

## SIMULATION OF THE PROCESS OF SCALING OF TUBE HEAT EXCHANGERS

L. S. Baran and Yu. S. Razladin

UDC 621.187.3

*A semiempirical model of the process of deposit formation on the inner surface of heat exchanger tubes is obtained. By experimental investigation, constants of the scaling process that close this model are obtained for carbonate-type deposits.*

The operating efficiency of heat exchange equipment depends on the state of the heat-transfer surface, which is mainly determined by the presence of a layer of deposits on the tube surface [1]. This fact predetermines the importance of simulating the dynamics of the scaling process for tubes; however, the current methods of this simulation, a survey of which is given in [2] and [3], are characterized either by incomplete consideration of the complex physicochemical transformations that accompany the process of scaling or by difficulties in quantitative estimation of this process.

The process of scaling can be classified by the following components of it:

crystallization (generation of crystallization nuclei, including those mixed with corrosion products, on microirregularities of the metal surface, which act as centers of deposit formation);

deposition (in proportion to the distance from the metal the process occurs by deposition of particles suspended in water onto the primary layer of crystals; this process is superimposed on crystallization and may have a catalytic effect on it);

buildup of organic substances (deposition of microorganisms and algae on a rough surface);

corrosion of metal.

The development of the scaling process can be represented in the following manner according to [2] and [3]. First, with clean and smooth tubes there is an induction period during which only minor deposition of scaling is observed. At some moment the active centers become so numerous that they begin to combine into a continuous coating, and the rate of scaling increases rapidly. Starting from this critical point, in the second step of the process of scaling the growth of the deposit occurs at a constant rate with subsequent asymptotic approach to some value. Owing to the diversity of salts of a fairly high concentration in the cooling water we observe a variety of crystalline formations, which leads to the appearance of irregular crystal aggregations with cavities between them in which suspended particles deposit. By entering into the noncompact crystal structure these particles decrease the shear strength of this structure.

In the third step of the process of scaling, by coating the crystal base, silt sediments form a loose and noncompact layer, which is periodically removed by shearing stresses in the liquid.

This three-step mechanism of the scaling process explains the presence of three prominent layers in the cross section of the deposit layer. The upper layer, consisting of sludge and silt particles that are mixed with some kind of crystalline matter, is laid freely and is the most sensitive to tangential stresses. The thin middle layer is represented by a crystallization front induced by a constant increase in temperature in operating with a constant heat flux. The lower layer is a certain crystalline formation produced when a large number of crystals of different crystalline substances that have nonuniformly distributed cavities merge.

The described mechanism of the scaling process shows that it is affected strongly by the following factors: the flow velocity, the liquid temperature, the material and its structure, the design of the equipment, and the chemical composition of the cooling water.

It is the last factor that presents a major difficulty in constructing a mathematical model of the process of scaling since for most once-through water-supply systems or circulating systems with cooling ponds no stability in the chemical composition of the scale is observed. The complexity of the physicochemical processes of tube scaling in these systems does not permit the establishment of a criterion that unambiguously describes the composition of the cooling water as a scale-forming factor. However, for cooling-tower systems inorganic mineral deposits are typical, investigation of which showed the approximate identity of the deposit composition in the tubes, in particular, that the CaO content is stable within 40-42%, and the unambiguous dependence of the process of deposition on the hardness  $H$  of the cooling water.

This fact permits the prediction of the kinetics of their growth for the given type of water-supply system. For this we describe the process of scaling on the basis of a material balance equation [4]:

$$\frac{1}{S} \frac{dm}{d\tau} = \Phi_d - \Phi_\tau. \quad (1)$$

A difference in the deposited substance concentrations can be considered a driving force of the process of deposition:

$$\Phi_d = K_p ((C_c - C_w)/(C_0))^n. \quad (2)$$

By using the Reitsner hypothesis of the similarity of thermal and diffusion layers [4]:  $(C_c - C_w)/(t_c - t_w) = -b$ , we obtain an expression for the concentration difference in terms of the heat flux  $q$  and the heat-transfer coefficient inside the tube  $\alpha_{in}$ :  $C_c - C_w = bq/\alpha_{in}$ .

