MIXING EFFICIENCY IN A FLUIDIZED BED

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The problem of the efficiency of fluidization and pseudoturbulent mixing of an axisymmetric jet with solid particles is analyzed.

In the majority of technological processes the use of a fluidized bed is determined by the high efficiency of the transfer processes in the bed. The possibility of estimating the mode of greatest mixing and the effect of the parameters of the "boiling" layer on the mixing efficiency takes on considerable importance in the selection of the parameters of the "boiling" layer.

In the practical application of a boiling layer, however, irregularities in the concentration of the solid and gaseous phases develop near the input devices which directly affect the rate of occurrence of the chemical reaction.

Using the statistical theory developed by Yu. A. Buevich to describe the hydromechanics of disperse systems one is able to estimate the dependence of the mixing efficiency in the bed on the concentration of the solid phase and analyze the properties of the mixing of the solid and gaseous phases near the input devices.

As numerous experiments with fluidized beds and theoretical works [1, 2] show, the pulsations of solid particles and elements of gas volume play a large role in the description of the hydromechanics of such layers, provided the Reynolds numbers for the flow over individual particles are not very small.

Taking the latter assumption as satisfied, let us calculate the equivalent temperature of the pseudoturbulent pulsations for a system whose solid phase consists of particles of two sizes. According to [3], the equations for the pulsation components of the velocities and the density can be written in the form

$$
\begin{gathered}
m^{(j)}\left[\frac{\partial \vec{W}^{(j)\prime}}{\partial t}+(\vec{W}^{(j)}\vec{\nabla})\vec{W}^{(j)\prime}\right]=\vec{F}^{(j)\prime}, \\
\left[\frac{\partial}{\partial t}+(\vec{V}\vec{\nabla})\right]\rho'-(1-\rho)\vec{\nabla}\vec{V}^{(j)\prime}=0, \\
d_0(1-\rho)\left[\frac{\partial}{\partial t}+(\vec{V}\vec{\nabla})\right]\vec{V}^{(j)\prime}=-\vec{\nabla}P^{(j)\prime}+\mu_0 S(\rho)\vec{\nabla}\vec{e}^{(j)\prime}-\sum_{j=1}^{2}\frac{\rho^{(j)}}{\sigma^{(j)}}\vec{F}^{(j)\prime}, \qquad (1)\\
\vec{F}^{(j)\prime}=-\sigma^{(j)}\vec{\Delta}P^{(j)}+\varkappa m^{(j)}\beta^{(j)}\left[K(\rho)\vec{u}^{(j)\prime}+\frac{dK(\rho)}{d\rho}\vec{u}^{(j)}\rho'\right]; \\
\vec{e}^{(j)\prime}=\left\|\frac{\partial V_i^{(j)\prime}}{\partial x_h}+\frac{\partial V_k^{(j)\prime}}{\partial x_i}-\frac{2}{3}\delta_{ih}\frac{\partial V_e}{\partial x_e}\right\|.
\end{gathered}
$$

Here, besides the notation put in the list, we take

$$
\vec{u}^{(j)\prime}=\vec{V}^{(j)\prime}-\vec{W}^{(j)\prime};\quad \vec{u}^{(j)}=\vec{V}-\vec{W}^{(j)};
$$

$K(\rho)$ is a function allowing one to take into account the constraint $\beta^{(j)}=9\mu_0/2a^{(j)2}d$ of the flow over particles in the system, where the index (j) indicates the number of the type of particles.

Let us move on to the spectral representation for the pulsation components:

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TABLE 1. Variation in Concentration of Solid Phase along Length of Jet

	$x=0$	$x=10r_0$	$x=20r_0$	$x=50r_0$
$r=0$	—1	—0,24	—0,12	—0,04
$r=r_0$	—1/2	—0,27	—0,17	—0,07
$r=5r_0$	0	—0,01	—0,07	—0,08

$$\varphi' = \int Z_\varphi \exp [i(\omega t + \vec{k}\vec{r})]\, d\omega d\vec{k}, \tag{2}$$

where $\varphi' \equiv \rho'$, P', W', V'.

