SIMULTANEOUS OPTIMAL CONTROL AND OPTIMAL CLEANING SCHEDULING OF SMALL HEAT EXCHANGER NETWORKS SUBJECT TO FOULING

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ABSTRACT

Refinery operations are responsible for a high fraction of the energy used in the world and have a significant environmental impact on account of CO_2 emissions. One of the major causes reducing their energy efficiency is fouling, the deposition of unwanted material over the surface of heat transfer units. The effects of fouling are more evident in the preheat train of the crude distillation unit where the thermo-hydraulic efficiency can decrease rapidly over time and many cleaning actions or other control-based mitigations alternatives have to be implemented. The optimal cleaning scheduling and optimal control problems are typically addressed separately. The former has been usually addressed using simple models and heuristics or stochastic algorithms, due to the complexity of MINLP formulations with other than unrealistically simple models. This paper presents a novel formulation and mathematical programming approach for fouling mitigation that treats simultaneously the optimal control problem of the network and the optimal cleaning scheduling, with realistic dynamic fouling models. The NLP and MINLP optimization problems are solved via deterministic optimization algorithms. Using two small examples it is shown that the simultaneous strategy has the potential to reduce operation cost by more than 10% over and above the use of individual strategies.

INTRODUCTION

Fouling is the deposition of unwanted material over the surface of heat transfer units which reduces the performance of the operation. It is caused by the presence of impurities in the crude oil, thermal decomposition and oxidation reactions of crude oil constituents [1]. In refinery operations fouling is a recurrent and ubiquitous problem, but it is in the preheat train (PHT) of the crude distillation unit (CDU) where its consequences have more impact. This is because the CDU processes all the crude oil that comes into the refinery at extreme conditions, such as high temperature, varying range of composition and high amounts of contaminants [2]. The main consequence of fouling is an increase in thermal resistance of the heat exchangers in the PHT, which reduces the coil inlet temperature (CIT) to the furnace; to compensate this, more fuel is burned, and carbon emissions and energy cost increase. In addition, fouling affects the hydraulic performance of the exchangers by causing obstruction of the flow, increasing pressure drop and, in extreme cases, generating a full blockage of the tube [2]. Therefore, alternatives for fouling mitigation are needed and of major importance.

NOMENCLATURE

A	[m^2]	Cross section area of flow
δ	[m]	Foulant layer thickness
E	[kJ/kmol]	Activation energy
λ	[W/mK]	Thermal conductivity
N	[-]	Total number of nodes
m	[kg/s]	Mass flow rate
M	[-]	Large value used in big-M constraints
η_b	[-]	Bypass fraction of the cold stream for a heat exchanger
Q	[MW]	Furnace duty
R	[m]	Radius
R_f	[m^{2}K/W]	Fouling resistance
Sp	[-]	Split fraction when there a bifurcation in the network
t	[days]	Time
T	[K]	Temperature
$\bar{t}$	[-]	Dimensionless time
τ	[Pa]	Shear stress
$\tilde{\tau}$	[days]	Period length
x	[-]	Mass fraction
y	[-]	Binary variable for cleaning action of a heat exchanger (1: cleaning, 0: normal operation)
Subscripts		
0	[-]	Initial condition
c	[-]	Coke – Aged deposit / cold stream
h	[-]	Hot stream
I	[-]	Inner side of the tube
f	[-]	Final condition
g	[-]	Gel – Fresh deposit
O	[-]	Outer side of the tube
$flow$	[-]	Condition evaluated at the flow boundary, that between the fluid and the fouling layer

Some options are: cleaning in place (chemical cleaning), mechanical cleaning, using antifoulant agents, and changing the operation conditions (e.g. controlling the flow rate distribution) [2], [3]. Some control optimisations (in milk fouling applications) used detailed dynamic models of individual exchangers [4]. Although cleaning options have been proven to be the most effective alternative to recover thermal and hydraulic efficiency [5], it is not easy to decide which heat exchanger to take out for cleaning and when, so that overall operational cost is minimum and the process throughput is maintained. These decisions have been made using heuristic criteria, (e.g. [2], [6], [7]), and mathematical programming, either MILP or MINLP models (e.g. [4], [8], [9]). The MINLP approach allows, in principle, integrating scheduling and control within a single framework. A large problem size (with detailed models) and the high number of binary variables in current formulations make it hard to solve, and only a local minimum can be guaranteed. The cleaning scheduling problem formulated as a MINLP model, was solved using heuristic approaches such as simulated annealing [10] or "greedy" algorithms [6] to produce a rapid solution, but there is no guarantee that those solutions are optimal. An alternative mathematical programming approach adjusts flow rate distributions to minimize operational cost [11].

