EXTRACTION OF CRUDE OIL FOULING MODEL PARAMETERS FROM PLANT EXCHANGER MONITORING

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ABSTRACT

Most of the semi-empirical 'threshold fouling' models for crude oil fouling in shell-and-tube exchangers have been developed and validated using data collected at what may be considered to be 'point' or localised conditions. In practice, both velocity and wall temperature can vary significantly within a heat exchanger, leading to difficulty in applying the models in exchanger design and extracting fouling information from exchanger performance monitoring.

A partial simulation model is presented here incorporating a linear temperature distribution. This short-cut model is compared with a more detailed simulation in order to establish its reliability. Pressure drop using a smooth layer model is also considered. The short-cut approach is employed in a data reconciliation study of an operating crude preheat train, which indicates that the original threshold fouling model of Ebert and Panchal (1997) gives a better description of the observed fouling behaviour.

INTRODUCTION

Fouling in crude oil preheat trains is often dominated by chemical reaction fouling in units operating at higher temperatures. Replicating the exchanger and fluid chemistry conditions in detailed laboratory or pilot-plant studies is not simple, and laboratory experiments are expensive and time consuming. This means that they can only yield data for a small range of crude compositions. On the other hand, monitoring of the performance of operational exchangers is becoming standard practice so data reconciliation represents an important source of information for the development, evaluation and characterisation of models for the prediction of crude (and other) fouling rates.

Unfortunately, the extraction of meaningful information from operational exchangers is not straightforward. With many types of fouling the rate is strongly dependant on local surface temperature, transport rates and shear stress. In practice, both the surface (wall) temperature and velocity vary across the length of a heat exchanger, and the distributions are dictated by exchanger geometry and thereby design. A further complication is the interaction between local fouling and each of the controlling factors after deposition has started. The fouling layer provides an additional resistance to heat transfer and affects surface temperature, while flow restriction will alter local velocity.

This complication is mirrored by problems associated with the use of fouling models in design. The models currently available provide prediction of local fouling rates, *i.e.* they provide 'point' values. The question then arises as to how these models should be used when large variations in wall temperature and/or velocity occur across an exchanger.

The challenge is therefore how to make use of this important source of data in analysis and subsequently in exchanger design. One answer is to develop exchanger simulations that incorporate fouling models and allow integration of performance over both time and space. The engineer could then compare these predictions with results obtained from monitoring and model parameters tuned by regression against the data. Exchanger simulations of this nature (although not necessarily used for parameter estimation) have been reported by Branch and Müller-Steinhagen (1991) and by Yeap *et al.* (2001). Commercial software packages with this facility do not currently exist, partly because they would be expensive to develop and could require significant amounts of staff time to operate.

This paper presents a somewhat simpler and faster approach. It involves the development of an integral form of the local fouling model which provides predictions of mean fouling rate across a heat exchanger. These equations can be used to determine fouling model parameters from data obtained through exchanger monitoring and then utilise this information in exchanger design.

CRUDE OIL FOULING MODELS

The 'threshold fouling' concept for crude oil fouling was introduced by Ebert and Panchal at the Engineering Foundation conference on fouling in San Luis Obispo in 1995 (published in 1997). This approach provides a semi-theoretical basis for quantitative interpretation of fouling data in terms of deposition and suppression (or inhibition) mechanisms. It should be noted that the latter term refers to suppression of deposition (i.e. mechanisms occurring in the fluid layer at the deposit surface) rather than disruption of an existing deposit layer (e.g. erosion of deposit). The latter approach underpins the 'asymptotic fouling' model presented by Kern and Seaton (1959). Ebert and Panchal originally proposed a model of the form

$$\frac{dR_f}{dt} = A_I \,\mathrm{Re}^{-0.66}\,\mathrm{Pr}^{-0.33}\exp\left(\frac{-E_I}{RT_f}\right) - C_I \tau_w \qquad (1)$$

while Polley *et al*. (2002) later suggested a modified form, *viz*.

$$\frac{dR_f}{dt} = A_{II} \,\mathrm{Re}^{-0.8}\,\mathrm{Pr}^{-0.33}\exp\left(\frac{-E_{II}}{RT_s}\right) - C_{II}\,\mathrm{Re}^{0.8} \qquad (2)$$

We term this the ESDU model. It differs primarily in the use of the surface temperature, T_s, in the deposition term, and suppression based on friction velocity or Reynolds number rather than wall shear stress. A critique of different threshold fouling models is given by Yeap *et al.* (2004).

