MANAGEMENT OF CLEANING TYPES AND SCHEDULES IN REFINERY HEAT EXCHANGERS

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ABSTRACT

Energy recovery and production in oil refinery pre-heat trains are greatly affected by fouling, the progressive build-up of unwanted material on the heat exchanger surfaces. Even when good design practices, operation or mitigation measures are in place, fouling cannot be completely eliminated in most situations. As a result, heat exchangers have to be periodically taken out of operation for cleaning. Traditional mechanical cleaning methods (e.g. hydro-blast) usually remove the whole deposit while chemical cleaning methods represent a less expensive option whose effectiveness depends on a number of factors (e.g. choice of chemicals, deposits composition and ageing, etc.). In this paper a detailed dynamic distributed model of shell and tube exchangers undergoing fouling has been used to simulate different cleaning schedules involving mechanical and chemical operations and assess their economic impact.

INTRODUCTION

The energy recovered in oil refinery pre-heat trains (PHT) is reduced over time due to crude oil fouling, considered as one of the major costs in oil refineries not only in terms of energy losses and fuel consumption but also greenhouse gases emission and continuity of operations [1]. Estimations suggest that fouling mitigation in crude distillation units (CDU) could lead to 15% fuel savings in the furnace downstream the PHT, equivalent to worldwide savings of about 500,000 bbl/day [2], the size of a large refinery. The effect of fouling increases over time as a consequence of ageing, which causes the modification of foulants properties from that of a gel like layer (fresh deposit) to coke like (aged deposit), with the most important impact noticeable trough the change in thermal conductivity and hardness.

Being able to describe fouling evolution is essential to evaluate its effect. Mathematical models that attempt to capture this behaviour exist in the literature [13]. In addition, ageing plays an important role, particularly for the establishment of optimal cleaning schedules since it defines the actual properties of the foulant to be removed [1, 4]. Even though the importance of considering ageing was highlighted early on in fouling research [3], it has continue to be a poorly understood process usually described with a simplified two-layer model [5]. Recently, a more realistic description of the deposit layer defined as a continuous domain has been presented [11].

Previous work focusing on managing cleaning scheduling for crude oil heat exchange networks accounts only for mechanical cleaning operations, considering a total removal of the deposit from the heat exchanger (HEX) surface [6, 7]. The publications considering chemical cleaning for the determination of cleaning schedules include them only in a very simplistic way leading to a partial recovery of exchangers thermal performance but do not describe the actual dynamics of the chemical cleaning process. Such analysis does not take into account the impact of ageing

NOMENCLATURE

b	[-]	Cleaning variable
CDU	[-]	Crude distillation unit
E_f	[J/mol]	Fouling deposition activation energy
HEX	[-]	Heat exchanger
HL	[-]	Hydraulic limit
k	[W/mK]	Thermal conductivity
n	[kg/m^{2}s]	Mass flux rate
NCl	[-]	Cleaning methods
P	[Pa]	Pressure
PHT	[-]	Pre-heat train
Pr	[-]	Prandtl number
R	[J/molK]	Ideal gas constant
Re	[-]	Reynolds number
T	[K]	Temperature
T_f	[K]	Tube-side film temperature
TL	[-]	Thermal limit
x	[-]	Volume fraction
Special characters		
α'	[m/s]	Modified deposition constant
δ	[m]	Fouling layer thickness
ΔP	[Pa]	Tube side pressure drop
γ'	[m^3/sN]	Modified suppression constant
τ_w	[N/m^2]	Wall shear stress
Subscripts		
Cl	Cleaning	
f	Fouling	
k	Type of cleaning	
l	Layer	
w	Wall	

on fouling induction period depending on the cleaning method used. Thus, the actual dynamics of deposition and growth after cleaning is not being accurately described.