This paper presents a novel mathematical programming formulation for fouling mitigation with detailed dynamic models, that treats simultaneously the optimal control problem (e.g. split fraction, bypass fraction, feed flow rate) and the optimal cleaning scheduling of the network. The problem is formulated as an MINLP using a time representation, with the objective to reduce the number of binary variables. The rest of this paper presents the time discretization with variable length. Results for two small case studies demonstrate the approach and potential benefit of a simultaneous solution.

TIME DISCRETIZATION APPROACH

The time discretization approach usually implemented for solving the optimal cleaning scheduling of a heat exchanger network divides the time horizon in multiple periods of equal length (months or weeks). Within each period two sub-periods are defined, a cleaning sub-period and an operating sub-period. A binary variable representing the decision of cleaning (or not) a heat exchanger in a certain period defines the existence of the cleaning sub-period [6], [9]. The problem with this approach is that it does not define accurately the starting time of the cleaning actions as the length of the periods is fixed. Another disadvantage is that this approach requires a large number of periods, which increases the number of binary variables, for capturing the dynamic behaviour of the process.

Another discretization approach more suitable for optimal cleaning scheduling problems is to divide the time horizon in periods of variable length [12]. Within each period a different task or mode of operation can occur in "slots". In our case, only two slots are possible: *operating* and *cleaning*. These two task are mutually exclusive allowing the use of a single slot to represent the period completely. The slots are further divided into discrete points using a discretization technique (e.g. BDF, Euler, Orthogonal Collocation) and the length of the slots can be variable or constant. For simplicity, the Euler method is used here. Figure 1 illustrates this partition of the time horizon.

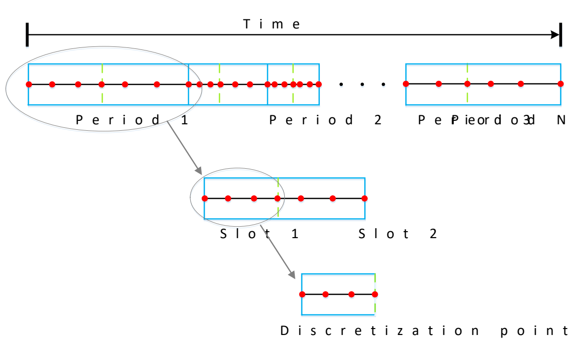

Figure 1. Discretization of the time horizon.

This time representation allows considering the length of the periods as an additional variable in the optimization problem defining accurately the starting time of cleaning actions. To consider the length of the period as a variable, differential equations are reformulated using a dimensionless time, $\bar{t}$, and indexing the variables in the set of periods (P) and the set of points (N) [13]. Equation (1) presents the transformation of the differential equations for any variable x_k, where k is an index for the periods and $\widetilde{\tau_k}$ is the length of period k. Additionally, for each period initial conditions have to be specified so the differential equations can be integrated. This is done by imposing continuity of the differential variable between periods, as represented in equation (2), where l refers to the inner points, and N_f is the final point of period k. It is assumed that all periods have the same number of points, but in a more general representation the number of points can vary among periods to have a more accurate representation of the problem in certain regions.

$$\frac{dx_k}{dt} = \frac{dx_k}{d\bar{t}_k}\frac{d\bar{t}_k}{dt} = \frac{1}{\widetilde{\tau_k}}\frac{dx_k}{d\bar{t}_k}, \forall k \in P \quad (1)$$

$$x_{k,l} = \begin{cases} x_0, & k = 1 \\ x_{k-1,N_f}, & k > 1 \end{cases}, \quad \forall k \in P, l = 0 \quad (2)$$

PROBLEM FORMULATION

A heat exchanger network is described as two directed graphs, one for the cold streams and one for the hot streams, which share the same nodes. The set of nodes is divided in the following subsets: source (SO), mixers (MX), splitters (SP), heat exchangers (HE), and sink (SI) nodes. At each node, the mass and energy balances must be satisfied for each network (cold and hot). Heat exchanger nodes require special treatment as they can be active or inactive depending on whether the unit is in an *operating* or *cleaning* state. For this purpose, the HE subset is replaced by a heat exchanger block (BHE) with the structure presented in Figure 2. In this structure both cold and hot networks are represented, and mixers and splitters are used to create a bypass for each stream. When a specific heat exchanger is in *cleaning* state, the flow from a mixer to the exchanger (and exchanger to corresponding splitter) does not exist and is diverted to the splitter. This is represented as a big-M constraint according to equation (3).

