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TWENTY YEARS OF EBERT AND PANCHAL – WHAT NEXT?

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ABSTRACT

Ebert and Panchal introduced the 'threshold fouling' approach for describing the initial rate of crude oil chemical reaction fouling at the meeting in this series of conferences held in San Luis Obispo in 1995. This paper summarises reviews of developments in the threshold modelling approach over the last ten years, following the review by Wilson *et al*. at the 2005 meeting. Three areas are considered: (*i*) The development of quantitative models, which has seen little activity but a switch toward using the threshold models to describe fouling dynamics. One of the reasons for the stagnation in development is the need to incorporate chemical understanding. (*ii*) The types and range of data sets which have been processed with these models, and an evaluation of the parameters. (*iii*) Applications where the models are used to predict fouling, or the likelihood of fouling. This is the area that has seen greatest activity, linked to the use of threshold models to describe fouling dynamics. Topics for future research and development are discussed.

INTRODUCTION

Fouling of heat exchangers processing crude oil is a long-standing challenge in oil refining sector. The heat exchanger networks in refinery distillation unit preheat trains are subject to chronic fouling, caused by different mechanisms in different parts of the train (Watkinson and Wilson, 1997). This reflects the nature of crude oil as a mixture, with different species promoting deposition under different combinations of temperature and pressure (and phase behaviour) encountered by the crude as it passes from storage through exchangers and a furnace before entering the column. Early in the preheat train, fouling is chiefly caused by deposition of entrained solids (sand, mineral and organic), and crystallization fouling (arising from minerals dissolved in any water present). Downstream of the desalter, chemical reaction fouling dominates and this can arise from any combination of mechanisms: autoxidation, condensation reactions catalyzed by FeS and other minerals present, and precipitation or gelation of asphaltenes. As the composition of a crude varies by source, and crudes are frequently blended to achieve a desired product slate, the chemical composition is often poorly known. The propensity of a mixture towards chemical reaction fouling is similarly poorly known: to date, most methods have focused on identifying compositions likely to promote precipitation of ashphaltenes and thereby cause acute fouling (Wiehe, 2008; Wilson and Polley, 2001). While the chemistry of the mechanism remains unclear, the impact is understood: chemical reaction fouling effectively limits the scope for heat recovery in refinery preheat trains using standard technologies owing to high fouling rates (Polley *et al*., 2005).

The first quantitative study of crude oil-related chemical reaction fouling was the work on gas oil by Watkinson and Epstein in 1969. Figure 1 summarises the development of chemical reaction fouling models over the intervening 5 decades. Initial work followed the deterministic path, seeking to develop numerical models based on established physical phenomena and supported by experiments.

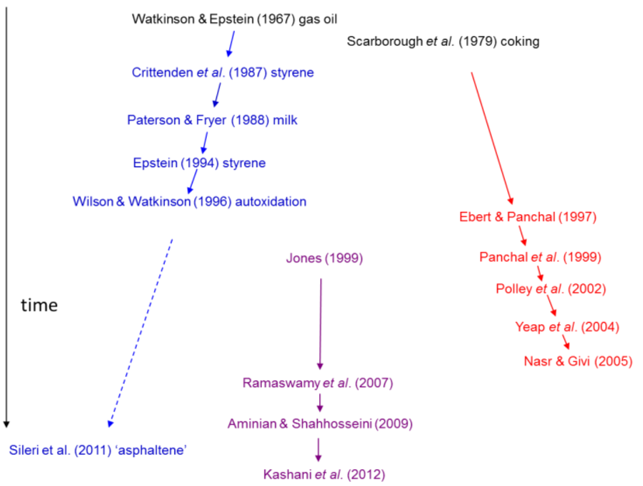

Fig. 1 Timeline summary of quantitative chemical reaction-related fouling model studies. Black font: tests with crude oils; blue – deterministic models; red – threshold fouling models; purple – artificial neural network approaches.

Three strands are shown in Figure 1. The first strand, labelled 'deterministic' models, sought to build predictive quantitative models based on physical analysis, in a similar vein to parallel work on particulate and crystallization fouling over this period. The strand fizzles out in the mid 1990s, mainly due to the complexity of crude oils: this point is discussed further later.

One approach to complexity is to adopt a semi-empirical approach, based on certain assumptions, and avoid extrapolation where those assumptions do not hold. This was the approach introduced to crude oil fouling by Ebert and Panchal at the fouling and cleaning conference held in San Luis Obispo 20 years ago, which was published in 1997. They introduced the following semi-quantitative model to provide a quantitative description of the initial rates of fouling, dR_f/dt, reported for high temperature (liquid phase) tubeside coker fouling studies by Scarborough *et al.* (1979):

$$\frac{dR_f}{dt} = \overbrace{a_1 \mathrm{Re}^{-b1} \exp\left(\frac{-E_a}{RT_f}\right)}^{\text{deposition}} - \overbrace{c_1 \tau_w}^{\text{suppression}} \quad (1)$$

where Re is the Reynolds number, T_f the film temperature, R the gas constant and τ_w the wall shear stress. Parameters a_1, b_1, E_a and c_1 were obtained by regression of the data sets and the fit is shown in Figure 2.