In this paper, Hexxcell $Studio^{TM}$ [10], a software specifically developed for more advanced modelling and simulation of heat exchangers undergoing fouling based on [2] and [11] is used. Various alternative cleaning schedules for the hot end section of a refinery PHT are simulated with both mechanical and chemical cleaning operations, assessing the thermo-hydraulic performance and attached economic costs. Mechanical cleanings are characterized by a fixed time operation while chemical cleanings are defined as condition-based [11], using a mathematical model of the chemical cleaning dynamics that allows establishing the effectiveness and depth of cleaning achieved by different chemical agents as well as the exchanger conditions left at the end of the partial cleaning [12]. Subsequent performance in operation will also depend upon the status of the deposits reached during cleaning. The distinctive advantages of this approach are that it is possible to (i) calculate the detailed interaction effects that cleaning individual exchangers has on fouling, heat duty and pressure drop of other exchangers in a network, (ii) describe and minimise the cleaning time needed for a specific chemical cleaning agent used, (iii) select the appropriate type of cleaning (mechanical or chemical) based on the deposit's conditions, and (iv) assessing the cleaning schedule performance based on thermal and hydraulic considerations, costs of energy and refinery margins. This framework sets the basis for a rigorous dynamic optimization of cleaning planning and scheduling which is under development.

MODELLING APPROACH

A detailed dynamic, distributed model for shell-and-tube heat exchangers defines the conditions in each tube capturing its thermal and hydraulic behavior [2]. At each point along the exchanger, the deposition rate is described by the adapted threshold model [11, 13]:

$$n_f(z) = \alpha' Re(z)^{-0.66} Pr(z)^{-0.33} e^{\frac{-E_f}{RT_{film}(z)}} - \gamma' \tau_w(z) \qquad (1)$$

The deposit is modelled as a varying-thickness solid undergoing a number of chemical reactions with axial and radial distributed. It is therefore able to track local deposition history and evolution at each point. Mass and energy balances are used to describe the deposit sub-system as detailed in [11]. In this paper, the crude oil deposit is assumed to be composed of organic matter only. The deposit is assumed to be initially formed of gel, gradually evolving to coke according to the kinetics as in [14]. Consequently, two pseudo-components (gel and coke) and a single chemical reaction (ageing) are used to define the deposit layer. Local thermal conductivity, which determines the resistance to heat transfer, is calculated as follows:

$$k = k_{coke} x_{coke} + k_{gel} x_{gel} \qquad (2)$$

where the (r,z) dependency of each variable is not shown for the shake of simplicity.

The fouling layer, described following the formulation developed in [11] allows the continuous simulation of cleaning schedules containing mechanical and chemical operations. For this purpose, fouling (n_f) and cleaning ($n_{Cl,k}$) rates in terms of mass fluxes depositing on (during operation) or leaving (during cleaning) a solid deposit of time-varying thickness δ_l at each point z along the tube axis are included:

$$\frac{d\delta_l(z)}{dt} = (1 - b(t)) n_f(t) - \sum_{k=1}^{NCl} b_k(t) n_{Cl,k}(t) \qquad (3)$$

In Equation (3), b_k is a 0-1 binary variable that defines whether a cleaning method k is used at each time, while b_{clean} indicates whether any one of NCl distinct cleaning methods is used (b_{clean}=1) or not (b_{clean}=0). The constraint $b_{clean} = \sum_1^{NCl} \leq 1$ ensures that at most one cleaning method is used at a time.

Mechanical cleaning operations (M) are assumed to last a fixed time t_M, with the rate adjusted to ensure total cleaning achieved in that time [11] (Equation (4)). The chemical cleaning (Ck) model adopted allows the definition of the operations as "fixed time" or "condition-based", in which case the cleaning finishes upon reaching a predefined termination condition [12] (Equation (5)). Its rate is proportional to the concentration of the cleaning agent (C) and a function of the coke fraction at the surface of the deposit layer ($x_{l,coke}$) and the cleaning time elapsed from start of the cleaning operation (t_{Cl}). Parameter n is a constant related to the speed of action of the chemical agent while a enables further adjustments of the model response to match that of experimental data. $k_{Cl,M}$ and $k_{Cl,Ck}$ are rate constants in the mechanical and chemical cleaning rate models respectively.

