



Journal of Applied Sciences

ISSN 1812-5654

science
alert

ANSI*net*
an open access publisher
<http://ansinet.com>

Crude Oil Fouling: A Review

U.B. Deshannavar, M.S. Rafeen, M. Ramasamy and D. Subbarao
Department of Chemical Engineering, Universiti Teknologi Petronas, 31750, Tronoh, Malaysia

Abstract: Fouling in crude preheat train heat exchangers in refineries is a complex phenomenon. Crude oil fouling undergoes different mechanisms at different stages of preheating. Understanding the fouling mechanisms is essential in formulating appropriate fouling mitigation strategies. The use of the concept of threshold fouling conditions is one of the approaches for mitigating fouling through operating conditions. In this study, an attempt has been made to review the various fouling models available in literature, their advantages and limitations.

Key words: Heat exchanger, fouling, crude oil, threshold conditions, preheat train

INTRODUCTION

Ever increasing energy cost has led to the pursuit of heat integration approaches in process industries in order to recover heat from the product streams as much as possible into the process streams and hence improve the energy efficiency of the plant. Generally multi-pass shell and tube heat exchangers are used as the heat recovery units. Due to the complex nature of crude oils the heat exchangers in the crude preheat train in refineries are prone to fouling. The total financial penalties associated with fouling may include the loss of thermal efficiency of heat transfer equipment, high fluid pressure drops, costs for anti foulant additives, physical and/or chemical cleaning and loss of production due to unscheduled plant shutdowns. Muller-Steinhagen (1995) estimated the total cost of all heat exchanger fouling in the UK is of the order of USD 2.5 billion and the equivalent cost in the USA is USD 14 billion. The typical annual cost of cleaning a fouled industrial heat exchanger is estimated at between USD 40000 and 50000 (Panchal and Huangfu, 2000). Crude oil fouling is generally believed to be caused by impurities in the crude oil such as corrosion products, water and salt, precipitation of insoluble asphaltene, thermal decomposition or auto-oxidation of reactive constituents in the oil.

There is a renewed interest in understanding fouling mechanisms, modeling the fouling processes and identifying appropriate fouling mitigation strategies in refineries, especially in crude preheat trains. There are only a few research groups pursuing intensive research on crude oil fouling besides our research centre are University British Columbia, Heat Transfer Research Inc., Argonne National Labs., a consortium of universities

comprising of Imperial College, Bath University and Cambridge University in association with Engineering Sciences Data Unit (ESDU), UK. Independent studies are also being carried out by the refineries, the results of which are not available in public domains.

In this study, an attempt is made to review the development of models for crude oil fouling in the refinery preheat trains. It also identifies the limitations of the models and provides recommendation for future research in this area.

FOULING MECHANISMS AND FACTORS INFLUENCING FOULING

Better understanding of fouling mechanisms and the various factors influencing fouling is essential for the development of appropriate fouling models. In general, fouling mechanisms are classified into five categories as: chemical reaction fouling, particulate fouling, corrosion fouling, crystallization fouling and biological fouling. In the case of crude oil fouling, crystallization of inorganics, corrosion, chemical reaction of organics, deposition of particulates or a combination of these play an important role (Bott, 1995). Fouling can be divided into these mechanisms in theory, but in practice, it is often the interaction between two or more types. The above fouling mechanisms generally occur in a series of steps as outlined below (Epstein, 1983):

Initiation or delay period: When a new or clean heat exchanger is commissioned, initially the heat transfer coefficient remains unchanged for a certain period of time before it starts to decline due to fouling. This initiation or delay period may last anytime from few seconds to several

days. The duration of this phase depends upon factors such as type of fouling, surface temperature and surface conditioning. For instance, no initiation period occurs for particulate fouling while for chemical reaction fouling there is an initiation period for fouling to begin.

Transport: The precursors that are responsible for the deposit formation on the surface are originally either suspended or dissolved in the bulk fluid and they are transported from bulk fluid to heat transfer surface through diffusion. The driving force for the transport is the difference between the concentrations of precursor in the bulk fluid and at the surface. The rate of transportation of these species can be described by:

$$\frac{dm}{dt} = k_t(C_b - C_s) \quad (1)$$

where, C_b and C_s are the concentrations of precursor in the bulk and at the surface, respectively and k_t is the mass transfer coefficient.

