EXPERIMENTAL INVESTIGATION OF THE MOTION OF A DISPERSE MATERIAL IN A RISING GAS SUSPENSION

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UDC 532.529.5:541.182.3

We present the results from an investigation into the quantitative relationships governing the interaction between the particles in a disperse material and between those particles and the walls of a channel in the case of vertical two-phase flows.

Numerous papers devoted to studying the quantitative relationships governing the motion of a disperse material in a rising gas suspension make the assumption that the particles move along rectilinear trajectories that are parallel to the axis of the channel, and that this motion is a consequence of weight and the forces of aerodynamic drag. In this case, the sliding velocity of the particles in a stabilized flow segment must be equal to the free-fall velocity of the particles. However, this fails to take into account two factors which have a decisive effect on the nature of the motion of a real gas suspension and the corresponding quantitative relationships, i.e., the collision of particles against the channel walls and with each other.

The interaction of the particles with the wall is a consequence of the collisions between the particles, the Magnus effect, turbulent pulsations, etc., and these factors have not been studied adequately. In a theoretical examination of this problem, we calculate the frequency of particle collison with the wall on the basis of the assumption that the only factor responsible for transverse movement of the particles in the vertical flow is their entrainment as a consequence of large-scale pulsations [1]. This assumption is debatable, since no consideration is given to one of the most important factors responsible for the lateral movement of particles, namely, their massive collisions with each other. The pressure losses in the flow as a result of material friction against the wall, determined in accordance with [1], are substantially understated in comparison with experimental data [2]. The experimental determination of the frequency of particle collisions with the wall has been applied only to conditions of horizontal flow [3], and the author employed a method which involves significant errors.

This investigation was performed on a test stand, whose diagram and description is given in [4]. The frequency of particle collision with the wall of a vertical channel is determined by means of piezoelectric gauges set flush with the inside surface of a glass tube 76 mm in diameter, at the quasi-stabilized and acceleration segment of the flow. The working element of the gauge was piezoelectric quartz crystal which was rigidly linked to a platform by means of a pin to record the collisions of large-size particles. The platform had a diameter of 7.5 mm and was set into an opening in the wall, with a clearance of 0.5 mm. In studying the interaction of a fine fraction with the wall, the particle collisions are picked up directly by the quartz crystal, which is 2×5 mm in size. The pulses generated by the collision of the particles against the gauge, after amplification, are recorded on the photographic paper of a loop oscillograph in the form of bursts. The amplification factor and the required recording time were chosen on the basis of the particle dimensions and the regime parameters of the flow. For the disperse material we used pellets of an aluminosilicate catalyst with an average diameter of 2.94, 2.5, and 0.338 mm ($\rho = 1200$ kg/m^3), rape ($\delta = 2.33$ mm, $\rho = 1100$ kg/m^3), and millet ($\delta = 2.36$ mm, $\rho = 1100$ kg/m^3). The tests were carried out at gas velocities of $w = 8$-25 m/sec (which corresponds to a Reynolds number range of $Re = (4\text{-}12) \cdot 10^4$) and concentrations of $\mu = 0.1$-5 kg/kg.

Tests have shown that the frequency of particle collision against the channel wall increases with a rise in the flow-rate concentration and in the flow velocity (Fig. 1). Here the effect of concentration in the

Institute of Technical Thermophysics, Academy of Sciences of the Ukrainian SSR, Kiev. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 16, No. 4, pp. 639-646, April, 1969. Original article submitted June 25, 1968.

