

WHEN TO CLEAN, HOW TO CLEAN: BIOFILMS

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ABSTRACT

Biofouling in heat exchangers can be managed by regular cleaning. A mathematical framework for the optimisation problem involved in selecting the best cleaning schedules for such units is presented which considers (i) an induction period associated with conditioning and colonisation, which introduces complexity to the fouling kinetics, and (ii) the existence of several outcomes from cleaning, depending on the choice of cleaning method. The problem is to decide how, when and which exchanger to clean. A mixed integer non-linear programming approach, based on the use of a logistic function to model fouling resistance-time dynamics, is shown to give tractable results. The methodology is illustrated with a case study involving a small network of three heat exchangers. An optimized solution based on a cost/performance analysis shows that the cleaning intervals and cleaning methods differ between each exchanger.

INTRODUCTION

The formation of biofilms on heat transfer surfaces, reducing the performance of heat exchangers, is a serious problem in many industrial and smaller-scale processes. Biofouling is a widespread phenomenon, caused by a wide range of micro-organisms in response to different local speciation and water quality (Bott, 1995).

In many industrial applications heat exchanger and process equipment fouling is managed by biocide treatment in combination with cleaning units to restore their performance (Müller-Steinhagen & Zettler 2011). The timing of cleaning actions can either follow a regular sequence or be determined by scheduling algorithms which monitor the extent of fouling from plant data and calculate the optimal time for cleaning. Sophisticated techniques are now available for generating cleaning schedules for large networks of heat exchangers (Ishiyama *et al.*, 2009; Lavaja & Bagajewicz, 2004; Rodriguez & Smith, 2007; Smaili *et al.*, 2002). The underlying problem is mathematically complex, and much of the work on this topic lies in framing the underlying mixed integer non-linear programming (MINLP) problem and devising efficient and robust methods for generating solutions. Napoles-Rivera *et al.*

(2012) developed a MINLP model for control of biofouling in seawater-cooled facilities which considered both biocide dosing and heat exchanger cleaning. In these formulations, only one form of cleaning is used, which restores the performance of the exchanger back to its clean level (Müller-Steinhagen & Zettler, 2011).

In several industrial sectors the plant operator has a choice of cleaning methods available, which differ in cost, associated downtime and effectiveness (Müller-Steinhagen & Zettler 2011; Simões *et al.*, 2010). The operator then has to decide how, when and which unit (in the case of networks) should be cleaned in order to mitigate fouling. This introduces complexity into the scheduling optimization problem via the element of choice.

The effectiveness of a given cleaning method is often determined by the state of the fouling layer. Prolonging cleaning can result in ageing, which may convert the foulant from a readily removable form to one harder to remove (Sommer *et al.*, 1999). This in turn affects the choice of cleaning method and its effectiveness. Ishiyama *et al.* (2011) presented an analysis of the heat exchanger cleaning scheduling problem where two cleaning methods were available and the deposit was subject to ageing. They modeled the foulant layer as existing in two states, labeled as a soft 'gel' and a hard 'coke' as their illustrative application was taken from oil refining. One cleaning method was faster and partially effective, only removing the soft layer, while the other required more resources but achieved complete cleaning. They showed that ageing can result in optimal schedules involving a combination of both methods, giving rise to a cleaning 'super-cycle'. Pogiatzis *et al.* (2012a) extended their analysis and presented a mathematical formulation of the optimization problem underlying the scheduling of cleaning actions where more than one cleaning method was available.

This paper explores the application of the element of choice of cleaning methods of differing effectiveness in the heat exchanger scheduling problem for units subject to biofouling. It considers the problem where three or more

methods are available, building on the characteristic behaviour observed in many cases of biofouling illustrated in the fouling resistance-time (R_f - t) data in Figure 1. The three phases of fouling growth reported by Bott (1995) are evident:

- I. An *induction* phase of length t_1 , where there is little loss in heat transfer. The experiment in Figure 1 started with a clean surface and this phase is associated with conditioning and bacterial colonization of the surface.
- II. A *growth* phase, where a biofilm is established and grows rapidly as long as nutrients are available and flow conditions favorable.
- III. An *asymptotic* stage where further growth is balanced by cell death and shear-induced removal, giving a final fouling resistance, $R_{f,\infty}$.

