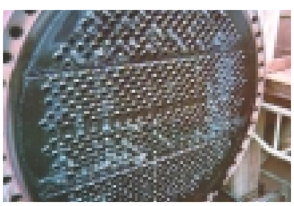

To Foul or Not to Foul That is the Question

T. Reg Bott,
Univ. of Birmingham

Here are some insights into the design, operation and research issues associated with heat exchanger fouling.

Fouling has been an impediment to efficient heat transfer since the advent of heat exchangers. Most heat exchangers are unique in terms of design, operating conditions and the fluids being processed. In addition, the heat exchanger typically represents a relatively small portion of the total capital investment for a facility. It is therefore not surprising that the causes and mechanisms of fouling processes have been neglected.

Nevertheless, the global cost of heat exchanger fouling is enormous, in terms of additional capital, as well as the costs of additional energy, mitigation, cleaning, increased maintenance and lost production. Cost data are difficult to obtain — often the true cost is hidden among other operating costs (*e.g.*, maintenance and steam costs) — but it is clear that there is a high price to be paid for heat exchanger fouling.

Current design practices attempt to account for the heat exchanger geometry, as well as the operating variables that are likely to affect deposit formation. During operation, the design criteria must be kept in mind to minimize deposit accumulation. Effective chemical and physical fouling-mitigation technologies are needed in many instances, and offline cleaning may also be necessary. Good fouling management also includes the use of continuous and reliable monitoring, either based on historical performance data or, preferably, real-time data through the use of a side-stream monitor. Such information could be valuable for the improvement of design procedures.

Six basic mechanisms responsible for deposit formation on heat-transfer surfaces are listed in Table 1. Most industrial fouling processes are likely to involve a combination of two or more of these mechanisms.

The effects of process variables

Flow velocity and temperature (or temperature difference) are probably the most significant variables that affect the fouling process.

Table 1. Fouling mechanisms and their effects at the heat-transfer surface.

Mechanism	Effects at the Heat-Transfer Surface
Particle Deposition	Accumulation of particles
Crystallization	Precipitation of dissolved salts (scale formation)
Chemical Reaction	Formation of insoluble products by chemical reactions
Corrosion	Accumulation of corrosion products
Biological Activity	Growth of living matter
Freezing	Solidification of the process fluid

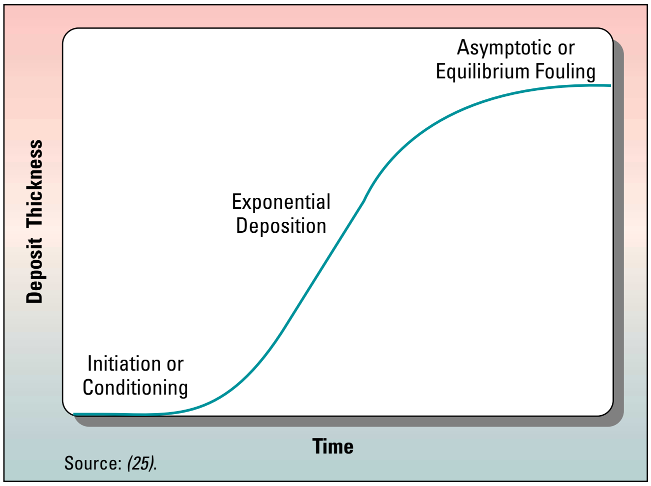

Figure 1. Idealized fouling curve.

Velocity. As velocity increases, the mass transfer of the fouling species increases, which provides more opportunity for deposition to occur on the heat-transfer surface. Simultaneously, however, the shear forces acting at the fluid/heat-transfer-surface interface increase, which aids deposit removal. The actual amount of fouling is a balance between these two opposing effects.

Figure 1 is an idealized representation of the fouling process. The final asymptotic level of the curve may be regarded as the equilibrium between the rate of deposition and the rate of removal. In many practical situations, the actual shape of the curve differs from the ideal due to the operating conditions under which the fouling accumulates. Figure 2 is a practical example involving biofouling; note the effect of velocity.

