TURBULENT MASS TRANSFER IN THE FLOW OF A GAS SUSPENSION IN A POTENTIAL FORCE FIELD WITH GAS INJECTION/SUCTION THROUGH POROUS CHANNEL WALLS

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The extensive use of disperse turbulent streams in power engineering, aviation, and chemical engineering requires the development of methods of acting on the characteristics of disperse flows. The deposition of particles during transport of a gas suspension in a channel, in particular, can be reduced or intensified in two ways. The first is by direct action on particles of the disperse phase, such as by altering the trajectories of charged particles in an electromagnetic field [1]. In this situation, an increase in the intensity of the external field increases or decreases the particle concentration near the confining surface (depending on the direction of the field strength vector). The second is by changing the characteristics of the carrier stream itself. This may be done by swirling the main stream using special swirlers mounted at the channel entrance [2], turbulizing the flow using artificial inserts [3], and gas injection or suction through porous channel walls. From the practical standpoint, gas injection/suction can be implemented relatively easily over the developed segment of flow to control the intensity of mass transfer. In this connection, it is timely to develop methods of calculating the characteristics of the disperse phase in a channel segment with permeable walls. Methods of calculating one-phase turbulent flow in channels with permeable walls have been studied fairly well [4].

In the present paper we use numerical modeling to compare two ways of acting on turbulent mass transfer of particles: the influence of an external field on particle dynamics and the use of gas injection/suction through the channel walls.

The intensity with which particles are deposited onto the channel walls is determined by several factors: turbulent diffusion, the nonuniformity of the field of turbulent pulsations, and convective transport of the disperse phase toward the walls [5, 6]. Gas injection displaces particles from the channel surface, on the one hand, while turbulization of the stream during injection [4], on the other hand, increases the pulsation velocity of the particles toward the walls, which should increase the rate of deposition of the contaminant. The presence of two factors with opposite influences on mass transfer makes it necessary to investigate carefully the mass transfer of particles in a channel segment with porous walls.

Methods of numerical modeling of particle deposition from a turbulent gas stream can be divided into two classes.

1. Integration of random Lagrangian particle trajectories in a given flow field of the fluid phase, when the equation of particle motion includes the random component of the gas velocity, whose intensity is determined by the local level of turbulent energy of the gas and by the given probabilistic law of variation of fluctuations of the component [7, 8]. Implementation of this method requires a considerable volume of calculations to obtain averaged data.

2. A simultaneous solution of the hydrodynamic equations for the fluid and disperse phases, written in the Eulerian representation. Allowance for turbulent diffusion in the equations of particle dynamics requires the formulation of boundary conditions allowing for the character of the interaction of particles with the surface [9]. The second calculation method is implemented on the basis of uniform algorithms for integration of the equations of turbulent flow of both the fluid phase and the particles. Averaged data of practical significance are obtained from the solution.

We investigate the intensity of action of the external field and of the permeability of the channel walls on the characteristics of particle mass transfer using the results of a calculation of stream dynamics in the developed segment of flow within the framework of a one-parameter model of turbulence [10]. We calculate the turbulent characteristics of the particles on the basis of the system of equations and boundary conditions obtained in [6, 9].

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1. SYSTEM OF EQUATIONS FOR CALCULATING PARTICLE HYDRODYNAMICS AND MASS TRANSFER

The equations of balance of momentum, intensity of transverse velocity pulsations, and particle concentration in a round pipe have the form

$$V_r \frac{dV_x}{dr} + \frac{1}{rc}\frac{d}{dr}(rc\overline{v_x v_r}) = \frac{U_x - V_x}{\tau}; \tag{1.1}$$

$$V_r \frac{d\overline{v_r^2}}{dr} + \frac{1}{rc}\frac{d}{dr}(rc\overline{v_r^3}) = \frac{2}{\tau}(f\overline{u_r^2} - \overline{v_r^2}); \tag{1.2}$$

$$cV_r = cU_{rs} - c\tau\frac{d\overline{v_r^2}}{dr} - D_p\frac{dc}{dr} = \frac{r}{R}Jc_m,$$

$$\overline{v_x v_r} = f\overline{u_x u_r} - \frac{1}{2}D_p\frac{dV_x}{dr},\quad \overline{v_r^3} = -D_p\frac{d\overline{v_r^2}}{dr}, \tag{1.3}$$

$$D_p = \tau(\overline{v_r^2} + g\overline{u_r^2}),\quad c_m = \frac{2}{R^2}\int_0^R drrc(r),\quad U_{rs} = U_r + W_r.$$

