EffectofBulkTemperatureand Heating Regimeon Crude Oil Fouling

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Abstract—**Semi-empirical threshold fouling models predict higher fouling rates at high surface/film temperatures. Several experimental fouling data were analyzed with respect to increase in surface and bulk temperatures that showed a decrease in fouling rates. The possible causes including the effect of temperature differentials, heating regime and the solubility of fouling precursors were identified and reported.**

Keywords :
Heat Exchanger, Threshold fouling models, Crude preheat train, Precursor solubility

I. INTRODUCTION

Fouling in heat exchangers is commonly encountered in almost all process industries. It is an undesirable process that reduces the realization of the maximum benefits of heat integration in process industries. Heat exchangers operating under fouled conditions experience reduced thermal efficiencies and increased pressure drops across the heat exchanger units. The extent of fouling depends on many factors such as the fluid type, presence of suspended or dissolved solids, heat exchanger type and design, and operating conditions.

Crude oil fouling in crude preheat train (CPT) of a petroleum refinery is one of the major problems encountered by the refineries with significant economic losses. For a refinery processing 100,000 bbl/day, a drop of 1°C in the coil inlet temperature (CIT) due to fouling results in approximately £ 25,000 of additional fuel cost and 750te of additional carbon dioxide emission each year[1]. On both economic and environmental considerations, process industries are highly motivated to minimize fouling. Fouling cannot be avoided, yet it can be mitigated.

Understanding the fouling characteristics in a given heat exchanger application is essential for devising appropriate fouling mitigation strategies. Developing mathematical models is one of the major activities in understanding the fouling characteristics. Several mathematical models describing crude oil fouling have been proposed in literature. They include theoretical, semi-empirical and empirical models[2-7]. The use of theoretical models in the HEN simulation has been rather very restrictive due to the many unknown constants in the models and complicated by the very complex nature of petroleum crude oils [8].

Traditionally, linear, asymptotic (exponential) and falling rate fouling models were developed based on the observed fouling behavior and utilized for the simulation and optimization of heat exchanger cleaning schedule[9-12]. Artificial neural network based fouling models have also been reported. Although, empirical models are widely used due to their simple forms and easy to develop the models, they do not provide any insight into the fouling mechanism.

Semi-empirical threshold fouling models such as Ebert-Panchal model assume that the net rate of fouling is the difference between the rate of formation by chemical reaction and the rate of removal by the wall shear. Arrhenius type chemical rate expressionis generally used to describe the chemical reaction in the literature [13] as

$$\frac{dR_f}{dt} \propto e^{-\left(\frac{E}{RT}\right)} \qquad (1)$$

The variable, temperature, T, used in the expression (1) depends on the assumption as to where the reaction is taking place. Some authors assume the reaction is taking place at the film while others assume it as the surface (wall). Hence, T_f or T_s has been used in the Arrhenius expression. According to this expression, the rate of fouling increases with increase in T_f or T_s. This fact has been very well supported by many experimental studies. On the contrary, it has also been observed from the data of our own experiments and from the data published in literature that the fouling rates do decrease with an increase in T_f or T_s, especially due to changes in the bulk temperature. This paper attempts to provide an analysis on the possible reasons for this behavior.

In this paper, a brief summary of the theoretical and semi-empirical (threshold) fouling models available in literature is provided in Section II. Section III analyses the effect of bulk temperature on the fouling behavior based on experimental data reported in literature and from this study. Discussions on the possible causes for the different behaviors in fouling due the changes in the heating regime are provided in Section IV. Some conclusions are drawn in Section V.

II. THRESHOLD FOULING MODELS

The threshold fouling concept for crude oil fouling was introduced by Ebert and Panchal[3]. This approach provided a semi-theoretical basis for quantitative interpretation of fouling data in terms of deposition and suppression or inhibition mechanisms. The proposed correlation for predicting the linear rate of fouling and threshold film temperature and fluid velocity is given by

$$\frac{dR_f}{dt} = \alpha Re^{-\beta} \exp\left(\frac{-E}{RT_f}\right) - \gamma\tau_w \qquad (2)$$

where R_f is the fouling resistance, Re the fluid Reynolds number, R the universal gas constant, T_f the film temperature and τ_w the wall shear stress; α, β, γ and E(chemical activation energy) are the model parameters. Panchal and co-workers [4] gave the revised form of (2) as:

