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TEN YEARS OF EBERT, PANCHAL AND THE 'THRESHOLD FOULING' CONCEPT

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ABSTRACT

Ebert and Panchal introduced the concept of 'fouling threshold' models for quantifying and mitigating fouling in crude oil processing at the Engineering Foundation Conference on Fouling Mitigation of Industrial Heat-Exchange Equipment held at San Luis Obispo. This paper reports on the development and application of the concept in the subsequent ten years: quantitative approaches now exist to counter fouling at the network, exchanger design, and operating levels. The implications for exchanger design are illustrated using two case studies. Areas requiring further attention and the likely state of the art in 2015 are discussed.

THE FOULING THRESHOLD CONCEPT

Fouling is a long-standing problem in the processing of crude oil and particularly in the preheat train networks on refinery primary and vacuum distillation units. Deposition can involve chemical reaction, particulate and corrosion fouling, with the composition and stability of the crude slate being major determining factors (ESDU, 2000; Mansoori, 2002). Blending of crudes can yield unstable mixes which precipitate species such as ashphaltenes and result in rapid fouling, which Wilson and Polley (2001) described as 'acute fouling' that can best be managed at a process chemistry (*i.e.* molecular) level. In preheat trains with correct blending and filtering of feedstock and desalter operation, the most severe fouling is usually the less rapid, 'chronic' fouling due to chemical reaction fouling above the desalter where wall temperatures are greatest. In these cases fouling can be mitigated by chemical routes, or optimisation of exchanger operation (and design), which requires an understanding of physical and chemical mechanisms. Efforts at modeling fouling rates in this region have not yet progressed beyond model systems (*e.g.* Crittenden *et al.*, 1987) due to the complexity of the chemistry and the possible interaction of deposition processes (Bott, 2001).

At the San Luis Obispo conference in 1995 Ebert and Panchal outlined an alternative, pragmatic concept of 'threshold fouling' for dealing with crude oil fouling. They proposed a semi-empirical approach to quantify the effect of flow velocity on tube-side fouling in crude oils at high temperatures which pilot plant studies (in their case, the work on coking by Scarborough *et al.*, 1979) indicated that:

(i) Fouling rates increased with increasing temperature – initially interpreted as film temperature, elsewhere as wall/deposit temperature.

(ii) Fouling rates decreased with increasing flow velocity.

They fitted the reported data shown in Figure 1 to a numerical model where the rate of fouling is presented as a competition between deposition and suppression terms, *viz.*

$$\frac{dR_f}{dt} = \text{deposition} - \text{suppression}$$

$$= \overbrace{A_I \,\mathrm{Re}^{-\beta} \exp\left(\frac{-E_I}{RT_f}\right)} - \overbrace{C_I \tau_w} \qquad [1]$$

and regression yielded the parameter set {A_I = 30.2×10^6 K m^2/kW h; β = -0.88, E_I = 68 kJ/mol and C_I = 1.45×10^{-4} m^2 K m^2/kW Pa h}.

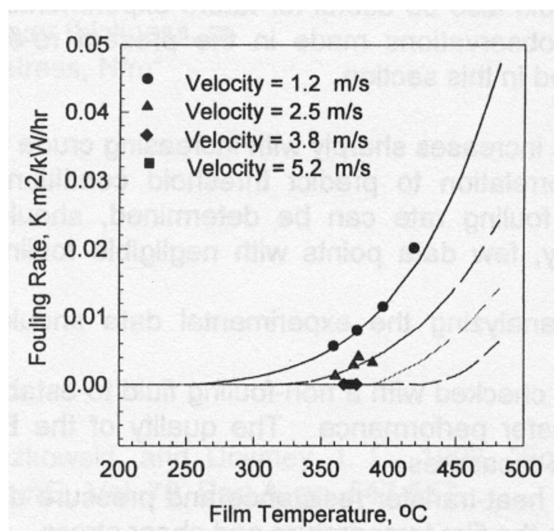


Figure 1 The Ebert-Panchal model (equation [1]) fitted to Scarborough *et al.*'s (1979) data, from Ebert and Panchal (1997).

This model allowed users to estimate operating conditions where the fouling rate would be close to zero – termed the 'fouling threshold'. This information, which could be obtained from pilot plant studies or reconciliation of exchanger operating data, offers a potential rational and quantitative basis for improving unit operation or guiding exchanger (and preheat train) design or revamping:

(a) The threshold allowed individual exchangers to be designed to be free from fouling, as described by Bott (2001), Butterworth (2002) and Polley *et al*. (2002a). It also allowed exchangers which *had* to be operated above the threshold to be identified and appropriate fouling mitigation technologies considered from an early stage.

(b) The emphasis on *rates* steered attention away from oversizing exchangers based on anticipated worst case design scenarios suggested by the use of asymptotic fouling resistances such as those published by TEMA (Stachura, 1998) and supported by the Kern and Seaton model (1959). It is noteworthy that few data sets for crude oil fouling indicate the existence of asymptotic fouling except where fouling results in reduction of heat transfer and surface temperature so that the rate is reduced significantly. Likewise, there is no evidence of deposit removal in crude oil fouling systems. We consequently use ‘suppression’ to describe the second term in Equation [1] in order to avoid confusion with Kern and Seaton’s ‘removal’ term: the model describes mechanisms occurring at the fluid-substrate interface, i.e. excluding erosion or other removal processes.

(c) The threshold concept provided a numerical tool which could be incorporated into the design and retrofit of heat exchanger networks. The existing methodologies had normally ignored fouling completely, with the exception of the model-driven analysis of Fryer *et al*. (1987), optimizing designs on the basis of clean heat transfer area and utility loading – then adding extra area using the arbitrarily assigned TEMA fouling factors which was critiqued by Kotjabasakis and Linnhoff (1986).

(d) The model parameters allowed different crudes to be compared on the basis of fouling propensity.

This paper considers how the concept has been developed in the 10 years since Ebert and Panchal introduced it.

THRESHOLD MODELLING

In the intervening ten years the basic formulation of the model has been revised, resulting in several variants. Panchal and co-workers (Panchal *et al*., 1999; Asomaning *et al*., 2000) considered data sets obtained from both (well defined) pilot plant tests and monitoring of plant exchangers to give the revised form of [1] as

$$\frac{dR_f}{dt} = A_{II}\ Re^{-0.66}\ Pr^{-0.33}\ exp\left(\frac{-E_{II}}{RT_f}\right) - C_{II}\,\tau_w \qquad [2]$$

where the fluid flow and thermal properties are accounted for by the use of the Prandtl number and a fixed power on the Reynolds number. Polley *et al*. (2002a) employed a deposition term closely related to that proposed by Paterson and Fryer (1985), with an explicit dependence on deposit or wall surface temperature T_s rather than film temperature T_f, and a mass transfer related suppression term analogous to that proposed by Crittenden *et al*. (1987).

$$\frac{dR_f}{dt} = A_{III}\ Re^{-0.8}\ Pr^{-0.33}\ exp\left(\frac{-E_{III}}{RT_s}\right) - C_{III}\ Re^{0.8} \qquad [3]$$