Here V_i and v_i are the averaged and pulsation components of the velocity of the disperse phase; U_i and u_i are the averaged and pulsation components of the velocity of the fluid phase; c and c_m are the particle concentration and its mass-averaged value; D_p is the turbulent diffusion coefficient of the particles; τ is the dynamic relaxation coefficient of the particles, which depends on the relative velocity of flow of the carrier gas over the particles (the particle drag coefficient is calculated from the mass-averaged velocity of phase slippage); J is the particle flux to the channel wall; f and g are functions describing the degree of entrainment of particles in the pulsating motion of the carrier phase, the values of which depend not only on the particle inertia but also on the averaged velocity of phase slippage [11]; R is the channel radius; W_r is the velocity of particle displacement in the mass force field.

The boundary conditions for Eqs. (1.1)-(1.3) of particle dynamics allow for momentum loss of a reflected particle following a collision with the surface and have the form (r = R)

$$\left[\frac{1-\varkappa_1\varkappa_2}{1+\varkappa_1\varkappa_2}\left(\frac{2}{\pi}\overline{v_r^2}\right)^{1/2} - V_r\right]V_x = -\frac{\overline{w_r^2}}{2}\frac{dV_x}{dr}; \tag{1.4}$$

$$\left[\frac{1-\varkappa_2^3}{1+\varkappa_2^3}\,2\left(\frac{2}{\pi}\overline{v_r^2}\right)^{1/2} - V_r\right]\overline{v_r^2} = -\tau\overline{v_r^2}\frac{d\overline{v_r^2}}{dr}; \tag{1.5}$$

$$\left[\frac{1-\varkappa_2}{1+\varkappa_2}\left(\frac{2}{\pi}\overline{v_r^2}\right)^{1/2} - V_r\right]c = 0, \tag{1.6}$$

where $\varkappa_1$ and $\varkappa_2$ are the coefficients of restitution of particle momentum in the longitudinal and transverse directions following a collision with the wall. The case of an absolutely absorbent surface (the deposition of drops) corresponds to $\varkappa_2 = 0$. An absolutely elastic surface is modeled with $\varkappa_2 = 1$.

The conditions of flow symmetry are set up at the center of the channel (r = 0):

$$\partial V_x/\partial r = \partial\overline{v_r^2}/\partial r = 0. \tag{1.7}$$

It is clear from Eq. (1.3) that the profile of particle concentration is formed under the influence of turbulent diffusion, which tends to reduce the concentration gradient in the stream, of convective transport with the total averaged transverse velocity, and of turbulent migration, which is proportional to the intensity gradient of particle velocity fluctuations in the transverse direction and displaces particles toward a decrease in the intensity of pulsating motion. With an increase in the time of dynamic relaxation of the particles in comparison with the characteristic time scale of fluctuations of gas velocity, a uniform profile of fluctuation energy of the disperse phase is formed [5, 6]. This decreases the influence of turbulent migration on the particle dynamics, and the concentration profile of the disperse phase is formed under the action of the convective term and of turbulent particle diffusion. For inertial particles ($\tau > T_E$, T_E being the characteristic time scale of correlations of energy-carrying fluctuations of the velocity of the fluid phase), $g \sim (T_E/\tau)^2 << 1$ [5, 6] and the turbulent diffusion coefficient of the particles is also uniform over the channel cross section. Approximating the transverse velocity by $U_{rs} = r/RU_{rs}^0$ (U_{rs}^0 is