Deposition: When the fouling precursors reach the heat transfer surface, they either stick to the surface, leave the surface or react to form substances that finally stick to the surface. Deposition can either be controlled by chemical reaction, diffusion or adhesion.

Removal: As the deposit layer starts building on the heat transfer surface, some part of it may be removed by the action of fluid shear and mass transfer. The amount of the deposit removed depends upon the strength of the deposit layer. The removal can also be by mass transfer where the fouling precursors are removed from the surface or the thermal boundary layer to the bulk fluid.

Aging: Every deposit layer on the surface is subjected to aging with time. Aging may increase the strength of the deposit by polymerization, re-crystallization, etc. Aging is the least investigated and understood step and is usually ignored in modeling attempts.

Factors influencing fouling: The most important factors influencing fouling are: (1) surface temperature, (2) bulk velocity, (3) bulk temperature, (4) crude type and (5) crude blending.

Surface temperature: The rate of fouling increases exponentially with increasing surface temperature for almost all fouling mechanisms (Scarborough *et al.*, 1979; Eaton and Lux, 1984; Crittenden *et al.*, 1992; Asomaning, 1997; Saleh *et al.*, 2005a; Srinivasan and Watkinson 2005).

The effect of surface temperature on the fouling rate is generally expressed by an Arrhenius-type equation.

$$\frac{dR_f}{dt} = A \exp(-E/RT_s) \quad (2)$$

Activation energy, E and the proportionality factor, A , in Eq. 2 are determined from experimental data at varying surface temperatures and constant velocity, fluid composition and geometry. There are also attempts to use the film temperature, T_b instead of surface temperature, T_s (Ebert and Panchal, 1995; Saleh *et al.*, 2005a; Srinivasan and Watkinson, 2005). Ebert and Panchal (1995) used the film temperature in their analysis of fouling rates and activation energy calculation for crude oil-slip-stream coking. Saleh *et al.* (2005a) calculated the activation energy values for a light Australian crude oil at film temperature and also at surface temperature. Activation energy determined based on film temperature will be higher than that based on the surface temperature. The use of film temperature or surface temperature depends upon the location of occurrence of the chemical reaction. If the chemical reaction occurs in the thermal boundary layer, film temperature is used. On the other hand, surface temperature is used if the chemical reaction occurs on the heat transfer surface (Asomaning *et al.*, 2000).

Flow velocity: In crude preheat trains, fouling rate decreases or increases with an increase in velocity. For a given bulk temperature and heat flux, the fouling rate decreases with an increase in flow velocity when the fouling is reaction controlled (Asomaning, 1997). In this case, an increase in velocity increases the heat transfer coefficient and thus reduces the wall and film temperatures. On the other hand, if the fouling rate is controlled by mass transfer of the fouling species from the bulk fluid to the surface, then the mass transfer coefficient from the bulk fluid to the surface will increase with increase in velocity leading to an increase in fouling rate.

For a case where the fouling rate decreases with increase in velocity, the effect of velocity can be summarized in two ways as:

- If the deposit layer is weak, the shear stress at the wall which is directly proportional to the fluid velocity may give rise to erosion of the fouling layer which offsets the deposition of the foulant
- If the foulant material is formed in the thermal boundary layer adjacent to the hot surface where the deposition rate is the highest, then the formed deposit diffuse back into the bulk fluid. The rate of mass transfer of foulant increases with increase in velocity and thus reduces the fouling rate (ESDU, 2000)

Watkinson and Epstein (1969) developed a model for gas oil fouling and found that the initial fouling rate is inversely proportional to mass flow rate and a similar dependence of initial fouling rate on flow velocity was observed by other researchers (Scarborough *et al.*, 1979; Paterson and Fryer, 1988; Asomaning, 1997; Saleh *et al.*, 2005a; Crittenden *et al.*, 2009).

Bulk temperature: The effect of bulk temperature on deposit formation was studied by a few researchers and contradicting conclusions were reported. Some researchers have observed that the fouling rate increased with a decrease in bulk temperature (Lambourn and Durrieu, 1983; Eaton and Lux, 1984; Fuhr *et al.*, 1991; Storm *et al.*, 1996; Asomaning, 1997). The decrease in bulk temperature at a constant velocity and surface temperature results in an increase in the thermal driving force and hence an increase in the fouling rate. An increase in fouling rate with an increase in bulk temperature has also been reported in the literature (Saleh *et al.*, 2005a; Srinivasan and Watkinson, 2005).