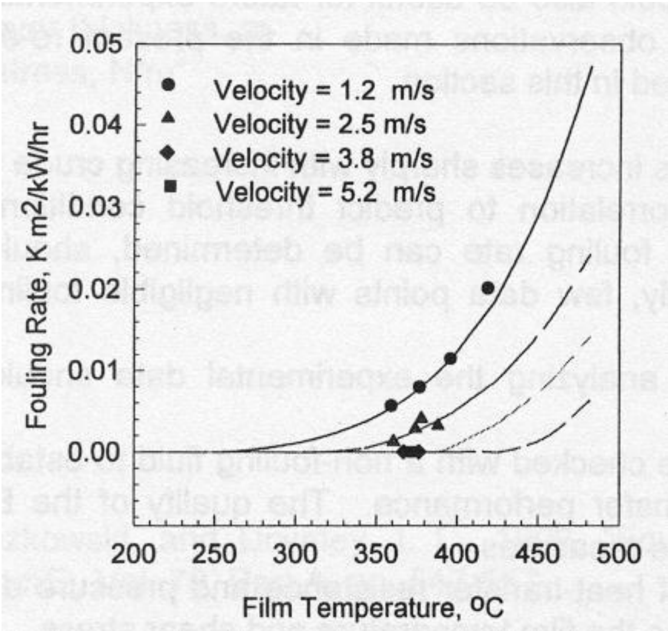

Fig. 2 The Ebert-Panchal model (equation [1]) fitted to Scarborough *et al.*'s (1979) data, reproduced from Ebert and Panchal (1997). Loci plotted for parameters $a_1 = 30.2\times10^6$ K m^2/kW h; $b_1 = -0.88$, $c_1 = 1.45\times10^{-4}$ m^2 K m^2/kW Pa h and $E_a = 68$ kJ/mol.

Ebert and Panchal termed their equation a 'threshold fouling' model as it provided two types of quantitative result:

(*i*) *Extrapolation* to estimate combinations of surface temperature and shear stress which gave no fouling, hence the 'fouling threshold', and

(*ii*) A framework for *interpolation* between measured data sets to estimate the fouling rate expected for different combinations of fluid velocity and surface/film temperature.

Figure 1 shows that the following decade was marked by active research into the fouling threshold approach. A number of variants of the original model have been developed (see Table A1). These have provided a basis for modelling crude oil fouling and have been employed to analyse experimental data and estimates of fouling obtained by reconciliation of plant operating data. Armed with these estimates of likely fouling rates for such streams, threshold fouling models have been adopted as a tool for predicting fouling rates in the design of individual exchangers, heat exchanger networks, and the operation (control and cleaning) thereof.

The assumptions and early development of the threshold fouling approach in the ten years since it was introduced were reviewed by Wilson *et al*. at the Kloster Irsee conference in this series held in 2005. Readers are strongly encouraged to consult the 2005 paper as the material remains relevant and is not reproduced here. The Enfield conference marks twenty years since the 'threshold fouling' concept was introduced. This paper seeks to review the progress made as a result of the concept, and present some of the challenges which the authors believe should be tackled in the next decade. Two of the authors (Wilson and Polley) contributed to the 2005 paper, in which they made some predictions of the state of the art in 2015: these are also reviewed.

The third strand of activity in Figure 1 is labelled 'artificial neural network' (ANN) approaches. These represent a second approach to complexity, wherein families of statistical learning algorithms are used to construct functional relationships between different, diverse inputs. The power of these techniques has grown strongly in the last decade owing to the speed and availability of computing capacity. ANN methods require relatively large and diverse training data sets. They do not assume any deterministic relationships unless the operator imposes these. The paper by Aminian and Shahhosseini (2009) provides a useful account of the application of ANN methods to crude oil threshold fouling modelling. Figure 1 shows that much of the literature in this field has been published *since* 2005.

This paper reviews the published activity in the area of threshold fouling models for crude oil fouling since 2005. The results of a series of reviews are presented: (*i*) the development of quantitative models; (*ii*) the types and range of data sets which have been processed with these models, accompanied by an evaluation of the parameters reported; (*iii*) applications where the models are used to predict fouling, or the likelihood of fouling, and issues resulting from such applications. These lead to conclusions outlining needs for research and/or development.

