FEATURES OF APPLICATION OF MULTIPHASE FLOWS IN DEVICES AND TECHNOLOGIES

Aleksey R. Evseev

Kutateladze Institute of Thermophysics, Siberian Branch of the Russian Academy of Sciences, Lavrentiev ave. 1, Novosibirsk, 630090, Russia

Abstract

The main problem of multiphase flow application in devices and technologies is optimization of the processes of fluid flow and heat transfer for the purposes of energy saving and environmental protection. This paper shows the effect of dispersed phase concentration on local characteristics of the two-phase flow. Using the LDA, the data on hydrodynamics in a sedimentation apparatus with inclined walls and distribution of concentration and velocity of sand particles in a gravitational jet were obtained.

Key words: *sedimentation apparatus with the inclined walls, gravitational jet, velocity of particles*

1. INTRODUCTION

The main problem of using the multiphase flows in devices and technologies is optimization of hydrodynamics and heat transfer processes for energy saving and environmental protection. To design the modern technological objects (nuclear reactors with spherical fuel elements, thermal boilers with boiling and circulating fluidized bed, chemical reactors with catalyst, distillation columns, etc.), it is necessary to create and improve the methods for calculating the multiphase dispersed flows that can take into account interaction of particles with turbulence, coagulation and fracture at collision of particles, phase transitions and other phenomena in order to optimize the processes. Due to the complexity of the phenomena, theoretical calculation methods are developed with the use of empirical information to specific flow regimes of the heterogeneous system, and determination of characteristic boundaries between different structural regimes of the mixture flow. Information about the velocity of particles and their concentration is required to analyze the mechanisms of heat and mass transfer processes, the effect of dispersed phase on turbulence of the continuous phase, etc.

Experimental investigation of such flows is associated with considerable difficulties, since new measurement methods need to be developed and applied because highly concentrated dispersed systems are mainly optically non-transparent, and the use of optical methods (LDA, PIV, PTV, etc.) is very limited or impossible.

In general, the joint motion of liquid and particles can be divided into several basic classes: sedimentation, when the particles can move through liquid in the total mass, as it occurs at deposition; filtration, when the particles are immobile in a close-packed layer, and liquid is filtered between them; boiling and circulating fluidized bed, when the relative movements of particles and liquid (gas) can have one or more circulation circuits; and hydrotransport with the transfer of particles by liquid or gas.

The report deals with physical modeling of two-phase flows with high concentration of dispersed phase, and measurement of local characteristics using LDA, fiber-optic sensors and the method of optical homogeneity.

2. SEDIMENTATION IN THE APPARATUS WITH THE INCLINED WALLS

Increasing the efficiency of processes and equipment designed to thicken the fine materials is an important task. The settling tanks of periodic action and continuous thickeners are the required technological equipment for the non-ferrous and ferrous metallurgy used after the flotation process of finely ground ores. The volume of application in deposition of fine materials is tens of millions of tons per year: cryolite (fractions of 10-40 μm) - about 1 million tons per year; pyrite (fractions of 45-250

μm) - about 10 million tons per year. The first material is the raw material for aluminum production, and the second is used for production of sulfuric acid. In the chemical and petroleum industries, the settling tanks and thickeners are used for the following purposes: to separate the liquid phase of suspensions prior to filtration; to wash the sediments by decantation; to catch the valuable or harmful products from wastewater; to separate impurities or large grains at elutriation of disperse systems, etc.

The time of suspension stay in the settler must be equal or greater than the time of particle deposition. For finely dispersed materials, the process of sedimentation under the action of gravity is slow, and it requires large reservoirs, and this is a significant disadvantage. It is shown in (Nakamura & Kuroda 1937, Graham & Lama 1963, Oliver & Jenson 1964, Kapoor & Acrivos 1995, Schneider 1982, Kerr, 2006, AL-kizwini 2015, et al.) that the process of particle deposition in sedimentation apparatus with inclined walls is significantly accelerated (2-3 times) because of the Boycott effect (1920), associated with the generation of convective motion. The review of early works is given in Hill et al. (1977).