Asphaltenes are large, complex ring structure molecules that are found in the crude oil and insoluble asphaltenes are considered to be the major cause of fouling in crude oil systems (Dickakian and Seay, 1988). The solubility of asphaltene plays an important role in crude oil fouling. Generally, the solubility of asphaltene in crude oil increases with increase in temperature (Fuhr *et al.*, 1991). A complex relationship between asphaltene solubility and temperature has been reported by Lambourn and Durrieu (1983) in which the solubility of asphaltene increased to a maximum at 140°C and then decreased at higher temperatures. At high bulk temperatures, the asphaltene is in the form of solution in crude oil and the fouling rate is low whereas at low bulk temperatures, asphaltene precipitates out from crude oil and the fouling rate is high.

The bulk temperature effects are also strongly interrelated with the Reynolds number (Asomaning, 1997). Increase in bulk temperature decreases the viscosity and hence increases the Reynolds number. At high Reynolds numbers, the thickness of the thermal boundary layer becomes smaller and the rate of formation of fouling precursors decreases due to the reduction in the volume for the chemical reaction.

Crude type: The crude oil is a mixture of a large number of hydrocarbons. The most commonly found molecules are paraffins, naphthenes, aromatic hydrocarbons and asphaltenes. The crude oils can be classified as light, medium or heavy according to its measured API gravity.

Heavy oils contain much higher proportions of asphaltenes and sulfur than medium or light oils and they tend to foul at a faster rate.

Crude blending: Another important factor which influences the fouling is crude blending. Blending of crudes can cause unstable mixes which precipitate species such as asphaltene and result in rapid fouling (Wilson and Polley, 2001). The crude oil incompatibility and the precipitation of asphaltene on blending of crude oils can cause significant fouling and coking in crude preheat train. For this reason, the crude oil compatibility model and tests were developed to predict proportions and order of blending of oils that would avoid incompatibility (Wiehe *et al.*, 2001). Saleh *et al.* (2005b) studied the effect of mixing and blending crude oils at certain operating conditions with the intention of using the results to guide a fouling mitigation strategy.

EXPERIMENTAL STUDIES ON FOULING

Crude oil fouling in preheat exchangers is a complex phenomenon that depends on a number of variables such as crude type and composition, design parameters of the heat exchangers and the operating conditions. Research using actual plant data is slow, subject to a variety of logistical and operational requirements which do not lend themselves well to fundamental scientific studies (Crittenden *et al.*, 1992) and can create difficulties in the interpretation of the thermal data (Takemoto *et al.*, 1999). Generally, the fouling characteristics of crude oils are established through experiments in laboratory experimental units which are designed and operated under controlled operating conditions to achieve accelerated fouling rates. Several types of laboratory units have been reported to be used in the study of crude oil fouling characteristics. Stirred batch cells (Eaton and Lux, 1984; Young *et al.*, 2009), recycle flow loop with a tubular cross section (Crittenden *et al.*, 2009) and recycle flow loop with annular cross section (Wilson and Watkinson, 1995; Bennett *et al.*, 2009) have been used to characterize crude oil fouling. Once-through continuous flow fouling units have been reported to be used in the refineries and are known as field fouling units (Kuru *et al.*, 1997). The disadvantage of field fouling units is that the crude oil properties do not remain constant as the crude to the refinery changes very frequently. Recycle flow loop with annular flow geometry has been predominantly used due to their advantages such as visual observation of the fouling deposits, easier to collect foulant samples and clean the surface for reuse, etc.

Whilst laboratory studies can eliminate the principal practical disadvantages of studying fouling on refinery exchangers they, in turn, introduce their own disadvantages, the principal one being that the crude oil is not exposed to the time-temperature-flow history of the crude in the oil refinery (Young *et al.*, 2009). One of the major drawbacks of the experimental results reported in literature is that the operating conditions are chosen arbitrarily. Guidelines or systematic procedures to choose the operating conditions have not been discussed by the researchers.

