A COMBINED EXPERIMENTAL-MODELLING APPROACH TO OPTIMISE CHEMICAL CLEANING OF HEAT EXCHANGERS

E. Diaz-Bejarano¹, H. Borgt² and F. Coletti^{1,*}

¹ Hexxcell Ltd., The Charter Building, Charter Place, Uxbridge London, UB8 1JG, UK
² The Dow Chemical Company, Technical Expertise & Support Technology Center, Midland, US *corresponding author: f.coletti@hexxcell.com

ABSTRACT

Periodic cleaning is a common and often necessary strategy to maintain the performance of heat exchangers over long operation runs. Although cleaning decisions should be based on economic drivers, they are very often made based on operators' experience and simplistic performance indicators. Understanding the characteristics of fouling deposits (e.g. composition, quantity, structure, physical properties) is of paramount importance to select an effective cleaning method. Lab experiments are typically used to determine fouling sample composition and the performance of various solvents. Based on this information, practical rules-of-thumb can be devised and successfully applied to assist operators in the selection of the cleaning method and its duration. However, lab conditions can differ significantly from the field and the extrapolation of the cleaning performance is not straightforward. In this paper, a framework integrating condition-based cleaning models that capture kinetics and efficiency of a cleaning action as a function of the characteristics of fouling deposits (e.g. composition, layering, degree of coking) with a predictive maintenance simulator is presented. The approach uses a few parameters, determined in the lab, to predict cleaning performance of given solvents. This provides field engineers with actionable information on the best method to be used; duration of the cleaning; and expected economic benefits.

INTRODUCTION

Cleaning of heat exchangers refers to the removal of unwanted material accumulated on the heat transfer surfaces. Cleaning has been subject to several studies in the past in the food, oil & gas, chemical and petrochemical industries [1–8].

Due to cost, downtime of the units to clean and health and safety hazards involved, the decision of cleaning heat exchangers in industrial plants must be well justified. Cleaning a heat exchanger is (and should be treated as) an economic decision that can be made to [8]:

- Prevent unscheduled downtime
- Maintain on-spec product
- Improve energy recovery efficiency

Making a cleaning decision is not an easy task, as it involves deciding:

- When to clean
- Which heat exchanger to clean (in the case of networks)
- How to clean (cleaning method)

For the intended cleaning action to be successful and economically advantageous, the three points above are key considerations. However, cleaning decisions are very often made based on past experience, simple performance indicators (e.g. when certain outlet T is reached) or when throughput limitations occur. Moreover, not being able to assess the economic benefits of a cleaning action, is the reason why operators may decide not to clean.

Advanced monitoring and predictive maintenance tools have been successfully used to make economically optimal cleaning decisions. These tools include predictive fouling models combined which. with techno-economic assessments models, allow operational teams to schedule cleaning actions based on economic KPIs. These include trade-offs between chemical and mechanical cleaning. However, selecting between chemical cleaning methods is still not straightforward since a number of necessary pieces of information are typically not readily available. These include:

- a) Composition of the fouling deposits (e.g. organic vs. inorganic species)
- b) Quantity and distribution deposit thickness, spatial distribution
- c) Physical nature (hard, soft, porous).

Lab tests on fouling samples are performed to better understand the causes of fouling; to test possible cleaning methods; identify cleaning efficiency and kinetics; and develop procedures for future cleaning. However, the integrity of collected field deposits are also important [9] and solubility testing of crushed deposits may be misleading if the original deposit presents a multi-layered structure, such as those reported in the literature for crude oil fouling deposits [10–12]. Thus, it may be challenging to extrapolate the learnings obtained at the lab level to the field.

Due to the practical difficulties involved in selecting an appropriate solvent, it is not uncommon that maintenance personnel defer to use mechanical cleaning, which typically ensure a high degree of cleanliness, in spite of being more expensive, more aggressive on the equipment and keeping the unit out of service for longer.