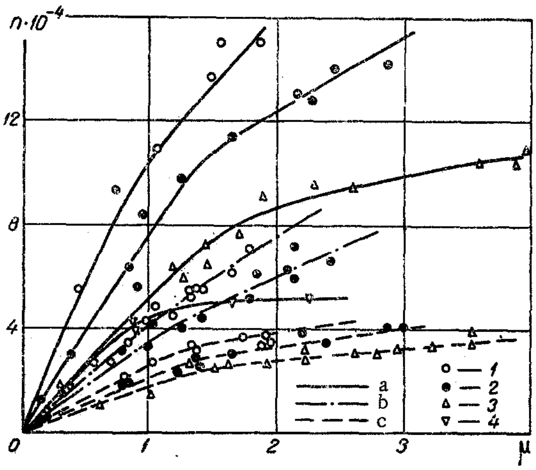

Fig. 1

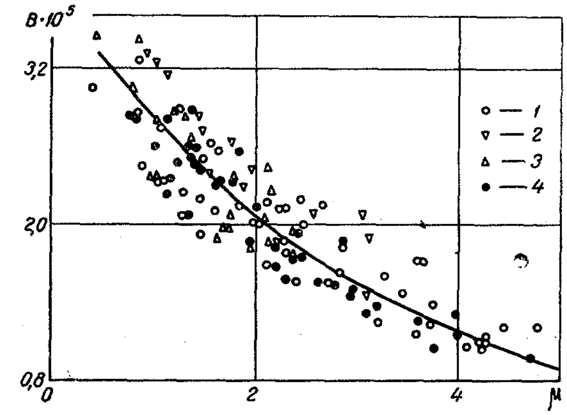

Fig. 2

Fig. 1. Frequency of collision for particles of the disperse material against the wall of a vertical channel ($m^{-2} \cdot sec^{-1}$): a) aluminosilicate catalyst (δ = 2.5 mm); b) millet; c) rape: 1) stabilized segment Re = $115 \cdot 10^3$; 2) the same, $85 \cdot 10^3$; 3) the same, $72 \cdot 10^3$; 4) acceleration segment, Re = $85 \cdot 10^3$.

Fig. 2. Dimensionless complex B as a function of the flow-rate concentration μ(kg/kg): 1) catalyst (δ = 2.94 mm); 2) catalyst (δ = 2.5 mm); 3) millet; 4) rape.

investigated range of change in the concentration varies: up to μ = 1-2.2 the rate of growth for the number of particle collisions against the wall is substantially higher than in the case of higher values of μ. We can assume that this pattern is a consequence of the growth in the number of particles colliding with each other as the value of μ increases. Our attention is drawn to the fact that this critical value of μ coincides with the magnitude of the concentration at which we find a minimum coefficient of heat transfer between the flow and the channel wall [5]. Currently available data provide no correct explanation for the complex mechanism relating the structure of the two-phase flow (including the critical value of μ) with the processes occurring at the boundary of the flow.

An increase in the velocity of the carrier flow leads to an increase in the radial component of the particle velocity and in the frequency of collision with the wall. The latter quantity, as follows from Fig. 1, also increases along the length of the acceleration segment.

Despite the fact that the particle dimensions for the materials used in the tests differ only slightly from each other, the collision frequency for equal flow velocities varies. This indicates that the collision frequency is a significant function of the physical properties of the material, and primarily of the particle elasticity characterized by the recovery factor k_n. The magnitude of k_n is determined experimentally and exhibits the following values: for the catalyst it is 0.924; the corresponding figure for millet is 0.75, and for rape it is 0.62. The lower the value of k_n, the more substantial the loss in the radial velocity on collision, which leads to a reduction in the frequency of collision with the wall.

With a reduction in particle size the frequency of collision is substantially raised. Thus, for a fine catalyst (δ = 0.338 mm) the value of n is greater by approximately two orders of magnitude than that for a coarse fraction (δ = 2.5 mm), whereas these particles differ in terms of size by factors of only 7-8.