We will use a simplified formula for calculating heat transfer inside the tube and a formula for the heat flux [5], and then the concentration difference  $C_c - C_w$  is equal to:  $C_c - C_w = b/0.084\Delta t d_{in} b / L Re^{0.2} Pr^{0.57}$  ( $Re > 10,000$ ). In doing this, since the scaling processes in heat exchange equipment that occur in reality are most often described by a rate equation for a first-order reaction, the value of  $n$  in expression (2) can be taken equal to unity.

If we denote the complex  $K_p b / 0.084 C_0$  by the symbol  $b_1$ , the parameter  $b_1$  can be interpreted as a constant of the scaling process, and then the final dependence for calculating the deposition rate can be expressed as

$$\Phi_d = b_1 \Delta t d_{in} / L Re^{0.2} Pr^{0.57}. \quad (3)$$

The rate of removal  $\Phi_\tau$  is proportional to the shearing stress in the liquid  $\tau_p$  and inversely proportional to the cohesive force of the deposit layer  $R_s$ :

$$\Phi_\tau = f \tau_p / R_s, \quad (4)$$

With steady-state motion in a tube of radius  $R$  the drop in the tube  $\Delta P$  depends completely on the friction on the tube wall  $\tau_p$ :  $\pi R^2 \Delta P = 2\pi R L \tau_p = \xi \pi R^2 L / d_{in} h_{dyn} / 2$  [5]. Then by using the Blasius formula to calculate the friction drag coefficient  $\xi$  and denoting the complex  $0.0332f/R_s$  by the symbol  $b_2$ , which can be interpreted as a second constant of the scaling process, we obtain the final expression for the rate of removal of deposited particles:

$$\Phi_\tau = b_2 h_{dyn} / Re^{0.25}. \quad (5)$$

Let us transform the first term of Eq. (1):  $S = 2\pi(R - \delta)L$ ;  $dm = d(\rho_s V_s) \approx 2\rho_s \pi R L d(R - \delta)\delta$ . In view of the calculations performed, Eq. (1) appears as

$$-\rho_s R \frac{d \ln(R - \delta)}{d\tau} = b_1 \Delta t \frac{d_{in}}{L} Re^{0.2} Pr^{0.57} - b_2 \frac{h_{dyn}}{Re^{0.25}}. \quad (6)$$

By denoting  $X = \Delta t d b / L Re^{0.2} Pr^{0.57}$ ,  $Y = h_{dyn} / Re^{0.25}$ , and  $A = b_1 X - b_2 Y$ , we obtain Eq. (6) as the simplest differential equation  $d \ln(1 - \delta) = -A d\tau$ . In view of the boundary conditions  $\delta|_{\tau=0} = 0$  a solution is the expression

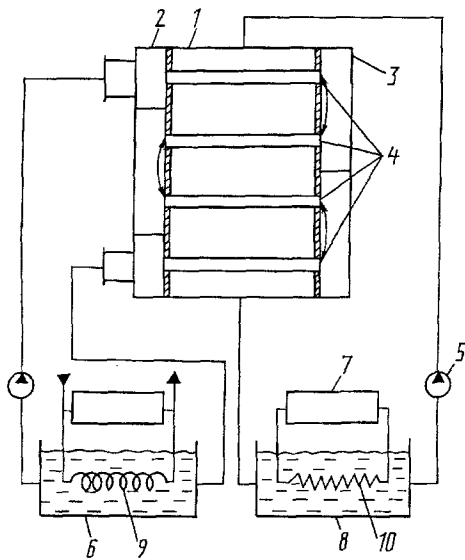


Fig. 1. Schematic diagram of the experimental section: 1) experimental heat exchanger; 2) inlet water chamber; 3) rotary water chamber; 4) investigated tubes; 5) circulation pump; 6) tank for preparation and cooling of the solution; 7) thermostating unit; 8) tank for the heating heat-transfer agent; 9) water-water heat exchanger; 10) electric heater.

