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Investigation of Fouling in Plate Heat Exchangers at Sugar Factory

Olexiy V. Demirskyy*[a], Petro O. Kapustenko[a], Gennadii L. Khavin[b], Olga P. Arsenyeva[a], Olexandr I. Matsegora[b], Sergey K. Kusakov[b], Igor O. Bocharnikov[a], Vladimir I. Tovazhnianskyi[a]

[a]National Technical University “Kharkiv Polytechnic Institute”, 21 Frunze Str.; 61002 Kharkiv; Ukraine
[b]AO SODRUGESTVO-T LLC, 2 Krsnoznamenny Per.; 61002 Kharkiv; Ukraine
o.p.arsenyeva@gmail.com

The fouling formation in heat transfer equipment is the complex process, which is determined by the physical properties of the heat carrier, material of the unit and hydraulic characteristics of the flow. The mathematical model based on the asymptotic behaviour of water fouling is examined. The fouling process supposes the net rate of fouling accumulation as the difference between the fouling deposition rate and the fouling removal rate. The relation for predicting the fouling resistance dynamics during the time is proposed. The investigation of precipitation and particulate deposition in purified juice heating PHE for the first stage evaporation, which operates in sugar plant, was examined. In this position M15M plate heat exchanger produced by Alfa Laval is used. The analysis and mathematical simulation of the experimental data are presented. For the juice heaters the content of fouling deposition is mostly the calcium salts as calcium carbonates and sulphates. The parameters of the equation for deposition term estimation were determined for the regarded heat carrier. It allows to determine the deposition term and to simulate the fouling formation in time. The comparison of the experimental data and mathematical calculations showed a good agreement. The proposed mathematical model enables to predict the fouling formation behaviour in PHE as purified juice heater and to determine the operation term for the cleaning of this unit. Basing on the observed model, the software, which enables to determine the periods of PHE cleaning during the operation was developed. The comparison of the industrial measurement data with calculation results is presented.

1. Introduction

Energy saving, pollution reduction and energy optimization are intrinsically interrelated and this cluster of issues constantly grows in importance (Klemeš and Varbanov, 2013). One of the ways to solve these problems is the use of efficient compact heat exchangers with enhanced heat transfer (Gough et al., 2013), among which Plate Heat Exchanger (PHE) are one of the most promising types (Klemeš et al., 2015). Their flexibility allows finding economically favorable solutions in different processes of heat utilisation, as shown by e.g. Arsenyeva et al. (2016). But the fouling formation on enhanced heat transfer surfaces of plates can lead to energy losses, additional power consumption and the costs of cleaning. This practical operational problem is a significant challenge in the progression towards sustainable development, as emphasized by Crittenden et al. (2015).

The fouling deposition process in PHEs occurs at developed turbulent flow and thus intensive hydrodynamic conditions. In PHE for heating thin sugar juice at evaporation station of sugar factory the deposition starts at the initial operation period. As a rule sediments are rather friable and thin. Further the properties of the deposits change and the mechanical strength increases. Most of the models describing the 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 (Arsenyeva et al., 2013).

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It was made the assumption that all effects contributing to fouling growth are accounted for by deposition term φ_d and mitigation are accounted by removal term φ_r.

$$d\delta / dt = \varphi_d - \varphi_r \qquad (1)$$

where φ_d is the fouling deposition term; φ_r is the fouling removal term; δ is the fouling thickness, mm; t is the time, s.
When the values φ_d are equal φ_r the layer of deposits not grow. It is possible in two cases: 1) the removal is stronger than the adhesion of fouling to the wall surface, only after some threshold conditions the fouling accumulation can start, as shown by Yang and Crittenden (2012); 2) the removal rate is directly proportional to thickness of deposits δ, or deposition rate is inversely proportional to δ. In this case after some time t^* the deposition thickness is stabilizing to certain asymptotic value δ^*.
In sugar production process at thin juice heating unit the deposits in heat exchangers occurs of precipitation and particular deposition fouling formation mechanisms and they mostly consist of crystal formations of calcium carbonate, gypsum, silicon and organic substances. The developed turbulent flow inside the channels between corrugated plates of plate heat exchangers has the complex structure with the fields of high and low velocities in channel cross-section. The low velocity is typical for the fields near the contact points of the adjacent plates or plate edges. These points are the centers of crystallization.
The present paper describes the developed mathematical model of heat transfer in plate heat exchangers accounting the fouling formation deposit in the unit. The basic mathematical relations are obtained and the constant parameters are analysed and evaluated from the series of experiments carried out with PHE unit operating for thin juice heating in sugar plant.