One theory of fouling *(1)* uses the asymptotic fouling curve shown in Figure 1, which may be represented by:

$$R_t = R_\infty(1 - e^{\beta t}) \quad (1)$$

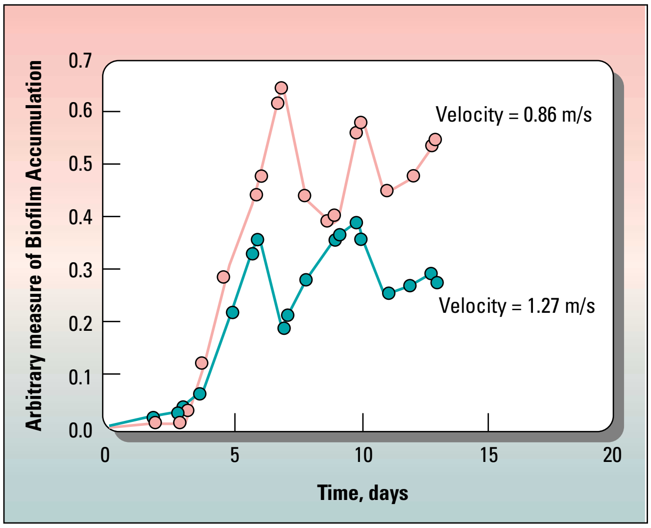

Figure 2. Growth curve of Pseudomonas fluorescens at two velocities.

Temperature. The prevailing temperature of a fluid passing through a heat exchanger can have a profound influence on the extent of fouling at heat-transfer surfaces. Table 2 indicates the temperature influence on the fouling mechanisms shown in Table 1. In general, the effect of different temperatures is to change the value of the asymptotic fouling level (other variables being constant). The presence of a deposit will affect the temperature distribution across the exchanger, which, in turn, changes the temperature at the point of deposition, thereby influencing the rate of temperature-dependent fouling.

Other factors. The rate of deposit formation is also influenced by the concentration and nature of the foulant (or the foulant precursor) and the process fluid in which they are carried — *e.g.*, the shape and size of particles, chemical composition, pH and availability of nutrients for biological growth. Additional factors that influence the fouling pro-

Table 2. The influence of temperature on fouling mechanisms.

Mechanism	Temperature Dependence
Particle Deposition	Little effect except as it affects the physical conditions
Crystallization	Solubility
Chemical Reaction	Rate of reaction
Corrosion	Rate of corrosion
Biological Activity	Metabolic activity
Freezing	Solidification

cess include the conceptual design and the geometry of the heat exchanger, and the material of construction and its surface properties.

Heat exchanger design with fouling in mind

Mitigation of heat exchanger fouling begins with design. It is fundamental that some prior knowledge of the potential fouling problem is available, so that appropriate initial design decisions may be made. Of importance also is the proposed geometry of the exchanger, since this can have a profound influence on fouling propensity.

The choice of heat exchanger will, as with any capital item, be constrained by the initial cost and the budget available for the project, but this cost has to be balanced against the associated costs of maintenance and cleaning. The simplest possible design to accommodate the required heat-transfer duty and operating conditions is often the best (and most conservative) approach, since this will facilitate cleaning and maintenance. Table 3 summarizes cleaning considerations for various types of heat exchangers *(2)*. Although these comments were made about ten years ago, they remain applicable today.

Shell-and-tube exchangers remain a common design for many heat-transfer duties even though there is limited geometric flexibility within the basic concept. It is therefore useful to examine the opportunities offered by these exchangers in operations that involve potential fouling problems.

The principal disadvantage of shell-and-tube heat exchangers with respect to fouling lies on the shellside. If any fouling is anticipated there, it is essential that the tube bundle be removable and the tubes arranged on a square pitch to facilitate cleaning. Baffles are included to give some support to the tubes, but principally to redirect the fluid across the tubes. The flow pattern developed on the shellside can leave stagnant areas where deposition can occur. Regions of recirculation are also possible, which can result in extended residence times, with an opportunity for chemical reactions to take place, and hot or cold spots that may influence the incidence of fouling. Careful conceptual design of the shellside may reduce or even eliminate fouling

Nomenclature

E = activation energy, J/kg
n = power on velocity
R = universal gas constant = 8.314 J/mok•K
Re = Reynolds number
R_f = fouling resistance, m²•K/W
R_t = fouling resistance at time t, m²•K/W
R_∞ = asympstotic fouling resistance, m²•K/W
t = time, s
T_f = film temperature, K
v = velocity, m/s
α, β, γ = undetermined constants
ϕ_D, ϕ_R = rate of deposition and removal respectively, kg/ m²•s
τ = wall shear stress, N/ m²

Table 3. Some considerations for the choice of heat exchanger design.