$$m_{i,j,k,l} \leq M y_{k,j}, \qquad \forall i \in MX_j, j \in HE, k \in P, l \in N \quad (3)$$

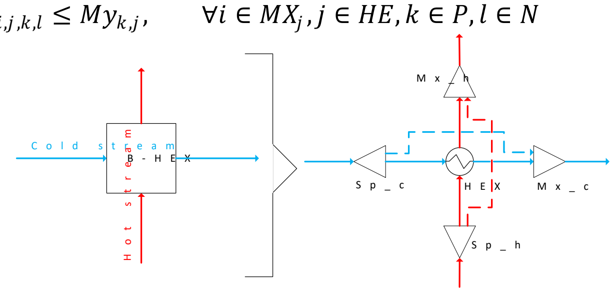

Figure 2. Structure of a BHE heat exchanger block: overall (left) and detailed (right).

This way of representing heat exchangers is a modelling device that allows representing a cleaning action. A physical infrastructure of mixers/splitters may or may not be present.

Also, only some units may have control bypasses with control valves, other units may not. This is represented by including suitable constraints in the model.

In the BHE structure the mass and energy balances apply at each node. In the heat exchanger, the NTU-ε model is used to compute the heat transfer rate between the cold and hot streams and the temperature of the outlet streams [7]. This model also requires the computation of the overall heat transfer coefficient, that depends on the convective heat transfer coefficients of the shell and tube side. These coefficients are explicit functions of the mass flow rate and are computed using the Bell-Delaware method [14]. For simplicity, it is assumed that all the physical properties of the streams (e.g. density, viscosity, heat capacity) are constant.

The tube-side pressure drop is another important variable of the heat exchanger and it is calculated using the same methodology [14]. The pressure drop also depends on the cross-sectional flow area which changes with time as a function of the fouling resistance, equation (4). As a first approximation, the fouling resistance is viewed as the sum of the resistance of two layers, a layer of fresh deposit (gel, with thermal conductivity $\lambda_g = 0.2\frac{W}{mK}$) and a layer of aged deposit (coke, with thermal conductivity $\lambda_g = 1.0\frac{W}{mK}$), and is assumed that the two layers do not mix. The gel is deposited first and then it is transformed into coke due to a chemical reaction. Deposit ageing cannot be ignored as it changes the thermal conductivity of the deposit. The coke has a greater thermal conductivity than the gel, reducing the rate of change of the thermal fouling resistance even while the thickness of the layer keeps growing [15]. The net deposition rate of the fresh deposit (gel) is modelled using the Ebert-Panchal model, that includes a deposition term and a suppression term, equation (5), while the ageing rate, (transformation of gel to coke) is modelled as a zero-order chemical reaction, equation (6) [16]. The fouling resistance of the layer may be used to calculate the layer thickness. Considering that deposition occurs over a curved surface, equations (7) - (8) are obtained which overcome the usual 'thin-layer' assumption. In order to quantify the age of the deposit a 'youth' variable is defined which for this binary system is the same as the mass fraction of gel in the deposited layer, equation (9) [16], [17].

$$A_{flow} = \pi R_{flow}^2 = \pi\left(R_I - \delta_g - \delta_c\right)^2 \tag{4}$$

$$\frac{dR_{f,g}}{dt} = \alpha Re^{-0.66} Pr^{0.33} \exp\left(-\frac{E_f}{RT_f}\right) - \gamma\tau \tag{5}$$

$$\frac{dR_{f,c}}{dt} = \frac{A_a}{\lambda_c} \exp\left(-\frac{E_a}{RT_f}\right) \tag{6}$$

$$\delta_c = R_I\left[1 - \exp\left(-\frac{\lambda_c R_{f,c}}{R_O}\right)\right] \tag{7}$$

$$\delta_g = (R_I - \delta_c)\left[1 - \exp\left(-\frac{\lambda_g R_{f,g}}{R_O}\right)\right] \tag{8}$$

$$x_g = \frac{\rho_g\left[2(R_I - \delta_c) - \delta_g\right]\delta_g}{\rho_g\left[2(R_I - \delta_c) - \delta_g\right]\delta_g + \rho_c\left[2R_I - \delta_c\right]\delta_c} \tag{9}$$

Note that in equations (5) - (6) the fouling rate is a function of the film temperature, which is a local variable in a distributed model. Here, it is estimated at each end of the heat exchanger using heat transfer coefficients calculated according to equations (10) and (11). This leads to two film temperatures, one at the inlet of the heat exchanger and other at the outlet, which generates two different fouling rates. To continue using a lumped parameter model an average fouling rate is computed between the two film temperatures [10], [17].

