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THE IMPACT OF AGEING ON FOULING AND CLEANING: CLOSING THE FOULING-CLEANING LOOP

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ABSTRACT

Process units subject to fouling often require cleaning on a regular basis, giving rise to fouling-cleaning operating cycles. The initial stages of fouling are strongly influenced by the effectiveness of the most recent cleaning step and, similarly, the effectiveness and rate of cleaning is determined by the extent and nature of the fouling layer present on the surface. The optimal operating cycle will therefore be determined by fouling-cleaning interactions. Deposit ageing is an important example of these, as an aged deposit is usually harder and therefore more difficult to clean. Ageing therefore introduces an element of choice into fouling-cleaning operating cycles, between in-situ 'chemical' methods and ex-situ 'mechanical' methods, with associated differences in effectiveness, time and cost. This paper reports a reformulation of the cleaning scheduling problem which considers the *choice* of cleaning method as well as the *timing* of cleaning. A two-layer model is used to describe ageing in terms of heat transfer and ease of removal. A case study based on a shell-and-tube heat exchanger processing crude oil is used to illustrate the concepts and scope of application of this approach.

INTRODUCTION

Process heat exchangers subject to fouling often require cleaning. Such cleaning operations are often performed on a regular basis, giving rise to fouling-cleaning operating cycles. Identification of the optimal operating period for an isolated exchanger subject to recurring fouling was first considered by Ma and Epstein (1981). The scheduling of heat exchanger cleaning operations has been considered since by many workers, both for individual units (*e.g.* Casado, 1990: Sheikh *et al.*, 1996) and for networks of exchangers (*e.g.* Müller-Steinhagen and Branch, 1997; Georgiadis *et al*., 2000; Ishiyama *et al*. 2009).

The analyses reported to date have all assumed that the cleaning action removes the whole fouling layer, so that the unit starts at the clean state when it is returned to operation. This is not always achieved in practice, and particularly when a less aggressive cleaning method is employed. There are a number of technologies available, which differ in terms of effectiveness, downtime and cost (Müller-Steinhagen, 2000). A choice often arises between a quick, less effective method and a rigorous but time-consuming alternative. An example from an oil refinery is the use of recirculating solvent to wash away the majority of a fouling layer, which requires units to be isolated but not dismantled, compared to water-jet blasting or pigging of tube bundles at remote locations. The former is an example of cleaning-in-place (CIP), which we label ‘chemical’ cleaning, while the latter is here termed ‘mechanical’ cleaning. This element of choice has not been considered in cleaning scheduling to date and this paper presents one approach to the problem.

It is recognized that cleaning methods vary noticeably between industries and applications. For instance, CIP is widely practised in the food sector as it avoids exposing process surfaces to the air and thereby inviting contamination. Likewise, pigging and water jetting is widely practised in other sectors where the fouling deposits cannot be removed by other means. This paper considers the case where the choice of cleaning method is purely techno-economic and free from other process factors/constraints.

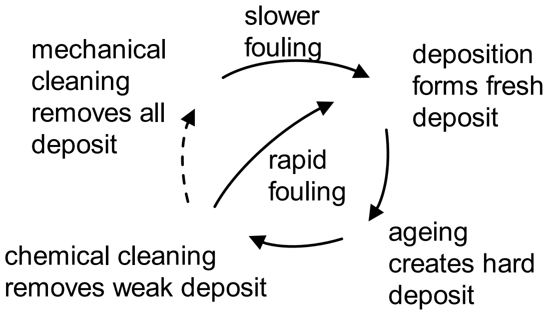
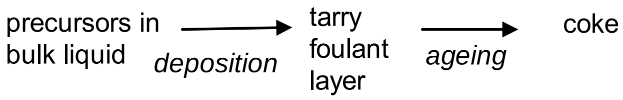


Figure 1 Fouling-cleaning cycle showing impact of chemical/mechanical cleaning

The selection of cleaning methods is determined by the nature of the fouling layer, which is, in turn, governed both by the deposition mechanism and subsequent ageing. Figure 1 shows a modified schematic of the ‘fouling-cleaning symbiosis’ cycle presented by Wilson (2005). The initial stages of fouling are strongly influenced by the effectiveness of the most recent cleaning step and, similarly, the effectiveness and rate of cleaning is determined by the extent and nature of the fouling layer present on the surface. The choice of cleaning method and optimal operating cycle will therefore be determined by fouling-ageing-cleaning interactions. This paper presents an analysis of the combined scheduling problem (cleaning type *and* timing) for a single heat exchanger subject to tube-side crude oil chemical reaction fouling. In crude oil fouling, the freshly deposited material often takes the form of a gel, which over time converts to a harder, 'coke' layer. The former may be removed by solvent washing, but the latter requires the unit to be isolated and dismantled for mechanical cleaning. Ageing therefore introduces a systematic factor into the choice of fouling-cleaning operating cycles, between in-situ 'chemical' methods and ex-situ 'mechanical' methods, with associated differences in effectiveness, time and cost. This requires a reformulation of the Ma and Epstein (1981) problem.

