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DIFFUSION ANOMALIES OF SOLID PARTICLES IN TURBULENT FLOWS

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Abstract. The main purpose of the present article is to confirm the existence of migration transfer simultaneous with the turbulent transfer in the two-phase boundary layer and to explain its possible mechanism. Neglect of migration transfer leads to significant mistakes both in the definition of flow parameters and in the intensity estimation of turbulent transfer in the admixture of solid particles, as shown in the article.

Key words: channel, turbulent jet, mass concentration, migration, Magnus force.

The distribution anomalies of solid admixture in a two-phase turbulent jet flowing out from a relatively long ($L/D>100$) round channel were observed and described for the first time in [1]. By measuring local values of admixture consumption with isokinetic tubes (with filters) the authors found such initial values of parameters where either the admixture rushed to the jet axis or, on the contrary, it was rejected far from the boundary jet in the radial direction. The first anomaly was named a "string" phenomenon and the second, "scattering".

The data on the influence of solid admixture on the intensity of turbulence [1] have more than once been applied by theorists and provide a good approximation of different numerical tests [2–4]. Quite a different aspect are the anomalies which cannot be explained within the boundary layer theory, but at that time no other substantial theory existed. Theorists have tried to develop more complicated and perfect models of solid particle influence on the turbulence of primary fluids for a long time, paying no attention to the description of anomalies. Nobody disagrees as to the existence of the anomalies, but they neglect them. The description of anomalies within the existing theories appeared impossible at that time, and so the problem remained unsolved. Are there any anomalies of solid phase distribution in a two-phase turbulent jet or is the phenomenon a result of methodical miscalculation by the authors [1]? The answer to that question could be convincing only if we prove it by repeating the laboratory tests on other experimental equipment and use fundamentally different methods to work out a physically valid description of these anomalies. That is what we expect to do in the present article.

The experimental equipment used differs from the equipment in [1] with regard to the direction of the gas-admixture flux (a vertical channel instead of a horizontal one) and the application of more contemporary devices for adjusting and measuring the admixture consumption. The velocities and concentration fields were measured in channels ($D=16, 35, 48, 62$ mm) and in the jets flowing out from these channels. Alumina of different medium-size fractions ($\delta=23, 32, 50, 60, 80, 138$ μm) was used as the particle material. A screw feeder was used for supplying admixture and the constant initial concentration value was checked by a laser concentration measurer (LCM). The stability zone in the flow channel ($x/D>50$) was investigated by measuring profiles in different sections of the flow channel after unscrewing the lower sections step by step. The average velocities varied from 6 m/s to 60 m/s and the Reynolds number, from $6\cdot10^3$ to $3\cdot10^5$. Earlier the velocities and mass concentration had been measured by isokinetic tubes [1], but now the velocity component of both phases was measured by a single-component laser-Doppler anemometer (LDA). The concentration fields were measured by a LCM with the intensity of light diffusion [5]. Signals from photo-receivers of LDA and LCM were sent into a computer after preliminary processing where the necessary parameters [5] were calculated by special programmes. There is no need to prove the superiority of contemporary measurements in comparison with the measurements made twenty years ago. The anomalies are so evident in many experimental regimes that measuring errors are almost excluded.

Extinction of the concentration of the dispersed phase in the jet formed in the channel with the diameter $D=35$ mm and at the mean velocity $u=14$ m/s with the initial concentration value $\alpha_0=0.05$ kg/kg is shown in Fig. 1. The so-called "string" phenomenon which occurs in case of fine particles ($\delta=23, 32$ μm) disappears in case of medium-size particles ($\delta=60$ μm) when the "scattering" phenomenon appears

