Study of Heat Exchanger Network Cleaning Schedule Design with Heuristic Scenario Analysis

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ABSTRACT: *The crude oil refinery heat exchanger network (HEN) cleaning schedule is critical to maximize energy recovery and simultaneously maintain HEN performance. In reality, the HEN configuration consists of multiple heat exchanger units with different sizes, fouling rates, and initial efficiencies. The plant availability and the HEN efficiency may decrease to a certain level after a period of operation due to fouling and heat exchangers taken offline for cleaning. Therefore, the cleaning and bypass procedure is deemed necessary. In this study, the heat exchanger performance represented by the overall heat transfer coefficient is evaluated based on a proposed heuristics algorithm for seeking the optimum cleaning schedule while incorporating rigorous cleaning rules. Four heuristic values for HEN cleaning schedule scenarios are proposed to evaluate the overall performance of the HEN. The additional heat duty on the process heater due to cleaning operation and the total annual cost are considered in a crude oil refinery HEN that consists of 11 heat exchanger units. The cleaning frequency of the heat exchanger is found to have a significant effect on HEN performance. The results from the scenario analysis suggest that there is a proper cleaning schedule for the optimum operation of a crude oil refinery HEN. It is also indicated that the design of the cleaning schedule depends on fouling resistance and the capacity of related heat exchangers.*

KEYWORDS: *Cleaning schedule; Fouling; Heat exchanger network; Overall heat transfer coefficient; Heuristics algorithm.*

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INTRODUCTION

It is well known that the Crude Distillation Unit (CDU) is one of the largest energy consumers in the oil refinery plant. The crude oil is heated in a process heater, typically until 350ºC, before being separated into its fractions in a distillation column. The process heater is generally used downstream after the Heat Exchanger Network (HEN). Depending on the crude unit design, some heat exchangers (HEs) are installed as a network upstream of the process heater to increase crude oil temperature gradually. The procedure is implemented by exchanging heat between crude oil as the cold stream with distillation fractions as the hot stream. The thermal energy recovery in HEN is critical for overall energy efficiency in CDU. With the help of the HEN, the heating load on the process heater can be reduced significantly. Note that a cut of about 1ºC temperature difference in the process heater equals a saving in energy cost of nearly 4 million US$/year in a big refinery [1].

Unfortunately, crude oil contains a variety of substance that tends to deposit as fouling when heated in the HEN. The fouling deposit grows over time, and it can decrease energy recovery in the HEN and increase the energy demand on the process heater [2]. Crude oil fouling in crude oil refineries may occur *via* any possible mechanisms that are categorized as crystallization fouling, particulate fouling, chemical reaction fouling, corrosion fouling, and biological fouling [3]. Fouling is a major cause of inefficiencies in the form of unwanted material deposited on heat transfer surfaces may create severe effects on refinery economics, operability, health and safety, and environmental impact, and increase the frictional pressure drop across the HE, thereby limiting the amount of flow that can be passed through the exchanger [4, 5]. Naturally, fouling on HEN cannot be avoided. However, it can be mitigated by periodic cleaning.

In practice, one should maintain the plant and the associated HEs' reliability at the maximum possible level, which for the latter is represented by the overall heat transfer coefficient. Dependable fouling model availability is scarce, although several empirical and theoretical models were proposed to describe heat exchanger fouling [3, 6–8]. Typical empirical fouling models in use are asymptotic, linear, and falling rates. A good fouling model will have characteristics such as 1) easy for data fitting so that rapid changes in monitored fouling rate can be identified and the change attributed to a known input, and 2) a simple model with a small number of adjustable parameters so that the essential physics of the system are retained for reliable results [9]. The former model is more suitable for crude oil refineries and more commonly used in the optimization of heat exchanger cleaning schedule purposes [9, 10].

Some of the studies on HEN cleaning scheduling and fouling have been done in the past. *Sanaye* and *Niroomand* [11] studied the effect of the temperature variation of hot and cold stream output effect on fouling and planned the optimal cleaning schedule according to temperature variation. *Ishiyama et al*. [12] studied the cleaning of HEN by controlling the desalter inlet temperature. *Rodriguez* and *Smith* [13] proposed cleaning of HEN to reduce fouling by combining operating conditions such as the wall temperature and flow velocity. *Jin et al.* [14] have studied the influence of fouling on heat exchangers' performance and outlet temperature. Compared with that of a single heat exchanger, the HEN cleaning scheduling problem is much more complicated because there are strong interactions between exchangers within a network [15].

Georgiadis and *Papageorgiou* [16] addressed the problem of cyclic cleaning and energy scheduling in particular classes of HEN by utilizing the linearized Mixed Integer Linear Programming (MILP) model, which can be solved by using standard branch and bound techniques. Unfortunately, it cannot guarantee the global optimum or even a feasible solution to this problem. *Smaïli et al.* [17] proposed a cleaning schedule strategy to minimize total operating costs by applying Mixed-Integer Nonlinear Programming (MINLP). The minimum utility requirement and the cleaning cost are also taken into account for the optimal cleaning schedule [18]. A specialized cleaning decision factor utilizing a Genetic Algorithm (GA) is implemented to determine the optimal cleaning schedule under fouling and different aging scenarios [19]. HEN cleaning scheduling problems with multistage Mixed-Integer Optimal Control Problems (MIOCPs) are proposed that show uncertainty is vital to be taken into account during the optimization of schedules for HEN maintenance problems [20]. An efficient and general NLP formulation for solving the optimal cleaning scheduling problem and the optimal control problem of HEN under fouling is used to define the flow rate distribution of the network [21]. HEN cleaning scheduling problem exhibits bang-bang behavior, which explains the need for combinatorial optimization methods [22]. A hybrid approach for mitigating fouling in HEN by simultaneously optimizing operation conditions and cleaning schedules can be achieved through the redistribution of velocity [23]. A mixed-integer nonlinear programming model is presented and is solved for scheduling cleaning operations in order to maintain optimal operation in such networks using the Outer Approximation/Extended Relaxation algorithm [24]. *Lavaja* and *Bagajewicz* [25] incorporated the cleaning scheduling problem into a MILP while not considering the linear approach to heat transfer processes or fouling models. A more developed MILP was proposed by *Lavaja* and *Bagajewicz* [10] with further consideration of the relational effect of each heat exchanger schedule. The HEN was decomposed in series and solved sequentially, and although the optimization problem was linearized, the procedure still cannot provide the global solution in many cases. Simple heuristic optimization of cleaning, schedules was proposed based on a primary and recursive heuristic algorithm with the optimization objective associated with minimum cost. The recursive option can potentially obtain better solutions but demands higher computational efforts [26].