TWO-LAYER MODEL

Ageing is modeled in terms of two sub-layers, of gel and coke, being a development of the concept proposed by Crittenden and Kolackowski (1979). The coke represents that part of the deposit that cannot be removed by cleaning-in-place 'chemical' methods.



The two-layer model is employed here as a simplification of ageing in real systems, which involves complex and largely non-quantified chemistry (see Fan and Watkinson, 2006). It represents the simplest quantitative treatment of the evolution of a deposit layer from freshly deposited material, which is deemed to be susceptible to chemical cleaning, to coke, which cannot.

The microstructural changes associated with deposit hardening on ageing not only modify the rheology of the deposit but also, normally, increase its thermal conductivity, λ. Ageing therefore couples thermal, fouling and cleaning performance: λ determines the temperature distribution within the deposit (and local ageing rate) as well as the deposit-liquid interface temperature (and deposition rate). Ishiyama *et al*. (2010) presented a quantitative distributed model of deposit ageing and used it to investigate the impact of ageing on chemical reaction fouling behaviour. They used a fouling model and parameter values for crude oil fouling and compared the effect of fouling on results obtained under typical laboratory test conditions with plant operating modes. They modeled the thermal conductivity as changing continuously from the initial gel value, λ_g, to that of coke, λ_c, using a simple kinetic scheme (see Figure 2(*a*)). They did not consider the impact of ageing on cleaning.

In this work we assume that the thermal conductivity of the deposit layer may be modeled using a simple two-layer model, as shown in Figure 2(*b*). A detailed justification of the two-layer model as a simplification of the ageing process in real systems is given in Ishiyama et al. (2011a). The key attribute of a two layer model is that it links, in the simplest way heat transfer and rheology of undoubtedly complex soft-solid layers. The overall thickness of the deposit, δ, is given by the sum of the gel and coke sub-layer thicknesses:

$$\delta = \delta_g + \delta_c \qquad [1]$$

In the absence of experimental data, and to simplify the mathematics, we assume that the overall fouling resistance of the deposit, R_f, is given by

$$R_f = \frac{\delta_g}{\lambda_g} + \frac{\delta_c}{\lambda_c} \qquad [2]$$

which assumes that the thermal resistance of the fouling layers can be adequately described by the thin-slab approximation. This represents an intrinsic linking of cleaning behaviour (equation (1)) and thermal performance (equation (2)) via the sub-layer thicknesses. In practice the division between rheological and thermal properties may lie at different points, which could modeled by using Ishiyama *et al.*'s distributed thermal model or a coarser version thereof. The simple (linked) model is used here as our aim is primarily to illustrate the concept.

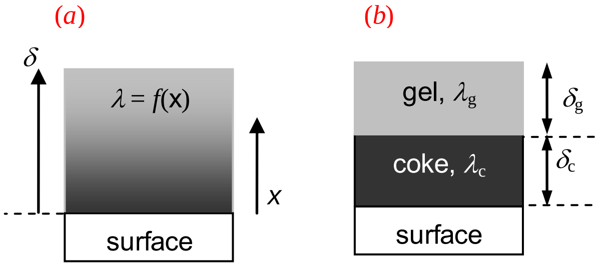


Figure 2: Schematic comparison of (*a*) distributed ageing and (*b*) two-layer models. The deposit changes from its initial gel form to a harder, coke, form over time. Darkness of shading indicates extent of ageing.

Before the two-layer model is employed in cleaning scheduling, the kinetics of the gel-coke evolution need to be established. Under different conditions, Ishiyama *et al.*'s distributed thermal model predicted zeroth order behaviour (coke formation as a moving front) as well as gradual transformation from gel to coke. Ishiyama *et al.* 2011(*a*) established the most appropriate kinetic scheme to use by comparing the R_f-time results from their distributed model with two limiting cases, namely zeroth order and first order kinetic schemes.

Both schemes employed the following equations of change, based on equations (1) and (2):

$$\dot{\delta}_{gel} = r_d - r_c \qquad [3]$$

$$\dot{\delta}_{coke} = r_c \qquad [4]$$

giving

$$\dot{R}_f = \frac{1}{\lambda_g}\left(r_d - r_c\right) + \frac{1}{\lambda_c} r_c \qquad [5]$$

Here r_d is the deposition rate and r_c the rate of conversion to coke, both written as velocities. The deposition rate employed a simplified expression for tubeside chemical reaction fouling (more complex models could be used as desired, such as those described by Yeap *et al.* (2004)):

$$r_d = \lambda_g a_d \, Re^{-0.8} \, Pr^{-0.33} \, exp\left(\frac{-E_d}{RT_s}\right) \qquad [6]$$

Here, *Re* and *Pr* are the Reynolds number and Prandtl numbers of the bulk liquid, respectively; T_s is the temperature at the deposit(gel)–liquid interface, *i.e.* in contact with the flowing fluid, *R* is the gas constant, E_d is the activation energy for deposition and a_d is a pre-exponential factor dictating the time-scale of deposition. They considered a single value of E_d, namely 50 kJ mol^{-1}, which is representative of temperature sensitivities reported in the literature (Yeap *et al*., 2004). Different activation energies were considered for the ageing step, r_c, so that the effect of temperature sensitivity on ageing was isolated from its effect on deposition.

