The minimum values of the heat-transfer coefficients obtained for type II tubes exceed, as distinct from the minimum values of α_ϕ for the type I tube, the heat-transfer coefficient for the smooth-walled tube (at corresponding angular coordinates around the perimeter of the tube).

The investigations showed that both the nature of the variation of the local heat transfer around the perimeter of a longitudinally profiled tube of type II and the absolute values differ considerably from those for smooth tubes and profiled tubes of type I.

Calculations of the heat-transfer coefficients α_ϕ averaged over the perimeter of profiled tubes of type II, carried out by numerical integration, indicate that for these tubes the degree of heat-transfer enhancement, as compared with the smooth-walled type, is considerably greater than for tubes of type I. In fact, $\alpha_\phi/\alpha_{gl} = 1.44$ for $\Gamma = 0.4$ kg/(m·sec) and $\alpha_\phi/\alpha_{gl} = 1.52$ for $\Gamma = 0.16$ kg/(m·sec).

Thus, the conclusion previously drawn from the results of experiments on a longitudinally profiled tube having 10 triangular grooves in its outer surface (type I) that in order to enhance substantially the heat transfer to a flowing film, as compared with a smooth tube, it is necessary to reduce the distance between grooves has been experimentally confirmed, together with the physical model of the process of heat-transfer enhancement on a profiled surface based on the continuous destruction of the hydrodynamic and thermal boundary layers.

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INVESTIGATION OF DROPLET DEPOSITION ON A PLATE WITH TWO-PHASE FLOW SEPARATION AT THE LEADING EDGE

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The shape of the leading edge of the plate and the Stokes and Reynolds numbers are shown to have a decisive influence on the droplet deposition rate.

The protection of the operators of manual pneumatic tools from the effects of the finely dispersed water and oil aerosols present in spent compressed air is a topical problem. One method of solution may be to intensify the deposition of the aerosols on the surfaces of the noise suppressor elements, from which the deposited moisture is carried away in the form of large drops resulting from the breakup of the liquid film in the exhaust. These drops settle out before they can reach the operator's breathing zone.

In the presence of a separationless turbulent two-phase flow the deposition of aerosol particles from 1 to 20 μm in diameter is chiefly determined by the turbulent-inertial mechanism [1]. When the two-phase flow separates, a considerable increase (by tens of times) in the rate of deposition of finely dispersed liquid aerosols, as compared with separationless steady flow, is observed near the attachment zone [2].

So far little has been published on the factors determining the particle deposition rate in the entrance zones of plates and channels. The influence of edge vortex effects on heat and mass transfer has been more carefully investigated. Thus, in [3] it was shown that in the case of flow separation on the flat leading edge of a plate the heat transfer coefficient reaches a maximum at $x/H = 8$, i.e., at the flow attachment point. The distance from the

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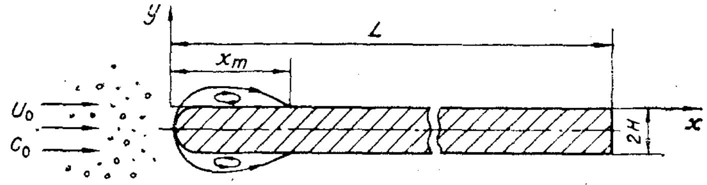


Fig. 1. Flow diagram and coordinate system selected.