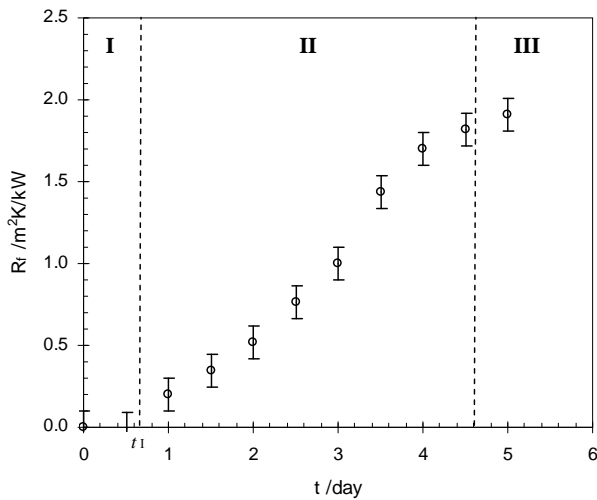


Fig. 1. Fouling caused by mixed biofilm growth in an experimental heat exchanger processing treated sewage sludge. Dashed vertical lines separate the stages in biofouling. Data reproduced from Yang *et al.* (2013).

Failure to remove the conditioning film or initial colonization sites during cleaning will allow the biofilm to re-establish itself quickly and significantly reduce or even eliminate the length of the induction phase (Brooks & Flint, 2008). An acceptable level of biofilm reduction, in effect a cleaning target, must be defined for each particular application (Wilson, 2003). In the power generation and petrochemical sectors, seawater is often used for cooling and biofilm formation becomes a matter of reduced operational performance and corrosion (Flemming, 2002). Similar considerations apply to sectors such as food manufacturing when the water is used as a heating or cooling medium and does not contact the product. A certain amount of biofilm can be tolerated and its accumulation must be managed according to cost/performance criteria (Pogiatzis *et al.*, 2012b). In applications where the water is a solvent or component of the product (biomedical, food, fine chemicals) the absence of biofilms is critical (Brooks & Flint, 2008). In these cases, a simple physical cleaning is

not sufficient and thorough disinfection is required to ensure that the biofilm is completely eliminated (Abreu *et al.*, 2013). This case is not addressed here.

The effects of biofilm ageing were not considered here. Ageing is known to make cleaning more difficult in crystallization fouling, wax deposition and crude oil heaters (Ishiyama *et al.*, 2011). Conflicting effects of ageing have been reported for biofouling: Ahimou *et al.* (2007) stated that biofilm cohesion may not be affected by age, and Epstein *et al.* (2011) reported that increased resistance to disinfection via non-wetting biofilm properties is not age related. Sommer *et al.* (1999) showed that biofilm age can increase resistance to chlorination, while Marchand *et al.* (2012) demonstrated that ageing can influence cleaning performance in dairy units. Ageing is therefore expected to play a role in some situations and not so much in others, depending on the micro-organisms, substrate and environment. It was therefore omitted from the present work but could be implemented in the algorithm using the approaches reported previously, *e.g.* Pogiatzis *et al.* (2012b).

This paper presents a formulation of the scheduling problem which incorporates the dynamics of biofouling in heat exchangers as well as considering a choice between three cleaning methods. The three cleaning methods represent operations which are followed by fouling starting from different points in the biofouling growth cycle. The paper concentrates on conceptual aspects rather than numerical detail. The results are accompanied by an extended discussion of application and other features which could be included in the formulation to capture further, detailed aspects of biofilm behaviour.

METHODOLOGY

Fouling and Cleaning

In order to simplify the analysis, three types of cleaning are considered which are differentiated by their efficacy. They are likely to differ in duration and cost. The cleaning methodologies are:

- (a) Simple flushes, *e.g.* of water alone, which remove most of the biofilm but leave the surface colonized and ready to restart growth when process operation resumes. There is no induction period, *i.e.* $t_1 \rightarrow 0$.
- (b) Chemical cleaning, which removes all biofilm and fouling exhibits a short induction period of length t_1/b , where $b < 1$.
- (c) Chemical cleaning followed by disinfection, yielding a longer induction period, t_1 .

The fouling behaviours associated with the different cleaning actions are compared in Figure 2(a). The growth and asymptotic phases are assumed to be insensitive to the cleaning method as they relate to the biofilm once it has been established. Seasonal variation in rates etc. is not considered.