In this context, the development of quantification tools that allow extrapolating experimental data and experience-based rules-of-thumb from the field to allow for the optimization of the cleaning- decision-making process. Condition-based cleaning models [13–15] aim at capturing the kinetics and the efficiency of a cleaning action as a function of the characteristics of fouling deposits (composition, layering, degree of coking, etc.). Such an approach has a great potential to bridge the gap between existing fouling /predictive maintenance simulators and experimental-based knowledge which, ultimately, to provides the field engineer with actionable information such as:

- That most advantageous cleaning method(s)
- The minimum duration of the cleaning needed to reach the (practical) maximum deposit removal.
- A way to quantify the economics of the cleaning action.

Recent research [13, 16] has led to the development of mathematical models that describe fouling as multi-components, dynamic systems and, more importantly, to the development of methods to detect and predict such different fouling behavior.

Condition-based cleaning models describe cleaning as a dynamic process in which the kinetics and efficiency of an action is a function of the characteristics of the fouling deposits (as described above). Such models can be taught using experimental data and used to determine the best cleaning method, duration of the cleaning and expected benefits, providing engineers with a quantitative tool for maintenance decision-making.

The combination of a multicomponent description of the fouling deposit, with condition-based cleaning models, allows us to:

- a) Obtain information from thermo-hydraulic measurements on the extent of fouling (thickness) and likely composition (organic/inorganic) and layering.
- b) Predict and build simulations for the growth of multi-component deposits, keeping information on layering as fouling forms;
- c) Simulate cleaning as a dynamic process, with an efficiency that depends on the time of cleaning and the type of deposit;
- d) Estimate the characteristics of the deposit from plant data.

e) Implementation of network simulations and coupled with economic models, allowing for assessment of the overall impact of fouling and cleaning.

In this paper, condition-based cleaning models for crude oil fouling deposits with mixed organicinorganic content, are proposed for use, based on lab and field experience. These models, implemented in a framework for the monitoring and prediction of crude oil fouling in refinery heat exchangers, allow simulation for how different cleaning methods would perform under several scenarios of fouling composition. At the network level, the evaluation of different cleaning agents on the economics of the process naturally leads to the selection of the best cleaning option. The path for further development and validation of such condition-based models is outlined and discussed.

The objective of this work is to bring together cleaning lab tests, field experience, and advanced models to provide field engineers with optimal cleaning solutions (e.g. selection of cleaning methods, duration and timing of cleaning actions). Based on quantitative, economic-based methods we focus on the modelling and selection of cleaning agents taking into account the relative content of organic-inorganic species in the deposit. Other aspects, such as the degree of coking or ageing, could be included in the future.

SOLVENT-BASED CLEANING KINETICS

Cleaning Types Considered

In this work, we consider fouling deposits to be composed of (generally defined) organic and inorganic species. Consistently, we consider three representative cleaning methods [8]:

- Organic solvent (e.g. petroleum-based solvent): effective in removing deposits with mediumhigh organic content. This is the preferred choice when organic content, $C_{org} > 30\%$. This is also a relatively inexpensive option as it may be available in the refinery, but it will take longer cleaning times than chemical solutions and may not provide complete cleaning.
- Chemical solution (e.g. HCl in water, NaOH in water, etc): this is quite efficient in removing deposits with very low amounts of organic matter ($C_{org} < 30\%$). A good cleaning agent is expected to remove 60 100% of the deposit. This is a more expensive option compared to the previous one but it keeps the units out of service for shorter periods (1 day) compared to mechanical cleaning.
- *Mechanical cleaning* (e.g. hydro blasting): it achieves cleaning efficiencies of 90-100% regardless of the type of fouling. On the other

Table 1 – Summary of solvent performance in the lab.

Characteristic	Solvent A	Solvent B
Time to maximum cleaning efficiency, T_L	3 h	6 h
Cleaning efficiency for 0% organic deposit (100% inorganic), $X_{L,0\%}$	100 %	0 %
Cleaning efficiency 100% organic deposit (0% inorganic), $X_{L, 100\%}$	0 %	100 %
Solvent applicability range (organic content of the deposit C_{org})	$0 < C_{org} < 30\%$	$30 < C_{org} < 100\%$

hand, it adds greater expense as the heat exchanger needs to be opened, the bundle removed with cranes and several parts (gaskets, bolts etc.) needing to be replaced. Overall, this is the most expensive options which takes the heat exchanger out of service for longer interval (3-4 days) versus chemical cleaning.