However, there is a lack of attention in the cleaning schedule design based on the efficiency represented by the overall heat transfer coefficient and reference to process heater heat duty. The overall heat transfer coefficient could be a significant decision parameter to maintain the performance of a heat exchanger while avoiding undesired performance deviation that could lead to an unplanned shutdown and lower the overall plant performance. Moreover, there is some commercial software in cleaning schedule decision-making activities, namely 1) Shell HEAT4N Software developed by Shell Global Solutions, which contains a straightforward approach to fouling calculations and a first-degree optimization model for a single heat exchanger and not for a network as a whole. With a poor Graphical User Interface (GUI), the software is not user-friendly, and the overall heat coefficient is fixed based on design conditions. Erroneous values may be expected when the inlet conditions drastically change during the operation of the heat exchanger. 2) Emerson Process Monitoring Software from Emerson connects to the DCS and monitors temperature and pressure measurements for potential fouling alerts. Unfortunately, the software does not include any feature related to the scheduling of heat exchanger cleaning [5].

This study aims to develop a heuristics algorithm for seeking the optimum cleaning schedule based on the overall heat transfer coefficient that corresponds to the additional heat duty process heater and Total Annual Cost (TAC). There are several novelties of the approach: 1) The cleaning decision methodology proposed in this study considers the interaction between the fouling of each HE, the performance of HEs in operation due to offline HEs under cleaning treatment, and the overall structure of HEN by taking the process heater's heat duty and TAC into account; 2) The involved HEs in the HEN will have the opportunity to be cleaned at least once during the whole operation to ensure the operability of all HEs and improve the performance of the previous approaches, which allow HE to be uncleaned during the whole operation year [27]; 3) The heuristics approach to cleaning decision limits is explicitly designed to ease the implementation of the cleaning scheduling algorithm by the intended users. It is expected that users would benefit from the proposed algorithm as a supporting decision tool for the heat exchanger cleaning schedule policy.

In this paper, different cleaning schedules based on overall heat transfer coefficient heuristics will be analyzed to correspond to the heat duty of the process heater and TAC. In section 2, the HEN model is described, including the process scenario of the cleaning schedule and its related constraints. In section 3, a case study is provided for a thorough discussion on fouling, cleaning scenario problems, and the economic comparison with previous literature. Finally, the conclusions are made at the end of this paper.

METHOD

A HEN in a crude oil refinery is studied in this work, which consists of one (1) cold stream and seven (7) hot streams. The downstream of the HEN is connected to a process heater, as shown in Fig. 1. HEN design parameters, i.e., overall heat transfer coefficient in clean conditions, surface area, the mass flow of hot and cold streams, and the specific heat of hot and cold streams, are shown in Table 1. In this process, crude oil in the storage is heated to 39 °C to maintain viscosity and pour point for more accessible transportation. Crude oil from the storage is pumped to HE-01 as a cold stream up to HE-04. After leaving HE-04,

Table 1: Typical design parameters of HE.

Number HE	U_c (W/m^2.°C)	A (m^2)	m_h (kg/hr)	m_c (kg/hr)	Cp_h (J/kg.°C)	Cp_c (J/kg.°C)
HE-01	689	650	372070	420279	2600	2150
HE-02	533	576	99246	420279	2475	2285
HE-03	618	1144	377161	420279	2530	2390
HE-04	293	744	96001	420279	2335	2470
HE-05	516	1624	377161	420085	2630	2530
HE-06	677	238	99246	420085	2670	2580
HE-07	176	296	14436	420085	2930	2605
HE-08	415	581	96001	420085	2590	2665
HE-09	544	495	121864	420085	2920	2755
HE-10	699	243	85828	420085	3140	2845
HE-11	562	327	96001	420085	2920	2935