The fouling model parameters are dimensional and contain contributions from a number of physical and chemical mechanisms, which will be determined by the composition of the crude. Identification of most likely values of the parameters (often three or more in any given model) requires much analysis and is unlikely to be easily combined with sophisticated exchanger simulation. This further supports the development and use of short-cut simulation approaches.

CONCEPT

For an exchanger operating under pure counter-flow, fouling rates at each end of the exchanger can be calculated from the terminal temperatures (data provided by the monitoring exercise) using the 'point' form of fouling model. The question then arises; "How can we use these rates to determine the overall behaviour within the exchanger?".

In both the Ebert-Panchal and ESDU models, temperature has a strong effect on deposition rate and a minor effect on the suppression effect, while flow velocity affects both contributions. Let us assume that flow velocity does not vary significantly over the length of the exchanger, so that the primary factor influencing fouling rate is temperature, chiefly via the pseudo-Arrhenius exponential term. If it is assumed that the temperature (wall or film) varies linearly along the length of the thermal path then this term can be integrated using a series expansion to give the length-mean value. The limits of the integral are set by the terminal conditions.

This integration provides a mean deposition term. The next issue is the handling of the suppression term. There appear to be two options available: either assuming that the suppression term is constant over the length of the unit, or to use a value based upon terminal conditions. We consider these options below. The mean fouling rate is then taken as the difference between the mean deposition and suppression terms. The approach has been applied to both the Ebert-Panchal model and the ESDU model (*i.e*. equations (1) and (2)). In the following text, this approximated approach is referred to as the short-cut model.

Comparison with Simulation

A simulation of the fouling inside a heat exchanger tube was constructed. Its input parameters are the flow rate of crude oil through the tube, the crude physical properties, the ratio of the heat capacity flow rates of the fluids involved in the heat transfer (in order that the exchanger temperature profile can be modeled) and the inlet temperatures of both the hot and cold streams. The simulated system consisted of a 5 m long tube with 15 mm i.d. (typical internal dimension of a ¾ inch heat exchanger tube). The exchanger is sub-divided into small intervals of length and the fouling evaluated within each interval. A small time interval is then selected and the change in the fouling resistance during that interval determined. The effects of fouling on outlet temperatures and wall temperature profile are determined, and the next time interval evaluated. The result is determination of both local and length mean fouling resistance over time. The length-mean resistances resulting from the integration are then compared with those predicted from the terminal temperature conditions using the short-cut model.

Figure 1 shows the variation in surface (i.e. interface between fouling layer and crude oil) temperature T_s along the tube at a mean flow velocity of 1.9 m/s, with approach temperatures of 340ºC (hot) and 300ºC (cold), which are typical values for an exchanger positioned at the hot end of a pre-heat train. The plot indicates that a linear variation in surface temperature is a reasonable approximation under these conditions.

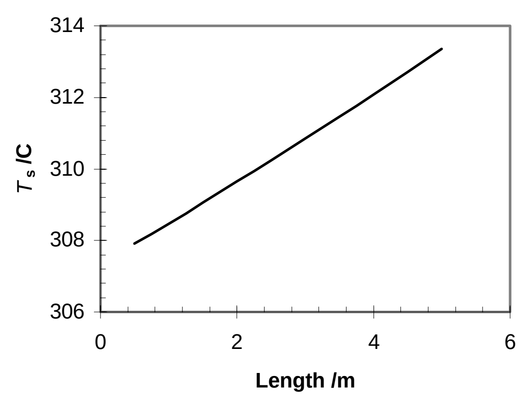

Figure 1 Simulated clean surface temperature profile.