Cleaning Efficiency and Kinetics based on Labtests and Experience

The removal kinetics can be studied by measuring the amount of fouling deposit dissolved or removed over time for each sample. For a sample deposit composed of particle(s) of characteristic length δ_L , the rate of dissolution can be expressed as:

$$\frac{d\delta_L}{dt} = r_{diss}[=]\frac{m^3}{m^2s} \tag{1}$$

where r_{diss} is the rate of dissolution. Kinetic studies in the lab, are necessary to establish the order of these kinetics. Here, assuming 0th order kinetics:

$$\frac{d\delta_L}{dt} = -k_v \tag{2}$$

where k_v is the dissolution constant that depends on the solvent, deposit nature, and other factors not considered here for simplicity (e.g. fluid velocity, temperature, etc.). Integrating over time and converting the characteristic length into cleaning efficiency, X:

$$X = \frac{k_v t}{\delta_{L,0}} 100 \tag{3}$$

where 0 indicates the value at the start of the experiment. Cleaning efficiency is defined as the percentage of the deposit thickness removed in a given time, t, the time of a cleaning test in the lab. Each solvent is characterized in any given experiment by the following quantities:

- The time, *T_L*, needed by the solvent to reach the maximum cleaning efficiency.
- The maximum cleaning efficiency, X_L , at end of the experiment. Since at t = 0 (start of the experiment), X = 0, this allows calculating the slope $\left(\frac{k_v}{\delta_{L,0}}\right)$ simply using the conversion at the end of the experiment and the time elapsed.
- The cleaning efficiency for 0% organic deposit (100% inorganic), X_{L,0%}
- The cleaning efficiency for 100% organic deposit (0% inorganic), *X*_{L, 100%}

• The range of composition, *C*_{org}, defined as the percentage of organic material in the layer at which the solvent is performing best.

It is to be noted that X_L , the maximum efficiency obtained in the lab is a function of the concentration of organics, *C*, at the surface of the layer. Based on the general definitions in the previous Section, two model solvents characterized as follows are considered here (Table 1):

- a) Solvent A: Chemical solvent (inorganic) characterized by a time of cleaning test: T_L = 3h. The cleaning efficiency for this solvent at 100% inorganic deposit $X_{L, 0\%}$ = 100% whereas at 100% organic deposit (100% inorganic), $X_{L, 100\%}$ is 0%. As the organic content decreases, the cleaning efficiency sharply increases for organic content < 30%.
- b) Solvent B: Organic solvent, characterized by a time of cleaning test: $T_L = 6h$. The cleaning efficiency of this solvent, $X_{L,0\%}$ is 0%. Conversely, $X_{L,100\%}$ is 100%. As the organic content increases, the cleaning efficiency increases for organic content > 30%.

The maximum efficiency obtained in lab experiments is modelled here as a function of the inorganic/organic content for given fixed duration of the cleaning lab test. An example is shown in Fig 1, where a model is proposed based on three points of efficiency (0%, 30% and 100% organic) for Solvents A and B. This graph illustrates the kinetics of the dissolution process depending on the nature of the fouling deposit. For pure components, the dissolution rate is maximum, and it is possible to dissolve the entire sample within time T_L if the right solvent is used. For mixtures, the dissolution rates are slower, and only part of the sample is dissolved within the dissolution time; that is, a longer time



Fig. 1. Model of maximum cleaning efficiency as function of proportion of organics/inorganics in the deposit for model solvents A and B.

would be required to achieve complete dissolution.

Extrapolation to the field

In the field, the deposits can be formed on the inner or outer surfaces of the tubes of shell-and-tube heat exchangers. As the dissolution rates are given per unit of area, the same dissolution law can be applied:

$$\frac{d\delta}{dt} = -k_{v,F} \tag{4}$$

where δ is the deposit thickness and $k_{v,F}$ the dissolution kinetics in the field, which will be different from those in the lab due to differences in the operating conditions.