DEVELOPMENT OF THRESHOLD MODELS

Threshold fouling models relate the observed initial (or early) linear fouling rate to thermal and hydraulic conditions. They feature a competition between deposition and suppression terms: Ebert and Panchal originally termed the latter a removal term and this was challenged within the fouling community on the basis of (*a*) conceptually, there is no removal when an *initial* fouling layer is being formed. This can be contested on the grounds that an initial layer of deposit with thickness in the micron range is unlikely to be detected using thermal or hydraulic measurements. Hence, the term 'early' is used here: (*b*) removal of a crude oil deposit layer, once formed, has not been demonstrated by any systematic study to date. The equations published to date are listed in Table A1. They take the form:

$$\frac{dR_f}{dt} = \begin{Bmatrix} a_1 Re^{b_1} \\ a_2 Re^{b_2} Pr^{0.33} \\ a_3 \dfrac{1}{h_{film}} \end{Bmatrix} \times \begin{Bmatrix} exp\left(\dfrac{-E_a}{RT_f}\right) \\ exp\left(\dfrac{-E_a}{RT_s}\right) \end{Bmatrix} - \begin{Bmatrix} c_1 \tau_w \\ c_2 Re^{d_2} \\ c_3 u^{d_3} \end{Bmatrix} \tag{2}$$

The first term on the RHS has three contributions: a scaling factor, a_i; a hydrodynamic term, often related to Reynolds number; and a temperature sensitivity based on the Arrhenius relationship. It can be seen from Table A1 that there have been few new developments in basic threshold modelling added in the last decade. Nasr and Givi (2006) proposed a suppression term of the form ($-cRe^{0.4}$), without any physically-based justification of the power 0.4. Polley (2010) reviewed the existing dynamic fouling models based on Equation (1) and proposed a generalized form where the prefactor in the deposition term involved the film heat transfer coefficient, *i.e*. a_3/h_{film}. One of the reasons for taking this approach was to extend the results to other geometries: this is considered further below. Deshannavar *et al*. (2010) presented a review of crude oil fouling models and cited most of those in Table A1. No new models nor data were presented.

Ramaswamy and Deshannavar (2014) reviewed the use of the Ebert-Panchal model (Equation (1)) for various data sets reported in the literature. They found that the threshold fouling model did not fully explain observations reported in the literature and a new set of their own data. Amongst these, they reported decreasing fouling rate with increased bulk temperature (at constant surface temperature), which could be due to fouling precursor solubility. They also reported a reduction in fouling rate and higher bulk and surface temperatures, which they attributed to small amounts of boiling. The latter observation is a reminder that phase behaviour always needs to be considered.

To the authors' knowledge, based on a systematic search of the published literature, there has been little development of threshold models since 2005. There are several reasons for the tailing off in this activity. One of these is that the number of data sets is relatively modest, and are rarely complete. Carefully controlled and fully documented laboratory studies are required to minimize uncertainty, which is essential in differentiating different models on the basis of regression analysis that is normally used for fitting threshold model parameters. Such tests are resource (time, funding, personnel) intensive. The alternative is to use data extracted from industrial operation, which usually features poorer precision and unquantifiable variation associated with changes in feedstocks.

A second reason is the limited number of manipulated variables available. Equation (1) contains four adjustable parameters. In a crude oil fouling test one can adjust three variables: flow rate, surface and bulk temperature, so the problem is mathematically poorly defined. Furthermore, the underlying optimisation problem in parameter optimisation is not straightforward: Costa *et al*. (2013) presented an analysis of the parameter estimation problem involving fouling rate models, for several threshold fouling models including Equation (1). They developed a procedure for addressing the problem using a computational routine called HEATMODEL. They compared the performance of a conventional optimization algorithm (Simplex) with a more complex hybrid genetic algorithm, using data from a Brazilian refinery. They showed that the Simplex method may become trapped in local optima in the parameter estimation search, owing to the complexity of the underlying optimization problem. This indicated the importance of using global optimization techniques for this task.

Furthermore, it is not known whether the model *is* exact. The chemistry involved is rarely understood, often to the extent that the identity of the fouling precursors is not known. The prefactor *a* in Equation (2) includes *all* the information about process chemistry. The relationship between a_i and c_i is likely to vary from one crude to another, *e.g*. via the concentration of precursors, rendering comparison between tests at different sites or on different crudes difficult. In another regard, crude oil fouling differs strongly from biofouling, particulate and crystallization fouling, where the fouling precursor is usually known or identifiable from the deposit. Chemical reaction fouling deposits, however, often undergo ageing which disguises the origin of the layer (Fan and Watkinson, 2011). Dilution of the crude to try to adjust the concentration of fouling precursors is rife with challenges as the diluent can affect the solubility of species such as asphaltenes.

It is the authors' opinion that the development of threshold models has reached a pragmatic plateau, in some ways mirroring that reached in detailed chemical reaction fouling models in the 1990s (see Figure 1). More information about the chemistry involved in generating deposits with specific crudes or crude blends, at various points in a fouling test history, is required in order to support more detailed modelling approaches. The chemistry is, undoubtedly, complex as crude oils contain many components. We postulate that there is likely in the future to be opportunities to merge the ANN and threshold modelling approaches, exploiting the ability of ANN techniques to construct functional relationships between different chemical parameters which can then explain trends observed in threshold model parameters. Core chemical understanding is still required, however: the parameters considered by the ANN (which will require resources to measure) have to be those directly related to fouling precursor concentration and behaviour.

Whereas the development of new threshold fouling models has effectively stalled, the last decade has seen more effort aimed at applying threshold modelling techniques to other geometries. Much of the early work focused on tube-side fouling, either because test systems were configured to gather this type of data or because industrial units tend to put the more heavily fouling stream on the tubeside as it was then simpler to clean.