$$n_{Cl,M} = k_{Cl,M} \delta_l \qquad (4)$$

$$n_{Cl,Ck} = \frac{k_{Cl,Ck} C}{1 + (a x_{l,coke}, t_{cl})^n} \qquad (5)$$

CASE STUDY

The case study analyzed is based on an actual refinery hot end PHT for which a detailed model including fouling was fitted to and validated against operational data [15]. The network consists of five shell and tube HEX (E01 to E05) distributed in two branches with a furnace (F01) to provide the additional thermal energy required for crude fractionation (Figure 1). The network has strong interactions between the different HEX. Flow is

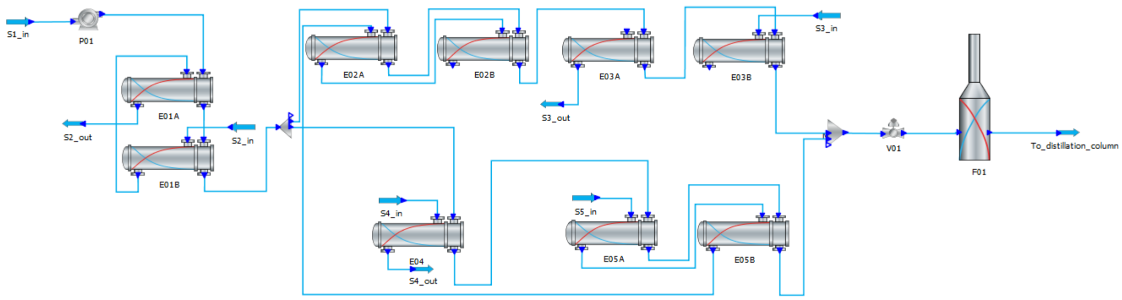

Figure 1. Hot end structure of the crude PHT considered [15].

Table 1. Inlet streams properties.

		S1	S2	S3	S4	S5
Volumetric flow rate	m^3/h	743	850	82	60	160
Temperature	$^\circ C$	160	250	350	320	330
Pressure	bar	12	5	5	5	5
API	$^\circ API$	35	3	30	30	17
MeABP	$^\circ C$	300	300	360	360	683.08
Kinematic viscosity	cSt	14	3.4	14	14	350

split downstream of E01, balancing the pressure drop in the two branches. E02 and E03 are included in the first branch (B1) and E04 and E05 in the second (B2). In addition, E05 outlet shell stream is directed to E02 to further heat recovery. Feed conditions are time-invariant, fixed to average values based on plant measurements (Table 1). Geometrical parameters of the HEX can be found in [15]. Fouling is considered to occur only in the tube-side. The fouling and ageing parameters where determined following a thermo-hydraulic analysis and parameter estimation detailed in [16]. All simulations are started from clean conditions. Two different cleaning schedules containing mechanical and chemical operations are simulated for the above PHT. The economic impact of both options is evaluated comparing their cost over the fixed time horizon of 550 days. Mechanical cleaning is assumed to remove the whole deposit from the exchanger surface in 10 days, whereas the duration and performance of the chemical cleaning will depend on a number of factors based on Equation (5).

Cost model

For the purpose of evaluating the different cleaning alternatives a cost model is defined. It includes the costs of fouling given by the KPIs defined in [15] together with the costs of the cleaning activities (Equation (6)). Fouling costs are divided in three types: extra fuel at the furnace (C_F), additional emissions (C_E) and loss of production (C_P). The last is broadly acknowledged to be the one with the highest impact. As fouling builds up, the pressure drop (ΔP) in the PHT increases, continuously opening the throttle valve (V01) until its maximum, hitting in this way the hydraulic limit (HL). On the other hand, the progress of fouling requires more fuel to be burnt in the furnace, until its maximum thermal limit (TL) is hit. In any of these cases, the throughput has to be reduced in order to maintain the specified temperature at the furnace outlet, causing important economic losses. The cleaning costs (C_C) (Equation (10)) comprise the expenses of the total number of mechanical (C_{MC}) and chemical (C_{CC}) activities performed in the operating period. Table 2 includes the parameters assumed for the calculations.