2. Process description

The sugar production process with 5-effect evaporation station is under consideration. For efficient energy consumption and process intensification the thin juice is pre-heated before the evaporation (Figure 1).

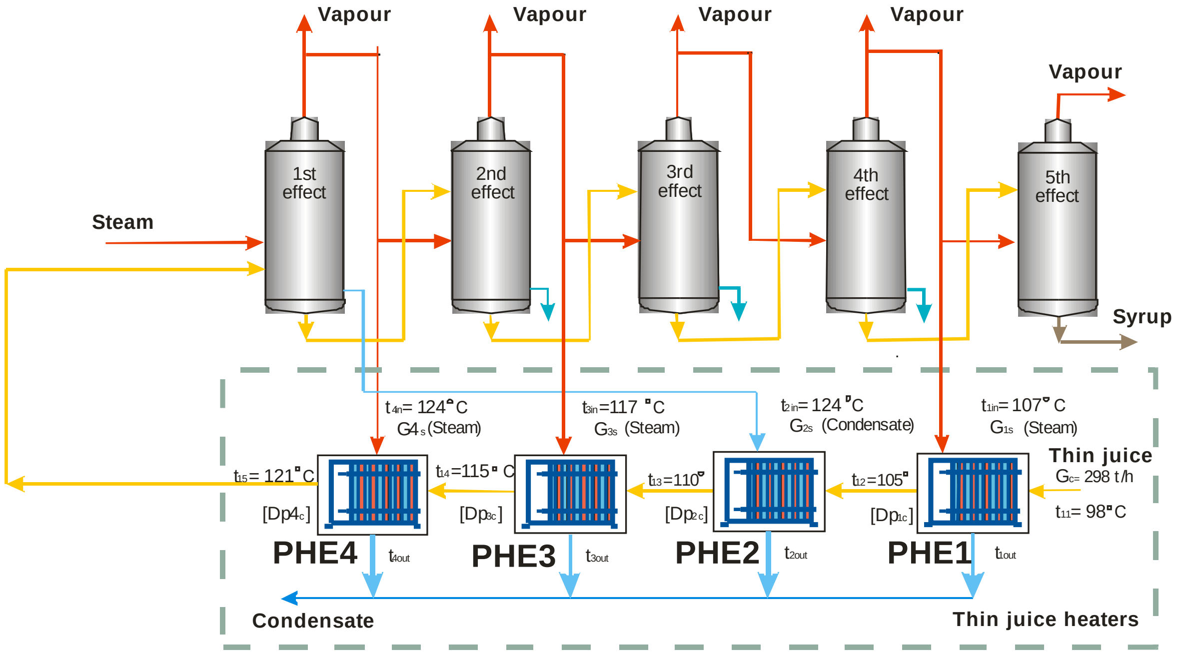

Figure 1: Flowsheet of 5-effect thin juice evaporation station

The existing heat exchangers network (HEN) of evaporation unit of the sugar factory uses plate heat exchangers for the thin juice heating. In two positions (PHE3, PHE4) the Alfa Laval equipment of M15M type is used, and in position PHE1 the GEA plate heat exchanger is installed. The hot heat carrier for positions PHE1,3,4 is the vapour from the previous evaporation effects, and the PHE2 unit is heated by condensate from the 1st evaporation effect. All heat exchangers are heated by the steam from the evaporation effects with the temperature from 107 ºC to 124 ºC. The design of heat exchangers for such conditions should unsure the operation under vapour condensation process providing low pressure drop and enough velocity of flow movement in the channels to prevent fouling formation. The design of heat exchanger for PHE2 position was carried out. It was selected Alfa Laval plate-and-frame heat exchanger of M15M type with 150 heat transfer plates, which was installed at sugar plant. From the beginning of operation the heat and hydraulic characteristics of this heat exchanger were monitored.

