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Exergy analysis for fuel reduction strategies in crude distillation unit

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ABSTRACT

Inefficient furnaces and heat exchangers contribute to the depletion of fossil fuel problem due to higher fuel demand and higher carbon emission. The method of exergy analysis is applied to the furnace and crude preheat train (CPT) in a crude distillation unit (CDU) to determine performance benchmark of the system. This paper presents exergy analysis and strategies to reduce exergy loss through process modification. The highest exergy loss was found to be located at the inlet furnace. The proposed options for fuel reduction strategies are reduction of heat loss from furnace stack and overall cleaning schedule of CPT. The feasibility and economic analysis for both options are investigated. From the results, overall cleaning schedule of CPT contributes to the highest energy saving of 5.6%. However, reduction of heat loss from furnace stack is the highest cost saving by about 6.4%.

1. Introduction

The exergy of the system is defined as the ability to do work or the work potential of a great variety of streams such as mass, heat and work that flow through a system at a specified reference temperature [1]. Exergy analysis is an effective method based on the second law of thermodynamic which can be used to systematically locate and quantify the inefficiency of a process system. Once the locations of the system's inefficiencies are identified, improvement can be made to reduce exergy loss of the system. Many researches and engineers conduct exergy analysis as a method for analyzing, designing and improving systems and processes. Some of the previous works done on the application of exergy analysis in industrial processes has been reported on crude distillation unit, power plant, cogeneration plant, cooling system and fuel cell system [2–6]. Doldersum [7] applied exergy analysis on distillation process. The author found that the exergy loss occurred in the furnace and distillation column. Several process modifications to reduce exergy loss were proposed. After the process modification, the total exergy loss was able to reduce by 70% that directly related in a reduction of fuel for almost 40%. Rivero et al. [8] studied exergy analysis on crude oil combined distillation unit. The economic improvement potential was analyzed for the process streams. The authors found that the highest cost of exergy loss is the atmospheric fired heater which about 45% of the total cost of exergy loss.

While there are many published approaches on determination of location and magnitude of exergy loss in distillation column [7–11], the strategies to achieve operational improvement is usually uncertain. This paper presents fuel reduction strategies in CDU by applying the concept of exergy analysis to determine location and quantity of exergy loss as well as to generate possible fuel reduction strategies through process modification.

2. Methodology

2.1. Establishment of base case data

The crude distillation unit (CDU) is the first step in a refinery complex to separate crude oil into different fractions. In a typical CDU, crude oil feed stream is preheated in a crude preheat train (CPT). CPT utilizes high temperatures of the distillation column product streams. The relevant process data are extracted from a typical refinery in Malaysia. The selected data has been agreed and validated by a local oil refinery's engineers after careful consideration. Fig. 1 shows a simplified process flow scheme of CDU crude preheat train. The crude oil is heated up to 112 °C before entering the desalter. The hot streams are the hot product streams coming out from crude tower. After desalter, the crude oil stream is further heated up using heat recovered from the process streams. At this end, the crude oil starts to vaporize at 203 °C. Then, the crude oil enters a pre-flash column to remove light naphtha, mixed naphtha

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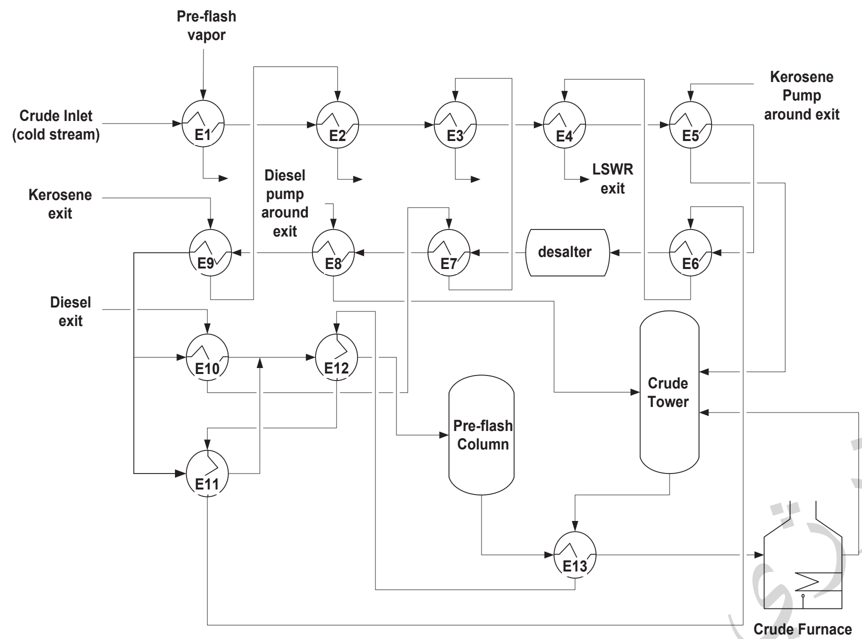