$$\frac{dR_f}{dt} = \alpha\, Re^{-0.66}\, Pr^{-0.33} \exp\left(- E/RT_f\right) - \gamma\tau_w \qquad (3)$$

where the fluid flow and thermal properties are accounted for by the use of the Prandtl number. Polley et al., [5] made simple modifications to the Ebert and Panchal threshold model with the assumptions: (i) that the reaction is taking place at the surface and (ii) that the removal term is mass transfer related and is proportional to $Re^{-0.8}$. The revised model is given by:

$$\frac{dR_f}{dt} = \alpha Re^{-0.8} Pr^{-0.33} \exp\left(\frac{-E}{RT_s}\right) - \gamma Re^{0.8} \qquad (4)$$

Nasr and Givi [6] proposed a latest threshold fouling model which is independent of Prandtl number, as:

$$\frac{dR_f}{dt} = \alpha\, Re^{-\beta} \exp\left(- E/RT_f\right) - \gamma Re^{0.4} \qquad (5)$$

The model was developed based on the experimental data measured by Saleh et al. [14] for Australian crude oil. Experiments were carried out to study the thermal fouling caused by heating the Gippsland crude oil at moderate temperatures.

Theoretical models have been presented by several authors and it is suggested to refer to the following articles for more details [2, 15, 16].

III. EFFECT OF BULK TEMPERATURE

Threshold fouling models describe the fouling rates as a function of surface/film temperature and fluid velocity. The effect of fluid velocity on fouling has been captured very well in all the threshold fouling models through the incorporation of Re number in the foulant generation and removal terms.

The threshold fouling models always predict higher fouling rates at higher surface/film temperatures. Majority of the semi-empirical models except that of Polley et al. have assumed that the chemical reaction producing the fouling precursors takes place at the film, i.e., the interface between the tube wall and the bulk fluid through the use of the film temperature, T_f, in the Arrhenius term. The film temperature T_f is affected by the surface temperature and /or the bulk temperature. One of the commonly used expressions for T_f is

$$T_f = T_b + 0.55(T_s - T_b) \qquad (6)$$

Polley et al. [5] assumed that the chemical reaction is taking place at the wall surface and used T_s in the Arrhenius term.

A. Analysis using literature data

The effect of bulk temperature on deposit formation has not been studied extensively as compared with the effect of surface temperature. Eaton and Lux [17] performed experiments using petroleum pitch to study the effect of bulk temperature. They conducted an experiment where the bulk temperature was raised to the surface temperature of 267°C which resulted in zero temperature difference between bulk and surface temperatures and found that no fouling occurred. At the same surface temperature and a much smaller bulk temperature of 38°C, fouling was found to be appreciable. Eaton and Lux concluded that the non-fouling condition was due to the zero temperature difference.

Asomaning [18] reported experimental data for 10% heavy oil and 90% fuel oil at bulk temperatures in the range of 60 to 140°C with a constant surface temperature of 220°C and a fluid velocity of 0.75 m/s. The data is shown in Table I. Considering the fouling data in Table I, it is observed that the initial fouling rate decreased with increase in bulk temperature. The increase in the bulk temperature also resulted in an increase in the film temperature and a decrease in the temperature difference between the surface and bulk temperature. The fouling models would have predicted higher initial fouling rates or the same value with increase in T_f or the constant value of T_s, respectively.

It is also observed that at bulk temperatures 85°C and below, the fouling was rapid as seen by the higher initial fouling rate and final fouling resistance. At bulk temperatures above 85°C, the fouling rate and final fouling resistances were very small.

TABLE I
EXPERIMENTAL DATA OF ASOMANING [18]

T_b (°C)	Initial T_s (°C)	Initial T_f (°C)	Heat Flux (kW/m²)	Initial Rate (m²K/kWh)	Max. R_f (m²K/kW)
60	220	148.0	207	0.0306	0.74
70	218	151.4	206	0.0236	0.72
85	220	159.3	240	0.0111	0.71
100	219	165.5	230	0.00046	0.025
115	219	172.2	232	0.00042	0.015
140	220	184.0	200	0.00032	0.014

It may also be noted that the difference between the surface and bulk temperatures, ΔT, decreased with the increase in bulk temperature at constant surface temperature. It is clearly understood that ΔT plays an important role in describing the fouling behavior.