For comparison, results are presented for the exchanger in Figure 1 subject to fouling described by the ESDU model with parameters {E_{II} = 48 kJ/mol; A_{II} = 1500 m^2K/W.hr; C_{II} = 1.5×10^{-9} m^2K/W.hr} (being the values previously derived by Polley *et al*. (2002) to fit the threshold fouling data reported by Knudsen *et al*. (1999)). The methodology has been tested over a range of parameters and found to be quite stable. Perhaps most significantly, it has been tested against the parameters extracted from the analysis of the industrial monitoring data described in later sections and found to be consistent. Final confirmation of the results of such studies using detailed simulation provides a valuable 'safety' check.

Comparisons with the detailed tube simulation provided guidance on how the suppression term should be handled. Early comparisons showed that although the velocity variation across the exchanger can be quite small, it could have a significant effect upon fouling rate. However, we found that if a log mean of the terminal velocities was used in the short-cut model, the comparisons between predicted fouling rates and integrated resistances were favourable.

Figure 2 shows the results obtained for the operating conditions described above and agreement between the short-cut model and the detailed simulation is very good.

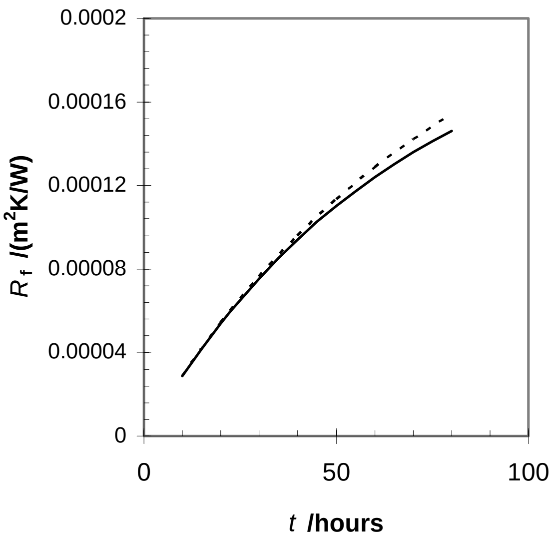

Figure 2 Overall fouling resistance for exchanger tube in Figure 1 with fouling rate given by equation (2) and parameters in text. Solid line – detailed simulation; dashed line – short-cut model.

Comparisons were conducted for a range of operating conditions. Figure 3 shows the results obtained for a unit operating with similar flow rates and lower temperatures, namely hot and cold inlets of 320ºC and 280ºC, respectively. The overall fouling rate is around 25% of the previous case, owing to the lower surface temperature, and the agreement between the two methods is less close.

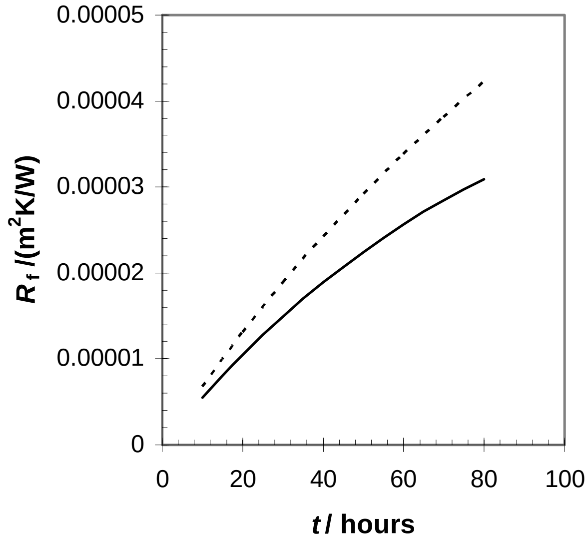

Figure 3 Comparison of detailed simulation (solid line) and short-cut model for exchanger in Figure 1 operating at colder inlet temperatures (see text).

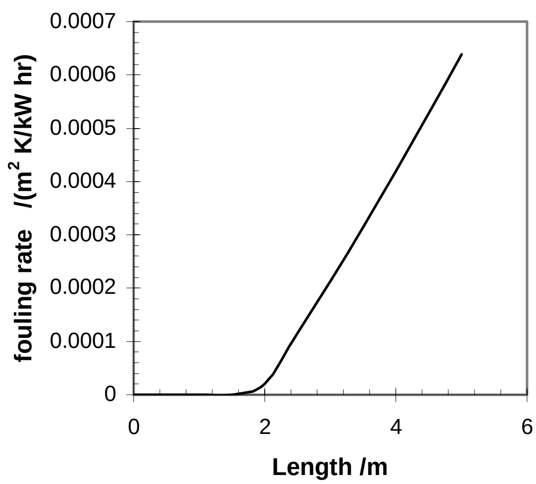

Figure 4 Calculated fouling rates for case with fouling threshold located midway along a tube.