Table 2. Cost model parameters (adapted from [15]).

Parameter	Symbol	Value	Units
Carbon content in fuel	cc	0.7	kgC/kg
Energy content of fuel	ec	11.7	kWh/kg
Cost of CO_2 emissions	P_{CO_2}	30	$\$/Ton$
Fuel price	P_F	27	$\$/MWh$
Profit margin per kg	P_{kg}	0.23	$\$/kg$
Furnace efficiency	$\eta_{furnace}$	90	$\%$
Price of mech. cleaning	P_{MC}	30,000	$\$/clean$
Price of chem. cleaning	P_{CC}	Cost model in [17]	$\$/day$

$$C = C_F + C_E + C_P + C_C \quad (6)$$

$$C_F = \frac{P_F}{\eta_{furnace}} \int_0^t (Q_{furnace}(t) - Q_{furnace}(0))dt \quad (7)$$

$$C_E = P_{CO_2} \frac{ccMW_{CO_2}}{ecMW_C \eta_{furnace}} \int_0^t (Q_{furnace}(t) - Q_{furnace}(0))dt \quad (8)$$

$$C_P = P_{kg} \int_0^t (\dot{m}(0) - \dot{m}(t))dt \quad (9)$$

$$C_C = \sum_{j=1}^{N_{HEX}} \int_0^t \left(\frac{P_{MC}}{t_{MC}} b_k(t) + P_{CC} b_k(t) \right) dt \quad (10)$$

RESULTS

The actual cleaning schedule, based on historical plant data, for the PHT has been simulated for 550 days after a major shut down (Figure 2.a). During this period, E01 undergoes two mechanical cleanings (after 205 and 420 days), E04 one chemical (after 220 days) and one mechanical cleaning (after 300 days), and E05 one mechanical cleaning (after 320 days). The chemical cleaning of E04, simulated in this initial case as a 5 days fixed time operation, was reported to be inefficient, recovering only a small fraction of the energy. The maximum heat capacity

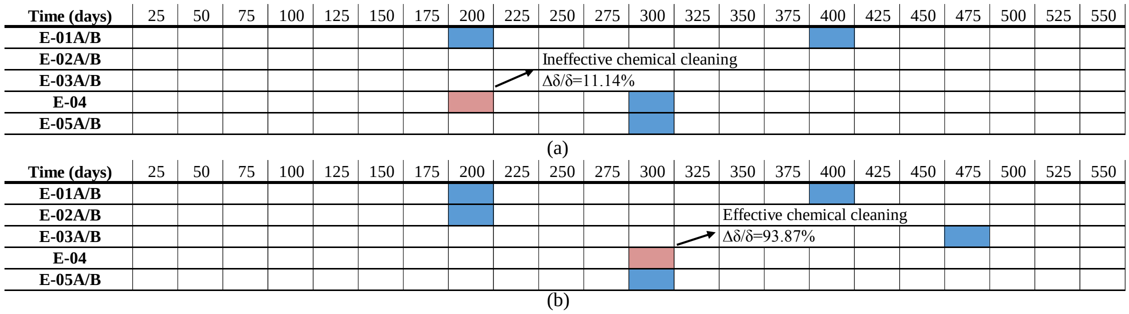

Figure 2. Case study cleaning schedule along 550 days. (a) Actual (b) Proposed.

