CHEMICAL ENGINEERING TRANSACTIONS

VOL. 29, 2012

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at: www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Hon Loong Lam, Jiří Jaromír Klemeš

ISBN 978-88-95608-20-4; **ISSN** 1974-9791

DOI: 10.3303/CET1229241

Mitigation of Fouling in Plate Heat Exchangers for Process Industries

Petro O. Kapustenko*[a], Leonid L. Tovazhnyansky[a], Olga P. Arsenyeva[b], Anna P. Yuzbashyan[b]

[a]National Technical University "KhPI", 21 Frunze Str., 61002 Kharkiv, Ukraine;
[b]AO "Sodrugestvo–T", Krasnoznamenniy per. 2, k. 19, 61002 Kharkiv, Ukraine;
petro.kapustenko@kpi.kharkov.ua

Among different methods for mitigation of fouling the use of enhanced heat transfer surfaces is one of the major categories. Heat transfer enhancement is one of the main features of Plate Heat Exchanger (PHE) and mitigation of fouling render even more advantages to the use of this type of heat transfer equipment in different applications at process industries. In present study the period of fouling deposit formation in PHEs and influencing it factors are investigated. To estimate development of fouling thermal resistance with time the Equation is proposed. The pictures of fouling deposit distribution along the plate of PHE for fresh water heating are analyzed. The conclusion is, that for scaling fouling there exist some threshold conditions on wall shear stress, wall temperature and salt content, after which fouling deposition starts. The expression of fouling deposition rate proposed for the tubes with heat transfer enhancement by Yang and Crittenden is used. Comparison with available in literature experimental data have shown good agreement with proposed model, when one its parameter is adjusted. For certain cooling water circuit of a big industrial enterprise this parameter can be determined by data about fouling in one heat exchanger. After that the model can be used for prediction of cooling water fouling development with a time in all heat exchangers of this circuit.

1. Introduction

When integrating renewables, polygeneration and CHP units with traditional sources of heat in industry and the communal sector, there is a requirement to consider minimal temperature differences in heat exchangers of reasonable size, as it is shown by Fodor et al. (2010). Such conditions can be satisfied by a plate heat exchanger (PHE). The design and operation of PHE are well described in literature, see e.g. book by Wang et al. (2007). There is also observation of much higher heat transfer coefficients and lower fouling tendencies in PHEs channels of complex geometry. Such effect is similar to that observed in enhanced tubes, see e.g. (Kukulka et al., 2010; Wang et al., 2009).
The threshold model describing dynamic behavior of fouling in enhanced tubes was proposed by Yang and Crittenden (2012). In a study presented here we are using this model and data on asymptotic fouling in PHE channels.

2. Fouling after long time of operation

In many cases of practical applications the fouling is stabilizing after some time of operation, showing asymptotic character. In Figure1 are shown two sides of the plate, which has worked about one year at DH system of Kiev (Ukraine) for tap water heating. In this case scaling is predominant fouling

Please cite this article as: Kapustenko P. O., Tovazhnyansky L. L., Arsenyeva O. P. and Yuzbashyan A. P., (2012), Mitigation of fouling in plate heat exchangers for process industries, Chemical Engineering Transactions, 29, 1441-1446

mechanism. Side a) was in contact with DH water. Here only particulate fouling takes place. The plate has some deposits which are almost evenly distributed along its length, with some increase towards the entrance of hot medium. It can be attributed to higher strength of the deposits at higher temperatures. Side b) of the plate was in contact with fresh water heated from 5÷10 °C to 57 °C for domestic hot water supply. On this side the plate surface near the entrance of cold fresh water clean, the deposits start and grow significantly towards the hot water exit with increase of water and wall temperatures. It can be judged by examining the pictures of fouling deposit distribution on small plate areas along the plate presented in Figure 2. We can conclude that for scaling fouling there exist some threshold conditions on water temperature and salt content, after which fouling deposition starts. So when the scaling is possible for cooling water of enterprise circuit, the outlet temperature should be kept below certain level, which depends of cooling water quality of that enterprise.