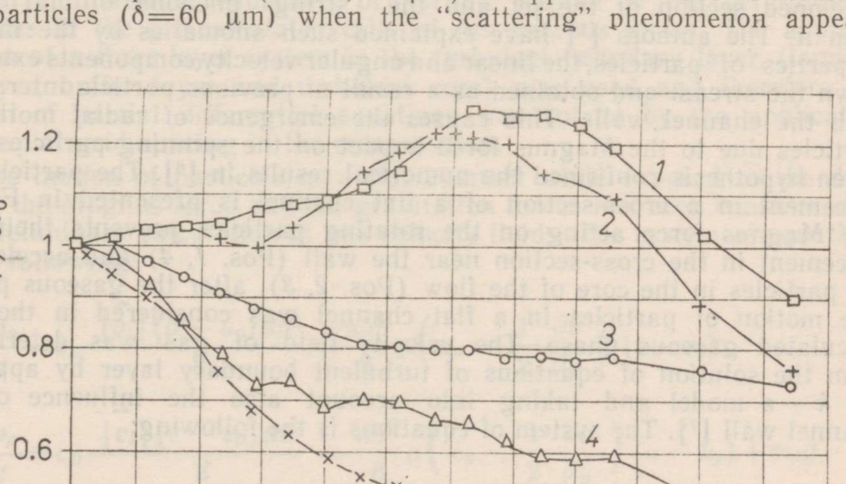

Fig. 1. Distribution of mass concentration in axial direction in jet. *1* — $\delta=23$ μm, *2* — $\delta=32$ μm, *3* — $\delta=60$ μm, *4* — $\delta=80$ μm, *5* — $\delta=138$ μm. Gas velocity $u=14$ m/s, $D=35$ mm.

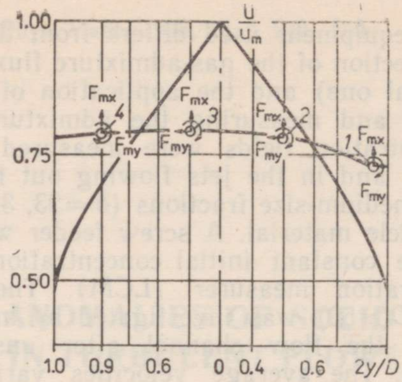

Fig. 2. Scheme of particle motion in the channel.

and becomes significant with large particles ($\delta=80$, 138 μm). The "string" phenomenon is characterized by the growth of axial concentration with the typical maximum in the main section of the jet where the intensive turbulent processes should lead to the natural diffusion of the admixture. The "scattering" phenomenon corresponds to the large particles of the admixture and is characterized by the unexpected decrease of the axial concentration in the developed section of the jet with the corresponding absence of the core jet. There are regimes with the influence of both anomalies: the "scattering" phenomenon in the developed section of the jet and the "string" phenomenon far away from it. The authors [1] have explained such anomalies by the inertial properties of particles, the linear and angular velocity components extended down the stream and obtained as a result of previous particle interaction with the channel walls. This causes the emergence of radial motion of particles due to the Magnus force impact on the spinning particles. The given hypothesis confirmed the numerical results in [6]. The particle displacement in a cross-section of a flat channel is presented in Fig. 2. The Magnus force acting on the rotating particles prevents their displacement in the cross-section near the wall (Pos. *1*, *4*) and accelerates the particles in the core of the flow (Pos. *2*, *3*), after the gaseous phase. The motion of particles in a flat channel was considered in the precalculated gaseous phase. The velocity field of gas was determined from the solution of equations of turbulent boundary layer by applying the $k-\varepsilon$ model and taking into account also the influence of the channel wall [7]. The system of equations is the following:

$$\frac{\partial u}{\partial x}+\frac{\partial}{\partial y}v=0, \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{\partial}{\partial y}(\nu_t+\nu)\frac{\partial u}{\partial y}-\frac{dP}{\varrho\, dx}, \tag{2}$$

$$u\frac{\partial k}{\partial x}+v\frac{\partial k}{\partial y}=\frac{\partial}{\partial y}\left(\frac{\nu_t}{\sigma_k}+\nu\right)\frac{\partial k}{\partial y}+\nu_t\left(\frac{\partial u}{\partial y}\right)^2-\varepsilon-2\nu\left(\frac{\partial\sqrt{k}}{\partial y}\right)^2, \tag{3}$$

$$u\frac{\partial \varepsilon}{\partial x}+v\frac{\partial \varepsilon}{\partial y}=\frac{\partial}{\partial y}\left(\frac{\nu_t}{\sigma_\varepsilon}+\nu\right)\frac{\partial \varepsilon}{\partial y}+C_{\varepsilon 1}\frac{\varepsilon}{k}\nu_t\left(\frac{\partial u}{\partial y}\right)^2-C_{\varepsilon 2t}\frac{\varepsilon^2}{k}+$$

