components; $Re_* = Vh/\nu$; $Re = \varepsilon Re_*$; S, median surface region in which liquid motion is studied; Γ, boundary of region S; $2q_j$, components of liquid specific flux vector in gap; $q_j^{(k)}$, coefficients of asymptotic expansion of function q_j; $\Phi^{(k)}$, vector potential of $q_j^{(k)}$; $\bar{e}_j$, unit vector tangent to coordinate line ξ^j; $\bar{n}$, external unit normal vector to contour Γ; q_n, component of specific liquid flux vector along external normal; $(U^{(k)})^j$, $(U^{(k)})_j$, contravariant and covariant components of vector $u_j^{(k)} = H_j(U^{(k)})^j = H_j^{-1}(U^{(k)})_j$; $(U^{(k)})_{j,\ell}$, covariant derivative of covariant vector; ρ, liquid density; ν, kinematic viscosity coefficient; V, flow velocity scale.

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LOCAL HEAT EXCHANGE OF A CYLINDER IN A SLIGHTLY DUSTY FLOW

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UDC 536.423

A study is performed of thermal resistances of convective heat exchange and thermal conductivity caused by reduction in the intensity of heat exchange when loose deposits are formed on the cylinder.

In energy and heat utilization apparatus, the dynamic equilibrium of the layer of loose deposits formed on tube surfaces is determined primarily by precipitation from the flow of fine particles, accompanied by destruction of the layer by collisions of coarser ash particles. In a number of devices (for example, gas-cooled reactors with spherical shells) the flow becomes contaminated by micron-size particles of a narrow fractional composition due to wearing and ablation of surfaces drafted by the flow. In view of the complete absence of binding components in the flow deposits of increased friability and an anomalously loose structure are formed. The absence of reliable information on the structure of such loose deposits, their distribution over surfaces, and their effect on heat transport prohibits determination of the local heat-exchange mechanism and sufficiently precise explanation of reductions in heat-exchange intensity.

The present author and Spokoinyi [1] studied mean heat exchange of a cylinder with a cooled slightly dusty ($\mu < 2 \cdot 10^{-3}$ kg·sec/(kg·sec)) air–graphite flow under conditions where a loose friable deposit was formed. The dispersed material used was type S-1 natural graphite powder ($\bar{d}_s = 7$ μm, $d_{t\ min} = 1.8$ μm, $d_{t\ max} = 15$ μm; $\rho_s = 2000$ kg/m³). The polystyrene cylindrical tube ($D = 21 \times 1.5$ mm; $\lambda_w = 0.1165$ W/(m·K)) was located horizontally in a cooled descending flow. Heat removal from the cylinder wall was accomplished by pumping a coolant liquid.

The experiments on local heat exchange studied the effective heat-liberation coefficient

$$\alpha^*_{\mathrm{fi}} = \frac{2\lambda_{\mathrm{w}}\left(t^{\mathrm{e}}_{\mathrm{w}\,i} - t^{\mathrm{in}}_{\mathrm{w}\,i}\right)}{D_{\mathrm{e}}\left(\bar{t}_f - t^{\mathrm{e}}_{w\,i}\right)\ln\dfrac{D_{\grave{\mathrm{e}}}}{D_{\mathrm{in}}}} \qquad (1)$$

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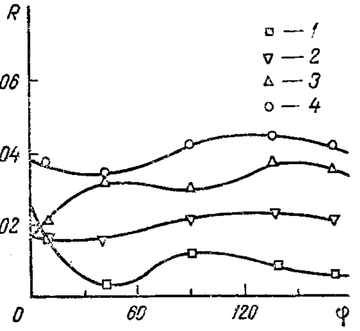

Fig. 1

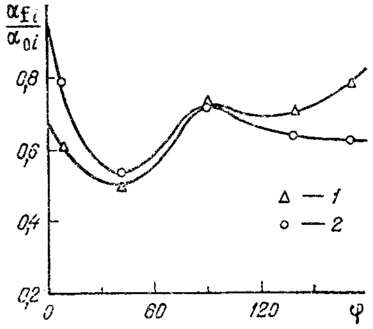

Fig. 2

Fig. 1. Distribution of thermal resistance over cylinder perimeter (Re_f = 5950): 1) thermal resistance to thermal conductivity of deposit layer; 2) air flow with clean cylinder surface; 3) dusty flow with surface deposit layer; 4) dusty flow with cylinder, including thermal resistance of deposit layer. R, $m^2 \cdot K/W$; ϕ, deg.

