We have derived a relationship between the coefficient characterizing the entrainment of the air by the jet and the hydrodynamic parameter q.

The results of these studies can be used, for example, to determine the shape and dimensions of the zones of dangerous concentrations in the case of gas discharge into the atmosphere, as well as in various branches of engineering, where we deal with the transverse injection of one gas into the moving flow of another.

NOTATION

X, Z, horizontal and vertical coordinates, m; d, tube diameter, m; $q = \rho_0 u_o^2/\rho_a u_a^2$, hydrodynamic parameter; ρ_0, ρ_a, density of gas and air, kg/m^3; u_0, u_a, velocity of gas and air, m/sec; $Ar = (\rho_a/\rho_0 - 1)gd/u_0^2$, Archimedes number; C, volumetric concentration at jet axis; $L^* = L/d$, dimensionless distance along jet trajectory; $L_{in}^* = L_{in}/d$, dimensionless initial segment of jet; T_0, T_a, temperature of gas and air, K; M_0, M_a, molecular weight of gas and air; th, hyperbolic tangent; K = 0.05625, empirical coefficient; g, acceleration of gravity, m/sec^2; $X^* = X/dq^{0.5}$, dimensionless complex; $Z^* = Z/dq^{0.5}$, dimensionless complex; $V^* = (1/c - 1)$, dimensionless complex.

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INTENSIFICATION OF HEAT-EXCHANGE PROCESSES IN THE PRESENCE OF A SURFACE WITH VARIABLE ROUGHNESS

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We investigate and evaluate the influence of variable roughness on the transfer of heat and momentum in the flow of disperse systems with precipitate deposition, and also on the efficiency factor for various thicknesses of deposit, and on the Re and Pr numbers.

The flow of disperse systems in tubular heat-exchange equipment is frequently accompanied by the deposition of a variety of particles onto the surfaces, these particles exhibiting a low coefficient of thermal conductivity. As a result of this particle deposition, the heat-exchange surface (i.e., of the deposited layer) is characterized by some level of roughness that is dependent on the dimensions of the deposited particles. We know that an increase in deposition thickness in tubes leads to an increase in linear velocity [1, 2], promoting a significant change in the coefficients of heat release and resistance. This increase in the velocity of flow leads to the entrainment of the finely dispersed component of the particles, thus increasing the surface roughness of the layer as a consequence of the deposition of large particles. In the case of large particle dimensions the height of the roughness projections may attain its maximum ($\Delta = a_{max}$), thus altering the structure of the turbulent boundary layer and leading to variable roughness in the surface of the layer, dependent on the thickness of the latter. As was noted in [3], the presence of roughness significantly changes the coefficient of effective utilization of these rough surfaces, in dependence on the deposition thickness.

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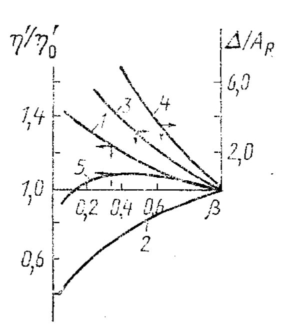

Fig. 1

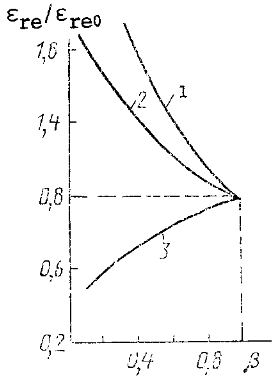

Fig. 2

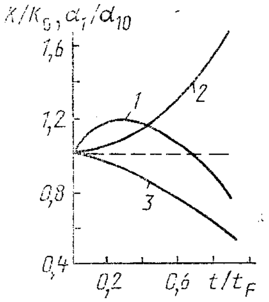

Fig. 3

Fig. 1. A change in the efficiency factor and in roughness as a function of the deposition thickness: 1) Re = 800, $\Delta/R = 0.0002$, Pr = 1000; 2) Re = 10^5, Pr = 1000; 3) m = 0.01; 4) 0.05; 5) 10; Re = 10^4.

Fig. 2. Asymptotic change in the resistance factor as a function of deposition thickness: 1) variable roughness; 2) constant roughness; 3) smooth surface.