Processing of the results from tests with catalyst particles (δ = 2.5 and 2.94 mm), and for millet and rape show that in $\mu - B$ coordinates (here $B = (n\delta^3/w\mu)(\rho/\rho_g)(Fr^{-2}/k_n^3)$*) all of the experimental points are grouped about some curve (Fig. 2). The method of least squares yields the following correlation:

$$B = a \exp(-b\mu). \qquad (1)$$

For the channel used in the experiments, with a diameter of D = 76 mm we have $a = 3.4 \cdot 10^{-5}$ and b = 0.265. The maximum deviation of the experimental points from curve (1) does not exceed ±15%. The

*In a turbulent regime of particle streamlining, the complex B has the form

$$B = 0.33\, n \frac{\delta^3}{w\mu} 1/k_n^3.$$

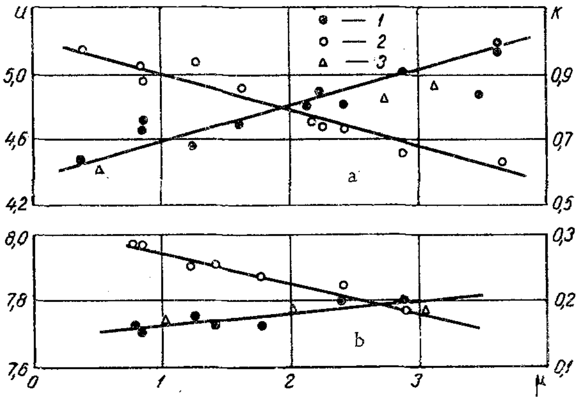

Fig. 3

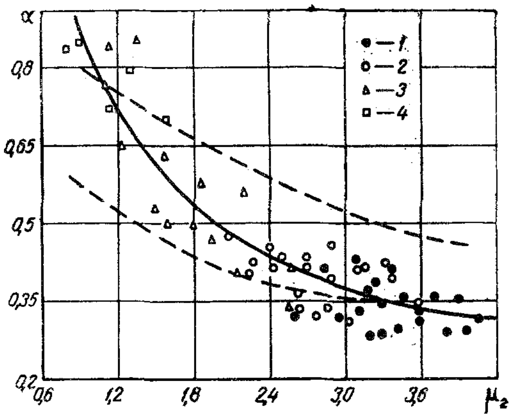

Fig. 4

Fig. 3. Average velocity u for the disperse material (in m/sec) and the Gasterstadt coefficient K as functions of the flow rate concentration μ (kg/kg) (w = 16.7 m/sec): 1) velocity; 2) Gasterstadt coefficient; 3) particle velocity determined by the radioactive tracer method; a) catalyst (δ = 2.5 mm); b) rape.

Fig. 4. Coefficient α as a function of the fine-fraction concentration: 1) $\mu_1/\mu_2 < 0.25$; 2) $\mu_1/\mu_2 = 0.9$-1.5; 3) $\mu_1/\mu_2 = 0.4$-0.5; 4) $\mu_1/\mu_2 > 1.6$.

data on the collision frequency for microspherical catalyst (δ = 0.338 mm) are grouped somewhat higher than the curve in Fig. 2, because of a substantial electrostatic effect.

The results of an experimental investigation into the interaction of particles (glass beads with dimensions of δ = 1, 2, 4, and 5 mm) with the walls of a vertical channel for Re = $(4.5$-$17) \cdot 10^4$ and μ = 0.1-8 kg/kg are given in [6]. The processing of the experimental data, by analogy with the above, demonstrates that they are also well described by Eq. (1), with the values of the coefficients a and b exclusively functions of the channel diameter. In the range D = 64-100 mm, these results are expressed by the following functions (D is expressed in meters):

$$a = (-11.3D^2 + 2.38D - 0{,}083)\cdot 10^{-3},$$

$$b = -141\,D^2 + 28.1\,D - 1.07.$$

The frequency of particle collisions with the wall (or the dimensionless parameter B) in the investigated range thus increases as the diameter of the channel is enlarged. At low concentrations (μ < 2 kg/kg) this relationship is quite substantial.