Experimental fouling data for refinery naphtha at two bulk temperatures, 46 and 63°C, with different initial surface temperatures have been reported by [19]. The thermal fouling profile for T_{so} at 200°C is shown in Fig. 1. It is seen that fouling is severe at lower bulk temperature.

Fouling data from Shell Wood River refinery have been reported by Panchal et al. [20] as shown in Table II. Experiments have been performed at two different fluid velocities, 0.98 and 1.16 m/s.

Comparing the fouling rate data at 0.98 m/s velocity in rows 2 and 3, and at 1.16 m/s velocity in rows 5 and 7, it is observed that increase in the surface temperature at constant bulk temperatures and velocities, has resulted in increased fouling rates with corresponding increase in film temperature and ΔT. This behavior is very well captured by the existing threshold fouling models.

Similar comparison of experimental data at constant surface temperature and velocity, a decrease in the bulk temperature has resulted in an increase in fouling rates (refer to rows 1 and 2 at 0.98 m/s velocity and a surface temperature of 255°C and rows 4 and 5 at 1.16 m/s and 260°C). This observation is not described by the threshold fouling models. It is well observed that the decrease in bulk temperature has resulted in an increase in ΔT.

B. Analysis using experimental data from AFFRU

Fouling experiments were carried out with several crude oils originating from Malaysia using an Annular Flow Fouling Research Unit (AFFRU). This experimental unit is equipped with two identical columns fitted with annular fouling probes. Experiments have been designed to accommodate different combinations of operating conditions such as flow velocity, surface temperature (heat flux) and bulk temperature.
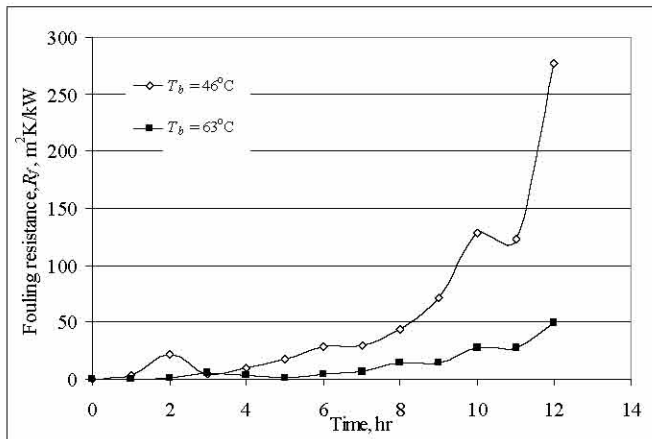
TABLE II
SHELL WOOD RIVER REFINERY DATA[20]

Sl. No.	Velocity (m/s)	T_s (°C)	T_b (°C)	T_f (°C)	ΔT (°C)	Fouling rate (m²K/kWh)x10⁶
1	0.95	255	230	243.75	25	0
2	0.98	255	220	239.25	35	1.1
3	0.98	295	223	262.60	72	8.1
4	1.15	260	230	246.50	30	0
5	1.16	260	220	242.00	40	0.5
6	1.16	270	227	250.65	43	0.8
7	1.16	288	223	258.75	65	5.6

Experimental data at constant surface temperatures and flow velocities at different bulk temperatures for crude oils B and C are shown in Figs. 2 and 3, respectively. Similar to the observations made earlier with fouling data reported in literature, it is observed from Figs. 2 and 3 that the fouling rates decreased with the increase in bulk temperature for two different crude oils.

It is consistently observed that the fouling rates increased with an increase in ΔT based on the analysis of fouling data of [18], [19] and data from this study. The increase in ΔT can be due to either the surface temperature or the bulk temperature.

C. Effect of asphaltene solubility on fouling

Dickakian and Seay [21], and Watkinson [22] performed experiments to study the effect of asphaltene on fouling. They analyzed the deposit formed on the heat transfer surface at various times and concluded that the deposits were due to the precipitation of asphaltene. Thus, asphaltene may be considered as a major cause of fouling in CPT. Solubility of asphaltene in crude oil increases with an increase in temperature [23].