Substituting (2) into (1), we find that $\vec{Z}_V^{(2)} = \vec{Z}_V^{(1)}$, and $Z_P^{(2)} = Z_P^{(1)}$. Using these two equalities one can obtain

$$\vec{A}(\omega, \vec{k}) Z_\rho = B(\omega, \vec{k}) \vec{Z}_{W^{(1)}}, \tag{3}$$

where

$$\vec{A}(\omega, \vec{k}) = [d_0(1-\rho)\, i(\omega + \vec{k}\vec{V}) + \mu_0 S(\rho) k^2 + \varkappa d K(\rho)(\beta_1\rho_1 + \beta_2\rho_2 + \beta_1(1-\rho))] \frac{(\omega + \vec{k}\vec{V})\vec{k}}{(1-\rho)k^2} + \varkappa m \beta_1 (1-\rho) \frac{dK(\rho)}{d\rho} \vec{u}_1$$
$$+ \frac{1}{3}\mu_0 S(\rho) \vec{k} \frac{(\omega + \vec{k}\vec{V})\vec{k}}{1-\rho} - \varkappa d K(\rho) \beta_2\rho_2 \left[- \frac{\varkappa d(\beta_1 - \beta_2) K(\rho) \dfrac{(\omega + \vec{k}\vec{V})\vec{k}}{(1-\rho)k^2}}{id\omega + id\vec{k}\vec{W}^{(2)} + \varkappa d K(\rho)\beta_1} - \frac{\varkappa d \dfrac{dK(\rho)}{d\rho}(\beta_1\vec{u}_1 - \beta_2\vec{u}_2)}{id\omega + id\vec{k}\vec{W}^{(2)} + \varkappa d K(\rho)\beta_2} \right] + \varkappa d \frac{dK(\rho)}{d\rho}(\beta_1\rho_1\vec{u}_1 + \beta_2\rho_2\vec{u}_2),$$

$$B(\omega, \vec{k}) = (1-\rho)\, di(\omega + \vec{k}\vec{W}^{(1)}) + \varkappa d K(\rho)\beta_1(1-\rho+\rho_1) + \varkappa d K(\rho)\beta_2\rho_2 \frac{id\omega + id\vec{k}\vec{W}^{(1)} + \varkappa d K(\rho)\beta_1}{id\omega + id\vec{k}\vec{W}^{(2)} + \varkappa d K(\rho)\beta_2}.$$

The expression for the equivalent temperature of the pulsation motion of particles of the first type in the vertical plane can be written in the form [3, 4] (the subscript 1 denotes the vertical component)

$$\Theta_1^{(1)} = \langle Z_{W_1}^{(1)*} Z_{W_1}^{(1)} \rangle = \int\int \frac{A_1^*(\omega, \vec{k})\, A_1(\omega, \vec{k})}{B^*(\omega, \vec{k})\, B(\omega, \vec{k})} (Z_\rho^* Z_\rho)^{(1)} d\omega d\vec{k}, \tag{4}$$

where

$$(Z_\rho^* Z_\rho)^{(1)} = \Psi_{\rho,\rho}^{(1)}(\omega, \vec{k}) = \frac{\Phi_{\rho,\rho}^{(1)}(\vec{k})}{M^{(1)}(\omega, \vec{k})} \left(\int_{-\infty}^{\infty} \frac{d\omega}{M^{(1)}(\omega, \vec{k})} \right)^{-1}, \tag{5}$$

$$M^{(1)}(\omega, \vec{k}) = (\omega + \vec{W}^{(1)}\vec{k})^2 + (\vec{k}\vec{D}^{(1)}\vec{k} - T_0^{(1)}\omega^2)^2. \tag{6}$$

Equation (5) for the spectral density ρ' of the process follows from the theory of steady random processes [3, 4]; $\vec{W}^{(1)}$ is the average velocity of particles of type 1, $\vec{D}^{(1)}$ is the pseudoturbulent diffusion tensor of particles of type 1, determined by the expression [3]

$$D_{ij}^{(1)} = \int_0^\infty d\tau \int\int \exp(i\omega\tau) \langle Z_{W_i}^{(1)} Z_{W_j}^{(1)} \rangle d\omega d\vec{k},$$

and the symbolic equality to $\vec{k}\vec{D}^{(1)}\vec{k}$ is denoted by the sum

$$\sum_{i,j} k_i D_{ij}^{(1)} k_j,$$

$$T_0^{(1)} \equiv tr\vec{D}^{(1)} / \Theta^{(1)}, \quad \Theta^{(1)} = \Theta_1^{(1)} + \Theta_2^{(1)} + \Theta_3^{(1)}.$$

We introduce the following notation: $b = \vec{W}^{(1)}\vec{k}$, $c = \vec{k}\vec{D}^{(1)}\vec{k}$, $d_0 = T_0^{(1)}$.

