THE MOTION OF SOLID-PHASE PARTICLES IN COUNTERCURRENT GAS-SUSPENSION JETS

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Results are presented from an experimental study of the motion of particles of a disperse material in countercurrent gas-suspension jets. Data have been obtained on the motion of the solid-phase particles in the acceleration segment and in the zone in which the gas-suspension jets intersect.

A possible means of intensifying the process of interphase transport in gas suspensions is the method of countercurrent jets [1-3]. The efficiency of this method is confirmed with regard to interphase heat and mass transfer and the mixing of finely dispersed powders [1-4]. For this method to be employed extensively by industry, we require a detailed study of the features encountered in the motion of disperse-material particles in countercurrent jets.

In this article we discuss the results of experimental investigations into the motion of solid-phase particles in countercurrent jets; these studies are based on the application of the method of radioactive isotopes [5-8].

The studies were carried out in two mutually complementary ways. The first of these, based on the measurement of absorption of radioactive emission by a two-phase flow, makes it possible to determine the local distribution of concentration for the disperse material in the longitudinal and transverse cross sections of a channel. The second method involves studying the motion of solid-phase particles labeled with a radioactive isotope. The former method yields time-averaged results and is convenient in studying two-phase flows with rather high concentrations of a finely dispersed solid phase. With the second method we can study the nature of the motion and measure the particle velocities in the two-phase flows for virtually any concentration of a coarsely dispersed solid phase.

For materials with spherical particles exhibiting $d \geq 1$ mm we conducted the studies according to the second method. The solid phase in these experiments was represented by the following materials: 3 fractions of silica gel with an average diameter of 1.32, 2.25, and 3.3 mm, as well as slag pellets with an average diameter of 1 mm. Cobalt-60 was the radioactive isotope used as the radiation source; it was introduced into polystyrene beads. The labeled particles were classified as to dimensions, shape, and weight with respect to the average values of the corresponding indices for the materials employed in the tests. In addition, the tests involved labeled particles, 2.25 mm in diameter, which were made of foam plastic, polystyrene, aluminum, and tin.

A diagram of the installation in which the tests were carried out with the labeled particles is shown in Fig. 1. The installation was made up of two acceleration (1, 2) and drainage (12) channels, fabricated of steel tubing with an inside diameter D = 21 mm, connected at cross joint 3. The flow rate of the disperse material fed into the gas flow from hopper 9 was regulated by means of valves 11. The operational channel was 1700 mm long from the point at which the disperse material was introduced into the flow to the plane at which the jet intersected. Air was drawn through blower 6, the air flow rate was regulated by slide valves 7, and it was measured with two lemniscate collectors 8 and type MM-250 micromanometers 19. The labeled particles were introduced through the special connecting tube 22, located near hopper 9. The labeled particles settled out in cyclone 4 from which they entered hopper 5 through valve 14. All of the experiments were carried out with the air at room temperature.

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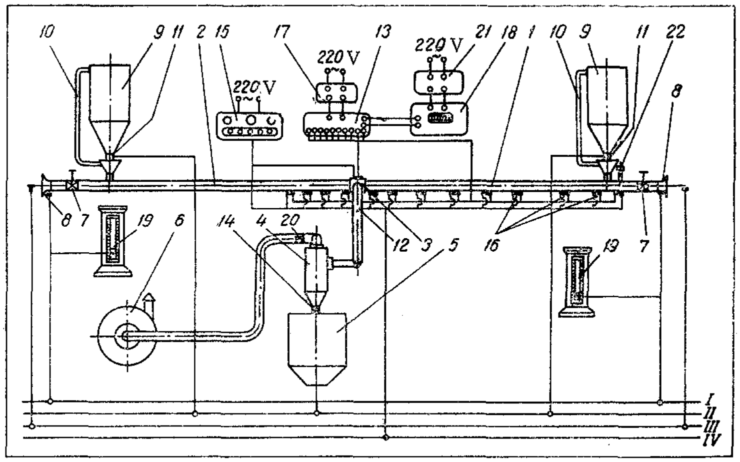

Fig. 1. Diagram of experimental installation to study the motion of particles in countercurrent gas-suspension jets by the method of labeled radioactive particles: 1 and 2) acceleration channels; 3) cross joint; 4) cyclone; 5 and 9) hoppers; 6) fan; 7) slide valves; 8) lemniscate collectors; 10) connecting hoses; 11 and 14) valves; 12) drainage channels; 13) amplifier; 15) VSV-2 high-voltage stabilizer; 16) radioactivity counters; 17 and 21) rectifiers; 18) N-700 oscillograph; 19) MM-250 micromanometers; 20) filter; 22) device for the introduction of the labeled particles. Measurements: I) gas flow rate; II) flow rate of material; III) temperature; IV) velocity of labeled particles.

