ON-LINE CLEANING SCHEDULE FOR HEAT EXCHANGERS IN A HEAT EXCHANGER NETWORK – THE CASE OF CRUDE DISTILLATION UNIT

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ABSTRACT

The scheduling of on-line cleaning interventions in the individual exchangers in a heat exchanger network can be based on a-priori knowledge of the time behaviour of the thermal resistance of fouling. Heat exchanger cleaning is postulated to maximise the avoided loss understood as the value of energy recovered if cleaning the heat exchanger network (HEN), minus the value of energy recovered without HEN cleaning, minus the cost of HEN cleaning. The optimal scheduling of cleaning interventions is presented on the example of Crude Distillation Unit where the HEN is composed of 31 exchangers and 26 process streams.

INTRODUCTION

In process plants incorporating heat exchanger networks for heat recovery, deposits building up on heat transfer surfaces hinder correct operation and lead to economic losses. The immediate causes of these losses are increased energy consumption and in certain cases also forced plant stoppages for heat exchanger cleaning. The detrimental effect of fouling can be reduced by adopting appropriate measures in HEN design. Important is the choice of:

A) Local parameters (selected when designing a heat exchanger) relating to fouling build-up in each single exchanger: φ – Biot number at maximum fouling, and ΔT_{minc} – minimum temperature difference in the absence of fouling. The consequences of fouling build-up are expressed by the relative capacity β of the heat exchanger (the ratio of exchanger capacity with maximum fouling on its heat transfer surface Q_f at the end of the period of continuous HEN operation, to the capacity of clean exchanger Q_c).

The heat exchanger is less sensitive to fouling if the values of local parameters φ and ΔT_{minc} are low (Figure 1).

B) HEN structure affecting interactions between the individual exchangers and thus influencing the recovery of heat; the more interactions occur, the better is the compensation of their negative effects (Brodowicz and Markowski 2003).

It follows from the above that the HEN is less sensitive to fouling if the values of local parameters are low and multiple interactions occur between the individual heat exchangers. If otherwise, then fouling build-up reduces heat recovery necessitating either periodic plant stoppages so that groups of heat exchangers can be cleaned, or on-line cleaning of the individual exchangers.

This paper deals with the scheduling of on-line cleaning interventions. It can be based on the a-priori knowledge of the time behaviour of the thermal resistance of deposits $R'_{fj}(t)$ in the individual exchangers (j=1..p). This is possible if operating parameters of the HEN have been measured and recorded during previous periods of uninterrupted HEN operation.

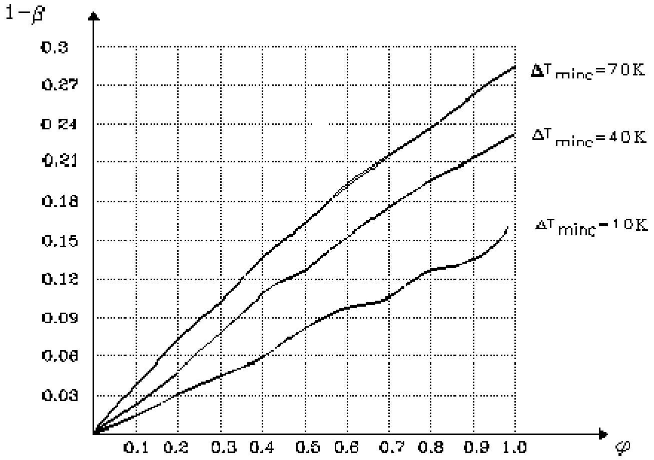

Figure 1. Reduction of the relative heat-exchanger capacity vs. local parameters relating to deposit build-up; $\beta = Q_f/Q_c$. (Markowski 2000)

In the literature, various methods for the optimisation of cleaning schedules for a single equipment item have been proposed (see for example Casado 1990, Sheikh et al. 1996). For complex HENs, Muller-Steinhagen (1998) proposed an integrated approach for developing alternative fouling mitigation strategies based on both experimental and modelling work. Smaili et al. (1999) analysed cleaning synchronisation of HEN for continuous processes subject to fouling (taking sugar manufacturing as an example) and arrived to the mathematical problem of mixed integer non-linear programming. Georgiadis et al. (2000) considered a general mathematical framework for the optimal periodic cleaning and energy management problem in HEN. Economic trade-offs between the total number and timings of cleaning operations and the cost and availability of the hot utility in the plant were illustrated. Georgiadis et al. (2001) considered heat integration and fouling aspects together with the production scheduling problem, and proposed a mathematical programming framework for the introduction of fouling considerations during the heat integration of batch plant operation. In particular, this reference demonstrates how fouling aspects can be incorporated within a general mathematical formulation proposed by Papageorgiou et al. (1994) for the scheduling and heat integration of multipurpose plant operation.

