FIT is expected to decrease due to increment in fouling. FIT is reduced until it reaches threshold temperature. Threshold temperature is the critical temperature of chronic fouling condition. The minimum allowable FIT temperature is expressed as inequality constraint as; $FIT_t \leq 200$

From historical data, the reduction of FIT per month is -0.56°C/month. Equation (2) shows reduction of FIT as time of operation increases.

$$FIT_t = (Tc2_{E13,t-1} - 0.5603)(1 - y_{i,t}^{cl}) + Tc2_{E13,t=0}(y_{i,t}^{cl}) \quad (2)$$

From historical data, fuel gas flow rate is plotted against FIT to obtain linear correlation between these two variables. As the time of operation increases, the value of FIT is expected to decrease due to the increment of fouling. Equation (3) shows linear correlation between fuel gas flow rate, FG_t and FIT at period t.

$$FG_t = -31.997 \times (Tc2_{E13}) + 10139 \quad (3)$$

The historical data for cleaned heat exchangers are collected in the first month of plant operation after refinery's turnaround. The values of the clean heat transfer coefficient, Uc_i are calculated using (4) where all heat exchangers are in clean condition.

$$Q = UA\Delta T_{lm} \quad (4)$$

Q, A and ΔT_{lm} indicates heat transfer rate, heat transfer area and difference in temperature between hot and cold stream respectively.

The equations that represent the relationship between the inlet and the outlet temperatures of the i^{th} heat exchanger are the heat duty as in equation (5) and (6).

$$Q_{i,t} = Fc_i Cc_i (Tc2_{i,t} - Tc1_{i,t}) \quad (5)$$

$$Q_{i,t} = U_{i,t} A_i \frac{(Th1_{i,t} - Tc2_{i,t}) - (Th2_{i,t} - Tc1_{i,t})}{\ln\left[\dfrac{(Th1_{i,t} - Tc2_{i,t})}{(Th2_{i,t} - Tc1_{i,t})}\right]} \quad (6)$$

These equations are rearranged to get the equations for outlet hot stream temperature, $Th2_{,i,t}$ and outlet cold stream temperature, $Tc2_{,i,t}$. Equation (7) and (8) are obtained from Lavaja & Bagajewicz [3].

$$Th2_{i,t} = \frac{(R-1)Th1_{i,t} + \left\{\exp\left[\dfrac{Uf_{i,t}A_i}{Fc_iCc_i}(R-1)\right] - 1\right\} RTc1_{i,t}}{R \times \exp\left[\dfrac{Uf_{i,t}A_i}{Fc_iCc_i}(R-1)\right] - 1} \quad (7)$$

where $R = \dfrac{Fc_iCc_i}{Fh_iCh_i} = \dfrac{Th1_{i,t} - Th2_{i,t}}{Tc2_{i,t} - Tc1_{i,t}}$

$$Tc2_{i,t} = Tc1_{i,t} + \frac{Th1_{i,t} - Th2_{i,t}}{R} \quad (8)$$

The fouling behavior of individual units in the CPT was investigated by analyzing operating data collected over 10 months. Figure 2 shows fouling resistance profiles for heat exchangers E1 until E13. The trends suggest that linear fouling behavior is occurred. The slope of the profile indicates the rate of fouling, $dRf_{i,t}$.