$$+2\nu\nu_t\left(\frac{\partial^2 u}{\partial y^2}\right)^2, \quad (4)$$

$$\nu_t=C_{\mu t}\frac{k^2}{\varepsilon}, \quad (5)$$

$$x=0, \quad u=1, \quad v=0, \quad \varepsilon=\varepsilon(y), \quad (6)$$

$$x\geqslant 0\begin{cases} y=0, \ \dfrac{\partial u}{\partial y}=\dfrac{\partial \varepsilon}{\partial y}=0, \quad v=0 \\ y=\pm 1, \quad u_\delta=0.01, \quad \varepsilon=\varepsilon_\delta, \end{cases} \quad (7)$$

where k — turbulent energy,
ε — velocity of the dissipation of turbulent energy,
ν_t — coefficient of turbulent viscosity,
ϱ — density of gas phase,
ν — coefficient of laminar viscosity,
$C_{\mu t}$, $C_{\varepsilon 1}$, $C_{\varepsilon 2t}$, σ_k, σ_ε — constants,
u_δ — velocity on the boundary,
ε_δ — dissipative function on the boundary.

The system of ordinary differential equations was solved by the standard Runge-Kutta method and the system of partial differential equations, by the tridiagonal method. The main difficulty in solving ordinary differential equations of particle motion is the definition of particles in the pre-calculated cells of the gaseous phase. The approximation of a three-layer system in the turbulent boundary layer (laminar sublayer, buffer layer and turbulent core) was used and therefore the system of partial differential equations was solved by the application of unequal grid spacing in the cross-section.

The motion of particles in a flat channel while exposed to the drag force, the Magnus force and the gravitation forces has been considered in the preliminary calculation of gas velocity fields. The system of equations is the following:

$$m_p\frac{du_p}{dt}=c_D\frac{|\vec{v}_r|(u-u_p)\pi\delta^2}{8}+\frac{\pi\delta^3}{8}\varrho\left(\omega_p-\frac{1}{2}\frac{\partial u}{\partial y}\right)(v-v_p), \quad (8)$$

$$m_p\frac{dv_p}{dt}=c_D\frac{|\vec{v}_r|(v-v_p)\pi\delta^2}{8}-\frac{\pi\delta^3}{8}\varrho\left(\omega_p-\frac{1}{2}\frac{\partial u}{\partial y}\right)(u-u_p)+m_p g, \quad (9)$$

$$I_p\frac{d\omega_p}{dt}=-\pi\mu\delta^3\left(\omega_p-\frac{1}{2}\frac{\partial u}{\partial y}\right), \quad (10)$$

$$\frac{dx_p}{dt}=u_p, \quad (11)$$

$$\frac{dy_p}{dt}=v_p. \quad (12)$$

where δ — diameter of the particle,
ω_p — angular velocity of the particle,
m_p — mass of the particle,
u_p, v_p — the axial and radial velocity components of the particle,
I_p — momentum of inertia of the particle,
μ — coefficient of dynamic viscosity of gas,
$|\vec{v}_r|$ — relative velocity of the particle,
c_D — drag coefficient of the particle,
g — acceleration of the external mass force (gravitational force),
$\frac{\partial u}{\partial y}$ — gradient of gas velocity.

In the equation describing inertial particle motion an additional Magnus component of acceleration is introduced (in axial and radial direction):

$$\frac{\pi\delta^3}{8}\varrho\left(\omega_p-\frac{1}{2}\frac{\partial u}{\partial y}\right)(v-v_p), \tag{13}$$

$$-\frac{\pi\delta^3}{8}\varrho\left(\omega_p-\frac{1}{2}\frac{\partial u}{\partial y}\right)(u-u_p), \tag{14}$$

where index p relates to the particle velocity. The angular velocity of the particle has been determined according to [8] and has the order of 10^4—10^6 c^{-1}. The particles could not obtain such a value of angular velocity in the jet due to the insignificant gradient velocity of the gaseous phase. The particles can obtain essential angular velocity only as a result of their interaction with the wall. So the anomalies of concentration distribution in the jet are very closely related to the specific features of the admixture motion in the channel. The next step in the numerical investigation of migration processes should be the draft calculation of the channel-jet system. However, we can get some model data from the calculation of the trajectory of separated particles (the Lagrangian description). Such a calculation is given below.

Eq. (10) was obtained in [9]. The initial conditions for particle motion were determined by the wall and are the following:

$$u_p|_{t=0}=\alpha_1 u, \quad v_p|_{t=0}=\alpha_2 u, \quad \omega_p=\alpha_3/2\bar{\delta}, \tag{15}$$

where α_1, α_2 and α_3 are numerical constants, and $\bar{\delta}=\delta/D$ is the relative diameter of the particle.