They reported that this model gave better agreement for a number of pilot plant and exchanger monitoring data sets reported by Asomaning *et al*. (2000), although for several sets they did not have access to the thermophysical properties and had to estimate these. They also discounted the high temperature data from Scarborough's study as these featured conditions alien to most preheat exchangers and were likely to feature coking reactions. Yeap *et al*. (2004) compared different forms of the RHS terms for a larger data set than Polley *et al*. and found best agreement with a deposition term based on the Epstein model for tube-side chemical reaction fouling (1994), *viz*.

$$\frac{dR_f}{dt} = \frac{A_{\mathrm{IV}} C_f u T_s^{2/3} \rho^{2/3} \mu^{-4/3}}{1 + B_{\mathrm{IV}} u^3 C_f^{\,2} \rho^{5/3} \mu^{-7/3} T_s^{2/3} \exp\left(E_{\mathrm{IV}} \big/ RT_s\right)} - C_{\mathrm{IV}} u^{0.8} \qquad [4]$$

as this could describe monitoring results which showed an increase in fouling rate with flow velocity: otherwise this model condensed to a form similar to equation [3]. Note that Equation [4] differs from that in the original paper, which included a typographical error. It should be noted that the agreement between measured and predicted rates with these models can be large, as illustrated in Figure 2, so the uncertainty in predicted thresholds in temperature and velocity should be considered.

Knudsen *et al*. presented the pilot plant data shown in Figure 3 in 1997 (published in 1999) demonstrating the existence of the fouling threshold. This trend could not be fitted to the Ebert-Panchal equation successfully but did fit Equation [3]: similarly, the fouling rates (occurring at conditions above the threshold) could be fitted to Equation [3] but neither set of parameters could adequately describe both the threshold locus and the measured fouling rates. This suggests that the physical mechanisms for deposition and attachment to a clean surface and to a fouled surface differ. This is understandable but raises the question as to whether fouling rates or the fouling threshold locus should be given priority in testing. In plant monitoring, only the latter is realistic but in pilot plant studies for industrial consortia such as HTRI and ESDU, it needs to be considered.

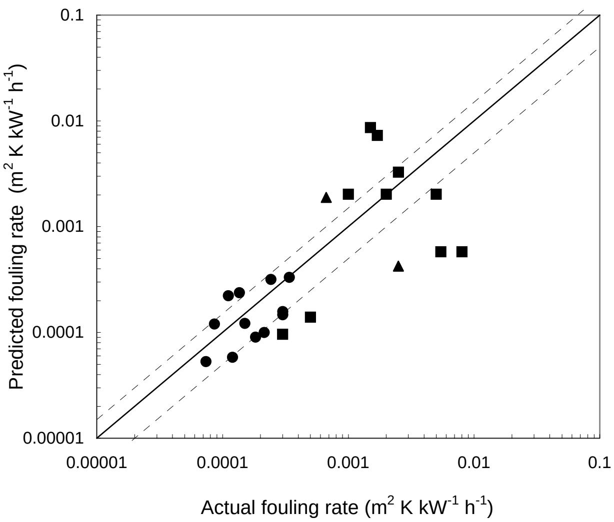


Figure 2 Agreement between Equation [4] with parameters obtained by regression of refinery monitoring data sets reported by Yeap *et al*. (2004). Dashed lines show ±50% confidence limits.

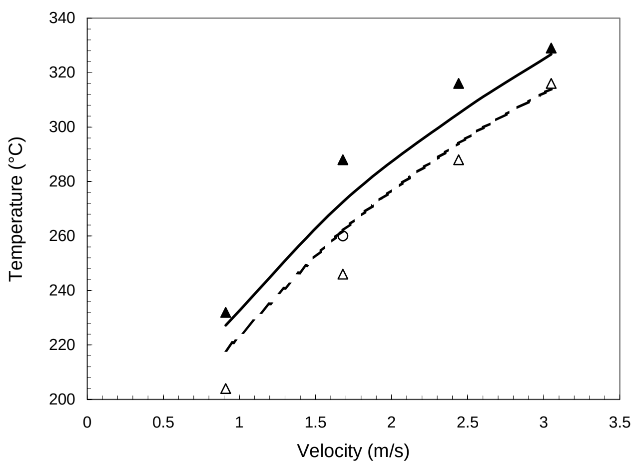


Figure 3 Pilot plant data of Knudsen *et al*. showing fouling threshold (surface temperature *v*. mean flow velocity) in an Alaskan crude oil (after Yeap *et al*. (2004). Filled symbols, fouling; open symbols, no fouling. Threshold models: Equation [3], dashed line, Equation [4] solid line.

The academic community has not warmed to the threshold fouling concept: less than 10 papers on the topic have appeared in academic journals in the last decade, and promulgation of the methodology is led by user companies (*e.g*. Total: Bories and Patreux, 2003; Polley *et al*., 2005a) and technology houses (*e.g*. ESDU, HTRI).

This can partly be attributed to technology stagnation in the refining sector and partly to the degree of empiricism involved in the model formulation. The model is based on a competition between deposition and suppression fluxes, m_d and m_r respectively.

$$\frac{dR_f}{dt} = m_d - m_r \qquad [5]$$

There are many assumptions about the nature and form of the deposition process. For example, if the change in R_f – quantifying the impact on heat transfer - were simply due to a difference in thickness of a thin deposit, δ, then in the absence of suppression, one would observe

$$\frac{dR_f}{dt} = m_d = \frac{d}{dt}\left(\frac{\delta}{\lambda_f}\right) \approx \frac{1}{\lambda_f}\frac{d\delta}{dt} \qquad [6]$$

Now the thickness of a layer generated by chemical reaction is related to the reaction rate, say g_d, the layer porosity ε_f and the true deposit density ρ_T, giving

$$\frac{dR_f}{dt} = \left(\frac{1}{\lambda_f}\frac{1}{\rho_T(1-\varepsilon_f)}\right) g_d \qquad [7]$$

assuming that the material parameters are not related to the rate or extent of reaction. Given that λ_f will be a function of ε_f, and that both λ_f and ρ_T are temperature dependent, it is immediately apparent that these threshold models lump several parameters together. The lumped parameters will contain temperature and fluid dependencies that are then (erroneously) represented by the activation energy, *Re* or *Pr* The information required to decouple the assumptions made, particularly about dependencies on temperature, are in the main not available. The desired approach, of being able to separate temperature, reaction and physical effects, is not yet possible owing to the complexity of the mechanisms and the shortage of reliable data. This applies equally strongly to the suppression term, where the mechanism(s) are not well understood so that quantitative modelling is empirical.

Nevertheless, the observation that under some conditions pre-heat train exchangers do not foul indicates that fouling could be mitigated by exchanger and network design. Papers have appeared illustrating the application of the threshold modelling approach to exchanger design (*e.g*. Butterworth, 2002), preheat train analysis (*e.g*. Panchal and Huang-Fu, 2000), network design and retrofit (Wilson *et al*., 2002; Yeap *et al*., 2004, 2005). The latter workers have also considered the impact of fouling on pressure drop and hydraulic performance, using simple models in the absence of reliable data for validation.

Current status

Threshold curve investigations for crude oil fouling are now being obtained from pilot plant testing (*e.g*. by HTRI) and exchanger monitoring (*e.g*. by Total). Figure 4 shows the fouling curves obtained from plant monitoring can be strarkly different from well-defined pilot plant testing, where local conditions are controlled (and measured) over time and shell side flow mal-distribution and fouling are absent.