The order of the kinetics as well as the kinetic constants, could be obtained by monitoring the removal processes as it is performed in the field. However, this is a difficult task. Alternatively, the dissolution time in the lab (T_L) can be related to the dissolution time in the field (T_F) by using an equivalency factor, F:

$$T_F = \frac{k_{\nu,L}/\delta_{L0}}{k_{\nu,F}/\delta_0} T_L = FT_L \tag{5}$$

Thus, the condition-based cleaning kinetics can be expressed as:

$$\frac{d\delta}{dt} = -k_{v,F} = -\frac{X_L(C)\,\delta_0}{FT_L}\tag{6}$$

Where δ_0 is the thickness of the deposit at the start of the cleaning. This can be estimated from plant data using hydraulic measurements [12]. The *F* parameter, is typically 5 - 10 for acid cleaning solutions (*i.e.* between 5 - 10 hours may be needed for a cleaning in the field if it took 1 hour to dissolve the sample in the lab).

Of all the information needed in Eq. (6) the concentration of organic concentration, C, in the deposits that are exposed to the solvent is certainly the piece of information that is more challenging to obtain, particularly in multi-layered deposits. However, recent work has shown the potential of obtaining this information from thermo-hydraulic plant measurements [12].

If the deposit is homogeneous, the time required in the field to achieve the same degree of cleanliness as in the lab is:

$$T_F = FT_L = 5 \ \delta_0 T_L \tag{7}$$

Thus, for the above assumptions, the rate of cleaning at each time is:

$$\frac{d\delta}{dt} = -k_{v,F} = -\frac{X_L(C)}{5T_L} \tag{8}$$

Where $X_L(C)$ should be re-evaluated as the composition of the exposed deposit varies with the removal.

CASE STUDIES

The concepts previously described are explored further by means of theoretical case studies. First, the deposition of fouling layers of various compositions is simulated to show how the extent and composition of fouling affects the thermohydraulic performance of a heat exchanger. This highlights the limitations of current monitoring methodologies and shows how monitoring data should be used to make cleaning decisions. Then, results from dynamic simulations are presented to show the removal of deposits of distinct composition over time if different solvents are applied. Here, we make use of the condition-based models discussed in the previous section.

Fouling deposition vs fouling factors

As discussed in the Introduction, it is widely recognized that thermal indicators on their own, such as R_j , do not represent the complexity of fouling deposits. Consideration of the deposit thickness, composition and physical properties, as well as the specific distribution and time-evolution within the heat exchanger is important to have the full picture and make well informed decisions. To illustrate this point, the development of four types of fouling deposit in a shell-and-tube heat exchanger was simulated here:

- Case I: Organic fouling at middle-level temperatures (constant low conductivity)
- Case II: Organic fouling at very high temperature (deposit ageing gradually increases its conductivity)
- Case III: Mixed organic and inorganic fouling (constant but higher conductivity; 66% organic content)
- Case IV: Organic fouling with an intermediate episode of inorganic breakthrough due to operational issues at the desalter

Fig. 2 shows the evolution of the average characteristics of fouling deposit (thickness and conductivity), and the response of the overall fouling resistance as sole fouling indicator. If the fouling resistance is taken as a sole indicator of the quantity of fouling, the insights obtained are quite limited and, in fact, some erroneous conclusions may be drawn. For example, Case II shows lower fouling than Case I, when in fact, the amount of deposit (thickness) is actually the same. Moreover, the fouling resistance in Case III shows significantly lower fouling than Case I when the amount of fouling is actually significantly larger (1.6 mm vs 1 mm, respectively).

Case IV presents essentially an identical behavior to Case I with a slow deposition period until ca. 100 days at which point fouling becomes much faster with material depositing at a high conductivity. This represents, for example, the



Fig. 2. Simulation of fouling over 300 days of operation considering four types of behavior. Graphs on left column show the deposit's average thickness and apparent conductivity. Graphs on the right column show the average thermal fouling resistance.

effects of carryover of inorganic species, originating from the desalter upstream from the heat exchanger. This problematic, and somewhat common, episode is not only undetected by the R_f monitor, it could even be mis-interpreted as a short period of "good" behavior.