$$T_{flow} = \frac{R_O}{R_{flow}}\frac{U}{h_c}(T_h - T_c) + T_c \tag{10}$$

$$T_f = T_c + 0.55(T_{flow} - T_c) \tag{11}$$

The set of constraints (3-11) define the operation of a heat exchanger and its fouling behaviour and are repeated for each unit within a network. Adding the connection between units enables constructing a whole network model. Additional constraints complete the definition for a specific heat exchanger network configuration, including: maximum number of cleaning actions per unit or per period, constraints to avoid consecutive cleanings of the same unit, constraints specifying that when the flow is split into different branches of the network, the pressure drop for all branches must be the same. Operational limits such as the furnace firing limit, maximum flow rates, and maximum pressure drop are also considered.

The objective function minimized is the additional operation cost due to fouling, that is, the difference between the actual operation cost and the operation cost at clean conditions. This objective function, taken from [5], [18], is composed by four terms: loss of production cost, equation(12); furnace fuel cost, equation (13); carbon emission cost, equation (14); and cleaning cost, equation (15), where $P_i \; for \; i = \{kg, fuel, CO_2, Cl\}$ is the unit price of each cost component i, and m_{CO_2} is the CO_2 tons emitted per MW consumed. Their sum is the total operation cost minimized in every optimization problem in the following case studies. The pumping cost due to the pressure drop generated by fouling could be easily added to the above cost model, but in [18] it was shown that this cost represents ~1% of the total operating cost, so it is. neglected here

$$P_{kg}\int_0^{t_f}(m_{clean} - m)dt \tag{12}$$

$$P_{fuel}\int_0^{t_f}\frac{(Q - Q_{clean})}{\eta}dt \tag{13}$$

$$P_{CO_2} m_{CO_2}\int_0^{t_f}\frac{(Q - Q_{clean})}{\eta}dt \tag{14}$$

$$P_{Cl}\sum_{j\in P, k\in HE} y_{j,k} \tag{15}$$

CASE STUDIES

To demonstrate the essential features of the model and approach presented, two case studies are presented for small heat exchanger networks over 1 year operation. The first configuration has two heat exchangers in series (HEN-S), the second one considers two exchangers in parallel (HEN-P). Figure 3 shows schematic representations of the two networks with source nodes, sink nodes and connections between the units. Each heat exchanger unit (not shown in detail) is a BHE block composed by the heat exchanger itself, two mixers and two splitters, as illustrated in Figure 2.

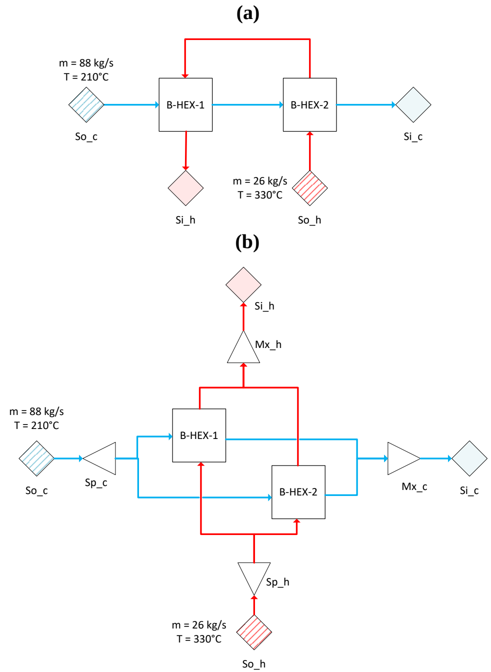

Figure 3. Small heat exchanger networks for the case studies (a) Series configuration, HEN-S, (b) Parallel configuration, HEN-P.

Four operational modes that consider different fouling mitigation strategies are analysed. Table 1 summarizes the operational modes for both network configurations and presents the most important decision variables of the optimization problem that arise in each case. The operating variables considered as degrees of freedom for optimization are: the cleaning schedule, the bypass fraction η_b within each exchanger and (for case HEN-P) the flow split fraction S_p between parallel exchangers. The latter two belong to the group of manipulated variables in an optimal control problem. Among the operational modes, a case is considered where all variables are fixed at their nominal value (Case 1). This provides a standard *base case* to validate and quantify any improvements in the operation of the process. The other three mitigation strategies are: an *optimal control* solution that modifies the operational conditions only (Case 2), an *optimal scheduling* solution that modifies the scheduling variables only (Case 3), and a simultaneous, integrated solution of the *optimal scheduling and control* problem (Case 4).