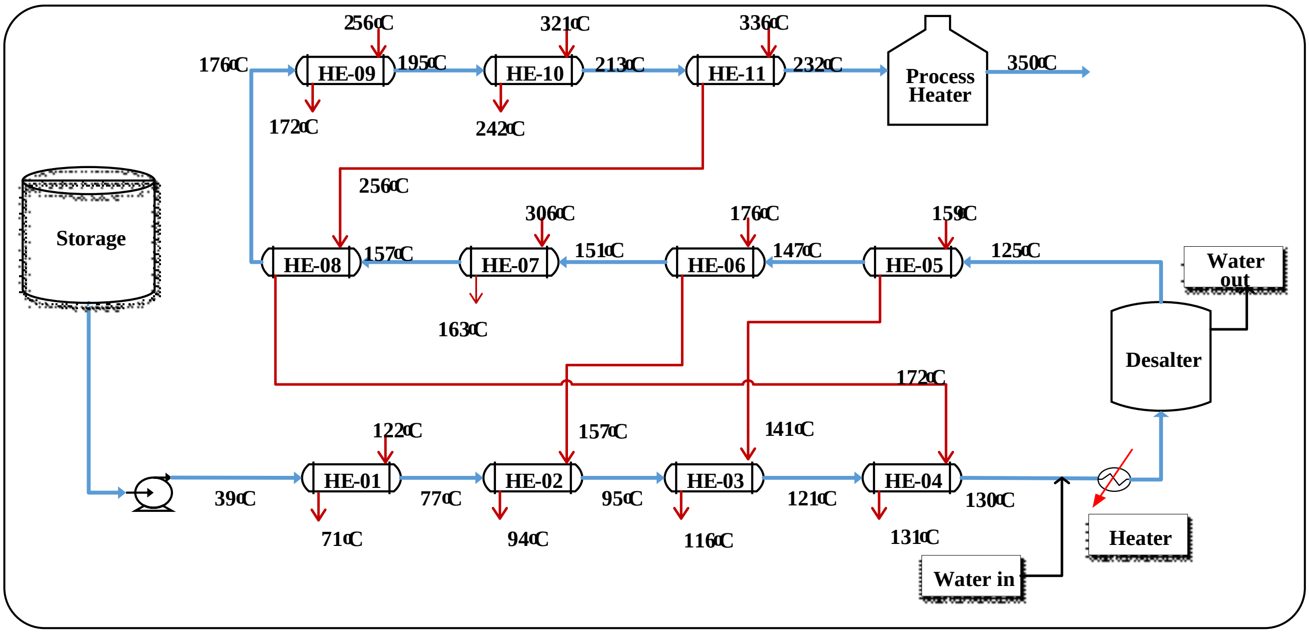

Fig. 1: Schematic diagram and typical operating conditions of the HEN in a crude oil refinery.

crude oil is sent to the desalter to remove salt from the crude oil. Crude oil from desalter is sent to HE-05 as a cold stream up to HE-11. After being treated in the last HE-11, crude oil is sent to the process heater to be heated to 350°C for subsequent treatment.

Fouling resistance and overall heat transfer coefficient model

Several empirical, semi-empirical, and theoretical models have been proposed in the literature to describe fouling in heat exchangers [28,29]. The asymptotic/exponential fouling model is one of the most commonly proposed fouling models in the optimization HEN cleaning schedule due to the simplicity of the model [11,30]. The proposed model by *Kern* and *Seaton* [10] is utilized in this work to determine the fouling condition of HEN as follows:

$$R_{f(t)} = R_{f\infty}\left(1 - \exp^{-\beta t}\right) \qquad (1)$$

On the other hand, the traditional overall heat transfer coefficient is modeled as follows:

$$U_{f(t)} = \frac{U_c}{1 + U_c \, . \, R_{f(t)}} \qquad (2)$$

By substitution of equation (1) into equation (2),

$$U_{f(t)} = \frac{U_c}{1 + U_c \, . \, R_{f\infty}(1 - \exp^{-\beta t})} \qquad (3)$$

The heat transfer rate in a heat exchanger is explained as

$$Q = m \, C_{p,h} \, (T_{h,i} - T_{h,o}) \qquad (4)$$

$$Q = m \, C_{p,c} \, (T_{c,o} - T_{c,i}) \qquad (5)$$

$$Q = U_f \, A \, LMPTD \qquad (6)$$

The log mean temperature used in the equation above is given by

$$LMTD = \frac{(T_{h,o} - T_{c,i}) - (T_{h,i} - T_{c,o})}{\ln\left(\frac{T_{h,o} - T_{c,i}}{T_{h,i} - T_{c,o}}\right)} \qquad (7)$$

The above equations can be simultaneously solved to yield expressions for $T_{h,o}$, and $T_{c,o}$. The results are shown below [11]

$$T_{c,o} = \qquad (8)$$
$$\left[\frac{\left(1 - \frac{m_h c_{p,h}}{m_c c_{p,c}}\right)\exp\left(-\frac{U_{f(t)}\,A}{m_h c_{p,h}}\,F\left(\frac{m_h c_{p,h}}{m_c c_{p,c}} - 1\right)\right)}{\exp\left(-\frac{U_{f(t)}\,A}{m_h c_{p,h}}\,F\left(\frac{m_h c_{p,h}}{m_c c_{p,c}} - 1\right) - \frac{m_h c_{p,h}}{m_c c_{p,c}}\right)}\right] T_{c,i} +$$
$$\left[\frac{\frac{m_h c_{p,h}}{m_c c_{p,c}}\exp\left(-\frac{U_{f(t)}\,A}{m_h c_{p,h}}\,F\left(\frac{m_h c_{p,h}}{m_c c_{p,c}} - 1\right)\right)}{\exp\left(-\frac{U_{f(t)}\,A}{m_h c_{p,h}}\,F\left(\frac{m_h c_{p,h}}{m_c c_{p,c}} - 1\right) - \frac{m_h c_{p,h}}{m_c c_{p,c}}\right)}\right] T_{h,i}$$

$$T_{h,o} = \qquad (9)$$
$$\left[\frac{\exp\left(-\frac{U_{f(t)}\,A}{m_h c_{p,h}}\,F\left(\frac{m_h c_{p,h}}{m_c c_{p,c}} - 1\right)\right) - 1}{\exp\left(-\frac{U_{f(t)}\,A}{m_h c_{p,h}}\,F\left(\frac{m_h c_{p,h}}{m_c c_{p,c}} - 1\right) - \frac{m_h c_{p,h}}{m_c c_{p,c}}\right)}\right] T_{c,i} -$$
$$\left[\frac{\frac{m_h c_{p,h}}{m_c c_{p,c}} - 1}{\exp\left(-\frac{U_{f(t)}\,A}{m_h c_{p,h}}\,F\left(\frac{m_h c_{p,h}}{m_c c_{p,c}} - 1\right) - \frac{m_h c_{p,h}}{m_c c_{p,c}}\right)}\right] T_{h,i}$$

And equations for k_1 and k_2 as proposed by [11] can be expressed as

$$k_1 = \frac{m_h c_{p,h}}{m_c c_{p,c}} \qquad (10)$$

$$k_{2(t)} = \frac{U_{f(t)}\,A}{m_h c_{p,h}} \qquad (11)$$

$$T_{c,o} = \left[\frac{k_1(\exp(-k_2 F(k_1 - 1)) - 1}{\exp(-k_2 F(k_1 - 1)) - k_1}\right] T_{h,i} + \qquad (12)$$
$$\left[\frac{(1 - k_1)\exp(-k_2 F(k_1 - 1))}{\exp(-k_2 F(k_1 - 1)) - k_1}\right] T_{c,i}$$

$$T_{h,o} = \left[\frac{\exp(-k_2 F(k_1 - 1)) - 1}{\exp(-k_2 F(k_1 - 1)) - k_1}\right] T_{c,i} - \qquad (13)$$
$$\left[\frac{(k_1 - 1)}{\exp(-k_2 F(k_1 - 1)) - k_1}\right] T_{h,i}$$

The HE units are assumed to be counter-current flow; hence the correction factor F is equal to 1. Constant mass flow rate is also assumed in this work for each HE unit.