Zeroth order ageing (Model 0)

The coke layer is assumed to grow as a front, with the rate of growth determined by the temperature at the sub-layer interface, T_{int}.

$$r_c = \begin{cases} k_0 & \text{when } \delta_g > 0 \\ 0 & \text{when } \delta_g = 0 \end{cases}$$

[7]

where the rate constant k_0 is given by

$$k_0 = a_0 \, exp\left(\frac{-E_0}{RT_{int}}\right) \qquad [8]$$

First order ageing (Model I)

The rate of growth of the coke layer is related to the amount of gel present. A simple physical interpretation of this model is not available but it avoids the bifurcation in [7] and proves to be mathematically similar to the distributed model in certain cases. This gives

$$r_c = k_I \delta_g = a_I exp\left(\frac{-E_I}{RT_{int}}\right)\delta_g \qquad [9]$$

Both kinetic schemes require T_{int} to be evaluated, which required solution of the associated heat transfer problem, including curvature and changes in *Re* with deposit thickness.

Distributed ageing model (Model II)

This is described in detail by Ishiyama *et al.* (2010). The rate of ageing is described by the first order decay of a localized structural variable, whose temperature sensitivity is quantified by the activation energy E_{II}.

Case Study

The zeroth and first order ageing models described above present readily tractable forms suitable for scheduling optimization calculations. Their suitability was tested by comparison with Ishiyama *et al.*'s distributed model over a range of conditions, where the latter was assumed to predict the true thermal effect of ageing. The test vehicle was a typical heat exchanger tube (nominal one inch, i.d. 0.0229 m) with a medium viscosity crude oil at 270ºC flowing at 0.3 kg s^{-1} (clean velocity ~1 m s^{-1}) on the tube-side. The values of *Re* and *Pr* were ~40,000 and ~9.5, respectively. Other parameter values were: a_d = 1 ×10^5 m^{2}K kW^{-1} h^{-1}, λ_g = 0.1 W m^{-1}K^{-1}, λ_c = 1.0 W m^{-1}K^{-1}. Further details of the simulations are given in Ishiyama *et al.* (2011a). Two primary parameters were investigated:

(*i*) *Ageing activation energy*

The activation energy for fouling, E_d, was kept constant at 50 kJ mol^{-1}. The effect of different ageing temperature sensitivity was studied by considering ageing activation energies of 10, 50 and 200 kJ mol^{-1}. In order to compensate for the difference in activation energies, the ageing prefactor a_i was adjusted to give the same initial ageing rate via:

$$a_{i,E\,j} = a_{i,10\text{ kJ mol}^{-1}} \exp\left(-\frac{10{,}000 - E_j}{RT_s}\right) \qquad [10]$$

(*ii*) *Relative rates of fouling and ageing*

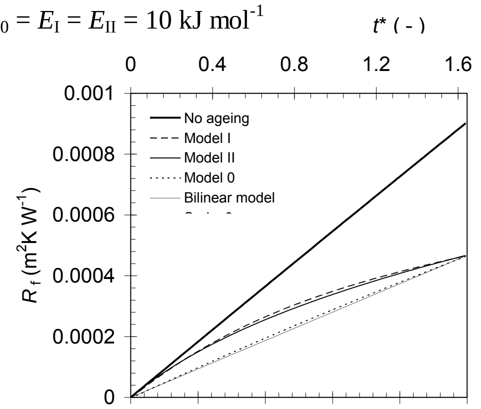
When ageing is rapid compared to the rate of gel deposition, the gel layer thickness approaches zero and the deposit takes the form of a coke sub-layer. Likewise, slow ageing means that the deposit behaves as if it were a gel sub-layer. Three scenarios were investigated, namely slow ageing with respect of fouling; medium ageing, and fast ageing. The a_i values used are given in Table 1.

Table 1: Kinetic parameters used in ageing models.

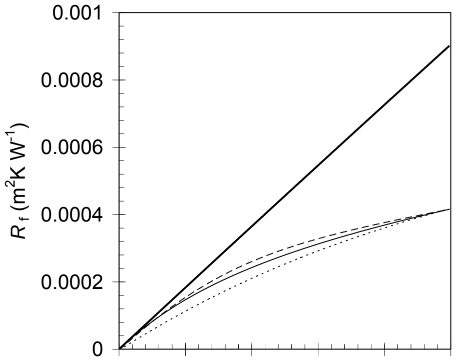
		$E_0 = E_I = E_{II}$ / kJ mol^{-1}		
Model	Ageing	10	50	200
	Slow	3.5×10^{-6}	0.1	0.20 ×10^{13}
Model 0	Medium	6.0×10^{-6}	1.0	0.85 ×10^{13}
a_0 (m day^{-1})	Fast	6.4×10^{-6}	10	1.2 ×10^{13}
	Slow	0.06	0.1	5.6 ×10^{16}
Model I	Medium	0.40	1.0	7.0 ×10^{17}
a_I (day^{-1})	Fast	0.85	10	3.4 ×10^{18}
	Slow	0.024	0.1	4.5 ×10^{16}
Model II	Medium	0.24	1.0	4.5 ×10^{17}
a_{II} (day^{-1})	Fast	2.40	10	4.5 ×10^{18}

Figure 3 shows the results obtained for the case of slow ageing when operating at constant heat flux, which is the mode employed in many experimental fouling tests. The plots all show a decrease in thermal fouling rate caused by the conversion of gel to coke (and decrease in deposit thermal resistance). Linear fouling would be observed in the absence of ageing as the gel-liquid interface temperature does not change noticeably. Also shown in Figure 3(*a*) is a relative time scale, *t**, where *t** = 1 indicates the time taken for the tubeside heat transfer coefficient to decrease to 50% of its initial value (fouling Biot number = 1).