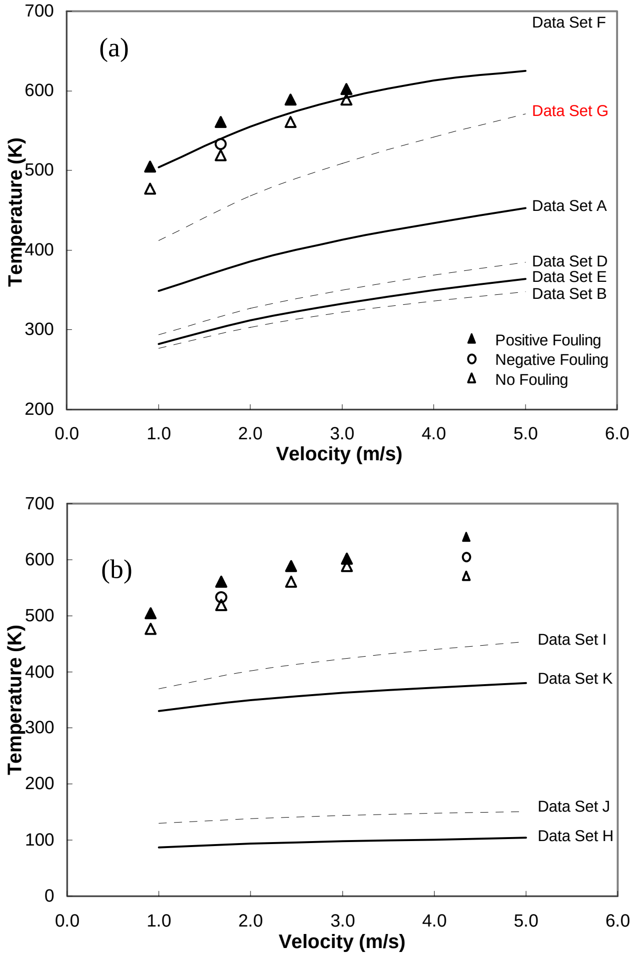


Figure 4 Threshold loci obtained from (a) pilot plant testing and (b) refinery monitoring, plotted for a standard tube size, by Yeap (2003). Symbols show Knudsen *et al.*'s data; set G is that of Srinivasan and Watkinson (2005).

The threshold loci at ~ 100 K in Figure 4(b), are clearly not physically realisable as these lie below the temperature of the crude feed. These were obtained from regression of refinery data sets and indicate that the threshold fouling model does not described the processes active in these cases. Pilot plant testing tends to yield larger activation energies, *E*. Asomaning *et al.* (2000) highlighted this aspect and the appropriate source of threshold model needs to be considered: refinery retrofits are likely to be based on analysis of operational data, but should new designs be based on lab testing? It would be prudent to include the results of monitoring existing exchangers operating on the same or similar crude slate. Polley *et al.* (2005a) describe a mathematical refinement for exchanger data reconciliation to give more reliable estimates of model parameters, but the need to identify and quantify shell-side fouling remains.

EXCHANGER OPERATION

The availability of a model for fouling rates allows designers and operators to use quantitative criteria to select appropriate operating conditions for exchangers subject to fouling – either to avoid significant fouling or reduce it to manageable levels. What constitutes a 'manageable level' will depend on the individual exchanger, as some installations will be limited by pressure drop considerations and some by thermal limitations. The relationship between thermal and hydraulic performance will depend on the design, and particularly on the sensitivity of the effectiveness, *e*, to changes in number of transfer units, *NTU*. This is illustrated in Figure 5, which shows the effect of fouling on the individual exchangers in the network described by Panchal and Huang-Fu (2000). The loci were calculated using the impact of a thin layer of deposit on pressure drop and on *NTU* via the overall heat transfer coefficient.

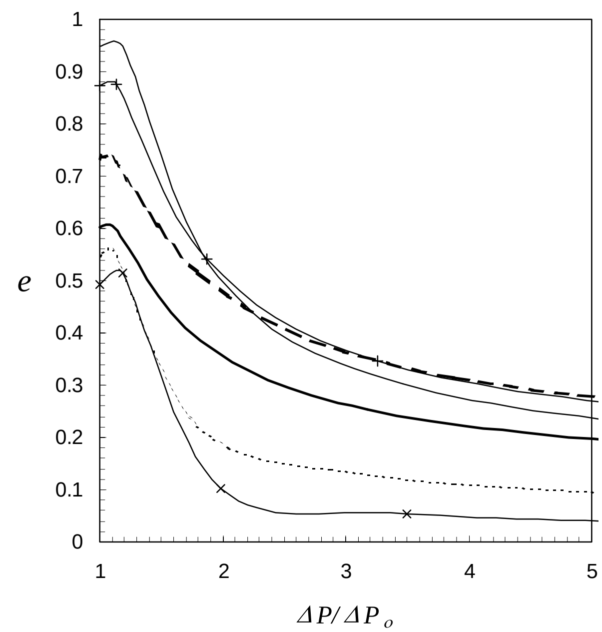


Figure 5 Thermo-hydraulic effect of fouling on exchangers in the network described by Panchal and Huang-Fu (2000). Each locus tracks the effect of a thin fouling layer in an individual heat exchanger design, expressed in terms of heat exchanger effectiveness, *e*, and the ratio of (fouled)/(cleaned) pressure drop exchangers for the constant mass flow-rate scenario. After Yeap (2003).

The Figure demonstrates how different exchanger designs respond to fouling: losses in heat transfer performance range from 50% to 90% over the range of film thicknesses considered. The initial rise in *e* is due to the fouling deposit being rougher than the clean tube. Most of the loss in heat transfer effectiveness has occurred by the time that the pressure drop has doubled, although this varies between exchangers: the Figure shows that the response of an exchanger to fouling (represented by the change in pressure drop) is determined by its design effectiveness: some of the units will not exhibit appreciable changes in thermal behaviour in the initial stages of fouling despite large changes in hydraulic performance. This also impacts on data reconciliation of plant data and highlights the need to collect pressure drop data if possible. Manageable levels will therefore need to be determined by reference to the network in which a unit operates.

Oversized exchangers will over-perform when clean and temperature control is frequently effected by bypassing one of the process streams. Knowledge of the crude fouling rate behaviour finally allows operators to select appropriate bypassing strategies – ideally with a non-fouling stream – as discussed by Bott (1990). Rodriguez (2005) used numerical simulation and optimization of a crude preheat train to demonstrate the effectiveness of this mitigation approach.

DESIGN

Network Design

Crude oil preheat trains are examples of heat exchanger networks, which are currently normally designed on the basis on thermodynamics and capital/operating cost optimization; neither pinch techniques or topological optimization, the two main approaches, include reference to fouling criteria. Wilson *et al*. (2002) demonstrated how the fouling threshold locus can be combined with the temperature field plot construction to give a graphical tool for including fouling propensity in the selection of stream matches in networks once the heat recovery targets had been established. Yeap *et al*. (2004) modified this construction to include hydraulic impacts of fouling, and Polley *et al*. (2005b) have recently shown how the fouling threshold can also set a practical limit in the amount of heat recovery in a network, termed the 'fouling limit'. Figure 6 shows an example of the thermal construction.