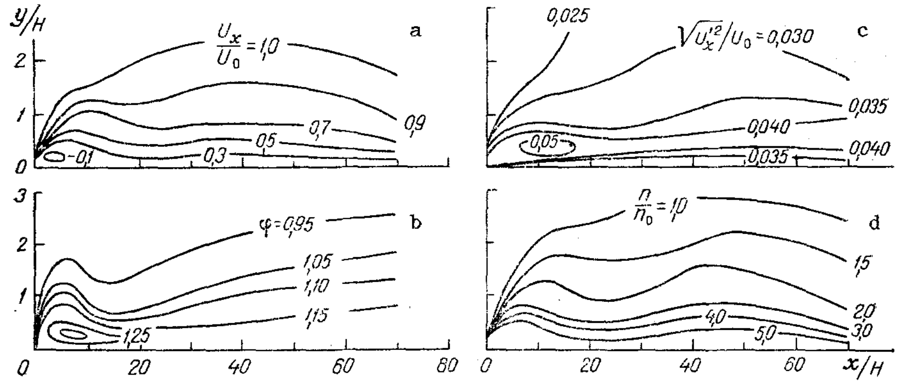


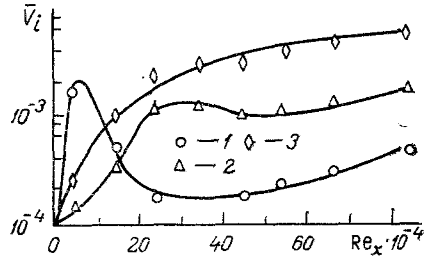
Fig. 2. Results of measuring the characteristics of the two-phase boundary layer on a plate with cylindrical leading edge (Re_H = 2320; c_0 = $0.2\cdot10^{-3}$ kg/m^3): a) mean droplet velocity field; b) variation of mean-velocity phase slip coefficient for droplets of diameter d_{dr} = $12\cdot10^{-6}$ m; c) droplet fluctuation velocity field; d) variation of droplet number concentration.

leading edge to the attachment point was constant over a broad range of variation of the flow velocity. In [4] the results of investigating the effect of a series of factors (shape of edge, Reynolds number, free-stream turbulence) on the mass transfer near the leading edge of a plate were reported.

It was established that these factors not only affect the value of the local mass transfer coefficient, which reaches a maximum at the point of attachment, but also determine the distance from the leading edge to the attachment point.

In order to study the deposition of droplets on a plate in the presence of separation of the two-phase flow at its leading edge, we carried out an experimental investigation. The method employed and some of the results were described in [2]. The DISA-55L laser anemometer used for measuring the mean and fluctuation droplet velocities gave an absolute error of ±0.003 m/sec. The anemometer unit measured the velocity of the droplets with the most probable cross-sectional area for the polydisperse flow investigated. As follows from [5], this condition corresponds to a linear projection diameter which, in all the experiments, was equal to $(12 \pm 1)\cdot10^{-6}$ m. Moreover, within the boundary layer we measured the phase slip coefficient with respect to the mean velocity and the relative number concentration of the droplets. The error in determining the coodinates of the measuring points did not exceed $\pm 25\cdot10^{-6}$ m. In the experiments we used polished glass plates of length L = 0.09 m and thickness 2H = 0.0024-0.0096 m with cylindrical and flat leading edges. The trailing edge was always flat. The velocity distribution in the film formed as a result of the coalescence of the droplets deposited on the plate was not measured, since the thickness of the plate was less than the diameter of the laser beam (10^{-4} m). The flow diagram and the coordinate system selected are shown in Fig. 1.

The results of measuring the longitudinal component of the mean velocity of droplets $12\cdot10^{-6}$ m in diameter (Fig. 2a) show that at the front of the plate where x/H < 5 (Re_x < 4800) and y/H < 0.3 there is a region in which the mean velocity has negative values. This particular motion may be associated with the fact that some of the droplets are entrained in the reverse ring flow within the separation bubble. The formation of a separation bubble near the leading edge of the plate led to a considerable increase in the thickness of the boundary layer (the measured values exceed by a factor of 2-3 the thickness of the separationless boundary layer).