All heat exchangers in the networks are of shell and tube type and, for simplicity, with the same internal configuration. The shell diameter is 1.4m, the tubes length is 6.1m, the number of tubes is 880, the number of passes per shell is 4, and the internal diameter of the tubes is 19.05 mm. It is assumed that each cleaning takes 10 days and recovers completely the thermo-hydraulic performance of the heat exchanger. Physical properties, operation conditions and cost parameters are taken from previous works [17], [18]. The network configurations analysed here were adapted from those references, where results were validated against real refinery data.

Table 1. Decision variables for the operational modes of each network*.

Case number	Case name	HEN-S			HEN-P		
		η_b	y	Sp	η_b	y	Sp
1	No mitigation	X	X	N/A	X	X	X
2	Bypass	O	X	N/A	O	X	O
3	Cleaning scheduling	X	O	N/A	X	O	O
4	Cleaning scheduling and bypass (By&CL)	O	O	N/A	O	O	O

* X: the variable is fixed and it is not considered as a decision within the optimization algorithm.
O: the variable is a decision variable for optimisation.
N/A: the variable does not apply to the network.

RESULTS AND DISCUSSION

All optimization problems were modelled in Pyomo [19] and solved using IPOPT for NLP problems and a branch and bound algorithm for MINLP problems.

Table 2 presents the optimal value of the objective function for each operational mode of the two network configurations as well as the components of the total operational cost. The loss of production cost is not presented in this table because it is zero for all the cases. This means that in none of the operational modes the furnace firing limit is reached, which would force a reduction in mass flow rate. For both network configurations, series and parallel, the mitigation alternatives (Cases 2-4) decrease the total operational cost, with fuel consumption representing the highest contribution (>90% for all cases). The use of bypasses alone during any time of the operation (case 2) increases the efficiency of each heat exchanger by reducing the mass flow rate. This is only useful under clean conditions or by the end of the operation. This alternative produces savings of less than 1% for both networks.

Table 2. Comparison of operational cost and savings for the operational modes of the HEN.

	Case No.	Fuel cost [10^3 $US]	Carbon emission cost [$10^3$$US]	Cleaning cost [10^3 $US]	Total cost [10^3 $US]	Marginal saving [10^3 $US]	Saving [%]
HEN-S	1	737.58	8.63	0	746.22	0.00	0.00
	2	730.49	8.55	0	739.04	7.18	0.96
	3	541.03	6.33	60	607.36	138.86	18.61
	4	473.86	5.54	60	539.41	206.81	27.71
HEN-P	1	950.60	11.12	0	961.72	0.00	0.00
	2	943.36	11.04	0	954.40	7.32	0.76
	3	783.72	9.17	60	852.88	108.84	11.32
	4	713.12	8.34	60	781.46	180.26	18.74

On the other hand, the optimal cleaning scheduling alone (Case 3) produces significant savings for both networks as it allows the fully restoration of the thermo-hydraulic performance of the unit. The cleaning actions are scheduled at times such that the operational window between two consecutive cleanings is long enough to offset the extra cost. The last operational mode (Case 4), simultaneous control of bypasses and cleaning scheduling, shows that although bypasses alone do not reduce significantly the operational cost of the process, they present a strong interaction with the cleaning scheduling problem. If these two problems are solved simultaneously the total cost of operation can be reduced further than the individual cases. The increase in saving between cases 3 and 4 in Table 2 serves to illustrate the strong interaction between these two mitigation alternatives and why they should be considered together at the same decision level.

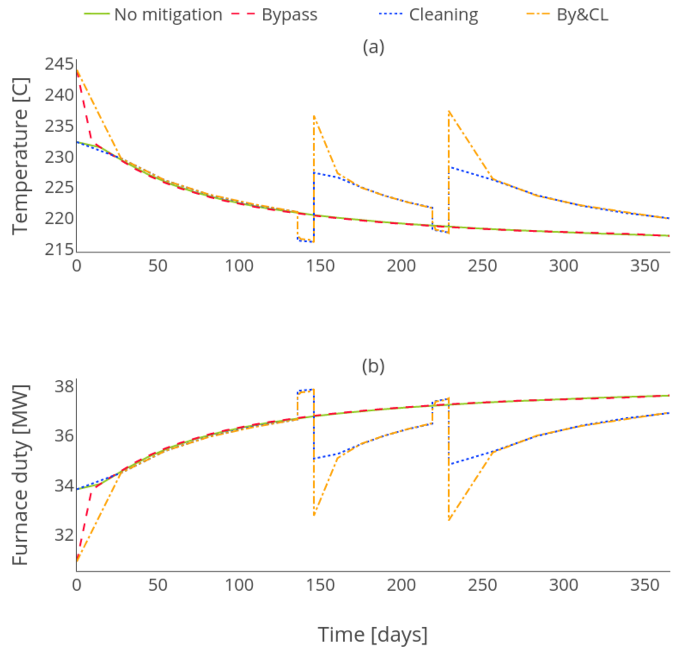

Figure 4. HEN-S response for each operational mode of: (a) coil inlet temperature and (b) furnace heat duty.