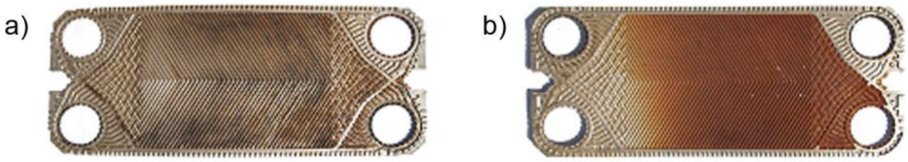

Figure 1: Two sides of the plate after one year in operation for tap water heating in DH system (fresh water coming from the left, heating DH radiator water from the right)

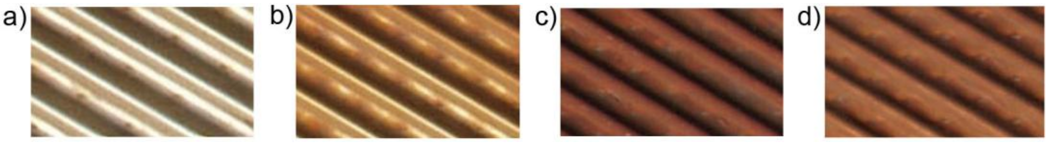

Figure 2: Photos of four parts of plate surface a, b, c, d – from heated water inlet to its exit from the PHE channel

The models describing the asymptotic fouling mechanisms are based on prediction of fouling accumulation rate as a difference between fouling deposition term φ_d and fouling removal term φ_r:

$$\frac{d\delta}{dt} = \varphi_d - \varphi_r \tag{1}$$

where δ – fouling thickness, mm; t – time, s.

In article by Arsenyeva (2011) it was shown that for the same fouling properties of fluid the asymptotic value of fouling thermal resistance, knowing the fouling deposit thermal conductivity λ_f , can be expressed as:

$$R_f^* = B^* \cdot \tau_w^{-1} \tag{2}$$

where $B^* = \varphi_d^*/(b^* \cdot \lambda_f^*)$.The values of coefficient B^* were estimated for a number of fluids, for which the experimental data on fouling were reported in literature. For conditions of tests reported for PHE channels by by Karabelas et al, (1997) $B^* = 3.5\cdot10^{-4}$ K·s/m; for tests by Bansal et al. (2000, 2008) $B^* = 2.05\cdot10^{-4}$ K·s/m; for tests by Zhenhua et al. (2008) $B^* = 1.45\cdot10^{-4}$ K·s/m. The wall shear stress on a main corrugated field of inter-plate channels was estimated using Equation proposed by Arsenyeva et al. (2011). The share of friction losses ψ estimated by Equation proposed in paper by Kapustenko et al. (2011).

3. The time dependence of fouling deposits

Let's assume that the removal term φ_r during all time of fouling deposit formation is

$$\varphi_r = b \cdot \tau_w \cdot \delta \tag{3}$$

where *b* is proportionality coefficient, [1/(Pa·s)].

The development of fouling thermal resistance R_f in time for deposit thermal conductivity λ_f can be described by Equation, which directly following from Eq.(1):

$$\frac{dR_f}{dt} = \frac{\varphi_d}{\lambda_f} - b \cdot \tau_w \cdot R_f \tag{4}$$

When φ_d, b, λ_f and τ_w not depend of the time of deposit formation *t* and deposit thickness δ, the integration of linear ordinary differential Equation (8) cause no problem. For approximate solution at time *t* we can use time averaged values of these parameters on time period 0÷*t*. Then the fouling thermal resistance at time *t* after integrating Eq. (4):

$$R_f(t) = \frac{B}{\tau_w} \cdot \left[1 - \exp\left(1 - \frac{\varphi_d}{B} \cdot \tau_w \cdot t\right)\right], \tag{5}$$

where $B = \varphi_d/(b \cdot \lambda_f)$.

To estimate coefficient B, we can take its value at asymptotic fouling conditions $B=B^*$. As it was observed on examining fouling deposit distribution along the plate, the water fouling process in PHEs exhibits the threshold behavior. In a last decade the concept of “threshold fouling” was to much extent investigated for tube-side crude oil fouling. After first introduced by Ebert and Panchal (1997), this concept was developed in papers by Polley et al. (2002), Young et al. (2011). Yang and Crittenden (2012) have proposed the application of their model also for the tubes with heat transfer enhancement. The deposition term in their model is expressed as:

$$\varphi_d = \frac{A_m \cdot C_f \cdot u \cdot T_s^{2/3} \cdot \rho^{2/3} \cdot \mu^{-4/3}}{1 - B_m \cdot u^3 \cdot C_f^2 \cdot \rho^{-1/3} \cdot \mu^{-1/3} \cdot T_s^{2/3} \cdot \exp(E/(R \cdot T_s))} \tag{6}$$

here T_s –surface temperature, K; ρ – fluid density, kg/m^3; μ - fluid dynamic viscosity, Pa·s; R=8.314 J/(mol·K) – universal gas constant; C_f – fanning friction factor; u – average flow velocity, m/s. The parameter values that give the best fittings with experimental data for investigated crude oil are:

E = 52100 J/mol; $A_m = 7.93 \cdot 10^{-10}$ kg$^{2/3}$K$^{1/3}$m$^{5/3}$(kW)$^{-1}$s$^{-1/3}$h^{-1}; $B_m = 1.8 \cdot 10^{-5}$m$^{13/3}$kg$^{2/3}$s$^{8/3}$K$^{-2/3}$.