These graphical tools have been applied to green field design and network retrofit, and allow (*i*) the network designer to select appropriate stream matches; (*ii*) to determine where pressure drop (and flow velocity) should be used to mitigate fouling; (*iii*) to identify matches where more expensive mitigation technologies such as tube inserts will be required in order to achieve enhanced heat recovery.

A numerical optimization approach to network design and retrofit employing these approaches in a simulated annealing optimization environment – albeit without hydraulic considerations – has recently been developed by Rodriguez and Smith (see Rodriguez, 2005).

The limitations of using threshold fouling models in design are currently the variability and uncertainty in the models, the lack of reliable data on tube and shell-side pressure drop and shell-side fouling. The above discussion relates wholly to tube-side crude fouling whereas many preheat trains are subject to some shell-side fouling – but this may just be due to bad exchanger design, as stated some 40 years ago by Gilmour (1965)!

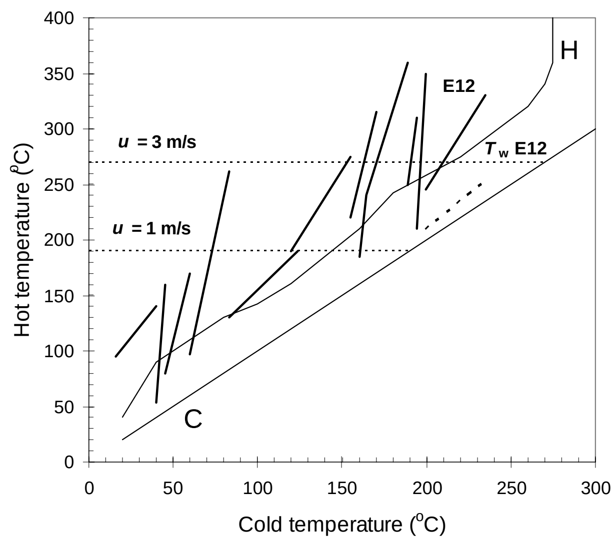


Figure 6 Temperature field plot construction for a preheat train network. C and H are composite curves for the cold and hot streams, respectively; dotted lines – fouling threshold loci for given crude and exchanger tube dimensions; solid lines – loci for individual exchanger match based on approach temperatures; dashed line – wall temperature for E12, which will foul if mean velocity u < 2.5 m/s.

Exchanger Design

The fouling threshold concept provides quantitative estimates for fouling rates (including zero rates) which can be employed to guide exchanger design, notably the selection of velocities, temperature matches and thermal contact patterns, and also inform the designer of heat recovery limitations (the 'fouling limit') and need to use more elaborate mitigation techniques, e.g. fluidized bed devices, tube inserts, to raise these. This information also provides a means of developing unified approach to fouling mitigation by allowing different options to be compared. Currently available mitigation options include:

(a) Increased tube-side velocity;

(b) Switching the crude from the tube side to shell side, which benefits from the difference between inner and outer surface areas on standard exchanger tubes – the lower heat flux on the outer surface reduces the surface temperature noticeably.

(c) Use of inserts (*e.g*. HiTran, Spirelf, Turbotal), offering enhanced heat transfer and fouling resilience but with increased pressure drop for a similar flow rate. Data presented by Bories and Patreux (2003) suggest that Turbotal units limit tubeside fouling resistance to values around 0.004 m^2K/W so if this figure is exceeded historically or predicted by the model over the expected run time, these units should be considered;

(d) Use of alternative baffle or tube type;

(e) Accepting fouling but cleaning regularly. Few plants actually monitor fouling and use this information to optimize their cleaning actions, despite the cost savings demonstrated by Smaïli *et al*. (2001) and Rodriguez (2005).

(f) Chemical additives.

These options are currently offered independently of the others, and are often offered as a panacea for all situations. Alternative baffle types are frequently proposed on the basis of user experience and anecdotal evidence, and rarely compare like with like. For example, where an existing unit suffers tubeside fouling, it may be proposed to switch the crude to the shell side and use new technology, whereas the existing shell design may be suitable for the duty. The engineer should check on the suitability of the existing shell design and examine how plugging some of the tubes would effect performance (see Gilmour, 1965). Similar arguments apply to use of tube inserts, which are often offered as a solution without appraisal of alternatives.

Being able to predict fouling rates opens up new approaches to design, as one no longer need to base design on assumed fouling factors. Bott (2001), Butterworth (2002) and Polley *et al*. (2002b) have described how threshold fouling can be included in the heat exchanger design methodology based on the parameter plot developed by Poddar and Polley (1996, 2000). Figure 7 shows an example.

For a given stream match, thermal duty, baffle configuration, number of passes and pressure drop guidelines, the parameter plot shows the combinations of length and number of tubes which can satisfy the required heat transfer and maximum pressure drop criteria.

The fouling models (Equations [1-4]) are used to determine if the fouling threshold is exceeded at the hottest point in the exchanger with the geometry displayed by the thermal duty line. Such designs fall in the shaded region of the plot. Geometry that, operating under the stated design condition, should not foul is easily identified. For instance, the point marked X on Figure 7 shows the design that satisfies thermal and both pressure drop criteria, and also lies under the fouling region so is not expected to foul. This methodology has been implemented in the ESDU Express™ design software. As will be demonstrated in the case study reported below, this program also uses fouling models to consider operation over time, and to explore the sensitivity of each design to changes in operating conditions. The approach again requires reliable fouling model parameters.

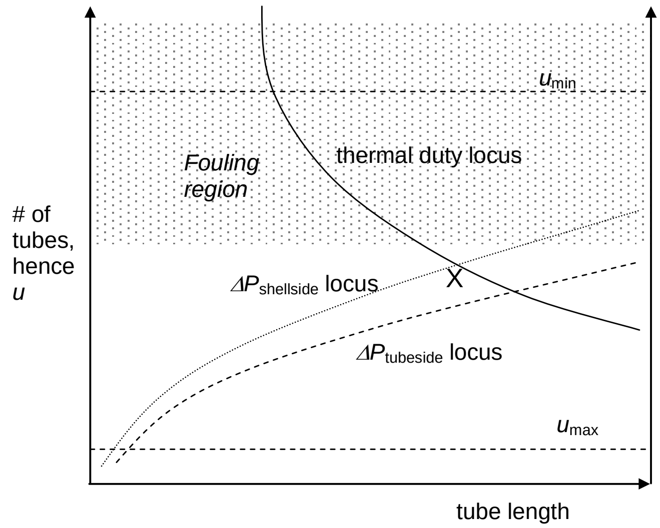


Figure 7 Schematic of parameter plot construction including fouling region predicted by threshold modeling.

Shell-side fouling

The tubes used in shell-and-tube exchangers employed in pre-heat trains are usually of low gauge (*i.e*. thick walled). The result is that the inside tube surface is usually more than 20% less than the outside surface area. This has a significant effect upon the wall temperature to which the crude oil is exposed. For instance, for the situation in which the hot and cold stream heat transfer coefficients are identical and a 12 gauge tube is used (o.d./i.d. ratio = 1.28), ~ 56% of the overall temperature driving force will be located on the tube-side. If the local hot and crude stream temperatures were 300ºC and 200ºC, respectively, the crude wall temperature would be 256ºC for tube-side flow and 244ºC if for shell-side, with a marked effect on fouling rates when the activation energies reported in threshold studies ranging from 30 to 60 kJ/mol.