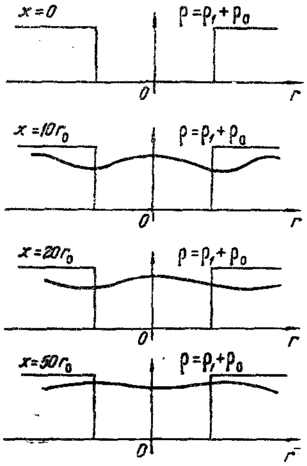

Fig. 1. Dependence of volumetric concentration $\rho = \rho_0 + \rho_1$ of solid particles on distance r to axis of tube for different values of x.

The integral entering into (5) is easily calculated if one assumes that $\vec{W}^{(1)} = 0$, i.e., that the particles of type 1 are at rest on the average.

We will further assume that $D_1^{(1)}, D_2^{(1)}, D_3^{(1)} \to 0$; $D_1^{(1)} \equiv D_{11}^{(1)}$, $D_2^{(1)} = D_3^{(1)} \equiv D_{22}^{(1)} = D_{33}^{(1)}$ are the components of the tensor along the principal axes. According to [5] this corresponds to the absence of very small-scale motions and allowance for only vertical pseudoturbulent pulsations. Then as $\vec{D}^{(1)} \to 0$

$$\frac{1}{M^{(1)}(\omega, \vec{k})}\left(\int_{-\infty}^{\infty} \frac{d\omega}{M^{(1)}(\omega, \vec{k})}\right)^{-1} = \frac{c/\pi}{\omega^2 + (c - d\omega^2)^2} \to \delta(\omega). \qquad (7)$$

Substituting (7) into (5), we obtain $\Psi_{\rho,\rho}(\omega, \vec{k}) = \Phi_{\rho,\rho}^{(1)}(\vec{k})\delta(\omega)$. According to [4],

$$\Phi_{\rho,\rho}^{(1)}(\vec{k}) = \frac{3}{4\pi}\frac{\rho_1 \rho}{(k_0^{(1)})^3}\left(1 - \frac{\rho}{\rho_*}\right) Y(k_0^{(1)} - k),$$

where

$$k_0^{(1)} = \left(\frac{9\pi\rho}{2}\right)^{\frac{1}{3}} \frac{1}{a_1}, \quad Y(x) = \begin{cases} 1, & x \geqslant 0 \\ 0, & x < 0. \end{cases}$$

Taking $\omega = 0$ in the expressions for $\vec{A}(\omega, \vec{k})$ and $B(\omega, \vec{k})$ and assuming that the inequalities

$$k_0 V \ll \beta_j, \quad \mu_0 k_0^2 \ll d_0 \beta_j, \quad k_0 W^{(2)} \ll \varkappa \beta_2$$

are satisfied, we obtain

$$\Theta_1^{(1)} = \frac{V^2}{K(\rho)^2}\frac{\rho\rho_1}{2}\left(1 - \frac{\rho}{\rho_*}\right)\left\{\left(\frac{K(\rho)}{1-\rho}\right)^2 \frac{2}{5} + 2\frac{K(\rho)}{1-\rho}\frac{dK(\rho)}{d\rho}\frac{2}{3} + 2\left(\frac{dK(\rho)}{d\rho}\right)^2\right\}. \qquad (8)$$

For the streamline mode a flow corresponding to $K(\rho) = 1$ Eq. (8) takes the form

$$\Theta_1^{(1)} = \frac{V^2 \rho_1}{5\rho_*}\frac{\rho(\rho_* - \rho)}{(1-\rho)^2}.$$

From this it is seen that the maximum equivalent temperature of the pseudoturbulent pulsations (the maximum statistical indeterminacy of the system) is reached when

$$\rho = \frac{\rho_*}{2 - \rho}. \qquad (9)$$

If one takes $\rho_* = 0.6$ [1], then from (9) we obtain $\rho = 0.4$.

Substituting $K(\rho)$, in the form proposed by Ergun, into (8), we find that $\Theta_1^{(1)}/V^2$ has a maximum at $\rho = 0.28$. Both the results obtained are in good agreement with the result of [6], where a somewhat different approach was used to determine the ρ corresponding to the maximum mixing in a fluidized bed. The temperature obtained as a function of ρ has a maximum in the interval of $0 < \rho < 1$, which agrees well with the fact, known from experiment and confirmed theoretically [6], of the presence in the system of a state corresponding to the maximum statistical indeterminacy.