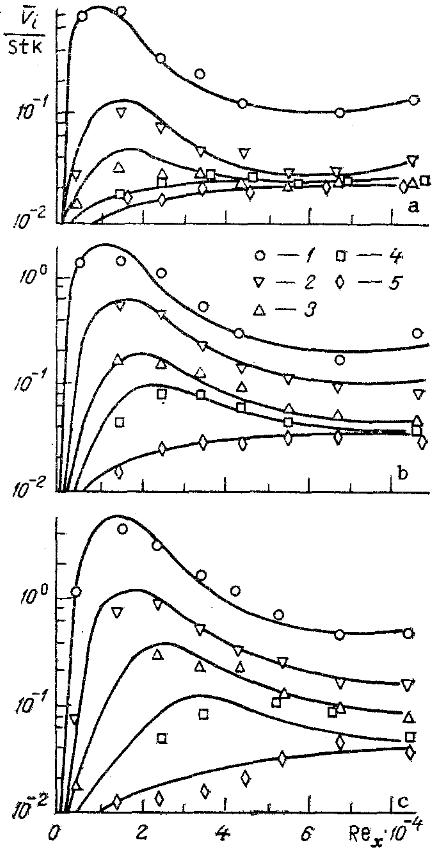


Fig. 3 Fig. 4

Fig. 3. Variation of droplet deposition rate along a plate with a cylindrical leading edge for Re_H = 2320: 1) $d_{dr} = 4 \cdot 10^{-6}$ m; 2) $12 \cdot 10^{-6}$; 3) $21 \cdot 10^{-6}$ m.

Fig. 4. Variation of droplet deposition rate along a plate with a flat leading edge for Re_H = 2320 (a); 4640 (b); and 9280 (c): 1) $d_{dr} = 4 \cdot 10^{-6}$ m; 2) $8 \cdot 10^{-6}$; 3) $12 \cdot 10^{-6}$; 4) $17 \cdot 10^{-6}$; 5) $21 \cdot 10^{-6}$ m.

The measurements of the mean-velocity phase slip coefficient $\phi = U_x/V_x$ showed (Fig. 2b) that outside the boundary layer the $12 \cdot 10^{-6}$ m droplets lag behind the carrier medium (ϕ = 0.95). On entering the boundary layer, they outstrip the decelerated air flow. Near the leading edge we noted a region in the center of which the phase slip coefficient reaches its greatest value: ϕ = 1.35. This region ($5 < x/H < 12$) coincides with the zone of incipient boundary layer formation.

In the free stream the longitudinal component of the fluctuation velocity of the droplets does not exceed 2% of the mean velocity U_0. The turbulent eddies generated upon separation of the flow at the leading edge lead to a considerable increase in the droplet fluctuation velocity, which reaches a maximum of $\sqrt{\overline{U'^2_x}}/U_0 = 0.06$ at the center of a region with the coordinates $5 < x/H < 20$; $0.3 < y/H < 0.6$ extending along the surface of the plate (Fig. 2c). With distance from the leading edge the width of the zone of intense fluctuation motion of the droplets increases, with a simultaneous decrease in the maximum of the fluctuation velocity to $\sqrt{\overline{U'^2_x}}/U_0 = 0.04$. At distances $y/H < 0.2$ the intensity of the turbulent fluctuations rapidly decreases.

Thus, the mean and fluctuation velocity measurements showed that in the boundary layer on a plate in a two-phase flow with separation at the leading edge, at the front of the plate ($x/H < 20$) there is a zone in which the longitudinal component of the mean droplet velocity reaches minimum values, while the intensity of the turbulent fluctuations sharply increases. In the same zone we also noted a considerable increase in the droplet concentration in the flow (Fig. 2d), the longitudinal and transverse droplet concentration gradients dn/dx and dn/dy reaching maximum values at $x/H < 5$, i.e., in the flow separation zone.

Near the trailing edge of the plate ($x/H > 50$) we note a decrease in the velocity of the droplets (Fig. 2a) and their concentration in the flow (Fig. 2d) and an increase in the phase slip coefficient (Fig. 2b). This variation of the measured parameters is due to the propagation upstream along the plate of pressure pulses associated with the formation of discrete eddies in the wake [6]. In [7] it is noted that the position of the eddy separation points on the trailing edge and the pressure in the separation zone depend on the structure of the two-phase boundary layer adjacent to the edge. At the same time, as follows from Fig. 2 and the data of [6], to a considerable extent the structure of the two-phase boundary layer near the trailing edge is determined by the vortex formation at that edge.