INFLUENCE OF FOULING ON HEN OPERATION

When considering a specific heat exchanger operated in a HEN, two types of fouling-induced effects can be identified (Brodowicz and Markowski, 2003): 1) changes in outlet temperature of process streams caused by the thermal resistance of fouling in the exchanger itself, 2) changes in inlet temperature of process streams caused by the thermal resistance of fouling in other exchangers ("antecedent exchangers" serving the same process streams).

Figure 2 illustrates effects of the latter type changing the driving force of heat exchange, heat flow and outlet temperature of both streams. In Figure 2a, this is indicated by the shift of operating lines from positions AB to positions CD. The geometric construction shown in Fig. 2b explains how specific disturbances in stream temperature at inlet (εT_{Ci} and εT_{Hi}) generate the response of the exchanger, that is, increments of stream temperature at outlet ($\varepsilon T^{\bullet}_{C}$ and $\varepsilon T^{\bullet}_{H}$). The response can also be derived from general relationships given in APPENDIX A .

Figure 3 illustrates the response of the exchanger to fouling on its heating surface. In Figures. 3a and 3b, changes in outlet temperature of both streams are indicated assuming no interaction with the HEN. In Figure 3c, the influence of antecedent exchangers is accounted for.

OPTIMAL CLEANING OF HEAT EXCHANGERS

The aim of on-line heat exchanger cleaning is to minimise the operating cost of the HEN, or maximise the avoided loss F understood as

$$F = H_{rc} - H_{rw} - C \tag{1}$$

where: H_{rc} - value of heat recovered when cleaning the HEN, H_{rw} – value of heat recovered without HEN cleaning, C - cost of HEN cleaning.

The avoided loss depends on the number of cleaning interventions performed on the individual exchangers n_j ($j=1..p$) and the time intervals $t_{j\mathbf{l}}$ ($\mathbf{l}=1..n_j+1$) between the cleaning interventions. The value of heat recovered is affected by the specific cost of heat K_q, and the cost of HEN cleaning is determined by the cost of cleaning each specific heat exchanger $K_{j\mathbf{l}}$. It is also assumed that exchangers are cleaned instantaneously. The avoided loss can be expressed as a function:

$$F = K_q \sum_{j=1}^{p} \sum_{\mathbf{l}=1}^{n_j+1} \int_0^{t_{j\mathbf{l}}} Q_{j\mathbf{l}} dt - K_q \sum_{j=1}^{p} \int_0^{t_e} Q'_j dt - \sum_{j=1}^{p} \sum_{\mathbf{l}=1}^{n_j} K_{j\mathbf{l}} \tag{2}$$

$$\text{subject to constraint :} \quad t_e = \sum_{\mathbf{l}=1}^{n_j+1} t_{j\mathbf{l}}, \; j = 1..p \tag{3}$$

In expression (2), $Q_{j\mathbf{l}}$ and Q'_j denote heat streams that depend on time and decision variables n_j and $t_{j\mathbf{l}}$, according to symbolic equations:
$Q_{j\mathbf{l}}=f(R_{f1}(n_1, t_{11},..t_{1\,n1}, t),..R_{fp}(n_p,t_{p1},..t_{p\,np} ,t))$ for $\mathbf{l}=1..n_j$ and $j=1..p$
$Q'_j=g(R'_{f1}(t),..R'_{fp}(t))$
where f and g denote functions expressing the consequences of fouling build-up (Markowski and Urbaniec, 2005), while R_{fj} and R'_{fj} denote thermal resistance of deposits in j-th exchanger subject to periodic cleaning or without cleaning, respectively.

As it has been assumed that the build-up of deposits in each exchanger follows a known pattern (based on the a-priori knowledge of the time behaviour of $R'_{fj}(t)$, obtained from measurements during previous periods of uninterrupted HEN operation), the following relationship is satisfied:
$R_{fj}(t)= R'_{fj}(t)$ for $t \le t_{j\mathbf{l}}$.

The optimal scheduling of on-line cleaning of the heat exchangers in the HEN can be reduced to maximising function F while satisfying the constraint imposed on time intervals between cleaning interventions. The function is non-linear and the decision variables are either integer (n_j), or continuous ($t_{j\mathbf{l}}$). In order to facilitate the search for global optimum, the number of variables can be reduced assuming that for each j-th heat exchanger at given n_j ($j=1..p$), the value of the thermal resistance of deposits, averaged over the period of continuous HEN operation, should attain its minimum:

$$R_{faj} = \frac{1}{t_e} \sum_{\mathbf{l}=1}^{n_j+1} \int_0^{t_{j\mathbf{l}}} R_{fj}(t_{j\mathbf{l}}, t)\, dt \rightarrow \text{minimum} \tag{4}$$

$$t_{j\mathbf{l}}, \mathbf{l} = 1..n_j + 1$$

It is important that the thermal resistance of deposits R_{fj} in time interval $[0, t_{j\mathbf{l}}]$ is a non-decreasing function of time, that is, $dR_{fj}/dt \ge 0$. Consequently, to satisfy expression (4), for each (j-th) heat exchanger time intervals between successive cleaning interventions should be equal