Exchanger Type	Materials of Construction	Cleaning	Comments
Shell-and-Tube	Most materials	Tubes relatively easy to clean, shell more difficult	Widely used
Gasketted Plate	Stainless steel (usually)	Easy to clean	Compact
Double Pipe	Commonly in carbon steel	Inner tube relatively easy, annular space more difficult or impossible (if welded)	Only useful for small heat-transfer areas
Immersed Coils	Most materials	Inside tubes impossible except by chemicals, outside of tubes possible but may be difficult	Limited application
Spiral	Most materials	Easy access to whole channel length	Compact; useful for slurries and fouling conditions
Graphite Block	Graphite	Impossible to clean mechanically, chemical cleaning possible	Useful for corrosive conditions
Scraped-Surface	Most materials	Self-cleaning generally	Incorporates moving parts
Plate-Fin	Aluminum, stainless steel, titanium	Only chemical cleaning possible	Highly compact
Air-Cooled	Aluminum fins on carbon steel tubes common, other combinations possible	Inside tubes relatively easy, finned surface more difficult	Large plot area required

Source: *(2)*.

— for example, through the use of helical baffles, rod baffles or twisted tubes.

Improvements on the tubeside may be made by using vibrating or fixed inserts to promote turbulence and to enhance heat transfer, which in turn may also reduce the incidence of fouling.

Traditional design method

The traditional method of making an allowance for fouling in the design of heat exchangers is to assign a value to the anticipated heat-transfer resistance, which is often referred to as the "fouling factor." Its value may be obtained from Tubular Exchanger Manufacturers Association (TEMA) standards *(3)*, from published literature, or from "in-house" experience.

This technique, however, is increasingly being questioned. It is simplistic and substitutes a static condition for what is a dynamic one. The exchanger does not suddenly reach the allowed fouling resistance as soon as it goes onstream. It will initially overperform, which has implications for control. The information on which the fouling heat-transfer resistance is based is often vague and may not apply strictly to the heat exchanger being designed. The fluids to be processed may be ostensibly the same as those from which the fouling data were obtained, but there may be important minor differences that result in a change in fouling propensity. The operating velocity and temperature in the proposed heat exchanger and its geometry may also be different. The results of using a fouling resistance out of context can be serious, in terms of poor performance and substantial additional costs to rectify the error in judgement *(2)*.

Fouling models based on laboratory experiments may also suffer from similar limitations. Nevertheless despite these rather adverse criticisms, the data may provide qualitative guidance on the likely severity of the fouling problem in a particular application.

Current design thinking

Current design methods aim to reduce the margin for expensive errors associated with fouling by using an iterative approach to evaluating the effects of variables on the fouling propensity. The techniques have generally been developed for shell-and-tube heat exchangers, but they could possibly be adapted for other types of heat exchangers.

The usual design constraints are the maximum pressure drop on both sides and the thermal requirements of the exchanger. Because of the importance of velocity on the fouling process, low-velocity constraints must also be considered. The complexity of shellside flow patterns makes it difficult to specify velocity constraints, but tubeside minimum and maximum velocities may be defined with some accuracy. The maximum allowable velocity is related to the maximum allowable pressure drop. The minimum velocity could be defined as the velocity of the threshold fouling rate.

Petroleum (reaction) fouling can be described by *(4):*

$$dR_f/dt = \alpha Re^{\beta}\exp(-E/RT_f) - \gamma\tau \qquad (2)$$

T_f is the mean film temperature where the reactions leading to the fouling are assumed to occur. Wall shear stress (τ) is a function of velocity. Table 4 summarizes the differences between Equations 1 and 2 *(4)*.

Figure 3 defines conditions for "fouling" and "no fouling" in terms of film temperature and wall shear stress *(4)*. It is possible to replace wall shear stress with velocity so that the minimum velocity to prevent fouling for different film tem-

Table 4. Comparison of Equations 1 and 2.

Application	Equation 1	Equation 2
Intended Prediction	Asymptotic fouling resistance	Film temperature at which fouling will occur
Rates of Deposition and Removal	Rate of removal proportional to fouling thickness	Rate of deposition and removal independent of fouling thickness.
Removal	From thermal boundary layer by transport mechanisms	From the surface by a detachment process
Foulant Formation	Not considered	Included

Source: *(4)*.