Unfortunately, the Ebert-Panchal model cannot be directly used for the modelling and prediction of fouling within exchanger shells. This is because it assumes that the suppression mechanism is controlled by wall friction, which cannot be estimated from shell-side pressure drop as this includes a significant contribution from form drag. One approach is to apply the heat and mass transfer analogy and thereby employ the shell-side heat transfer coefficient as a measure of the wall friction and shear stress. This approach has been used in assessing the use of a helical baffle with crude oil flowing on the shell-side of the exchanger in the following example. Experimental measurements of shell-side fouling rates are obviously needed for the development of a reliable methodology.

A RATIONAL APPROACH TO THE CONSIDERATION OF FOULING IN DESIGN: TWO CASE STUDIES

The emergence of threshold models has reinforced the message that the use of a fixed set of fouling factors for the design of shell-and-tube heat exchangers for crude pre-heat trains is no longer an acceptable practice. In some cases their use leads to designs that foul unnecessarily. In other situations they under predict fouling by a very large margin. The question that arises is: 'How is the void left by abandoning fixed fouling factors to be filled?' Some may suggest the use of heuristics (*e.g.* a minimum velocity). However, we propose that fouling models present the rational way forward. Consider the design of a heat exchanger to satisfy the duty described in Table 1. Fouling is described by the revised Ebert-Panchal model with parameters determined from analysis of data from an operational refinery using the technique reported by Polley *et al.* (2005a).

Table 1 First case study unit specification

		Tube-side (crude)	Shell-side (residue)
Flow rate [kg/s]		152	75.6
T_{inlet}	[ºC]	260	338
T_{outlet}	[ºC]	285	286
R_f	[m^{2}K/W]	Equation [2]	0.0006
C_p	[J/kg K]	2720	2720
ρ	[kg/m^3]	846	846
μ	[cP]	0.5	2.0
λ	[W/m K]	0.1	0.1

The first step is to consider the position of the fouling threshold for this stream match. This is plotted in Figure 8, which was generated this using ESDU's Express™ software, executed in the 'design' mode with the crude-side fouling factor set to zero.

The shaded region indicates geometries that would operate within the fouling region. Tube count is shown on the left hand axis and tube velocity on the right hand axis. The vertical line indicates tube length of 20 feet (6.1 m) that is used as standard in many refineries. The Figure shows that the 'clean' duty line cuts the length line at a tube count of 1600. The use of higher velocity will require the use of more than one shell in series. (Note: in order to keep the discussion within reasonable bounds we have fixed the number of tube passes. Manipulation of the number of passes is discussed in the second case study).

With 1600 tubes the tube velocity is 1.3 m/s (which is typical of many pre-heat train exchangers). This point is seen to lie well within the fouling region. Under constant inlet conditions, the fouling model predicts that the overall R_f would reach 0.011 m^2 K/W after 8000 h. We know that the unit will not achieve the specified performance and, like most refinery exchangers it will foul. The R_f values can be used to determine expected performance and this is plotted on Figure 9.

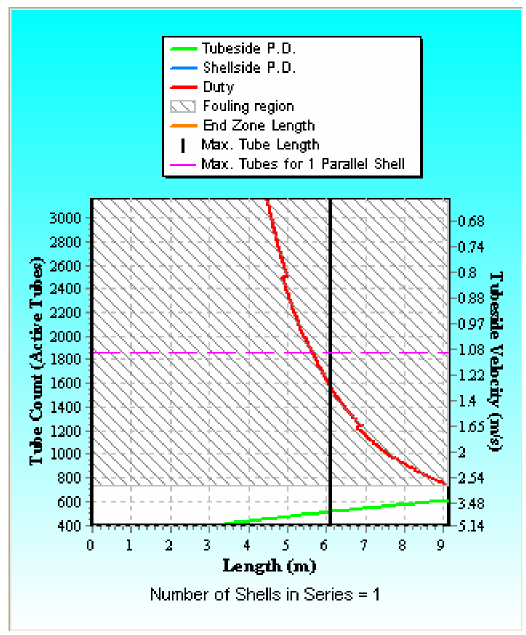


Figure 8 Parameter plot for case study problem

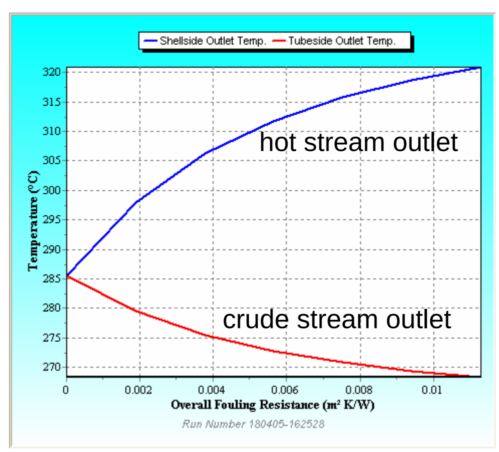


Figure 9 Thermal response of first design to fouling.

Such a rapid deterioration in performance is unlikely to acceptable. Options available to the designer include:

(i) Switching the crude oil from the tube-side to the shell-side and use a helical baffle;

(ii) Using tube inserts, *e.g*. Turbotal;

(iii) Increasing the number of shells in series.

I. Crude on shell-side, helical baffles

The parameter plot for the scenario with the crude stream on the shell side in Figure 10 shows two duty lines, for helix angles of 10^{o} and 17.5^{o}. In both cases the design is deep in the fouling region indicated by the hatching and the design duty cannot be achieved in a single shell (despite the crude side fouling resistance being set at zero).

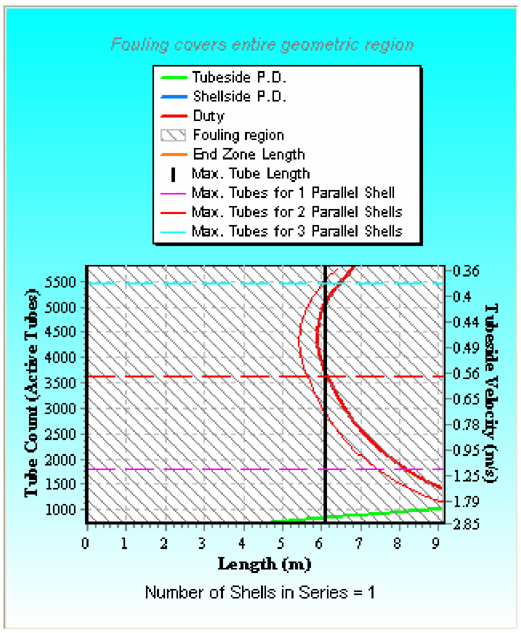


Figure 10 Parameter plots for case study with crude on shell-side and helical baffles.

II. Use of inserts

Bories and Patreaux (2003) presented operating data that suggest that Turbotal inserts control fouling at a fixed level, at $R_f \sim 0.004$ m^{2}K/W (based on outside area). Figure 9 indicates that with an overall fouling resistance of 0.0046 the single shell operating at a velocity of 1.3 m/s would achieve a steady crude outlet temperature of 274^{o}C.