of the furnace is considered to be 120 MW [15] and a constant pressure drop through the system of 13 bar is used. The unit with the greater duty in clean conditions (22.58 MW) is E01AB and, consequently, it is particularly important for heat recovery in the network. Despite fouling accumulating at a slower rate, after 200 days Q/Q_0 (ratio of the heat duty and the heat duty at time 0) in E01 has decreased to 0.4, whilst it is maintained above 0.8 for the other units (Figure 3.a). At this point, the deposit thickness is less than 1 mm ($R_{f,eq} < 3.75 Km^2/kW$) (Figure 3.g), while in E02 is about 1.5 mm ($R_{f,eq} \approx 6 Km^2/kW$) (Figure 3.d). Even though E03 operates at higher temperatures than E02, it presents a lower fouling rate due the higher shear. Interesting phenomena are unveiled when considering the dynamics of fouling due to the interactions between various heat exchangers. Whilst fouling decreases the heat recovery in the PHT, it actually increases the performance of some units. One such example is E02, which is affected by the reduction in the tube outlet temperature of E01 and increase in shell outlet temperature of E05 due to fouling, leading to a much higher temperature driving force and a consequent increase in heat duty (Figure 3.a). In spite of being the most fouled unit, its Q/Q_0 stays above 1 for the first 200 days. In terms of pressure drops, E01 is the lowest contributor. In contrast, the hottest heat exchangers (E03 and E05), more heavily fouled, present a substantial increase in ΔP (1.5 bar per shell after 200 days) (Figure 3.e). E02 and E03 (in branch B1) have faster deposition rates that leads to flow imbalance between branches B1 and B2 (Figure 3.f), making the split fraction increase from 56.7% in B1 (4 shells in this branch vs. 3 in B2) at time 0 to 60% after 200 days.

The first mechanical cleaning is carried out after 205 days in E01 with a substantial increase in the heat duty recovered and the furnace inlet temperature (CIT). The energy recovered in the PHT (overall Q/Q_0) increases 35.2%, whereas the decrease in the overall pressure drop is negligible. Immediately after E04 is chemically cleaned, barely improving the performance of the unit ($\approx$ 11% deposit removal). The combination of these two initial cleanings leads to $\Delta CIT = 13.6°C$. The poor effectiveness of the chemical cleaning makes necessary to perform a second cleaning, this time mechanical, 80 days after (300 days). The pressure drop in the unit decreases by 0.51 bar (35%), causing an overall decrease in the $\Delta P/\Delta P_0$ of 10.3%, but only a small recovery in the overall Q/Q_0 of 1.4%. The following mechanical cleaning of E05 positively impacts the thermal and, more importantly, the hydraulic performance of the PHT: ΔP decreases by 1 bar/shell. This increases by 10% the overall Q/Q_0 (with a subsequent $\Delta CIT = 2.9°C$) and decreases $\Delta P/\Delta P_0$ 60%. Finally, E01 is mechanically cleaned for the second time, under similar circumstances and with similar improvements as in the first case. Figure 3.c, shows that the TL is not reached at any point thorough the operating period. As a result, the throughput is maintained and the extra cost of fouling are only associated to the additional fuel burned, its related CO_2 emissions, and cleaning (Figure 3.h). The total costs amount to \$5.86 MM, the fuel cost term being dominant ($C_F = \$4.61 MM$), with minor contributions due to emissions ($C_E = \$1.13 MM$) and cleanings ($C_C = \$0.123 MM$).

Using this base case as a reference, alternative cleaning schedules have been analyzed following a sensitivity analysis [17]. The main findings of the study were that: (i) the most significant benefit is achieved if E02 and/or E03 are cleaned in the first 18 months, (ii) small variations of the cleaning time of E01 and E05 do not have a significant effect on performance, but these are important penalties if they are considerably delayed, and (iii) an efficient application of the chemical cleanings by the correct selection of appropriate chemical agent and time (e.g. avoiding chemical cleaning of aged deposits) plays an important role. Based on the results obtained, an alternative schedule is proposed with five mechanical cleanings and one (effective) chemical cleaning, i.e. only one additional operation (Figure 2.b). Mechanical cleanings of E01 are moved forward to 180 and 375 days, showing minor improvements. An additional mechanical cleaning of E02 at 220 days has been introduced, with an important impact on ΔP recovery ($\approx$ 8.5%) but small thermal effect ($\Delta CIT = 1°C$). E04 is chemically cleaned at 300 days. This time, the operation has been simulated as condition-based, stopping the cleaning when the maximum performance of the agent is reached ($t_{Cl} = 4.47 days$). The chemical cleaning removes $\approx$ 94% of the deposit, thus improving the thermal response of the network by $\Delta CIT = 6°C$. Though performed at the same time as before (320 days), the mechanical cleaning of E05 shows a different outcome due to the change in the state of the PHT ($\Delta CIT = 9.6°C$, $\Delta P/\Delta P_0 = 55.7\%$). Finally, E03 is mechanically cleaned after 485 days, obtaining a significant impact on the hydraulic performance (68% reduction in $\Delta P/\Delta P_0$).