For performance evaluation, the overall HEN performance in terms of the heat duty of the process heater is formulated by

$$Q_{\text{process heater}} = \qquad (14)$$
$$\int_0^t m_c \, Cp_c \left(T_{o,\text{process heater}} - T_{c,o\,(t)}^{HE-n}\right) dt$$

where $Q_{\text{process heater}}$ is the heat duty process heater and $T_{o,\text{process heater}}$ is the temperature at the outlet of the process heater at 350 °C. The heat duty correlation can be approximated using a discrete left Riemann sum [31]. The discrete approximation is selected because of the discontinued profile of HEN daily performance when considering the periodic cleaning schedule of each HEs.

$$Q_{\text{process heater}} = \qquad (15)$$
$$\sum_{t=0}^{H} m_c \, Cp_c \left(T_{o,\text{process heater}} - T_{c,o\,(t)}^{HE-n}\right) \Delta t$$

Where H is the operating horizon defined in 360 days and $T_{c,o\,(t)}^{HE-n}$ is temperature cold out at the heat exchanger for the inlet temperature process heater and n for HE 8, 9, 10, and 11.

The evaluated process heater heat duty is calculated to be consistent with the total operation horizon of 360 days.

HEN cleaning schedule scenarios

A regular cleaning schedule is desired in HEN operation to minimize fouling growth. However, there is a tradeoff between the frequency of the HEN cleaning schedule, the overall productivity, and economic losses. Therefore, approaches to determine a proper HEN cleaning schedules are deemed necessary for the optimal performance of HEN.

Traditionally, the cleaning decision of a HE in HEN is determined when U_f reached the user-given value of U_{dirty} as U_f decreases over time as described in Eq. (3). The predetermined design values U_{dirty} of each HE may differ within the HEN according to the user requirement. The value of U_{dirty} may be decided using visual or other arbitrary specifications that will be costly when the HE is decided to be cleaned. A sensitivity analysis based on U_f reduction is arguably reasonable to determine the optimum cleaning frequency of the HEN. Four heuristic values for HEN cleaning schedule scenarios are proposed to evaluate the overall performance of the HEN. In these scenarios, the cleaning decision is made when the U_f has reached a given fractional value of U_c, i.e., 0.9, 0.8, 0.7, and 0.6, respectively. These fractional values are selected for easy user application, which is consistent with the main objective of the simplicity approach. For each scenario, the cleaning decision limits of U_f are as follows:

$$U_{f1} = 0.9\ U_c \tag{16}$$

$$U_{f2} = 0.8\ U_c \tag{17}$$

$$U_{f3} = 0.7\ U_c \tag{18}$$

$$U_{f4} = 0.6\ U_c \tag{19}$$

Cleaning Priorities

A maximum of 4 HEs is allowed to be cleaned in every cleaning campaign within the cleaning schedule in the proposed scenarios. Specific attention should be put on the desalter temperature inlet, as it may affect the operability of the primary process. An additional utility heater is coupled with the desalter to maintain adequate desalter inlet temperature when the cleaning procedure is ongoing. Cleaning time is assumed to be five days for each HE. The required heat duty in the process heater is determined accordingly, following the HEN cleaning schedule for the entire operation time horizon. Additional cleaning priority is given to HE with less cleaning frequency when two HEs or more enter the cleaning schedule on the same day. Also, if two or more HEs that enter the cleaning schedule have the same cleaning campaign history, then cleaning priority is given to the HE with the highest cold inlet flow temperature due to its potentially higher fouling rate. Suppose there is any HE that appears uncleaned in the cleaning schedule after following the priorities above. In that case, consequently, the corresponding cleaning decision limit scenario should not be suggested as a reference to the final decision of the cleaning schedule.

When a HE enters the cleaning process, the respective HE is bypassed, and its heat duty is distributed among the other HEs in the HEN. The bypass procedure is done on the argument that it is not wise to have a redundant backup or spare HEs to replace the HEs under cleaning, which consequently increases the labor, maintenance, and most importantly, HEs total capital costs. The operating conditions of each HE at various positions within HEN are affected after the bypass procedure has been implemented. The temperatures of both streams at the outlet of the other HEs are also affected because of the bypass procedure.

This work assumes that the pressure drop is neglected in cleaning scheduling calculation, and it is deemed insignificant to the overall result. Moreover, the approach is proposed to be user-friendly. Hence the complexities raised by pressure drop calculation are considered unnecessary. Constant mass flow rate is also assumed so that the heat duty and the outlet temperature of the corresponding HEs are affected only by their U_f.

Total Annual Cost (TAC)

Obtaining the optimal Heat Exchanger Network (HEN) configuration with the lowest TAC is still an issue for industry and academia. The difficulties are due to its combinatorial nature and the highly nonconvex yet nonlinear characteristics of the objective function [32]. The TAC is described by

$$\mathrm{TAC} = \mathrm{Capital\ Cost} - C_E \sum_{n=1}^{N_E} \sum_{t=1}^{N_{tf}} \left(Q_{n,t}^{cl} - Q_{n,t}^{wcl}\right) y_{n,t} + C_{cl,n,j}\left(1 - y_{n,t}\right) + C_E\left(Q_{process\ heater} + Q_{hbd}\right) \tag{20}$$

Energy cost is assumed to be 216.845 US$/MW, and cleaning cost is 10000 US$/cleaning action [18]. The capital cost of the heater before the desalter and process heater is calculated according to the online cost estimator tool provided by *Peters et al*. [33]. The heater capital cost is determined to be 667792 US$, and the process heater is 6880887 US$, accordingly.