A particular feature of threshold models is that under some circumstances, fouling will start part way along the tube and a simple integration will include the (false) negative fouling rate predicted for those regions. Figure 4 shows the initial fouling rates for the case with inlet temperatures of 330ºC (hot) and 270ºC (cold). The fouling threshold is located mid-way along the tube. Such cases are readily detected and eliminated in the algorithms for the short-cut method for predicting exchanger behaviour. The comparison of overall fouling resistances in Figure 5 indicates reasonably good agreement, while it should be noted that the fouling resistances are very low. These results suggest that the short-cut method can be applied over large operating ranges, with due care paid to non-fouling regions.

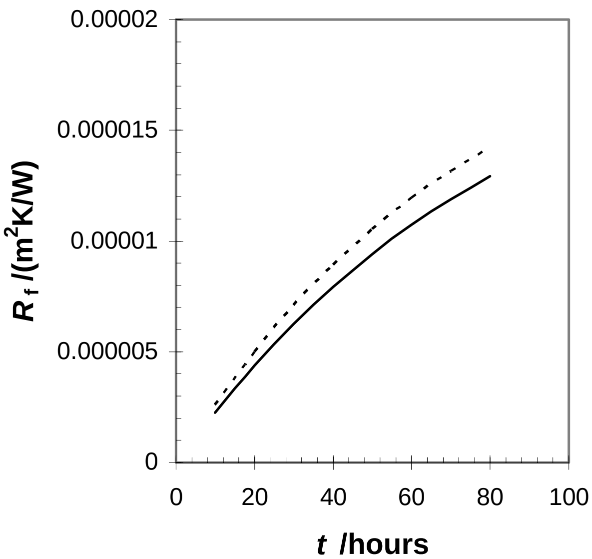

Figure 5 Comparison of overall R_f for simulation (solid line) and short-cut model (dashed line) for case in Figure 4.

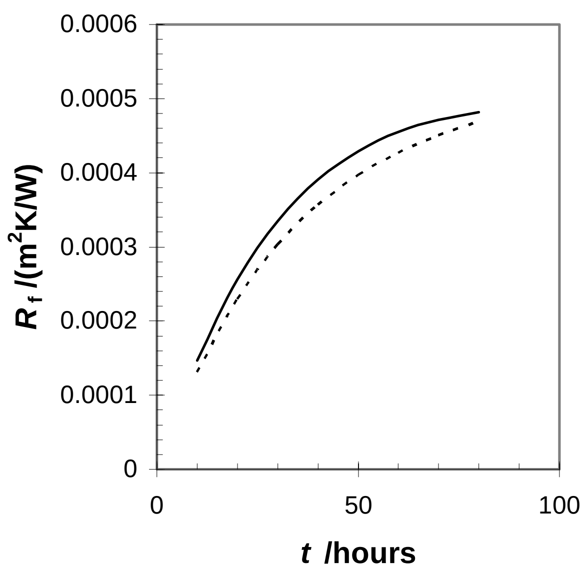

Figure 6 Asymptotic fouling behaviour predicted at high crude temperature and large temperature difference. Solid line – simulation; dashed line – short-cut approach.

Finally, Figure 6 shows how the two approaches compare for a case featuring very initial high fouling rates generated by a high crude temperature and a large temperature difference. Both methods predict asymptotic behaviour, with the short-cut approach reaching an asymptote before the detailed simulation.

Qualitatively similar results have been found for the unmodified Ebert-Panchal model, equation (1). Both of these short-cut models have been incorporated into ESDU's EXPRESS™ program which was used in the following study of industrial monitoring data. The package allows one to determine which fouling model fits the data better in a given situation and generates the associated fouling model parameters.