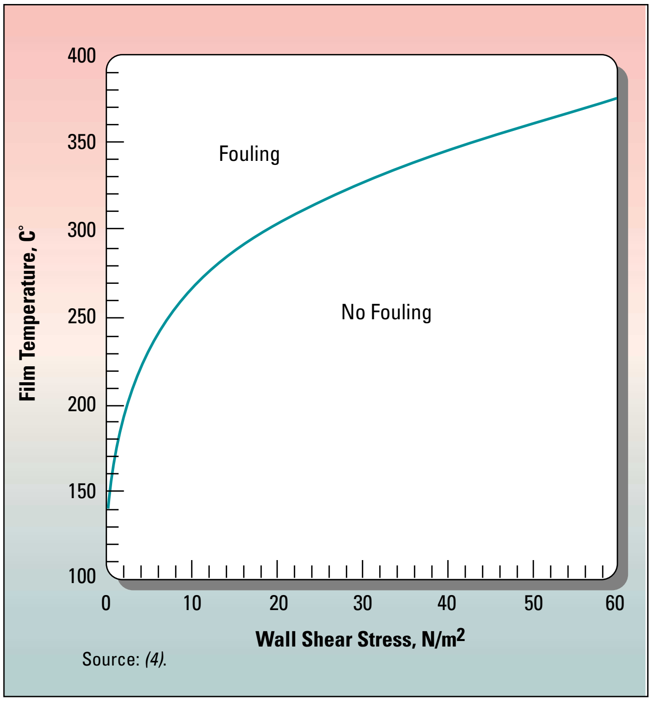

Figure 3. Threshold film temperature as a function of wall shear.

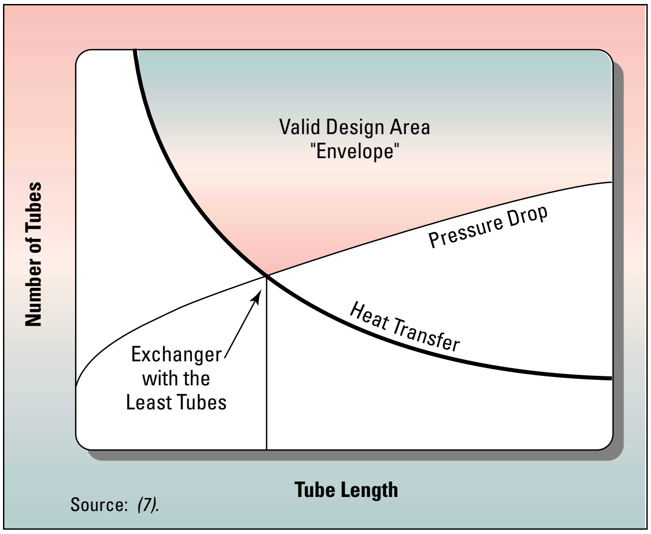

Figure 4. Envelope curve for a clean exchanger.

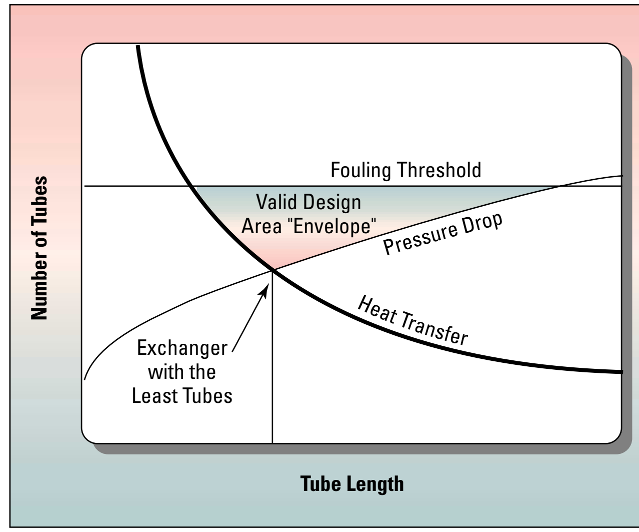

Figure 5. Envelope curve with fouling in mind.

peratures could be obtained. Laboratory and field fouling data on crude oils have been correlated with Equation 2 *(5, 6).*

The "envelope method" is a simplified design method for shell-and-tube heat exchangers that takes into account the problem of fouling *(7).* The aim is to design an exchanger that achieves the required heat duty within the constraints of the stream pressure drop (and any other constraints that may be required). For a given number of tubes and tube passes, the tubeside velocity that will fully exploit the allowable pressure drop is calculated. A set of points relating the allowable pressure drop to the number and length of tubes and another set of points for the desired heat transfer are also calculated, as shown in Figure 4 *(7).* All exchangers in the shaded area will satisfy the criteria and are therefore valid designs.

The fouling resistance (R_f) can be related to velocity by *(7):*

$$R_f \propto 1/v^n \tag{3}$$

The problems, of course, are assigning values to *n* and introducing a constant to make the proportionality into an equation. These depend on the nature of the fouling problem, and *n* may vary between 0.2 and 2 *(7).*

A similar graphical technique originally developed to provide guidance on allowable pressure drop and geometry can be extended to allow for fouling *(8).* The method takes into account the effects of velocity and wall temperature on design.

