INTENSIFICATION OF HEAT-TRANSFER PROCESSES IN DISPERSE SYSTEM FLOW WITH SOLID PHASE DEPOSITION

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UDC 536.24

The influence of the thickness of particle deposits and surface roughness on the heat-transfer and resistance coefficients is examined. It is shown that for high degrees of roughness resulting from the deposition of coarse particles, the efficiency decreases with increase in the thickness of the layer deposited, even at large Re numbers.

The flow of disperse systems in heat-exchangers leads to the deposition of solid-phase particles on the heat-transfer surface, an example being the deposition of contaminant particles (clay, sand, tar, coke, etc.) from crude oil on tube walls.

As noted in [1, 2], the formation of a layer of particles with low thermal conductivity on a heat-transfer surface leads to a fall in the overall heat-transfer and resistance coefficients (for a smooth surface $\varepsilon/\varepsilon_0 \approx \beta^{1/4}$) and an increase in the surface heat transfer coefficient ($\alpha/\alpha_0 \approx \beta^{-1.8}$). The surface of the deposited layer is characterized by a certain degree of roughness which mainly depends on the particle size. For coarser particles the height of the asperities may be maximal ($\Delta = a_{\max}$), which changes the structure of the turbulent boundary layer ($\mathrm{Re}_r = \Delta \cdot U^*/\nu > 60$) as a result of the increased generation of turbulence near the wall (surface of deposits). However, large values of the Reynolds number Re_r have different effects on the resistance and surface heat-transfer coefficients.

It is known that the use of rough surfaces is one means of intensifying heat transfer [3]. In some cases the heat-transfer rate can be increased severalfold by creating artificially rough surfaces, although this leads to an increase in flow resistance.

Our object was to investigate the effect of the thickness of the deposits and the roughness of the surface on the heat-transfer and resistance coefficients, so as to be able to select certain conditions for intensifying heat-transfer processes. Taking surface roughness into account, the resistance coefficient is given by [4]

$$\varepsilon = 0{,}11\left(\frac{\Delta}{D} + \frac{68}{\mathrm{Re}}\right)^{1/4}. \qquad (1)$$

Setting $D = D_0\beta$ and $\mathrm{Re} = \mathrm{Re}_0\beta^{-1}$ [2], from (1) we obtain

$$\varepsilon = 0{,}11\left(\frac{\Delta}{D_0\beta} + \frac{68\beta}{\mathrm{Re}_0}\right)^{1/4}. \qquad (2)$$

For smooth tubes $\Delta/D_0 \ll 68/\mathrm{Re}_0$ expression (2) coincides with the result $\varepsilon/\varepsilon_0 \approx \beta^{1/4}$ [2]. Obviously, for a surface with developed roughness ($\Delta/D_0 \gg 68/\mathrm{Re}_0$) we have $\varepsilon/\varepsilon_0 \approx \beta^{-1/4}$, i.e., as the thickness of the deposit increases so does the resistance coefficient (Fig. 1). For certain values of the roughness and Re the $\varepsilon(\beta)$ curve passes through an extremum. As the thickness of the deposits increases, the resistance coefficient for developed roughness depends only slightly on the Re number.

Particle deposition in tubes is migrational and gravitational in character [5]. At high flow temperatures in horizontal tubes the rate of gravitational settlement is much greater than the rate of migrational deposition. Obviously, at higher values of the flow velocity due to an increase in deposit thickness ($U/U_0 = \beta^{-2}$) [2] larger particles will be deposited, since the finely dispersed component will be entrained by the convection flow. Consequently, as the thickness of the deposits grows, the roughness of the surface increases up to values

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Institute of Theoretical Problems of Chemical Engineering, Academy of Sciences of the Azerb. SSR, Baku. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 52, No. 2, pp. 252-255, February, 1987. Original article submitted November 12, 1985.

0022-0841/87/5202-0188$12.50

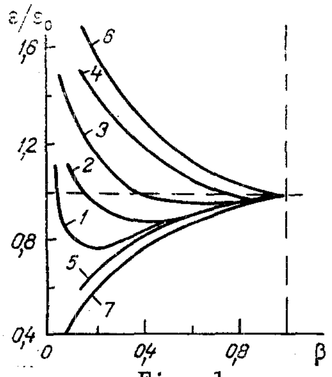

Fig. 1

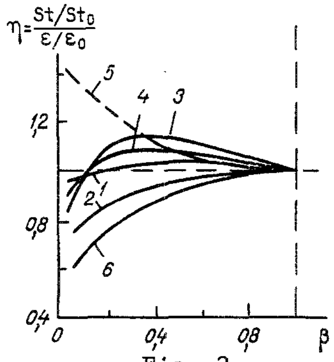

Fig. 2

Fig. 1. Resistance coefficient as a function of deposit thickness for: 1) $\Delta/D_0 = 0.001$, $Re = 4 \cdot 10^3$; 2) 0.001 and 10^4; 3) 0.01 and 10^4; 4) 0.02 and $6 \cdot 10^3$; 5) 0.001 and $3 \cdot 10^3$; 6) developed roughness: $\Delta/D_0 >> 68/Re$; 7) smooth surface: $\Delta/D_0 << 68/Re$.