Fig. 3. Change in the heat-transfer coefficient (1), in the coefficient of heat released (2) ($\alpha_1/\alpha_{10} = \beta^{-1.5}$), and in the deposition thickness (3) in heat-exchange equipment over time (t_F = 6000 h).

It is the purpose of the present study to investigate the influence exerted by the variable roughness formed in the flow of disperse systems with deposition of a solid phase on the transfer of heat and momentum.

It was noted in [4] that the deposition of solid undeformed particles out of a disperse flow onto the surface of the tubes is migrational-gravitational in nature, and the migration mechanism for the deposition is characteristic of vertical tubes. It should be noted that since the migrational velocity of the particles depends on the concentration gradients (diffusion transfer), on temperature on pressure (thermobarodiffusion), and on the velocity of the flow (ascending and turbulent migration), the migrational particle velocity will be significant only in the boundary layer. In the case of horizontal tubes for "liquid–solid particle" systems at high temperatures the rate of gravitational precipitation becomes considerably larger than the migrational component. For the sake of simplicity, if we examine the linear law governing resistance, we find that particle deposition in horizontal channels will be subject to the following expression [5]:

$$V = V_0(1 - \exp(-\tau/\tau_r)), \tag{1}$$

where $V_0 = (1/18)(\Delta\rho g/\eta)a^2$ is the rate of deposition in a fluid at rest.

The second term in (1) defines the entrainment of the particles by a convective flow.

Assuming that $\tau = \tau_0\beta^2$ [1, 5], we obtain

$$V = V_0(1 - \exp(-m\beta^2)), \quad m = \tau_0/\tau_r. \tag{2}$$

Thus, if we choose some critical rate of deposition V_{cr}, below which no particles settle out, the critical dimension of such particles can be found in the following manner:

$$a_{cr} = \left[\frac{18\eta V_{cr}}{\Delta\rho g}\right]^{0.5}(1 - \exp(-m\beta^2))^{-0.5}. \tag{3}$$

As follows from (3), with an increase in the deposition thickness δ the critical particle dimension shifts in the direction of high values, i.e., the dimensional spectrum of the deposited particles $a(\beta) \geq a_{cr}$. If we treat particle distribution in the flow, as derived in [4]:

$$P(\xi, \tau) = \frac{N_0}{v_0}\frac{2(1-\tau_R)}{\tau_R^{0.5}}\exp(-2\xi)\,\mathrm{sh}(2\xi\tau_R^{0.5}),$$

where $\tau_R = m_R\tau/(1 + m_R\tau)$; $m_R = 1/2N_0\omega(\xi, \beta)$; $N_0 = 6\varphi/(\pi a_0^3)$; $\xi = v/v_0$, $\omega(\xi, \beta)$ is some function dependent on the nature of the hydrodynamic interaction of the particles in the flow, then the number of particles settling out will be defined as

$$N_{dep} = \int_{\xi_{cr}}^{\infty} P(\xi, \tau)\, d\xi.$$

Since the increase in the deposition thickness is a factor in the extent to which a_{cr} increases, then N_{dep} diminishes, although $\xi_{cr}/\xi > 1$.

The roughness of the deposited surface layer is defined as $\Delta = a\varepsilon_1$, where ε_1 represents that fraction of the particles participating in the formation of the roughness, $0 \le \varepsilon_1 \le 1$. As $\varepsilon_1 \to 0$ we have a smooth surface ($\Delta = 0$), while as $\varepsilon_1 \to 1$ the maximum roughness is $\Delta = a$. Then, taking (3) into consideration, we define the lower threshold of roughness in the form

$$a > \Delta \geqslant A_R\,(1 - \exp(-m\beta^2))^{-0,5}, \tag{4}$$

where $A_R = \varepsilon_1[18\eta V_{cr}/\Delta\rho g]^{0.5}$. With low values for m or with a large relaxation time, expanding the exponent in linear series, we obtain $\Delta \ge A_R m^{-0.5}\beta^{-1}$.