(Markowski and Urbaniec, 2005, see APPENDIX B). Constraint (3) is then transformed into

$$\left.\begin{aligned} &\frac{t_e}{t_{j\mathbf{l}}} = n_j + 1; \\ &t_{j\mathbf{l}} = t_{j,\mathbf{l}+1} \quad \text{for } \mathbf{l} = 1..n_j,\ j = 1..p \end{aligned}\right| \qquad (5)$$

This makes it possible to eliminate variables $t_{j\mathbf{l}}$ from expression (2). The maximisation of function F is then reduced to determining matrix **n**={n_j, j=1..p} whose elements express the number of cleaning interventions in each exchanger during the period of continuous HEN operation.

To summarize the above reasoning, it can be noted that two versions of the problem of maximization of the avoided loss F, defined by expression (2), have been formulated (note: j=1..p; **l**=1..n_j+1)

A) full version - maximize F with respect to n_j and $t_{j\mathbf{l}}$, subject to constraint (3),
B) reduced version - maximize F with respect to n_j while using constraint (5) for elimination of $t_{j\mathbf{l}}$.

Both versions and especially the full one might be difficult to solve numerically for large HENs. Numerical methods insensitive to the existence of local extrema, e.g. probabilistic methods, should preferably be applied.

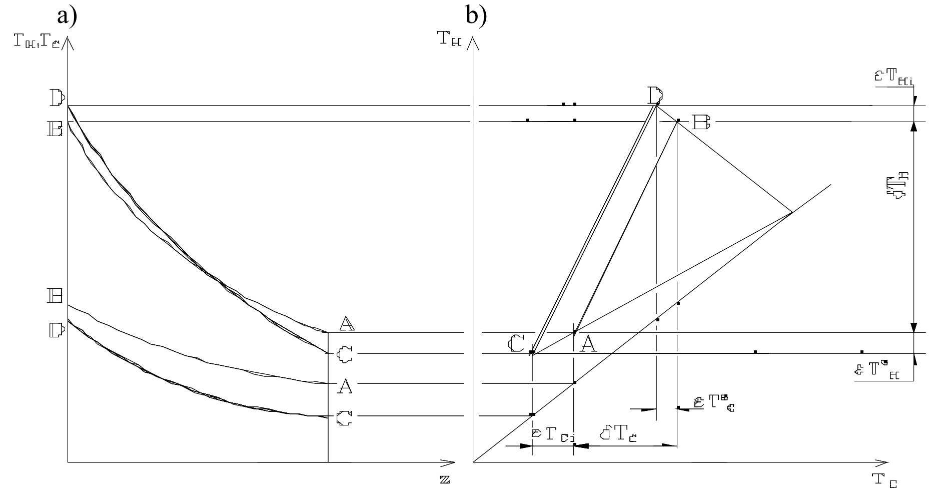

Figure 2. Changes in the temperature of heat–exchanging media under influence of fouling on the heat transfer surface of antecedent heat exchangers: a) temperature distributions along the exchanger, z denoting abstract coordinate along flow path, b) operating lines in the coordinate system T_H, T_C; AB lines represent clean exchanger, CD lines represent clean exchanger influenced by fouling in antecedent exchangers.