Thirteen SBT-11 and STS-5 counters 16 were mounted along the duct through which the particles moved; the voltage to these counters was applied from a high-voltage VSV-2 stabilizer 15. The pulses picked up in the detectors on passage of a labeled particle were transmitted to the input of the single-stage amplifier 13 whose output was connected to the N-700 oscillograph 18. The amplifier and the oscillograph were powered from the net through rectifiers 17 and 21.

The stay time was measured according to the signals of the two adjacent counters and this, consequently, provided the velocity of the particles at the corresponding segment of the installation. The adjacent detectors were never separated by more than 250 mm.

The time spent by the particles in the intersection zone and the magnitude of particle scattering to the opposite jet are determined to a substantial degree by the velocity of the particles at the end of the acceleration segment.

The results from the investigation into the motion of disperse particles in the acceleration segment are shown in Fig. 2. Curves 1, 2, 3, 4, and 5 characterize the change in the velocity of a solitary particle along the acceleration segment. The effect of the gas velocity W on the magnitude of W_s/W can be traced in curves 3, 4, and 5. A certain reduction in the magnitude of W_s/W with increasing W is noted only at the beginning of the acceleration segment, where the relative velocity of particle motion $(W - W_s)$ is comparatively close to the velocity of the gas. Subsequently, when $l_a > 1000$-1200 mm this effect is not noted. Similar results were obtained in a number of references [6, 9, 12], in which it was established that in the segment of uniform motion for a horizontal gas suspension the ratio W_s/W for a given disperse material is independent of the gas velocity. It follows from a comparison of curves 1, 2, and 3 that the magnitude of W_s/W, all other conditions being equal, increases with a reduction in the free-fall velocity of the particles. A similar pattern is noted in [6, 13] for the steady-state segment of horizontal pneumatic transport.

Figure 2 shows data on the influence exerted by the effective concentration (β_{eff}) on W_s/W (curves 6, 7, 8, 9). These studies show that for a mass movement of particles the magnitude of W_s/W diminishes by approximately 10-15% with an increase in the solid-phase concentration.

The nature of the function $W_s/W = f(\beta_{eff})$ can be explained by the fact that with an increase in the concentration, resulting from the collisions between the particles, there is a slight increase in the number

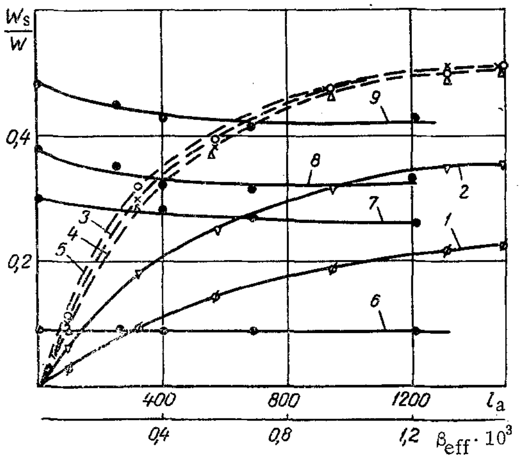

Fig. 2

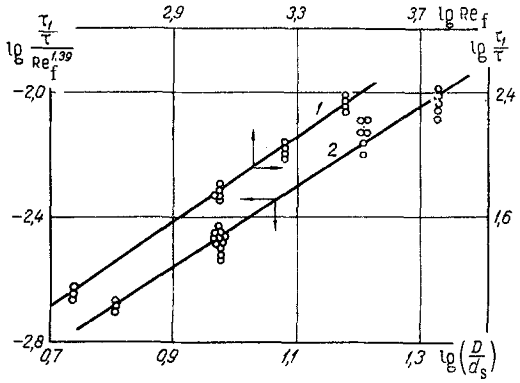

Fig. 3

Fig. 2. Motion of disperse-material particles in the acceleration segment of countercurrent jets: 1, 2, 3, 4, 5) the ratio W_s/W as a function of the length l_a of the acceleration segment for solitary particles [1) d_s = 2.25 mm; γ_m = 7160 kg/m^3; W_f = 18.5 m/sec; W = 21.7 m/sec; 2) d_s = 2.25 mm; γ_m = 2970 kg/m^3; W_f = 11.8 m/sec; W = 21.7 m/sec; 3, 4, 5) d_s = 1.32 mm; γ_m = 1720 kg/m^3; W_f = 6.5 m/sec; W, respectively, 9, 18.3, and 24.6 m/sec]; 6, 7, 8, 9) the ratio W_s/W as a function of the effective concentration β_{eff} for d_s = 1.32 mm; γ_m = 1720 kg/m^3; W_f = 6.5 m/sec; W = 21.7 m/sec; [6) l_a = 96 mm; 7) 320; 8) 570; 9) 940].