For intensified heat transfer the velocity u is defined as equivalent velocity, which is velocity in a bare tube that gives the same wall shear stress as in a tube with heat transfer enhancement of a same internal diameter operating at a different average fluid velocity. Let’s assume that the above is justified also for PHE channel and bare tube of the same equivalent diameter *de*.

For developed turbulent flow in a straight bare tube with internal diameter *de* the Fanning friction factor can be calculated by Blazius Equation:

$$C_f = 0.0791 \cdot (u \cdot \rho \cdot de/\mu)^{-0.25} \tag{7}$$

Wall shear stress in a straight bare tube:

$$\tau_w = C_f \cdot \rho \cdot u^2/2 \tag{8}$$

For known shear stress in channel with enhanced heat transfer the equivalent velocity in bare tube can be calculated from Eq.(8), substituting C_f from Eq.(7):

$$u = \left(\frac{\tau_w \cdot de^{0.25} \cdot 2}{\mu^{0.25} \cdot \rho^{0.75} \cdot 0.0791}\right)^{\frac{1}{2-0.25}} \tag{9}$$

The product of C_f and *u* from Eq.(8):

$$P_{cu} = C_f \cdot u = \frac{2 \cdot \tau_w^{1-\frac{1}{1.75}}}{\rho} \left(\frac{de^{0.25} \cdot 2}{\mu^{0.25} \cdot \rho^{0.75} \cdot 0.0791} \right)^{-\frac{1}{1.75}} \tag{10}$$

Eliminating C_f and u from Eq.(6),using Eq.(8) and Eq.(10) we obtain expression for deposition term through wall shear stress:

$$\varphi_d = \frac{A_m \cdot P_{cu} \cdot T_s^{2/3} \cdot \rho^{2/3} \cdot \mu^{-4/3}}{1 - B_m \cdot P_{cu} \cdot 2 \cdot \tau_w \cdot \rho^{-4/3} \cdot \mu^{-1/3} \cdot T_s^{2/3} \cdot \exp(E/(R \cdot T_s))} \tag{11}$$

Using Eq.(11) and the value of B^*, which was presented in previous chapter by analysis of asymptotic fouling thermal resistance data, we can calculate fouling thermal resistance at time *t* by Eq.(5). As the properties of crude oil and water considerably different, the empirical parameters A_m, B_m and E should be corrected to fit experimental data for water fouling.

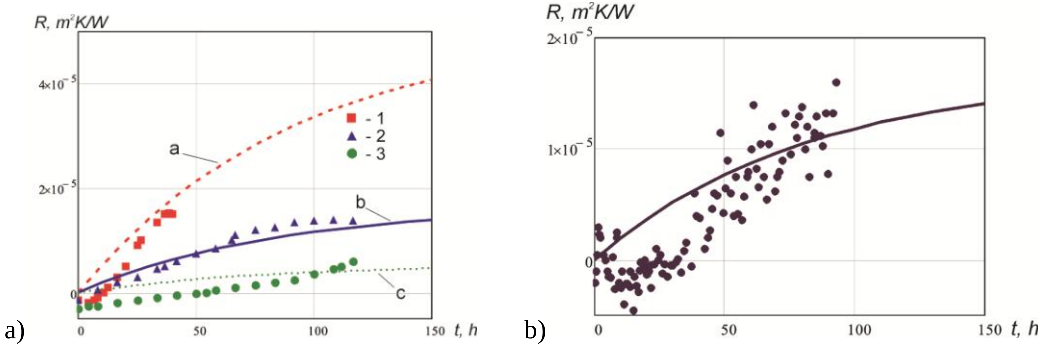

Figure 3: Fouling thermal resistance at PHE channel with β = 60° under calcium sulfate precipitation: a) data of Bansal et al. (2000) – 1 and line a – w = 0.183 m/s; 2 and line b – w = 0.352 m/s; 3 and line c – w = 0.667 m/s; b) data of Bansal et al. (2008) w = 0.352 m/s

To fit experimental data for precipitation of calcium sulfate in PHE channels, presented by Bansal et al. (2000) we have adjusted only one parameter A_m. For the value $A_m = 6.5 \cdot 10^{-12}$ $kg^{2/3}K^{1/3}m^{5/3}W^{-1}s^{-1/3}h^{-1}$ the computed thermal resistances of fouling at different flow velocities are presented by curves in Figure 3a in comparison with experimental data taken from a graph at the paper. There are also data for calcium sulfate fouling in PHE presented for one flow velocity by Bansal et al. (2008). Taken from a graph at that paper data are shown in Fig.3b. Counting on scattering of the data, the compliance with calculation by presented model (solid line on Figure 3b) is rather good. The lower values at initial period can be explained as it was done by the authors of discussed paper. The initial delay period may be required for the formation of the deposit on the heat transfer surface.