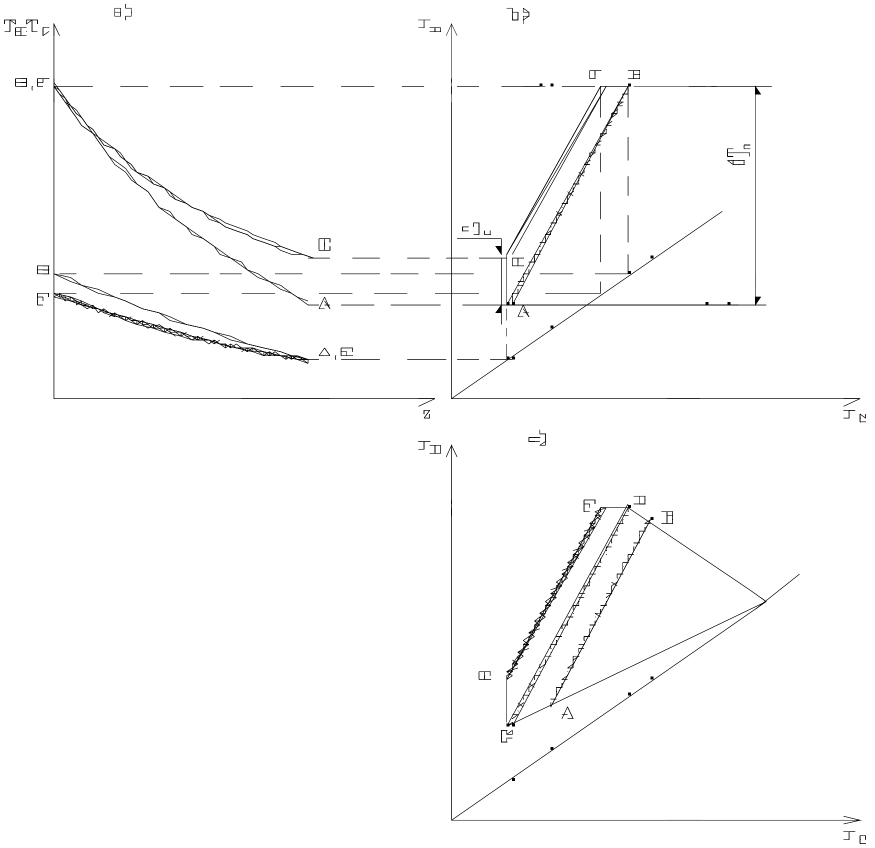

Figure 3. Sequence of determining the influence of HEN fouling on the operation of a single heat exchanger: a), b) effect of deposits formed in the heat exchanger (without influence of antecedent exchangers), c) combined effect of fouling in the heat exchanger and the influence of antecedent exchangers; EF lines represent individual exchanger with fouling.

EXAMPLE OF SCHEDULING OF CLEANING INTERVENTIONS

A real network of tube-in-shell heat exchangers in a crude distillation unit rated 400 metric tons of crude oil per hour is considered. Most exchangers are of the same size (Table 1). It is assumed that refinery is operated at constant throughput. It is also assumed that the HEN is started in clean condition for which the total heat duty is 58145 kW. The network is schematically shown in Figure. 4 where horizontal lines symbolize process streams and circles linked by vertical lines symbolize heat exchangers. The values of operating parameters corresponding to clean heat transfer surfaces (without fouling) are given in Table. 1, and those corresponding to the maximum thermal resistance of fouling – in Table. 2. The following economic data are specified:

- Specific cost of heat $K_q=12.1\cdot 10^{-9}$ \$/J,
- Cost of each cleaning operation $K_{jl}=3100$ \$,
- Duration of the period of continuous HEN operation $t_e=1$ year =31536000 s.

The schedule of cleaning interventions was optimised using the reduced decision model described above. The constrained maximum of the objective function was determined using a numerical method based on the Monte Carlo algorithm. The maximum value of the avoided loss is $F=1.01\cdot 10^6$ \$. The number of cleaning interventions, respectively time intervals between interventions, in the individual exchangers can be found in Table 3.