In order to speed-up the identification of the fouling parameters, fouling profile plots such as Figure 7 are generated for the conditions operating in the exchanger. These plots are used to compare the data with behaviour predicted for a range of activation energies.

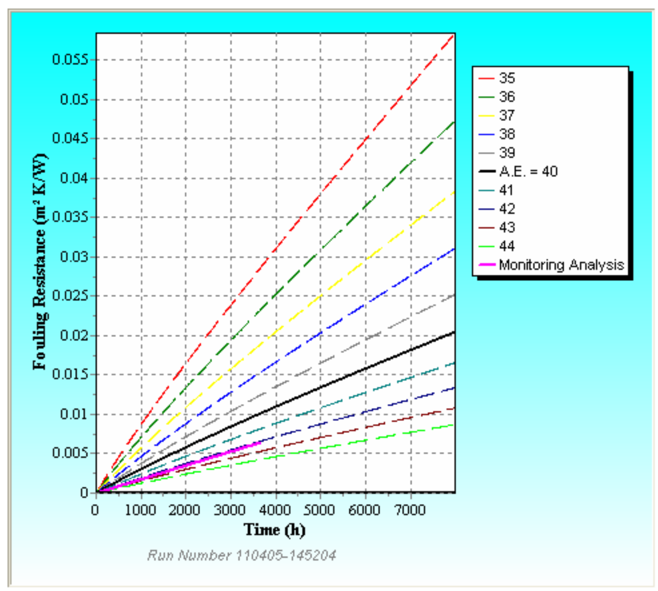

Figure 7 Example of a fouling profile set generated by the EXPRESS™ program showing effect of activation energy E ('A.E.' on legend) on R_f for a given exchanger configuration. Plant data set marked as 'monitoring analysis'.

The above analyses have assumed that the streams are in pure counter-flow. With most industrial equipment this will not be the case as multiple tube passes are used. The effect of this on the methodology is the subject of further research. So, in some regards, the evolution of the technology is following that used to handle the effects of variation in physical properties across heat exchangers. It is noteworthy that engineers still use the concept of 'effective mean temperature difference' and the 'effectiveness-NTU approach'. Both concepts are based upon non-variant physical properties and heat transfer coefficient!

Pressure Drop

Pressure drop considerations are important for pre-heat train operation and in exchanger design. Yeap *et al*. (2004) have looked at a variety of models for the prediction of pressure drop under fouled conditions. The simplest model is one that assumes a uniform fouling layer. The simplest way of extending this model to industrial exchangers is the assumption that the hydraulic behaviour is given by flow through a tube having a fouling layer equal to that associated with the mean fouling resistance.

The detailed simulation of a heat exchanger tube generated local fouling resistances and hence local layer thicknesses, and included a determination of the effect of fouling on pressure drop. This is compared with the short-cut method (for the process conditions relating to Figures 1 and 2) in Figure 8. We see that the former gives reasonable description of hydraulic performance under conditions in which it provides good prediction of thermal behaviour.

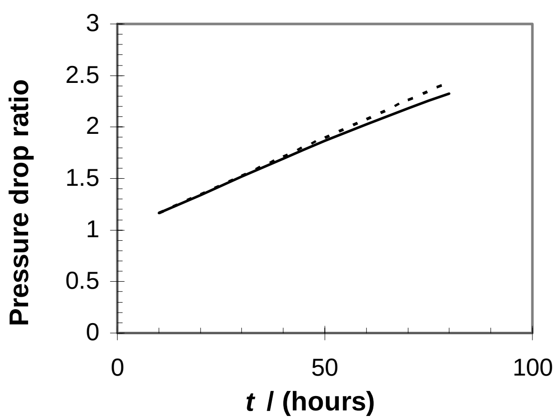

Figure 8 Comparison of estimated pressure drop ratio (fouled/clean) corresponding to the case in Figure 2 with constant mass flow rate. Solid line, simulation; dashed line, short-cut method.

ANALYSIS OF INDUSTRIAL DATA

Three considerations must be addressed during the analysis of data obtained from exchanger monitoring. These are:

(i) How tube-side and shell-side fouling resistances can be separated out from measurements of overall values and the uncertainties in the prediction of true overall heat transfer coefficients.