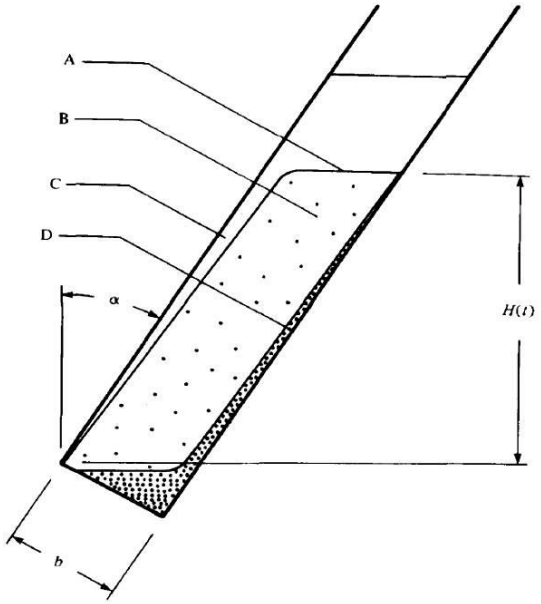


Figure 1. Model of sedimentation apparatus with the inclined walls: A-boundary of suspension, B-suspension, C-layer of pure liquid, D-deposit of solid particles, α-angle of plate inclination, b-distance between the plates, H-height of suspension (Acrivos & Hekbolzheimer 1979).

The scheme of a typical apparatus for depositing a fine material equipped with inclined plates is shown in Fig. 1 (Acrivos & Hekbolzheimer 1979). Here, A is the interface between the pure liquid and the suspension; B is suspension of liquid and particles; D is the deposit of particles on the upward facing surface of the sedimentation apparatus; A is the angle of wall inclination (45-60°), which is chosen from the condition of downward movement of solid particles. Visualization of the process (Rubin & Zahavi 1975, Evseev et al. 1989) showed that an increase in the deposition rate in the presence of inclined planes is associated with formation of a thin layer of light liquid (under the upper plate), which moves upward to unite with the region of light liquid above the suspension; the clear liquid is continuously fed to this thin layer from the suspension.

The mechanism of convective motion in the sedimentation apparatus with inclined walls resembles the phenomenon of thermal-gravitational convection near a heated wall. The convective motion inside the apparatus arises under the action of buoyancy forces, since the density of liquid in the sedimentary boundary layer in zone C is less than the density of suspension in zone B. During the sedimentation process, the dispersed phase (like a piston) squeezes out liquid that flows upwards in zone C (along the path of least resistance). The deposit settles in zone D. The deposit slides down the inclined wall (α =

45-60°) to the bottom of the apparatus and then is removed. The rate of gravitational deposition of particles is summed up with the rate of convective motion, increasing the productivity of apparatus. At b << H, the package of inclined plates inside the apparatus can be more than 10-20, the productivity of thickeners and clarifiers is thereby substantially increased.

To measure the velocity profile in the layer of clarified liquid above the upper wall of inclined channel of the plate sedimentation tank (in zone C and in the border zone D), a laser Doppler anemometer (LDVA-1) with a fiber-optic sensor was used (Lisizin et al. 1980, Evseev et al. 1987).

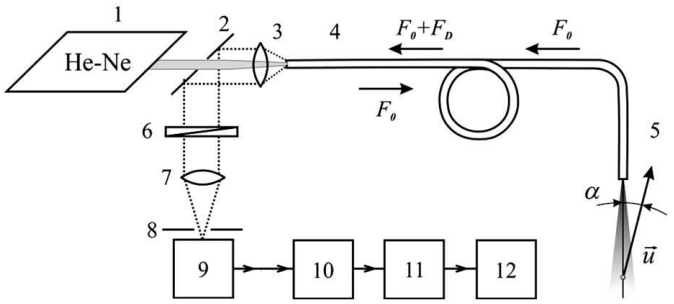


Figure 2. The sheme of the single-fiber LDVA-1 for measuring the particle velocity in the two-phase flows.