High surface temperatures or heat fluxes and low velocities are generally used to accelerate the fouling rates. Knudsen *et al.* (1999) described the experimental procedure for the determination of threshold fouling curve for a desalted crude oil. Tests were performed in a circulation system in which the crude oil is circulated through an annular test section at velocities ranging from 0.91 to 3.1 m sec⁻¹ and at two bulk temperatures of 149 and 204°C. The experiments have been carried out at surface temperatures ranging from 177 to 329°C and the experimental data were reported.

CRUDE OIL FOULING MODELS

Mathematical models to represent fouling are necessary to predict the fouling rates as a function of key design and operational parameters. A large number of semi-empirical models for crude oil fouling have been reported in literature (Kern and Seaton, 1959; Crittenden and Kolczkowski, 1979; Crittenden *et al.*, 1987; Epstein, 1994; Ebert and Panchal, 1995; Panchal *et al.*, 1997; Polley *et al.*, 2002; Nasr and Givi, 2006). These models were developed based on the experimental data from laboratory test rigs.

The models describing fouling usually are based on the well-known concept of Kern and Seaton (1959) approach where the net fouling rate is the difference between the rates of deposition and removal.

$$\text{Fouling rate} = \text{Rate of deposition} - \text{Rate of removal}$$

The basic differences between various models reported in literature are in the description of the deposition and removal terms. The rate of deposition is described by either a transport-reaction model or reaction alone model while the rate of removal is described either by shear-related or mass-transfer related expressions. In general, transport-reaction models are more rigorous than the reaction alone models.

A transport-reaction model was developed by Crittenden and Kolaczowski (1979) considering chemical

reaction as well as the transport of fouling precursor to and from the heated surface. They also proposed a modified model that includes a back-diffusion term (Crittenden *et al.*, 1987). Epstein (1994) observed that at time zero, it is fundamentally difficult to justify the finite concentration of foulant at the surface which would be required for back diffusion to occur. Epstein developed a model for the initial chemical reaction fouling rates at the surface in which the surface attachment is proportional to residence time of the fluid at the surface. The greater the residence time, the greater would be the opportunity for the chemical reaction to occur. The relationship between the initial fouling rate and the mass flux is given as:

$$[dR_f/dt]_{t=0} = m\phi/k_f\rho_f \tag{3}$$

where, *m* is the stoichiometric factor, ρ_f the foulant density, k_f the thermal conductivity of foulant and ϕ is the deposition mass flux. The driving force for the mass transfer from the bulk fluid to the heater surface of foulant precursor was expressed as the difference between its bulk and surface concentrations, C_b and C_s , respectively (Epstein, 1994). The deposition mass flux is given by:

$$\phi = \frac{C_b}{\left(kS_c^{2/3}/u(f)^{1/2}\right) + \left(k'\rho u^2 f/\mu \exp(-E/RT_s)C_s^{n-1}\right)} \tag{4}$$

where, k' and k'' are constants, S_c is Schmidt number, f is the friction factor, ρ is the fluid density, μ is fluid viscosity and n is the order of the reaction plus attachment process. The first term in the denominator represents the mass transfer of foulant or precursor to the heated surface and the second term represents the reaction and attachment aspects. Epstein's model showed an excellent fit to Crittenden's data for initial fouling rates of polymerization of styrene (Crittenden *et al.*, 2009). It was also able to explain the effects of temperature and velocity. This model could not be used for describing the crude oil fouling due to the reasons such as the order of the reaction + attachment term, n and S_c are unknown for the crude oil fouling and it is also difficult to isolate the key precursors of fouling as the crude oil has complex compositions and this creates difficulty in finding out the concentration of exact precursor and its role in fouling.

Yeap *et al.* (2005) reduced the Epstein's model to a function of groups of dimensional parameters A, B, C and E for turbulent flow conditions with mean velocity, u , with a mass transfer related removal term as:

$$\frac{dR_f}{dt} = \frac{AC_f u T_s^{2/3} \rho^{2/3} \mu^{-4/3}}{1 + Bu^3 C_f^2 \rho^{-1/3} \mu^{-1/3} T_s^{2/3} \exp(E/RT_s)} - Cu^{0.8} \tag{5}$$

They estimated the parameters of the above model using plant data from a UK refinery that processes mainly light to medium North Sea crudes.