Fig. 2. Relative intensity of heat exchange of dusty flow with deposit layer surface: 1) Re_f = 3260; 2) 5950.

from the dusty gas to the cylinder surface, considering the thermal resistance to thermal conductivity of the deposit layer

$$R_{\text{dep}\,i} = \delta_{\text{dep}\,i}/\lambda_{\text{ef}\,i}, \tag{2}$$

and connective heat exchange with the surface of the deposit layer

$$\alpha_{\text{fi}} = \left(\frac{1}{\alpha^*_{\text{f}\,i}} - \frac{\delta_{\text{dep}\,i}}{\lambda_{\text{ef}}}\right)^{-1}. \tag{3}$$

Local thermal flux values were calculated, following Eq. (1), both from the temperature change in the cylinder wall, and from the temperature gradient on the external surface of the cylinder wall [2] with consideration of heat leakage along the perimeter. Processing the experimental data for the two variants of thermal flux determination revealed the need to consider heat losses in the cylinder wall along the periphery, since otherwise the error in determination of local effective heat liberation coefficients reached 20%.

Data on local heat exchange of the cylinder with a descending slightly dusty flow were processed and analyzed for a stabilized deposit layer thickness. A series of 24 experiments (total number of points 120) were performed, demonstrating good reproducibility of the results. The maximum uncertainty in determining the mean value of the effective heat-liberation coefficient did not exceed 9%, with the corresponding uncertainty for local values being 20%, with uncertainties of 12 and 30% respectively in the local thickness value and thermal resistance to thermal conductivity of the deposit layer. The uncertainties of direct measurements did not exceed values permissible in thermophysical experiment.

Experimental data on deposit thickness, particle concentration in the layer and effective thermal conductivity coefficient, obtained without interrupting the particle precipitation process by the local electrical conductivity method [2], permitted clarification of the thermal resistance distribution about the cylinder perimeter, which was analogous to the distribution of the deposit layer about the perimeter. The deposit thickness was maximal in the frontal zone, increasing with flow velocity and exceeding the values in the downstream zone by 3-7 times, the latter being weakly dependent on velocity.

The presence of deposits with a low effective thermal conductivity coefficient ($\bar{\lambda}_{ef}$ = 0.045 W/(m·K)) essentially determines the character of the local heat exchange coefficient and affects both redistribution of thermal resistance and hydrodynamic conditions for flow over the body. The heat liberation coefficient for the dusty flow with respect to the surface of the deposit layer α_f, defined by Eq. (3), was lower than the heat liberation coefficient of a pure flow over the entire perimeter.

The experimental points shown in Fig. 1 correspond to values obtained after averaging a set of points for measurements in a given regime. The character of the distribution of total thermal resistance for flow over a cylinder by a dusty flow with deposits present

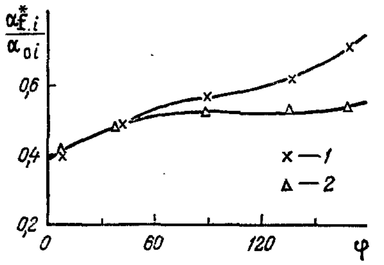

Fig. 3

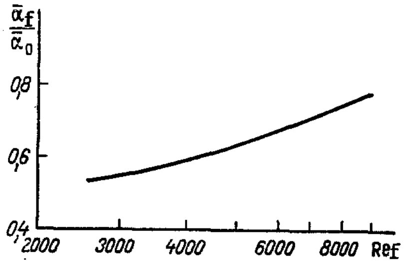

Fig. 4

Fig. 3. Distribution of relative heat exchange intensity about cylinder perimeter: 1) $Re_f = 3260$; 2) 5950.

Fig. 4. Change in relative intensity of heat exchange of dusty flow with surface of deposit layer with growth in dusty flow velocity.

or an air flow is one and the same. Some deviation from equidistance is found in frontal zone ($\phi \lesssim 40°$), where thermal resistance of the deposit layer is maximal. At the same time the thermal resistance to thermal conductivity of the deposit layer is nonmonotonically distributed about the cylinder perimeter, and thus the character of the distribution of thermal resistance of heat exchange of the dusty flow with the surface deposit layer differs significantly from the same dependence for a nondusty flow. In all zones (Fig. 2) the presence of particles in the flow leads to a reduction in the relative intensity of heat exchange of the dusty flow with the surface of the deposit layer. The presence of particles in the flow has the greatest effect on characteristics of the carrier medium in the zone $\phi \simeq 40°$ and in the downstream zone. In the frontal zone ($\phi \simeq 30°$) due to collision of particles in the incident and reflected flow a region of increased particle concentration is formed in the immediate vicinity of the wall [3].