3. Experimental investigation of fouling formation

The measurements were taken during the maintenance cleaning for two heat exchangers: PHE1 and PHE2. The PHE1 unit was cleaned 3 times: the 1st time was after 10 days of operation, the 2nd after 50 days of operation, and the 3rd after 80 days of operation. The PHE2 was cleaned 2 times: after 15 days of operation, then after 90 days of operation. It enabled to examine the fouling formation process inside this unit and experimentally investigate it.
The fouling formation was studied for the PHE2 heat exchanger. The operating conditions for PHE2 unit are as follows:

- The cold heat carrier is thin juice;
- The hot heat carrier is steam condensate after the 1st effect evaporator;
- The average flowrate of thin juice is G_2=270 m^3/h;
- The average operating temperatures:
  - The inlet temperature of thin juice is t_{21}=105 °C; the outlet temperature of thin juice is t_{22}=110 °C;
  - The inlet temperature of condensate is t_{11}=124 °C;
- The operation time before the full stop was 130 days.

PHE2 heats the thin juice by the heat from condensate. The heat exchanger was operating 13 days after the last cleaning. The first measurement took place after the start-up, which for this case took a long period because of several stops of the equipment. And the stable operating conditions started after 96 h of working. The operating parameters for different time periods during 13 days of operation are presented in Table 1.

Table 1: The operating parameters of PHE2 heat exchanger

Parameters	96 h	144 h	216 h	264 h	312 h
The flowrate of thin juice, m^3/h	265	260	270	277	265
Inlet temperature of thin juice, ºC	103	101	100.5	102	101.7
Outlet temperature of thin juice, ºC	108	105	106	107	106
Condensate flowrate, m^3/h	65	63	61	66	64
Inlet temperature of condensate, ºC	123.5	123.5	123.5	123.5	123.5
Outlet temperature of condensate, ºC	105	102.8	104.8	106.1	104.8

After 130 days of operation the unit was disassembled and the fouling formation examined. It was estimated, that the existing deposition is in form of mechanical impurities and fibers. The type of mechanism of fouling formation is precipitation and particulate fouling. The difference between the hot and cold sides is great. The deposits mostly occur on the thin juice side. The deposits on condensate side are absent. The localization of deposits takes place mostly in the distribution area of the juice inlet at the plates, where the most heavily fouling takes place and many mechanical impurities are located in collectors. The disassembling of PHE2 showed that sediments mostly relate to the fouling appeared by scaling mechanism.
The obtained data were analysed to calculate the fouling thermal resistance (R_f) value at time t, depending from the clean and dirty heat transfer coefficients, according to Eq(1).

$$R_f = \frac{1}{K_f} - \frac{1}{K} \tag{2}$$

where K_f is the overall heat transfer coefficient accounting the layer of fouling sediments, W/(m^2·K); K is the heat transfer coefficient of PHE with clean surface, W/(m^2·K).
The value of overall heat transfer coefficient is calculated as:

$$K = \left(\frac{1}{h_{hot}} + \frac{1}{h_{cold}} + \frac{\delta_w}{\lambda_w} \right)^{-1} \tag{3}$$

where h_{hot} and h_{cold} are the film heat transfer coefficients for hot and cold sides, W/(m^2·K); δ_w is the thickness of the plate, m; λ_w is the heat conductivity of the plate material, W/(m·K).

The calculations were carried out according to equations presented in Arsenyeva et al. (2012). The results for overall heat transfer calculated for the observed time periods are presented in Table 2.

Table 2: The calculated values of overall heat transfer coefficients for clean and contaminated surface

Time τ, hours	Fouling thermal resistance $\times 10^4$, m^2 K / W	Heat transfer coefficient for clean surface K, W/(м^2·K)	Heat transfer coefficient with fouling K_f, W/(м^2·K)	Relation $K_f/K \times 100$ %
96	0.27	2,673	2,493	93.3
144	1.10	2,220	1,784	80.4
216	1.55	2,668	1,887	70.7
264	1.67	2,686	1,853	69.0
312	1.9	2,382	1,640	68.8

The change of the overall heat transfer coefficient with fouling thermal resistance during the time in comparison with clean surface was analysed (Figure 2). The calculations were made based on the experimental data (points on Figure 2) for 960 h of operation. The dependence shows the asymptotic behaviour of fouling formation and the maximal decrease of heat transfer coefficient is expected to be within 60% from the initial clean value. For prediction the fouling threshold value the corresponding mathematical model was developed.