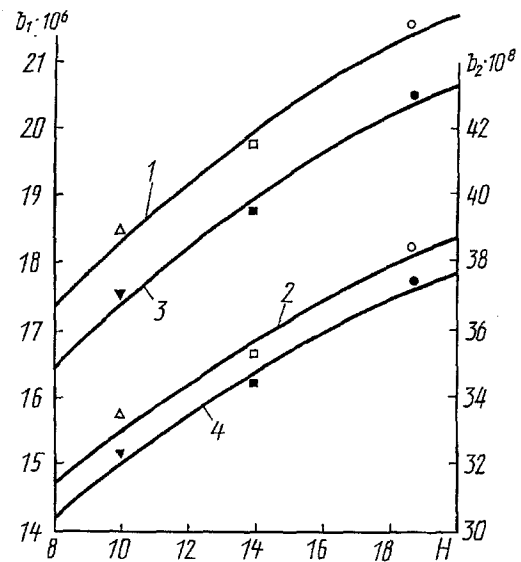


Fig. 2. Dependence of the constants of the scaling process  $b_1$  and  $b_2$  on the hardness  $H$  and the temperature of the cooling water: 1, 2) dependences for the constant  $b_1$  on  $H$ : 1)  $t_1 = 15$ , 2)  $10^\circ\text{C}$ ; 3, 4) dependences for the constant  $b_2$  on  $H$ : 3)  $t = 15$ ; 4)  $10^\circ\text{C}$ .  $H$ , mg-eq/liter.

$$\frac{\delta}{R} = 1 - \exp \left\{ - \left( b_1 \Delta t \frac{d_{in}}{L} \text{Re}^{0.2} \text{Pr}^{0.57} - b_2 \frac{h_{dyn}}{\text{Re}^{0.25}} \right) \tau / \rho_s \right\}, \quad (7)$$

which describes the dynamics of the process of scaling of the tube surface of the heat exchanger. To close this equation, it is necessary to identify the constants of the scaling process  $b_1$  and  $b_2$ . In the subsequent discussion, as was noted earlier, we will assume that they depend only on the hardness of the water and regime factors, which is, in general, true only to some extent and for a narrow class of cooling systems.

Investigation of scale formation on the inner surface of the tubes was performed on an experimental section whose schematic diagram is shown in Fig. 1. In this installation the heating heat-transfer agent (distillate) washed the surface of the tubes in question from the outside and the cooling heat-transfer agent (a specially prepared solution whose chemical composition, which was approximately identical to the composition of cooling water in circulating cooling systems, was maintained unchanged during the entire testing period) circulated inside the tubes.

The temperature regime of the heating heat-transfer agent was maintained stable by using a thermostating unit and electric heating, and that of the cooling heat-transfer agent by using a water-water heat exchanger built into a tank for collection and preparation of the solution.

Tubes 3 m long with inner diameter 26 mm and wall thickness 1 mm (MNZh5-1 material) were investigated. In the experiments we varied different parameters: the hardness of the solution was changed from 10 to 19 mg-eq/liter, the solution velocity was changed from 1.2 to 1.8 m/sec, and the solution temperature was changed within  $10\text{-}15^\circ\text{C}$  in order that the similarity of thermal loads correspond to a real operating regime of heat exchange equipment.

During experiments of duration 1.5 to 3 months the temperature and flow-rate characteristics of the heat-transfer agents were recorded, the correctness of measurements being confirmed by the balance of the heat lost by the hot heat-transfer agent and absorbed by the cold one. These measurements permitted monitoring of the thermal resistance of the deposit layer during the entire experiment and indirect monitoring of the deposit layer thickness,

which on completion of the experiments was also determined by weighing the specimens on an analytical balance and by investigating specially prepared sections using a microscope.