Fig. 1. CDU crude preheat train flow scheme.

and light hydrocarbon gases from the crude oil. The vapour is risen up to pre-flash overhead distillate and the liquid flows downward to the bottom. The preflash column bottom is further heated by heat exchanger E13 before entering furnace at design temperature of 215 °C. The preheated crude oil enters furnace at furnace inlet temperature (FIT). In a furnace, the heat source is provided by the burning fuel with air at theoretical flame temperature (TFT). The heat from the burning of fuel with air is transferred to the crude oil [12]. Then, the heated crude oil enters the crude distillation column at tower inlet temperature (TIT). The remaining heat in the furnace leaves through furnace stack at stack temperature (*T* stack).

2.2. Exergy analysis

Fig. 2 shows an exergy composite curve. The upper line is the hot composite curve and the lower line is the cold composite curve. The area under the hot composite curve is the amount of exergy source (ΔE_H) and the area under the cold composite curve is the amount of exergy sink (ΔE_C). Note that ΔE_H is partly covered by ΔE_c in Fig. 2. The gap between hot composite curve and cold composite curve is the exergy loss which is $\Delta Ex_{loss} = \Delta E_H - \Delta E_C$ [13].

The exergy source in a system is provided by hot process streams that transfer heat and is calculated as follows:

$$\Delta Ex_{source} = (H_{h2} - H_{h1}) - T_o(S_{h2} - S_{h1}) \quad (1)$$

On the other hand, the cold process stream that receives heat is the exergy sink:

$$\Delta Ex_{sink} = (H_{c2} - H_{c1}) - T_o(S_{c2} - S_{c1}) \quad (2)$$

Exergy is never conserved in real processes. Exergy will degrade and will be lost. Exergy loss reflects the irreversibility in the heat transfer process. Exergy loss can be calculated from an exergy balance as follows:

$$\Delta Ex_{loss} = \sum \Delta Ex_{sources} - \sum \Delta Ex_{sinks} = T_o(\Delta S_c - \Delta S_h) \quad (3)$$

where ΔS_c is change in entropy for cold streams and ΔS_h is change in entropy for hot streams.

2.3. Generation of possible fuel reduction strategies

Fig. 3 shows a typical exergy composite curve for furnace. *T* stack is located at the initial point of hot composite curve while TFT is located at the end point of hot composite curve. FIT is located at the initial point of cold composite curve while TIT is located at the end point of cold composite curve.

The fuel reduction strategies are generated from exergy composite curve analysis. As shown in Fig. 3, amount of exergy loss is represented by the gap between hot and cold composite curve. Thus, the idea to minimize exergy loss of the system is to obtain closer gap between hot and cold composite curve. The closer gap between hot and cold composite curve can be obtained by:

a) Reducing theoretical flame temperature (TFT)
b) Reducing stack temperature (*T* stack)
c) Increasing tower inlet temperature (TIT)
d) Increasing furnace inlet temperature (FIT)

These four options are the possible fuel reduction strategies for CDU. Two options are chosen to be implemented in this study which are reducing *T* stack and increasing FIT. The proposed options for fuel reduction strategies in this study are reduction of heat loss from furnace stack and overall cleaning schedule of CPT. The first

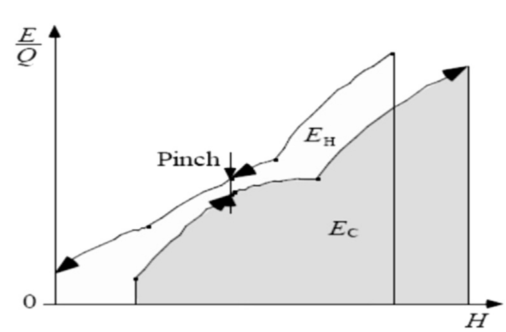

Fig. 2. Exergy composite curve.