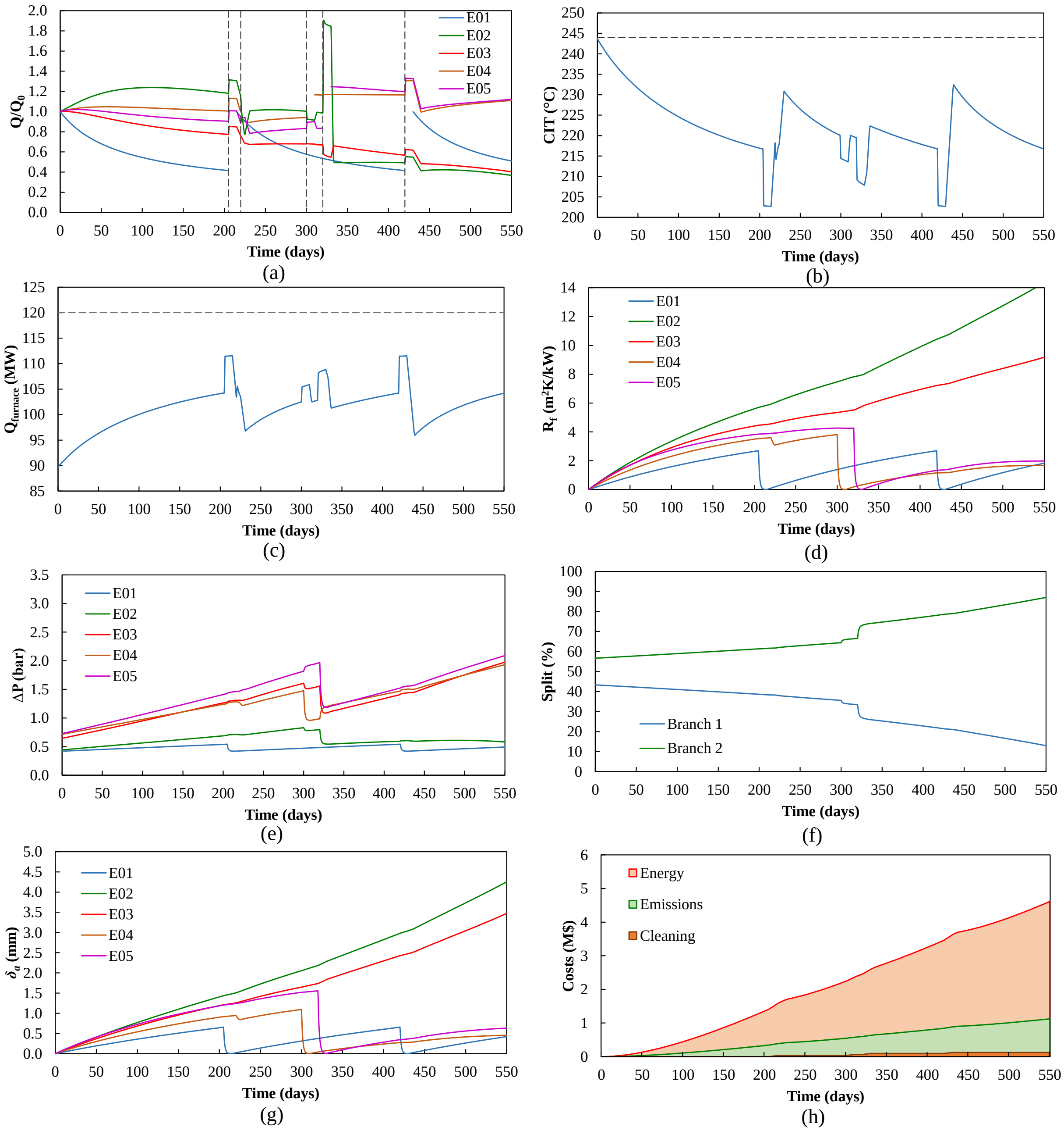

Figure 3. PHT results from the application of the actual cleaning schedule along 550 days.