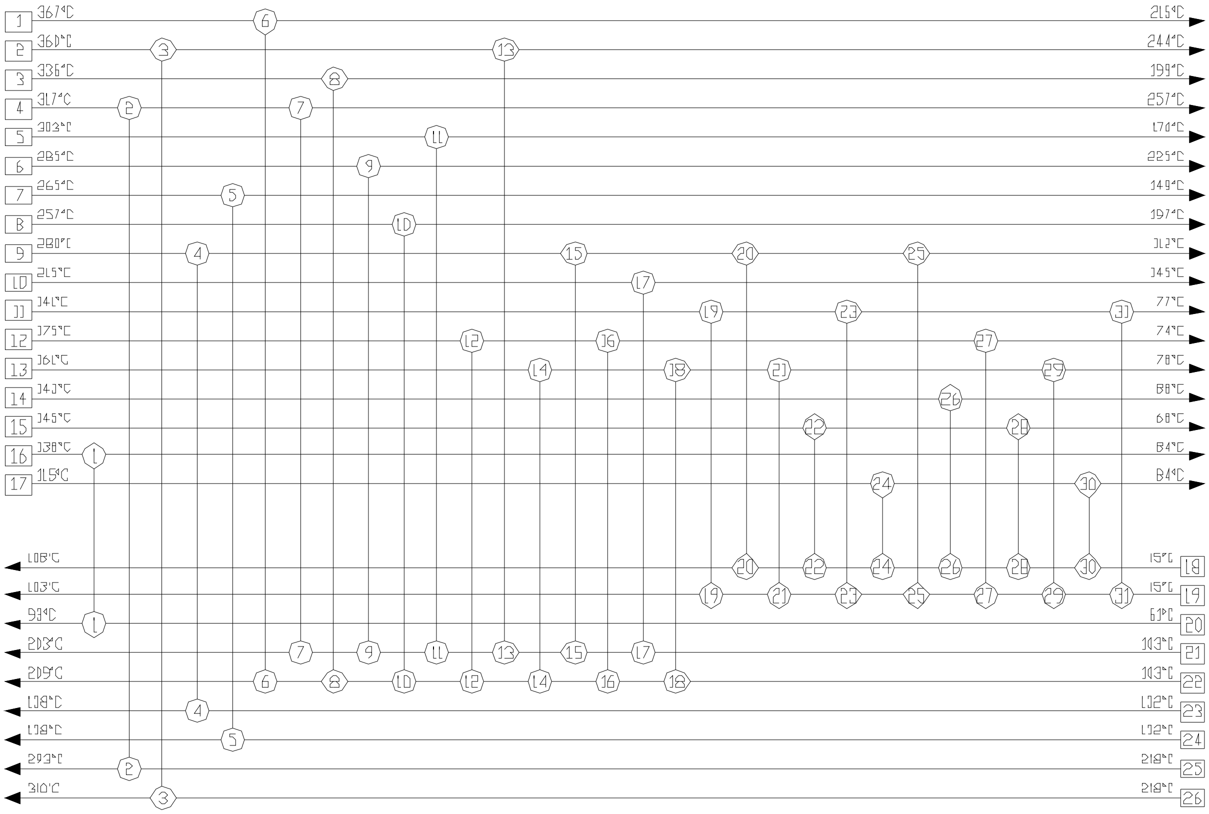

Figure 4. Heat exchanger network in a crude distillation unit.

Table 1. Process data for the HEN without fouling.

Exchanger No.	Temperature inlet/outlet [°C]		Mass flowrate [kg/s]		Heat exchanged [kW]	Heat transfer surface [m²]
	Shell side	Tube side	Shell side	Tube side		
1	2	3	4	5	6	7
1	138/84	61/93	8.6	11.6	1241	191
2	317/270	218/271.9	40.8	21.7	3934.7	398
3	360/268	218/281.6	25.8	20.8	4711.1	398
4	280/182	132/138	24.6	23.7	4415	222
5	265/149	132/138	14.4	23.7	4415	222
6	367/215	192/207	5	61.1	1623.4	257
7	270/257	193/203	40.8	61.1	1068.8	257
8	336/197.4	182/192	5	61.1	1388.6	257
9	285/225	164/193	24.5	61.1	3227	257
10	257/197	136/182	44.5	61.1	5129.8	257
11	303/170	149/164	6.6	61.1	1696.5	257
12	175/142	128/136	15.4	61.1	845.2	257
13	268/244	138/149	25.8	61.1	1226.1	257
14	161/141	117/128	35.5	61.1	1228.7	257

Table 1. continued

1	2	3	4	5	6	7
15	182/132	117/138	24.6	61.1	2288.9	257
16	142/120	113/117	15.4	61.1	522.9	257
17	215/145	103/117	12.1	61.1	1587.3	257
18	141/123	103/113	35.5	61.1	1119.5	257
19	141/97	88/103	38.5	61.1	1325.9	257
20	132/115	99/108	24.6	61.1	757.5	257
21	123/102	74/88	35.5	61.1	1293.2	257
22	145/103	90/99	12.1	61.1	847.8	257
23	97/77	59/74	38.5	61.1	1376.6	257
24	115/107	77/90	86.4	61.1	1247.6	257
25	115/112	57/59	24.6	61.1	126.4	257
26	143/88	61/77	15.5	61.1	1479.8	257
27	120/74	44/57	15.4	61.1	1182.3	257
28	103/68	53/61	12.1	61.1	691.3	257
29	102/78	28/44	35.5	61.1	1483.2	257
30	107/84	15/53	86.4	61.1	3468.6	257
31	77/77	15/28	38.5	61.1	1195.2	257

Table 2. Process data for the HEN with maximum fouling in the heat exchangers.

Exchanger No.	Temperature inlet/outlet [°C]		Heat exchanged [kW]	Fouling resistance (TEMA standards) R_f^* [m^2K/W]	Biot number φ [-]
	Shell side	Tube side			
1	2	3	4	5	6
1	138/88.1	61/90.6	1142.7	0.000706	0.2
2	317/278.2	218/262.3	3402.3	0.001861	0.442
3	360/273.1	218/278.1	4505.9	0.003489	0.129
4	280/195.1	132/137.2	3834.9	0.000529	0.273
5	265/149.3	132/137.5	4102.2	0.000529	0.273
6	367/216.1	179.7/194.1	1595.6	0.001861	0.3
7	278.2/267.4	182.4/190.5	875.6	0.001861	0.574
8	336/197.8	167.2/179.7	1397.2	0.001861	0.293
9	285/238.3	159.8/182.4	2215.7	0.001861	0.535
10	257/209.2	130.8/167.2	4086.9	0.001861	0.554
11	303/181.4	145.7/159.8	1489.9	0.001861	0.333
12	175/145.3	124/130.8	761.8	0.001861	0.456
13	273.1/251.4	135.6/145.7	1108.5	0.003489	0.184
14	161/146	115.8/124	921.7	0.001861	0.608
15	195.1/142.2	114/135.6	2299.2	0.001861	0.488
16	145.3/124.2	110.9/115.8	541.2	0.001861	0.419
17	215/159.3	103/114	1263.3	0.001861	0.453
18	146/130.7	103/110.9	940.2	0.001861	0.565
19	141/122.4	83.1/95.6	1134.6	0.001861	0.437
20	142.2/120.7	90.7/101.3	1061.5	0.001861	0.451