Lambourn and Durrieu [24] reported a complex relationship between asphaltene solubility and temperature. They observed that 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 is low; whereas at low bulk temperatures, asphaltene precipitates out from crude oil and the fouling rate is high.
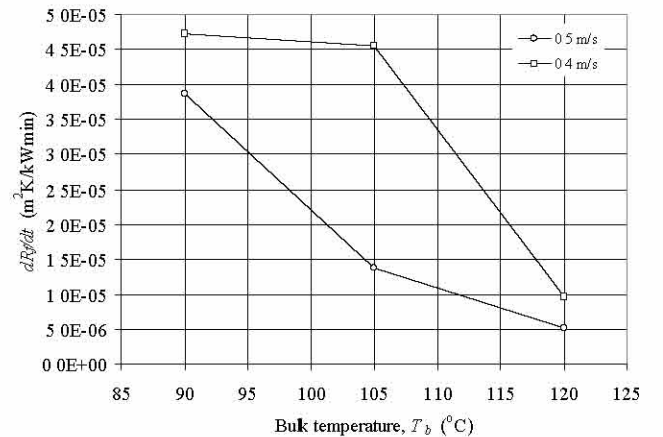
Fig. 1. Fouling profiles for refinery naphtha at $T_{so} = 200$°C [19]

Fig. 2. Initial fouling rate vs. bulk temperature for different velocities of crude oil B ($T_{so} = 214\pm2$°C)
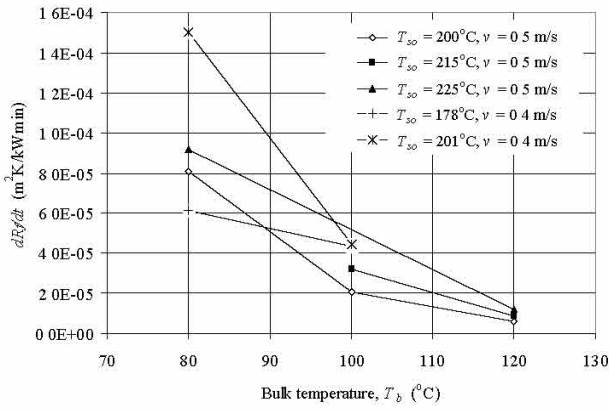
Fig. 3. Initial fouling rate vs. bulk temperature at different initial surface temperatures and flow velocities of crude oil C

Fig. 4. Fouling rate vs. surface temperature of Knudsen et al. data [25]

Fig. 5. Fouling profiles for refinery naphtha at $T_b = 46°C$ [19]

The observations made so far based on the data from various studies lead to the conclusion that the solubility/dissolution phenomena of fouling precursors such as asphaltene along with ΔT play an important role in crude oil fouling.

IV. EFFECT OF HEATING REGIME

Fouling data reported by Knudsen et al. [25] is shown in Table III. It is observed that the fouling rate increases with increase in surface temperature initially, and further increase in surface temperature results in decreased fouling rates. Beyond surface temperatures of 315°C, the fouling rate again increases much rapidly. A plot of the fouling rate data against surface temperature at different flow velocities is shown in Fig. 4.

Thermal fouling profiles for refinery naphtha at different initial surface temperatures of 200, 250 and 300°C at a constant bulk temperature of 46°C of [19] are shown in Fig. 5.
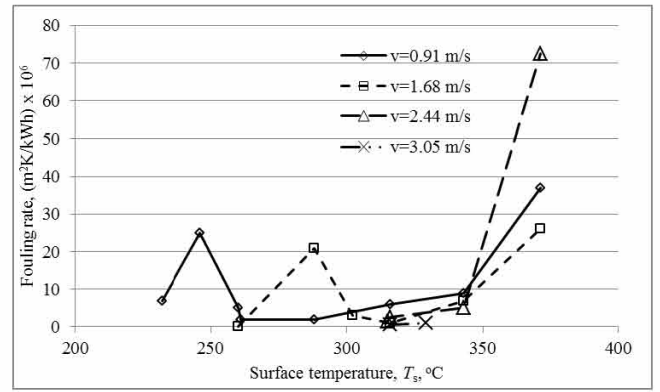
It is observed that fouling rate decreases with an increase in surface temperature from both the sets of data of [25] and [19]. The drop in fouling rates with increase in surface temperatures have not been captured by the threshold fouling models since the phenomenon taking place at various surface temperatures may be different. It is believed that at low surface temperatures forced convective heat transfer regime prevails while above certain surface temperatures (velocity dependent) the transition from nucleate boiling to film boiling takes place. Under the transition heat transfer regime, the fouling rates are expected to be lower due to the large amounts of bubbles being produced at the surface which dislodges the foulant deposits from the surface. When the surface temperatures become very high, stable film boiling takes place and the deposition might be due to coking.