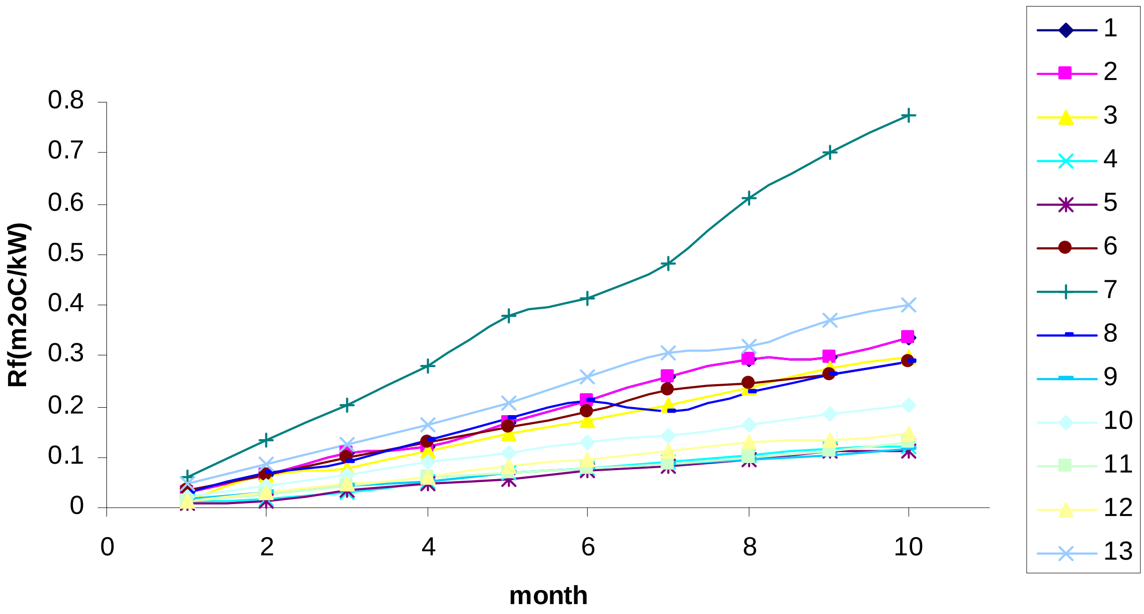

Figure 2. Fouling resistance behavior for CPT

The historical data for this study is tabulated as in Table 1. The parameters are inlet cold stream temperature (Tc1), outlet cold stream temperature (Tc2), inlet hot stream temperature (Th1), outlet hot stream temperature (Th2), mass flow rate for hot stream (Fh), mass flow rate for cold stream (Fc), specific heat for cold strem (Cc), specific heat for hot stream (Ch), cross sectional area (A), clean heat transfer coefficient (Uc) and fouling rate (dRf).

Table 1. Data for heat exchanger network

Parameters	Heat exchanger												
	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13
Tc1 (^{o}C)	33	66	89	100	102	106	120	160	200	205	205	223	200
Tc2 (^{o}C)	66	89	100	102	106	112	160	200	205	230	215	232	215
Th1 (^{o}C)	83	205	170	185	145	225	235	205	230	279	242	300	347
Th2 (^{o}C)	40	79	120	179	130	185	170	180	205	235	225	242	300
Fh (kg/s)	16	15.6	24	17	19.8	17	24	39.1	15.6	24	17	17	17
Fc (kg/s)	75	75	75	75	75	75	75	75	75	42	33	75	68
Cc (kJ/kg^{o}C)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Ch (kJ/kg^{o}C)	7.2	1.8	1.4	3.0	2.0	1.3	3.9	6.2	1.9	2.0	3.4	1.4	3.4
A (m^2)	411.5	111.0	361.8	111.0	180.9	111.4	132.5	125.0	111.4	169.9	153.7	165.5	78.2
Uc (kW.m^2/^{o}C)	1.073	0.660	0.095	0.033	0.100	0.085	0.736	4.470	0.542	0.320	0.185	0.212	0.227
dRf (m^2.^{o}C/kW)	0.035	0.060	0.033	0.013	0.012	0.032	0.070	0.030	0.011	0.020	0.012	0.015	0.040

3.2 Case 1: CPT online cleaning schedule

The model for Case 1 involves a set of operational equations and constraints to formulate online cleaning schedule for CPT. The equation for fouled heat transfer coefficient $Uf_{i,t}$ is calculated using (9).

$$\frac{1}{Uf_{i,t}} = \frac{1}{Uc_i} + Rf_{i,t} \tag{9}$$

$Rf_{i,t}$ is the fouling resistance for i^{th} heat exchanger in period t. Equation (10) is the linear fouling resistance equation, $Rf_{i,t.}$

$$Rf_{i,t} = (Rf_{i,t-1} + dRf_{i,t})(1 - y_{i,t}^{cl}) + (Rf_{i,t=0})(y_{i,t}^{cl}) \tag{10}$$

where fouling resistance of i^{th} heat exchanger in period t-1 is $\mathrm{Rf}_{i,t-1}$ and initial fouling resistance at period $t=0$ is $Rf_{i,t=0}$. The $Rf_{i,t=0}$ for all heat exchangers is zero because at period $t=0$, all heat exchangers are in clean condition.