Table 2. continued

1	2	3	4	5	6
21	130.7/110.7	69.5/83.1	1229	0.001861	0.501
22	145/102.8	81.4/90.7	847	0.001861	0.403
23	122.4/102.6	56.2/69.5	1207.8	0.001861	0.361
24	115/108.4	70.3/81.4	1010.7	0.001861	0.621
25	120.7/118.3	55/56.2	122	0.001861	0.348
26	143/95.6	56.2/70.3	1282.2	0.001861	0.419
27	124.2/81.5	42.9/55	1095.3	0.001861	0.28
28	102.8/70.5	49.1/56.2	648.3	0.001861	0.301
29	110.7/88	27.6/42.9	1399.9	0.001861	0.28
30	108.4/88.1	15/49.1	3108.5	0.001861	0.202
31	102.6/83.8	15/27.6	1146.8	0.001861	0152

Table 3. Optimal schedule of on-line cleaning interventions in the HEN shown in Fig. 4. The period of continuous HEN operation is 1 year.

Exchanger No. j	No. of cleaning interventions n_j	Time interval between cleaning interventions t_{jl}; months	Exchanger No. j	No. of cleaning interventions n_j	Time interval between cleaning interventions t_{jl}; months
1	1	6	17	5	2
2	5	2	18	2	4
3	5	2	19	2	4
4	3	3	20	3	3
5	4	2.4	21	1	6
6	2	4	22	2	4
7	4	2.4	23	1	6
8	1	6	24	3	3
9	4	2.4	25	0	-
10	4	2.4	26	2	4
11	0	-	27	3	3
12	2	4	28	5	2
13	0	-	29	1	6
14	2	4	30	3	3
15	0	-	31	2	4
16	1	6			

CONCLUSIONS

The results of the above example demonstrate that optimization of the schedule of on-line cleaning of heat exchangers operated in a HEN makes it possible to significantly reduce the operating cost. The reduction is equivalent to 6% of the value of heat recovered in the HEN.

A prerequisite for optimal scheduling of cleaning interventions is the a-priori knowledge of the time behaviour of the thermal resistance of fouling. The necessary data can be collected if operating parameters of the HEN have been measured and recorded during previous periods of uninterrupted operation. However, measurements of this kind require increasing the number of temperature sensors to be placed in the HEN far above the number typical of the current industrial practice.

NOMENCLATURE

c	specific heat, J/kgK
C	cost of HEN cleaning, $
H_{rc}	value of heat recovered when cleaning the HEN, $
H_{rw}	value of heat recovered without HEN cleaning, $
k	overall heat transfer coefficient, W/(m^{2}K)
K_{jl}	cost of cleaning j-th exchanger after **l**-th period of its continuous operation, $
K_q	specific cost of heat, $/J
m	mass flowrate, kg/s
n	number of cleaning interventions during the period of continuous HEN operation, dimensionless (n_j – of j-th exchanger)
p	number of heat exchangers in the HEN, dimensionless
Q	heating capacity, W (Q'_j – of j-th exchanger if operated without periodic cleaning, Q_{jl} – of j-th exchanger in **l**-th period of continuous operation)
R^*_f	maximum double-side thermal resistance of fouling on the heat transfer surface, m^{2}K/W
R_{faj}	average thermal resistance of fouling in j-th exchanger assuming n_j cleaning interventions during the period of continuous HEN operation, m^{2}K/W
R_{fj}	thermal resistance of fouling in j-th exchanger assuming periodic on-line cleaning, m^{2}K/W
R'_{fj}	thermal resistance of fouling in j-th exchanger without on-line cleaning, m^{2}K/W
t	time, s
t_e	duration of the period of continuous HEN operation, s
t_{jl}	duration of **l**-th period of continuous operation of j-th exchanger, s
T	temperature, °C
z	abstract coordinate along flow path in the exchanger, dimensionless
β	coefficient reflecting the change in heat exchanger capacity, $\beta=Q_f/Q_c$, dimensionless
δT	stream temperature change in the exchanger, K
ΔT	temperature difference, K
εT	temperature change caused by fouling, K
φ	Biot number, $k_c R^*_f$, dimensionless

Subscripts

Multiple subscripts should be interpreted in the same order as they are listed below:

C	cold process stream
H	hot process stream
c	clean exchanger
f	fouled exchanger
i	exchanger inlet
o	exchanger outlet
j	j-th heat exchanger
l	**l**-th period between cleaning interventions

Superscript

•	fouling in antecedent exchangers taken into account

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APPENDIX A

Changes in stream temperature and heating capacity induced by fouling in antecedent exchangers