III. Multiple shells in series

Assuming that this is unacceptable, but noting that it provides a guide to future direction of the design, we consider more than one shells in series. This provides the opportunity not only to provide more area but also to increase crude oil velocity (assuming that the 20 foot tube specification cannot be changed). The parameter plot for two shells in series for this scenario (Figure 11) indicates that the tube velocity would need to be in the region of 3 m/s in order to suppress fouling.

A range of alternative designs can be quickly generated and evaluated. Table 2 shows a series of candidates where tube count has been used as the primary variable, with a tube length of 6.1 m. Each design has the crude flowing through the tubes, with two shells-in-series, and uses segmental baffles. None use inserts. The Table gives predictions of fouling behaviour (these include estimates of crude side pressure drop as hydraulic behaviour must also be considered). Fouling has a significant impact on pressure drop, so comparisons of clean ΔP values for alternative designs are not meaningful.

Fouling influences ΔP in two ways: via flow constriction and surface roughness. In the absence of other information the constriction can be related to fouling resistance and an assumed λ_f value. Here, we have assumed that $\lambda_f = \lambda$(oil) and a typical bitumen roughness of 0.01 mm. The impact of roughness is clearly evident from comparing the 'smooth' and 'rough, 0 h' (*i.e*. no change in i.d.) values.

Table 2 Comparison of different candidate designs

Tube Count	u	T_{outlet} crude	R_f overall	ΔP		
		0, 8000 h	8000 h	smooth	rough	
					0h	8000 h
	m/s	°C	m^{2}K/W	kPa		
1600	1.27	291, 271	0.018	52	68	150
1200	1.69	290, 274	0.012	86	120	200
1000	2.03	289, 273	0.008	120	170	235
750	2.70	288, 288	0.0006	203	305	305

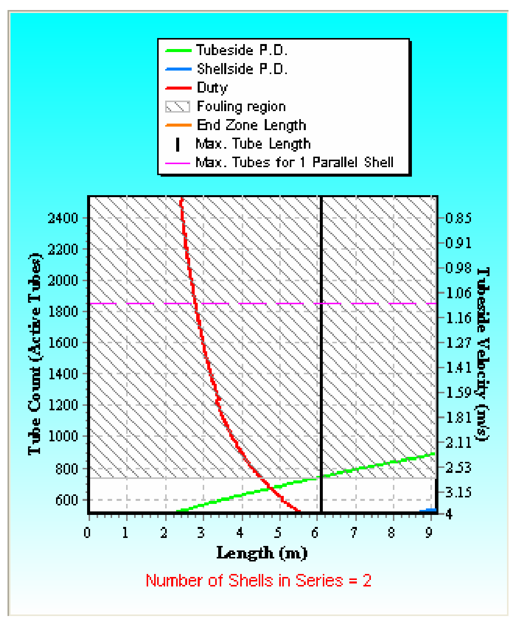


Figure 11 Parameter plot for two shells in series (crude on tube side, segmental baffles, no inserts)

We make the following observations:

(*a*) Increasing tube velocity from 1.3 to 2.0 m/s has little effect on the heat recovery level. The higher the velocity, the smaller the exchanger and the lower the capital cost. However, this cost benefit is paid for in pressure drop.

(*b*) It is possible to obtain a design that is free from fouling at the specified operating condition. The clean pressure drop for this unit is lower than the final fouled pressure drop for a unit operating at a lower tube velocity. However, the presence of surface roughness results in an immediate increase (of around 50%) in ΔP.

The sensitivity of ΔP in the high velocity design to early deposition (roughness) indicates that the non-fouling design is deficient. The fouling rate is very sensitive to velocity and the proposed operating velocity is close to the threshold. Given that pre-heat train throughput is likely to fluctuate, small reductions in flow can therefore be expected to result in deposition.

Summary

If the non-fouling design is deemed ‘poor’ how does the designer proceed? The *more prudent* option would appear to be a design operating in the traditional velocity region (1.2 to 1.8 m/s). The *better* option would be to accept the larger design (1600 tubes), and to fit it with Turbotal inserts. If the limiting R_f behaviour is correct, the threshold model predicts that the crude outlet temperature would reach the asymptotic level of 282°C after 1600 hours operation, (although the inserts are likely to extend this initial period). We therefore favour this option for the final design.

Table 3 Second case study unit specification

	Tube-side (crude)	Shell-side (residue)
Flow rate [kg/s]	152	75.6
T_{inlet} [ºC]	189	286
T_{outlet} [ºC]	210	230
R_f [m^{2}K/W]	Equation [2]	0.0006
C_p [J/kg K]	2500	2620
ρ [kg/m^3]	865	840
μ [cP]	0.7	10
λ [W/m K]	0.1	0.1

Second Case Study

The results of the design process are problem specific. Let us now consider a unit positioned upstream of the first case study, which was located at the hottest part of the train. The crude is again matched against the residue stream but with different physical properties, as summarised in Table 3. The initial design uses four tube passes with helical baffles on the shell side (the choice of helical baffles is dictated by the large viscosity changes on the shell-side). The parameter plot in shown in Figure 12.

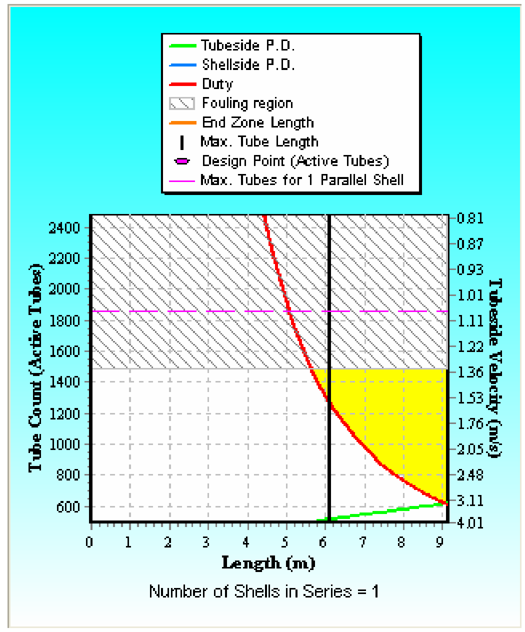


Figure 12 Parameter plot for second case study basic design (4 tube passes)

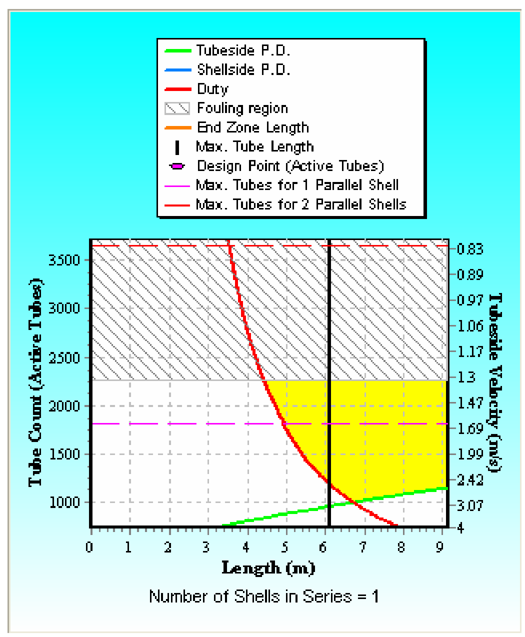


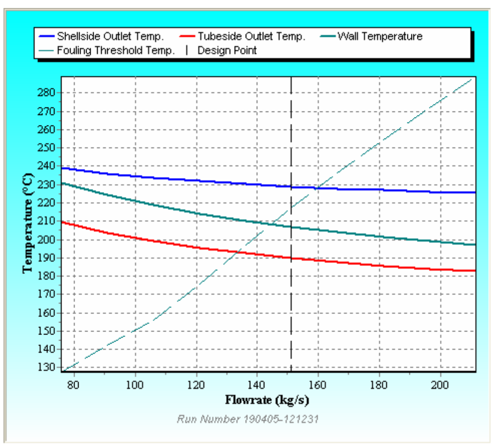
Figure 13 Parameter plot for 6 tube-pass design