Figure 4 shows the profiles of the coil intel temperature (CIT) and the furnace heat duty for the operational modes of the series network configuration, HEN-S, and Figure 5 shows the fouling behaviour and the value of the manipulated variables for its two heat exchangers. In Case 1 (continuous line in Figure 5), the CIT decreases by 15°C and the furnace duty increases by 3.8 MW by the end of a year of operation. This mode of operation is highly expensive with high pressure drop in a short time; thus, it is necessary to implement a mitigation alternative. The first mitigation alternative, the use of bypasses, presents a similar behaviour than the one observed in the case of no mitigation. There is a significant difference in the CIT and furnace duty at the initial point. The operation start with a 0.57 bypass fraction in order to maximize the efficiency of the two heat exchangers, but then it changes to zero and remains there for almost the whole operation. Close to the final time the bypass fraction increases, which slightly increases the outlet temperature, but also the fouling rate. Increasing the bypass fraction reduces the mass flow rate through the heat exchanger, the Reynolds number, and the overall heat transfer coefficient, but they strong and nonlinear interactions lead to an increase on the outlet temperature of the cold stream. However, higher outlet temperatures enhance the fouling rate which makes this alternative inconvenient for long term operations. Other works [10], [20] also analyse fouling mitigation by changing the HEN operational conditions including bypasses, and show that it has a higher impact on the operational cost than the one reported here. Their models assumed constant Reynolds number, do not consider pressure drop limitations of the network, nor changes in the available cross sectional flow area. These factors change with the operational conditions and affect the heat transfer rate and the fouling rate. If they are not considered the benefits of this mitigation alternative may be overpredicted.

In Figure 5 it can be observed that in the Cases 3 and 4 two cleaning actions are found to be executed, one for each heat exchanger, with, the cleanings applied at the same time for both cases. The HEX-1 cleaning starts at day 219 of operation and at day 137 for HEX-2. HEX-2 is cleaned first because it is the last unit in the network and for this reason it is subject to a higher film temperature that produces a higher fouling rate. Right before the HEX-2 cleaning, its fouling resistance is 3.5% higher than that of the HEX-1 and the coke mass fraction of the fouling deposit is 2.6% higher in HEX-2 than in HEX-1, which means that this deposit is 'older', or has seen higher temperatures.

The differences between cases 3 and 4 are more significant after a cleaning action has taken place. In Figure 4 a higher CIT and a lower furnace duty are observed for case 4 than for case 3 after the cleaning actions. This improvement in operation is achieved because the flow rate is gradually diverted from the heat exchanger before it is taken out of operation instead of a sudden change in the operation. Also, after the thermo-hydraulic performance of one heat exchanger is recovered completely by a cleaning, a higher fraction of the total flow rate is sent to this unit (Figure 5 (e,f)).

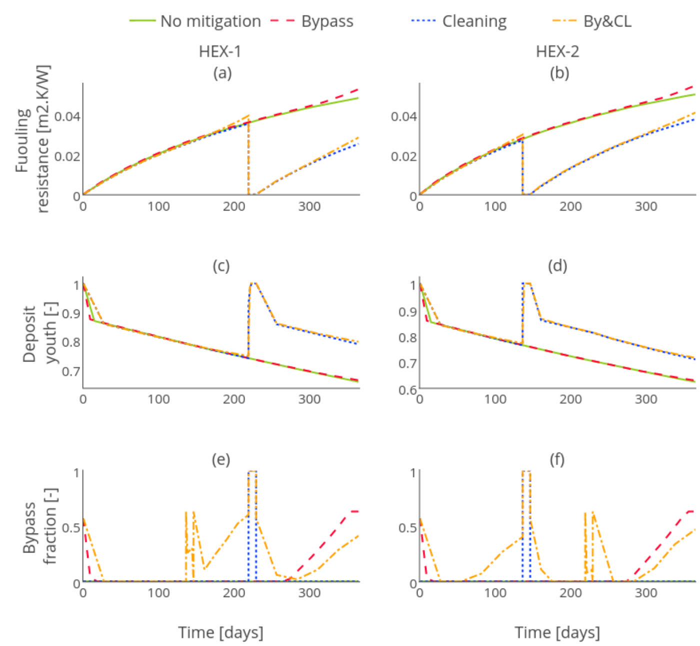

Figure 5. HEN-S fouling behaviour and mitigating actions:(a,b); fouling resistance; (c,d) youth of the deposit and manipulated variables; (e,f) bypass fractions.

