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INFLUENCE OF COLLISIONAL DISSIPATION ON INTERNAL PULSATIONS IN A FLUIDIZED BED

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It is shown that the presence of energy dissipation in particle collisions results in degeneration of their random pulsations and a decrease in pulsation-induced stressed and favours instability of the system.

Collisional dissipation by particles suspended in a gas flow decreases random pulsations of both phases, thus inevitably causing a decrease in the pressure and the quasiviscous stresses in the disperse phase. This effect is especially manifested when the particle concentration increases in a gas suspension. On the assumption that momentum and energy exchange between particles is accomplished due to inelastic collisions, the effective temperature and the modulus of elasticity of the pseudogas of particles are also determined.

The discovery of the physical effects that are attributable to the collisional dissipation require, naturally, an exact account of the interaction between individual particles, which cannot be met successfully using a purely continuum model. For such an account a microscopic approach that is based on results of the kinetic theory of dense gases and is rather extensively described in the literature [1–4] is usually adopted. However since the effective stresses and the pulsation energy flux in both phases depend mainly on the pulsating flow of the latter, the problem of correct closure of the conservation equations with account for pulsations in the system of these equations remains, in fact, unsolved [5].

In [5, 6] these pulsations are considered on the assumption that the pulsation energy is equidistributed with respect to the translational degrees of freedom of the particles due to the collisions between the particles. The equations of conservation of mass and momentum of both phases and the equation of the pulsation energy of the dispersive phase have been formulated. However, the influence of energy dissipation in particle collisions, which make a specific contribution to different characteristics of pseudoturbulent pulsations and determine, in turn, the effective pulsation pressures and the quasiviscous stresses in continuous and dispersive phases, has been neglected. In the present work such an account is made for monodisperse systems of relatively coarse particles suspended in a gas flow.

In accordance with [6] we shall consider a system of particles of radius a and density d_1 characterized by the ensemble-averaged velocity of the particles $\langle w \rangle$, liquid velocity in its specific volume $\langle v \rangle$, volumetric concentration of particles $\langle \rho \rangle$, and liquid pressure $\langle P \rangle$. We represent the local values of the above variables in the form

$$\mathrm{w} = \langle \mathrm{w} \rangle + \mathrm{w}' ; \quad \mathrm{v} = \langle \mathrm{v} \rangle + \mathrm{v}' ; \quad \rho = \langle \rho \rangle + \rho' ; \quad P = \langle P \rangle + P' ,$$

where primes denote pseudoturbulent variables, which depend on the pulsation of the phases.

For the collision force acting on an individual particle from the side of the other particles, surrounding it in a one-dimensional flow, in which the acceleration by the field of external mass forces and the mean velocity of interphase sliding are collinear, we write the expression [6]

$$\mathrm{f}_c = - d_1 \frac{\rho}{n} [A\mathrm{w}' + B (\mathrm{u}_0 \mathrm{w}') \mathrm{u}_0] , \quad \mathrm{u}_0 = \frac{\mathrm{u}}{u} , \tag{1}$$

where A and B are unknown coefficients to be determined.

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Hence the energy dissipation in inelastic collisions per unit volume of the medium and per unit time may be determined in the following form:

$$q_c + \langle f_c' w' \rangle = - \frac{d_1 \rho}{n} (A \langle w'^2 \rangle + B \langle w_1'^2 \rangle). \tag{2}$$

Here the subscript indicates the direction along the first coordinate axis, which coincides with that of the sliding velocity u of a liquid.

On the other hand, q_c may be represented as the product of the collision frequency of the particles by the mean energy loss per collision, i.e.,

$$q_c = K_c \chi \nu_0 \theta. \tag{3}$$

For ν_0 we may use the expression for rarefied gas viscosity [7]

$$\nu_0 = 16 n^2 a^2 \left(\frac{\pi \theta}{m} \right)^{1/2}.$$

On the basis of the Carnahan–Starling model [5] we repsent the function χ as follows:

$$\chi = \frac{G(\rho) - 1}{4\rho}; \quad G(\rho) = \frac{1 + \rho + \rho^2 + \rho^3}{(1 - \rho)^3}.$$

The procedure for calculating the pulsation temperature of a gas of particles θ, is described in [6]; its final form is

$$\theta = mu^2 \langle R'^2 \rangle M^2 \frac{x^2}{[y + (x + y)x]^2}; \quad M = \frac{3}{2(1 - \rho)} + \frac{1}{2} \frac{d \ln K(\rho)}{d\rho};$$

$$K(\rho) = \frac{3}{8} \xi \left(\frac{1 - \rho}{1 - 1.17 \rho^{2/3}} \right)^2; \quad \langle R'^2 \rangle = \rho^2 \frac{1}{1 + 2\rho \frac{4 - \rho}{(1 - \rho)^4}}; \tag{4}$$

$$x = \frac{A}{2Fu}; \quad y = \frac{B}{2Fu}; \quad F = \frac{K(\rho)}{\kappa a}; \quad \kappa = \frac{d_1}{d_0}.$$