Based on the observations, it can be concluded that fouling experiments to determine the threshold fouling conditions need to be conducted at the respective heat transfer regime as that in the real plant to have meaningful fouling results. Experiments conducted at high surface temperatures especially under transition and film boiling conditions may not represent the real conditions of a crude preheat train.

TABLE III
KNUDSEN ET AL. [25] DATA

Sl. No.	Velocity (m/s)	T_s (°C)	T_b (°C)	Fouling Rate (m²K/kWh) x 10⁶
1	0.91	232	204	7
2	0.91	246	204	25
3	0.91	260	204	5
4	0.91	261	204	2
5	0.91	288	204	2
6	0.91	316	204	6
7	0.91	343	204	9
8	0.91	371	204	37
9	1.68	260	204	0
10	1.68	288	204	21
11	1.68	302	204	3
12	1.68	316	204	1.1
13	1.68	343	204	7
14	1.68	371	204	26
15	2.44	315	204	1.5
16	2.44	316	204	2.7
17	2.44	343	204	5
18	2.44	371	204	72.5
19	3.05	316	204	0.5
20	3.05	329	204	1

V. Conclusions

The effect of bulk temperature and heat transfer regime on crude oil fouling was analyzed using data reported in literature and our own experimental data. It has been found that the existing threshold fouling models do not adequately explain the phenomenon of reduced fouling rates at high bulk temperatures with constant surface temperatures. A number of experimental data has been shown to prove this point. The possible reasons for this behavior could be the dissolution of fouling precursors at high bulk temperatures or the low temperature differentials between the surface and bulk temperatures. If the temperature difference is the possible reason, then the threshold fouling models need to be modified to take the temperature differentials into account.

On the other hand, the observation that fouling rates decreases with the increase in surface temperature indicates that the transition heat transfer regime is prevailing. This indicates that again the inapplicability of threshold fouling models to describe fouling data under these conditions. Care should be taken to avoid the transition heat transfer regime while conducting fouling experiments.

Nomenclature

E	=	Activation energy (kJ/mol)
Pr	=	Prandtl number
R	=	Universal gas constant (kJ/mol K)
Re	=	Reynolds number
R_f	=	Fouling resistance (m^{2}K/kW)
T	=	Temperature ($^{\circ}$C)
v	=	Velocity (m/s)
dR_f/dt	=	Fouling rate (m^{2}K/kWh)

Greek symbols

α	=	Deposition constant (m^{2}K/kWh)
β	=	Constant (-)
γ	=	Removal constant ((m^{2}K/kWh/Pa)
τ	=	Shear stress (N/m^2)
ΔT	=	Temperature differential ($^{\circ}$C)

Subscripts

b	=	Bulk
f	=	Film
o	=	Initial
s	=	Surface
w	=	Wall

References

[1] B. L. Yeap, "Design of Heat Exchanger Networks with Fouling Mitigation," in *CGPS dissertation*: University of Cambridge , UK, 2001.

[2] B. D. Crittenden and S. T. Kolaczkowski, "Mass transfer and chemical kinetics in hydrocarbon fouling," in *Proc. Conf. Fouling – Science or Art? Inst. Cor. Sci. Tech. and I. Chem. E* University of Surrey, Guildford, 1979, pp. 169-187.

[3] W. A. Ebert and C. B. Panchal, "Analysis of Exxon crude oil slip-stream coking data," in *Fouling Mitigation of Industrial Exchange Equipment* Begell House, NY, 1995, pp. 451-460.

[4] C. B. Panchal, W. C. Kuru, C. F. Liao, W. A. Ebert, and G. W. Palin, "Threshold conditions for crude oil fouling," in *Eng. Foundation Conf., Understanding of Heat Exchanger Fouling and its Mitigation* Lucca, Italy, 1997.

[5] G. T. Polley, D. I. Wilson, B. L. Yeap, and S. J. Pugh, "Evaluation of laboratory crude oil threshold fouling data for application to refinery pre-heat trains," *Applied Thermal Eng.*, vol. 22, pp. 777-788, 2002.