Considering the particle velocities obtained by interaction with the wall and determined according to [8], we get

$$u'_p=\frac{(5+2k_t)}{7}u_p\pm\frac{(1-k_t)\delta}{7}\omega_p, \tag{16}$$

$$v'_p=k_n v_p, \tag{17}$$

$$\omega'_p=\frac{(2+5k_t)}{7}\omega_p\pm\frac{10(1-k_t)}{7\delta}u_p, \tag{18}$$

where k_t, k_n are coefficients of recovery of the tangential and normal velocity components of the particle. Expressions (16—18) describe the boundary conditions for Eqs. (8—10).

The particle trajectories obtained by numerical calculation are all presented in Fig. 3. The larger particles show saltatory motion (from wall to wall) with the essential axial lag velocity between the phases. Diminution of the particle size leads to the decrease of velocity of phases and the particles concentrate near the wall. A model based on experimental data (Fig. 4) explains the distribution of the mass concentration in a cross-section of a square channel (80×80 mm) with the peak

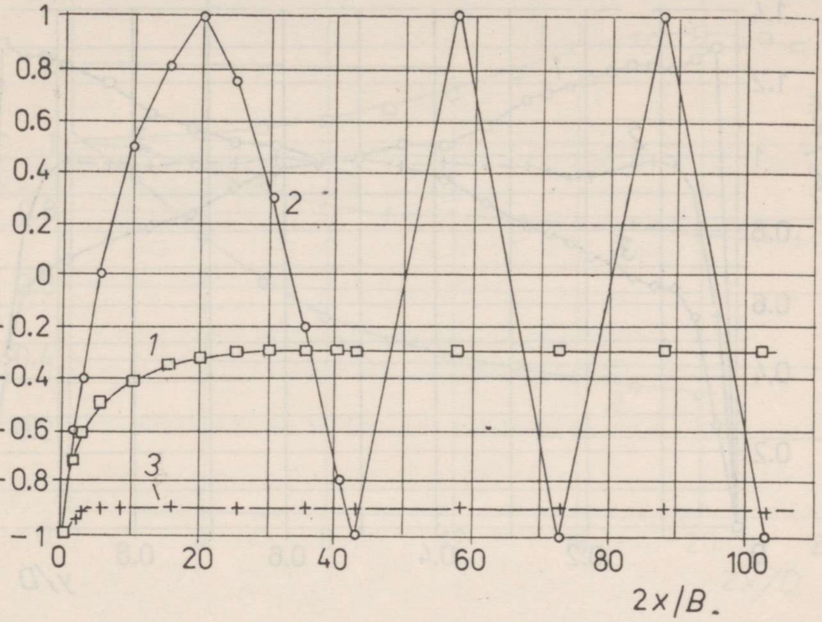

Fig. 3. Particle trajectories in flat channel. *1* — δ=23 μm, *2* — δ=80 μm, *3* — δ=138 μm.

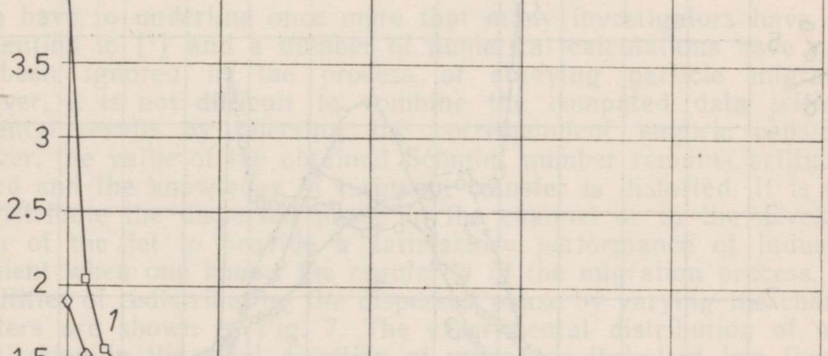

Fig. 4. Experimental distribution of mass concentration in the same flat channel. *1* — δ=23 μm, *2* — δ=50 μm, *3* — δ=60 μm, *4* — δ=138 μm.