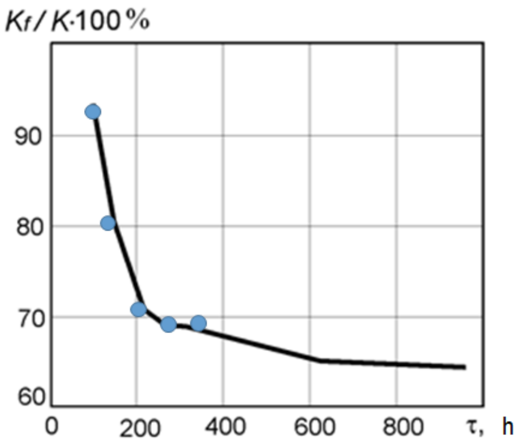

Figure 2: The ratio between heat transfer coefficients for clean and contaminated surface in time

4. The mathematical modelling of fouling process

4.1 The dynamic formation of fouling deposits

The asymptotic behavior of fouling deposits on heat transfer surfaces has been observed by many researchers, see Panchal and Knudsen (1998). It usually happens when the stream velocity is high enough to ensure a certain level of shear stress τ_w on the wall. It assumes that at asymptotic fouling condition the fouling growth is occurred by the deposition rate term φ_d^* and all mitigation effects by the removal rate term φ_r^*. It is assumed that φ_r^* is proportional to shear stress at the wall raised to a certain power m and to the deposit thickness δ^*. Hence:

$$\varphi_r^* = b \cdot \tau_w^m \cdot \delta^* \tag{4}$$

where b is a proportionality coefficient, [1/(Pa·s)]. When the deposition thickness reaches its asymptotic value, its time derivative equals zero and from Eq(1) follows:

$$\delta^* = \varphi_d^* / (b \cdot \tau_w^m) \tag{5}$$

Knowing the fouling deposit thermal conductivity, λ_f, the asymptotic value of fouling thermal resistance can be expressed as follows:

$$R_f^* = B^* \cdot \tau_w^{-m} \quad (6)$$

where $B^* = \varphi_d^*/(b^* \cdot \lambda_f^*)$.
The development of the fouling thermal resistance R_f with time for the deposit of thermal conductivity λ_f can be described by the following equation:

$$\frac{dR_f}{dt} = \frac{\varphi_d}{\lambda_f} - b \cdot \tau_w \cdot R_f \quad (7)$$

For an approximate solution at time *t* it is possible to use time averaged values of these parameters for the time period 0 to *t*. Then the fouling thermal resistance at time *t* after integrating Eq(7) is as follows:

$$R_f(t) = \frac{B}{\tau_w} \cdot \left[1 - \exp\left(1 - \frac{\varphi_d}{B} \cdot \tau_w \cdot t\right)\right] \quad (8)$$

In this equation, $B = \varphi_d/(b \cdot \lambda_f)$. To estimate the coefficient *B*, it is possible to take its value at asymptotic fouling conditions, i.e. $B=B^*$.
For corrugated channels of plate heat exchangers the wall shear stress on a main corrugated field of inter-plate channels is calculated according to the following relation:

$$\tau_w = \zeta_s \cdot \psi \cdot \rho \cdot w^2 / 8 \quad (9)$$

The friction factor for the total pressure losses (due to friction on the wall and form drag) are estimated using the relation from paper by Arsenyeva et al. (2011). The share of friction losses ψ is estimated using the equation by Kapustenko et al. (2011).
As showed the experimental measurements of plate heat exchanger for thin juice heating before the evaporation at sugar plant, the fouling deposit distribution along the plate exhibits the threshold behaviour. Using the model proposed by Yang and Crittenden (2012), the deposition term can be expressed by the following equation:

$$\varphi_d = \frac{A_m \cdot P_{cu} \cdot T_s^{2/3} \cdot \rho^{2/3} \cdot \mu^{-4/3}}{1 + B_m \cdot P_{cu} \cdot 2 \cdot \tau_w \cdot \rho^{-4/3} \cdot \mu^{-1/3} \cdot T_s^{2/3} \cdot \exp(E/(R \cdot T_s))} \quad (10)$$

where T_s is the surface temperature, K; ρ is the fluid density, kg/m^3; μ is the fluid dynamic viscosity, Pa·s, *R* is the universal gas constant equal to 8.314 J/(mol·K), P_{cu} is calculated according to Eq(11), in which D_{eq} is the channel equivalent diameter, m. In this relation the empirical parameters A_m, B_m and *E* are depend from the physical property of heat carrier. For the thin juice they was estimated basing on the experimental data of the observed plate heat exchanger.