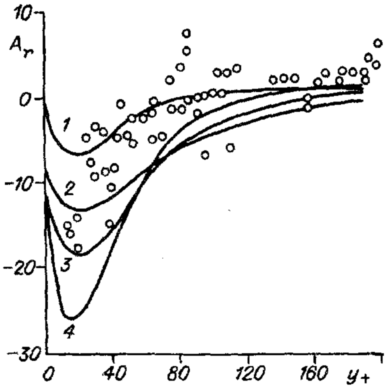

Fig. 1

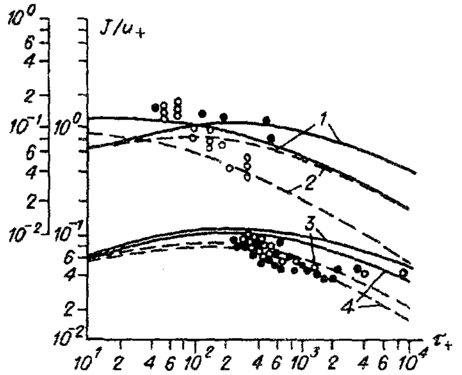

Fig.2

the total velocity at the channel wall), we write the solution of Eq. (1.3), representing the concentration distribution, and the equation for the rate of deposition of inertial particles:

$$\frac{c}{c^0} = \frac{J^0}{U_{rs}^0} + \left(1 - \frac{J^0}{U_{rs}^0}\right) \exp\left(-\frac{R\xi U_{rs}^0}{D_p}\right); \tag{1.8}$$

$$\frac{c_m}{c^0} = \frac{J^0}{U_{rs}^0} - \frac{2D_p}{U_{rs}^0 R}\left(1 - \frac{J^0}{U_{rs}^0}\right)\left[\exp\left(-\frac{RU_{rs}^0}{2D_p}\right) - 1\right], \quad \xi = (1 - r/R)^2/2; \tag{1.9}$$

$$J = \frac{J^0}{c_m}, \quad J^0 = \frac{1 - \varkappa_2}{1 + \varkappa_2}\left(\frac{2}{\pi}\overline{v_r^2}\right)^{1/2}. \tag{1.10}$$

Here c^0 is the concentration at the channel wall; J^0 is the transverse particle velocity at the channel wall. The turbulent diffusion coefficient D_p of the particles and the intensity of their transverse velocity fluctuations from (1.8)-(1.10) in the core of the flow are calculated in the local-equilibrium approximation from Eq. (1.2), which is converted into an algebraic equation by dropping terms associated with the intensity gradient of transverse velocity pulsations of the disperse phase. It is clear from (1.8)-(1.10) that a radial velocity toward the channel walls ($U_{rs}^0 > 0$) reduces the particle concentration in the core of the flow in comparison with its value at the wall, while a velocity toward the center of the pipe ($U_{rs}^0 < 0$) increases the particle concentration in the stream core and reduces the rate of deposition of the contaminant onto the inner surface.

On the basis of the results of a calculation of the characteristics of a turbulent stream in a stabilized segment of flow with gas injection/suction through porous walls [10], we determine the averaged axial and normal components of the gas velocity, the turbulent shear stress, and the turbulent gas energy E. The intensity $\overline{u_r^2}$ of transverse velocity fluctuations and the characteristic time scale of energy-carrying velocity pulsations of the fluid phase are calculated from the equations

$$\overline{u_r^2} = k_r E\,[1 - \exp(-\alpha_r \mathrm{Re}_t)]^2, \quad \mathrm{Re}_t = LE^{1/2}/\nu, \quad T_E = \gamma L/E^{1/2},$$

where Re_t is the Reynolds number of the turbulence; L is the turbulent mixing length, corresponding to the Nikuradse equation; $k_r = 0.25$; $\alpha_r = 0.03$; $\gamma = 1.16$ [7, 8]. The characteristics of the carrier stream are approximated by cubic splines.