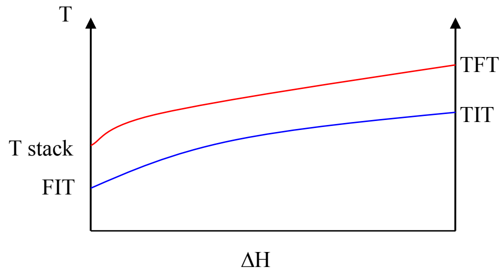

Fig. 3. Location of TFT, *T* stack, FIT and TIT on exergy composite curve.

option is using approximate analysis to reduce *T* stack. While, the second option are generated from the optimization of overall cleaning schedule of CPT to improve FIT.

3. Results & discussion

3.1. Exergy analysis

3.1.1. Exergy composite curve

The hot and cold streams of the process are described in Tables 1 and 2 respectively. T_i is inlet temperature and T_o is outlet temperature.

The extracted process data as shown in Tables 1 and 2 is used to obtain exergy composite curve for hot and cold composite as shown in Fig. 4. The exergy composite curve is generated from software packages called WORK from Centre for Process Integration, University of Manchester.

The upper line is the hot composite curve and the lower line is the cold composite curve. The area under the hot composite curve is the amount of exergy source (ΔEx_{source}) and the area under the cold composite curve is the amount of exergy sink (ΔEx_{sink}). Exergy loss (ΔEx_{loss}) is the area between exergy source and exergy sink. The axis of exergy composite curve is Carnot factor (*Y*) versus enthalpy (*X*). Carnot factor (CF) is the measure of exergy level, $CF = 1 - T_o/T_i$, where T_o is the ambient temperature and T_i is the process temperature. The ambient temperature (T_o) of the system is 27 °C.

The region that contributes to the highest exergy loss is identified as the largest gap between hot and cold composite curves. In Fig. 4, the largest gap is at the end of the curve which is at the temperature region of furnace. Furnace has temperature region from TFT to stack temperature for hot composite curve and temperature region from FIT to TIT for cold composite curve. The value of TFT to stack temperature is 1615 °C–290 °C and the value of FIT to TIT is 215 °C–367 °C.

Table 1
Temperature inlet and outlet for cold streams.

Streams	Cold streams	T_i (°C)	T_o (°C)	ΔH (kW)
C1	Crude oil to E1	33	66	4959.43
C2	Crude oil to E2	66	89	3456.57
C3	Crude oil to E3	89	100	1653.14
C4	Crude oil to E4	100	102	300.57
C5	Crude oil to E5	102	106	601.14
C6	Crude oil to E6	106	112	901.72
C7	Crude oil from desalter to E7	120	160	6011.43
C8	Crude oil to E8	160	200	6011.43
C9	Crude oil to E9	200	205	751.43
C10	Crude oil to E10	205	230	2098.50
C11	Crude oil to E11	205	215	663.46
C12	Crude oil to E12	223	232	1352.57
C13	Preflash bottom to E13	200	215	2041.78
C14	FIT to TIT	215	367	50,795.00

Table 2
Temperature inlet and outlet for hot streams.

Streams	Hot streams	T_i (°C)	T_o (°C)	ΔH (kW)
H1	Preflash vapour to E1	83	40	4959.43
H2	Kerosene exit to E2	205	79	3456.57
H3	Diesel exit to E3	170	120	1653.14
H4	LSWR to E4	185	179	300.57
H5	Kerosene pump around to E5	145	130	601.14
H6	LSWR to E6	225	185	901.72
H7	Diesel exit to E7	235	170	6011.43
H8	Diesel pump around to E8	205	180	6011.43
H9	Kerosene exit to E9	230	205	751.43
H10	Diesel exit to E10	279	235	2098.50
H11	LSWR to E11	242	225	663.46
H12	LSWR to E12	300	242	1352.57
H13	LSWR from crude tower to E13	347	300	2041.78
H14	TFT to *T* stack	1615	290	50,795.00

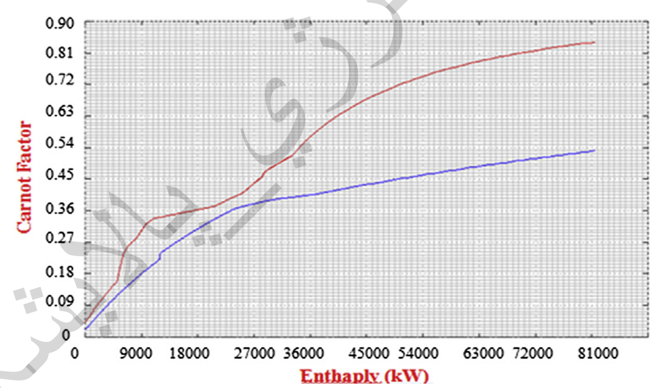

Fig. 4. Exergy Composite Curve for CDU crude preheat train.