A flow chart of the cleaning schedule of the HEN procedure is shown in Figure 2. The procedure starts by providing HE design parameters and operational R_f data. Generalized Reduced Gradient (GRG) method is then

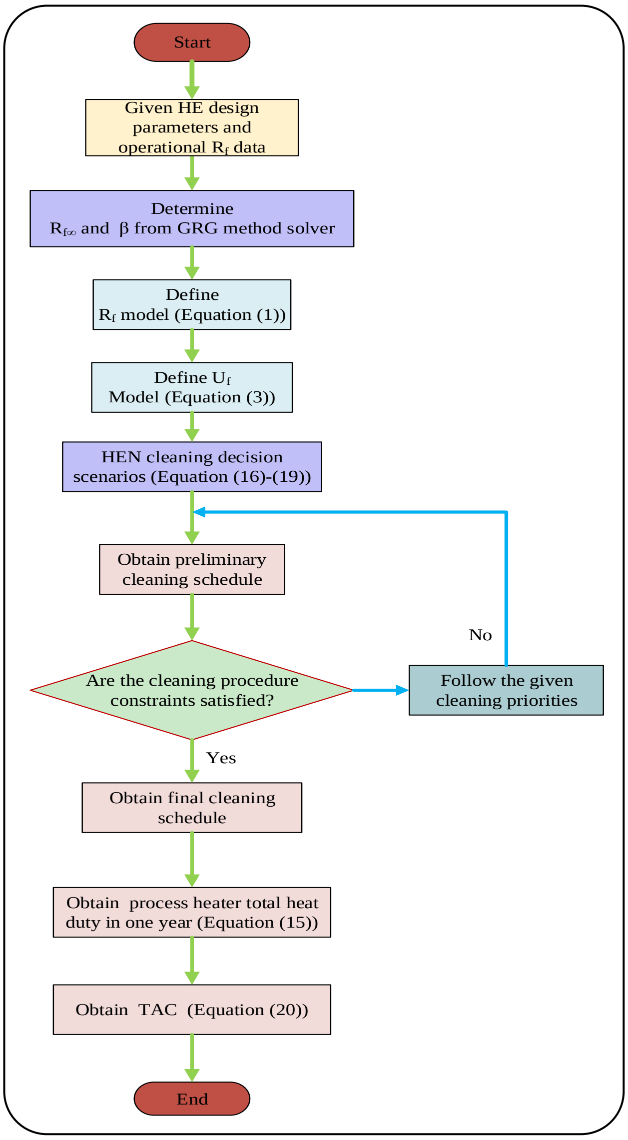

Fig. 2: Flowchart to generate the cleaning schedule of HEN.

utilized to determine $R_{f\infty}$ and β. The corresponding R_f and U_f are defined with the respective equations (1) and (3). The HEN cleaning schedule is predetermined by considering the decision scenarios of equations (16)-(19). Adjustments to the initial schedule are made accordingly to satisfy operational constraints and to clean priorities as described previously through iteration. The final decision on the cleaning schedule is then reported, and the HEN performance in terms of process heater heat duty is subsequently calculated for further evaluation. It is evident that manual evaluation is required, i.e., cleaning priorities, for the cleaning schedule arrangement so automatic mathematical optimization is difficult to be performed in this heuristic approach. The effect of disturbances is not addressed in this approach as the operational disturbances are assumed to be not significant to the overall performance of the HEN.

RESULTS AND DISCUSSION

In this section, descriptions of R_f determination, effects of the cleaning procedure to process temperatures, heat duties, and results of different cleaning scenarios are elaborated. Of all the results shown in the following, Excel and MATLAB are used as computational tools in an Intel® Core™ i5-8265U 8.00 GB RAM platform. The typical configuration of Fig. 1 is taken into consideration, along with the design parameters in Table 1.

Determine R_f Model from Operation Data

The typical operational fouling data are usually derived from the annual technical history sheets of the various HEs hot and cold streams inlet and outlet temperature in the crude oil refinery. From operational fouling data, the output is $R_{f\infty}$ and β, which is obtained from fitting the operational fouling data. R_f model is subsequently obtained from the equation (1) calculation.

For discussion purposes, HE-01 is chosen due to the smallest value of R_f in model fitting. Note that the R_f characteristics of other HEs are quite similar; hence HE-01 is taken into consideration based on the aforementioned reason. Although it is arguably important, the crude oil composition may affect the fouling resistance and other parameters as well. Unfortunately, the HEs' operational data, HEs' specification and the light crude oil-specific composition are under a confidentiality agreement with a real oil company. Note that the HEs are designed according to TEMA specifications. In fact, the TEMA internal design is indirectly reflected in the R_f characteristics of each HE. Therefore, the details of each HE TEMA table are not critical in this study and the information is also under the same confidentiality agreement. Fig. 3 shows the model fitting result for R_f in HE-01, according to Equation (1). The Generalized Reduced Gradient (GRG) nonlinear method is implemented in this work o obtain the $R_{f\infty}$ and β parameters. Unitary initial guesses for parameters $R_{f\infty}$ and β are used for solving the problem where the minimum Root Mean Square (RMS) objective function is chosen to determine the appropriate parameters $R_{f\infty}$ and β. Table 2 shows the fitted parameters

Table 2: R_f model result for each HE.

Number HE	$R_{f\infty}$ ($m^2 {}^\circ C/W$)	B (unit/day)	R_f at t = 360 day ($m^2 {}^\circ C/W$)
HE-01	0.0013	0.0105	0.0013
HE-02	0.0077	0.0199	0.0077
HE-03	0.0107	0.0165	0.0106
HE-04	0.0075	0.0125	0.0074
HE-05	0.0102	0.0131	0.0101
HE-06	0.0081	0.0053	0.0069
HE-07	0.0035	0.0010	0.0034
HE-08	0.3870	0.00005	0.0073
HE-09	0.4160	0.00005	0.0076
HE-10	1.9000	0.00002	0.0148
HE-11	0.0076	0.0150	0.0076

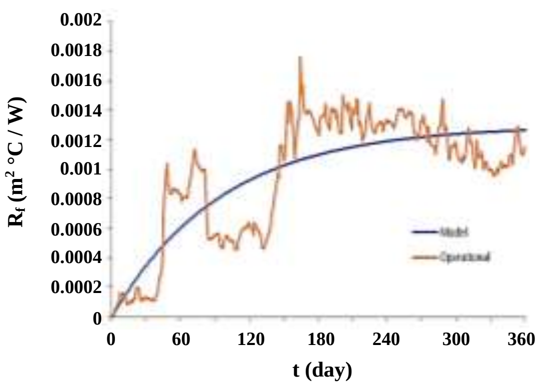

Fig. 3: Model fitting of Rf in HE-01.