(a)

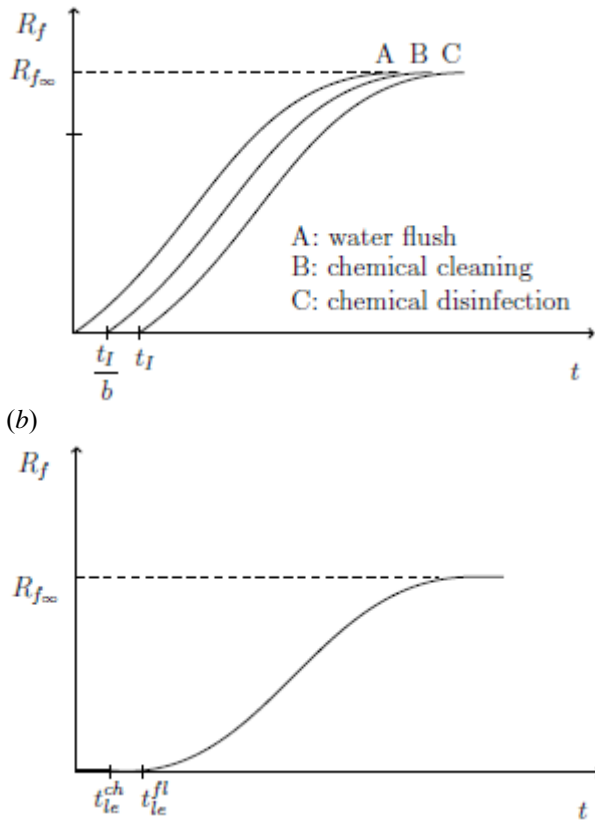


Fig. 2 Schematic of biofouling behaviour (a) following different cleaning actions; (b) sigmoidal growth model of Nebot *et al.* (2007) employed in simulations, showing ‘leap’ times.

Chemical cleaning and disinfection will require a longer time to clean but allow the unit to run at maximum efficiency for longer. This will incur a higher cleaning cost, both in terms of resources (chemical agents and energy) and capital expenditure. The latter factors are considered using a single, lumped cleaning cost in this work.

The above scenario represents a new scenario for the heat exchanger cleaning scheduling problem. An analysis and solution method are described and illustrated with a case study involving a small network of three units.

IMPLEMENTATION

The impact of biofouling is quantified via the thermal fouling resistance, R_f , which quantifies the impact of the biofilm on the overall heat transfer coefficient, U , at time t . R_f is defined as

$$R_f(t) = \frac{1}{U(t)} - \frac{1}{U_{clean}} \quad (1)$$

where U_{clean} is the overall heat transfer coefficient in the clean state. Biofouling could be occurring on either or both sides of the heat transfer surface. Different fouling and cleaning behaviours on the two sides could be incorporated in the model of exchanger performance, as needed (with commensurate increase in complexity of the optimization

problem). Cleaning is assumed to be equally effective on both sides.

Changes in pressure drop are assumed not to affect flow rates, so the cost incurred by fouling is calculated on the basis of reduction in heat duty, both during operation and while cleaning, and expenditure on cleaning.

Changes in pressure drop caused by the build-up of biofilm are assumed not to affect flow rates, so the cost incurred by fouling is calculated on the basis of reduction in heat duty, both during operation and while cleaning, and expenditure on cleaning. The effect of fouling on pressure drop and flow rates has been considered previously (Ishiyama *et al.*, 2009) and could be incorporated in the model of the heat exchanger if required.

The amount of heat transferred in the heat exchanger, Q , is calculated using the log-mean temperature difference method (Hewitt *et al.*, 1994).

The total cumulative fouling penalty, P_f , is calculated from

$$P_f = \int_0^{t_H} f_e (Q_{cl} - Q(t)) dt + \sum_{k=1}^3 \sum_{i=1}^{nu} y_{k,i} C_{k,i} \quad (2)$$

The first term accounts for reduction in heat transfer and the second relates to the cost of cleaning operations: Q is the heat transfer duty in the key exchanger(s), f_e is the cost of energy, t_H is the operating horizon length, nu is the number of units, and $C_{k,i}$ is the cost of cleaning unit i using method k . Variable $y_{k,i}$ is the binary decision variable determining how and when a unit will be cleaned. This penalty function contains continuous and discrete variables. The scheduling task is therefore a non-convex mixed-integer nonlinear programming (MINLP) optimization problem.