Figure 6 and Figure 7 present similar results for the parallel network, HEN-P. Figure 6 shows the profiles of the coil inlet temperature (CIT) and the furnace heat duty for all operational modes, and Figure 7 the fouling behaviour and the value of the manipulated variables for the two heat exchangers. The base case (no mitigation) and the mitigation alternative that only uses the bypasses, Case 2, show a similar behaviour. The CIT drops by 10°C and the furnace duty increases by 2.5MW after 1 year operation. The major difference between Case 1 and Case 2 is observed at the beginning and end of the operation, when the bypass fraction is different from zero, but these actions only lead to a 0.76% reduction in operating cost. In both cases the split fraction among the branches of the network is held constant at the value of 0.5, Figure 7 (g – j), because the two heat exchangers have the same specifications and it is necessary to equalize the pressure drop of the branches.

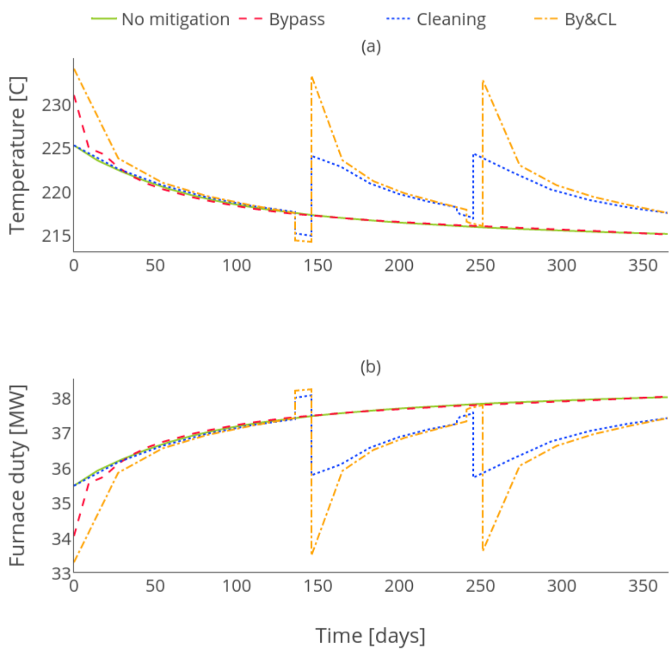

Figure 6. HEN-P response for the operational mode in the variables (a) coil inlet temperature and (b) furnace heat duty.

Optimal cleaning scheduling of the HEN-P results in a lower operation cost. In cases 3 and 4 two cleaning actions are applied, one for each heat exchanger. In both cases HEX-2 is cleaned first, starting at day 137 of operation and HEX-1 is cleaned second, starting at day 235 for Case 3 (optimal cleaning scheduling only) and at day 241 in Case 4 (simultaneous optimal control and scheduling). This difference in the second cleaning action arises because the use of a bypass reduces the mass flow rate sent to HEX-1, increasing its thermal efficiency and allowing a longer operation of the unit (Figure 7 (e-f)).

As for the HEN-S configuration, with HEN-P the simultaneous optimization of the operating conditions (bypass fraction and split fraction) and cleaning schedule also results in the lowest operation cost. The bypasses allow a gradual reduction of the flow rate of the cold stream sent to the heat exchanger, instead of a sudden change, that increases the thermal efficiency. The HEN-P configuration has additional degrees of freedom which are the split fraction of the cold and hot streams. Before any cleaning actions the split fraction is held constant at 0.5, but after any cleaning the mass flow rate of both hot and cold streams sent to the cleaned unit increases because it offers a higher heat transfer rate than the fouled unit (Figure 7 (g – j)). For example, 86% and 61% of the total cold steam flow rate is sent to HEX-2 after it has been cleaned in Case 3 and Case 4, respectively. However, the mass flow rate of the cold stream cannot be sent completely to the cleaned heat exchanger due to its capacity limitation and due to the pressure drop constraint of the branches in the network.