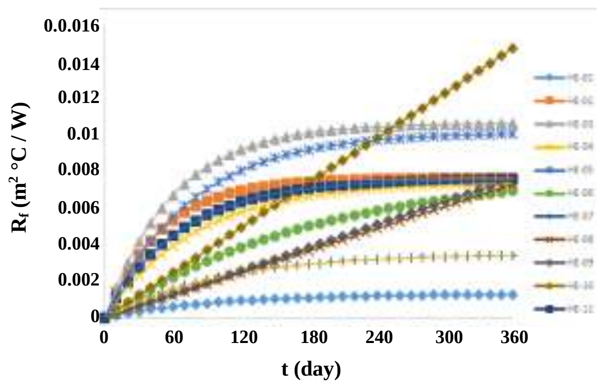

Fig. 4: Profile of Rf model of all HE.

$R_{f\infty}$ and β for all of the other HEs involved in this work. As HE-1 to HE-11 are operated in different temperature profiles, the operational data of each HE is characteristically specific to each HE's TEMA design, operating condition, and actual performance. Therefore, the differences in the fouling resistance of each HEs in Table 2 inherently incorporate the corresponding HE characteristics.

Fig. 4 shows all of the R_f model profiles of the available HEs. It is obvious that HE-10 has a significantly high final value of fouling resistance R_f (1.48E-02 $m^2 {}^\circ C/W$) due to the dynamic interrelation between $R_{f\infty}$ and β, which values are 1.90E+00 $m^2 {}^\circ C/W$ and 2.17E-05 unit/day, respectively. On the other hand, HE-01 shows the lowest R_f (1.27E-03 $m^2 {}^\circ C/W$). Although the values of $R_{f\infty}$ and β cause these behaviors, they can be indirectly affected by the operating temperature of those HEs since HE-01 has the lowest operating temperature (HE-01 cold stream inlet temperature 39 °C and outlet temperature range at 59-95 °C as shown in Fig.1). While in the HE-08, HE-09, and HE-10, the fouling characteristic exhibits linear fouling models. It is shown in small β values and tabulated in Table 2.

Cleaning Schedule Scenario

In the subsequent section, the most optimal scenario performance is taken into account, which is the one with $0.7U_c$ decision limit. Fig. 5 shows the U_f profile of HE-10 where HE-10 has the most U_c and R_f values, albeit its small β compared with other HEs. Under $0.7U_c$ decision limit, HE-10 should be cleaned ten times according to the schedule shown in Fig. 5. The first cleaning time is

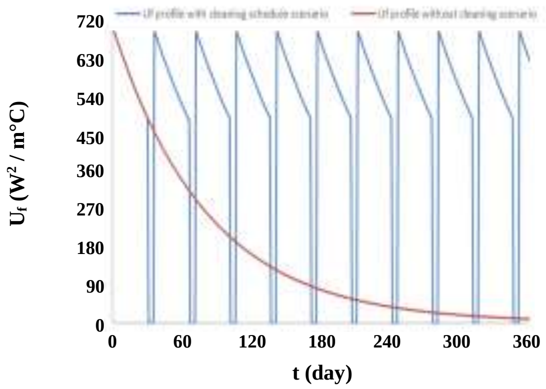

Fig. 5: U_f profiles of HE-10 without and under cleaning schedule with 0.7Uc decision limit.

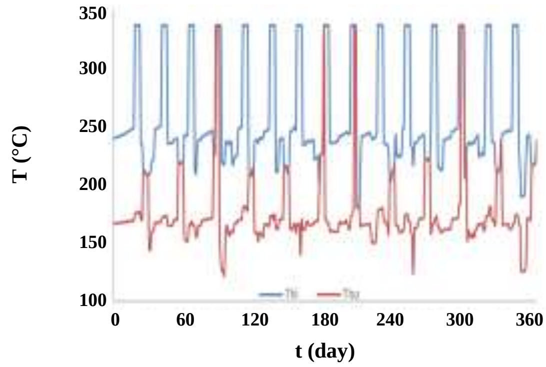

Fig. 7: Hot stream inlet and outlet temperature profiles of HE-08 under cleaning schedule with 0.7Uc decision limit.

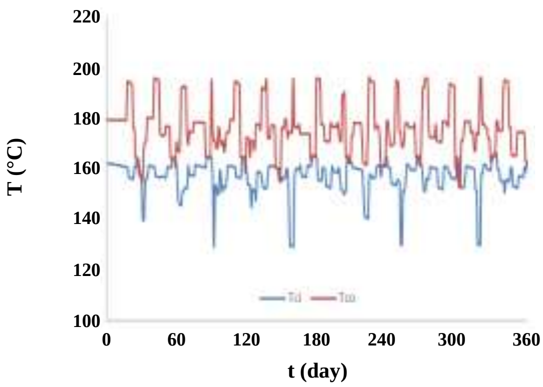

Fig. 6: Cold stream inlet and outlet temperature profiles of HE-08 under cleaning schedule with 0.7Uc decision limit.