(ii) How the performances of individual exchangers should be 'weighted' given inaccuracies in sensors and performance measurement.

(iii) Identification of causes for exchanger under-performance other than that due to fouling.

The first of these challenges is partly met by dealing with fouling rates rather than absolute values. The effect of inaccuracies in the prediction of clean heat transfer coefficients are then reduced, provided that there are not very large changes in throughput during the monitoring period so that these inaccuracies are systematic and uniform. Similarly, if the level (and rate) of fouling occurring on the crude (tube) side is significantly higher than on the shell side of the exchanger, the rate of change in the overall value will relate predominantly to the crude side.

Under-performance can be the result of a range of causes. Many can be characterized as being due to one of three types: the result of poor flow fields, departure of temperature field from the expected form, or due to the presence of contaminants. We are currently seeking to develop and systematic procedure for the identification of causes of underperformance.

The data presented here were supplied from a crude oil preheat train operated by Total which featured fourteen heat recovery units. Eleven of these were positioned above the desalter and were studied in this work. In the data reconciliation work we adopted the following methodology:

(a) Once overall fouling resistances had been generated from plant operating data, a plot of R_f against time was generated (*e.g*. Figure 9).

(b) A start time was identified, and the overall fouling resistance at this point was set as the hot side value in order to determine the surface temperature on the tube inner wall.

(c) Linear regression was used to obtain the fouling rate and the fouling rate data were modelled using both models (Equations (1) and (2)). Only results for Equation (1) are presented here.

Using ESDU's EXPRESS™ program it was possible to select a set of parameters that fitted measured rates very closely. When the results for the whole portfolio of exchangers were examined the model parameters were found to differ for each unit. However, three of the units were identified as under-performing for reasons other than fouling (i.e. (*iii*) above) and once these poorly designed or operated units had been removed from the analysis the differences in the fouling parameters identified for individual exchangers were much smaller.

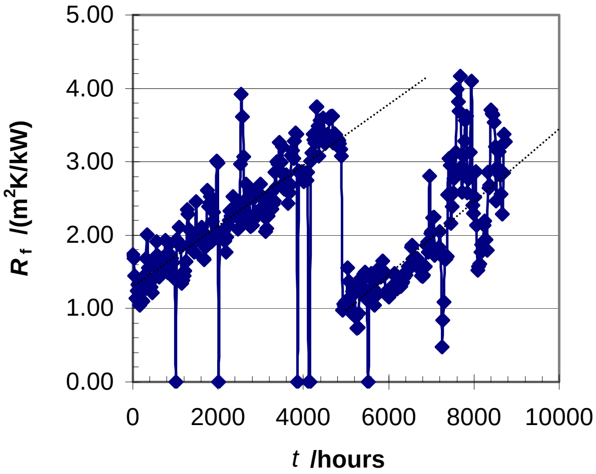

Figure 9 Example of preheat train unit fouling resistance profile with dashed line showing regressed linear fouling rate.

The final stage of the analysis is the determination of a global set of parameters that provides best fit to the overall collection of measurements. Here the question of how much 'weight' should be given to individual units arises. In the situation in which the plant measurements can be considered be of similar accuracy, the weighting should be based upon the effect that fouling has upon the basic measurements. This is controlled by the effectiveness of each individual exchanger (*e.g.*, Incropera and De Witt, 1996); the lower the effectiveness the more sensitive the outlet temperature will be to changes in overall heat transfer coefficient and the more reliable the measurement of fouling rate.

Figure 10 shows individual comparisons between the short-cut predictions and the measured fouling profiles for the operational pre-heat train. The plots show predictions of fouling behaviour based on inlet (D) and outlet (A) conditions as well as the integrated mean (B) for the global set of fouling parameters, applied to each exchanger. The 'measured', *i.e.* regressed, fouling rate is superimposed on the plot (C). There are three cases where the measured rates are effectively coincident with the predicted values. In one case the predicted rate is 50% higher than the measured value while in another case the predicted rate lies 20% above the measured value. In the final case the initial rates coincide but the predicted rate falls away more rapidly than the measured performance and after 6000 hours the predicted level is about 60% of the measured level. The comparison between measured and predicted performance is better than obtained in many laboratory studies.