3.1.2. Distribution of exergy loss

Table 3 shows amount of exergy source, exergy sink and exergy loss for heat exchanger network and furnace. From Table 3, furnace contributes to 86% of total exergy loss in the system.

A Sankey diagram for CPT and furnace of CDU is illustrated in Fig. 5. The exergy source is the exergy input and exergy sink is the exergy output of the system. Amount of exergy source is 46,829 kW

Table 3
Exergy loss for heat exchangers and furnace in CDU crude preheat train.

Furnace/heat exchangers	Exergy source (kW)	Exergy sink (kW)	Exergy loss (kW)	Exergy loss percentage (%)
Furnace	36,879.16	23,611.04	13,268.12	86.28
E7	2212.81	1641.36	571.45	3.72
E2	938.38	496.96	441.42	2.87
E13	1014.37	766.89	247.48	1.61
E1	505.37	341.98	163.40	1.06
E3	465.26	303.54	161.72	1.05
E6	335.45	193.55	141.91	0.92
E8	2136.32	2027.76	108.56	0.71
E10	909.99	814.73	95.25	0.62
E12	605.96	541.82	64.14	0.42
E4	102.39	59.47	42.92	0.28
E5	161.77	122.78	38.99	0.25
E11	270.46	251.36	19.10	0.12
E9	291.74	277.34	14.40	0.09
Total	46,829.42	31,450.57	15,378.86	100

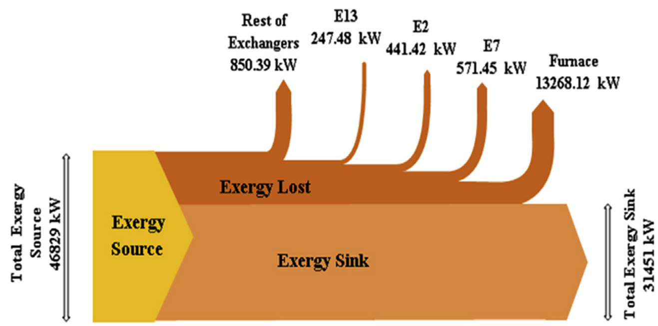

Fig. 5. Sankey diagram for CDU crude preheat train.

and amount of exergy sink is 31,451 kW. The total exergy losses in CDU crude preheat train is 15,379 kW. The highest exergy loss in the system is furnace followed by heat exchanger E7, E2, E13 and the rest of heat exchangers.

3.2. Generation of possible fuel reduction strategies

The proposed method to reduce exergy loss of the system is by exploring process modification of hot and cold stream temperatures of the furnace. The justification of the options to minimize exergy loss is explained as follows.

(a) Reducing theoretical flame temperature (TFT)

Fig. 6 shows the exergy composite curve where the hot composite curve is closer to the cold composite curve when TFT_o is reduced to TFT_i. Note that TFT_i is less than TFT_o. The strategy to reduce TFT is by using lower quality of fuel gas. However, reducing TFT is limited by the target temperature of tower inlet temperature (TIT). TFT should be hot enough to provide sufficient heat to the crude oil in order to meet the target temperature of TIT.

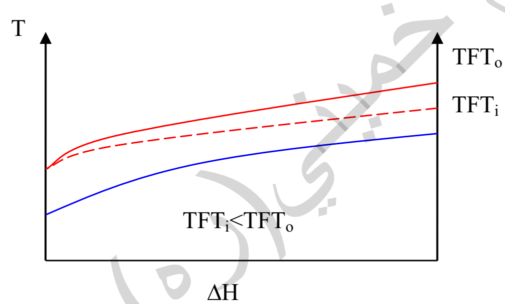

Fig. 6. Hot composite curve is closer to cold composite curve when TFT_o is reduced to TFT_i.

(b) Reducing stack temperature (*T* stack)

Fig. 7 shows the exergy composite curve where the hot composite curve is closer to the cold composite curve when $T\ stack_o$ is reduced to $T\ stack_i$. Note that $T\ stack_i$ is less than $T\ stack_o$. Usually the heat at the furnace stack is used as the heat source to preheat the boiling feed water for steam generation. This technique will reduce the stack temperature. However, reducing stack temperature is limited by the acid dew temperature of the flue gas. Stack temperature must always greater than acid dew temperature of flue gas to avoid environmental problem and corrosion.