The fouling threshold is predicted to occur at a tube-side velocity of around 1.4 m/s, while the intersection of the duty line with the length line occurs at *c*. 1.55 m/s. We can therefore find a non-fouling design that uses a single shell. If the standard length of 6.1 m is required, the use of a velocity greater than 1.55 m/s would require the use of either two shells-in-series or an increase in the number of tube passes from four to six. The parameter plot for a six-pass unit is shown in Figure 13 and optimal designs for each configuration are compared in Table 4.

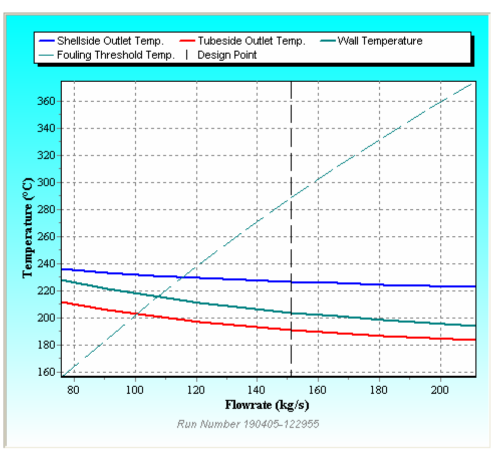
Table 4 Comparison of candidate designs, second case study

Design	Tube count	u m/s	T_{outlet} crude °C	ΔP clean kPa
4 pass	1280	1.55	189	39.6
6 pass	1500	2.0	191	91.5

Because of the fixed tube length, the higher velocity actually increases the size of the exchanger. The unit is oversized but the effect upon crude outlet temperature is not large. However, the effect on clean ΔP is marked.



(a)



(b)

Figure 14 Thermal response of (a) 4-pass and (b) 6-pass designs to variations in tube-side flow rate.

In evaluating the two designs we should also consider the response to deviations away from the design conditions. The effect of changes in tube-side flow rate upon each design is shown in Figure 14. The plots show stream T_{outlet}, the (clean) wall temperature at the hottest point in the exchanger and the effect of flow rate on the fouling threshold temperature. If T_s lies below the threshold temperature the unit will not foul. At the point where the T_s and threshold lines cross, fouling is initiated at the hot point.

Figure 14(a) shows that whilst the unit operates above the fouling threshold at the design throughput (indicated by the vertical dotted line), a flow reduction of just 5% (7 kg/s) would initiate fouling. The 6-pass unit, with higher velocity, has the advantage of operating further from the fouling threshold. Figure 14(b) shows that this unit is more robust; the flow would need to be reduced by nearly one third before fouling is initiated. Despite being larger, more expensive and requiring a larger ΔP, this unit is selected on the basis of *resilience*.

The aim of these examples is to demonstrate how Ebert & Panchal's concept has opened up the way to systematic approaches for considering fouling in network and exchanger operation and design.

THE FUTURE OF THRESHOLD MODELLING

Interest in and acceptance of the threshold modelling approach is expected to increase once examples of successful implementation of the methodology are publicised. The issues of parameter uncertainty, shell-side fouling and reliable pressure drop prediction will require attention and dedicated testing, possibly using side-stream monitoring to compare with exchanger data reconciliation. The need for more data sets with well characterized fluid properties and fouling layer properties is paramount. Several of the techniques presented here are already available within software packages, but input data – particularly for shell-side fouling – are still needed.

The threshold modelling approach should not be viewed as the cure for all fouling ills: however, as Gilmour pointed out in 1965, a large amount of these can be attributed directly at poor design and operation of shell-and-tube units.

This paper has focussed on fouling arising in petroleum crude preheat trains, which is anticipated to become more important as high crude prices last. A concerted period of high crude oil prices is expected to favour alternative sources, which will create a need for testing of crudes derived from Canadian tar sands, Brazilian oil shales and - possibly universally - coal liquefaction. However, the approach is not restricted to pre-heat trains. Other refinery applications will benefit from the development of the approach.

What has been achieved with this type of fouling model may be extendable to models describing other types of fouling.

This paper has deliberately not given much consideration to variation in fouling behaviour between crudes and the use of anti-fouling chemicals. This is an area where much of the outstanding work needs to be done.

CONCLUSIONS

The work of Ebert & Panchal, building to a limited extent on the pioneering work of Gilmour, has provided a significant impetus to the development of procedures for the mitigation of crude oil preheat train fouling through design. Both the concept of the fouling threshold and the model they developed for the prediction of fouling rates have found application.

In pre-heat train design the threshold concept can be used to identify the maximum heat recovery level at which fouling can be eliminated through good exchanger design. Operating beyond this level requires either the use of tube inserts or the instigation of regular cleaning. The fouling model can be used to indicate which strategy should be adopted. Having identified the heat recovery level, the fouling threshold can then be used to develop 'field plots' which guide the engineer in the development of an efficient pre-heat train structure.

In exchanger design the threshold concept can be used to identify geometries that are unlikely to foul. It can also be used to determine the sensitivity of the design to changes in operating conditions.

It is not always advisable to operate below the fouling threshold. Situations in which this is the case can be identified. In these circumstances the fouling model is a useful tool for identifying better shell-and-tube designs from the wide range available.

There is much left to do. Much that needs to be confirmed. However, the way to a rational way of identifying and quantifying fouling mitigation strategies has been opened.

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NOMENCLATURE

A_i	parameter in fouling model, m^2K/J
B_{IV}	parameter in Equation [4]
C_f	Fanning friction factor
C_i	parameter in fouling model, units vary
C_p	specific heat capacity, J/kg K
e	heat exchanger effectiveness, -
E_i	fouling model activation energy, J/mol
g_d	foulant generation rate, kg/m^2s
m_d	deposition rate, m^2K/J
m_r	suppression rate, m^2K/J
ΔP	pressure drop, Pa
Pr	Prandtl number, -
R	gas constant, J/mol K
Re	Reynolds number, -
R_f	fouling resistance, m^2K/W
T	temperature, K
t	time, s
T_f	film temperature, K
T_s	surface temperature, K
u	mean velocity, m/s
β	index in Equation [1], -
δ	fouling layer thickness, m
ε_f	fouling layer porosity
λ	thermal conductivity
μ	viscosity, Pa s
ρ	bulk density, kg/m^3
ρ_T	deposit density, kg/m^3
τ_w	wall shear stress, Pa

Subscript

f	foulant

REFERENCES

Asomaning, S., Panchal, C.B. and Liao, C.F., 2000, Correlating field and laboratory data for crude oil fouling, *Heat Transfer Eng*., Vol. 21(2), 17-23.