The mixing of a gas jet with a stream of a mixture of solid particles and gas can be described using the mechanism of pseudoturbulent mixing.

The equation of pseudoturbulent diffusion in cylindrical coordinates, according to [1, 2], is written in the form

$$V_r \frac{\partial \rho}{\partial r} + (V_x - W_0) \frac{\partial \rho}{\partial x} = \frac{1}{r} \frac{\partial}{\partial r} \left[D_2(\rho) \frac{\partial}{\partial r} (r\rho) \right] + \frac{\partial}{\partial x} \left[D_1(\rho) \frac{\partial \rho}{\partial x} \right], \tag{10}$$

where W_0 is the velocity of the solid phase, which is taken as constant; $D_1(\rho)$ and $D_2(\rho)$ are the longitudinal and transverse coefficients of pseudoturbulent diffusion.

For simplicity, we assume further that $V_r = 0$ and $V_x = V_0 = \text{const}$ ("upper" estimate); moreover, $\rho = \rho_0 + \rho_1$ and $\rho_1 \ll \rho_0$, so that from (10) we obtain

$$\frac{\partial^2 \rho_1}{\partial x^2} - \gamma \frac{\partial \rho_1}{\partial x} = -\alpha^2 \left(\frac{\partial^2 \rho_1}{\partial r^2} + \frac{1 + 2\nu}{r} \frac{\partial \rho_1}{\partial r} \right), \tag{11}$$

where

$$\gamma = \frac{V_0 - W_0}{D_1(\rho_0)}; \quad \alpha^2 = \frac{D_2(\rho_0)}{D_1(\rho_0)} = 0.422 \ [1]; \quad \nu = \frac{1}{2} + \frac{\rho_0}{2D_1(\rho_0)} \frac{\partial D_1(\rho_0)}{\partial \rho_0}.$$

The boundary condition allowing for the axial symmetry of the jet has the form

$$\rho_1 = \begin{cases} 0, & r > r_0 \\ -\rho_0, & r < r_0 \end{cases} \quad \text{at} \quad x = 0, \tag{12}$$

where r_0 is the radius of the tube through which the vapor is introduced (here it is assumed that the gas carrying the solid particles moves with the same velocity V_0 and has the same physical properties as the vapor introduced into the stream).

Then we can write the solution of Eq. (11) in the form [9]

$$\rho_1 = -\rho_0 r_0 \left(\frac{r}{r_0} \right)^{-\nu} \int_0^\infty \exp\left[-\left(\sqrt{\frac{\gamma^2}{4} + \alpha^2 \lambda^2} - \frac{\gamma}{2} \right) x \right] J_\nu(\lambda r) J_{\nu+1}(\lambda r_0)\, d\lambda. \tag{13}$$

If the force of gravity is neglected then the results of [1] can be applied directly to the calculation of the pseudoturbulent diffusion coefficient $D_1(\rho_0)$. Then (for medium Reynolds numbers)

$$D_1(\rho_0) = [3.58^2 (V_0 - W_0)^2 \rho_0^2 (0.6 - \rho_0)(1.0389\rho_0^2 + 0.1473\rho_0 + 0.2165)]/[1.3563\,(1 - \rho_0)^2 0.6\beta\,(1 - \rho_0)^{-5.58}], \quad 0 < \rho_0 < 0.28,$$

$$D_1(\rho_0) = [3\,(2\rho_0 + 1)^2 (0.6 - \rho_0)(1 - \rho_0)(1.0389\rho_0^2 + 0.1473\rho_0 + 0.2165)]/[1.3563 \cdot 0.6 \cdot 25\beta\rho_0], \quad 0.28 < \rho_0 < 0.6, \tag{14}$$

where

$$\beta = 9\mu_0 / 2a^2 d_1.$$

It should be noted that the maximum of the diffusion coefficient $D_1(\rho_0)$ is reached at $\rho_0 = 0.28$, which agrees well with the results of [6], according to which the maximum mixing in a disperse system is reached when $\rho_0 = 0.2$–0.3 and is qualitatively confirmed by the estimate obtained in the first part of the present work.