Thus, Eq. (4) yields the relationship between the surface roughness and the thickness of the deposited layer (Fig. 1). Having determined the resistance factor in rough tubes in the form [6]

$$\varepsilon_{re} = 0,11\left(\frac{\Delta}{d} + \frac{68}{\mathrm{Re}}\right)^{0,25}, \tag{5}$$

we obtain ($\mathrm{Re} = \mathrm{Re}_0\beta^{-1}$, $d = d_0\beta$):

$$\varepsilon_{re} \geqslant 0,11\left[\frac{A_R}{d_0}\,\frac{(1 - \exp(-m\beta^2))^{-0,5}}{\beta} + \frac{68\beta}{\mathrm{Re}}\right]^{0,25}.$$

In the case of pronounced roughness $\Delta/d \gg 68/\mathrm{Re}$ and low values for m, we find the asymptotic value of the resistance factor in the form

$$\varepsilon_{re}/\varepsilon_{re0} \geqslant M_R\,\beta^{-0,5},$$

where $M_R = (A_R m^{-0.5}/\Delta_0)^{0.25}$; Δ_0 is the initial roughness of the surface.

When $M_R = 1$, we obtain $\varepsilon_{re}/\varepsilon_{re0} \approx \beta^{-0.5}$, while in the case of a constant roughness we have $\varepsilon_{re}/\varepsilon_{re0} \approx \beta^{-0.25}$ [3], i.e., the resistance factor in the case of variable roughness increases more rapidly (Fig. 2).

In order to evaluate the influence exerted by roughness on the intensity of heat exchange, we introduce the efficiency factor [7]:

$$\eta' = \frac{\mathrm{St}}{\varepsilon_{re}}, \tag{6}$$

where St is the Stanton number defined for surfaces in a regime of total roughness:

$$\mathrm{St} = \frac{\xi_{re}/8,0}{(m_{co} - 8,48)\sqrt{\xi_{re}/8,0} + 1};$$

here $m_{co} = 4.5(y_+)^{0.24}\mathrm{Pr}^{0.44}$; $y_+ = yU_*/\nu$; $U_* = \sqrt{\tau_w/\rho}$.

Let us transform (6) as follows:

$$\eta'/\eta_0' = \frac{(m_{co} - 8,48)\sqrt{\varepsilon_{re0}/8,0} + 1}{(m_{co} - 8,48)\sqrt{\varepsilon_{re}/8,0} + 1}, \tag{7}$$

where η_0' is the coefficient of efficiency for a clean tube.

Expression (7) is simplified in the case of large Pr and Re

$$\eta'/\eta_0' \approx (\varepsilon_{re}/\varepsilon_{re0})^{-0,5} \approx \beta^{0,25}, \tag{8}$$

while in the case of small values for Δ and with large Pr we have

$$\eta'/\eta_0' \approx \beta^{-0,125}. \tag{8'}$$

Having analyzed the cited asymptotic relationships, we might note that with an increase in the roughness and thickness of deposition the coefficient of effective utilization of rough surfaces diminishes in the case of large Re and Pr quantities. With small values for the roughness or particle dimensions of the disperse phase, corresponding to small deposition thicknesses, and with large Re and Pr numbers the region of effective utilization of rough surfaces increases in size (see Fig. 1). With average roughness values we observe an increase in the coefficient η' for the efficiency in the case of small deposition thicknesses, and η', passing through a maximum, diminishes with large values of δ. Consequently, the settling out of particles onto the smooth tube surface, given a small thickness for the layer, improves the exchange of heat between the flow and the surface of the deposited layer, but its continued growth significantly increases the hydrodynamic resistance. This fact must necessarily be taken into consideration in designing tubular apparatus involving external exchange of heat (heat exchangers, tubular furnaces, etc.).

The linear coefficient of heat transfer for a contaminated heat-exchange surface [2, 3]:

$$\frac{1}{K} = \frac{1}{2\alpha_1(\beta)R\beta} + \frac{1}{2\lambda_s}\ln\frac{R_1}{R} - \frac{1}{2\lambda_c}\ln\beta + \frac{1}{2\alpha_2 R_1} \tag{9}$$

diminishes as a consequence of the increase in the thermal resistance of the layer (here λ_s and λ_c are the coefficients of thermal conductivity for the wall and the contamination). Such a reduction will be partially offset by the increase in the heat-transfer coefficient for rough surfaces in the case of small layer thicknesses (Fig. 3), which follows out of the asymptotic value of the heat-transfer coefficient:

$$K^{-1} \approx \frac{1}{2\alpha_1(\beta)R\beta} - \frac{1}{2\lambda_C}\ln\beta.$$