Laser beam 1 passes through the hole in mirror 2, installed at an angle to the beam direction, then, it is introduced by micro-objective 3 into optical fiber 4, whose end serves as a sensor (fig. 2). The wave reflected from the output end of the optical fiber, related to the difference in the refractive indices of the quartz fiber and the two-phase medium, acts as the reference beam in the circuit. When the particle approaches the end, the scattered light of the probing radiation partially comes back into the light guide. Together with the reference wave, the radiation scattered by the particle passes through the light guide in the reverse direction and it is directed by micro-objective 3 to the inclined mirror, then to polarization filter 6, whose transmission plane is orthogonal to the plane of laser beam polarization. Lens 7 directs the beams through diaphragm 8 to photodetector 9. The electronic part of the measurement system includes photodetector 9, high and low frequency filter 10, processor for treating the Doppler signals 11, and computer 12.

Investigations on the measurement of the cryolite particles velocity (d_p = 40 μm, ρ_p = 3000 kg / m3) were performed in a device with inclined walls (60°) of 0.15 × 0.1 m^2 section and height of 0.5 m. The weight concentration Φ of cryolite in the experiments was 10, 20 and 30 %. The experiments were carried out in the following sequence. The cryolite suspension in distilled water was thoroughly stirred with a mixer to the uniform state. When the mixer was switched off, the suspension was held in the channel for 3 minutes to decay the vortex motions, then the velocity was measured. The mixing cycle (pause of 3 min. and measurement during 3 min.) was repeated as many times as required. The cryolite particles in suspension formed a bound structure with a distinct interface between suspension and pure liquid at consolidated deposition. The research method is given in (Evseev et al. 1989). The particle velocity was measured in three cross-sections of the boundary layer below the upper wall of the channel at distances X = 55, 100 and 180 mm from its bottom.

The results of measurements are shown in Fig. 3: here, the distance normal to the upper inclined wall is shown along the abscissa, and the average particle velocity, determined by averaging 80-100 measurements is shown along the ordinate axis. When cryolite is deposited, a convective upward flow of clarified liquid is formed under the upper wall of the apparatus in a thin boundary layer (~ 2 mm). At the same time, the rate of cryolite deposition increases by almost 40%. A transition zone of about 4 mm in thickness is observed between the upward flow of clarified liquid and the main flow of depositing particles, where concentration of particles varies from almost zero to the average concentration in the apparatus.

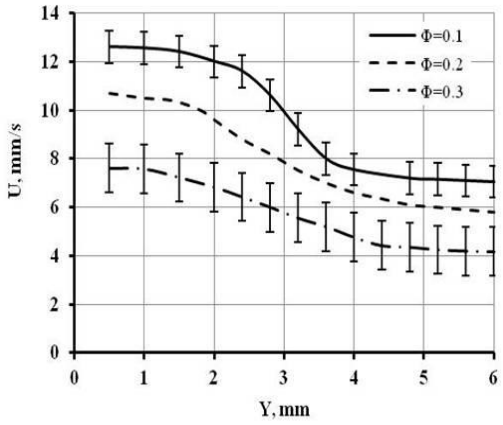


Figure 3. The velocity profiles of cryolite particles ("ceiling" plate) when deposited in the settling apparatus with inclined walls at concentration Φ = 0.1, 0.2, and 0.3.

The maximal velocity is observed at distances of 0.5-2.0 mm from the inclined wall. At these distances, the average velocity is almost constant and is 12-13 mm/s (Φ = 0.1). The minimal particle velocity is in the outer part of the clarified liquid flow. The area of transition from the inner part of the layer of clarified liquid to its outer part is from 2 to 4 mm in all cross-sections. This region is characterized by the maximal change in velocities. All velocity profiles of particles have an inflection point, which indicates the strong vortex flows within the considered layer. Velocity distribution depends essentially on cryolite concentration and under the experimental conditions does not depend on the longitudinal coordinate. With an increase in mass concentration of the solid phase, relative relaxation of particle motion is observed; not only the difference in velocities between the inner and outer parts of the layer decreases, but also the absolute value of velocity in its internal part.