Considerable interest has been expressed in the concept of threshold fouling conditions for crude oils using less rigorous semi-empirical models. Ebert and Panchal (1995) proposed a semi-empirical model for predicting the linear rate of fouling as a function of film temperature and fluid velocity Eq. 6.

$$\frac{dR_f}{dt} = \alpha Re^\beta \exp(-E/RT_f) - \gamma \tau_w \quad (6)$$

where α , β , E and γ are constants to be determined from the experimental data. This model was originally developed using the Exxon crude-oil-slip stream coking data obtained by Scarborough *et al.* (1979) in a joint research project with US Department of Energy. This model assumes that foulant forming reactions occur in the thermal boundary layer at a mean film temperature, T_f , foulant is transported by diffusion and turbulence eddies from the boundary layer to the bulk flow and the net rate of deposition is the difference between the rate of formation and rate of removal. This model allowed users to estimate operating conditions where the fouling rate would be close to zero which is termed as the threshold fouling conditions. The threshold fouling curve was determined by setting Eq. 6 to zero and calculating film temperatures for a wide range of wall shear stresses.

Ebert and Panchal model ignored the effect of crude oil thermal conductivity and specific heat and only considered the effect of crude oil density and viscosity through Reynolds number. Panchal *et al.* (1997) modified the Ebert and Panchal model by incorporating the Prandtl number. The revised model is given as:

$$\frac{dR_f}{dt} = \alpha Re^\beta Pr^{-0.33} \exp(-E/RT_f) - \gamma \tau_w \quad (7)$$

The value of β was assumed to be -0.66 and the film temperature T_f was determined as:

$$T_f = T_b + 0.55(T_s - T_b) \quad (8)$$

Experimental data from a high pressure autoclave fouling unit under various operating conditions were used in their study.

Polley *et al.* (2002) observed that (1) for turbulent flow through circular tubes, the exponent of the Reynolds number of -0.8 is more appropriate than -0.66; (2) the use of wall temperature in the Arrhenius term is more appropriate than the film temperature and (3) the removal

mechanism is by mass transfer prior to the formation of a deposit; a simplistic approach to introduce mass transfer dependence is to use Reynolds number to a power of 0.8, in the same way that the convective mass transfer coefficient varies with velocity. Based on these observations Polley *et al.* (2002) made simple modifications to the Ebert and Panchal model as:

$$\frac{dR_f}{dt} = \alpha Re^{-0.8} Pr^{-0.33} \exp(-E/RT_w) - \gamma Re^{0.8} \quad (9)$$

Polley *et al.* (2002) verified their model using Knudsen's experimental data. Nasr and Givi (2006) proposed a threshold fouling model which is independent of Prandtl number as:

$$\frac{dR_f}{dt} = \alpha Re^{-\beta} \exp(-E/RT_f) - \gamma Re^{0.4} \quad (10)$$

The model was verified with the experimental data by Saleh *et al.* (2005a) for Australian crude oil. The activation energy was determined through the Arrhenius plot. In this model, the value of β was determined together with the other model parameters α and γ . A value of -1.547 was reported for the Australian light crude oil. The authors have claimed that their model describes the data better than the earlier models. It may be noted that Nasr and Givi model has become more empirical than the earlier models since a value of -1.547 for β has no physical significance as compared to the other models. The disadvantage with this model may be that it cannot be used for extrapolation at other operating conditions.

Neural Networks (NN) based models have recently become the focus of much attention largely because of their capability to handle complex and non-linear systems. A neural network fouling model has been developed successfully for preheat exchangers of crude distillation unit based on the plant historical data (Radhakrishnan *et al.*, 2007). NN models were also developed based on experimental data from a lab-scale test rig (Aminian and Shahhosseini, 2008). The major advantage with NN modeling is that it is independent of fouling mechanism whereas the semi-empirical models cannot describe fouling mechanisms other than the reaction fouling.