It is possible to relate fouling to velocity and to the tube count at which fouling will start. This is displayed as a horizontal line on Figure 5. All designs above this fouling threshold line are not viable. Heat exchanger designs that take into account the fouling threshold, for a given set of thermal and pressure drop constraints, must have tube counts below the threshold line.

If crude oil is being processed, it is usually passed through the tubes, and an increase in tube count results in a decrease in velocity; geometries above this line will foul. To reduce the incidence of fouling by bringing the design into the valid design area, the designer can change the baffle cut (and spacing) on the shellside and the number of passes on the tubeside to change the position of the threshold line.

Fouling in crude oil preheaters is discussed in detail in *(9),* which provides a basis for making design decisions in order to reduce the detrimental effects of fouling and to minimize the associated costs throughout the life of the exchanger.

Neural networks, using only input and output data, allow for the prediction of outcomes of hypothetical data without a need to understand the relationships that exist in the heat exchanger. Although the methodology is very useful for scheduling operations, it is also possible that neural networks could be used for design. The use of neural networks in petroleum refinery operations is explored in *(10).*

Operation

Clearly, if a heat exchanger has been designed to operate under certain conditions of velocity and temperature, it is imperative that these conditions be maintained during operation. If the final design allows for the accumulation of deposits, then initially the exchanger will overperform. Depending on the duty of the exchanger, one may be tempted to use a bypass so that the mixed exit temperature from the heat exchanger system is the desired value. An alternative, if the flowrate of the stream is not critical (*e.g.*, cooling water), is to reduce this variable. Both these alternatives effectively reduce the stream velocity through the exchanger, with the potential to accelerate the fouling process.

For a heat exchanger that has become fouled, increasing the velocity directly or reducing the flow through the bypass may restore some of the heat-transfer capacity. In most instances the deposit will be difficult or impossible to remove by simply increasing velocity. An alternative is to include a pump-around system so that the design velocity may be maintained.

The golden rule is to try to operate heat exchangers as near to the design conditions as possible, particularly if the design procedure has attempted to minimize the potential fouling.

Online cleaning and fouling control

Even if a heat exchanger has been designed to minimize the incidence of fouling, for one reason or another there may be a tendency to foul. It is prudent under these circumstances to consider some method of fouling control.

Common practice for the control of fouling is to use chemical additives. Different additives reduce the fouling problem by chemical or chemico-physical effects. Proprietary formulations are usually blends of chemicals with different functions. Dosing may be continuous or intermittent, depending on the particular problem and the effectiveness of the additive. There is considerable potential for minimizing costs by optimizing dose and application frequency. In most cases, additives are considered contaminants, and high levels may not be acceptable. Thus, in certain applications, it may be necessary to treat the stream prior to its next destination (*e.g.*, cooling water prior to discharge to the environment). Constant vigilance is required to account for changes in the fouling propensity that might occur during operation — for example, microbial activity depends on the source of the water and the season, and crude feedstocks in petroleum processing are subject to frequent changes such as with the inclusion of "rerun" material or changes in the origin of the crude.

The maintenance of operating conditions, especially in relation to flow velocity, is vital to the success of a chemical dosing program. The mass transfer of the additive toward a heat-transfer surface is very dependent on the level of turbulence in the bulk fluid, which in turn is a function of velocity. Figure 6 illustrates how, in the application of chlorine as a biocide in a simulated biofouling system, the effectiveness of biofilm removal is dependent on velocity *(11)*.

The foregoing discussion applies essentially to liquid systems. The use of antifoulants in gas streams, notably in fluegas systems, is less developed and generally involves the modification of the deposit to make it more susceptible to the effects of removal forces.

Due to public concern and political pressure to reduce the use of toxic chemicals, particularly those employed in water treatment, there is an increased interest in the use of non-chemical methods for fouling control. Promising techniques currently under investigation *(12)* include tube inserts, ultrasound and the circulation of polymer fibers. The use of an additive in conjunction with a physical method of control may be more effective than either technique alone *(13);* although there is still a potential environmental impact due to the use of toxic chemicals, because of the enhancement through the physical method, smaller quantities of chemicals can be used. Ultimately, the acceptability of these experimental methods of fouling control will be reliability and cost effectiveness.