3. INVESTIGATION OF FINE PARTICLES MOTION IN A GRAVITATIONAL JET

Widespread use of gas jets heavily loaded with particles in the modern technologies (coal gasification, atomizing a coal-water slurry, combustion of toxic wastes, etc.) led to intensive investigation of their structure by the modern methods based on the principle of laser Doppler anemometry, PIV and others. The dense layer of particulate material, moving under gravity, is used in the apparatuses of boiling and circulating fluidized bed: riser under the cyclone in CFB, circulation pipelines between the fluidized bed apparatuses, bins above the feeders and chutes beneath them, etc. The granular material structure provides the mobility (flowability) of mixture in a free bulk state under the influence of gravitational forces. The particulate material in the form of gravitational jet, whose characteristics are used to determine the looseness of material, physical studies, calibration measurements and others, flows from a hole in the bottom of the hopper (container).

In previous experiments (for example, Modarress et al. 1984, Tsuji et al. 1988) and theoretical studies (for example, Terekhov & Pakhomov 2011) on the two-phase jets, the influence of dispersed phase on turbulence of the continuous phase, the effects of lacing and turbophoresis of particles, corresponded to a small ratio (1-2) of mass flow rates of phases were studied. In the work (Protasov et al. 2006), the effect of interparticle collisions on the rate of gravitational sedimentation of bidisperse mixture of particles in the air at rest was studied in a tube using LDA.

In our experiments, the jet of sand flowed out of the inner copper cone with a full angle at the apex of 30°, height of 80 mm, hole diameter d = 4.7 mm, and it was collected into a container at a distance of 1.5 m from the hole. The outer cone served as a reservoir for sand with a volume of about two liters. After emptying the outer cone, the sand from the container was periodically returned back to the outer cone. The volume flow rate of sand through the hole in the cone was 2.43 (cm^3/s), and its bulk density

was 1600 kg/m^3. The average diameter of the sand particles was d_p = 0.15 mm, and the density was ρ_p = 2620 kg/m^3.

The axial velocity of particles and their counting concentration were measured with the help of a single-component LDA with the tracking type electronic unit developed at the Institute of Thermophysics SB RAS (Belousov et al. 1989). To distinguish the Doppler signals from the sand particles, the method of amplitude discrimination was used. In the range of dimensionless heights h/d from 5 to 182, the following parameters of the gravitational jet were measured: time-average axial velocity of particles and their RMS pulsations, spectral characteristics of pulsation velocities of particles and their relative (countable) concentration. Mass concentration was calculated using counting concentration of particles by the method developed at the Institute of High Temperatures of the Russian Academy of Sciences (Varaksin et al. 2001). Distribution of probability density of sand particle velocity on the axis of the gravitational jet at h/d = 100 is shown in Fig. 4 as an example.

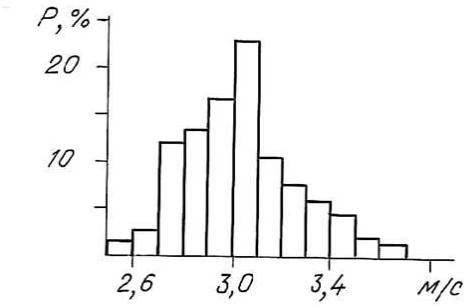
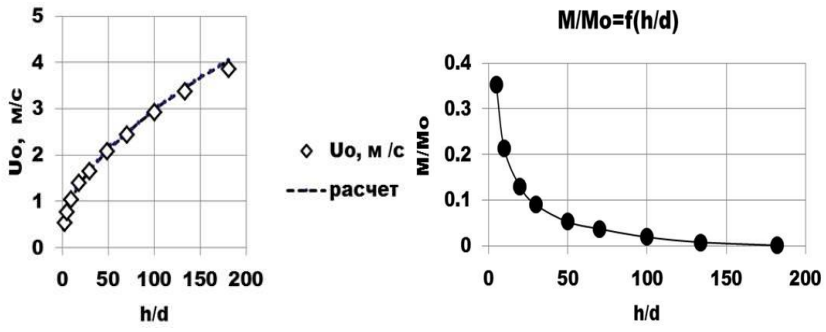


Figure 4. Distribution of probability density of sand particle velocity on the axis of gravitational jet (h/d=100).