In many refineries, however, the crude flows on the shell-side rather than tube-side and individual exchangers can be fitted with tube inserts. This led to the extension of the Ebert-Panchal model to other exchanger geometry (Aquino *et al*., 2007). There are a number of applications where shell-side and other geometries experience fouling, and there has been some success in developing analogues of Equation (1) to describe these. Table A2 summarises efforts in this area. In pipe flows the Reynolds number can be used to estimate, via correlations, a number of quantities, including the wall shear stress and film heat transfer coefficient. In other geometries these have to be estimated separately, hence the use of wall shear stress as the hydraulic parameter in the suppression term and the film heat transfer coefficient, rather than bulk velocity, in the deposition term. The fact that these variations of the threshold model give working descriptions for all the geometries listed in Table A2 indicates that it is a useful, even if not exact, construction.

Tubeside inserts require further mention. Some types of tube insert limit the thickness of the fouling layer to the clearance between the insert and the tube wall. This results in asymptotic fouling behaviour. In an exchanger with multiple tube passes it is possible to have asymptotic fouling in the hottest pass and low or modest fouling in the coldest pass. Engineering insight is required for such configurations rather than naïve application of fouling models: techniques for analyzing this situation were developed by Gonzales Garcia and Polley (2009).

THRESHOLD MODELS FOR FOULING DYNAMICS

Ebert and Panchal's name for the modelling approach that they introduced in 1995 indicated the intended primary use, namely the identification of combinations of operating parameters (flow velocity and wall temperature) that would result in low fouling rates and thus allow exchangers to be operated for long periods before cleaning, or even mitigate fouling completely. As more crudes were tested, it became apparent that the threshold regions in temperature and velocity space varied between crudes and between crudes and crude blends, so a single design was likely to be resilient. This is illustrated by Figure 3, which shows the threshold locus calculated from fitting the Panchal *et al*. (1999) model, Equation [A] in Table A1, to R_f-time data obtained from reconciliation of refinery operating data. The model parameters are given in Table 1, alongside values reported by some previous studies using this model.

Figure 3 shows a marked difference in fouling thresholds for the different datasets, which involved different feedstocks and unit design. Similar variation was also evident when comparing thresholds generated by analysis of laboratory fouling data, see Wilson *et al.* (2005).

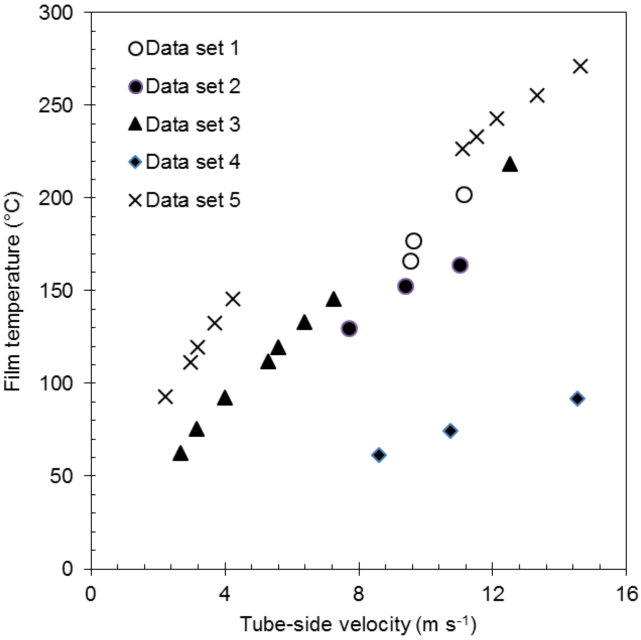

Fig. 3 Threshold fouling loci obtained by fitting the Panchal *et al*. (1999) model to different sets of refinery fouling data (Labels identified in Table 1).

Table 1. Threshold fouling model parameters obtained from regression of refinery fouling data to the Panchal *et al*. (1999) model Equation [A] in Table A1.

Data Set	Source	a_1 m^2 K kW^{-1}h^{-1}	E_a kJ mol^{-1}	c_1 m^{2}K kWh^{-1} Pa^{-1}
1	Ishiyama *et al*. (2013a)	900	21	8.1×10^{-8}
2	Ishiyama *et al*. (2013a)	900	21	8.1×10^{-8}
3	Ishiyama *et al*. (2010a)	926	36.4	4.3×10^{-8}
4	Kiat (2009)	1.09×10^{6}	47	5.9×10^{-8}
5	Ishiyama *et al*. (2015)	50,000	40	3.0×10^{-8}
6	Panchal *et al*. (1999)	53,000	48	1.45×10^{-4}
7	Yeap *et al*. (2004) Data set A	640	29	2.41×10^{-5}
8	Data set B	1,800	29	2.35×10^{-5}
9	Data set C	940	29	2.46×10^{-5}
10	Data set D	4,100	28	2.63×10^{-5}
11	Data set E	2,900	29	2.63×10^{-5}
12	Data set F	6,400	28	2.53×10^{-5}
13	Data set G	6,000	31	3.02×10^{-6}