(a) $E_0 = E_I = E_{II} = 10$ kJ mol^{-1}



(b) $E_0 = E_I = E_{II} = 50$ kJ mol^{-1}



(c) $E_0 = E_I = E_{II} = 200$ kJ mol^{-1}

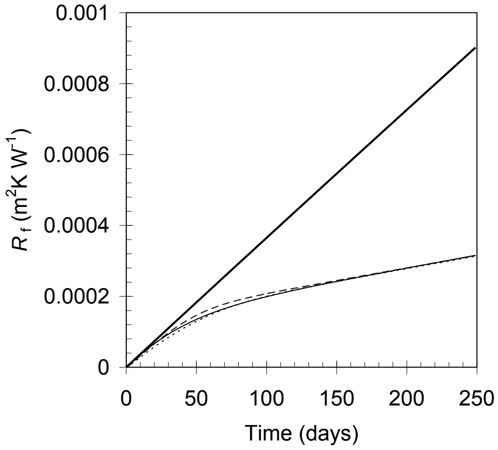
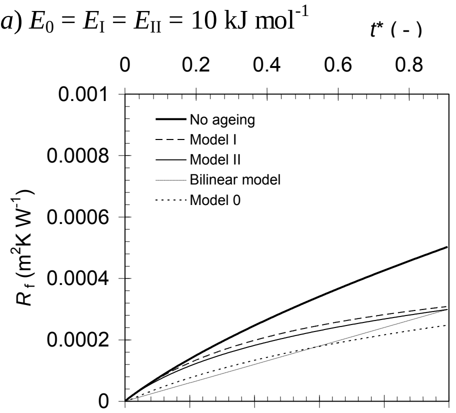


Figure 3 Comparison of ageing models under constant heat flux operation. Key in (a) common to all plots.

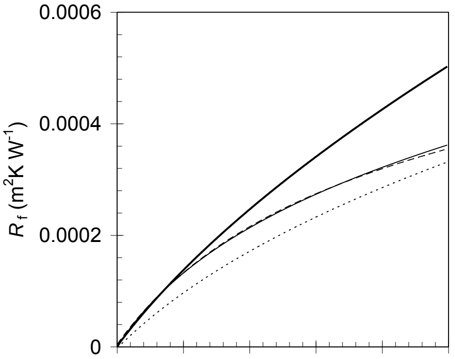
Table 2: Summary of relative agreement of the two-layer models with Model II for constant heat flux operation. Entry indicates good agreement

	Ageing rate		
Activation energy	Slow	Medium	Fast
$E_i = 10$ kJ mol^{-1}	Model I	Model I	Both
$E_i = 50$ kJ mol^{-1}	Model I	Model I	Both
$Ei = 200$ kJ mol^{-1}	Both	Both	Both

(a) $E_0 = E_I = E_{II} = 10$ kJ mol^{-1}



(b) $E_0 = E_I = E_{II} = 50$ kJ mol^{-1}



(c) $E_0 = E_I = E_{II} = 200$ kJ mol^{-1}

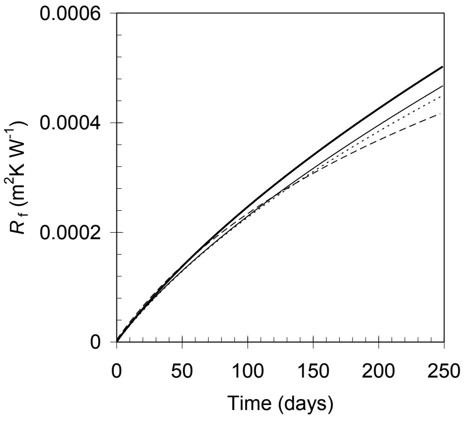


Figure 4 Comparison of ageing models under constant wall temperature operation. Key in (a) common to all plots.

Table 3: Summary of relative agreement of the two-layer models with Model II for constant wall temperature operation. Entry indicates good agreement

	Ageing rate		
Activation energy	Slow	Medium	Fast
$E_i = 10$ kJ mol^{-1}	Model I	Model I	Both
$E_i = 50$ kJ mol^{-1}	Model I	Neither	Both
$Ei = 200$ kJ mol^{-1}	Neither	Neither	Neither

The plots show that the agreement between each of the two-layer models and Model II varies, depending on the relative rate of ageing and temperature sensitivity. The summary of the agreement observed across all nine scenarios in Table 2 indicates that Model I provided a satisfactory shortcut description for all cases. Model 0 could be used to describe cases with rapid ageing or high temperature sensitivity.