We assume that $y = -\sigma x$ and write an equation stemming from (2) and (3) with account for relations (4):

$$\sigma - 3 = S(\rho) \left(\int_0^1 \frac{t^4 dt}{(s^2 - t^2)^2} \right)^{1/2} \Big/ (|x| \, |\sigma(x + 1) - x|);$$

$$S(\rho) = \frac{3\kappa K_c}{2\sqrt{\pi}} \frac{(G(\rho) - 1)}{K(\rho)} M \sqrt{\langle R'^2 \rangle}; \quad s^2 = \frac{(2|x| - 1)(\sigma - 1)}{(\sigma - 1)|x| - \sigma}. \tag{5}$$

The calculation of the coefficients A and B, which determine all the statistical characteristics of fluctuation, including the effective pressure P and temperature of the gas of particles θ, is simple though rather cumbersome and is reduced to the following sequence of operations.

From the isotropy condition for the pulsations

$$\int d\omega d\mathbf{k} \, [\Psi_{w1,w1}(\omega, \mathbf{k}) - \Psi_{w2,w2}(\omega, \mathbf{k})] = 0,$$

TABLE 1. s, x, y as Functions of σ, Calculated by Eq. (6)

σ	s	x	y	σ	s	x	y
3.010	1.577	−5.595	16.840	3.095	1.442	−26.106	80.800
3.020	1.558	−6.152	18.578	3.097	1.440	−28.022	86/790
3.030	1.539	−6.880	20.845	3.100	1.438	−30.132	93.410
3.050	1.506	−8.858	27.018	3.103	1.433	−38.709	120.113
3.070	1.476	−12.493	38.355	3.105	1.430	−44.361	137.741
3.080	1.462	−15.752	48.517	3.107	1.428	−51.918	161.310
3.090	1.448	−21.715	67.100	3.110	1.424	−71.602	222.681

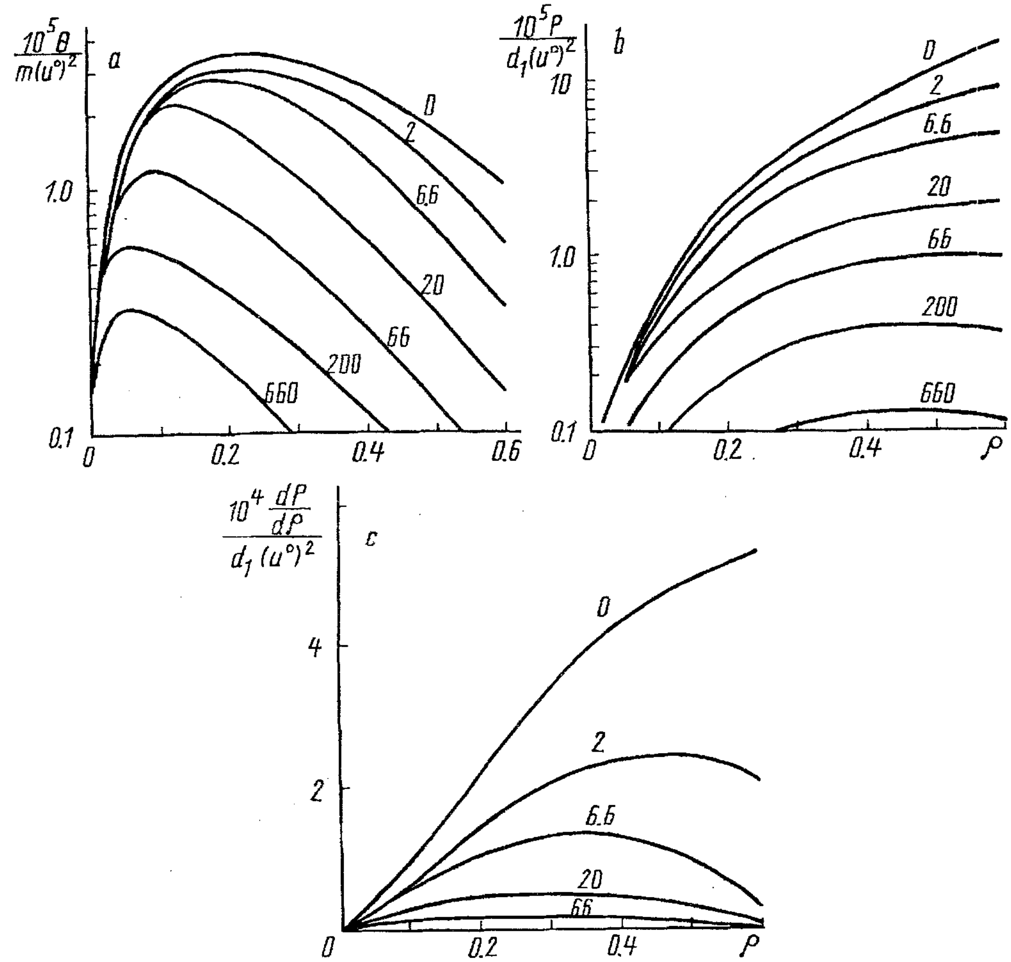

Fig. 1. Plots of pulsation temperature (a), pressure (b), and modulus of elasticity (c) vs particle concentration for various h (the figures at the curves).

