DEPOSITION OF MICROPARTICLES FROM A TURBULENT STREAM ONTO A PIPE WALL

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An equation for the flux of particles to the inner wall of a pipe, in good agreement with experimental data, is obtained under certain assumptions about the mechanism of transport of solid microparticles in a turbulent gas or liquid stream. The problem of the variation in the density of microparticles along the length of a pipe is also solved.

Many papers have been devoted to the problem of the transport of microparticles from a turbulent stream to a solid wall. Extensive experimental material has been accumulated. But the problem of the transport of particles to a pipe wall has not been solved theoretically because of the complexity of the determining equations and the uncertainty in the coefficients in them. The equations derived in [1-3] have a general qualitative character. As will be shown below, however, under certain fairly obvious assumptions, a solution can be obtained that describes the experimental data of [4] well.

The following equation from molecular-kinetic theory is well known:

$$q_y = \frac{1}{2}\overline{V}\overline{l}\,\frac{\Delta n}{\Delta y}. \tag{1}$$

If particles in a turbulent stream are treated as a kind of gas, then the analog of the mean velocity $\overline{V}$ will be the rms velocity of turbulent pulsation of a particle toward the wall, $\sqrt{\overline{V_p'^2}}$; the analog of the mean free path $\overline{\ell}$ will be the quantity

$$l_p = \sqrt{\overline{V_p'^2}}\,\tau_p, \tag{2}$$

where τ_p is the relaxation time, defined by the equation [2]

$$\tau_p = \frac{1}{18}\frac{\rho_p}{\rho_0}\frac{d^2}{\nu}. \tag{3}$$

The particle density varies from the mean value n over the cross section at the boundary of the turbulent core to zero near the wall. This variation occurs over a distance δ equal to the sum of the thicknesses of the laminar sublayer and the buffer layer (Fig. 1). According to well-known data, of [5], for example,

$$\delta = 25\frac{\nu}{u_*}. \tag{4}$$

In contrast to an ideal gas of noninteracting particles, in which each of them having a velocity component $V_y < 0$ reaches the wall, in a turbulent stream not all the particles having an rms pulsation velocity in the y direction "penetrate" the thickness δ of the layer and reach the wall. We must therefore introduce an additional factor $0 < f(\ell_p/\delta) < 1$ into the right side of Eq. (1). For approximately 1 μm particles, $\ell_p/\delta \approx 0.1$. To first order, therefore, we may set $f(\ell_p/\delta) = \ell_p/\delta$. For the case of a "gas" of microparticles in a turbulent medium, Eq. (1) thus takes the form

$$q_y = \frac{1}{2}\sqrt{\overline{V_p'^2}}\,n\left(\frac{l_p}{\delta}\right)^2. \tag{5}$$

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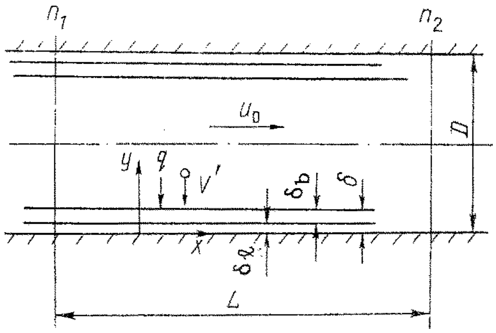

Fig. 1. Diagram of particle motion in a pipe.

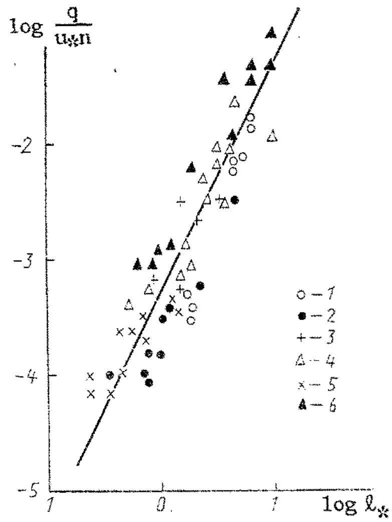

Fig. 2. Comparison of calculation and experiment: 1-6) experimental data of [4]; 1) iron particles, d = 0.8 μm, glass pipe, D = 5.4 mm; 2) iron particles, d = 1.3 μm, glass pipe, D = 13 mm; 3) aluminum particles, d = 1.81 μm, copper pipe, D = 13.8 mm; 4) iron particles, d = 1.57 μm, glass pipe, D = 13 mm; 5) iron particles, d = 0.8 μm, pipes of various materials, D = 25 mm; 6) iron particles, d = 13-26 μm, copper pipe, D = 25 mm; straight line: calculation from Eq. (8).

Particles with a size ~1 μm follow all turbulent pulsations [2], so that

$$\sqrt{\overline{V_p'^2}} = \sqrt{\overline{V_0'^2}}. \tag{6}$$

In accordance with the data of [3], at the boundary between the turbulent core and the buffer layer we have

$$\sqrt{\overline{V_0'^2}} = 0.9u_*. \tag{7}$$

Substituting Eqs. (7), (2), and (4) into Eq. (5) with allowance for (3) and (6), we obtain

$$\frac{q_y}{u_* n} = 5.8\cdot 10^{-4} l_*^2, \tag{8}$$

where

$$l_* = \frac{1}{18}\frac{\rho_p}{\rho_0}\left(\frac{du_*}{\nu}\right)^2 = 27.8\frac{l_p}{\delta}.$$

As seen from Fig. 2, Eq. (8) describes the experimental data fairly well.

On the basis of Eq. (8) we determine the variation of particle density along a pipeline as a gas or liquid moves through it. The differential equation of material balance is

$$-\frac{\pi D^2}{4} u_0 \frac{dn}{dL} = \pi D q_y. \tag{9}$$

After substituting Eq. (8) into it and integrating, we obtain

$$\ln \frac{n_2}{n_1} = -2.32 \cdot 10^{-3} l_*^2 \frac{L}{D} \frac{u_*}{u_0}. \tag{10}$$

Using the well-known equation from hydraulics

$$\frac{u_*}{u_0} = \frac{1}{2\sqrt{2}} \sqrt{\xi},$$

we finally obtain

$$n_2 = n_1 \exp\left(-8.2 \cdot 10^{-4} l_*^2 \frac{L}{D} \xi^{0,5}\right). \tag{11}$$

In analyzing Eqs. (8) and (11), we may draw some general conclusions. In a suspension or aerosol of polydisperse composition, the large and heavy particles will primarily be deposited. The transport of particles to a rough wall is more intense than to a smooth one, other conditions being equal. The equations obtained can be used in cryogenic engineering to solve problems associated with the transport and deposition of solid impurities in liquids and gases moving through pipelines.

NOTATION

ρ_p, density of particle material; ρ_0, density of carrier stream; D, inside diameter of pipe; d, particle diameter; $u_* = \sqrt{\sigma_w/\rho_0}$; σ_w wall frictional stress; ξ, wall frictional coefficient; ℓ_p, particle mean free path; V_p', pulsation component of particle velocity toward the wall; n, average particle density over a cross section; δ_ℓ, thickness of laminar sublayer; δ_b, thickness of buffer layer; δ, total thickness of laminar and buffer layers; ν, kinematic viscosity coefficient; u_0, average stream velocity over a cross section; L, distance between control cross sections of pipe; $\ell_* = 27.81\ell_p/\delta$, dimensionless particle mean free path; V_0', pulsation component of stream velocity toward the wall.

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