It is clear that thermal indicators alone are not enough on their own to discern between the distinct types of fouling. Pressure drop measurements provide a direct quantification of the thickness profile. While its use has been recommended by many engineers and researchers in the past [17–22], these measurements are rarely available for single heat exchangers.

Considering both the thermal and hydraulic response of the heat exchangers, the conclusions above can be reached more rapidly by using the TH- λ plot [23]. This plot denotes the thermal performance (expressed in terms of heat duty divided by heat duty in clean conditions, Q/Q_c) against the hydraulic performance (expressed in terms of pressure drop divided by pressure drop in

clean conditions, $\Delta P / \Delta P_c$). The Q and ΔP are measurable quantities (Q calculated from temperatures and flowrates), while Q_c and ΔP_c are calculated for the same input conditions but considering a clean heat exchanger. When the heat exchanger is clean, the performance is at (1,1). As fouling progresses, Q/Q_c gradually decreases and $\Delta P / \Delta P_c$ gradually increases. The plot also includes λ -lines (dashed lines) that serve as a reference to provide an idea of the likely composition and (possible) changes in composition of the deposit. In this plot (Fig. 3) it is clear that: a) the impact of fouling (Case I) is mainly on the thermal performance; b) the deposit in (Case II) is undergoing a gradual transformation towards higher conductivity that reduces its thermal impact; c) the impact of fouling (Case III) is mainly hydraulic; d) there is an intermediate change in behavior in Case IV, with fast build-up of material but little thermal impact. This indicates fast accumulation of inorganics, after which the behavior tends to return to the initial trend line.



Fig. 3. TH- λ Plot for the four cases (a-d) in Fig. 2. Dashed lines indicate reference λ -lines.

The discussion above has some important practical implications. First, R_f alone cannot distinguish between different types of behavior and would not be able to detect certain types of severe fouling build-up. Second, the combination of Thermal and hydraulic measurements (temperature, ΔP) and advanced models can be potentially used to detect and diagnose changes in fouling behavior [24]; Third, knowing the nature and extent of the deposit is key to selecting and applying effective mitigation options, from heat exchanger redesign to cleaning intervals.

Finally, from the point of view of network performance and maintenance, a demonstrated fouling behavior similar to Case I has a greater impact on the overall heat loss. Proper cleaning of a heat exchanger undergoing such type of fouling will increase the energy recovery and, eventually, the inlet temperature to the furnace (CIT). This is of particularly importance in thermally limited networks (i.e. network where the furnace capacity represents a bottleneck). On the other hand, fouling behavior such as that shown in Case III (or Case I with an acute episode as in Case IV) has a greater impact on pressure drop. Cleaning a heat exchanger undergoing such fouling may not be as necessary for heat recovery but can be of great importance if the network is hydraulically limited (*i.e.* production compromised by the pumping capacity). The best cleaning methods to use for an optimal cleaning are also subject to the characteristics of the deposit, as discussed in the following.

Condition based cleaning

The description of fouling multias components, dynamic systems and, more importantly, the development of models and tools to detect and predict such different fouling behaviors, opens the door to describe the cleaning of fouling at a similar level of detail. Condition-based cleaning models describe cleaning as a dynamic process in which the kinetics and efficiency of an action is a function of the characteristics of the fouling deposits

(as described above). As discussed earlier, such models could be trained using experimental data and used to determine the best cleaning method; duration of the cleaning; and expected benefits; providing engineers with a quantitative tool for maintenance decision-making. Consistently with the previous examples, we consider two model cleaning methods as defined in previous Section: an organic solvent (Solvent A) and an inorganic chemical agent (Solvent B).