Particle interaction with the loose deposit layer is accomplished by attachment of breakoff of particles in the boundary layer with losses of kinetic energy. Therefore, along with possible intensification of convective transport, turbulization of the boundary layer by particles causes losses of flow energy to acceleration and removal of particles from the layer region, and thus the reverse effect of particles on the carrier medium and heat exchange increases. Reduction in heat liberation in the frontal zone is caused by formation of a rough surface on the deposit layer on the cylinder and an increase in boundary layer thickness due to breakoff of the flow from roughness elements and expansion of the turbulent wake beyond the cylinder [4]. With an overall reduction in the intensity of heat transport the relative contribution of the downstream zone to total heat transport is significantly less than the contribution of the frontal zone.

Aside from the direct influence of the wall, the micron particles themselves exert an effect on high frequency pulsations of the carrier medium in the downstream zone in the form of viscous dissipation [5]. With increase in Reynolds number the relative heat exchange coefficient of the dusty flow with the deposit layer surface α_f/α_0 at the frontal point increases, while it decreases at the downstream point; in the equatorial zone the process is self-similar relative to flow velocity.

It is evident from Fig. 3 that in the frontal zone we have self-similarity of the relative intensity of heat exchange $\alpha_{fi}{}^*/\alpha_{0i}$ of the slightly dusty flow in the presence of a deposit layer with respect to Reynolds number. In this zone the reduction in heat exchange intensity is caused basically by the presence of additional thermal resistance to thermal conductivity. In the downstream zone for an insignificant change in the thermal resistance to thermal conductivity of the deposit layer $\delta_{dep}/\lambda_{ef}$, depending on the regime parameters the effect of the latter on $\alpha_{fi}{}^*/\alpha_{0i}$ is more significant, while the greater Re_f, the more intensely does the participation of particles in the flow and the presence of loose deposits affect the reduction in relative heat exchange intensity. With increase in flow velocity (Fig. 4) there is a relative intensification of heat exchange of the suspension-bearing flow with the surface of the deposit layer.

The studies performed show that the appearance of additional thermal resistance to thermal conductivity due to deposition of particles and formation of a deposit layer is an important but not unique cause of reduction in heat exchange intensity. The net effect of changes in hydromechanical and thermal conditions for flow over the cylinder in the presence of the deposit layer is also important. Changes in the surface state and form of the body over which flow occurs should also be noted (in the experiments performed the longitudinal axis of the cylinder increased by 6-16%) on the distribution of thermal resistance over cylinder perimeter.

NOTATION

d_s, D, characteristic dimensions of particles and cylinder diameter; R, thermal resistance; t, temperature; α, λ, heat liberation and thermal conductivity coefficients; δ, height of deposit layer; μ, mass flow rate concentration; ϕ, angle measured from frontal point of cylinder. Subscripts: s, solid component; w, value at wall; dep, value characterizing deposit; e, in, values on external and internal cylinder walls; f, dispersed flow; ef, effective value; i, local value of quantity.

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CALCULATION OF THE PROBABILITY OF PASSAGE OF GAS PARTICLES THROUGH A CIRCULAR CHANNEL WITH ABSORBING WALLS

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We consider the mass transport of a gas subject to free-molecular flow in a circular channel with absorbing walls. An analytical expression for the gas flow rate is obtained.

In the development of various vacuum devices it is necessary to be able to calculate the flux of gas through channels joining the operating cavities of the devices. The gas flow rate through a channel in problems of this kind is conveniently represented in terms of the probabilities of passage, return, and absorption (capture of molecules by the walls of the channel).

The presently existing analytical expressions for these probabilities, which are so crucial in technology, either do not take into account absorption of molecules by the lateral walls of the channel [1], or are correct only for long channels [2]. In the present paper we obtain an analytical expression free from these restrictions.

We consider two volumes V_1 and V_2 joined by a cylindrical channel of radius R and length H, in which there is steady, free-molecular gas flow (Fig. 1). Because the contributions of the fluxes from the volumes V_1 and V_2 to the total gas flux through the channel can be separated in this case, there is no loss of generality in assuming that the volume V_2 is a vacuum.

We make the following assumptions in formulating the problem. The velocities of the molecules entering the channel are described by a Maxwellian distribution function; when a molecule collides with the wall of the channel it is absorbed with probability α and is diffusely reflected with probability $\beta = 1 - \alpha$ (α depends on the nature of the surface and

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