Given are values of stream temperature at the exchanger inlet in the absence of fouling, T_{Hi} and T_{Ci}. Assuming known values of fouling-induced temperature decrements (or increments) εT_{Ci} and εT_{Hi}, their consequences can be described by the following relationships (Brodowicz and Markowski 2003):

a) if $Q^{\bullet}_c/Q_c>1$

$\varepsilon^{\bullet}T_C=\varepsilon T_{Ci}+\lambda\cdot(T_{Ci}-T_C)$ and $\varepsilon^{\bullet}T_H=-\varepsilon T_{Ci}+\lambda\cdot(T_{Hi}-T_{Ci})$

$Q^{\bullet}_c/Q_c=1+\lambda$

where: $\lambda=(-\varepsilon T_{Ci}+\varepsilon T_{Hi})/(T_{Hi}-T_{Ci})$ and $\lambda > 0$

b) if $Q^{\bullet}_c/Q_c<1$

$\varepsilon^{\bullet}T_C=[\varepsilon T_{Ci}+\lambda\cdot(\delta T_C-\varepsilon T_{Ci})]/(1+\lambda)$

$\varepsilon^{\bullet}T_H=[\varepsilon T_{Hi}+\lambda\cdot(\delta T_H+\varepsilon T_{Ci})]/(1+\lambda)$

$Q^{\bullet}_c/Q_c=1/(1+\lambda)$

where: $\lambda=(\varepsilon T_{Ci}-\varepsilon T_{Hi})/(T_{Hi}-T_{Ci}+\varepsilon T_{Hi}-\varepsilon T_{Ci})$ and $\lambda > 0$

APPENDIX B

Fouling build-up and total heat recovery in the HEN

A question may be posed if fouling build-up in a heat exchanger really causes a reduction of the total heat recovery in the HEN. As can be found in the example relating to the network shown in Figure 4, heat recovery may be increased locally in certain exchangers. This is exemplified by exchanger No. 16 whose capacity in clean condition of the HEN is 522.9 kW but fouling causes it to attain 541.2 kW.

Graphical explanation of the interaction between exchangers operated on the same process stream is shown in Figure B1. For the hot stream leaving the exchanger represented in Figure B1b, the deposit build-up may result in the outlet-temperature surplus εT_{Hi}; assuming that $\varepsilon T_{Ci}=0$, the exchanger capacity is reduced (relative to the reference situation) by $m_H\cdot c_H\cdot\varepsilon T_{Hi}$. The hot stream then enters the subsequent exchanger in which the temperature surplus at outlet is $\varepsilon T^{\bullet}_H$ causing its capacity to increase (relative to the reference situation). However considering both exchangers, their combined capacity is reduced by $m_H\cdot c_H\cdot\varepsilon T^{\bullet}_H$. In a different case, assuming $\varepsilon T_{Hi}=0$ and $\varepsilon T_{Ci}\neq0$ (Figure B1a), the combined capacity is reduced by $m_C\cdot c_C\cdot\varepsilon T^{\bullet}_C$.

The same observation is true in the general case of two exchangers, $\varepsilon T_{Hi}\neq 0$ and $\varepsilon T_{Ci}\neq0$.

It follows from this reasoning that owing to the compensating interactions between neighbouring exchangers, the capacity of some exchangers may be increased relative to the reference situation. However, the total heat recovery in a HEN can never be increased if the deposits build up on the heat transfer surfaces of the individual exchangers. Then in the HEN the value of heat recovered reaches maximum if the value of the thermal resistance of deposits in each individual heat exchanger, averaged over the period of continuous heat exchanger operation, attains its minimum (see equation (4)).

Let us now consider the properties of function $R_{fj}(t)$ in a heat exchanger subject to periodic on-line cleaning, assuming initially that $n_j=1$, as shown in Figure B2a.

It is essential that the thermal resistance is a non-decreasing function of time, that is, areas indicated in Figure B2b and B2c always satisfy the relationship $P_2 > P_1$.

If the duration of the period between cleaning interventions is changed, that is, the exchanger is cleaned after $t_l-\Delta t$, as shown in Figure B2b (alternatively, $t_l+\Delta t$, as shown in Figure B2c), then the average thermal resistance increases by $(P_2-P_1)/\Delta t$. The above reasoning can be extended to $n_j=$ 2,3,4... and in each case, the average thermal resistance of deposits increases for non-equal periods between cleaning interventions. It can thus be concluded that to minimise the average value of thermal resistance of deposits in the heat exchanger over the production period during which n_j cleaning interventions are planned, the periods between interventions should be of equal duration.