When $y_{i,t}^{cl}$ = 0, the expression becomes $Rf_{i,t} = (Rf_{i,t-1} + dRf_{i,t})$

The fouling resistance for i^{th} heat exchanger in period t is the summation of fouling resistance in period t-1 and fouling rates.

If $y_{i,t}^{cl}$ = 1, the expression reduced to $Rf_{i,t} = Rf_{i,t=0}$

The i^{th} heat exchanger is being cleaned in period t, thus fouling resistance for i^{th} heat exchanger in period t equal to zero.

3.3 Case 2: simultaneous CPT online cleaning and retrofitting schedule

Case 2 is simulated to identify which heat exchanger is selected to change into high efficiency heat exchanger while performing online cleaning throughout the time horizon. The second binary variable, $y_{i,t=0}^{cg}$ is to determine which heat exchanger is selected to change into high efficiency heat exchanger in period $t=0$. The purpose of changing high efficiency heat exchanger in period $t=0$ is to formulate new online cleaning after the installation of high efficiency heat exchangers at initial period.

$$y_{i,t=0}^{cg} = \begin{cases} 1 & i^{th} \text{ heat exchanger is changed in period } t = 0 \\ 0 & \text{otherwise} \end{cases}$$

The $y_{i,t=0}^{cg}$ is introduced in the equation of fouled heat transfer coefficient as in (11). The clean heat transfer coefficient for high efficiency heat exchanger is twice the previous clean heat transfer coefficient for shell and tubes heat exchanger [6].

$$Uf_{i,t} = \frac{1}{\dfrac{1}{Uc_i + Uc_i \times \sum_t y_{i,t}^{cg}} + Rf_{i,t}} \tag{11}$$

Hesselgreaves [7] recommended the fouling resistance value for compact heat exchangers, such as plate and frame heat exchanger or Compabloc welded plate heat exchangers, are in the order of one tenth of TEMA values. Thus, when $y_{i,t=0}^{cg}$ is selected, $Rf_{i,t}$ is reduced by one tenth or 10% from the previous $Rf_{i,t}$.

$$Rf_{i,t} = (Rf_{i,t-1} + dRf_{i,t} - dRfhhx_{i,t})(1 - y_{i,t}^{cl})(1 - y_{i,t}^{cg}) + (Rf_{i,0})(y_{i,t}^{cl} + y_{i,t}^{cg}) \tag{12}$$

The additional term for fouling resistance equation is $\mathrm{dRfhhx}_{i,t}$. This is the term added in equation (12) to indicate if $y_{i,t=0}^{cg}$ is selected or not selected. The term in equation (13) is the value of 90% reduction of fouling rates for ith high efficiency heat exchanger.

$$dRfhhx_{i,t} = (dRfhex_i)\, y^{cg}_{i,t=0} \tag{13}$$

There are two inequality constraint for Case 2. The first constraint shows that changing high efficiency heat exchanger is allowed in period in period *t=0* only. ($y^{cg}_{i,t=0} \le 1$)

The second constraint demonstrates that changing i^{th} high efficiency heat exchanger is not allowed at all period *t* except at initial period. The i^{th} high efficiency heat exchanger is only allowed to change at initial period. ($\sum_t y^{cg}_{i,t+1} \le 0$)

3.4 Feasibility analysis

3.4.1 FIT profiles

Figure 3 shows FIT profiles for Case 1 and Case 2. Value of FIT for Case 2 at initial period is higher than FIT for Case 1. This is due to the installation of high efficiency heat exchangers at the beginning of plant operation. The installation of new high efficiency heat exchangers improves FIT from 215^{o}C to 227^{o}C. At 24 months, FIT is relatively high at 213^{o}C and 225^{o}C for Case 1 and Case 2 respectively.