ASSESSMENT AND FUTURE DIRECTIONS

Extrapolating the laboratory data to field fouling situations has several shortcomings. Asomaning *et al.* (2000) has identified issues of significance, when assessing the appropriateness of extrapolating laboratory

fouling data to the field include: (1) effect of fluid composition, (2) effect of fluid recirculation in the laboratory unit on fouling data, (3) the nature of fouling mechanisms in the field and in the laboratory, (4) the fluid dynamics of heat exchangers in the field and fouling units in the laboratory, (5) pressure effects and the predominance of sub-cooled boiling conditions in laboratory units and (6) the fact that laboratory experiments are done under carefully controlled conditions while field processes are subjected to vagaries of the process. These factors should be addressed whenever data obtained in the laboratory are to be extrapolated to the field. If the mechanisms in the field and in the laboratory are not identical, the data from the two situations will not be comparable. Recirculation of test fluid, which results in long periods of heating, may alter its composition and result in differences between the fouling results obtained in the laboratory and the field. If the crude oil is heated for a long time with recirculation, the state of aggregation and the solubility behavior of asphaltene can change and the fouling data obtained will differ from that obtained with once-through flow conditions. Laboratory fouling tests are usually performed under severe and accelerated conditions such as high surface temperatures and low velocities, resulting in asymptotic thermal fouling resistance versus time plots. On the other hand, conditions in the field may give rise to linear curves with the same fluid. Given the accelerated nature of laboratory tests, fouling rates, induction periods and fouling resistances may not be comparable to those in the field. Accelerated fouling conditions, which are usually found in the laboratory, may give rise to rapid aging of deposits and this aging could result in weakening of the deposit strength due to rapid thermal degradation. This will facilitate removal and thereby result in asymptotic fouling curves. Aging could also result in strengthening of the deposit due to further polymerization. This could favor linear fouling curves. Whether both of these processes occur in the laboratory and field experiments to the same degree is not known. The predictive ability of laboratory data may improve if experiments are planned to minimize the effects of factors identified and listed.

In most of the reported studies on hydrocarbon fouling, reference to boiling was rarely made although the operating conditions used suggest that it was indeed often present (Oufer, 1990). The fouling characteristics determined at these operating conditions will be influenced by boiling and are not applicable to crude preheat exchangers. Generally, the crude preheat exchangers operate in the forced convective heat transfer regime and it is only appropriate that the heat transfer in

the laboratory experimental units is also in the same heat transfer regime to study the fouling in the preheat exchangers. The effect of bulk temperature is not studied extensively as compared to the surface temperature. Usually the activation energy is determined at different surface temperatures by keeping the bulk temperature constant. In crude preheat trains, the crude oil is subjected to different bulk temperatures as it passes through a series of heat exchangers. The effect of salvation of precursors varies with bulk temperature and it differs from crude to crude. Activation energy determined at a constant bulk temperature may not be applicable for the same crude at other bulk temperatures and therefore, the activation energy shall be determined as a function of bulk temperature. Determining the solubility of precursors at different temperatures is therefore a step necessary in determining true activation energy. More research is required in investigating the effect of bulk temperature on fouling.

CONCLUSION

Fouling is a complex phenomenon which follows different mechanisms. Several factors such as surface and bulk temperatures, fluid velocity, crude type/composition and crude blending affect the fouling rate. Threshold fouling models are gaining considerable interests in recent years for mitigating fouling by estimating threshold operating conditions. More research is required to understand the fouling mechanisms better and also to study the effect of bulk temperature on fouling.

ACKNOWLEDGMENTS

Authors of the study gratefully acknowledge the support and facilities provided by Universiti Teknologi Petronas.

NOMENCLATURE

| Variable | Description | Units |
|----------------|----------------------------------|--------------------------------------|
| A | Proportionality factor in Eq. 2 | m ² K kJ ⁻¹ |
| A | Parameter in Eq. 5 | m ² K kJ ⁻¹ |
| B | Parameter in Eq. 5 | - |
| C | Parameter in Eq. 5 | Units vary |
| C | Concentration of precursor | mol L ⁻¹ |
| C _f | Fanning friction factor in Eq. 5 | - |
| E | Activation energy | kJ mol ⁻¹ |
| f | Friction factor | - |
| k _t | Mass transfer coefficient | m sec ⁻¹ |
| k _f | Thermal conductivity of foulant | W m ⁻¹ K ⁻¹ |
| Pr | Prandtl number | - |
| R | Universal gas constant | kJ mol ⁻¹ K ⁻¹ |
| Re | Reynolds number | - |
| S _c | Schmidt number | - |
| T | Temperature | °C |
| u | Fluid velocity | m sec ⁻¹ |