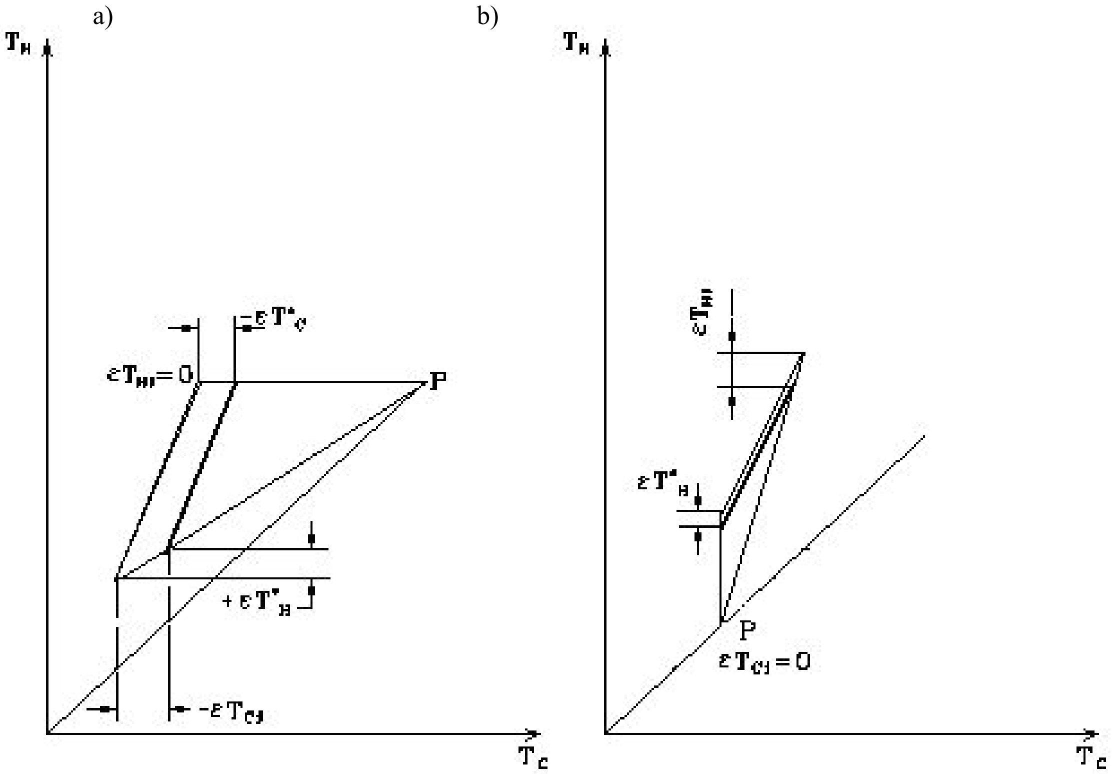

Figure B1. Graphical interpretation of the relationship between inlet-temperature increments εT_{Hi} and εT_{Ci} for the hot and cold stream, respectively, and outlet-temperature changes $\varepsilon T^{\bullet}_{H}$ and $\varepsilon T^{\bullet}_{C}$: a) $\varepsilon T_{Hi} = 0$ and $\varepsilon T_{Ci} < 0$, b) $\varepsilon T_{Hi} > 0$ and $\varepsilon T_{Ci} = 0$.

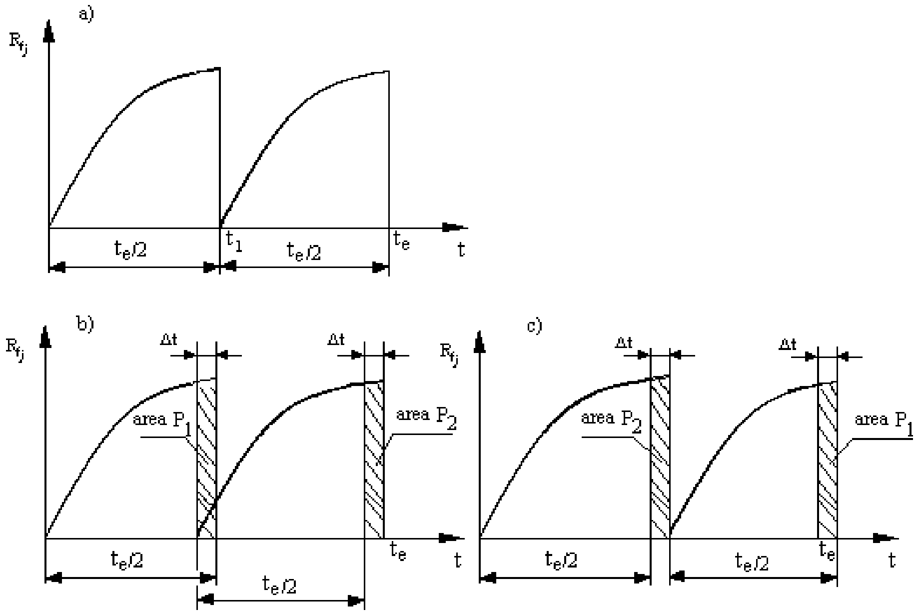

Figure B2. Heat resistance of deposits as a function of time at $n_j = 1$: a) reference situation, b) cleaning intervention advanced by Δt, c) cleaning intervention delayed by Δt.