The values of a_1 and E_a in Table 1 vary noticeably. The E_a values are all less than than 50 kJ mol^{-1}, whereas Ebert and Panchal reported a value of 68 kJ mol^{-1}. This difference is usually attributed to the original Scarborough *et al.*

(1979) study involving temperatures at which coking (and reaction control) were important. Coking reactions are not usually observed at the temperatures encountered in preheat trains, and reaction control results in their activation energies being greater than those reported for fouling mechanisms involving mixed reaction and diffusion. Direct comparison of these parameters is not recommended as they are not independent (see Barrie *et al*., 2013). Instead, Figure 4 compares the fouling rate predicted by each parameter set for a set of conditions typical of those encountered in a preheat train. There is no evident correlation with E_a. There is an appreciable range in values and the need for chemical insight to explain these variations is the dominant research need.

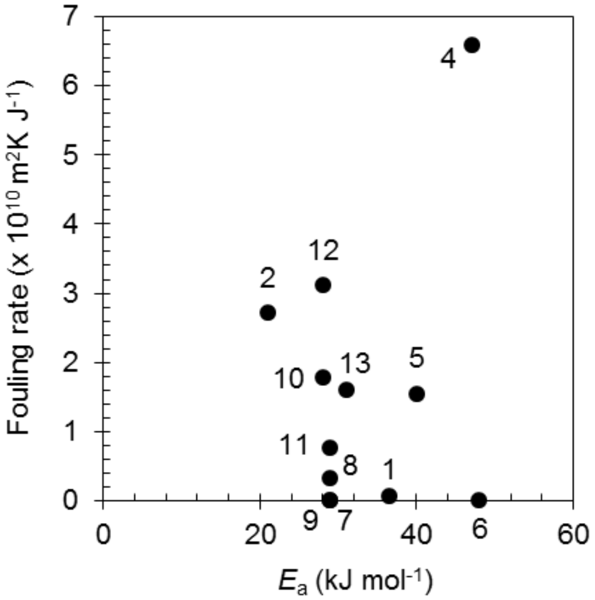

Fig. 4 Fouling rate predicted for benchmark conditions (velocity 2 m s^{-1}, Re = 17100, Pr = 10, T_f = 503 K, τ_w = 7.2 Pa) using the parameters reported in Table 1 (labels given in Table 1). Equation [A] predicted negative values for 6, 7 and 9 so these are plotted as zero.

One feature of Table 1 is the absence of new published laboratory data sets, as there have been few new studies in the last decade with the exceptions of propriety work at oil companies (*e.g*. Joshi *et al*. 2013) and HTRI, and at the University of Bath (e.g. Yang and Crittenden, 2012; Harris 2014). The Bath stirred cell device allows tests to be performed with smaller volumes and associated lower costs. Most new data sets have come from analysis of refinery units of sidestream monitors. At this point we introduce a caveat: fouling models usually provide a prediction of fouling at a 'point' condition. In reality the controlling factors (temperatures and wall shear) vary along the length of the exchanger. Recognition of this problem led to the development of an integrated form of Ebert-Panchal equation (Ishiyama *et al*., 2008) and ultimately to the detailed simulation approach of Coletti and co-workers (Coletti *et al*., 2009, 2011a,b).

Over the last decade, the application of threshold fouling models then moved in two directions:

(i) Identification of fouling-resilient designs, using the threshold model to identify heat exchanger configurations and networks that would experience acceptably low fouling rates for a number of candidate crudes. This was discussed at length in the 2005 paper.

(ii) Using the fouling threshold model equation to describe fouling dynamics.

The latter direction constitutes an important shift in focus. The early work on fouling thresholds used measurements of fouling rates related to the early development of a fouling layer, in order to extrapolate back to when the layer was first formed and thus identify the relationships between temperature and hydraulics controlling the initial deposition step(s). More recently, the threshold fouling model equations have been used to describe and to predict fouling behaviour when the fouling layer is well established, *i.e*. as a growth law. As a growth law it can then be used to estimate how changes in operating parameters, including the change in deposit surface temperature resulting from the growth of the layer itself, affect the deposition process. This has become accepted practice and is rarely challenged. In effect, it accepts the earlier statement that fouling rate measurements are not accurate enough to monitor the initial process of deposit formation, so that early rate measurements relate to the lay down of material on an already fouled surface.

Threshold-fouling-dynamics (to differentiate it from true threshold modelling) has proved to be a very useful approach for managing crude oil fouling. It has provided a quantitative tool to calculate fouling rates for use in static and dynamic analyses of heat transfer systems subject to fouling. The effect of absolute temperature and flow conditions can now be incorporated, allowing the field to move away from the TEMA approach. Fouling rates can now be included in design tools, network analyses (including pinch technology) and detailed simulations of plant and unit operations.