| Variable | Description | Units |
|----------------------|----------------------|-----------------------|
| Greek letters | | |
| α | Deposition constant | $m^2K kWh^{-1}$ |
| β | Constant | - |
| γ | Removal constant | $m^2KkWh^{-1}Pa^{-1}$ |
| ρ | Density | $kg m^{-3}$ |
| μ | Fluid viscosity | Pa-s |
| ϕ | Deposition mass flux | $kg m^{-2}sec^{-1}$ |
| τ | Shear stress | $N m^{-2}$ |
| Subscripts | | |
| b | bulk | |
| f | film, foulant | |
| s | surface | |
| w | Wall | |

REFERENCES

Aminian, J. and S. Shahhosseini, 2008. Evaluation of ANN modeling for prediction of crude oil fouling behavior. *Applied Thermal Eng.*, 28: 668-674.

Asomaning, S., 1997. Heat exchanger fouling by petroleum asphaltene. Ph.D. Thesis, University of British Columbia.

Asomaning, S., C.B. Panchal and C.F. Liao, 2000. Correlating field and laboratory data for crude oil fouling. *Heat Trans. Eng.*, 21: 17-23.

Bennett, C.A., R.S. Kistler, K. Nangia, W. Al-Ghawas, N. Al-Hajji and A. Al-Jemaz, 2009. Observation of an isokinetic temperature and compensation effect for high temperature crude oil fouling. *Heat Trans. Eng.*, 30: 794-804.

Bott, T.R., 1995. *Fouling of Heat Exchangers*. Elsevier, New York.

Crittenden, B.D. and S.T. Kolaczowski, 1979. Mass transfer and chemical kinetics in hydrocarbon fouling. *Proceedings of the Conference on Fouling Science or Art?*, (CFSA'79), Institute of Corrections Science and Technology and Institute of Chemical Engineering, London, pp: 169-187.

Crittenden, B.D., S.T. Kolaczowski and D.Z. Phillips, 2009. Crude oil fouling in a pilot-scale parallel tube apparatus. *Heat Trans. Eng.*, 30: 777-785.

Crittenden, B.D., S.T. Kolaczowski and I.L. Downey, 1992. Fouling of crude oil preheat exchangers. *Trans. Chem.*, 70: 547-557.

Crittenden, B.D., S.T. Kolaczowski and S.A. Hout, 1987. Modelling hydrocarbon fouling. *Trans. Chem. Part A*, 65: 171-179.

Dickakian, G.B. and S. Seay, 1988. Asphaltene precipitation primary crude exchanger fouling mechanism. *Oil Gas J.*, 86: 47-50.

Eaton, P. and R. Lux, 1984. Laboratory fouling test apparatus for hydrocarbon feedstocks: fouling in heat exchange equipment. *ASME HTD.*, 35: 33-42.

Ebert, W.A. and C.B. Panchal, 1995. Analysis of Exxon Crude-Oil Slip Stream Coking Data. In: *Fouling Mitigation of Industrial Exchange Equipment*, Paschal, C.B. and W.C. Kuru *et al.* (Eds.). Begell House, New York, pp: 451-460.

Epstein, N., 1983. Thinking about Heat transfer fouling: A 5x5 matrix. *Heat Trans. Eng.*, 4: 43-56.

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.*, 4: 225-229.

Fuhr, B.J., C. Cathrea, L. Coates, H. Kalra and A.I. Majeed, 1991. Properties of asphaltene in waxy crude. *Fuel*, 70: 1293-1297.

Kern, D.Q. and R.E. Seaton, 1959. A theoretical analysis of thermal surface fouling. *Br. Chem. Eng.*, 4: 258-262.

Knudsen, J.G., D. Lin and W.A. Ebert, 1999. The Determination of a Threshold Fouling Curve for Crude Oil. In: *Understanding Heat Exchanger Fouling and its Mitigation*, Bott, T.R. (Ed.). Begell House, New York, pp: 265-272.