The corresponding plots for operation at constant wall temperature are presented in Figure 4. The non-ageing reference case exhibits falling rate fouling behaviour owing to the change in gel-liquid interface temperature. The summary in Table 3 includes some important differences from Table 2, in that neither two-layer model provided a good approximation to the distributed model for scenarios with strong temperature sensitivity, and, interestingly, for the case of medium ageing rate and mid-range temperature sensitivity. In the absence of supporting information (e.g. experimental measurements) the results in tables 2 and 3 together indicate that the 1st order form of the ageing equation could describe both the constant heat flux and constant wall temperature cases adequately. For the purposes of this paper a tractable ageing model is required for the optimization calculations.

SCHEDULING WITH CHOICE: SUPERCYCLES

Fouling causes reduced heat transfer efficiency, and thermal performance is used here to construct a cost function for the optimisation algorithm. The impact on chemical and mechanical cleaning on fouling and the heat duty of an exchanger, *Q*, is shown schematically in Figure 5. Linear deposit growth kinetics are employed for illustration.

Identifying a cleaning schedule requires selection of cleaning method (chemical or mechanical) and time of cleaning (t_M, t_C). The choice of cleaning method introduces two dimensionless ratios, namely

$C_{c,C}/C_{c,M}$	ratio of cleaning costs
τ_C/τ_M	ratio of cleaning period lengths

Both ratios are expected to be < 1 in order to offset the poorer cleaning performance expected for chemical cleaning.

Figure 5(*b*) shows that chemical cleaning results in an increase in heat duty when the unit is returned to operation but that the decay caused by fouling continues. Mechanical cleaning, however, restores the unit to its clean state and effectively restarts the process. The period between each mechanical clean, which can include any number of chemical cleans, is repeated if the parameters remain constant: this is termed the 'supercycle' and the identification of a supercycle with the lowest time-averaged cost is the objective for the scheduling problem.

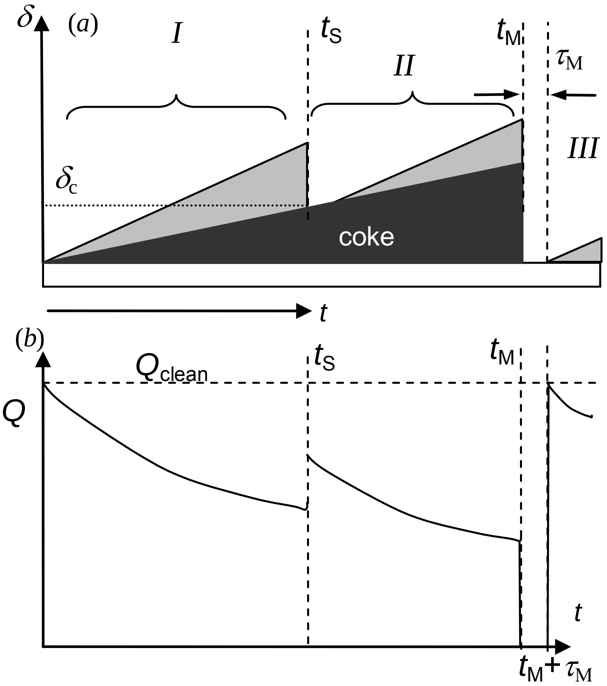


Figure 5: Schematic of the impact of ageing described by the two-layer model on (*a*) deposition, and (*b*) heat transfer. I - deposit, thickness δ, grows and an aged layer, labelled 'coke', grows simultaneously; II - solvent cleaning at time t_S leaves the aged layer – fouling restarts from δ_c; III - mechanical cleaning at time t_M removes all deposit and fouling restarts from a clean surface. τ_M is the duration of the mechanical cleaning step: the duration of the chemical cleaning step, τ_C, is zero here.

It should be noted that the impact of different cleaning methods on fouling induction periods has not been considered here but could be introduced readily. Chemical cleaning is deemed to leave a residual fouling layer on which deposition is likely to start soon after the unit is returned to service, whereas a mechanically cleaned surface may require conditioning before deposit can attach and grow.

The objective function is written in terms of cost, with three components:

(*i*) Cost of additional heating, provided elsewhere in the process, to compensate the loss in heat duty due to fouling (at C_E \$/kJ)

$$C_E \int_0^t \left(Q_{cl} - Q(t')\right) dt' \qquad [11]$$

(ii) Additional heating costs during the period when the HTE is taken off-line for cleaning

$$C_E \, Q_{cl} \, \tau_{\imath} \qquad [12]$$

(iii) Cost of each cleaning action, C_{cl}.

These costs are then summed and the total averaged loss, *TAL*, calculated from

$$TAL = \frac{\left(C_{\mathrm{E}} \int_0^{t_M} \left(Q_{\mathrm{cl}} - Q(t') \right) dt + N_{c,C} C_C + C_{C,M} \right)}{t_{\mathrm{cycle}} = t_M + \tau_M} \qquad [13]$$

where cost item (*ii*) is incorporated in the integral.