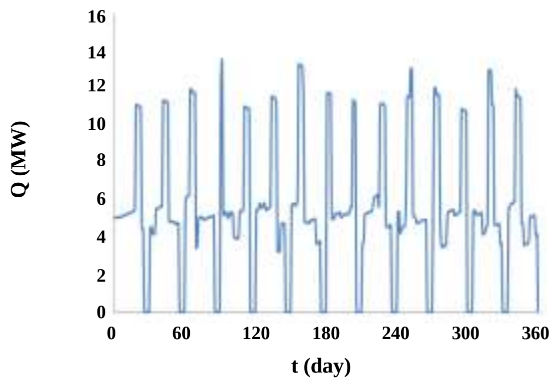

Fig. 8: Heat duty profiles of HE-08 under cleaning schedule with 0.7Uc decision limit.

on the 29th day, followed by another cleaning on the 66th day, and so on. By doing so and considering other HEs cleaning schedules, the duty of a process heater is projected to be at the lowest compared with other scenarios (Eqs. (16)-(19)).

Fig. 6 shows the cold stream temperature profile of HE-08. HE-08 is selected since it has the most interconnected network with other HEs, i.e., HE-04, HE-07, HE-09, and HE-11, as shown in Fig. 1. Based on Fig. 6, the condition at day 256 shows the lowest cold inlet temperature $T_{c,i}$ 114^{o}C, and $T_{h,i}$ 215 ^{o}C due to scheduled cleaning in other HEs, specifically in HE-05. There is no temperature cross during the whole 360 days of operation in this case. The corresponding $T_{c,o,}$ and $T_{h,o}$ according to Eqs. (12-13).

Fig. 7 shows the hot stream temperature profile of HE-08. It can be observed that on day 209, the hot inlet temperature $T_{h,i}$ is as low as 180^{o}C and $T_{c,i}$ is 156^{o}C because of the cleaning procedure on HE-09 and HE-10. The cleaning procedure puts HE-09 and HE-10 offline. Hence the cold stream temperature entering HE-11 is now lower than before. Subsequently, the outlet of the hot stream from HE-11 that enters HE-08 has a low temperature as a result. Day 94 shows the lowest hot outlet temperature $T_{h,o}$ 121^{o}C, and $T_{c,o}$ 137^{o}C when the entering cold inlet temperature HE-08 is low due to the cleaning schedule of the related upstream HEs, specifically HE-05.

Fig. 8 shows the fluctuation of HE-08's heat duty profile for the whole operation horizon. The change in the magnitude of operating temperature and the shifting of the cleaning schedule of the upstream HEs will directly impact HE-08's operational performance in terms of heat duty. As some of the upstream HEs are under cleaning procedure, the bypass actions are carried out so that more heat duty is required on HE-08 to fulfill the outlet temperature requirements, as shown in Fig. 8 with an increased heat duty profile. Similarly, when HE-08 itself is under cleaning procedure, it is bypassed, and there is no heat duty for HE-08, as shown in Fig. 8 when the heat duty profile is zero.

Table 3: Total number of HE cleaning procedures.

Scenario of U_f limit	Total number of cleaning procedure											Total
	HE-01	HE-02	HE-03	HE-04	HE-05	HE-06	HE-07	HE-08	HE-09	HE-10	HE-11	
U_{f1}	12	21	29	14	22	21	8	26	27	25	29	234
U_{f2}	7	15	20	9	15	14	5	17	17	15	20	154
U_{f3}	4	11	15	7	11	10	2	12	12	10	15	109
U_{f4}	3	8	12	5	8	8	0	8	9	7	12	80

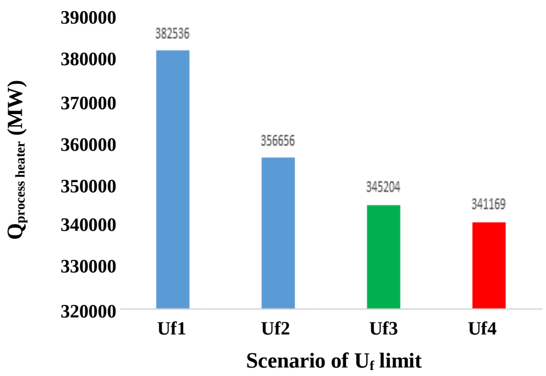

Fig. 9: Process heater total heat duty in one year.

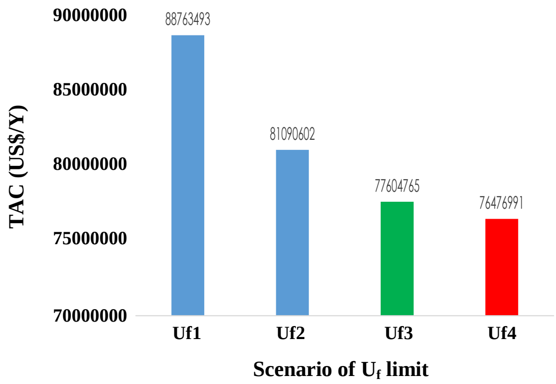

Fig. 10: HEN cleaning total annual cost.

Table 3 shows that HE-11 is the most frequently cleaned, and HE-07 is the least cleaned compared to the other HEs. The interaction of U_c and R_f is used to determine the cleaning frequency of each HE in this work. According to the results in Table 3, the cleaning schedule based on U_{f4} should not be used as a reference due to the HE-07, which appears uncleaned during the overall operation horizon after following the proposed cleaning scheduling algorithm. On the other hand, the scenario of U_{f3} should be recommended for users as the schedule fulfills the requirement that all the HEs have the minimum cleaning number at least once within the entire time horizon.

Fig. 9 shows a load of additional heat duty of the process heater to maintain proper operation of the overall system for all cleaning schedules scenarios. The U_{f4} scenario is highlighted in red because there is an uncleaned HE using the U_{f4} decision limit. However, it has the lowest required heat duty in the process heater (341169 MW), which correlates to $0.6U_c$ decision limit. Therefore, the simulation result shows the optimal cleaning schedule scenario is selected to be the one with $0.7U_c$ decision limit, which is highlighted in green, as it has the lowest required heat duty on the process heater (345204 MW). At the same time, it simultaneously satisfies the condition that each HE is cleaned at least once within the operation horizon.