The calcium carbonate scaling in annular smooth channel between enclosing tube of 22 mm inner diameter and inside tube of 16 mm outer diameter was investigated by Zhenhua et al. (2008). These data for two different velocities are fitted by the model at $A_m = 1.5 \cdot 10^{-10}$ $kg^{2/3}K^{1/3}m^{5/3}W^{-1}s^{-1/3}h^{-1}$ (see Figure 4a). Other model parameters B_m and E not changed.

The particulate fouling in PHE channels from water with suspended calcium carbonate particles was investigated by Karabelas et al. (1997). In Figure 4b presented the comparison of these data with prediction by model (solid lines calculated for $T_s = 37\ ^oC$). All parameters in Eq.(11) are the same as in calculations for Fig.4a. It let to conclude that the values of parameters in Eq.(11) for similar salt and impurities content have close numerical values.

Equation (11), beside wall shear stress and physical properties of the fluid, accounts for the effect of surface temperature T_s.. We can guess that the coefficient B depends of the surface temperature in the same way. For two surface temperatures T_{s1} and T_{s2}, when all other conditions the same, let us assume:

$$B(T_{s1})/B(T_{s2}) = \varphi_d(T_{s1})/\varphi_d(T_{s2}). \tag{12}$$

The data for calcium carbonate scaling at three different wall temperatures, when velocity and salt concentration are the same, are presented by Zhenhua et al. (2008). These data are shown on Fig.4c. The lines on the graph are calculated by Eq.(5) using Eq.(11) and relation (12). The value of coefficient B is taken from previous estimation for data of this paper, which were taken at T_s = 51 ^oC. The prediction of the asymptotic fouling thermal resistance is fairly good. The description by the model of time dependence is reasonable, with some overestimation of fouling thermal resistance.

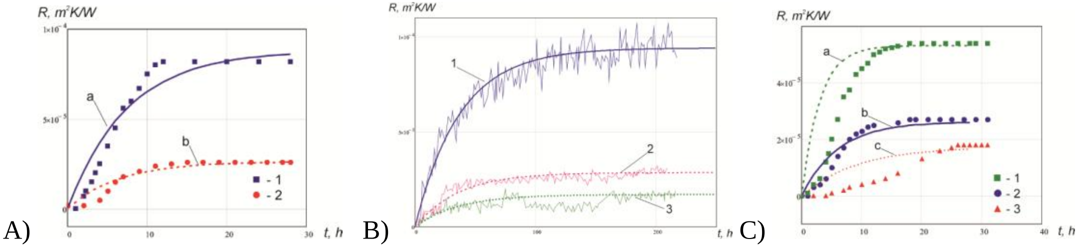

Figure 4: A) Fouling thermal resistance at calcium carbonate scaling in annular channel after Zhenhua et al. (2008): 1 and line a – w = 0.6 m/s; 2 and line b – w = 1.2 m/s; B) Particulate calcium carbonate fouling thermal resistance at PHE channel with β = 30^o after Karabelas et al. (1997): 1 and line a – w = 0.5 m/s; 2 and line b – w = 1.0 m/s; 3 and line c – w = 1.35 m/s; C) Fouling thermal resistance at calcium carbonate scaling in annular channel [11] w = 1.2 m/s: 1 and line a – T_s = 64 ^oC ; 2 and line b – T_s = 51 ^oC;3 and line c – T_s = 44 ^oC

4. Discussion of the results

Analyzing the results we can conclude that presented mathematical model is capable to predict fouling thermal resistance for precipitation and particulate fouling at different flow velocities and surface temperatures. The model can be used for PHEs with enhanced heat transfer and also for straight channels without heat transfer intensification. It predicts the effects of wall shear stress and surface temperatures, but the influence of salts concentrations and solid particles content and sizes is not accounted.