The solution method involves discretization of the time horizon into a number of intervals of equal length. Figure 3 shows that each interval is subdivided into two sub-intervals, corresponding to the length of the chemical cleaning and disinfection stages, and a longer operating period. The length of each interval, t_j could also be allowed to vary (Pogiatzis *et al.*, 2012a) by adjusting the length of the operating sub-interval, but this is not done here. The scheduling problem involves identifying the set of cleaning decisions $\{y_{k,i,j}\}$ that minimizes P_f over the time horizon. A solution path based on Generalised Benders Decomposition (Benders, 1962; Geoffrion, 1972) was developed for this application. Further details of the formulation and its implementation are given in (Pogiatzis *et al.*, 2012b).

The existence of the fouling induction period introduces complexity into the MINLP problem. Fig. 2 shows that the fouling rate switches from zero to a finite value which decreases to zero over a prolonged period. This introduces considerable numerical effort into the already complex formulation, such as introducing further sub-

intervals to represent t_1 and t_1/b . An alternative method is proposed, which involves a small degree of approximation.

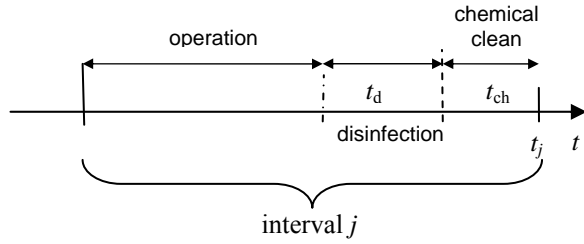


Fig. 3 Sub-discretisation of time intervals. Flushing is assumed to take negligible process time.

The logistic model proposed by Nebot *et al.* (2007) is used to describe the evolution of R_f over elapsed time, t^* :

$$\frac{dR_f}{dt^*} = k_f (R_{f,\infty} - R_f) R_f \quad (3)$$

Elapsed time relates to the time since the unit was completely clean, and is reset to zero after chemical cleaning and disinfection. This expression gives sigmoidal behaviour, with an initially low rate, followed by rapid growth and approach to an asymptote at long time. Comparison of Figs. 1 and 2(b) shows that this formulation gives a reasonable approximation to the observed biofouling behaviour. In particular, the different cleaning actions can be modelled by starting the R_f calculation from a different time point, t_0^* , on the sigmoid curve, *viz.*

- (a) $t_0^* = 0$ for chemical cleaning and disinfection;
- (b) $t_0^* = t_{c,L}$ for chemical cleaning;
- (c) $t_0^* = t_{fl,L}$ for water flushing

Here, $t_{c,L}$ and $t_{fl,L}$ are the ‘leap’ times related to the starting point on the sigmoid curve, shown in Fig. 2(b). The values of the leap times are calculated once k_f and $R_{f,\infty}$ are set. Equation (3) is then used to evaluate the fouling resistance and the duty in the exchanger is calculated.

Fouling is modelled in terms of its thermal effect, via the overall heat transfer resistance. Deposition could be occurring on either or both sides of the heat transfer surface. Cleaning is assumed to be equally effective on both sides. The performance of each exchanger is modelled using the log mean temperature difference method. Different fouling and cleaning behaviours on the two sides could be incorporated in the model of exchanger performance, as needed (with commensurate increase in complexity of the optimization problem).

CASE STUDY

A small heat exchanger network is used to demonstrate various aspects of the scheduling problem. Figure 4 shows the three fictional heat exchangers that transfer heat from three hot process streams to a cooling water stream which is subject to biofouling. The cooling water stream passes through exchanger 1 and is then split to pass through

exchangers 2 and 3. The operating and design parameters for the system are summarized in Table 1. The network is assumed to start with all exchangers clean ($U(t=0) = U_{clean}$).

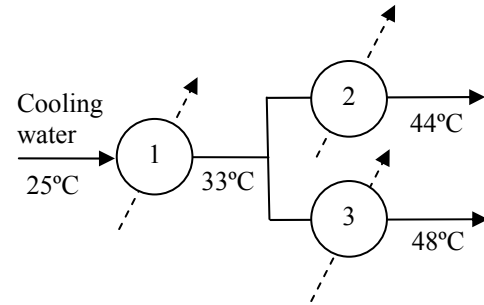


Fig. 4 Case study heat exchanger network showing cold stream temperatures under clean conditions. Solid line – cooling water; dashed lines, hot process streams.