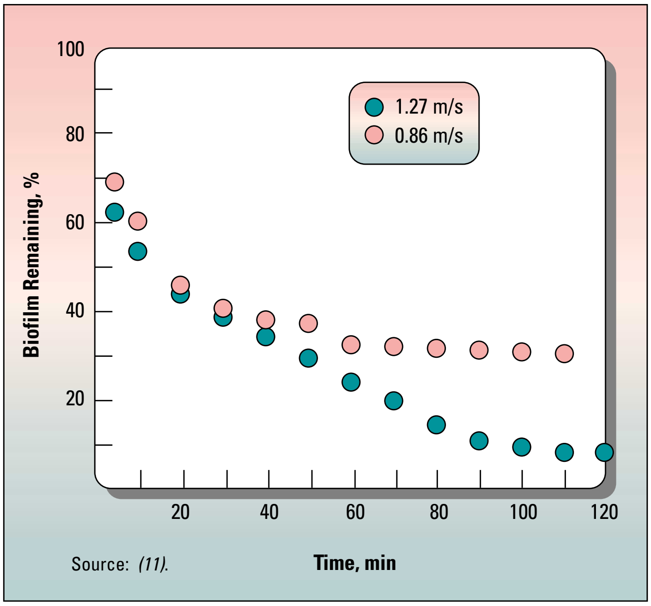

Figure 6. The effect of velocity on the effectiveness of chlorine as a biocide at a concentration of 6.3 mg/L for the removal of biofilms.

The use of physical methods for online control in combustion systems is well-established. The use of jets of steam or air to dislodge mineral deposits at high temperature (soot blowers) is a common practice. Sonic vibrations have also been employed. Online water washing and shot cleaning have also been used, but less extensively than soot blowing. A suitable additive that weakens the structure of deposits can assist its physical removal.

The mitigation of fouling and cleaning of heat exchangers is discussed in more detail in *(14)*.

Materials of construction

It may be possible to mitigate heat exchanger fouling through the choice of materials of construction or, perhaps more importantly, by surface finish. Smooth surfaces are less hospitable to deposits than rough ones. For example, the food industry typically employs highly polished surfaces, generally stainless steel, the fine finish of which may be achieved by mechanical polishing or by electrochemical means.

It is also possible that reductions in fouling propensity could be achieved through surface treatment by coating the surface chemically to reduce the adhesion of deposits *(15,16)*. Work has recently been reported on the successful modification of the surface itself to reduce fouling *(17,18)*.

Sophisticated materials of construction, surface treatment and modification of more conventional materials are expensive. Furthermore, consideration must be given to the robustness of the surface finish under continuous operation, possibly under aggressive conditions. In view of the severe cost penalties and the uncertainty regarding the maintenance of antifouling characteristics, the use of these techniques to overcome fouling, at least in the foreseeable future, is limited.

Monitoring

In order to investigate the incidence of fouling and the effectiveness of mitigation, and to provide data for design purposes, it is necessary to have an accurate assessment technique. In the laboratory, the method must be able to obtain data under conditions that are likely to be encountered in a process plant, but it may be difficult to achieve all the conditions. Provided there is an adequate monitoring technique available, it is possible to assess the benefits of the mitigation technology, but perhaps not in absolute terms. Nevertheless, comparisons between results obtained under different operating conditions are valuable because they provide a basis on which further developments may be made.