From (14) it is easy to find that $\nu \simeq -1/2$ at $\rho_0 = 0.4$. For this case (13) takes on a simpler form

$$\rho_1 = -\rho_0 \frac{2}{\pi} \int_0^\infty \exp\left[-\left(\sqrt{\frac{\gamma^2}{4} + \alpha^2 \frac{y^2}{r_0^2}} - \frac{\gamma}{2} \right) x \right] \frac{1}{y} \cos\frac{yr}{r_0} \sin y\, dy. \tag{15}$$

Dividing the region of integration in (15) into two intervals in accordance with the inequalities $\gamma/2 \gtrless \alpha(y/r_0)$ and performing a series expansion of the radical inside the exponent sign in each of them, we obtain

$$\rho_1 = -\rho_0 \frac{2}{\pi} \int_0^{\frac{\gamma r_0}{2\alpha}} \exp\left(-\frac{\alpha^2 y^2}{\gamma r_0^2} x \right) \frac{1}{y} \cos\frac{yr}{r_0} \sin y\, dy$$

$$-\rho_0 \frac{2}{\pi} \int_0^\infty \exp\left(-\alpha \frac{y}{r_0} x\right) \frac{1}{y} \cos \frac{yr}{r_0} \sin y dy$$

$$+\rho_0 \frac{2}{\pi} \int_0^{\frac{\gamma r_0}{2\alpha}} \exp\left(-\alpha \frac{y}{r_0} x\right) \frac{1}{y} \cos \frac{yr}{r_0} \sin y dy, \qquad (16)$$

where we are confined in both cases to the highest term in the expansion inside the exponent sign.

If for V_0, W_0, a, d_1, ρ_0, μ_0, and r_0 we take the numerical values $V_0 = 40$ m/sec, $\mu_0 = 1.4 \cdot 10^{-5}$ N · sec/m^2, $W_0 = 4$ m/sec, $a = 50 \cdot 10^{-6}$ m, $d_1 = 1200$ kg/m^3, $\rho_0 = 0.4$, and $r_0 = 0.2$ m, then we have $\gamma r_0/2\alpha = 0.64$. Using for this case the approximation

$$\sin y = y - \frac{1}{6} y^3,$$

we obtain analytical expressions for the variation in the concentration of the solid phase in the jet along the length x for three values of the coordinate r.

For $r = 0$ at $x = 0$

$$\rho_1 = -\rho_0 \frac{2}{\pi} \int_0^\infty \frac{1}{y} \sin y dy = -\rho_0,$$

when $x \neq 0$

$$\frac{\rho_1}{\rho_0} = \left(-\frac{2}{\pi} + \frac{\gamma r_0^2}{6\pi\alpha^2 x}\right) \frac{\sqrt{\pi\gamma}\, r_0}{2\alpha\sqrt{x}} \Phi\left(\frac{\sqrt{\gamma x}}{2}\right) - \frac{\gamma^2 r_0^3}{12\pi\alpha^3 x} \exp\left(-\frac{\gamma x}{4}\right) - \frac{2}{\pi} \operatorname{arctg} \frac{r_0}{\alpha x}$$

$$+\left(\frac{2}{\pi} - \frac{2r_0^2}{3\pi\alpha^2 x^2}\right)\left(-\frac{r_0}{\alpha x}\right)\left[\exp\left(-\frac{\gamma x}{2}\right) - 1\right] + \frac{1}{3\pi}\left(\frac{\gamma^2 r_0^3}{4\alpha^3 x} + \frac{\gamma r_0^3}{\alpha^3 x^2}\right) \exp\left(-\frac{\gamma x}{2}\right). \qquad (17)$$

For $r = r_0$ at $x = 0$

$$\rho_1 = -\rho_0 \frac{2}{\pi} \int_0^\infty \frac{1}{y} \cos y \sin y dy = -\frac{1}{2} \rho_0,$$

when $x \neq 0$

$$\frac{\rho_1}{\rho_0} = \left(-\frac{2}{\pi} + \frac{2\gamma r_0^2}{3\pi\alpha^2 x}\right) \frac{\sqrt{\pi\gamma}\, r_0}{2\alpha\sqrt{x}} \Phi\left(\frac{\sqrt{\gamma x}}{2}\right) - \frac{\gamma^2 r_0^3}{3\pi\alpha^3 x} \exp\left(-\frac{\gamma x}{4}\right)$$

$$-\frac{1}{\pi} \operatorname{arctg} \frac{2r_0}{\alpha x} + \left(\frac{2}{\pi} - \frac{8r_0^2}{3\pi\alpha^2 x^2}\right)\left(-\frac{r_0}{\alpha x}\right)\left[\exp\left(-\frac{\gamma x}{2}\right) - 1\right] + \frac{4}{3\pi}\left(\frac{\gamma^2 r_0^3}{4\alpha^3 x} + \frac{\gamma r_0^3}{\alpha^3 x^2}\right) \exp\left(-\frac{\gamma x}{2}\right). \qquad (18)$$