Table 1 Design and operating parameters for case study

Unit	$T_{h,in}$ °C	W_h kW/ K	W_w kW/ K	U_{cl} W/m ² K	A m ²	Q_{cl} MW
1	200	45.1	315	550	33	2.6
2	190	44.0	157.5	550	30	1.8
3	210	56.8	157.5	550	32.5	2.3

Table 2 Case study cleaning action parameters

Mode	Duration (days)	Cost (€ per clean)
Flush	0	C_{fl} , 1000
Chemical	t_c , 1	C_{ch} , 2500
Chemical + disinfection	td , 5	C_{cd} , 3500

A time horizon of 360 days is used, discretized into 24 intervals. Table 2 summarizes the cost and duration of each type of cleaning action. The cost of energy, f_e , was set at 500 €/MWday. The reduction in cooling duty for each exchanger was summed in calculating P_f . Three scenarios were considered, with the parameters given in Table 3. Scenario A is the base case, Scenario B features less severe fouling, with $R_{f,\infty}$ halved. Scenario C experiences more rapid fouling (k_f increased by a third) but the same $R_{f,\infty}$ as the base case. The differences in $R_{f,\infty}$ and k_f result in different $t_{c,L}$ and $t_{fl,L}$ values as these are calculated from the R_f - t profile.

The system of equations was written and solved in GAMS (Brooke *et al.*, 1992). The MINLP problem has 216 binary variables, 5100 continuous variables and 5400 constraints. The problem is non-convex so a multiple starting point search is performed using 100 different, randomly selected starting points to increase the possibility of finding a good local solution. The Scenario A runs reported here took 50 minutes on an ASUS™ Chassis computer with 2.21 GHz CPU and 2 GB RAM. Scenario B and C took around 38 minutes on the same machine.

RESULTS AND DISCUSSION

Scheduling

In the absence of cleaning, biofouling causes the overall heat transfer coefficient in Scenario A (base case) to decrease by 31% whilst in Scenario B (less severe fouling) the reduction is smaller, at 18%. The summary of results in Table 5 shows that the cost of not cleaning the network over the one year horizon under base case conditions is 240 k€. The optimal cleaning schedule yields a saving of 46%.

The distribution of solutions obtained for each Scenario is summarized in Figure 5. The histograms indicate that a range of local optima exist, with the width of the range of solutions varying for each scenario: the range for Scenario A is 602 k€ whereas that for Scenario B is 23 k€. The optimal cleaning schedule obtained for each scenario, corresponding to the best local solution found with the multi-start approach, is presented in Table 4.

All three types of cleaning are performed and the units are cleaned regularly, but the distribution of types is not random. Unit 1 is only cleaned by water flushing or chemical action, and never by chemical cleaning and disinfection. The penalty for taking this larger duty unit off-line for 5 days is not matched by its performance afterwards. This is illustrated by the individual R_f - t plots in Figure 6, where the fouling resistance in unit 1 does not exceed $R_{fc}/2$. Units 2 and 3, in contrast, are cleaned by water flush or with chemicals and disinfectant. The number of cleaning actions over the year is large (28), with several intervals seeing two cleaning actions. Most of the cleaning actions are water flushes, which are attractive owing to the absence of downtime for cleaning more than compensating for the lack of an induction period subsequently.

In Scenario B the exchangers experience a reduced extent of fouling and the fouling penalty for the worst case (no cleaning) is now 120 k€. The lower R_{fc} value results in smaller heat losses and reduced incentive to clean: the number of cleans is reduced to 13, giving an optimal cleaning cost of 70 k€, which is still a substantial saving. The schedule in Table 4 shows only chemical cleaning (no water flushes) for unit 1 and noticeably fewer water flushes (and only one disinfection) for units 2 and 3.

Reducing the rate of fouling in Scenario C (rapid fouling) does not change the worst case penalty significantly from the base case because the R_f values reach their asymptotic values relatively early. There are more cleaning actions than Scenario B, (18 actions) and a noticeable change in the scheduling pattern as there are now two chemical cleans plus disinfection. Water flushing is still common, but much less frequent than the base case (9 vs. 21 above).