The aim of the scheduling calculation is to minimise *TAL* subject to various constraints. There are a number of approaches for generating solutions to this problem, and a relatively simple method is employed here. A stepwise marching algorithm is used to evaluate the best local decision (lowest cost) of available options. Chemical cleaning is favoured if it gives *TAL* lower than that given by mechanical cleaning at that point in time. Cleaning is performed and the algorithm moves on to the next period, until mechanical cleaning is performed and the system resets. A detailed description of the search algorithm is given by Ishiyama *et al*. (2011b). More mathematically elegant methods for determining the periods between cleans were presented by Pogiatzis *et al*. (2010) and are discussed in a sister paper being presented at this conference.

CLEANING SUPERCYCLE CASE STUDY FOR A SHELL-AND-TUBE HEAT EXCHANGER

Ishiyama *et al*. considered optimizing chemical and mechanical cleaning on an evaporator with fixed temperature driving force: this case study considers a countercurrent heat exchanger with a clean heat duty of 11.7 MW. The unit is a single segmental baffled, shell-and-tube unit with crude flowing on the tube-side. The crude temperature is initially raised from 220 °C to 237 °C. The physical properties of process streams are summarized in Table 4 while design and initial operating parameters are given in Table 5. Deposition (gel formation) is modeled using equation (6) with a_{d} = 36 $\mathrm{m^2K\ kW^{-1}\ h^{-1}}$ and E_{d} = 50 $\mathrm{kJ\ mol^{-1}}$. Ageing of the deposit described by equation 9 (first order model) with E_1= 50 $\mathrm{kJ\ mol^{-1}}$. a_1 values of 100, 500 and 1000 $\mathrm{day^{-1}}$ were considered here.

Table 4: Case study stream properties [*T* in °C]

Cold stream	
Density, $\mathrm{kg\ m^{-3}}$	882.1 -0.801 *T*
Dynamic viscosity, Pa s	$\alpha \exp(\beta / (T + 273.15))$; $\alpha = 0.32\times10^{-5}$ Pa s; $\beta = 2396.3$ K
Specific heat capacity, $\mathrm{J\ kg^{-1}\ K^{-1}}$	1890 + 3.805*T*
Thermal conductivity, $\mathrm{W\ m^{-1}\ K^{-1}}$	0.129 – 0.0013 *T*
Hot stream	
Density, $\mathrm{kg\ m^{-3}}$	934.3 -0.720*T*
Dynamic viscosity, Pas	$\alpha = 2.145\times10^{-14}$ Pa s; $\beta = 11735$ K
Specific heat capacity, $\mathrm{J\ kg^{-1}\ K^{-1}}$	1893 + 3.540 *T*
Thermal conductivity, $\mathrm{W\ m^{-1}\ K^{-1}}$	0.129 – 0.0013 *T*

Figure 6(a) shows the overall fouling resistance-time profiles for different rates of ageing (varying a_1) while Figure 6(b) compares the deposit thickness reached after 1000 days of operation. Fouling in all cases causes a significant reduction in the overall heat transfer coefficient. This is not matched by the deposit thickness, however: ageing actually results in a slightly larger total amount of deposit. This occurs because the increase in overall thermal conductivity with ageing reduces the overall fouling resistance, so that the deposit surface temperature is higher, promoting deposition. The growth of the coke layer with increasing a_1 is evident.

The cleaning super-cycle algorithm described above was used to identify optimal combinations of chemical and mechanical cleaning actions for different costing scenarios. Figure 7 shows the results from one scenario, where two chemical cleaning operations are be performed for each mechanical one, giving a supercycle period of ~850 days. The *residual* fouling resistance following chemical cleaning actions is evident, and does not follow a linear trend.

The influence of different cost and cleaning time ratios on supercycle and TAL for a_1 = 500 $\mathrm{day^{-1}}$ is summarized in Figure 8. Fig. 8(*a*) shows that the length of the supercycle (and number of chemical cleaning actions) increases with increase in mechanical cleaning parameters ($C_{\mathrm{cl,M}}$ and τ_{M}). The number of solvent cleaning actions in each optimised supercycle is marked on Figure 8(a). As a discrete action, solvent cleaning gives rise to a series of steps in the solution plane. The Figure shows that more chemical cleans are employed as mechanical cleaning becomes less attractive.

The mixed cleaning strategy can be compared with one based solely on mechanical cleaning. The optimization problem then is similar to that considered by Casado (1990) and the results for this case are plotted as a continuous plane on Fig. 8(*b*). The plot demonstrates that a mixed cleaning strategy is always economically more attractive for the parameter set considered here. As a_1 increases and the effectiveness of chemical cleaning decreases, mechanical cleaning is likely to become more attractive and eventually be the only mode used.

This case study shows how mixed cleaning strategies could be evaluated for heat exchangers and other processes subject to fouling and faced with a choice of removal methods. Relatively simple numerical techniques were used here and more elegant approaches are being developed in our group.