Results are summarized in Figure 4. As in the base case scenario, fuel cost is the dominant contributor to the total fouling costs ($C_F = \$4.33MM$). Together with the cost of emissions ($C_E = \$1.06MM$) and cleaning ($C_C = \$0.154MM$) the operating costs are now \$5.54 MM, a savings \$317K (5.4%) over the plant schedule. There are further large opportunities for optimisation over this second manual schedule.

CONCLUSIONS

The modelling framework presented allows the continuous simulation of fouling-cleaning cycles including mechanical and chemical cleanings, setting up the basis for a future dynamic optimization formulation. The results obtained highlight (i) the very important difference in the thermal and hydraulic effects of cleaning each heat exchanger, (ii) the very important thermal and hydraulic effects of fouling/cleaning each heat exchanger on the PHT and (iii) the economic impact of these effects and the need to include them in the choice of cleaning schedules.

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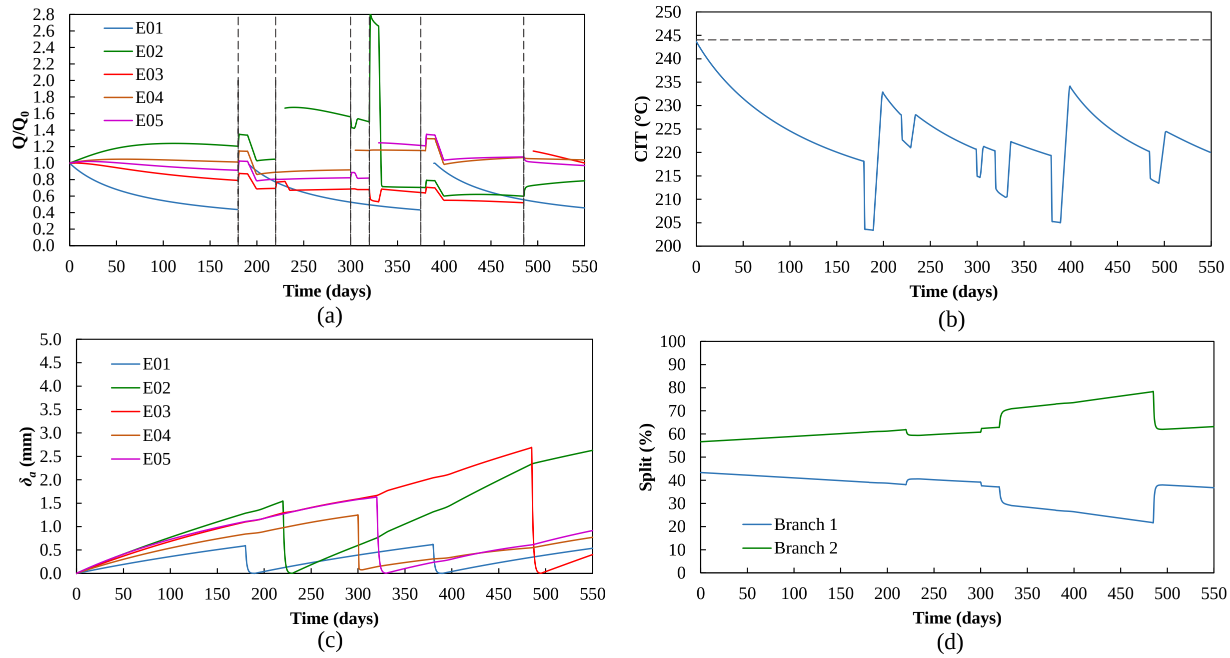

Figure 4. PHT results from the application of the proposed cleaning schedule along 550 days.

acknowledged.