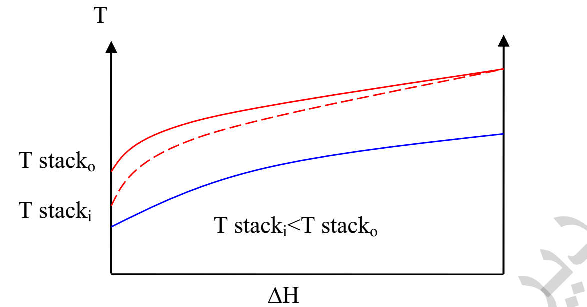

Fig. 7. Hot composite curve is closer to cold composite curve when $T\ stack_o$ is reduced to $T\ stack_i$.

(c) Increasing tower inlet temperature (TIT)

Fig. 8 shows the exergy composite curve where the cold composite curve is closer to the hot composite curve when TIT_o is increased to TIT_i. Note that TIT_i is greater than TIT_o. The method to increase TIT is by increasing temperature difference of the furnace (ΔT). ΔT is the temperature difference between TIT and FIT. One way to increase ΔT is by reducing crude oil flow rate to the furnace. Heat duty is defined as $Q = mC_p\Delta T$ where flow rate (m) is inversely proportional to ΔT. Thus, decreasing flow rate (m) will increase ΔT of the furnace. However, reducing flow rate of crude oil will also reduce the production of the plant.

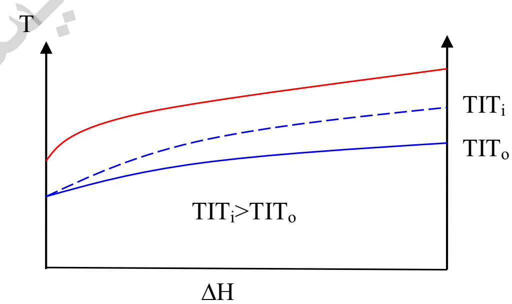

Fig. 8. Cold composite curve is closer to hot composite curve when TIT_o is increased to TIT_i.

(d) Increasing furnace inlet temperature (FIT)

Fig. 9 shows the exergy composite curve where the cold composite curve is closer to the hot composite curve when FIT_o is increased to FIT_i. Note that FIT_i is greater than FIT_o. The high heat transfer efficiencies of crude preheat train may increase FIT. The heat exchangers with high heat transfer efficiencies can be

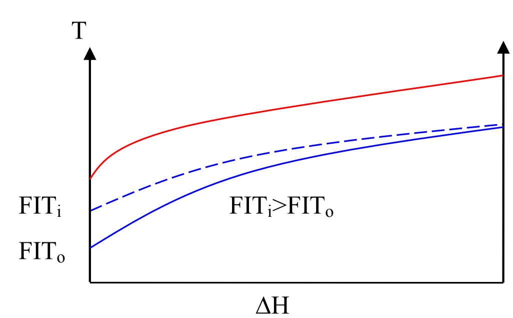

Fig. 9. Cold composite curve is closer to hot composite curve when FIT_o is increased to FIT_i.

achieved by reducing the fouling rate. Cleaning heat exchangers at certain period of time may reduce fouling rate [14].

3.3. Fuel reduction strategies

3.3.1. Reduction of heat loss from furnace stack

The process fluid goes to convection section and then flows to radiation section of the furnace. The operation will control the opening of stack damper in order to recover more heat at the convection section. However, during this adjustment, the amount of excess oxygen will be monitored closely to avoid incomplete combustion. When more heat is recovered in the convection section, process fluid will have higher amount of heat that are going to radiation section. Thus, the firing of fuel gas consumption in the furnace will reduce due to lower stack temperature of furnace in convection section. Reducing stack temperature will recover the available heat instead of wasting the heat into the atmosphere.

The reduction of heat loss from furnace stack is demonstrated in Fig. 10. The temperature versus enthalpy in furnace operation is shown. When $T\text{stack}_1$ is reduced to $T\text{stack}_2$, the amount of heat loss is reduced. From Eq. (4), η is the furnace efficiency, ΔT is the temperature difference from theoretical flame temperature (TFT) to stack temperature (Tstack), m is flue gas flow rate, C_p is the specific heat of the flue gas and ΔH_c is the heat of combustion of the fuel gas [15].

$$\eta = \frac{Q_{\text{process}}}{Q_{\text{fuel}}} = \frac{mC_p\Delta T}{\Delta H_c} \tag{4}$$

From this equation, when T stack is reduced, ΔT will be increased. Thus, the furnace efficiency, η increases.