Fig. 3. The quantity τ_1/τ as a function of both Re_f and D/d_s for a solitary particle: 1) $\tau_1/\tau = f(Re_f)$; 2) $((\tau_1/\tau)/Re_f) = f(D/d_s)$.

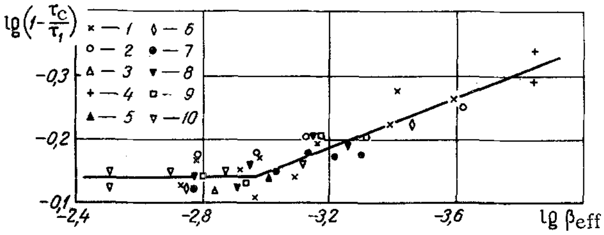

Fig. 4. The quantity $(1 - \tau_c/\tau_1)$ as a function of the effective gas-suspension concentration β_{eff}, derived with the aid of: a) the labeled particle method: 1) d_s = 1.32 mm and γ_m = 1720 kg/m^3; 2) 2.25 and 1174; 3) 3.3 and 1100; 4) 1.0 and 2010; b) the degree of absorption by the gas-suspension flow of the radioactive emission: 5) silica gel, d_s = 2.25 mm; γ_m = 1240 kg/m^3; 6) silica gel, d_s = 1.32 mm, γ_m = 880 kg/m^3; 7) poppy, d_s = 0.99 mm, γ_m = 1100 kg/m^3; 8) sand, d_s = 0.88 mm, γ_m = 2650 kg/m^3; 9) sand, d_s = 0.67 mm, γ_m = 2650 kg/m^3; 10) sand, d_s = 0.28 mm, γ_m = 2650 kg/m^3.

of particle collisions against the wall. These data are in agreement with those of [6], where it is demonstrated that the length of the acceleration segment increases as the concentration grows.

The experiments carried out with all of the investigated model materials demonstrated that the acceleration of the disperse phase takes place primarily in a segment 1000-1300 mm in length. For acceleration segments of greater length the velocity of the particles per unit length increases substantially more slowly. Special experiments in which the particles were introduced into the stream at l_a = 500, 1000, and 1700 mm demonstrated that with the acceleration segment changed in length from 1000 to 1700 mm the time spent by the particle in the jet intersection zone (τ_c) increases by no more than 5-12%, whereas for l_a = 500 mm the value of τ_c may be as much as 25-35% smaller than when l_a = 1700 mm. In this connection, to reduce the dimensions of the installation and the hydraulic losses in the acceleration segment, we can recommend an optimum length of 1500-2000 mm for the acceleration segment.

In the installation whose diagram is shown in Fig. 1 we also investigated the nature of solid-phase particle motion in the zone of jet collision.

The first series of tests involved solitary labeled particles. Here we measured the average stay time of the labeled particles in the zone of jet intersection of gas velocities of 9-30 m/sec. Because the motion of a single particle in the jet intersection zone depends significantly on a number of factors whose effect is statistical in nature (turbulent variations in gas velocity, collision with the walls, etc.), the stay time for the labeled particles, given the same gas-phase velocity, was determined by averaging the results from 15-20 experiments.

It was established on the basis of the experimental results (see Fig. 3) that when D/d_s = const the ratio τ_1/τ in the investigated range of velocities is virtually independent of the gas velocity and depends strongly on the aerodynamic characteristics of the particles. The experimental results are approximated with a maximum error of ±9.6% by the following relationship:

$$\frac{\tau_1}{\tau} = 0.34 \cdot 10^{-4}\,\mathrm{Re}_f^{1,4}. \tag{1}$$

The introduction of the simplex D/d_s has made it possible to generalize all of the experimental data for solitary labeled particles, given maximum scattering of ±12.5% (see Fig. 3), by the following relationship:

$$\frac{\tau_1}{\tau} = 1.7 \cdot 10^{-4}\,\mathrm{Re}^{1,4}\left(\frac{D}{d_s}\right)^{1,33}. \tag{2}$$

In the second series of experiments, the labeled particles were introduced into the flow together with the other particles of the disperse material to determine the effect of concentration on the average time (τ_c) spent by the solid-phase particles in the jet intersection zone.