Table A3 lists papers where threshold-fouling-dynamics models have been used in studies of individual exchangers. Table A4 summarises papers where these have been employed in analyses of plant or preheat train design and operation. These are not intended to be exhaustive lists, as the intention is to illustrate the range of activity that has been facilitated by the concept. In the age where simulation has become a standard tool for process engineering, these Tables demonstrate that the threshold-fouling-dynamics approach has provided the quantitative tool for inclusion in numerical calculations.

Typically a plant's own operating data records are interrogated to generate fouling resistance-time data sets. These are compared with a fouling model (such as one of those in Table A1) and a set of parameters obtained by regression analysis (see Yeap *et al*., 2004). This provides the operators with a locally tuned fouling model which should allow them to predict how their system will respond to changes in operating parameters, *as long as the crude or crude slate does not change substantially*. Examples of this approach include the studies by Ishiyama *et al*. (2010a), and Ratel *et al*. (2013). Some of the results are included in Table 1 and Figure 4.

Coletti and co-workers (*e.g*. Coletti *et al.*, 2011a,b) have employed a different approach to interrogate plant operating data. Rather than calculating the overall heat transfer coefficient from plant data and estimating the fouling resistance from this parameter, which introduces uncertainty from the intermediate calculation, they have used model-based parameter estimation techniques to determine Ebert-Panchal model parameters from temperature and flow measurements. This represents a more efficient use of the data but is still subject to the fundamental uncertainty associated with the accuracy of the Ebert-Panchal model.

Over the last five years these methods have become available in new commercial software tools such as SmartPM^{TM} from IHS and Hexxcell *Studio*^{TM}, which have joined the family of monitoring and simulation. It should be noted that some monitoring packages contain data reconciliation techniques and exchanger heuristics that lead to final readings that are incorrect. Individual instrument readings always provide a safer source of performance measurements. Work needs to be directed at how errors in individual measurements (such as drift and off-set) can be identified and corrected.

FUTURE PROSPECTS: TEN MORE YEARS?

The title of this section is deliberate. In the medium to long term the dominance of distillation for separation of crude oil mixtures is likely to be challenged on the grounds of energy consumption and separation efficiency. Even if new technologies are used, fouling *is* still likely to happen, and many of the findings from thermal fouling research are likely to apply!

The use of threshold fouling models to quantify fouling dynamics has enabled work in crude oil fouling to catch up with developments in other branches of fouling research. The availability of numerical tools to calculate the likely rate of crude oil fouling and its impact on unit (and plant) thermal and hydraulic performance opens up the field to engineering analysis and decision making. Broadly put, it provides a basis for replacing the TEMA approach which is a static method aimed primarily at heat exchanger design. We expect the methods and approaches described above to become more widely used over the next decade.

Threshold fouling models have evolved since 1995 and this evolution is expected to continue, particularly for complex flow patterns and complex geometries. Particular targets for these to meet (our ‘wish list’) include:

Properties of an Ideal Fouling Model

A good fouling model provides the following:

(i) Predictions of fouling rates across individual operational exchangers to an accuracy better than ±20% (a typical value being ±10%).

(ii) It predicts how changes in operating conditions or geometry affect the fouling rate, to the same accuracy.

(iii) It can be fitted to data easily, so that rapid changes in monitored fouling rate can be identified and the cause the change attributed to a known input.

(iv) Plant data are subject to noise and this affects data fitting. It is highly desirable to have a small number of adjustable parameters in the model, which still retain the essential physics of the system, in order to retain the reliability of the result.

It must be appreciated that the fouling mechanism can change along the length of a pre-heat train. Consequently, the model user, whether an operator, plant engineer or design needs to understand the various mechanisms and remember that one model will not fit all crudes.

Important fundamental questions remain. The importance of chemical mechanisms has been highlighted, as these determine the fouling mechanism and the validity of the assumptions in the derivation of the threshold fouling model equations. More work needs to be done to establish the link between crude composition and fouling behaviour. This will require fundamental studies in chemistry, rheology, fluid mechanics and surface materials science in order to elucidate the interactions involved (see Sileri *et al*., 2011; Coletti and Hewitt, 2014). The long term goal here would be to be able to anticipate the likely fouling behaviour of a crude or crude mixture based on its composition, to the extent that only a small number of heat transfer tests would be needed to determine the fouling parameters. This would bring crude oil fouling to a point of parity with crystallization fouling in aqueous streams. There, the theory is mature but there are still considerable uncertainties in calculating nucleation rates and the strength of deposits (which determine asymptotic fouling behaviour) as well as fouling from mixtures of inverse solubility salts.

The need to establish whether deposit removal can occur – and hence how to promote this – has also been mentioned.

Fundamental research requires long-term commitment of resources (funding, time and personnel). Variations in the price of crude oil tend to dictate the research agenda in the oil industry, so that the emphasis in the last few years has switched from dealing with fouling caused by ‘opportunity crudes’ (cheaper but more prone to fouling) to lean operation. Somehow fouling needs to be kept on the research agenda.