Fuel gas flow rate is calculated by dividing furnace duty with heat of combustion of the fuel gas. This is the fuel gas consumption at 100% efficiency. The fuel gas consumption at 100% efficiency is divided by actual furnace efficiency to obtain the exact fuel gas consumption.

$$m_{\text{fuel}} = \frac{Q_{\text{furnace}}}{\Delta H_c} \times \frac{1}{\eta} \tag{5}$$

The flow rate of fuel gas, m is calculated using Eq. (5). Furnace stack temperature is plotted against volume flow rate of fuel gas. Fig. 11 shows the relation between fuel gas flow rate and the furnace stack temperature. The slope of the graph is 2.6 Nm^3/h °C. This slope indicates that if stack temperature is reduced by 1 °C, 2.6 Nm^3/h of fuel gas can be saved.

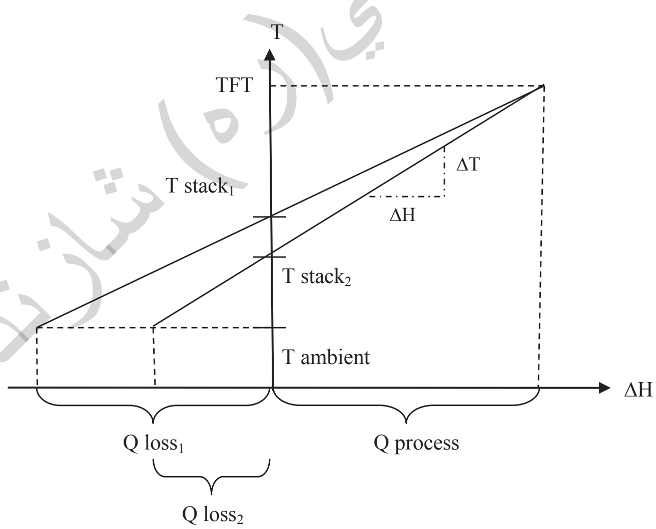

Fig. 10. Temperature-enthalpy profile for furnace operation.

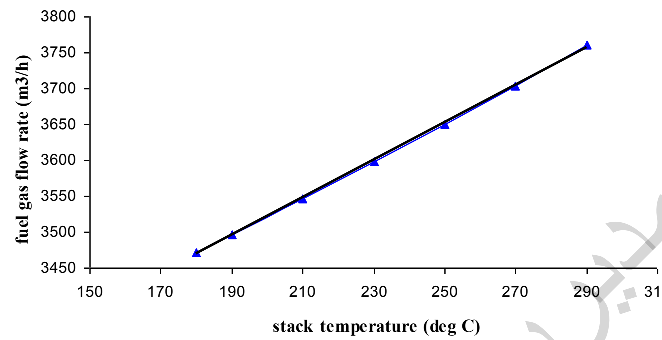

Fig. 11. Fuel gas flow rate versus stack temperature of furnace.

The current stack temperature is 290 °C. If 50 °C reductions in stack temperature, the new stack temperature is 240 °C. Thus, the amount of fuel gas saving as 50 °C reduction in stack temperature is 130 Nm^3/h. In the plant historical data, the best practice for stack temperature is 169 °C. However, reducing stack temperature is limited by acid dew temperature of flue gas. The stack temperature must always higher than acid dew temperature of flue gas to avoid corrosion and environmental problems.

3.3.2. Overall cleaning schedule of CPT

The model minimizes the expected cost throughout the time horizon. The cost is the tradeoff between extra fuel costs due to fouling, heat exchangers cleaning costs, loss in production costs due to plant shutdown and increased heat recovery after cleaning.

$$\text{Cost} = \alpha \sum_t (\text{FG}_t - \text{FG}_{t=0})C_{\text{fl}} + \sum_t (y_t)\left(C_{\text{cl}} + C_{\text{pl}}\right) \tag{6}$$

FG_t (m^3/h) is the fuel gas consumption at time t, $\text{FG}_{t=0}$ 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 and C_{pl} is the loss in production cost due to plant shutdown. Symbol α is the conversion factor with unit of GJ h/month m^3.

The binary variable y_t is defined to identify at what period t the crude preheat train is shutdown for cleaning.

$$y_t \begin{cases} 1 & \text{if the plant is shutdown to clean CPT in period } t \\ 0 & \text{otherwise} \end{cases}$$

The historical data for fuel gas flow rate and furnace inlet temperature (FIT) is collected. From the historical data, fuel gas flow rate is plotted against FIT to obtain linear correlation between these two variables. Fuel gas is expected to increase as FIT is decreased due to fouling in CPT as shown in Fig. 12. Eq. (7) shows linear correlation between fuel gas flow rate and FIT.