From the derived values of n we can determine the average axial velocity of the particles and the Gasterstadt coefficient which characterizes the pressure losses in the flow as a result of the friction of the material against the wall. Using the expression derived in [7], i.e.,

$$K = 1.197\,\frac{\rho}{\rho_g}\,\delta^3\,\frac{u}{\lambda w^2}\,\frac{n}{\mu}\,(1 - k_t), \tag{2}$$

with consideration of (1) we find

$$K = 1.197\,a\exp(-b\mu)\,\mathrm{Fr}^2\,\frac{u}{\lambda w}\,k_n^3\,(1 - k_t). \tag{3}$$

To determine the average axial velocity of the particles, we can use the equation of motion for a large particle, giving consideration to its interaction with the wall [8], so that

$$\left(\frac{w-u}{v}\right)^2 - 1 - \frac{\lambda K}{Dg}\,\frac{wu}{2} = 0.$$

Unlike the familiar [2] correlation for the determination of K, in addition to the regime flow parameters w and μ, Eq. (3) also enables us to provide explicitly for the physical properties of the material and of the tube wall (k_n, k_t). Calculations with (3) and (4) show that u and K are strong functions of μ (Fig. 3).

We know that with an increase in the velocity of the transporting flow the ratio u /w also increases [9]. Since λ diminishes in this case, as follows from (3), the Gasterstadt coefficient increases as w increases. For example, when μ = 2 kg/kg and w = 11.4 m/sec the Gasterstadt coefficient for rape amounts to K = 0.12, while for w = 23 m/sec we have K = 0.26.

We see from (3) that the value of K depends on the coefficient k_t which characterizes the state of the particle surface and the wall. The quantity k_t is determined in the following manner. The tangential components of velocity for the center of gravity of the particle, before and after the collision, as follows from [10], are associated by the relationship

$$u_t' = \frac{u_t}{7}(5 + 2k_t),$$

whence

$$k_t = 3.5\frac{u_t'}{u_t} - 2.5,$$

or

$$k_t = 3.5k_n \operatorname{tg}\varphi \operatorname{ctg}\varphi' - 2.5, \qquad (5)$$

where $\varphi = (\widehat{\mathbf{u}, \mathbf{u}_t})$ and $\varphi' = (\widehat{\mathbf{u}', \mathbf{u}_t'})$. The values of the angles φ and φ' were determined by measurement on the photographs obtained by dropping the test particles onto an inclined plate which is similar in roughness to the inside surface of the tube. For the catalyst we have k_t = 0.3, and for rape the corresponding figure is 0.33.

The values calculated with (3) and (4) for the velocity of catalyst particles (δ = 2.5 mm) and rape are in good agreement with the direct-measurement results for the velocity of the material at the stabilized segment (Fig. 3). The velocity was measured by means of a radioactive isotope method. One of the catalyst particles (δ = 2.5 mm) was tagged with the Sc^{46} isotope, yielding γ radiation of rather high energy. The instant at which the particle passes a control point is recorded by means of two operating sensors (a P-349-2 scintillation attachment with NaI (Tl) crystals), separated by 600 mm. The signal generated in the sensor on passage of the tagged particle is transmitted through an amplifier to the loop oscillograph and recorded in the form of a burst. Since the rape particles differ little in terms of density and size from the catalyst particles, we also used the tagged catalyst particle to determine the average velocity of rape motion.

This method of measuring velocity also enabled us to study certain quantitative relationships in the process of collision between the particles of a polydisperse material in a vertical two-phase flow. On the basis of a number of simplifying assumptions, an approximate theoretical solution for this problem has been found in [11]. The results from an experimental determination of the effect of collision between the rising flow of the fine fraction and a single large particle serves as a confirmation of the validity of the model adopted in [11]. Below we present the results from a more detailed study of this question, in connection with the interaction between two large groupings of particles.

We used a mixture of two narrow fractions of the catalyst (δ_1 = 2.5 mm and δ_2 = 0.338 mm) as the disperse material. The test involved the measuring of the average velocity of motion for the large fraction at the stabilized segment of the flow and the tests were carried out in the range w = 10.5-15.1 m/sec at concentrations of μ_1 = 0.525-2.78 kg/kg, μ_2 = 0.605-4.3 kg/kg, and μ_1/μ_2 = 0.197-2.13.