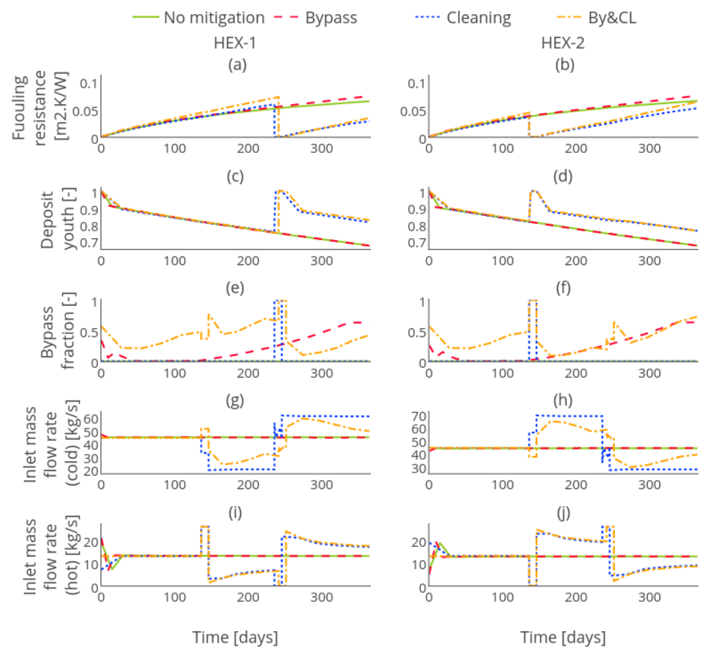

Figure 7. HEN-P fouling behaviour and mitigating actions: (a,b) fouling resistance; (c,d) youth of the deposit and manipulated variables; (e,f) bypass fraction; (g,h) inlet flow rate of the cold stream and (i,j) inlet flow rate of the hot stream.

COMPUTATIONAL ASPECTS

All optimization problems are solved by discretising the time horizon in 5 periods each with 5 points, i.e. all equations and variables are defined at those 25 discrete points. Only the binary variables are defined for each period. This model only has two differential equations per heat exchanger: the fouling deposition rate and the ageing rate. All other constraints are algebraic equations.

For both network configurations, Case 2 is an optimal control problem which does not include integer variables. It is a NLP problem, and is solved efficiently in less than 60 seconds. Cases 3 and 4 include 10 binary variables and are MINLP problems. Note that formulating the same problem using a discrete time representation using a time step of 10 days would require 72 binary variables. Even when the number of binary variables is low, the NLP sub-problems are hard to solve and lead to many infeasible cases due to the high nonlinearities and non-convexities. The solution of Cases 3 and 4 for both networks using a branch and bound algorithm takes between 2.0 and 3.5 hours, which make this approach unviable for larger networks. Another difficulty is the existence of multiplicity during the solution of the MINLP problem which means that there are different feasible solutions that share the same objective function value or even multiple optimal solutions. This can be observed in the HEN-P configuration, in which the cleaning of the two heat exchangers can be exchanged producing the same solution. The solutions presented here are local minimizers. In order to improve the accuracy of the solution or to reach a different optimal point the number of periods may be increased. However, the complexity of the problem increases exponentially with the number of periods and the solution is very sensitive to this parameter.

It is noted that this work focused on an initial comprehensive, flexible yet parsimonious problem formulation for the simultaneous optimization of cleaning scheduling and operation of HEN. The formulation of the problem presented has many advantages compared to the discrete time approach. No effort was made to consider solution aspects, and standard algorithms were used, and there is clearly enormous scope to address the solution efficiency issues noted.

CONCLUSIONS AND PERSPECTIVES

Fouling reduces the thermo-hydraulic performance of heat exchanger networks and has a significant impact in the operation of a PHT. The operation and cleaning scheduling to mitigate fouling of two small heat exchanger networks is addressed here using a mathematical programming approach. On one side, the optimal control problem defines the flow rate distribution within the network, and the time profiles of split fraction and bypasses. On the other side, the optimal cleaning scheduling problem defines which unit to clean and when to clean it. Both mitigation alternatives, applied individually, significantly reduce the operation cost. The integration of these two mitigation actions, usually considered at different decision levels, leads to higher savings of around 20% even for the small cases analysed here, indicating considerable potential of a simultaneous solution.

The time discretization approach proposed considers the length of each period as a decision variable within the optimization algorithm. This provides two advantages in comparison with a discrete time approach: a significant reduction of the number of binary variables and the accurate definition of starting times for cleanings. The MINLP problems were solved using standard algorithms.

It is clearly necessary to test this formulation for larger networks, where it is expected that the computational time will increase exponentially with the number of periods and number of heat exchangers. Therefore, efficient optimization algorithm are required for solving this large-scale problem. Some alternatives that have been proved very beneficial in other applications include the use of decomposition strategies, and the formulation of the problem using complementarity constraints. The efficient solution of larger problems of this type will be presented in future publications.

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