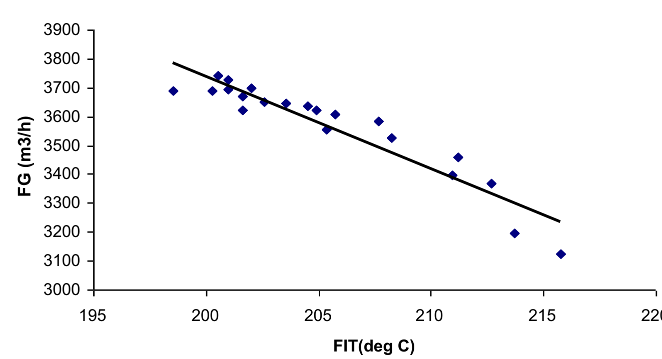

Fig. 12. Linear correlation for fuel gas flow rate and FIT.

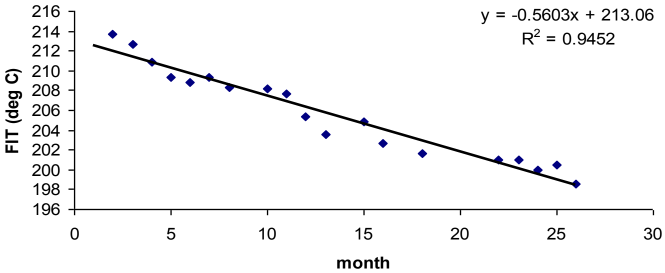

Fig. 13. Linear trends for FIT profile.

$$FG_t = -31.997 \times (FIT_t) + 10,139 \quad (7)$$

Furnace inlet temperature (FIT) is the crude oil exit temperatures of crude preheat train before additional heating is provided by furnace. As time of operation increases, the value of FIT is expected to decrease due to the increment of fouling. FIT is reduced until it reaches threshold temperature. Threshold temperature is the critical temperature of chronic fouling condition. The value of critical temperature in this case is 200 °C.

The graph of FIT versus month is plotted to obtain the slope of the graph. The slope is the amount of FIT reduction per month of operation as shown in Fig. 13. The reduction of FIT per month is −0.56 °C/month Eq. (8) is the reduction in FIT as time of operation increases.

$$FIT_t = (FIT_{t-1} - 0.5603)(1 - y_t) + FIT_{t=0}(y_t) \quad (8)$$

During any period when no cleaning is performed, $y_t = 0$, the expression becomes

$$FIT_t = FIT_{t-1} - 0.5603 \quad (9)$$

Eq. (9) indicates that FIT at period t is equal to FIT at previous period $t - 1$ deducted by 0.56. When cleaning is performed at certain period t, $y_t = 1$, the expression reduces to

$$FIT_t = FIT_{t=0} \quad (10)$$

Eq. (10) shows that FIT at period t is equal to FIT at period $t = 0$ when cleaning is performed. FIT at $t = 0$ is the maximum value of FIT at clean condition.

The initial assigned value of FIT at $t = 0$ is the maximum value of FIT in the refinery at clean condition which is at 215 °C.

$$FIT_{t=0} = 215 \quad (11)$$

The minimum allowable FIT is greater than 200 °C. FIT at any period of t should not less than critical temperature that is determined by process engineer in the refinery.

$$FIT_t \geq 200$$

3.4. Feasibility and economic analysis

The current practice in the refinery to reduce energy consumption due to fouling is to shutdown the plant for crude preheat train (CPT) overall cleaning. The fouling rates formation in the crude preheat train are observed by monitoring furnace inlet temperatures (FITs). When FIT reaches the minimum allowable temperature which is below 200 °C, the engineers may consider to shutdown the plant for CPT cleaning.

The current practice to minimize energy consumption is non-optimal overall cleaning schedule of CPT because the engineers do not use any optimization tool to predict when the optimal period to shutdown the plant for CPT cleaning. The refinery's turnaround is every five years. For the last five years, the plant was shutdown twice to clean CPT. From Table 4, cleaning schedule for Option 2 is on 17th and 44th months. Meanwhile for current practice, the cleaning schedule is on 28th and 49th months.

Table 5
Comparison of energy saving for all options.