The system of Eqs. (1.1)-(1.3) with the boundary conditions (1.4)-(1.6) is solved numerically by the sweep method. The equation for the particle concentration is integrated using a predictor–corrector algorithm in a three-step scheme [12]. For fine particles ($\tau_+ \lesssim 10$, where $\tau_+ = \tau u_+^2/\nu$, u_+ is the dynamic stream velocity, and ν is the kinematic viscosity) the grid is bunched up near the boundary so that there are at least six grid nodes over a distance $y_+ \sim \tau_+$ from the wall ($y_+ = yu_+/\nu$). The values of the dynamic characteristics of particles in the interior of the stream are chosen to equal their values in local equilibrium. The proposed calculation scheme enables us to calculate the flow of the carrier phase and the dynamics of the disperse phase on grids with independent spacing of nodes over the channel radius.

2. INFLUENCE OF THE EXTERNAL FIELD ON MASS TRANSFER OF THE DISPERSE CONTAMINANT

To test the predictive properties of the mathematical model described, we compared the results of a calculation of the pulsation characteristics and deposition rate of particles with available experimental data in channels with impermeable walls.

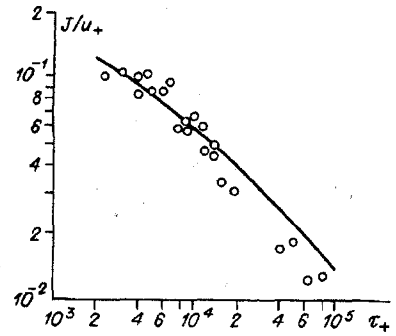

Fig. 3

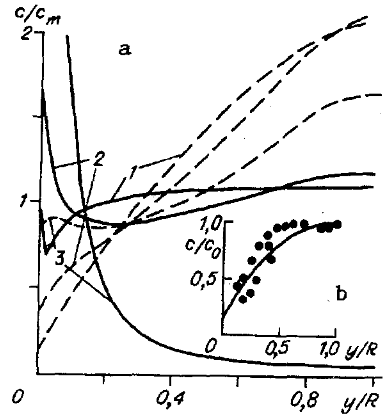

Fig. 4

In Fig. 1 we give the distribution of the quantity

$$A_r = \frac{1}{\bar r}\frac{d}{d\bar r}\left[\bar r\,(\overline{v_r^2})_+\right],\quad \bar r = \frac{r}{R},\quad (\overline{v_r^2})_+ = \frac{\overline{v_r^2}}{u_+^2}.$$

Curves 1-4 are plotted for the following dimensionless dynamic relaxation times: $\tau_+ = 1.2, 30.1, 17.6, 7.1$. The experimental data of [13] are marked by circles. It is seen from Fig. 1 that the gradient of the particles' fluctuation energy depends nonmonotonically on their inertia. The distribution of pulsation energy over a cross section is uniform for large particles, while for very fine particles the distribution of the intensity of fluctuating motion coincides with the pulsation energy profile of the fluid phase. The intensity gradient of transverse pulsations of particle velocity does not vanish at the channel wall, in contrast to the intensity gradient of transverse velocity fluctuations of the fluid phase. This result underlines the important role of turbulent particle migration in mass transfer.

In Fig. 2 we give the rate of deposition of particles as a function of their inertia and of the coefficient of restitution of transverse momentum. Curves 1 and 2 are calculated for the experimental conditions of [14]. The experimental data are denoted by circles (Re = 6000 for open circles and Re = 50,000 for filled ones). Curves 3 and 4 correspond to the experimental data of [15] (Re = 525,000 for open circles and Re = 94,600 for filled ones). The dashed lines are the calculated particle deposition rate for $\varkappa_2 = 0.5$ and the solid lines are the calculated intensity of particle deposition onto a fully absorbing surface ($\varkappa_2 = 0$). The influence of the coefficient of restitution of transverse particle momentum is significant for relatively large particles ($\tau_+ > 10^2$), which is related to the nonzero velocity of inertial particles at the channel surface. The decrease in deposition with increasing particle size is explained by the overall decrease in the degree of entrainment of the contaminant in the fluctuating motion of the carrier gas in the core of the flow. This effect is illustrated in Fig. 3, in which a comparison is made with the experimental data of [16] (the experimental deposition rates are denoted by circles).