CONCLUSIONS

Developments in the use of the threshold fouling approach to model fouling rates in crude oil over the last ten years have been reviewed and discussed. The field has seen some significant changes, which can be summarised as

1. There have been few laboratory experimental studies of crude oil fouling published in the open literature since 2005. An increasing number of studies based on reconciliation of refinery data have been reported, indicating that the threshold fouling approach has become an accepted tool for analyzing fouling data.
2. There have been few developments in threshold fouling models *per se*. One reason is the need to link thermal behaviour with chemical composition and mechanisms.
3. Extension of the threshold fouling approach to geometries other than pipe flows has allowed fouling in these cases to be quantified.
4. The threshold fouling approach allows crude oil fouling to be predicted quantitatively, albeit with some uncertainty. This has enabled simulation and modelling tools for fouling mitigation to finally supplant the static TEMA approach.
5. Fundamental challenges still remain which require concerted, combined research effort to solve. Such activity will generate more data sets, preferably of high quality, which will both allow (*i*) further development of deterministic models, and (*ii*) identification of key parameters for ANN modelling. The latter has considerable potential for interrogating complex data fields such as arise in crude oil fouling.

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NOMENCLATURE

a_i parameter in fouling model, m^2K/J
b_i parameter in fouling model, -
c_i parameter in fouling model, units vary
d_i parameter in fouling model, -
e parameter in fouling model, $m^{13/3}\ s^{8/3}\ kg^{2/3}\ K^{-2/3}$
E_a fouling model activation energy, J/mol
f Fanning friction factor, -
h_{film} film transfer coefficient, m^2K/W
P absolute pressure, bara
Pr Prandtl number, -
R gas constant, J/mol K
Re Reynolds number, -
R_f fouling resistance, m^2K/W
t time, s
T_f film temperature, K
T_s surface temperature, K
u mean velocity, m/s

Greek
μ viscosity, Pa s
ρ bulk density, kg/m^3
τ_w wall shear stress, Pa

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Table A1. Threshold and related fouling models, listed in chronological order. Equations [A] and [B], referred to in the text, are highlighted.

Source	Expression	Justification	Comments
Ebert and Panchal (1997)	$\frac{dR_f}{dt} = a_1 Re^{b_1} exp\left(\frac{-E_a}{RT_f}\right) - c_1\tau_w$	Original threshold fouling model	τ_w is wall shear stress, *Re* is the bulk Reynolds number
Panchal *et al.* (1999)	$\frac{dR_f}{dt} = a_2 Re^{-0.66} Pr^{-0.33} exp\left(\frac{-E_a}{RT_f}\right) - c_2\tau_w$ **[A]**	Adaption of Ebert and Panchal (1997)	*Pr* is the Prandtl number
Polley *et al*. (2002)	$\frac{dR_f}{dt} = a_3 Re^{-0.66} Pr^{-0.33} exp\left(\frac{-E_a}{RT_f}\right) - c_3 u^{0.8}$	Suppression term based on mass transfer argument	
Saleh *et al*. (2003)	$\frac{dR_f}{dt} = a_4 P^b u^d exp\left(\frac{-E_a}{RT_f}\right)$		*P* is the absolute pressure
Yeap *et al*. (2004)	$\frac{dR_f}{dt} = \frac{a_5 f u {T_s}^{2/3} \rho^{2/3} \mu^{-4/3}}{1 + e u^3 f^2 \rho^{-1/3} \mu^{-1/3} {T_s}^{2/3} exp\left(\frac{E_a}{RT_s}\right)} - c_5 u^{0.8}$	Deposition term based on Epstein (1994) model, written in terms of physical properties	*f* is the Fanning friction factor, ρ the liquid density, μ the viscosity
Nasr and Givi (2006)	$\frac{dR_f}{dt} = a_6 Re^b exp\left(\frac{-E_a}{RT_f}\right) - c_6 Re^{0.4}$	Modification of Polley *et al*. (2002) model	
Polley (2010)	$\frac{dR_f}{dt} = \frac{a_6}{h_{film}} exp\left(\frac{-E_a}{RT_f}\right) S_p(\tau_w)$	Film heat transfer term to give length-scale. Sticking probability, S_p, rather than suppression.	Film heat transfer coefficient, h_{film}: S_p is a function of τ_w, with $0 < S_p < 1$
Polley *et al*., (2011)	$\frac{dR_f}{dt} = \frac{a_1}{h_{film}} exp\left(-\frac{E_a}{RT_{film}}\right) - a_2\tau_w$ **[B]**	Modification of Panchal *et al*. (1999)	
Yang and Crittenden (2012)	$\frac{dR_f}{dt} = \frac{a f u {T_s}^{2/3} \rho^{2/3} \mu^{-4/3}}{1 + e u^3 f^2 \rho^{-1/3} \mu^{-1/3} {T_s}^{2/3} exp\left(\frac{E_a}{RT_s}\right)} - c\tau_w$	Modification of Yeap *et al*. (2004) model	

T_s is the surface temperature; T_f is the film temperature (an average of bulk and surface temperatures).

Table A2. Models for predicting crude oil fouling in different geometries, listed in chronological order.