The main priority for research, however, is in experimental studies to quantify the extent of ageing, either in terms of heat transfer, ease of cleaning, or, ideally, both, in order to close the fouling-cleaning loop. The ageing models employed here represent candidate mathematical forms to describe what in reality must be complicated interactions between chemical reaction, microstructure, heat transfer and rheology. The zeroth and first order models are proposed as tractable forms which we anticipate will be replaced in due course by detailed (and probably more complicated) forms based on experimental evidence. The aim of this work was to demonstrate the potential cost savings and other returns achievable by considering ageing in the fouling-cleaning loop, in order to encourage support for research in this area.

Table 5: Case study exchanger specifications

Description	Value
Tube length	6 m
Tube external diameter	0.0254 m
Tube internal diameter	0.0199 m
Total number of tubes	800
No. of tube side passes	1
Shell diameter	1.3 m
Baffle spacing	0.3 m
Baffle cut	25%
Initial fouling resistance	0 $m^2K W^{-1}$
Clean overall heat transfer coefficient	900 $W m^{-2}K^{-1}$
Cold stream flow/inlet temperature	256 $kg s^{-1}$ / 220 °C
Hot stream flow/inlet temperature	60 $kg s^{-1}$ / 320 °C

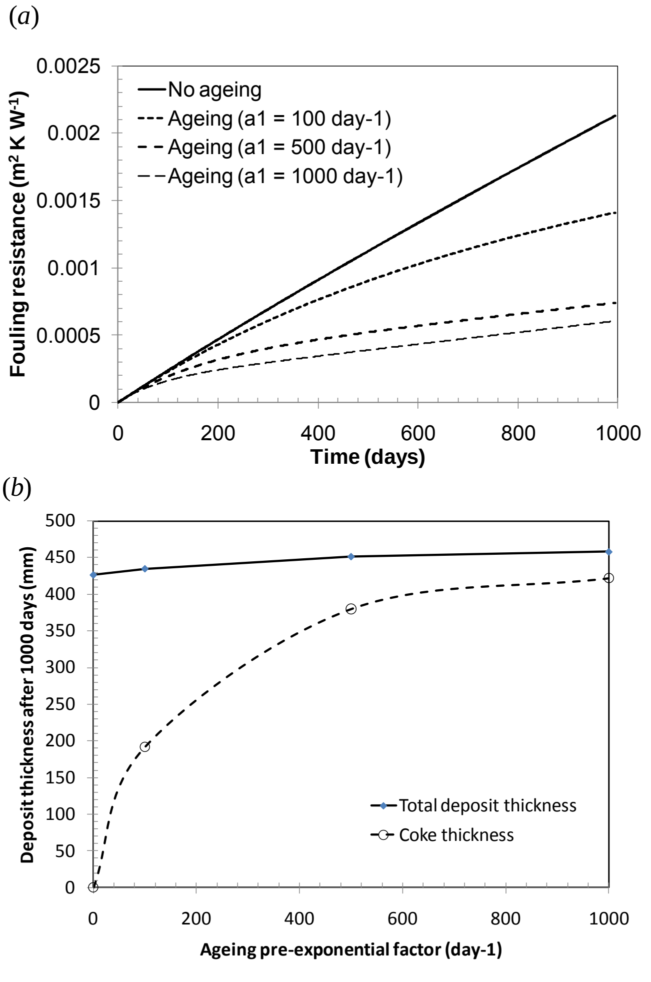


Figure 6: Effect of ageing on (*a*) overall fouling resistance and (*b*) deposit thickness after 1000 days of operation.

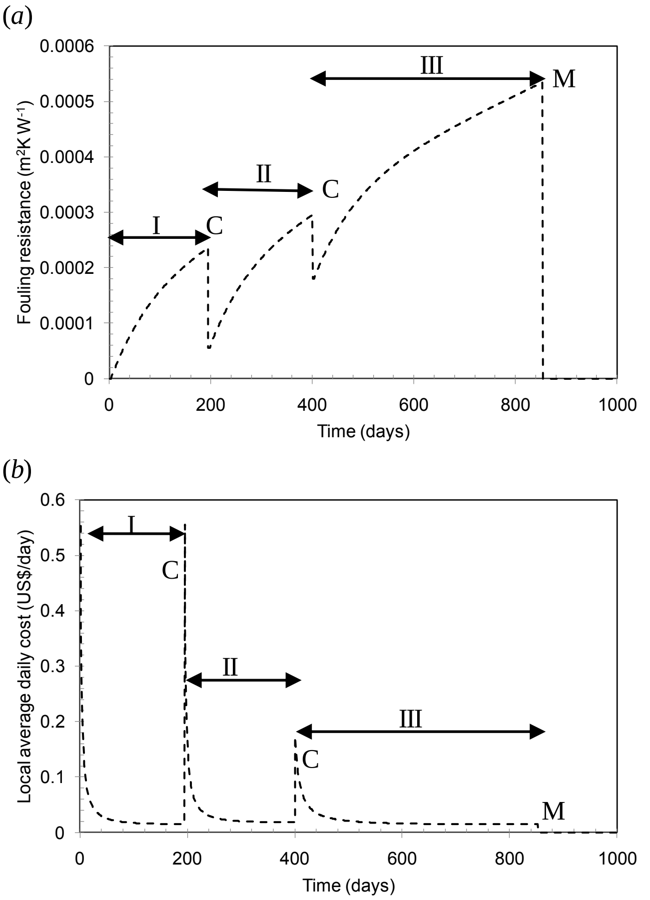


Figure 7: Evolution of (*a*) overall fouling resistance and (*b*) local value of average daily cost. Labels C and M denote chemical and mechanical cleaning actions, respectively. Periods I and II represent sub-cycles ending with a chemical clean; period III ends with mechanical cleaning. Parameters: $C_{c,M}/C_{c,C}$ = 1.5, τ_M/τ_C = 7, a_1 = 500 day^{-1}. Solid line in (a) presents the thickness of the coke layer in absence of any cleaning action.

