TURBULENT DIFFUSION OF PASSIVE IMPURITY IN GAS SUSPENSION AT LARGE REYNOLDS NUMBERS

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Experimental results on the turbulent diffusion of passive impurity in a gas-suspension flow in a vertical cylindrical channel are outlined. On the basis of introducing simple approximations of spectral functions of the velocity pulsations, the influence of the discrete phase on the turbulent diffusion coefficient is estimated.

The influence of a small volume concentration of particles in turbulent gas-suspension flows on the pulsational characteristics of the gas phase has been the subject of many theoretical studies, for example, [1-4]. However, there have only been a few experimental investigations of the influence of particles on the turbulent heat- and mass-transfer coefficients [5, 6], at Re up to 53,000. In the present work, experimental results on the turbulent diffusion of passive impurity in gas-suspension flow at Re = 68,000-136,000 are outlined. The measurements are made at the axis of a vertical cylindrical channel of diameter 250 mm following the dynamic-stabilization section. In this case, it may be assumed that the turbulence at the tube axis is almost isotropic [7], and Taylor theory is used. In diffusional measurements, an impurity source is introduced in the given flow, and the transport characteristics are determined from the intensity of its erosion. The dispersion is calculated as

$$\langle y^2 \rangle = \int_{-\infty}^{\infty} \gamma x_2^2 dx_2 \left(\int_{-\infty}^{\infty} \gamma dx_2 \right)^{-1},$$

and is related to the Lagrangian of the correlation coefficient R_L by the Taylor formula [7]

$$\langle y^2 \rangle = 2 \langle u'^2 \rangle \int_0^t (t-\tau) R_L(\tau) d\tau.$$

At large distances from the source x_1, the turbulent diffusion coefficient is

$$D_T = \frac{1}{2} \bar{u} \frac{d \langle y^2 \rangle}{dx_1}. \tag{1}$$

Since the concentration distribution beyond the point source is Gaussian in flow at the tube axis

$$\gamma(x_2) = \gamma_m \exp\left(-\frac{x_2^2}{2 \langle y^2 \rangle} \right),$$

it follows, according to [8], that $\sqrt{\langle y^2 \rangle} = 0.425b$, where b is the width of the profile $\gamma(x_2)$ when $\gamma = 0.5\gamma_m$.

In the experiments, a gas suspension consisting of air and aluminum-hydroxide particles (according to All-Union State Standard GOST 11841-76) with mean-mass dimension $d_p = 49$ μm. Carbon dioxide is used as the marker gas; it is fed to the flow through a capillary of diameter 1.2 mm. The injection rate is controlled by a precise-regulation spigot. The CO_2 impurity is sampled in cross sections at different distances from the source, and its concentration is determined on an LKhM-8 gas chromatograph. The accuracy of transverse displace-

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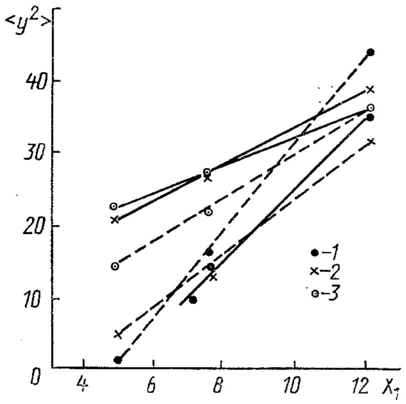

Fig. 1

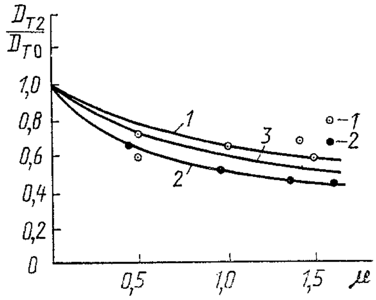

Fig. 2

Fig. 1. Dependence of the impurity dispersion on the distance to the source: continuous curves) Re = 68,000; dashed curves) Re = 136,000; 1) $\mu = 0$; 2) 0.95; 3) 1.65; $\langle y^2 \rangle$, mm^2; x_1, mm.