The process plant itself is, in a sense, the monitor, pro-

Literature Cited

1. **Kern, D. Q., and R. E. Seaton,** "A Theoretical Analysis of Thermal Surface Fouling," *Brit. Chem. Eng.*, **4** (5), pp. 258–262 (1959).
2. **Bott, T. R.,** "Fouling Notebook," Institution of Chemical Engineers, Rugby, U.K. (1990).
3. **Stachura, V. J., ed.,** "Standards of the Tubular Exchanger Manufacturer's Association," 7th ed., TEMA, New York, NY (1998).
4. **Ebert, W. A., and C. B. Panchal,** "Analysis of Exxon Crude Oil Slip Stream Coking Data," in Panchal, C. B., *et al.*, eds., "Fouling Mitigation of Industrial Heat Exchange Equipment," UEF/Begell House, New York, NY, pp. 451–460 (1997).
5. **Panchal, C. B., *et al.*,** "Threshold Conditions for Crude Oil Fouling," in Bott, T. R., *et al.*, eds., "Understanding Heat Exchanger Fouling and its Mitigation," UEF/Begell House, New York, NY, pp. 273–281 (1999).
6. **Knudsen, J. G., *et al.*,** "The Determination of the Threshold Fouling Curve for Crude Oil", in Bott, T. R., *et al.*, eds., "Understanding Heat Exchanger Fouling and its Mitigation," UEF/Begell House, New York, NY, pp. 265–272 (1999).
7. **Butterworth, D.,** "Designing Shell-and-Tube Heat Exchangers with Velocity-Dependent Fouling," Proceedings of the 2nd International Conference on Petroleum Phase Behavior and Fouling, Copenhagen, Denmark, AIChE (Aug. 2000).
8. **Poddar, T. K., and G. T. Polley,** "Heat Exchanger Design Through Parameter Plotting," *Transactions of IChemE*, **74,** Part A, pp. 849–852 (1996).
9. **ESDU,** "Heat Exchanger Fouling in the Preheat Train of Crude Oil Distillation Levels," Data Item 00016, ESDU International, London, U.K. (July 2000).
10. **Jones, G. M., *et al.*,** "Fouling Allowance in the Design of Refinery Heat Exchangers," Proceedings of the 2nd International Conference on Petroleum Phase Behavior and Fouling, Copenhagen, Denmark, AIChE (Aug. 2000).
11. **Bott, T. R., and R. J. Taylor,** "The Effects of Velocity on Biocide Use for Biofilm Removal in Flowing Systems," AIChE Symposium Series, **93,** pp. 322–326 (1997).
12. **Bott, T. R.,** "Potential Physical Methods for the Control of Biofouling in Water Systems," *Transactions of IChemE*, **79** (A4), pp. 484–490 (2001).
13. **Bott, T. R., and T. Liu,** "Enhancement of Ozone Effectiveness for Biofilm Control in Aqueous Systems Using Ultrasound," Proceedings of the International Regional Conference on Ozonation and AOPs in Water Treatment: Applications and Research, Poitiers, France, sponsored by the International Ozone Association (Sept. 1998).
14. **Müller-Steinhagen, H., ed.,** "Heat Exchanger Fouling — Mitigation and Cleaning Technologies," IChemE/Publico Publications, Essen, Germany (2000).
15. **Santos, R. C. C.,** "Polymer Coatings in Relation to Single and Mixed Population Biofilms," PhD Thesis, Univ. of Birmingham, Birmingham, U.K. (1993).
16. **Förster, M., and M. Bohnet,** "Modification of the Characteristics of Heat-Transfer Surfaces as a Fouling Mitigation Strategy," Proceedings of the Conference on Mitigation of Heat Exchanger Fouling and its Economic and Environmental Implications, Banff, Canada, sponsored by United Engineering Foundation, New York, NY (1999).
17. **Zhao, Q., and H. Müller-Steinhagen,** "Influence of Surface Properties on Heat Exchanger Fouling," Proceedings of the Conference on Mitigation of Heat Exchanger Fouling and its Economic and Environmental Implications, Banff, Canada, sponsored by United Engineering Foundation, New York, NY (1999).
18. **Kim, K-H, *et al.*,** "Effect of Plasma Polymerized Film on Fouling of Heat Exchangers," Proceedings of the Conference on Mitigation of Heat Exchanger Fouling and its Economic and Environmental Implications, Banff, Canada, sponsored by United Engineering Foundation, New York, NY (1999).
19. **Panchal, C. B., *et al.*,** "Development of High Temperature, High Pressure Fouling Units," in Bott, T. R., *et al.*, eds., "Understanding Heat Exchanger Fouling and its Mitigation," UEF/Begell House, New York, NY, pp. 359–366 (1999).
20. **Glen, N. F., *et al.*,** "Monitoring the Heat-Transfer Properties of a Heat-Transferring Surface," International Patent Application (Europe and U.S.), 99/02428 (1999).
21. **Smaïli, F., *et al.*,** "Scheduling of Heat Exchanger Cleaning in Refinery Heat Exchanger Network," Proceedings of the Conference on Mitigation of Heat Exchanger Fouling and its Economic and Environmental Implications, Banff, Canada, sponsored by United Engineering Foundation, New York, NY (1999).
22. **Sheikh, A. K., and J. Al-Bagawi,** "Statistical Characterization of Time Between Cleaning of Thermosyphon Reboilers in Oil Industry," Proceedings of the Conference on Mitigation of Heat Exchanger Fouling and its Economic and Environmental Implications, Banff, Canada, sponsored by United Engineering Foundation, New York, NY (1999).
23. **O'Donnell, B. R., *et al.*,** "Optimize Heat Exchanger Cleaning Schedules," *Chem. Eng. Progress*, **97**(6), pp. 56–60 (June 2001).
24. **Wilson, D. I., *et al.*,** "Mitigation of Fouling in Refinery Preheat Trains by Optimal Management of Cleaning and Confinement Treatment," Proceedings of the 2nd International Conference on Petroleum Phase Behavior and Fouling, Copenhagen, Denmark, AIChE (Aug. 2000).
25. **Bott, T. R.,** "The Fouling of Heat Exchangers," Elsevier, Amsterdam, p. 4 (1995).

vided there is sufficient instrumentation available to assess heat exchanger performance. Unfortunately, more often than not, instrumentation is far from adequate, and assumptions that have to be made make the resulting data of doubtful quality. The responses of the plant in terms of heat-transfer efficiency or pressure drop are perhaps the best measures of the effectiveness of the mitigation technology employed. A better nonintrusive approach would be to use a well-instrumented monitor on a side stream whose velocity and temperature could be made similar to those encountered in the plant itself.