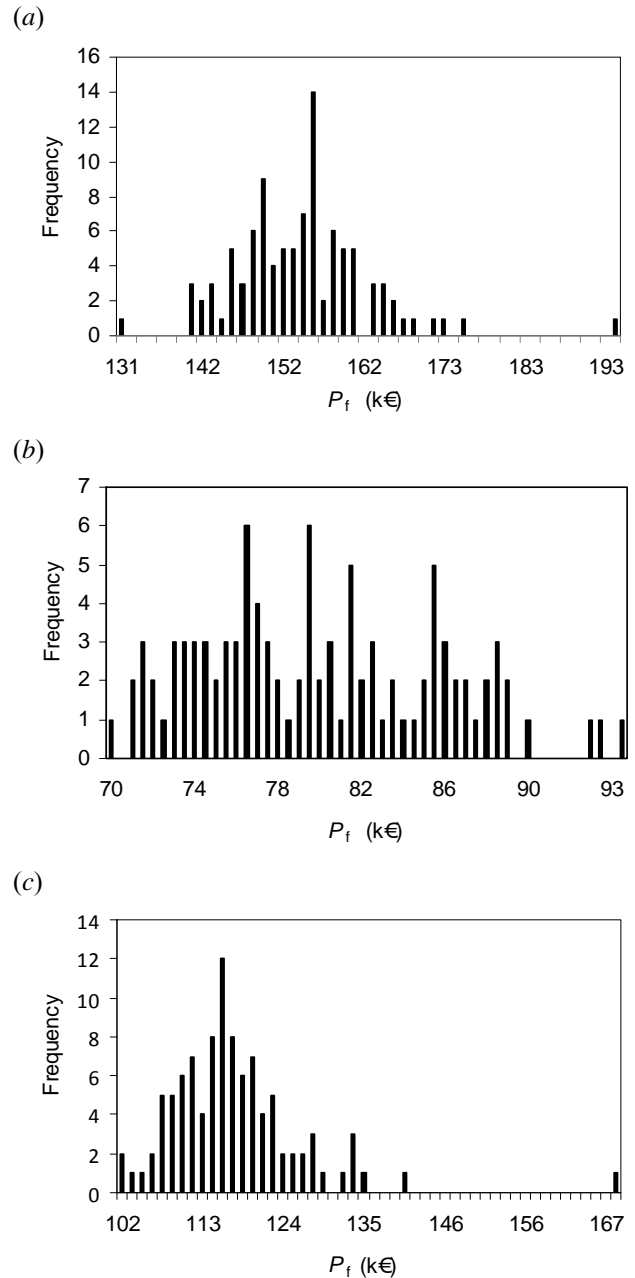


Figure 5 Distribution of solutions generated by the GBD algorithm for 100 random starting points.

The results above demonstrate that the particular features associated with biofouling, namely the existence of a fouling induction period and asymptotic fouling, can be handled by the fouling model formulation presented here.

Table 3 Case study scenarios: parameters for biofouling model (Equation [3])

Unit	$R_{f\infty}$ m ² K/kW	$R_{f,0}$ m ² K/kW	k_f m ² K/kW.day	$t_{c,L}$ days	$t_{fl,L}$ days	P_f €
Scenario A – base case						<i>No cleaning</i>
1	0.8	1×10 ⁻⁴	0.18	19	38	240 k€
2	0.8	1×10 ⁻⁴	0.22	15	30	<i>Optimal</i>
3	0.8	1×10 ⁻⁴	0.25	13	26	131 k€
Scenario B – less severe fouling						<i>No cleaning</i>
1	0.4	1×10 ⁻⁴	0.18	240 k€	62	120 k€
2	0.4	1×10 ⁻⁴	0.22	26	52	<i>Optimal</i>
3	0.4	1×10 ⁻⁴	0.25	23	46	70 k€
Scenario C – less rapid fouling						<i>No cleaning</i>
1	0.8	1×10 ⁻⁴	0.12	120 k€	48	220 k€
2	0.8	1×10 ⁻⁴	0.15	19	38	<i>Optimal</i>
3	0.8	1×10 ⁻⁴	0.17	17	34	102 k€

Table 4 Optimised cleaning schedules for case study scenarios.