This was precisely the purpose of the series of experiments whose method is based on the measurement of the absorption of radioactive emission by a two-phase flow. The diagram of the experimental installation and the measuring method are similar to those described in [10]. We employed 3 narrow sand fractions with d_s = 0.28, 0.67, and 0.88 mm in the experiment (the quantity d_s was determined according to [11]), and we used poppy and 2 fractions of silica gel with d_s = 1.32 and 2.25 mm. Dynamic calibration was carried out for all of the above-enumerated materials through the use of a limited pulsating fluidized bed [2], all the way to $\beta_{eff} = 0.1\ m^3/m^3$

According to the data obtained in the measurement of the local longitudinal and transverse concentrations of material, through the calibration we determined the average true quantity of material in the zone of intersection, and subsequently, by dividing by the per-second flow rate of the disperse phase, we found the average stay time for the particles in the jet intersection zone for each regime.

Figure 4 shows the experimental data with regard to the particle stay times in the jet intersection zone, and these data have been obtained both by means of the labeled particles and from the measurements of the local concentrations. For the latter case τ_1 was determined from formula (2). The experimental results, shown in functional form $(1 - \tau_c/\tau_1) = f(\beta_{eff})$ in Fig. 4, show that the particle stay time in the jet intersection zone diminishes to $\beta_{eff} \cong 1 \cdot 10^{-3}\ m^3/m^3$ as the concentration increases. For $1.0 \cdot 10^{-3} < \beta < 3.5 \cdot 10^{-3}$ the magnitude of τ_c becomes approximately constant:

$$\frac{\tau_c}{\tau_1} \cong 0.28. \tag{3}$$

We should take note of the fact that a further rise in concentration ($\beta_{eff} > 3.5 \cdot 10^{-3}$), in a number of cases led to the deposition of material in the jet intersection zone at the bottom of the channel and thus to cessation of material transport.

For $\beta_{eff} < 1 \cdot 10^{-3}\ m^3/m^3$ the experimental data with respect to the particle stay times in the jet intersection zone are approximated with a maximum error of ±18.2% by the following relationship:

$$\frac{\tau_c}{\tau_1} = 1 - 2.74 \cdot \beta_{eff}^{0.2}. \tag{4}$$

The reduction in the stay time of the disperse material in the jet intersection zone with an increase in concentration can be explained by the increase in the number of collisions between particles, which disrupts the oscillatory motion and accelerates the removal of the particles from the reactor. When $\beta_{eff} \geq 1 \cdot 10^{-3}$ the oscillatory motion of the particles in the jet intersection zone no longer exerts significant influence on the average stay time of disperse material in the apparatus.

From expressions (2) and (4) we have the following generalized relationship for the determination of the average stay time of the disperse particles in the zone in which the countercurrent jets collide:

$$\frac{\tau_c}{\tau} = 1.7 \cdot 10^{-4}\,\mathrm{Re}_f^{1,4}\left(\frac{D}{d_s}\right)^{1,33}(1 - 2.74\,\beta_{eff}^{0.2}), \tag{5}$$

and this is the actual function in the case of $\beta_{eff} \leq 1.0 \cdot 10^{-3}$.

For the case in which $1 \cdot 10^{-3} \le \beta_{eff} < 3.5 \cdot 10^{-3}$ it follows from (2) and (3) that

$$\frac{\tau_c}{\tau} = 0.47 \cdot 10^{-4}\, \mathrm{Re}_f^{1.4} \left(\frac{D}{d_s}\right)^{1.33}. \tag{6}$$

Comparison of the solid-phase stay times in the jet intersection zone, calculated according to formulas (5) or (6), with the stay time for the material in an equal-length segment of the horizontal gas-suspension flow shows that for countercurrent jets this quantity is many times greater. Thus, for example, for silica gel $d_s = 2.25$ mm when $\beta_{eff} = 0.48 \cdot 10^{-3}$ the stay time of the silica gel in the jet intersection zone is greater by a factor of 10.7 than in the equal-length segment of uniform gas-suspension motion. This substantial increase in the stay-time duration of the material in countercurrent jets is one of the factors responsible for the high intensity of the processes of interphase transport per unit volume of the zone of gas-suspension jet intersection [1, 2, 4].

NOTATION

l_a	is the length of the acceleration segment of the channel for the countercurrent jet;
D	is the inside channel diameter;
d_s	is the decisive geometric dimension of the particle;
β_{eff} and β_t	are the effective and true volume concentrations of the disperse material, respectively;
W	is the gas velocity in the channel;
W_s	is the average velocity of the solid phase;
τ, τ_1, and τ_c	are the times needed to pass the intersection zone (150mm), respectively, by the gas flow, the solitary particle, and the gas suspension;
W_f	is the particle free-fall velocity;
Re_f	is the Reynolds number calculated according to W_f and d_s.

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