FOULING THRESHOLDS

One of the significant uses of the Ebert-Panchal Model is the identification of the velocity at which fouling is suppressed. Having generated parameters from analysis of plant data it becomes possible to identify the position of this 'threshold'. It is also possible to determine how 'sensitive' this threshold is to the parameters (e.g. activation energy).

Figure 11 shows a range of loci ('fouling thresholds') relating the film temperature at which fouling is initiated as a function of velocity. Each locus relates to a different value of E_I, the other parameters being fixed. The sensitivity of the threshold line to the activation energy is very evident.

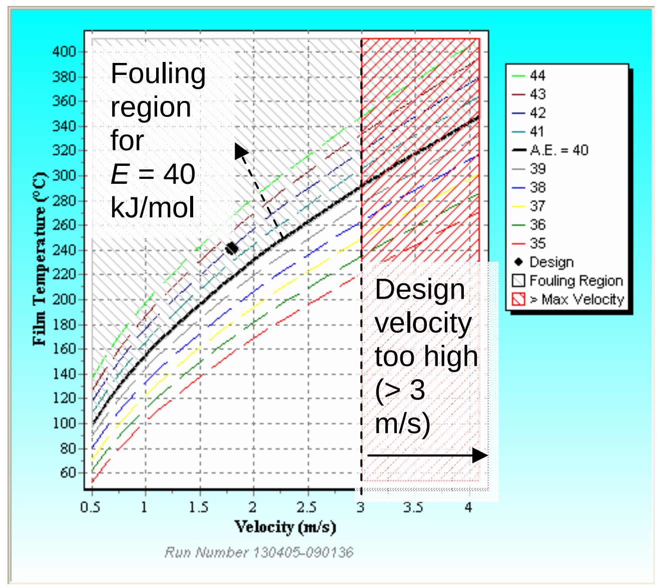

Figure 11 Threshold fouling loci from EXPRESS™ for equation (1) with parameters obtained from reconciliation of monitoring data for different activation energies ('A.E.') given in the legend. Uppermost locus, 44 kJ/mol; lowest locus, 35 kJ/mol. Upper hatched region shows fouling region for E = 40 kJ/mol, locus indicated by solid black line. Hatched region on right shows prohibited region for design, as velocities > 3 m/s are not permitted. Circle indicates exchanger design conditions.

Also shown on the plot is the point representing the conditions at the exit of the exchanger. In this case the unit would not foul if the activation energy is around 42 kJ/mol. Having determined the activation energy and other model parameters for a given crude slate from the analysis of monitoring data, it is then possible to identify the velocity at which an exchanger needs to be operated in order to suppress fouling. This information can be used for exchanger revamping or the fouling model can be used in design to generate a geometry in which fouling is suppressed. These features are built into EXPRESS™.

This investigation of industrial monitoring data indicated that the Ebert-Panchal model, equation (1) appears to provide a reasonable model for fouling associated with the thermal decomposition of asphaltenes. Its applicability for other mechanisms is yet to be demonstrated. It should be noted that the ESDU model, equation (2) did not fit the data well (data not reported).

CONCLUSIONS

An integrated form of the Ebert-Panchal type of threshold fouling model has been developed to describe exchangers that operate with large temperature differences, both for data reconciliation purposes and for simulation of the exchanger's performance. This short-cut model gives reasonable agreement with detailed simulations and allows one to consider the temperature range within a unit rather than being tied to a point, *e.g.* worst case, evaluation.

The short-cut model has been used to determine fouling model parameters for an operational pre-heat train. The results are very encouraging. The unmodified Ebert-Panchal model (equation 1) provided a good fit to the measured data.

ACKNOWLEDGEMENTS

Permission from Total to publish these results is gratefully acknowledged, as is travel funding for DIW from the Royal Society, the University of Cambridge and Jesus College, Cambridge.