Dependence of the average velocity of sand particles on the axis of gravitational jet (U_0) vs. the height (h/d) is shown in Fig. 5a, where calculated dependence U = $(2gh)^{0.5}$, characteristic of the velocity of ideal liquid outflow is shown for comparison by the solid line. The difference between calculated and measured velocities of the sand particles on the jet axis did not exceed 5%. Fig. 5b shows the relative variation of mass concentration of sand particles on the axis of gravitational jet. The mass flow rate concentration of particles at the jet outlet from the hole, determined by the weight method, was taken as a scale. According to the diagram, the mass concentration of particles on the jet axis decreases exponentially with a height increase.



(a) (b)

Figure 5. Dependence of the following parameters on height ((h/d) on the axis of gravitational jet: average velocity of sand particles (a), and relative mass concentration of particles (b).

The dimensionless profile of particle velocity in the near zone of the gravitational jet varies little over the jet cross-section at dimensionless heights h/d from 10 to 30. It can be assumed that in the near zone of the gravitational jet up to height h/d ~ 30, the regime of sand particle motion is close to the dense layer regime. At the periphery of the jet, aerodynamic braking of particles is greater than in the central zone. However, the difference in velocities of particle motion over the jet cross-section is not large and makes up ~ 15%. In the far zone of the gravitational jet at dimensionless heights h/d from 50 to 182, aerodynamic braking of particles at the jet periphery acts more strongly, since the velocities of particles are much higher (at much lower concentration) than in the near zone. Therefore, at the large distances from the cone, the dimensionless profile of average velocity is gradually transformed to the bell-shaped form (Fig. 6), characteristic of jet flows (h/d = 182). Here R is the radius of the aperture in the cone, r is the transverse coordinate.

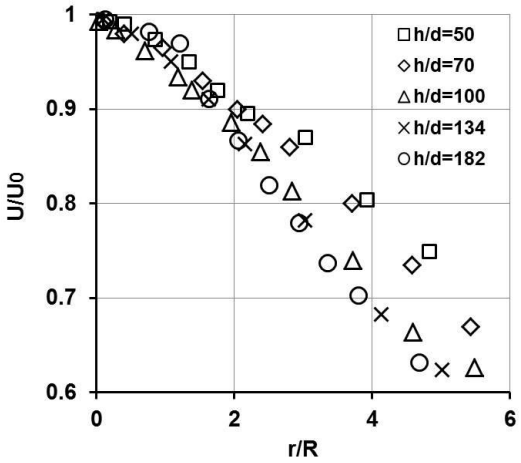


Figure 6. Distribution of relative axial average velocity of particles over the jet cross-section in the range of (h/d) = 50-182.

With an increasing height, the relative level of the rms pulsations of particle velocity decreases from ~ 15% in the near zone (h/d ≤ 30) to ~ (5-7)% in the far zone of the jet, which can be attributed to the region of turbulent motion. The degree of turbulence in the central zone of the jet at h/d> 50 is 5%, and at the periphery of the jet, it increases gradually to 7% (Fig. 7). At such heights, the motion of particles is apparently affected by turbulence in the continuous gas phase.