The experimental results confirmed the earlier conclusion [4, 11] as to the substantial effect exerted by the collisions on the velocity of particle motion in a two-phase flow. For example, for w = 10.52 m/sec and μ_2 = 3.4-4.16 kg/kg the average velocity for the large particles is 5.86-6.17 m/sec, i.e., it exceeds the "theoretical" magnitude of $w - v_1$ by a factor of 3.6-3.8.

As in [4], the experimental data were processed in dimensionless quantities y_{th} and y_{exp}. It follows from [4, 8, 11] that for the test conditions the experimental value of the dimensionless acceleration of the large particles, resulting from collisions with the fine fraction, can be calculated as follows:

$$y_{exp} = 1 + \frac{\lambda K_1 w u_1}{2Dg} - \left(\frac{w - u_1}{v_1}\right)^2. \qquad (6)$$

The values of the Gasterstadt coefficient K_1 were determined from (2). The velocity of the fine particles in the stabilized segment for each of the tests was calculated from the equation

$$u_2 = w - v_2 \left[0.598 \frac{\rho \delta_2^3 n_2 (1 - k_t)}{g D \rho_g w \mu_2} u_2^2 + 1 + \frac{y_{exp} \mu_1}{u_1 \mu_2} u_2 \right]^{2/3}, \quad (7)$$

which, as shown by calculation, is solved by the method of iterations. The "theoretical" value of the acceleration for the large particles, caused by collisions, according to [11] is equal to

$$y_{th} = \frac{3}{4} \frac{(1 + k_n) \rho g (\delta_1 + \delta_2)^2 w \mu_2}{\rho (\delta_1^3 + \delta_2^3) g} \frac{(u_2 - u_1)^2}{u_2}. \quad (8)$$

The correction factor α, by means of which we provide for the difference between the real conditions of the collision process and the conditions corresponding to the model adopted in [11], is obviously equal to

$$\alpha = \frac{y_{exp}}{y_{th}}. \quad (9)$$

The results obtained in the processing of the experimental data on the basis of the outlined method (Fig. 4) are satisfactorily described by the relationship

$$\alpha = 0.8 \, \mu_2^{-0.687}, \quad (10)$$

which was derived by the method of least squares. We see from Fig. 4 that in the range studied here the coefficient α is independent of the relationship between the concentration of the fraction and the velocity of the gas stream. It is characteristic that the values of α were lower than in [4], where larger particles (δ_2 = 2-3 mm) were used as the fine fraction. To determine the factors for this divergence, we carried out a series of tests to determine the reduced free-fall velocities for a large particle in a gas stream and for a microspherical catalyst (δ_2 = 0.338 mm). The dashed lines in Fig. 4 show the limits of the field of experimental points for this series. Since most of the points of the second series are also within these limits, there is apparently no basis for the contention that the quantitative relationships governing the interaction between the flow of the fine fraction and the single large particle, on the one hand, and between the fractions of a two-fraction material, on the other hand, are different.

In the light of the above we can assume that the difference between the resulting experimental data and the results cited in [4] are explained primarily by the difference in the dimensions of the fine-fraction particles. Apparently, with a reduction in δ_2, the fraction of the energy expended on the lateral movement and rotation of the particles increases, thus reducing the effect of the collisions.

NOTATION

D	is the channel diameter;
g	is the acceleration of the force of gravity;
K	is the Gasterstadt coefficient;
k_n and k_t	are, respectively, the recovery factors for the normal and tangential velocity components on collision;
n	is the collision frequency for the particles against the wall;
u	is the viscosity of the disperse material;
v	is the free-wall velocity for the particles;
w	is the gas velocity;
δ	is the particle size;
λ	is the resistance factor for the flow of a pure gas;
μ	is the mass flow-rate concentration;
ν	is the kinematic coefficient of viscosity;
ρ and ρ_g	are, respectively, the density of the particles and of the gas;
$Fr = v/\sqrt{g\delta}$	is the modified Froude number;
$Re = wD/\nu$	is the Reynolds number.

Subscripts

1, 2	pertain, respectively, to the coarse and fine fractions.
th, exp	refer, respectively, to theoretical and experimental values.

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