Reference	Geometry	Modification to Ebert-Panchal (E-P) equation
Master *et al*. (2003)	Helical baffle (shell-side)	Use of E-P model where the shear stress is calculated based on shell-side uniform velocity. Ebert-Panchal model is not fitted to monitoring data.
Bombardelli *et al*. (2005)	Distillation columns	Coking in distillation columns is related to operating conditions. A new dynamic fouling model is introduced with variables relating to the viscous sub-layer thickness, mean fluid velocity, adherence probability and operating temperature.
Panchal *et al*. (2006)	Fired heater	E-P model with Reynolds number calculated using the two-phase flow viscosity.
Aquino *et al*. (2007)	Turbotal tube-inserts	E-P model is modified to describe fouling rates in tubes equipped with tube inserts.
Polley *et al*. (2011)	Tube inserts, Segmental baffle shell-side, Compabloc™	Proposes a new fouling model called the Asphaltene Precipitation Mode, using a sticking probablity instread of a suppression term in the Ebert-Panchal model.
Yang and Crittenden (2012)	Fouling in tubes with HITRAN tube-inserts	Modified the model presented in Yeap (2004), with suppression term amended to include shear stress rather than average fluid velocity (equation [B]) in Table A1).
Morales-Fuentes *et al*. (2010)	Fired heater	The deposition term is presented via the two-phase flow film transfer coefficient (equation [B) in in Table A1).
Brignone *et al*. (2015)	Fouling on the shell-side (EMBaffle)	The deposition term is presented via the film transfer coefficient. Equivalent shear stress used to evaluate the suppression constant (equation [B) in Table A1).

Table A3 Applications where threshold fouling dynamics are used to predict or explain individual heat exchanger performance

Reference	System	Description
Ishiyama *et al*. (2008)	Shell-and-tube exchanger	The thermal and hydraulic impacts of tube-side fouling is analysed for cases where a centrifugal pump and control valve determine the throughput. The phenomenon of 'thermo-hydraulic channelling', caused by fouling coupling thermal and hydraulic performance in parallel units, is discussed, including its control. Over-design of exchangers, using guidelines such as those provided by TEMA, is shown to be capable of exacerbating fouling problems.
Coletti and Macchietto (2009, 2011a)	Shell-and-tube exchanger	Threshold fouling models are incorporated in detailed numerical simulations of a heat exchanger where local temperature and flow behaviour are calculated. Local and overall fouling behaviour can be compared. This distributed approach avoids the effects of averaging across the exchanger on the estimation of fouling behaviour.
Ishiyama *et al*. (2010b), Coletti *et al*. (2010), Ishiyama *et al*. (2011a,b)	Shell-and-tube units	The effect of deposit ageing on fouling behaviour is considered. Threshold fouling models are used to calculate the rate of deposition of ‘fresh’ material, which is then converted to a more conductive ‘aged’ material. Implemented in simple and detailed exchanger simulations, and also in models for scheduling cleaning by more than one method.

Table A4 Examples of use of threshold fouling approaches to identify fouling-resilient network design and operation

Reference	Description
Rodriguez and Smith (2007)	The influence of operating variable such as wall temperature and velocity on fouling rates are incorporated in optimal preheat train operation, including cleaning actions.
Ishiyama *et al*. (2009)	Crude preheat train simulation with fouling dynamics including temperature and flow rate dependent fouling rates, pressure drop, throughput variation and flow split optimisation. Robust algorithm for cleaning schedule optimisation.
Kumana *et al*. (2010)	The use of dynamic fouling models to mitigate fouling for individual units and networks is discussed. Case studies show fitting dynamic fouling models to plant data, to predict future performance.
Ishiyama *et al*. (2010a)	Control of preheat train operation, including constraints imposed by desalter temperature operating ranges, are included in a simulation which optimises cleaning schedules and hot stream bypassing. Includes fouling analysis based on refinery operating data.
Coletti and Macchietto (2010); Coletti *et al*., 2011b)	The dynamic distributed fouling model is applied to units in a network, so that the thermo-hydraulic performance of the system can be simulated.
Pan *et al*. (2012)	Retrofitting networks with tube-inserts for heat transfer intensification and fouling mitigation.
Polley *et al*. (2013)	Considers the use of dynamic fouling models (including crude oil and cooling water systems) in thermo-hydraulic simulations to identify industrially relevant and practically viable solutions to fouling. This is combined with analysis of heat recovery networks when considering retrofits in order to generate robust solutions.
Ishiyama *et al*. (2013b)	Demonstrates methods of extracting dynamic fouling model parameters from plant monitoring data and utilizing dynamic fouling simulations to optimize heat exchanger network performance.
Wang and Smith (2013)	A novel design approach is used to solve heat-exchanger network retrofit problems on the basis of heat transfer enhancement. Simulated annealing is used to optimize the retrofit problem including fouling considerations. The results show that heat-transfer enhancement is a very attractive option for retrofitting when fouling is considered.
Coker (2014)	Summarizes the importance of using dynamic fouling models in heat exchanger fouling mitigation. References are made on how EXPRESSplus and SmartPM software uses dynamic fouling models in fouling mitigation.