Bories, M. and Patreaux, T., 2003, Preheat train crude distillation fouling propensity evaluation by Ebert and Panchal model, *Proc*. Heat Exchanger Fouling & Cleaning: Fundamentals & Applications, Santa Fe, July 2003.

Bott, T.R., 1990, *Fouling Notebook*, publ. IChemE, Rugby.

Bott, T.R., 2001, To foul or not to foul?, *Chem. Eng. Prog.*, November, 30-37.

Butterworth, D., 2002, Design of shell-and-tube heat exchangers when the fouling depends on local temperature and velocity, *Appl. Thermal Eng.*, Vol. 22(7), 789-801.

Crittenden, B.D., Kolaczkowski, S.T. and Hout, S.A., 1987, Modelling hydrocarbon fouling, *Chem. Eng. Res. Des.*, Vol. 65, p171-179.

Ebert, W. and Panchal, C.B., 1997, Analysis of Exxon crude-oil slip stream coking data, in *Fouling Mitigation of Industrial Heat Exchange Equipment*, Panchal, C.B., Bott, T.R., Somerscales, E.F.C. and Toyama, S.. (eds.), Begell House, NY, 451-460.

Epstein, N., 1994, A model of the initial chemical reaction fouling rate for flow within a heated tube, and its verification, *Proc*. 10th Int. Heat Trans. Conf., Brighton, IChemE, Vol. 4, 225-229.

ESDU (Engineering Sciences Data Unit), 2000, Heat exchanger fouling in the preheat train of crude oil distillation levels, *Data Item 0016*, ESDU Intl., London, UK.

Fryer, P.J., Paterson, W.R. and Slater, 1987, Robustness of fouling heat-exchanger networks and its relation to resilience, *Chem. Eng. Res. Des*., Vol. 65(3), 267-271.

Gilmour, C.H., 1965, No fooling – no fouling, *Chem. Eng. Prog*., Vol. 61(7), 49-54.

Kern, D.W. and Seaton, R.E., 1959, A theoretical analysis of thermal surface fouling, *Brit. Chem. Eng*., Vol. 4(5), 258-262.

Knudsen, J.G., Lin, D. and Ebert, W.A., 1999, The determination of the threshold fouling curve for a crude oil, in: Bott, T.R., Melo, L.F., Panchal, C.B. and Somerscales, E.F.C., (eds.) *Understanding Heat Exchanger Fouling and its Mitigation*, Begell House, NY, 265-272.

Kotjabasakis, E. and Linnhoff, B., 1986, Sensitivity tables for the design of flexible processes. I. How much contingency in heat exchanger networks is cost-effective?, *Chem. Eng. Res. Des*., Vol. 64, 197.

Mansoori, G.A., 2002, Physicochemical basis of fouling prediction and prevention in the process industry, *J. Chin. Inst. Chem. Engrs*., Vol. 33(1), 25-31.

Panchal, C.B. and Huang-Fu, E.P., 2000, Effects of mitigating fouling on the energy efficiency of crude-oil distillation, *Heat Transfer Eng*., Vol. 21, 3-9.

Panchal, C.B., Kuru, W.C., Liao, C.F., Ebert, W.A. and Palen, J.W., 1999, Threshold conditions for crude oil fouling, in: Bott, T.R., Melo, L.F., Panchal, C.B. and Somerscales, E.F.C., (eds.) *Understanding Heat Exchanger Fouling and its Mitigation*, Begell House, NY, 273-279.

Paterson, W.R. and Fryer, P.J. 1988, A reaction engineering approach to the analysis of fouling, Chem. Eng. *Sci*., Vol. 43, 1714-1717.

Poddar, T.K. and Polley, G.T., 1996, Heat exchanger design through parameter plotting, *Chem. Eng. Res. Des*., Vol. 74A, 849-852.

Poddar, T.K. and Polley, G.T., 2000, Optimising the design of shell-and-tube heat exchangers, *Chem. Eng. Prog*., September 2000.

Polley, G.T., Wilson, D.I., Yeap, B.L. and Pugh, S.J. (2002a), Evaluation of laboratory crude oil fouling data for application to refinery pre-heat trains, *Applied Thermal Eng.*, Vol. 22, 777-788.

Polley, G.T., Wilson, D.I., Yeap, B.L. and Pugh, S.J. (2002b), Use of crude oil threshold data in heat exchanger design, *Applied Thermal Eng.*, Vol. 22, 763-776.

Polley, G.T., Wilson, D.I., Pugh, S.J. and Petitjean, E., 2005a, Extraction of crude oil fouling model parameters from plant exchanger monitoring, this meeting.

Polley, G.T., Wilson, D.I., Petitjean, E. and Derouin, C., 2005b, The fouling limit in crude oil pre-heat train design, *Hydrocarbon Proc*., May 2005.

Rodriguez, C.A., 2005, Fouling mitigation strategies for heat exchanger networks, PhD dissertation, University of Manchester.

Scarborough, C.E., Cherrington, D.C., Diener, R. and Golan, L.P., 1979, Coking of crude oil at high heat flux levels, *Chem. Eng. Proc*., Vol. 75, 41-46.

Smaïli, F, Vassiliadis, V.S. and Wilson, D.I, (2001) Mitigation of fouling in refinery heat exchanger networks by optimal management of cleaning, *Energy & Fuels*, Vol. 15(5), 1038-1056.

Srinivasan, M. and Watkinson, A.P., 2005, Fouling of some Canadian crude oils, *Heat Transfer Eng*., Vol. 26(1), 7-14.

Stachura, V.J., (ed.), 1998, *Standards of the Tubular Exchanger Manufacturers Association*, 7th edn., publ. TEMA, New York, NY.

Wilson, D.I. and Polley, G.T., 2001, Mitigation of refinery preheat train fouling by nested optimization, Advances in Refinery Fouling Mitigation Session #46, AIChE, Houston, 287-294.

Wilson, D.I., Polley, G.T. and Pugh, S.J., 2002, Mitigation of crude oil preheat train fouling by design, *Heat Transfer Eng.*, Vol. 23, 24-37.

Yeap, B.L., 2003, Designing heat exchanger networks to mitigate fouling, PhD Dissertation, University of Cambridge.

Yeap, B.L., Hewitt, G.F., Wilson, D.I. and Pugh, S.J., 2002, Simulating the fouling behaviour in shell-and-tube heat exchangers, in *Mitigation of heat exchanger fouling and its economic and environmental implications*, publ. Publico, Essen, 275-282.

Yeap, B.L., Wilson, D.I., Polley, G.T. and Pugh, S.J., 2004, Mitigation of crude oil refinery heat exchanger fouling through retrofits based on thermo-hydraulic fouling models, *Chem. Eng. Res. Des*., Vol. 82A, 53-71.

Yeap, B.L., Wilson, D.I., Polley, G.T. and Pugh, S.J., 2005, Retrofitting crude oil refinery heat exchanger networks to minimize fouling while maximizing heat recovery, *Heat Transfer Eng*., Vol. 26, 23-34.