Options	Fuel gas			
	Extra flow rate (Nm^3/year)	Amount of energy (GJ/year)	Energy saving (GJ/year)	Percentage saving (%/year)
Current Practice	99,598,913	2,888,368	–	–
Option 1	98,460,113	2,855,343	32,486	1.14
Option 2	94,022,631	2,726,656	161,712	5.60

Table 5 demonstrates the comparison of energy saving for all options. Extra fuel gas flow rate (ΔFG) 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 (Nm^3/year) with heating value of fuel gas. The heating value is 14.95 kWh/kg or 0.029 GJ/Nm^3. For option 1, 1 °C reduction in stack temperature will save 2.6 Nm^3/h of fuel gas as explained in Fig. 11. The amount of fuel gas saving as 50 °C reduction in stack temperature is 130 Nm^3/h which equal to energy saving of 32,486 GJ/year. For Option 2, the amounts of extra fuel gas flow rate are obtained from optimization model. From Table 5, option 2 has higher energy saving compared to option 1.

The total cost calculation for current practice is the summation of fuel gas cost, heat exchanger cleaning cost, lost in production cost due to plant shutdown. The current practice cost is calculated as demonstrated in Table 6. In conversion column, the value of 0.029 GJ/m^3 is multiplied by 24 h/day and 30 day/month. From the plant historical data on fuel gas price, cleaning cost and production lost cost, the value of fuel gas price is RM 14.55/GJ, cleaning cost is RM 40,000/unit and production lost cost is RM 545,000/day. CDU is expected to shutdown for 10 days during crude preheat train cleaning. The annual total cost for current practice is RM 44,415,030/year.

Table 7 demonstrates the cost for all options. Option 1 has the highest percentage of cost saving at about 6.44%. Option 2 is the lowest cost saving at about 5.31%. This is due to additional cost for heat exchanger cleaning and production lost cost.

4. Conclusion

Exergy analysis is conducted for CPT and furnace in CDU. From exergy composite curve, the highest exergy loss occurs in the furnace as depicted by the largest gap between the exergy source and exergy sink of exergy composite curves. Exergy loss in the

Table 4
Current practice and optimal cleaning schedule for Option 2.

	Month									No. of cleaning
	1–16	17	18–27	28	29–43	44	45–48	49	50–59	
Current practice				•				•		2
Option 2		•				•				2

Table 6
Current practice cost calculation.

Details	Amount	Cost	Multiply	Conversion	RM
Total extra fuel gas flow rate	11,528 Nm^3/h	RM 14.55/GJ	60 months	20.88 GJ.h/month.m^3	210,135,151
Heat exchanger cleaning	13 units	RM 40,000/unit	2 times	–	1,040,000
Production lost	10 days	RM 545,000/day	2 times	–	10,900,000
Total (RM)					222,075,151
Annual cost (RM/year)					44,415,030

Table 7
Cost for all options.

Options	Total cost (RM)	Annual cost (RM/year)	Cost saving per year (RM/year)	Percentage of cost saving (%/year)
Current Practice	222,075,151	44,415,030	–	–
Option 1	207,765,480	41,553,096	2,861,934	6.44
Option 2	210,290,613	42,058,123	2,356,908	5.31

furnace contributes to 86% of total exergy loss in the system. From exergy composite curve analysis, possible fuel reduction strategies are generated. From the possible fuel reduction strategies, two proposed options are implemented. The proposed options are reduction of heat loss from furnace stack and overall cleaning schedule of CPT. Comparison of energy and cost saving are made for all the options. From the results, option 2 is the highest energy saving compared to option 1. However, option 1 is the highest cost saving. This is due to additional cost for heat exchanger cleaning and lost production in option 2.

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Nomenclature

C_{cl}: heat exchanger cleaning cost (RM/unit)
C_{fl}: furnace's fuel cost (RM/GJ)
C_{pl}: production lost cost due to plant shutdown (RM/unit)
FG: fuel gas flow rate (m^3/h)
FIT: furnace inlet temperature (°C)
m: mass flow rate (kg/h)
T: temperature (K)
T stack: stack temperature (°C)
TFT: theoretical flame temperature (°C)
TIT: tower inlet temperature (°C)
Q: heat duty (kW)
y: binary variable for CPT cleaning
ΔEx_{source}: exergy source (kW)
ΔEx_{sink}: exergy sink (kW)
ΔEx_{loss}: exergy loss (kW)
ΔFG: extra fuel gas flow rate (m^3/h)
ΔH: enthalpy (kW)
ΔH_c: heat of combustion (kW)
ΔS_c: entropy change for cold stream (kW/°C)
ΔS_h: entropy change for hot stream (kW/°C)
α: conversion factor (GJ h/month m^3)
η: furnace efficiency