Open circles – water flush; grey circles - chemical cleaning; black circles – chemical cleaning and disinfection

Scenario A – base case

Unit	Period																								Mode				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	fl	c	d		
1			●			●			○			●		○		●			○	●						4	5		
2			○		○		○			○		○	○		○	○			●								9		1
3				○		○		○	○		●			○		●			○		○	○					8		1
Total																											21	5	2

Scenario B – less severe fouling

Unit	Period																								Mode				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	fl	c	d		
1							●						●						●									3	
2						○		○				●					○			○							4		1
3				●						●				○		●					○						2	3	
Total																											6	6	1

Scenario C – less rapid fouling

Unit	Period																								Mode				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	fl	c	d		
1								●					●		○				●								2	1	2
2					●				○		○		●					●									2	1	2
3				○		○		○		●			●			○		●			○						5	3	
Total																											9	5	4

The fouling parameters used in the Scenarios are based loosely on those reported by Nebot *et al.* (2007). Scenario B represents a process change which reduces $R_{f\infty}$, such as operating at higher flow velocities to increase the shear stress acting on the biofilm (Moreira *et al.*, 2013a),

reducing the nutrient load (Moreira *et al.*, 2013b) or manipulating surface adhesion (Rosmaninho *et al.*, 2007). Scenario C represents a process change which decreases the rate, such as reducing the level of nutrients present in the water (Moreira *et al.*, 2013b) or changing the temperature,

which affects both oxygen solubility and bacterial growth rates (Bott, 1995). The scheduling model can be used to quantify the benefit obtained from such a process modification and therefore determine the return on any capital expenditure associated with implementing that measure.

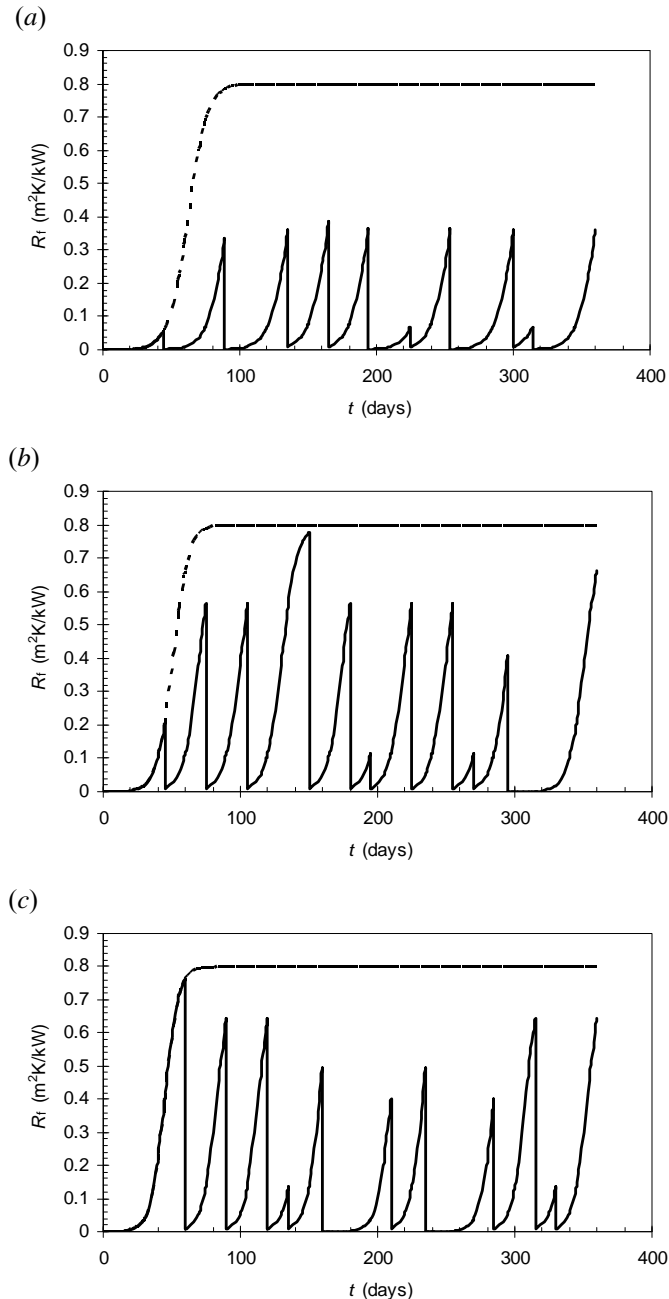


Figure 6 Individual fouling profiles for each unit for Scenario A. Dashed line shows profile in absence of cleaning for (a) unit 1; (b) unit 2; and (c) unit 3.