Figure 2 gives some results of the investigations. Processing the obtained data by the least-squares method led to the following dependences:  $b_1 = (4.08 \pm 0.6) \cdot 10^{-3} t_1^{0.33} H^{0.25}$  and  $b_2 = (9.98 \pm 1.7) \cdot 10^{-8} t_1^{0.25} H^{0.25}$ .

The investigations performed permit the description of the process of scale formation in tube systems of heat exchangers as a dependence between the scaling layer thickness and the factors that determine this process (design parameters, i.e., the length  $L$  and the tube diameter  $d_0$ ; regime factors, i.e., the velocity  $W_{\text{wat}}$ , the water temperature  $t_1$ , and the heating  $(t_2 - t_1)$  of the cooling water; the time after cleaning of the tube system  $\tau$ ; scale-forming factors, i.e., the hardness of the circulating water  $H$  and the scale density  $\rho_s$ ).

Later on we expect to develop an integral criterion that takes more complete account of the scale-forming properties of different cooling media and to expand the investigations performed to a wider class of water-supply systems, including once-through systems.

## CONCLUSIONS

A semiempirical model of the process of deposit formation on the inner surface of the tubes of heat exchange equipment is developed that permits the determination of the dynamics of deposit layer growth as a function of the heat exchanger design and regime and scale-forming factors of the circulating heat-transfer agent. The experimental investigations performed permitted the determination of the constants of the scaling process for scalings of predominantly carbonate type.

## NOTATION

$S$ , area of the inner surface of the tube;  $m$ , mass of the deposited substances;  $\tau$ , time;  $\Phi_d$ , deposition rate;  $\Phi_r$ , removal rate;  $K_p$ ,  $n$ , rate constants and order of the deposition reaction;  $C_c$ ,  $C_w$ ,  $C_0$ , concentrations of the substance in the flow core, at the phase interface, and of saturation under the given conditions, respectively;  $t_c$ ,  $t_w$ , temperatures in the flow core and at the wall, respectively;  $b$ , constant of the similarity of diffusion and thermal layers;  $t_2$ ,  $t_1$ , temperatures at the outlet and at the inlet of the heat-transfer agent into the tube;  $d_{\text{in}}$ ,  $L$ , inner diameter and length of the tube;  $Re$ , Reynolds number;  $Pr$ , Prandtl number;  $W_{\text{wat}}$ , velocity of the water in the tube;  $\nu$ ,  $a$ , coefficients of dynamic viscosity and thermal diffusivity for the cooling water;  $f$ , proportionality constant in the rate of scale removal;  $h_{\text{dyn}}$ , dynamic head;  $\xi$ , friction drag coefficient;  $\rho_s$ ,  $V_s$ , density and volume of the scale;  $\delta$ , deposit layer thickness;  $\bar{\delta} = \delta/R$ , relative thickness of the deposit layer;  $\bar{\tau} = \tau/\rho_s$ , reduced time;  $\Delta t$ , heating of the heat-transfer agent in the tube.

## REFERENCES

1. L. S. Baran, F. Z. Ratner, and Yu. S. Razladin, "Simulation and Diagnostics of Contamination of Condensation Units in Steam Turbines," Abstracts of Papers of the Republican Scientific-Technical Conference "Mathematical Modeling of Processes and Constructions of Power and Transport Turbine Installations in Systems of Their Automated Design" (Gotvald, 7-9 September 1988) [in Russian] Kharkov (1988), pp. 106-107.
2. J. Taborek, T. Aori, R. Ritter, et al., Chemical Eng. Progress, **68**, No. 2, 59-67 (1972).
3. J. Taborek, T. Aori, R. Ritter, et al., Chemical Eng. Progress, **68**, No. 7, 69-78 (1972).
4. I. I. Sagan' and Yu. S. Razladin, Control of Scale Formation in Heat Exchangers [in Russian], Kiev (1986).
5. B. S. Petukhov and V. K. Shilov (eds.), Handbook of Heat Exchangers [Russian translation], Moscow (1987), Vol. 1.