Fig. 10 depicts the optimal total annual cost for different scenarios in this study. The highest TAC corresponds to U_{f1} at 88763493 US$/year, with the total number cleaning of 234 as described in Table 3. Since the cleaning procedure decision of $0.9U_c$ is relatively quick to be met, and a high TAC for U_{f1} is expected. With the lower decision limit of $0.8U_C$, the U_{f2} schedule results in lower TAC of 81090602 US$/year with a total number of cleaning of 154, accordingly. The optimal TAC of 77604765 US$/year is correlated to scenario U_{f3}'s low total number of cleaning (109) and the minimum annual process heater total heat duty (345204 MW). Although the cleaning schedule based on U_{f4} is lower with the TAC 76476991 US$/year with total number of cleaning of 89, the schedule does not meet the minimum cleaning number at least once within the entire time horizon.

Literature comparison

The solutions reported by *Smaili et al.* [24] and *Lavaja et al.* [25] computed a HEN, which consists of 10 HEs. The proposed method is implemented onto the same 10 HEs HEN, and the corresponding total Net

Table 4: Comparison for NPC.

Method	NPC (US$)		
	d_t=1	d_t=0.75	d_t=0.5
U_{f1}	1571869	1178902	785935
U_{f2}	1555490	1166617	777745
U_{f3}	1257274	942956	628637
U_{f4}	821114	615836	410557
Smaili et al. [24]	885111	663833	442556
Lavaja et al. [25]	874545	655908	437273

Present Cost (*NPC*) is compared with the literature as shown in Table 4.

$$\mathrm{NPC} = \sum_t d_t \frac{(\mathrm{Ef}_t - \mathrm{Ef}_t^{cl})}{\eta_f} C_{EF} + \sum_t d_t \sum_t Y_{it} C_{cl}$$

where Ef_t is the actual process heater energy consumption, Ef_t^{cl} is the process heater energy consumption for clean condition, C_{EF} is the process heater fuel cost, C_{cl} cleaning cost, η_f is the process heater efficiency, d_t is the discount factor, and Y_{it} value is 1 if the ith HE is cleaned in period t and 0 otherwise.

In this case, the proposed method performs better than those reported in the literature [24, 25] in terms of total NPC, as shown in Table 4, specifically for scenario U_{f4}. Different discount factors (d_t) are also considered for the completeness of economic comparison as a multiplicative factor to the NPC. Note that the NPC from the literature was reported in April 2004, with the exchange rate was 1 £ = 1.8155 US$. Consequently, the NPC will be proportionally lower as the d_t is decreased and the trend is the same for all of the different scenarios and results from the literature listed in Table 4. As U_{f4} scenario considers higher tolerances on fouling, i.e., $0.6U_c$, before cleaning, this strategy results in lower overall NPC. The results suggest that refineries may delay cleaning their HEs at a higher degree of fouling and carefully follow their HEs operability.

CONCLUSIONS

A heuristic heat exchanger network cleaning scheduling method based on the fouling model in terms of the decreasing overall heat transfer coefficient with cleaning decision limits is presented. The heuristic method consists of varying the cleaning decision when the U_f has reached a given fractional value of U_c, i.e., 0.9, 0.8, 0.7, and 0.6, respectively, to fulfill operational requirements that each HE should be cleaned once within the time horizon. The corresponding overall performance of the HEN is evaluated, and the change in outlet temperatures of hot and cold streams is simulated as well. The results for 10 and 11 HEs indicate that the design of the cleaning, schedule depends on fouling resistance and the capacity of related HEs. According to the proposed cleaning strategy, the heuristics of the cleaning decision limit significantly affects the cleaning frequency of each HE and is directly related to the overall performance of the HEN as reflected in the heat duty requirement in the process heater and the total annual cost. The proposed method allows the user to select the most appropriate cleaning schedule and ensure that all the HEs receive cleaning treatment by dismissing the infeasible decision limit. The heuristics of the discreet cleaning decision limit provide easiness of implementation. At the same time, the user can achieve desirable cleaning schedule outcomes using the proposed approach.

Nomenclatures

$R_{f(t)}$	Fouling resistance, m^2.°C/W
$R_{f\infty}$	Asymptotic fouling resistance, m^2.°C/W
β	Fouling time constant, unit/day
t	Time, day
U_f	Overall heat transfer coefficient on the fouled condition, W/m^2.°C
U_c	Overall heat transfer coefficient on the clean condition, W/m^2.°C
Q	Heat duty, MW
A	Heat transfer surface area, m^2
$C_{p,h}$	Heat capacity hot stream, J/kg.ºC
$C_{p,c}$	Heat capacity cold stream, J/kg.ºC
LMTD	Logarithmic mean temperature difference, ºC
$T_{h,i}$	Temperature of hot in, ºC
$T_{h,o}$	Temperature of hot out, ºC
$T_{c,i}$	Temperature of cold in ºC
$T_{c,o}$	Temperature of cold out ºC
m_h	Mass flow rate hot, kg/h
m_c	Mass flow rate cold, kg/h
N_E	Number of HE in the HEN
N_{tf}	Number of days (time horizon)
n	1, 2,.., N_E HE number
$Q_{n,t}^{cl}$	Heat duty in the nth at the time t in a cleaning schedules, MW

$Q_{n,t}^{wcl}$	Heat duty in the n^{th} at the time t in without cleaning schedules, MW
Q_{hbd}	Heat duty heater before desalter, MW
U_{f1}	Cleaning decision limits based on U_f when reaching 10%, W/m^2.°C
U_{f2}	Cleaning decision limits based on U_f when reaching 20%, W/m^2.°C
U_{f3}	Cleaning decision limits based on U_f when reaching 30%, W/m^2.°C
U_{f4}	Cleaning decision limits based on U_f when reaching 40%, W/m^2.°C
NPC	Net Present Cost, US$
Ef_t	Actual process heater energy consumption, MW
Ef_t^{cl}	Process heater energy consumption for clean conditions, MW
C_E	Energy cost, US$/MW
C_{cl}	Cleaning cost, US$
C_{EF}	Process heater fuel cost, US$
η_f	Process heater efficiency
d_t	Discount factor
Y_{it}	Value is 1 if the ith HE is cleaned in period t and 0 otherwise

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