REFERENCES

[1] Coletti F., Joshi H.M., Macchietto S., and Hewitt G.F., Introduction to *Crude Oil Fouling, in Crude Oil Fouling: Deposit Characterization, Measurements, and Modeling*, F. Coletti and G. F. Hewitt, Eds. Gulf Professional Publishing, 2014.

[2] Coletti F. and Macchietto S., A Dynamic, Distributed Model of Shell-and-Tube Heat Exchangers Undergoing Crude Oil Fouling, *Ind. Eng. Chem. Res.*, vol. 50, no. 8, pp. 4515-4533, Apr. 2011.

[3] Epstein N., Thinking about Heat Transfer Fouling: A 5x5 Matrix. *Heat Transfer Engineering*. 4 (1), 43-56, 1981.

[4] Muller-Steinhagen H.; Introduction. In: Muller-Steinhagen, H. and Zettler, H. U. (eds.). *Heat exchanger fouling. Mitigation and cleaning technologies*. 2nd edition., Publico Publications. 2011, pp. 2-20.

[5] Ishiyama E. M., Paterson W. R. and Wilson D. I., Exploration of alternative models for the aging of fouling deposits. *AIChE Journal*. 57 (11), 3199-3209, 2011.

[6] Lemos J. C., Assis B. C. G., Costa A. L. H., Queiroz E. M., Pessoa F. L. P., Liporace F. S. and Oliveira, S. G., A sliding mixed-integer linear programming approach for the pptimization of the cleaning schedule of crude preheat trains. *Heat Transfer Engineering*. 36, 642-651, 2015.

[7] Gonalves C. O., Queiroz E. M., Pessoa F. L. P., Liporace F. S., Oliveira S. G. and Costa A. L. H., Heuristic optimization of the cleaning schedule of crude preheat trains. *Applied Thermal Engineering*. 73 (1), 3-14, 2014.

[8] Ishiyama E. M., Paterson W. R. and Wilson D. I., Aging is important: closing the fouling-cleaning loop. *Heat Transfer Engineering*. 35 (3), 311-326, 2014.

[9] Diaby A. L., Bari S. L., Miklavcic S. J. and Addai-Mensah J., On a precursor model to a genetic algorithm model for the scheduling of heat exchanger network cleaning. *Brisbane, Qld.* , Chemeca 2013, Engineers Australia. pp.506-514, 2013.

[10] Hexxcell. *Hexxcell Ltd.* [Online] Available from: http://www.hexxcell.com/ [Accessed February 2016].

[11] Diaz-Bejarano E., Coletti F. and Macchietto S., A new dynamic model of crude oil fouling deposits and its application to the simulation of fouling-cleaning cycles. *AIChE J*. 62(1), pp.90-107, 2016.

[12] Lanchas-Fuentes L., Diaz-Bejarano E., Coletti F. and Macchietto S., Condition-based chemical cleaning of crude oil fouling deposits a conceptual model. *In ESCAPE 26*. June 12-15, Portoroz, Slovenia.

[13] Panchal C. B., Kuru W. C., Liao C. F., Ebert W. A., and Palen J. W., Threshold conditions for crude oil fouling, in *Understanding Heat Exchanger Fouling and its Mitigation*, 1997, pp. 273-281.

[14] Coletti F., Ishiyama E. M., Paterson W. R., Wilson D. I., and Macchietto S., Impact of Deposit Aging and Surface Roughness on Thermal Fouling: Distributed Model, *AIChE J.*, vol. 56, no. 12, pp. 3257-3273, 2010.

[15] Coletti F. and Macchietto S., Refinery pre-heat train network simulation undergoing fouling: assessment of energy efficiency and carbon emissions. *Heat Transfer Engineering*. 32 (3-4), 228-236, 2011.

[16] Diaz-Bejarano E., *A reaction engineering approach to crude oil fouling deposits: Monitoring, Diagnosis and Cleaning*. PhD Thesis, Imperial College London, 2016

[17] Lanchas-Fuentes L., *Optimal Operation of Large Heat Exchange Networks*. Master Thesis, Imperial College London, 2015