Fig. 4 shows the average rate of decrease of the deposit thickness in Case I (100% organic deposit) and Case III (66% organic, 33% inorganic) by using cleaning Solvent A and B. The x axis shows the cleaning time. Negative values indicate times before the start of the cleaning. In Case I (Fig.4.a), Solvent A is very effective and leads to the complete removal of the deposit in about a day. Solvent B, however, is very ineffective for this type of deposit and cannot clean any of it. In Case III (Fig.4.b), Solvent A is quite effective too, as the organic portion is still dominant. However, the efficiency achieved after 24h of cleaning is only 60% and two full days would be needed to completely remove the deposit. This is due to the larger deposit thickness when the cleaning starts and the slightly lower removal rates. Solvent B is still very ineffective and should not be used to remove this type of fouling.

The results are particularly interesting if Case IV is considered. After 200 days, about 80 days after the inorganic breakthrough event, the deposit shows the stratification in Fig. 5 (right hand side): a sandwich-type structure with high organic content deposit at the bottom and top and high inorganic



Fig. 4 Removal of the fouling deposit by cleaning after 200 days of operation: (a) fouling type in Case I; and (b) fouling type in Case III.



Fig. 5 Removal of a multi-layered fouling deposit (Case IV) by cleaning after 200 days of operation using solvents A and B on their own or in sequence (left); and radial composition profile of the deposit at the beginning of the cleaning action (right).

content material in the middle. If Solvent B is used, the deposit remains intact, as the material at the top is of organic nature. If Solvent A is used, it is possible to remove the top organic layer within less than half a day (24% removal). However, when the inorganic sub-layer is reached this solvent loses efficiency and it is not able to clean the deposit further. At that point, swapping from Solvent A to B (swap point indicated in the figure as "A \rightarrow B") would allow continuing removal of the inorganic portion until reaching the bottom organic layer at ca. 0.4 mm from the tube wall (40% of the deposit removed, 64% in total). At that point, continuing with Solvent B would be pointless, as the deposit is no longer removable by that type of solvent. A new solvent swap, " $B \rightarrow A$ " would be required to remove the remaining deposit, achieving a total removal (100% efficiency) in about 1.5 days. Although it is not shown here, ageing of organic deposits (Case II) leads to a gradual hardening of the layer, making it insoluble in organic solvents. In such cases, mechanical cleaning is required to completely remove the fouling deposits. An example of condition-based cleaning under ageing conditions is reported in [13].

CONCLUSIONS

The work presented here has shown severe limitations of the fouling factor approach, provided that the type of fouling is correctly identified, condition-based cleaning models are useful to select the most adequate solvent, define the optimal time of cleaning to achieve an acceptable removal (avoiding loss of efficiency due to short times; or redundant, costly long times) and even define sequential cleaning treatments involving several cleaning solutions to remove multi-layered fouling deposits. The kinetics of different solvents with respect to distinct types of deposits can be obtained in lab experiments and their extrapolation to the field confirmed by appropriate monitoring of the cleaning process [8].

The determination of the type of fouling can be done by sampling the deposit upon heat exchanger dismantling. However, this is not practical. By the time the sample is sent to the lab and the compositional analysis produced the heat exchanger needs to be back online. Therefore, the cleaning method(s) to be applied must be decided even before the heat exchanger is taken off-line for cleaning. Advanced thermo-hydraulic model-based monitoring, has emerged as a promising option to obtain insights into the likely composition of the deposits formed inside the heat exchanger [12]. These analytics would allow preparing well in advance the cleaning procedure to be followed, but also allow for faster reaction time to unexpected events such as the breakthrough in Case IV. Sampling of fouling deposits during heat exchanger dismantling would still be necessary to verify and improve the results of the model-based monitoring and the efficiency of cleaning methods for future events with the same heat exchanger assets.

NOMENCLATURE

Corg Organic content of the deposit, %

- F Equivalency factor, -
- k_v Dissolution constant, m³/ m² s
- Q Heat duty, W
- R_f Thermal fouling resistance, m² K / W
- r_{diss} Rate of dissolution, m³/ m² s
- T Dissolution time, h
- X Cleaning efficiency, -
- ΔP Pressure drop, bar
- δ Deposit thickness, m
- δ_L Particle characteristic length, m
- λ Deposit thermal-conductivity, W/mK

Subscript

- 0 Start of the cleaning
- *c* Clean conditions
- F Field
- L Lab
- 0%, 100% Cleaning efficiency for given organic content

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