[6] M. R. J. Nasr and M. M. Givi, "Modeling of crude oil fouling in preheat exchangers of refinery distillation units," *Applied Thermal Eng.*, vol. 26, pp. 1572-1577, 2006.

[7] T. R. Bott, *Fouling of Heat Exchangers*: Elsevier Science & Technology Books, 1995.

[8] B.D. Crittenden, S.T. kolaczkowski and S.A. Hout, "Modeling hydrocarbon fouling," *Trans IChemE, Part A, Chem Eng Res Des*, 65, 171-179, 1987.

[9] F. Smaïli, V. S. Vassiliadis, and D. I. Wilson, "Mitigation of fouling in refinery heat exchanger networks by optimal management of cleaning," *Energy & Fuels, Vol.*, vol. 15, pp. 1038-1056, 2001.

[10] S. Sanaye and B. Niroomand, "Simulation of heat exchanger network (HEN) and planning the optimum cleaning schedule," *Energy Conversion and Management*, vol. 48, pp. 1450-1461, 2007.

[11] E. M. Ishiyama, A. V. Heins, W. R. Paterson, L. Spinelli, and D. I. Wilson, "Scheduling cleaning in a crude oil preheat train subject to fouling: Incorporating desalter control," *Applied Thermal Engineering*, vol. 30, pp. 1852-1862, 2010.

[12] M. C. Georgiadis, L. G. Papageorgiou, and S. Macchietto, "Optimal cyclic cleaning scheduling in heat exchanger networks under fouling," *Computers & Chemical Engineering*, vol. 23, pp. S203-S206, 1999.

[13] A. P. Watkinson and D. I. Wilson, "Chemical reaction fouling: A review," *Experimental Thermal and Fluid Science*, vol. 14, pp. 361-374, 1997.

[14] Z. S. Saleh, R. Sheikholeslami, and A. P. Watkinson, "Fouling characteristics of alight Australian crude oil," *Heat Transfer Eng.*, vol. 26(1), pp. 15-22, 2005.

[15] N. Epstein, "A Model of the Initial Chemical Reaction Fouling Rate for Flow Within a Heated Tube and its Verification," Proc. 10th *International Heat Transfer Conference*, Brighton, U.K, 1994.

[16] W.R. Paterson, P.J. Fryer, "A Reaction Engineering Approach to the Analysis of Fouling," *Chem. Eng. Sci.*, Vol. 43, pp. 1714-1717, 1988.

[17] P. Eaton and R. Lux, "Laboratory fouling test apparatus for hydrocarbon feedstocks, Fouling in

Heat Exchange Equipment," *ASME HTD* vol. 35, pp. 33-42, 1984.

[18]   S. Asomaning, *Heat exchanger fouling by petroleum asphaltenes*, Ph.D. Thesis, University of British Columbia, 1997.

[19]   A. S. Kovo, "Mathematical modeling and simulation of fouling of Nigerian crude oil equipment installations," *Leonardo Journal of Sci.*, Vol. 9, pp. 111-124, 2006.

[20]   C.B. Panchal, W.C. Kuru, C.F. Liao, W.A. Ebert, "Threshold conditons for crude oil fouling," in: T.R. Bott et al. (Eds.), *Understanding Heat Exchanger Fouling and its Mitigation*, 273, Begell House, New York, 1999.

[21]   G. B. Dickakian, S. Seay, "Asphaltene precipitation primary crude exchanger fouling mechanism," *Oil and Gas Journal*, Vol. 86, pp. 47-50, 1988.

[22]   A. P. Watkinson, "Chemical reaction fouling of organic fluids," *Chem. Eng. Tech.*, Vol. 15, pp. 82-90, 1992.

[23]   B. J. Fuhr, C. Cathrea, L. Coates, H. Kalra, A. I. Majeed, "Properties of asphaltenes in waxy crude," *Fuel*, Vol. 70, pp. 1293-1297, 1991.

[24]   G. A. Lambourn, M. Durrieu, "Fouling in crude oil preheat trains," in: *Heat Exchangers - Theory and Practice*, J. Taborek et al. (Eds.), Hemisphere Publishing Corporation, pp. 841-852, 1983.

[25]   J.G. Knudsen, L. Dahcheng, W.A. Ebert, "The determination of the threshold fouling curve for a crude oil," in: T.R. Bott et al. (Eds.), *Understanding Heat Exchanger Fouling and its Mitigation*, 265, Begell House, New York, 1999.