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Nomenclature

A, *B*, *C*	parameters in fouling models	
E_i	activation energy, model *i*	kJ/mol
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

Greek

τ_w	wall shear stress	Pa

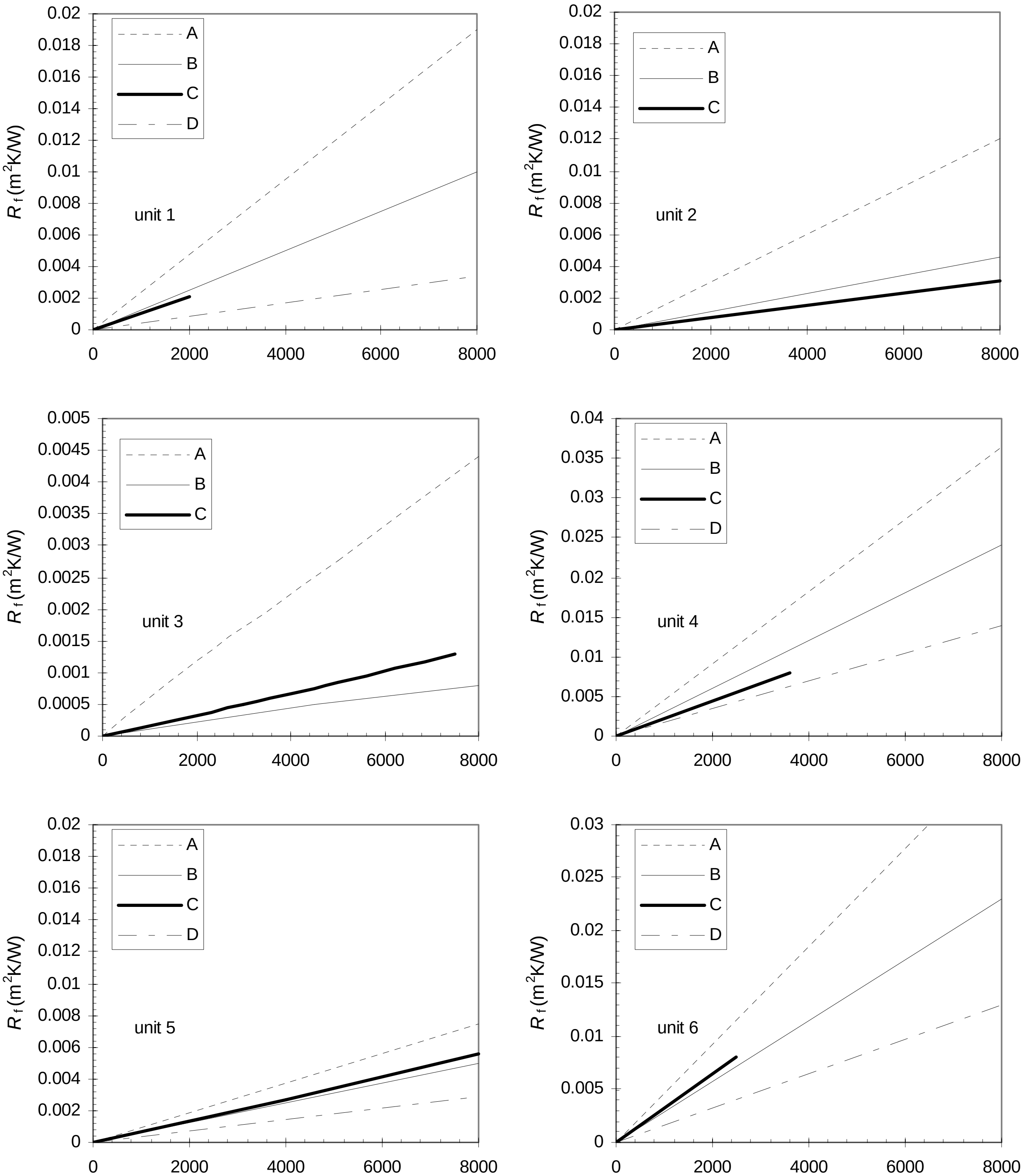

Figure 10 Comparison from EXPRESS™ of fouling models with reconciled exchanger data. Time (up to 8000 hours) on *x*-axis. Labels: A – fouling rate based on exchanger hotter inlet conditions; B – short-cut model; C – reconciled fouling data; D - fouling rate based on exchanger colder inlet conditions.