of concentration near the wall. The admixture with fine particles ($\delta = 23$, 32 μm) actually concentrates near the wall. The larger particles ($\delta = 80$, 138 μm) have an almost uniform concentration profile in the cross-section. The concentration profiles in the cross-section of a round channel are shown in Fig. 5. The peculiarities of the admixture distribution in the round channel are the same as those in the square channel section. The concentration of the large-particle admixture distributes

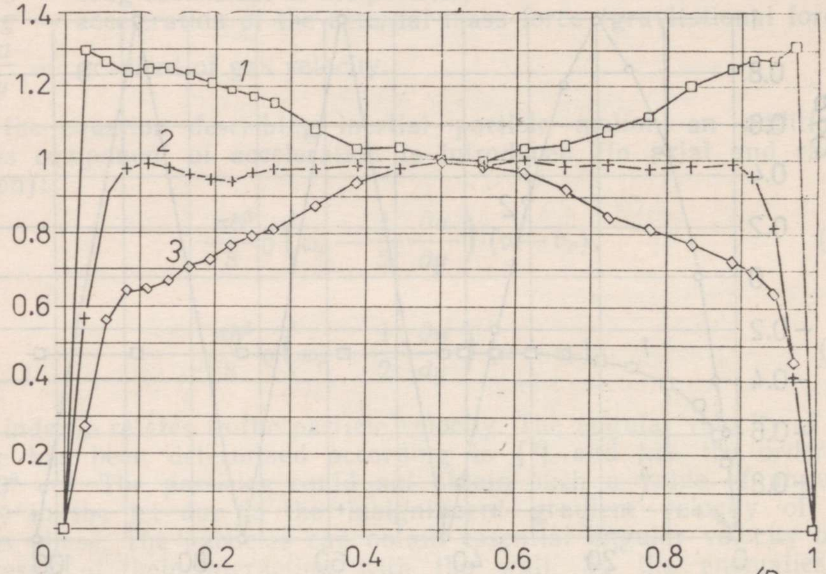

Fig. 5. Experimental distribution of mass concentration in round tube. *1* — $\delta = 23$ μm, *2* — $\delta = 60$ μm, *3* — $\delta = 80$ μm. $u = 14$ m/s, $D = 35$ mm.

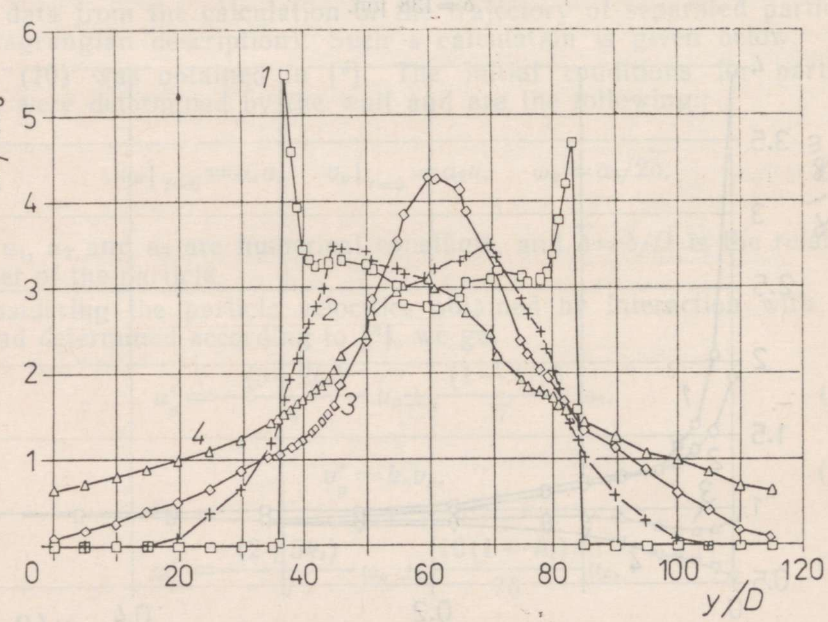

Fig. 6. Transformation of the mass concentration profiles of channel flow into the jet profiles. *1* — $z = 0$, *2* — $z = 120$ mm, *3* — $z = 280$ mm, *4* — $z = 400$ mm.

more or less uniformly while that of fine particles ($\delta \sim 23$, 32 μm) has its peak near the wall. In spite of this, the "string" phenomenon (Fig. 1) can be observed. The experimental transformation of anomalous admixture concentration profiles ($\delta=23$ μm, $u=14$ m/s, $\alpha=0.05$ kg/kg) in the channel into anomalous jet profiles in different cross-sections ($z=0$, $z=120$ mm, $z=280$ mm, $z=400$ mm) is given in Fig. 6.