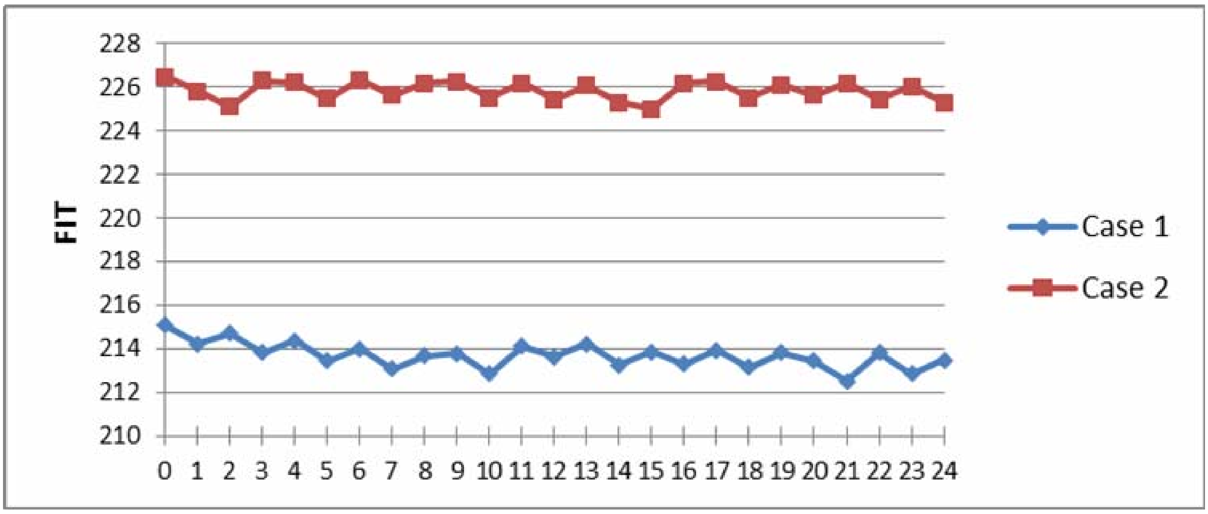

Figure 3. FIT profiles

3.4.2 Energy saving

Table 2 demonstrates the comparison of energy saving for all cases. Extra fuel gas flow rate is the total amount of additional fuel gas needed due to fouling in CPT. The amount of energy is calculated by multiplying extra fuel gas flow rate with heating value of fuel gas. The approximate heating value for fuel gas is 0.029 GJ/Nm^3. Energy saving is the difference between energy of current practice an energy of the cases.

Table 2. Comparison of energy saving for all cases

Cases	Fuel gas			
	Extra flow rate (Nm^3/year)	Amount of Energy (GJ/year)	Energy saving (GJ/year)	Percentage saving (%)
Current Practice	2472	71.69	-	-
Case 1	1120	32.48	39.21	55
Case 2	971	28.16	43.53	61

The comparison shows that Case 2 results in the highest percentage of cost saving which are about 61%. The great amount of extra fuel gas is reduced due to the usage of high efficiency heat exchangers with very low fouling rates in Case 2.

3.4.3 Cleaning schedule

Table 3 shows optimum cleaning schedule for Case 1. There are 16 numbers of cleaning in the schedule for 24 months period. The optimum cleaning schedule for Case 2 is shown in Table 4. Total number of cleaning is 17. Six heat exchangers are selected to change into high efficiency heat exchangers. The selected heat exchangers are E2, E9, E10, E11, E12, E13.

3.5 Economic analysis

The cost calculation for base case is demonstrated in Table 5. From the plant historical data, the value of fuel gas price and cleaning cost is RM 14.55/GJ and RM 40,000/unit respectively.