Kuru, W.C., C.B. Panchal, C.F. Liao, J.W. Palen and W.A. Ebert, 1997. Development of high temperature, high pressure fouling units. *Proceedings of the Understanding Heat Exchanger Fouling and its Mitigation*, May 11-16, Lucca, Italy, pp: 201-208.

Lambourn, G.A. and M. Durrieu, 1983. Fouling in Crude Oil Preheat Trains. In: *Heat Exchangers Theory and Practice*, Taborek, H. and Afghan (Eds.). Hemisphere, New York, pp: 841-852.

Muller-Steinhagen, H., 1995. Fouling of heat exchangers surfaces. *Chem. Ind.*, 5: 171-175.

Nasr, M.R. and M.M. Givi, 2006. Modeling of crude oil fouling in preheat exchangers of refinery distillation units. *Applied Thermal Eng.*, 26: 1572-1577.

Oufer, L., 1990. Fouling characteristics of organic fluids. Ph.D. Thesis, Oregon State University.

Panchal, C.B., W.C. Kuru, C.F. Liao, W.A. Ebert and J.W. Palen, 1997. Threshold conditions for crude oil fouling. *Proceedings of the Understanding Heat Exchanger Fouling and its Mitigation*, May 11-16, Pascoli, Italy, pp: 273-273.

Panchal, C.B. and E.P. Huangfu, 2000. Effects of mitigating fouling on the energy efficiency of crude oil distillation. *Heat Trans. Eng.*, 21: 3-9.

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

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

- Radhakrishnan, V.R., M. Ramasamy, H. zabiri, V. do Thanh and N.M. Tahir *et al.*, 2007. Heat exchanger fouling model and preventive maintenance scheduling tool. *Applied Thermal Eng.*, 27: 2791-2802.
- Saleh, Z.S., R. Sheikholeslami and A.P. Watkinson, 2005a. Fouling characteristics of a light Australian crude oil. *Heat Trans. Eng.*, 26: 15-22.
- Saleh, Z.S., R. Sheikholeslami and A.P. Watkinson, 2005b. Blending effect on fouling of four crude oils. *Proceedings of the 6th International Conference on Heat Exchanger Fouling and Cleaning—Challenges and Opportunities, (ICHEFCCO'05), Kloster Irsee, Germany*, pp: 37-46.
- Scarborough, C.E., D.C. Cherrington, R. Diener and L.P. Golan, 1979. Coking of crude oil at high heat flux levels. *Chem. Eng. Prog.*, 75: 41-47.
- Srinivasan, M. and A.P. Watkinson, 2005. Fouling of some Canadian crude oils. *Heat Trans. Eng.*, 26: 7-14.
- Storm, D.A., R.J. Barresi and E.Y. Sheu, 1996. Flocculation of asphaltenes in heavy oil at elevated temperature. *Petroleum Sci. Technol.*, 14: 243-260.
- Takemoto, T., B.D. Crittenden and S.T. Kolaczkowski, 1999. Interpretation of fouling data in industrial shell and tube heat exchangers. *Trans. Chem. Part A*, 77: 769-778.
- Watkinson, A.P. and N. Epstein, 1969. Gas oil fouling in sensible heat exchanger. *CEP Symp. Ser.*, 65: 84-90.
- Wiehe, I.A., R.J. Kennedy and G. Dickakian, 2001. Fouling of nearly incompatible oils. *Energy Fuels*, 15: 1057-1058.
- Wilson, D.I. and A.P. Watkinson, 1995. Model experiments of autoxidation reaction fouling. *Trans. Chem. Part A*, 73: 59-68.
- Wilson, D.I. and G.T. Polley, 2001. Mitigation of refinery preheat train fouling by nested optimization. *Advances in refinery fouling mitigation session. Arch. Houston.*, 46: 287-294.
- Yeap, B.L., D.I. Wilson, G.T. Polley and S.J. Pugh, 2005. Retrofitting crude oil refinery heat exchanger networks to minimize fouling while maximizing heat recovery. *Heat Trans. Eng.*, 26: 23-34.
- Young, A., S. Venditti, C. Berruoco, M. Yang and A. Waters *et al.*, 2009. Characterisation of crude oils and their fouling deposits using a batch stirred cell system. *Proceedings of the International Conference on Heat Exchanger Fouling and Cleaning VIII, June 14-19, Austria*, pp: 17-26.