$$\langle w_1'^2 \rangle = \frac{x^2}{L^2}(Mu)^2 \langle R'^2 \rangle \int_0^1 \frac{t^4}{(s^2 - t^2)} dt =$$

$$= \langle w_2'^2 \rangle = \frac{(x+y)^2}{2L^2}(Mu)^2 \langle R'^2 \rangle \int_0^1 \frac{t^2(1-t^2)}{(s^2-t^2)^2} dt. \quad (6)$$

Hence

$$\left[\frac{2+(\sigma-1)^2}{(\sigma-1)^2}s^2-1\right]\Bigg/\left[3s^2\frac{2+(\sigma-1)^2}{(\sigma-1)^2}-1\right]=\frac{s}{2}(s^2-1)\ln\frac{s+1}{s-1}.$$

The functional L is written in the form [6]

$$L = y + (x + y)\,x\,,$$

and y and x are expressed as functions of σ and s^2. For this, we determine the functions $S = S(\sigma)$ from Eq. (6) and hence x, $y = x(\sigma)$, $y(\sigma)$. From (5) at the fixed value $h = kK_c/\xi$ we determine $\rho = \rho(\sigma)$ or the relation $\sigma = \sigma(\rho)$ reciprocal to the latter. Now it is easy to determine the sough values of x and y. The calculations show that the condition $\sigma \geq 3.0$ is physically meaningful (see Table 1). Here equality corresponds to the case of zero dissipation in collisions of particles of the dispersive phase.

Calculation results are shown in Fig. 1. The curves corresponding to $h = 0$ pertain to collisions of absolutely elastic particles and coincide will the curves obtained for P, θ in [6] with neglect of collisional dissipation. Moreover, we note that the calculated pulsation energies are in qualitative agreement with results reported in [7–9]. Some increase in particle pulsations begins with an increase in their concentration, and when the latter attains 0.2–0.3 the pseudoturbulence undergoes a substantial decrease. It is also seen that with an increase in the concentration the effect of the dissipation on the pulsation energy and the pressure of the gas of particles is more pronounced than for a dilute mixture (Fig. 1a, b), which is explained by an increase in the collision frequency of the particles. Therefore the substantial dissipation in collisions should favor a decrease in both the pressure and the quasiviscous stresses with an increase in the concentration. The modulus of elasticity of the dispersive phase at a high concentration of it ($h > 100$) can become negative, which entails loss of thermodynamic stability and, consequently, stratification of the initially homogeneous bed (Fig. 1c). In any case, with enhancement of the dissipation the conditions for disturbance of the hydrodynamic stability of disperse flows are less stringent.

It is worth noting that experimental investigations of the effect of passing from a uniform to a nonuniform state of fluidization are a more complicated problem that is generally agreed. As a result, a substantial scatter of experimental data is observed that only allows a conclusion about their presence and influence on the mentioned effect of cohesion forces acting between particles [10]. However, in any case the energy lost by colliding particles may be taken as some effective cohesion. The available rather numerous data on the tendency toward formation of channels and macroscopic aggregates of particles with a decrease in their size may also confirm the disturbance of thermodynamic stability upon enhancement of collisional dissipation or cohesion of particles. Actually, in increase in the number of particles at the expense of a decrease in their size at constant volumetric concentration causes an increase in collision frequency and favors stratification.

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NOTATION

a, particle radius; d_1, d_0, density of the particle material and the liquid, respectively; $K(\rho)$, function stemming from the model of jet flow around particles; s, function introduced into (5); $\Psi_{w,w}$, spectral density; $\mathbf{k}$, wave vector; ω, frequency; m, particle mass; K_c, coefficient characterizing the energy loss in a single collision between particles; q_c, energy dissipation in the pseudogas of particles; θ, effective temperature of the gas of particles; P, pressure of the particles; $\mathbf{u}$, relative liquid velocity; $\mathbf{v}$, $\mathbf{w}$, liquid and particle velocities; u^0, velocity of free fall of a particle; ρ, particle concentration; ν_0, viscosity of the pseudogas of particles; h, dissipation parameter; χ, Enskog factor; n, number density of the particles; A and B, coefficients introduced into (1).

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