Table 6 shows the cost saving for Case 2 is higher than Case 1. The base case is the operation of CPT with no cleaning. The great amount of extra fuel gas is reduced due to the usage of high efficiency heat exchangers. The high efficiency heat exchanger has higher overall heat transfer coefficient and lower fouling rates than conventional shell and tube heat exchanger.

Table 3. cleaning schedule for Case 1

Hex	Month																No. of cleanings
	2	4	6	8	9	11	12	13	15	16	17	18	19	20	22	24	
E1																	0
E2																	0
E3																	0
E4																	0
E5																	0
E6																	0
E7					•									•			2
E8	•	•	•	•		•		•	•		•		•		•	•	11
E9																	0
E10							•					•					2
E11																	0
E12																	0
E13										•							1
Total No. of Cleaning																	16

Table 4. cleaning schedule for Case 2

Hex	Month														No. of cleanings
	3	4	6	8	9	11	13	15	16	17	19	20	21	23	
E1															0
E2															0
E3															0
E4															0
E5															0
E6															0
E7			•					•				•			3
E8	•	•	•	•	•	•	•		•	•	•		•	•	12
E9															0
E10						•									1
E11															0
E12															0
E13					•					•					2
Total No. of Cleaning															17

Table 5. Base case cost calculation

Details	Amount	Cost	multiply	Conversion	RM
Total extra fuel gas flow rate	4,948 Nm^3/h	RM 14.55/GJ	24 months	20.88 $GJ.h/month.m^3$	36,078,103
Heat Exchanger cleaning	13 units	RM 40,000/unit	-	-	-
Annual cost (RM/year)					18,039,052

Table 6. Total cost for Case 1 and Case 2

Case	Total Cost (RM)	Annual cost (RM/year)	Cost saving per year (RM/year)	Percentage of Cost Saving per year (%/year)
Base case	36,078,103	18,039,052	-	-
Case 1	16,976,448	8,488,224	9,550,828	53
Case 2	14,832,581	7,416,290	10,622,761	59

3.5.1 Payback period

In refinery's CPT, the most common high efficiency heat exchangers is Alfa Laval Compabloc welded plate heat exchanger. Compabloc welded plate heat exchanger is the most highly efficient compact heat exchanger with design pressure up to 450 psi [8]. The proposed purchase cost equation for Compabloc welded plate heat exchanger is calculated using (14) as shown below,

$$C_{ph} = 7000 \times A^{0.49176} \quad (14)$$

C_{ph} is the purchase cost ($), A is the heat transfer area (ft^2) with the range of 150-15000 ft^2. The material is stainless steel. The operating pressures are limited to 300 psig [9]. In Case 2, six conventional shell and tubes heat exchangers are selected to change into high efficiency heat exchangers. Table 7 summarizes the purchase cost for selected Compabloc welded plate heat exchangers. The total investment cost is RM 4,428,076. Thus, the payback period for purchasing high efficiency heat exchangers is 5 months.

Table 7. Purchase cost for compabloc heat exchangers

Heat Exchanger	Area (m^2)	Area (ft^2)	Cp ($)
E2	111	1,194.8	228,238.8
E9	111.4	1,199.1	228,642.9
E10	169.9	1,828.8	281,385.2
E11	153.7	1,654.4	267,855.2
E12	165.5	1,781.4	277,777.8
E13	78.2	841.7	192,125.4
Cp ($)			1,476,025
Cp (RM)			4,428,076

4. Conclusion

In this article, two models are developed to optimize cleaning schedule for the operation of CPT. Case 2 is the most cost effective model compared to Case 1. The replacement of selected conventional shell and tube heat exchangers to new high efficiency heat exchangers with reasonable payback period has improved FIT and reduced extra fuel gas flow rate. The high efficiency heat exchanger has higher overall heat transfer coefficient and lower fouling rates than conventional shell and tube heat exchanger. This factors help to improve heat transfer efficiency in the heat exchanger.

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