Fig. 2. Dependence of the turbulent diffusion of passive impurity on the disperse-phase concentration: 1) data of [6], Re = 53,000; 2) experiment, Re = 100,000; 3) calculation by Eq. (8).

ment of the sampling unit is ±0.05 mm; longitudinally, the corresponding figure is ±0.1 mm. It is known that, in diffusional measurements, the results are distorted because of the influence of the finite size of the source, molecular transport, and the injection rate of impurity. In the given experimental conditions, the influence of the source dimensions on the experimental error is the most significant but, as shown by estimates by the data of [8], the error in measuring the dispersion in the present study is no more than 3%.

Experimental results for the dispersion of impurity erosion behind the source are shown in Fig. 1, from which it is evident that the measurements are made at a distance from the source sufficient to ensure the validity of Eq. (1), since $d\langle y^2 \rangle / dx_1 = \text{const}$. The diffusion coefficients are determined from the slope of the curves in Fig. 1.

The ratio of turbulent diffusion coefficients in two-phase D_{T2} and single-phase D_{T0} flows is shown in Fig. 2 as a function of the flow-rate mass concentration μ of the particles. For comparison, the experimental results of [6] are also shown in Fig. 2. The somewhat lower values of D_{T2}/D_{T0} in the present experiments (curve 2) are explained in that, according to [9], small-scale pulsations, the proportion of which in the spectrum increases with increase in Re, are suppressed primarily at small concentrations of disperse-phase particles.

The diffusion coefficient may be expressed in the form: $D_T = \langle u'^2 \rangle \Lambda_{L\gamma}$, where $\Omega_{L\gamma}$ is the Lagrangian of the integral scale of turbulent pulsations of the passive-impurity concentration.

Suppose that the particle dimensions are small and less than the internal scale of turbulence, and their concentration in the gas is slight. Suppose also that the ratio between the Euler and Lagrangian scales in two-phase flow with a low particle concentration remains the same as in single-phase flow. Then the ratio of turbulent diffusion coefficients of the passive impurity must be calculated as follows, according to [7]

$$\frac{D_{T2}}{D_{T0}} \sim \int_0^\infty \frac{E_2(k)}{k} dk \left(\int_0^\infty \frac{E_0(k)}{k} \right)^{-1}, \tag{2}$$

where $E_2(k)$ and $E_0(k)$ are three-dimensional spectral functions of the velocity pulsations of the carrier medium in the two-phase and one-phase flows, respectively.

At large wave numbers, $E_0(k)$ may be approximated in the form [10]

$$E_0(k) \sim \varepsilon_0^{2/3} k^{-5/3} \exp[-\alpha k^2 \eta_0^2]. \tag{3}$$

In two-phase flow, the total energy of turbulent-pulsation dissipation ε_2 consists of the turbulent dissipation ε_B related to the work of ordinary turbulent stress in the gas and the energy of viscous dissipation ε_p at the particles [11, 12]. Calculations of the degeneracy of isotropic turbulence in the gas suspension on the basis of numerical solution of the dynamic equation [11] show that ε_B in two-phase flow is related to the corresponding quantity in single-phase flow as follows

$$\varepsilon_B \approx \varepsilon_0 (1+\mu)^{-1}, \tag{4}$$

which is in qualitative agreement with [12]; the Kolmogorov scales in two-phase and single-phase flows are related approximately as follows

$$\eta_2 \approx \eta_0 (1+\mu). \tag{5}$$

The approximation of the spectrum $E_2(k)$ for a gas with particles is introduced by analogy with Eq. (3)

$$E_2(k) \sim \varepsilon_B^{2/3} k^{-5/3} \exp[-\alpha k^2 \eta_2^2]. \tag{6}$$

The possibility of choosing ε_B as the determining parameter for the intensity of velocity pulsations in the gas suspension was also indicated in [12]. The above considerations are very approximate, and all the calculations must be regarded as rough estimates. Substituting Eqs. (3) and (6) into Eq. (2) and taking account of Eqs. (4) and (5), the following result is obtained after integration with respect to k_e to ∞

$$\frac{D_{T2}}{D_{T0}} \approx (1+\mu) \frac{\Gamma\left(-\frac{5}{6}\right) - g\left[-\frac{5}{6};\ \alpha k_e^2 \eta_0^2 (1+\mu)^2\right]}{\Gamma\left(-\frac{5}{6}\right) - g\left[-\frac{5}{6};\ \alpha k_e^2 \eta_0^2\right]}, \tag{7}$$

where $g(a; z)$ is an incomplete gamma function. The wave number k_e corresponding to the region of energy-containing vortices may be estimated according to [12]. Using the first term of the expansion of $g(a; z)$, it is found that

$$\frac{D_{T2}}{D_{T0}} \approx (1+\mu)^{-2/3}. \tag{8}$$

Calculations using Eq. (8) (Fig. 2) are in satisfactory agreement with experimental data, despite the constraints which follow from the above assumptions regarding the small concentration and size of the particles.