Fig. 2. Efficiency as a function of deposit thickness for: 1) $\Delta/D_0 = 0.001$, $m = 10$, $Re = 10^4$; 2) 0.04, 10^2 and 10^4; 3) 0.001, 10^2 and 10^4; 4) 0.001, 60, and 10^4; 5) large values of Re and Pr and small values of Δ/D_0; 6) large values of Δ/D_0 and small values of Re and Pr.

$\Delta = a_{max}$. This makes it possible to determine the dependence of the resistance coefficient on the roughness (particle size) and deposit thickness only, i.e., $\varepsilon \approx 0.11(\Delta/D_0\beta)^{1/4}$. In order to estimate the effect of the roughness and deposit thickness on the heat transfer we introduce the efficiency:

$$\eta = \frac{St/St_0}{\varepsilon/\varepsilon_0}.$$

In the fully developed roughness regime the heat-transfer coefficient of rough surfaces is determined from the relation [3]

$$St = \frac{\varepsilon/8}{(m - 8{,}48)\sqrt{\varepsilon/8} + 1},$$

where $m = 4.5\,(y_+)^{0.24}Pr^{0.44}$. As follows from Fig. 2, the efficiency depends on the roughness of the surface and the thickness of the deposits and on the Re and Pr numbers. As the roughness decreases and the Pr and Re numbers increase, the region of efficient utilization of rough surfaces grows. At large deposit thicknesses the efficiency η is much reduced. For large roughnesses or dispersed-phase particle sizes the efficiency decreases with increase in deposit thickness even at large Re numbers. Thus, an increase in efficiency is ensured only for a thin deposit formed by deposition of the finely dispersed component of the solid phase. For apparatus with external heat transfer, particle deposition on the heat transfer surface leads to a fall in the overall heat-transfer coefficient $k^{-1} \sim \ln \beta^{-1}$ [6]. The increase in the surface heat-transfer coefficient due to particle deposition can compensate to some extent for the decrease in the overall heat-transfer coefficient only if the deposit is not very thick.

In the general case the surface roughness (pitch and height of the asperities) depends to a considerable extent on the particle distribution in the disperse flow. The character of the surface roughness can be predicted by constructing the evolution of the particle-size distribution function with respect to time on the basis of the Fokker—Planck equations or the integral coagulation equation with allowance for deposition.

NOTATION

a, particle size; D, tube diameter; R, tube radius; y_+, dimensionless coordinate; U_*, dynamic velocity; U, flow velocity; α, surface heat transfer coefficient; $\beta = 1 - \delta/R$; δ, thickness of the deposits; Δ, height of the roughness. Subscripts: 0, without deposition.

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DETERMINATION OF THE THERMOPHYSICAL CHARACTERISTICS BY THE SELF-OSCILLATION METHOD

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UDC 536.2

A method is proposed for measuring the thermophysical characteristics by means of the self-oscillation frequency and the gain coefficient of the automatic regulation system containing the specimen under investigation.

The phenomenon of exciting self-oscillations in automatic regulation systems is well known [1, 2]. For a regulator of low inertia the self-oscillation frequency depends only on the physical characteristics of the object of regulation. If material with unknown thermophysical characteristics is taken as such an object, and a temperature stabilizer as regulator, then stable, almost sinusoidal, temperature oscillations can be obtained in the specimen under investigation. The frequency of these oscillations permits an assessment of the thermal diffusivity of the material. The heat conduction equation with nonlinear boundary conditions will be the mathematical model of this system. Similar equations with a weak nonlinearity are investigated by asymptotic methods. Thus, an algorithm to compute the self-oscillation in nonlinear parabolic systems with a small parameter [3] used in this paper was developed and given a foundation comparatively recently. Asymptotic methods are based on the fact that the desired periodic solution is bifurcated from the equilibrium state as the small parameter increases. Let us note that the bifurcation of periodic solutions can occur only in the case of a nonlinearity of a definite kind (soft excitation mode), the amplitude of the self-oscillations here diminishes together with the parameter. In the opposite case the amplitude of the periodic solutions does not decrease with the diminution of the parameter (hard excitation mode) and asymptotic methods are unsuitable. Although the self-oscillation frequency of a system with such kind of nonlinearity indeed contains information about the thermophysical characteristics of the material, it is not possible to extract it without relying on numerical methods. In other words, the presence of self-oscillations without making the kind of nonlinearity specific cannot be used to determine the thermal diffusivity. Unfortunately, these well-known facts are not always taken into account [4]. Without delving into an analysis of the problem, the authors of the mentioned paper try to obtain a relationship between the frequency and the thermal diffusivity by assuming that the phase shift of the temperature oscillations in the specimen equals π and is 2π in combination with the phase shift of the inverting amplifier signal. Overlooked here is that a phase shift also exists between the power liberated in the heater and its temperature by virtue of the integrating properties of the specimen. Then the total phase shift in the system exceeds 2π which contradicts the self-oscillation condition. This and other examples indicate the necessity of a complete analysis of such systems.

Let us turn to a description of one of the possible methods of realizing the self-oscillation method, the construction of its mathematical model, and also the derivation of

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0022-0841/87/5202-0190$12.00