For $r = 5r_0$ at $x = 0$

$$\rho_1 = -\rho_0 \frac{2}{\pi} \int_0^\infty \frac{1}{y} \cos 5y \sin y dy = 0,$$

when $x \neq 0$

$$\frac{\rho_1}{\rho_0} = \left(-\frac{2}{\pi} + \frac{38 y r_0^2}{3\pi\alpha^2 x}\right) \frac{\sqrt{\pi\gamma}\, r_0}{2\alpha\sqrt{x}} \Phi\left(\frac{\sqrt{\gamma x}}{2}\right) - \frac{19\gamma^2 r_0^3}{3\pi\alpha^3 x} \exp\left(-\frac{\gamma x}{4}\right) - \frac{1}{\pi} \operatorname{arctg} \frac{2\frac{\alpha x}{r_0}}{\frac{\alpha^2 x^2}{r_0^2} + 24}$$

$$+\left(\frac{2}{\pi} - \frac{152 r_0^2}{3\pi\alpha^2 x^2}\right)\left(-\frac{r_0}{\alpha x}\right)\left[\exp\left(-\frac{\gamma x}{2}\right) - 1\right] + \frac{76}{3\pi}\left(\frac{\gamma^2 r_0^3}{4\alpha^3 x} + \frac{\gamma r_0^3}{\alpha^3 x^2}\right) \exp\left(-\frac{\gamma x}{2}\right). \qquad (19)$$

Here $\Phi(z) = 2/\sqrt{\pi}\int_0^z \exp(-t^2)dt$. The results of calculations by Eqs. (17)-(19) of the relative concentration ρ_1/ρ_0 of the solid phase along the length of the jet are presented in Table 1.

Curves corresponding to the data presented in Table 1 are shown in Fig. 1. Thus, with the help of Eq. (15) one can estimate the length at which equalization of the concentration of the solid particles occurs.

The average value of the concentration $\bar{\rho}_1$ over a cross section can be calculated from the equation

$$\bar{\rho}_1 = \frac{\int_0^R \rho_1(r)\, r dr}{\int_0^r r dr},$$

or using Eq. (15)

$$\bar{\rho}_1 = -\rho_0 \frac{4r_0}{\pi R^2}\int_0^\infty \exp\left[-\left(\sqrt{\frac{\gamma^2}{4}+\frac{\alpha^2 y^2}{r_0^2}}-\frac{\gamma}{2}\right)x\right]\left[R\sin\frac{yR}{r_0}+\frac{r_0}{y}\left(\cos\frac{yR}{r_0}-1\right)\right]\sin y dy,$$

where R is the radius of the outer cylindrical surface confining the system.

Thus, using the spectral theory of the concentration of disperse systems [1, 2] one can solve the problem of the efficiency of mixing of a homogeneous boiling layer and of the pseudoturbulent mixing of a vapor jet containing solid particles, which have importance in chemical technology.

NOTATION

m_1, m_2, masses of particles of first and second types; $\vec{W}^{(j)}$, velocities of particles of j-th type; $\vec{W}^{(j)\prime}$, pulsation components of particle velocities; $\vec{V}$, velocity of fluid phase; V_r, V_x, radial and axial components; ρ, volumetric fraction of solid particles in medium; ρ', pulsation component of ρ; d_0, density of fluid phase; $\vec{V}^{(j)\prime}$, pulsation component of velocity of fluid phase near a particle of the j-th type; $P^{(j)\prime}$, pulsation component of pressure near a particle of the j-th type; μ_0, viscosity coefficient of fluid phase; $S(\rho)$, a function of ρ allowing for the change in viscosity due to the presence of solid particles in the medium; σ_j, volume of the particle of the j-th type; ρ_j', volumetric fraction of particles of the j-th type; d, density of material of solid particles; $a^{(j)}$, radius of particles of j-th type; $\Theta^{(j)}$, equivalent temperature of pseudoturbulent pulsations of particles of j-th type; $\vec{D}^{(j)}$, pseudoturbulent diffusion tensor of particles of j-th type; ρ_*, volumetric fraction of solid particles corresponding to close packing.

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