The action of an axisymmetric external field on the particles can significantly change the distribution of particle concentration over the pipe cross section and their rate of deposition onto the walls. In Fig. 4a we show the distribution of the contaminant's concentration for different radial velocities of particle displacement $W_r = \bar r W_r^0$ in the external field. The solid lines give the results of calculations for $W_r^0/u_+ = +0.3$ and the dashed lines give those for $W_r^0/u_+ = -0.1$. Curves 1 are calculated for $\tau_+ = 10$ and $\varkappa_2 = 0$; 2) $\tau_+ = 300$, $\varkappa_2 = 0$; 3) $\tau_+ = 300$, $\varkappa_2 = 1$. It is seen that efficient control of particle mass transfer is accomplished at relatively low transverse convective velocities produced by the external field. Note that considerable increase in particle concentration at an absolutely elastic surface ($\varkappa_2 = 1$) in a field toward the channel walls, which is explained by the combined motion of particles in the external field and due to turbulent migration, which shifts particles toward the channel walls. A comparison of the calculated profile of drop concentration ($W_r^0 = 0$, $\varkappa_2 = 0$) with experimental data [17] (points) is shown in Fig. 4b. The rate of drop deposition onto the walls as a function of the dimensionless dynamic relaxation time in external fields of different intensity and direction are given in Fig. 5, in which the dashed line shows the empirical curve generalizing the experimental data of [14, 15], the solid lines 1-5 are calculated for $W_r^0/u_+ = 0, 0.1, -0.05, -0.1$, and -0.25, and the dot-dashed line corresponds to $W_r^0 = 0$ and $\varkappa_2 = 0.5$. It is seen that external action on the disperse contaminant considerably alters the mass-transfer intensity in the entire range of particle sizes under consideration. The maximum effect is observed for very fine and very large particles, however. The intensity of penetration of fine particles to the channel walls is insignificant, and the convective velocity considerably reduces their concen-

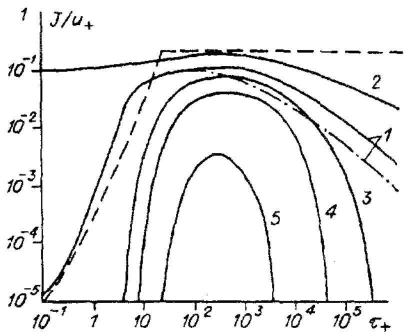

Fig. 5

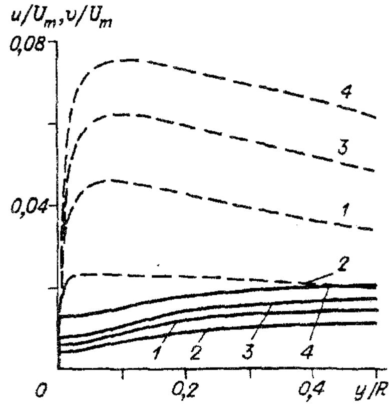

Fig. 6

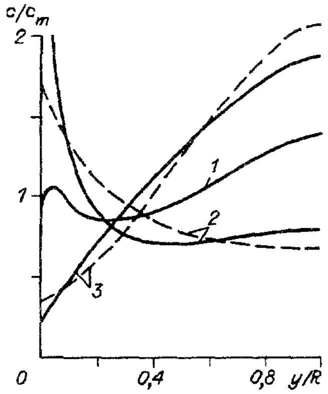

Fig. 7

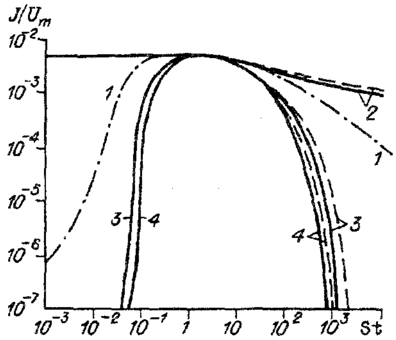

Fig. 8

tration at the wall. For very large particles colliding with the channel walls, the rms velocity of their fluctuating transverse motion is lower than the convective velocity due to the external field.