With large deposition thicknesses or as small $\beta \to 0$ we have

$$K^{-1} \to \frac{1}{2\lambda_C}\ln\beta^{-1},$$

from which follows the reduction in the coefficient of heat transfer as the deposition thickness increases. Let us examine the influence exerted by the thickness of the deposited layer on the transport of mass to the rough surface formed by the settling out of the solid phase. As was noted in [8], the turbulent diffusion flow to the rough surface is characterized by the expression

$$\frac{\mathrm{Nu_{ro}}}{\mathrm{Nu_0}} \approx \sqrt[4]{\frac{\varepsilon_{re}}{\varepsilon_{re0}}}\frac{1}{\sqrt{\mathrm{Re_{ro}}}}.$$

The error in this formula, as noted by the author, makes it possible to achieve reduced values for the magnitude of the diffusion flow. Here $\mathrm{Re_{ro}} = v'\Delta/\nu$, $v' = (\varepsilon_R\lambda/\rho)^{0.33}$ is the pulsation rate; $\lambda = (\nu^3/\varepsilon_R)^{0.25}$ is the inside scale of the turbulent pulsations; $\mathrm{Nu_{ro}} = j_D d/DC_0$ is the Nusselt diffusion number.

Having determined the relationship between the specific dissipation energy ε_R and λ relative to β in the form of [4]:

$$\varepsilon_R = \varepsilon_{R0}\beta^{-7,5};\quad \lambda = \lambda_0\beta^{1,875};\quad v'/v_0' = \beta^{-1,875},$$

we find that

$$\mathrm{Re_{ro}} = \mathrm{Re_{ro0}}\beta^{-1,875}.$$

We then have

$$\frac{\mathrm{Nu_{ro}}}{\mathrm{Nu_0}} \approx \beta^{0,8}\frac{1}{\sqrt{\mathrm{Re_{ro0}}}}. \tag{10}$$

As follows from (10), with an increase in the thickness of the deposition the diffusion flow to the rough surface diminishes, and this may lead to a decrease in the concentration of particles at the surface and to a reduction in the migration component of the rate of deposition.

NOTATION

a, particle dimension; d, tube diameter; D, diffusion factor; C, particle concentration; g, acceleration of free fall; j_D, diffusion flow at the surface; R, R_1, inside and outside radii of the tube; U_*, dynamic velocity; v, particle volume; y, coordinate; α_1, α_2, coefficients of heat transfer from the internal and external media; $\beta = 1 - \delta/R$, choking factor; Δ, roughness height; δ, thickness of deposition; ε_{re}, resistance; ε_R, specific dissipation energy; ν, kinematic viscosity; $\Delta\rho = \rho_{re} - \rho$; ρ_{re}, ρ, density of particles and the carrier phase; η, dynamic viscosity; τ, stay time; τ_r, relaxation time; τ_w, tangential friction; φ, volumetric particle fraction. Subscript: 0, for a clean tube.

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CHANGES IN THE STRUCTURE OF TURBULENT FLOWS SUBJECTED TO THE ACTION OF FLOW ACCELERATION

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We examine the effects resulting from the laminarization of turbulent flows subjected to the action of flow acceleration. We describe the factors and conditions for the appearance of this phenomenon. As a theoretical base for this investigation we employ a mathematical model of a boundary layer for a broad range of turbulent Reynolds numbers, based on a modified e-ε turbulence model.

The theory of hydrodynamic stability [1] rejects the possibility of a reverse transition from turbulent flow to laminar. However, in a number of experimental studies into turbulent flows [2, 3] a significant deviation was noted in the integral characteristics of heat exchange and friction, as well as in the profiles of the average velocity and temperature from those universal relationships applicable to a turbulent flow regime in the direction of relationships that are more in line with the laminar regime. This phenomenon has been designated as the laminarization of turbulent flows.

In their effort to generalize and systematize questions related to the phenomenon of turbulent-flow laminarization, the authors of [4], on the basis of studies that they carried out, came to the conclusion that it is possible to isolate certain external factors which, under these conditions, lead to a change in the mechanism of turbulent exchange:

flow acceleration which strives to reduce the extent to which the turbulent frictional stresses affect the average flow characteristics [3, 5];

the curvature of the streamlined surface, resulting in transverse flows through the channel [6];

the cooling of the boundary layer, which results in a tendency to stabilize the vortex structure of the boundary layer [7].

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