The big industrial enterprises usually have quite a big numbers of heat exchangers, which are using water of the centralized cooling water circuit of the enterprise. The salts and solid particles contents in this water are the same for all heat exchangers. Therefore, by monitoring water side fouling development in one heat exchanger (in PHE or inside tubes of tubular heat exchanger) we can estimate parameters B and A_m in proposed here mathematical model. It will enable to account for cooling water fouling in all PHEs of this enterprise. The threshold values of wall shear stress and surface temperature can be calculated. After that in a design and selection of PHEs for the enterprise the wall shear stress should be kept higher than threshold value, or maximal if to reach threshold is not possible. The wall surface temperature must be kept lower threshold value, or minimal. When the conditions to prevent fouling completely cannot be reached, the asymptotic fouling thermal resistance should be calculated by the model and included into design of the PHE.

5. Conclusion

On initial stage of fouling formation it can be described by “threshold model” proposed for bare tubes and tubes with enhanced heat transfer by Yang and Crittenden (2012). For correct predictions of fouling thermal resistance by this model it is necessary to determine experimentally for given cooling water fouling properties one model parameter. For certain cooling water circuit of a big industrial enterprise this parameter can be determined by data about fouling in one heat exchanger.

In present form the proposed mathematical model can give accurate results only having some reference point for cooling water concerned. It does not account for salt content and solid particles size and concentrations effects on fouling thermal resistance. To estimate fouling thermal resistance just on a data of water purity and chemical content more experimental data are needed. Important that the data obtained for smooth channels can be used directly for PHEs, utilizing proposed approach.

Acknowledgement

The support of EC Project INTHEAT (contract № FP7-SME-2010-1-262205) is sincerely acknowledged.

References

Arsenyeva O.P., 2011, Calculation of thermal resistance for fouling on cooling water side in plate heat exchangers working at industrial enterprises. Integrated Technologies and Energy Saving. (4): 43 – 47 (in Russian).

Arsenyeva O., Tovazhnyansky L., Kapustenko P., Khavin G., 2011, The generalized correlation for friction factor in crisscross flow channels of plate heat exchangers, Chemical Engineering Transactions, 25, 399–404.

Bansal B, Muller-Steinhagen H, Xiao Dong Chen, 2000, Performance of plate heat exchangers during calcium sulphate fouling — investigation with an in-line filter. Chemical Engineering and Processing, 39, 507–519.

Bansal B, Xiao Dong Chena, Muller-Steinhagen H., 2008, Analysis of ‘classical’ deposition rate law for crystallisation fouling. Chemical Engineering and Processing, 47, 1201–1210.

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

Fodor, Z., Varbanov, P., Klemeš, J., Total site targeting accounting for individual process heat transfer characteristics, Chemical Engineering Transactions, 2010, 21; 49–54.

Kapustenko P., Arsenyeva O., Dolgonosova O., 2011, The Heat and Momentum Transfers Relation in Channels of Plate Heat Exchangers, Chemical Engineering Transactions, 25, 357–362.

Karabelas A.J., Yiantsios S.G., Thonon B., Grillot J.M., 1997, Liquid side fouling of Heat Exchangers. An Integrated R&D Approach for Conventional and Novel Designs. Applied Thermal Engineering, 7 (8-10), 727 – 737.

Kukulka D.J., Czechowski H., Kukulka P.D.. 2010, Factors Associated With Fouling in the Process Industry. Heat Transfer Engineering, 31(9), 782-787

Polley G.T., Wilson D.I., Yeap B.L., Pugh S.J., 2002, Use of crude oil threshold data in heat exchanger design, Appl Therm Eng, 22, 763–776.

Panchal C.B., Knudsen J.G., 1998, Mitigation of Water Fouling: Technology Status and Challenges. Advances in Heat Transfer, 31, 431 – 474.

Wang, L., Sunden, B., Manglik, R.M., 2007, PHEs. Design, Applications and Performance, WIT Press, Southhampton, UK.

Wang Q.W., Lin, M., Zeng, M., 2009, Effect of lateral fin profiles on turbulent flow and heat transfer performance of internally finned tubes, Applied Thermal Engineering, 29, 3006-13

Young A., Venditti S., Berrueco C., Yang M., Waters A., Davies H., Hill S., Millan M. & Crittenden B., 2011, Characterization of Crude Oils and Their Fouling Deposits Using a Batch Stirred Cell System, Heat Transfer Engineering, 32 (3-4), 216-227.

Yang M, Crittenden B., 2012, Fouling thresholds in bare tubes and tubes fitted with inserts. Applied Energy, 89, 67–73

Zhenhua Quan, Yongchang Chen and Chongfang Ma, 2008, Experimental Study of Fouling on Heat Transfer Surface During Forced Convective Heat Transfer. Chinese Journal of Chemical Engineering, 16(4), 535–540.