APPLICATION AND EXTENSION

The case study results demonstrate that the mathematical formulation gives tractable results in a reasonable time scale, such that the approach could be applied to schedule

cleaning on plants in real time. Ideally the fouling growth rate model (Equation (3)) would be linked to a biofilm monitoring system so that parameters k_f and $R_{f,\infty}$ can be identified and refined in an adaptive fashion. Several methods are available for biofilm monitoring (see Janknecht & Melo, 2003) but the estimation of the thermal fouling resistance is very convenient for heat exchanger equipment (Marchand *et al.*, 2012). Furthermore, plant monitoring data could be correlated against the cleaning performance of different methods for specified biofilm ages (or formation conditions) and this information used to predict the b and t_1 parameters. Online monitoring can also enable determination of the cleaning endpoint (see Pereira *et al.*, 2008) and again this historical information can be used to improve the model.

An important facet of biofilm behaviour that is commonly associated with biofilm cleaning/disinfection but which is not considered in the model presented here is the development of resistance to antimicrobial agents. Mah & O'Toole (2001) reported that biofilm cells can be up to 1000 times more resistant than cells grown in suspension: this resistance can either be intrinsic or acquired (McDonnell & Russell, 1999). Intrinsic resistance explains phenomena like reduced penetration of antimicrobials due to diffusion limitations (Mah & O'Toole, 2001), degradation of the antimicrobials by specific enzymes (McDonnell & Russell, 1999) or the existence of naturally resistant forms, *e.g.* spore formers, (Stewart, 2002). Acquired resistance is commonly obtained through mutation or acquisition of genetic material from plasmids or transposons (McDonnell & Russell, 1999). Some features of the intrinsic resistance (such as reduced penetration of the agent) may promote the formation of a concentration gradient inside the biofilm where cells are exposed to sub-lethal concentrations of that agent, thereby facilitating acquired resistance events (Stewart 2002).

Once a certain antimicrobial agent is found to be active against a particular organism, the effects of intrinsic resistance can often be circumvented by manipulation of the operating conditions used during treatment, such as reagent concentration, contact time, temperature and turbulence of the cleaning/disinfection solution (Marchand *et al.*, 2012). The effectiveness of a disinfection step can decrease between successive runs and this has been attributed to acquired resistance (McDonnell & Russell, 1999). An effective countermeasure is to change the disinfection protocol periodically. The alternative disinfection protocols (usually employing a different antimicrobial) are likely to have different associated costs and operating conditions (such as contact time).

Acquired resistance and changing effectiveness was not included in the formulation presented here but it can be readily implemented by extending the choice of cleaning methods to have two disinfection steps. The constraint set for the optimization problem would then include a statement limiting the maximum number of times each

disinfection step could be applied in succession as well as modifying t_1 and b parameters to include changes arising from acquired resistance. Similarly, the maximum time period over which a particular step should be applied can be set as a constraint.

CONCLUSIONS

A mathematical formulation for the problem of optimising cleaning schedules for heat exchangers subject to biofouling, which can exhibit sizeable induction periods, has been developed. The formulation includes, for the first time in this field, considerations of three different cleaning mechanisms with varying cost and effectiveness which also determine the subsequent fouling behaviour. Solutions can be obtained in reasonable time scales and a case study network is used to demonstrate the versatility of the approach and the scope for exploring the impact of different fouling mitigation strategies. The overall savings that can be attained by using this approach can be significant and the tool can also be used to evaluate process changes involving substantial capital costs. Potential modifications to handle biofilm behaviour such as ageing and biocide resistance have been discussed.

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NOMENCLATURE

Roman

- A Heat transfer area, m^2
 C_k Cleaning action cost, method k , €/clean
 f_e Energy cost, €/W.day
 k_f Fouling rate parameter, $m^2 K/J$
 P_f Total cost of fouling, €
 Q Heat transfer duty, W
 Q_{cl} Heat transfer duty, clean condition, W
 R_f Fouling resistance, $m^2 K/W$
 $R_{f,\infty}$ Asymptotic fouling resistance, $m^2 K/W$
 T Temperature, K
 t Time, s
 t^* Elapsed time (Equation (3)), s
 t_H Operating horizon length, s
 t_1 Induction period length, s
 t_0^* Fouling starting point, s
 W Heat capacity flow rate, W/K
 y Cleaning decision variable, -

Subscript

- c chemical cleaning + disinfection
d chemical cleaning
fl flush cleaning
h hot stream

- w cooling water stream
L leap time

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