The basic criteria for a monitor are *(19):*

- low cost
- compact design for ease of maintenance
- the ability to withstand high temperatures (where high-temperature fouling is to be investigated)
- known fluid dynamics
- ease of transportation
- ease of installation.

A monitor meeting these requirements that may be used for laboratory or plant studies has been developed by the National Engineering Laboratory (which is now known as PUVNEL; East Kilbride, Scotland, U.K.) *(20).* It consists basically of an electrically heated tube that is fully instrumented from which data on fouling for the given conditions may be calculated.

Online monitoring provides a continuous assessment of fouling that allows for effective control. It is also a source of data that will be of considerable value for design purposes.

Offline cleaning

Recognizing that a heat exchanger is likely to foul during operation, despite attention to the potential fouling in the design and subsequent operation, offline cleaning is likely to be required at some stage.

One possibility is to install a duplicate heat exchanger so that one is in operation while the other is available for cleaning. However, the additional capital expenditure involved may not be acceptable, in which case consideration must be given to scheduling the cleaning such that production disruptions are minimized. An arbitrary, perhaps unplanned, shutdown to deal with a fouling problem is likely to be much more expensive than one that is incorporated into a planned maintenance schedule. Mathematical and statistical methods are available for the determining such schedules *(21–23)* and for optimizing online mitigation techniques *(24).*

The future

Relatively good progress toward understanding heat exchanger fouling and its mitigation has been achieved over the past 30 years. The information that is available as a result will enable a more rational approach to the development of practical solutions to fouling problems. Yet the cost of fouling worldwide remains enormous. At the same time, there is a limit to substantial future progress by the piecemeal approach evident in recent years.

Apart from helping to solve a current problem, it is generally recognized that effective monitoring of heat exchanger performance and potential fouling is essential if further progress is to be made. The collection of data that monitoring offers could provide a reliable database for designers and operators of heat exchangers in the future. However, this requires a consistent method of reporting so that different sources of data are compatible. If this could be achieved, industry could realize long-term benefits through the reduction of capital and operating costs. Yet this presents a problem as to who would set the standards under which such a data collection project would be conducted. An even more important question, perhaps, is how the financial backing could be secured. These are certainly difficult problems, but substantial future progress will surely depend on this approach.

A great deal could be achieved by collective action of an independent organization with the backing of interested parties. Groups of companies with a common interest, such as oil refiners or industries that have similar cooling water requirements, could work together. Commercial confidentiality need not be jeopardized, as the heat exchanger is generally not a trade secret. The returns on such an investment would be enormous.

These suggestions regarding the future are indeed ambitious. Unless something along these lines is attempted, the question of "to foul or not to foul?" will remain largely unresolved. CEP

Acknowledgements

The author acknowledges the contributions that friends and colleagues around the world, his research fellows, and postgraduate students have made through papers, discussions and research to understanding fouling phenomena, and indeed to the author's own personal development. Financial assistance from many industrial organizations is also gratefully acknowledged.

This article is based on the acceptance lecture given by the author when he received the Donald Q. Kern Award from AIChE's Heat Transfer and Energy Conversion Div. in June 2001.

T. REG BOTT is senior research fellow in the School of Engineering at the Univ. of Birmingham (Edgbaston, Birmingham, B15 2TT, England, U.K.; Phone: +44-(0)121-414-5330; Fax: +44-(0)121-414-5324; E-mail: s.c.cohen@bham.ac.uk). He began his career by spending seven years in industry. In 1968, he was named the Institution of Chemical Engineers (IChemE) Fellow in Heat Transfer to investigate heat-transfer problems in industry. Of major concern was the incidence of heat exchanger fouling, and as a result he directed his research into this area. He was the IChemE's Research Fellow on heat exchanger fouling in 1987. He has published over 300 papers, and has written four books and co-authored several others. He holds BSc, PhD and DSc degrees in chemical engineering from the Univ. of Birmingham, and he is a chartered engineer and a Fellow of IChemE.