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, \( \lambda \). Ageing therefore couples thermal, fouling and cleaning performance: \( \lambda \) 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 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):

\[
\delta_{gel} = r_d - r_c \\
\delta_{coke} = r_c
\]

giving

\[
R_f = \frac{1}{\lambda_g} (r_d - r_c) + \frac{1}{\lambda_c} r_c
\]

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)):  
\[ r_d = \lambda_d a_d Re^{-0.8} Pr^{-0.33} \exp\left(\frac{-E_d}{RT_s}\right) \]  

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, \( T_{in} \).  
\[ r_c = \left\{ \begin{array}{ll} k_0 & \text{when } \delta_\theta > 0 \\ 0 & \text{when } \delta_\theta = 0 \end{array} \right. \]  

[7]  
where the rate constant \( k_0 \) is given by  
\[ k_0 = a_0 \exp\left(\frac{-E_0}{RT_{int}}\right) \]  

[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  
\[ r_c = k_1 \delta_\theta = a_1 \exp\left(\frac{-E_1}{RT_{int}}\right) \delta_\theta \]  

[9]  
Both kinetic schemes require \( T_{in} \) 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 \( E_{d,c} \).

**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 270°C 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: \( a_d = 1 \times 10^3 \text{ m}^2 \text{K} \text{W}^{-1} \text{h}^{-1} \), \( \lambda_d = 0.1 \text{ W m}^{-1} \text{K}^{-1} \), \( \lambda_c = 1.0 \text{ W m}^{-1} \text{K}^{-1} \). 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 sensitivities 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 \( a_0 \) was adjusted to give the same initial ageing rate via:  
\[ a_{0I} = a_{0} \times 10^{\frac{E_d}{RT_{s}}} \exp\left(\frac{-10,000 - E_1}{RT_{s}}\right) \]  

[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 \( a_0 \) values used are given in Table 1.

**Table 1: Kinetic parameters used in ageing models.**

<table>
<thead>
<tr>
<th>Model</th>
<th>Ageing</th>
<th>10</th>
<th>50</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 0</td>
<td>Slow</td>
<td>3.5×10(^6)</td>
<td>0.1</td>
<td>0.20×10(^{13})</td>
</tr>
<tr>
<td>( a_{0I} ) (m day(^{-1}))</td>
<td>Medium</td>
<td>6.0×10(^6)</td>
<td>1.0</td>
<td>0.85×10(^{13})</td>
</tr>
<tr>
<td></td>
<td>Fast</td>
<td>6.4×10(^6)</td>
<td>10</td>
<td>1.2×10(^{13})</td>
</tr>
<tr>
<td>Model I</td>
<td>Slow</td>
<td>0.06</td>
<td>0.1</td>
<td>5.6×10(^{16})</td>
</tr>
<tr>
<td>( a_{0I} ) (day(^{-1}))</td>
<td>Medium</td>
<td>0.40</td>
<td>1.0</td>
<td>7.0×10(^{17})</td>
</tr>
<tr>
<td></td>
<td>Fast</td>
<td>0.85</td>
<td>10</td>
<td>3.4×10(^{18})</td>
</tr>
<tr>
<td>Model II</td>
<td>Slow</td>
<td>0.024</td>
<td>0.1</td>
<td>4.5×10(^{16})</td>
</tr>
<tr>
<td>( a_{0I} ) (day(^{-1}))</td>
<td>Medium</td>
<td>0.24</td>
<td>1.0</td>
<td>4.5×10(^{17})</td>
</tr>
<tr>
<td></td>
<td>Fast</td>
<td>2.40</td>
<td>10</td>
<td>4.5×10(^{18})</td>
</tr>
</tbody>
</table>

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).
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

<table>
<thead>
<tr>
<th>Activation energy</th>
<th>Ageing rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_i = 10 \text{ kJ mol}^{-1}$</td>
<td>Slow Model I</td>
</tr>
<tr>
<td>$E_i = 50 \text{ kJ mol}^{-1}$</td>
<td>Slow Model I</td>
</tr>
<tr>
<td>$E_i = 200 \text{ kJ mol}^{-1}$</td>
<td>Both Both Both</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Activation energy</th>
<th>Ageing rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_i = 10 \text{ kJ mol}^{-1}$</td>
<td>Slow Model I</td>
</tr>
<tr>
<td>$E_i = 50 \text{ kJ mol}^{-1}$</td>
<td>Slow Model I</td>
</tr>
<tr>
<td>$E_i = 200 \text{ kJ mol}^{-1}$</td>
<td>Neither Both Neither</td>
</tr>
</tbody>
</table>
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 optimization algorithm. The impact on chemical and mechanical cleaning on fouling and the heat duty of an exchanger, \( Q_c \), 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

\[
C_{c,c}/C_{c,M} \quad \text{ratio of cleaning costs}
\]

\[
\tau_C/\tau_M \quad \text{ratio of cleaning period lengths}
\]

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 \( \delta_C \) grows and an aged layer, labelled 'coke', grows simultaneously; II - solvent cleaning at time \( t_S \) leaves the aged layer - fouling restarts from \( \delta_C \); III - mechanical cleaning at time \( t_M \) removes all deposit and fouling restarts from a clean surface. \( \tau_M \) is the duration of the mechanical cleaning step: the duration of the chemical cleaning step, \( \tau_C \), 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 \( C_E \$/kJ)\)

\[
C_E \int_0^t (Q_i - Q(t))dt \quad [11]
\]

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

\[
C_E Q_{io} \tau_i \quad [12]
\]

(iii) Cost of each cleaning action, \( C_{c,b} \).

These costs are then summed and the total averaged loss, \( TAL \), calculated from
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 $a_1 = 500$ 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 ($C_{cl,M}$ and $s_b$). 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

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube length</td>
<td>6 m</td>
</tr>
<tr>
<td>Tube external diameter</td>
<td>0.0254 m</td>
</tr>
<tr>
<td>Tube internal diameter</td>
<td>0.0199 m</td>
</tr>
<tr>
<td>Total number of tubes</td>
<td>800</td>
</tr>
<tr>
<td>No. of tube side passes</td>
<td>1</td>
</tr>
<tr>
<td>Shell diameter</td>
<td>1.3 m</td>
</tr>
<tr>
<td>Baffle spacing</td>
<td>0.3 m</td>
</tr>
<tr>
<td>Baffle cut</td>
<td>25%</td>
</tr>
<tr>
<td>Initial fouling resistance</td>
<td>0 m²K W⁻¹</td>
</tr>
<tr>
<td>Clean overall heat transfer coefficient</td>
<td>900 W m⁻²K⁻¹</td>
</tr>
<tr>
<td>Cold stream flow/inlet temperature</td>
<td>256 kg s⁻¹ / 220 °C</td>
</tr>
<tr>
<td>Hot stream flow/inlet temperature</td>
<td>60 kg s⁻¹ / 320 °C</td>
</tr>
</tbody>
</table>

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: $C_{CM}/C_{CC} = 1.5$, $\tau_M/\tau_C = 7$, $a_1 = 500$ 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

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- $a_0$: pre-exponential term in Eqn. 8, m s$^{-1}$
- $a_1$: 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 $W$ 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$^{-1}$
- $k_1$: 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$^{-1}$

Subscripts

- c: coke layer
- cl: clean
- g: gel layer
- s: surface

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