Evidently the dimensions of particles with $d_p < 40$-50 μm — for the given experimental conditions, this corresponds to $Stk = \tau_d/\tau_\eta \leq 10$, since $\tau_\eta \sim (\nu_0 L u^{-3})^{1/2}$ cm [10] — does not have a great influence on the diffusional characteristics of the carrier medium when the particle concentration is small. The same conclusion was reached in [4], where, within the limits of experimental accuracy the dimensions of particles with $d_p < 50$ μm had no influence on the turbulence intensity, i.e., the principal influence of small particles is through their concentration. The region of applicability of the given approximate results is limited by the particle concentrations $\mu \leq 1.5$ and $Stk \leq 1.0$. At large particle sizes, the results of [12] must be used for the spectral functions.

NOTATION

$\bar{u}$, mean gas velocity; γ, concentration of passive impurity; t, τ, time; D_T, turbulent diffusion coefficient of passive impurity; $\Lambda_{L\gamma}$, Lagrangian integral scale of turbulent concentration pulsations; ε, dissipation rate of turbulent energy; E, three-dimensional function of energy spectrum; μ, mass concentration of particles in gas; k, wave number; τ_d, dynamic-relaxation time; τ_η, internal time scale of turbulence.

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DYNAMICS OF THE Z PINCH WITH A LIGHT LINER.

II. SINGLE-ENVELOPE LINERS AND THE ANOMALIES OF THE CUMULATION STAGE

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The results of calculations of the compression of single-envelope liners toward the axis in the one-dimensional magnetic radiative gas dynamics approximation are considered. A refinement is proposed for the method of calculating the cumulation stage, making it possible to obtain better agreement with experimental data.

As shown by experiments [1-3], a cylindrical liner accelerated by the magnetic pressure of the intrinsic current to velocities of 200-400 km/sec can be an effective means of increasing the power. The power increases as a result of a substantial shortening of the plasma retardation time at the symmetry axis in comparison with the linear acceleration time. In real systems relativistic-electron-beam generators are used as energy sources giving a current pulse of several megamperes with a rise time of less than 100 nsec and the energy is delivered to the liner by magnetically insulated vacuum lines, i.e., the power supply is a system with distributed parameters and the equation for long lines must be used to describe this system. In order to solve such equations one must know the electrical engineering parameters of the line (per unit length), which cannot be reproduced from the published data. With acceptable accuracy for practical purposes one can use an ordinary RLC circuit (a system with concentrated parameters), choosing its parameters so that the dependence of the current on time would correspond sufficiently well to the experimental data until the maximum current is attained. This is how we conduct the calculation here, as described earlier [4]. After the current reaches maximum, a crowbar-breaker is tripped and we then calculate a close inductance-liner circuit, while the processes in the disconnected part of the circuit, capacitance-external resistance, are not considered in this case. We note that the approximation in which the dependence of the current on time is prescribed beforehand is unsatisfactory for reasons discussed below. The method of calculating the system of magnetic radiative gasdynamic (MRGD) equations is described in the first part of this communication [4]. Since the calculation of the ionization component of the plasma from the system of nonstationary equations of charge kinetics is fairly long, however, in this part of the study the composition of the plasma is found from the stationary equations, i.e., we set $dN_2/dt = 0$. As shown by comparison of the calculations of liner compression with steady-state and transient kinetics, the results differ little and the calculation time increases by an order of magnitude. This is because all the plasma properties according to the steady-state kinetics can be calculated beforehand and the ready tables can be used in the MRGD calculations.

Let us consider the results of calculations of the following variants of compression of single-envelope liners (Sections 1, 2 – see [4]).

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