$$P_{cu} = \frac{2 \cdot \tau_w^{1-\frac{1}{1.75}}}{\rho} \left(\frac{D_e^{0.25} \cdot 2}{\mu^{0.25} \cdot \rho^{0.75} \cdot 0.0791}\right)^{-\frac{1}{1.75}} \quad (11)$$

4.2 Estimation of empirical parameters for thin juice

Based on the experimental data the fouling thermal resistance was calculated using Eq(8) for 5 measurement points (Table 2). To obtain the prediction in any time intervals the empirical parameters A_m, B_m and E of Eq(10) were evaluated numerically. For the thin juice the following parameters can be used: *E* = 52,100 J/mol; $A_m = 1.9 \cdot 10^{-11}$ kg$^{2/3}$K$^{1/3}$m$^{5/3}$(kW)$^{-1}$s$^{-1/3}$h^{-1}; $B_m = 1.2 \cdot 10^{-4}$ $1.8 \cdot 10^{-5}$m$^{13/3}$kg$^{2/3}$s$^{8/3}$K$^{-2/3}$; $b = 2.3 \cdot 10^{-4}$ 1/(Pa·s).
The prediction of fouling deposit in plate heat exchanger operating as thin juice heater for the thin juice side is presented in Figure 3 by the line. Points are the experimental data. The deviation between calculated data and experimental results is within 10 %, excluding the first experimental point, what can be explained by the initial stop of the heat exchanger.
The fouling formation prediction also can help to organize the proper operating period between maintenance. Expensive cost related to the maintenance shutdown impose that it should be planned carefully and heat transfer equipment in operation should stand the operating period between cleaning. According to the proposed model, from Figure 3 it can be seen, that after 650 h of operation the fouling resistance will reach the value 0.00029 m^2·K / W, what corresponds the 40 % decrease of heat transfer coefficient in comparison with the clean surface. Thus, it can be expected that approximately after 650 h of operation, the unit needs the cleaning.

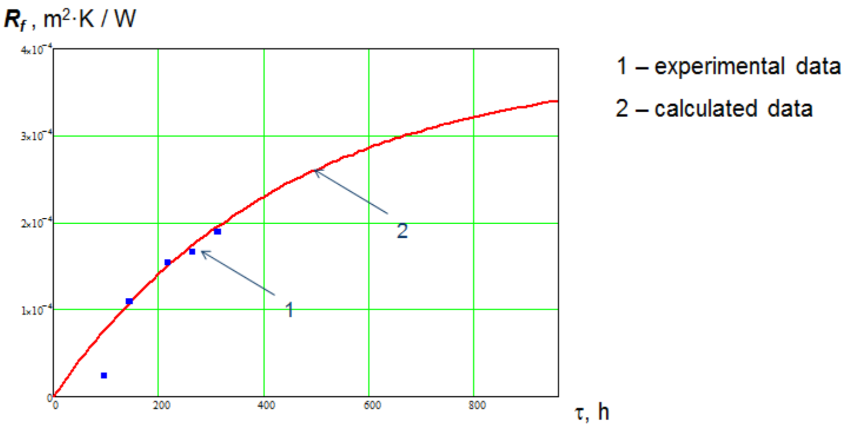

Figure 3: The prediction of fouling deposit thermal resistance of thin juice during time for plate heat exchanger

5. Conclusions

The proposed mathematical model enables to predict the fouling formation behavior in plate purified juice heater to determine the operation term for the cleaning of the unit. The comparison of the industrial measurement data with calculation results is presented. The deviation between experimental results and calculated values are within 10 %. The obtained mathematical model enables to simulate and design the parameters of plate heat exchangers accounting the deposits formation on the heat transfer surface, and can be used for energy saving reconstructions in the sugar and other industry.

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