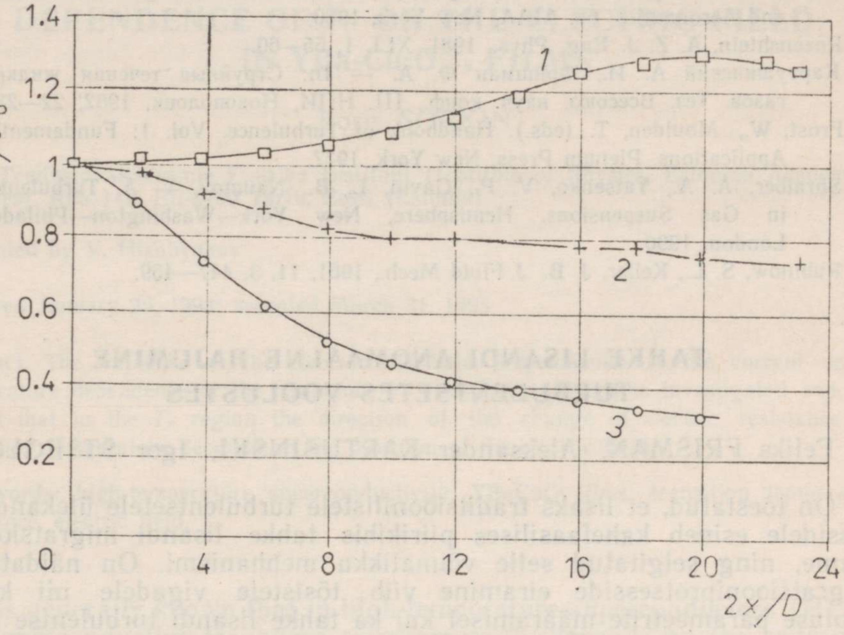

Fig. 7. Distribution of mass concentration in axial direction in jet from tubes of different diameters. *1* — $D=48$ mm, *2* — $D=35$ mm, *3* — $D=16$ mm. Particle size $\delta=60$ μm.

We have to underline once more that many investigators have paid no attention to [1] and a number of numerical calculations have up to now been ignored in the process of studying particle migration. Moreover, it is not difficult to combine the computed data with experimental results by selecting the correspondent empiric constants. However, the value of the obtained Schmidt number remains artificially lowered and the knowledge of turbulent transfer is distorted. It is easy to redistribute the dispersed phase in the channel or in the developed section of the jet to provide a satisfactory performance of industrial equipment when one knows the regularity of the migration process. The possibilities of redistributing the dispersed phase by varying the channel diameters are shown in Fig. 7. The experimental distribution of mass concentration in the axial direction of two-phase turbulent jets flowing out from channels of different diameters ($D=16$, 35, 48 mm) for the same average velocity of the gaseous phase $u=14$ m/s and mass concentration ($\alpha_0=0.05$ kg/kg) with the particle size $\delta=60$ μm varies essentially.

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TAHKE LISANDI ANOMAALNE HAJUMINE TURBULENTSETES VOOLUSTES

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On tõestatud, et lisaks traditsioonilistele turbulentsetele ülekandeprotsessidele esineb kahefaasilises piirikihis tahke lisandi migratsioonülekanne, ning selgitatud selle võimalikku mehhanismi. On näidatud, et migratsiooniprotsesside eiramine viib tõsistele vigadele nii kandva vooluse parameetrite määramisel kui ka tahke lisandi turbulentse massiülekande intensiivsuse hindamisel.

АНОМАЛЬНОЕ РАССЕИВАНИЕ ТВЕРДЫХ ЧАСТИЦ В ТУРБУЛЕНТНЫХ ПОТОКАХ

Феликс ФРИШМАН, Александр КАРТУШИНСКИЙ,
Игорь ЩЕГЛОВ

Основная задача данной статьи — подтвердить существование в двухфазных пограничных слоях наряду с турбулентным переносом т. н. миграционного переноса примеси и объяснить его возможный механизм. Показано, что пренебрежение миграционным переносом приводит к существенным ошибкам как в определении параметров течения, так и в оценке интенсивности турбулентного переноса массы примеси твердых частиц.