Consequently, the two-phase boundary layer on a short plate of finite thickness is formed under the influence of vortex edge effects which determine the droplet velocity and concentration in the flow at $y/H < 2$.

The vorticity of the carrier medium near the leading edge affects not only the motion of the droplets but also their deposition on the plate. In this connection, one of the determining factors is the droplet diameter. As may be seen from Fig. 3, the deposition rate V_i for droplets of diameter $d_{dr} = 4 \cdot 10^{-6}$ m increases in the separation zone, reaching a maximum $V_{im} = 0.03$ m/sec at $x/H = 5$, i.e., at the point of attachment of the flow. This value of the deposition rate is an order greater than that determined by turbulent-inertial transport [1] in the case of separationless flow over the plate. With distance from the leading edge the deposition rate decreases and when $20 < x/H < 60$ coincides with the results of calculations made using the method of [1] for a developing separationless boundary layer. Near the trailing edge ($x/H > 60$) the deposition rate for droplets with $d_{dr} = 4 \cdot 10^{-6}$ m again increases as a result of the trailing edge effects.

The variation of the deposition rate for larger droplets 12 and 21 μm in diameter (Fig. 3) indicates that under the experimental conditions the edge vortex effects have only a slight influence on the deposition of droplets with $d_{dr} = 12 \cdot 10^{-6}$ m and no influence at all on the deposition of droplets with $d_{dr} = 21 \cdot 10^{-6}$ m. Consequently, in order to increase the droplet deposition rate it is necessary to increase the vorticity of the carrier medium in the boundary layer. As shown in [4], the shape of the leading edge and the Reynolds number have a decisive influence on the intensity of the mass transfer processes on the surface of the plate, the greatest values of the mass transfer coefficient being observed on a plate with a flat leading edge.

The results of the experimental investigation of the rate of droplet deposition from a polydisperse flow onto a plate with a flat leading edge are presented in Fig. 4. As for a plate with a cylindrical edge, over the entire range of Reynolds numbers investigated ($2 \cdot 10^3 \leq Re_H \leq 9.3 \cdot 10^3$) an increase in the rate of deposition of droplets less than $17 \cdot 10^{-6}$ m in diameter near the leading edge is observed, the maximum rate of deposition of droplets with $d_{dr} = 4 \cdot 10^{-6}$ m on a plate with a flat leading edge being an order greater than for a plate with a cylindrical edge (Fig. 4a).

As the Reynolds number Re_H rises, the droplet deposition rate increases over the entire length of the plate, and the dimensionless distance from the leading edge to the point of maximum deposition rate (x_m/H) decreases. As for mass transfer on a plate in a single-phase flow [4], the quantity x_m/H is proportional to $Re_H^{-2/3}$:

$$\frac{x_m}{H} = 10^3 \, Re_H^{-2/3} \left(1 + 6 \, Re_H^{0,17} \, Stk\right). \tag{1}$$

The empirical relation determining the maximum dimensionless rate of deposition of droplets of a given diameter on a plate with a flat leading edge has the following form:

$$\bar{V}_{im} = 10^{-9} \, Re_H^2 \left[1 + 10^{-4} \, Stk^{-2} \left(0.7 - 10^{-4} \, Re_H\right)\right] \exp\left(-2 \cdot 10^{-3} \, Re_H \, Stk\right). \tag{2}$$

Taking into account the fact that the rate of droplet deposition along the plate is determined by the turbulent-inertial transport and edge vortex effects, the relation generalizing the results obtained can be represented in the form of a sum of three terms:

$$\bar{V}_i = \bar{V}_{i1} + \bar{V}_{i2} + \bar{V}_{i3}, \tag{3}$$

where $\bar{V}_{i1}$ is the deposition rate associated with the effect of flow separation at the leading edge; $\bar{V}_{i2}$ is the deposition rate determined by the turbulent-inertial mechanism; and $\bar{V}_{i3}$ is the deposition rate associated with the trailing edge vortex effects.