CONCLUSIONS

1. Two-layer models to represent ageing of fouling deposits were compared in terms of heat transfer. The first order, two layer model proved to be more robust in mimicking the distributed ageing model presented by Ishiyama *et al*. (2010).
2. The first order, two layer model was used to link heat transfer and cleaning performance in a cleaning scheduling formulation including a choice between two different cleaning methods. The resultant mixed cleaning strategy gives rise to a cleaning supercycle.
3. The approach was demonstrated for a shell-and-tube heat exchanger undergoing deposition and ageing. The optimal number of chemical cleaning actions between each mechanical cleaning episode was evaluated.

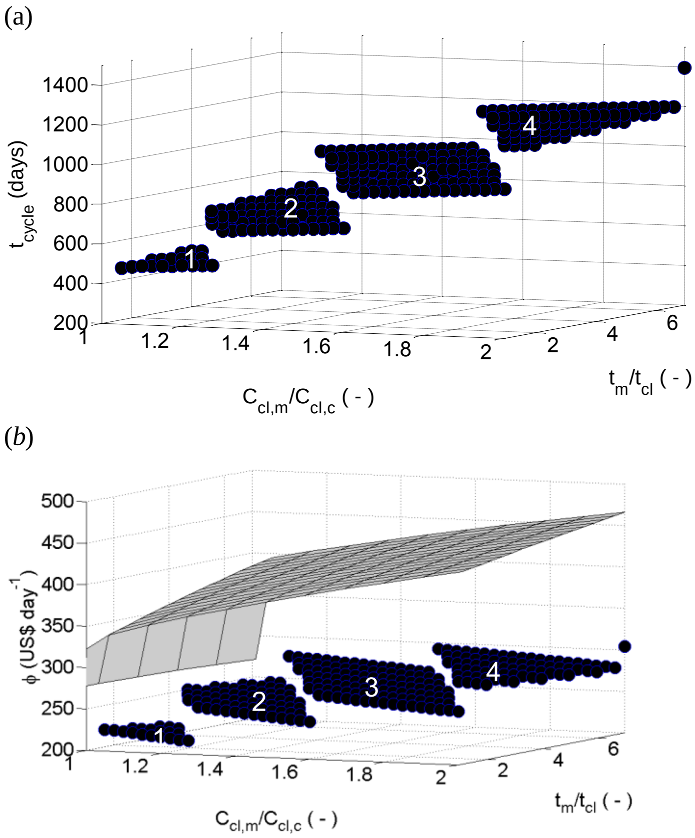


Figure 8: Effect of cost ratio and cleaning duration ratio on (*a*) supercycle period and (*b*) total averaged daily cost for a_1 = 500 day^{-1}. Symbols indicate a mixed cleaning scenario: numerical values indicate the number of chemical cleaning actions per supercycle. Surface in (*b*) shows the cost for mechanical cleaning alone

NOMENCLATURE

Roman

a_0	pre-exponential term in Eqn. 8, m s^{-1}
a_I	pre-exponential term in Eqn. 9, s^{-1}
a_{II}	pre-exponential term of Model II, s^{-1}
a_d	pre-exponential term in Eqn.6, m^2 K J^{-1}
C_E	energy cost, US $ W^{-1} day^{-1}
$C_{c,C}$	cost of chemical cleaning action, US$ clean^{-1}
$C_{c,M}$	cost of mechanical cleaning action, US$ clean^{-1}
E_d	activation energy, J mol^{-1}
E_0	activation energy in Eqn. 8, kJ mol^{-1}
E_I	activation energy in Eqn. 9, kJ mol^{-1}
E_{II}	activation energy of Model II, kJ mol^{-1}
k_0	kinetic parameter, m s^{-1}
k_I	kinetic parameter, s^{-1}
$N_{c,C}$	number of chemical cleaning actions, -
Pr	Prandtl number, -
Q	heat duty, W
R	gas constant, J mol^{-1} K^{-1}
Re	Reynolds number , -
r_c	rate of coke formation, m s^{-1}
r_d	net rate of deposition, m s^{-1}
R_f	fouling resistance, m^{2}K W^{-1}
t	time, days
t_M	time at a mechanical clean, days
T	temperature, K
TAL	total averaged loss, US $ day^{-1}

Symbols

δ	deposit thickness, m
λ	deposit thickness, m
τ_C, τ_M	time taken for a chemical/mechanical cleaning action, days

Subscripts

c	coke layer
cl	clean
g	gel layer
s	surface

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