3. INFLUENCE OF GAS INJECTION/SUCTION ON MASS TRANSFER OF THE DISPERSE CONTAMINANT

We consider the stabilized flow of a gas suspension in a round pipe with porous walls, through which gas injection/suction takes place. The intensity of gas supply through the pipe walls is defined by the parameter $P_v = U_r^0/U_m$ (U_m is the mass-averaged flow velocity of the gas). Because of the distortion of the parameters in a channel with porous walls, the inertia of contaminant particles is characterized by the Stokes number $St = \tau U_m/R$, and the deposition intensity is characterized by J/U_m. The carrier stream is calculated for the experimental conditions of [17]. In Fig. 6 we show the influence of the transverse stream velocity on the intensity of transverse pulsations of gas velocity (dashed lines) and particle velocity (solid lines, St = 10). Curves 1-4 correspond to $P_v = 0$, $0.5\cdot10^{-2}$, $-0.5\cdot10^{-2}$, and $-1\cdot10^{-2}$. It is seen that laminarization of the flow by gas suction decreases the intensity of turbulent fluctuations of particle velocity. Gas injection, by contrast, leads to turbulization of the stream and to higher transverse rms particle velocities in comparison with the undisturbed stream. The transverse particle velocity at the wall can exceed the velocity of the injected gas. This effect is of decisive importance for the dynamics of the deposition of contaminant particles onto the inner surface of the pipe. The convective transverse component of the stream velocity changes the particle concentration in the cross section. Figure 7 illustrates the distribution of the contaminant's concentration (St = 100) in a pipe with absorbing walls ($\varkappa_2 = 0$) for different gas injection/suction intensities. The results of a calculation based on the complete system of Eqs. (1.1)-(1.7) are denoted by solid curves and those based on the algebraic Eqs. (1.8)-(1.10) are denoted by dashed curves. Curves 1-3 correspond to $P_v = 0$, $0.5\cdot10^{-2}$, and $-0.5\cdot10^{-2}$. The increase in the contaminant's concentration at the wall during gas suction and its decrease during gas injection are clearly seen from Fig. 7.

The intensity of deposition of the contaminant is determined by the product of the characteristic transverse velocity of chaotic motion and the particle concentration at the wall, (1.3) and (1.6). In Fig. 8 we give the particle deposition rate in channels with permeable walls ($\varkappa_2 = 0$) as a function of the Stokes number. Lines 1 are the result of a calculation in a pipe with walls that are impermeable to gas; lines 2-4 correspond to $P_v = 0.5 \cdot 10^{-2}$, $-0.5 \cdot 10^{-2}$, and $-1 \cdot 10^{-2}$; the dashed lines are the results of a calculation based on Eqs. (1.8)-(1.10). It is seen that gas suction increases the intensity of deposition of both fine and large contaminant particles. Gas injection can be used for efficient control of the rate of deposition of dine ($St < 10^{-1}$) or very large ($St > 10^3$) contaminant particles. The transverse velocity of chaotic motion of fine particles at the wall is considerably lower than the transverse stream velocity. For very large particles, which are weakly entrained in the turbulent motion of the carrier gas, the fluctuation velocity is lower than the transverse velocity in the entire pipe cross section. For medium-sized particles ($10^{-1} < St < 10^3$) the effect of inertia is important, owing to which particles in this range penetrate into the viscous sublayer with the relatively high intensity of the turbulent pulsations that they acquire in the core of the flow. From a comparison of Figs. 5 and 8 one can see the fundamental difference between the methods of controlling mass transfer of a contaminant by means of an external field applied directly to the contaminant particles and by influencing the particle dynamics by distorting the turbulent flow of the stream itself.

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