For $\bar{V}_{i1}$ we obtained the following expression:

$$\bar{V}_{i1} = \bar{V}_{im} \left(\frac{x_m}{x}\right)^{1,33} \exp\left(-\left|1 - \frac{x_m}{x}\right|\right), \tag{4}$$

where $\bar{V}_{im}$ is determined from expression (2), and x_m in accordance with expression (1).

In [2] an empirical relation was obtained between the rate of droplet deposition on a plate and the distance from the leading edge. This relation was found for the case in which the droplet deposition is not influenced by vortex effects. For separationless turbulent flow the rate of deposition of droplets less than $25 \cdot 10^{-6}$ m in diameter is determined by the turbulent-inertial mechanism and depends on the Reynolds (Re_x) and Stokes numbers as follows:

$$\bar{V}_{i2} = 8.5 \cdot 10^{-5} \, \mathrm{Stk} \, \mathrm{Re}_x^{0.5} \, . \tag{5}$$

The effect on the deposition rate of the pressure pulses that occur when eddies are shed from the trailing edge of the plate can be taken into account by means of the simple expression

$$\bar{V}_{i3} = 4 \cdot 10^{-4} \, \mathrm{Stk}^{0.2} H (L - x)^{-1}. \tag{6}$$

By adding expressions (4), (5), and (6) we can obtain an empirical relation that describes the variation of the droplet deposition rate along a plate with flat leading and trailing edges in the range of Re_H and Stk numbers investigated:

$$\bar{V}_i = \bar{V}_{im} \left(\frac{x_m}{x} \right)^{1.33} \exp \left(- \left| 1 - \frac{x_m}{x} \right| \right) + 8.5 \cdot 10^{-5} \, \mathrm{Stk} \, \mathrm{Re}_x^{0.5} + \tag{7}$$

$$+ 4 \cdot 10^{-4} \, \mathrm{Stk}^{0.2} H (L - x)^{-1},$$

$$2 \cdot 10^3 \leqslant \mathrm{Re}_H \leqslant 9.3 \cdot 10^3; \; 8 \cdot 10^{-3} \leqslant \mathrm{Stk} \leqslant 0.2.$$

Here, x_m is found from expression (1) and $\bar{V}_{im}$ from expression (2).

NOTATION

x is the longitudinal coordinate; x_m, longitudinal coordinate of the point at which the maximum rate of deposition of droplets of the i-th diameter is observed; y, coordinate along the normal to the plate surface; H, half-thickness of the plate; L, length of the plate; U_0, droplet velocity in the undisturbed flow; U_x, longitudinal component of the droplet velocity; V_x, longitudinal component of the gas velocity; ϕ, phase slip coefficient with respect to mean velocity; U_x', longitudinal component of the droplet fluctuation velocity; n, local number concentration of droplets in the boundary layer; n_0, concentration in the undisturbed flow; c_0, mass droplet concentration in the undisturbed flow; V_i, deposition rate for droplets of the i-th diameter; d_{dr}, droplet diameter; $\bar{V}_i = V_i U_0^{-1}$, dimensionless deposition rate for droplets of the i-th diameter; V_{im}, maximum droplet deposition rate; ρ_{dr}, and ρ_g, densities of the droplets and the gas respectively; ν_g, kinematic viscosity of the gas; $Re_H = 2HU_0\nu_g^{-1}$, Reynolds number; $Stk = \rho_{dr} d^2_{dr} U_0/18\rho_g\nu_g L$, Stokes number. Subscripts: dr, droplet, g, gas, and 0, coordinate x = 0.

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