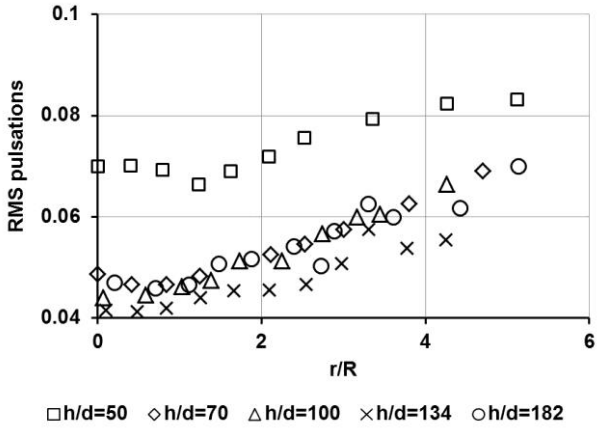


Figure 7. Profiles of RMS pulsations of particle velocity in cross-sections (h/d) = 50-182

The profiles of relative concentration of particles in different jet cross-sections have a bell-shaped form, characteristic of two-phase jets. As the distance from the hole in the cone increases, the relative concentration of particles on the jet axis decreases exponentially. In this case, distribution of particles within a cross-section is equalized, so that the difference between relative concentration in the central zone of the jet and its peripheral part decreases.

A spectral analysis of pulsation motion of sand particles was performed at different points along the jet axis. Measurement results are shown in Fig. 7, where wave number $K = 2\pi f / U_0$ (см$^{-1}$) is plotted along the abscissa axis, and normalized energy spectrum of longitudinal pulsations of particle velocity E is plotted along the ordinate axis. Here, $E = \Phi U_0 / \left(u'^2\right) h \quad \Phi = \left(u'^2\right)_f / \nabla_f$, where f is pulsation frequency (Hz), ∇_f is width of band 1/3 of octave filter, $\left(u'^2\right)_f$ is intensity of particle velocity pulsations in band 1/3 of octave filter, $\left(u'^2\right)$ is intensity of particle velocity pulsations in a wide band., Height h and average velocity of particles on the jet axis U_0 are chosen as characteristic length and velocity scales on the diagram. According to the diagram, the spectral function in the range of wave numbers 10 <K <100 decreases in accordance with the $K^{-5/3}$ dependence, characteristic of isotropic turbulent flows. The obtained experimental data can be used for calibration of fiber-optic sensors, verification of results of numerical simulation of these phenomena, etc.

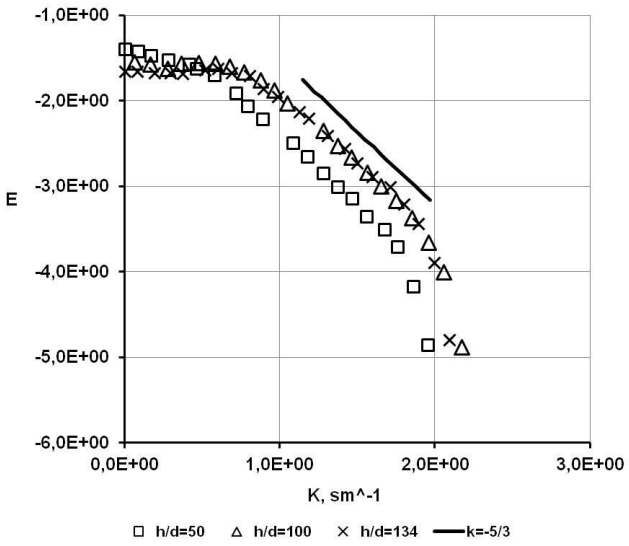


Figure 8. Normalized spectra of pulsation velocities of particles on the axis of a gravitational jet (symbols as in fig. 7).

4. CONCLUSIONS

1. The average velocity profile of particles in the sedimentary boundary layer was measured under the upper inclined wall (60°) during cryolite deposition (10-40 μm) at weight concentration in experiments of 10, 20, and 30 %; the profiles of particle velocity have an inflection point in any cross-section of the boundary layer, which indicates the intense vortex flows within this layer.
2. With an increase in weight concentration of cryolite, the particle velocity in the sedimentary boundary layer decreases; at φ = 0.2-0.3, particle velocity distribution is the function of concentration and it does not depend on the longitudinal coordinate.
3. Visual studies have shown that the vortex flows have a strong influence on distribution of particle in the region of boundary layer output and its connection with the zone of clarified liquid above

the suspension, and in the region of the upward flow under the upper inclined plane at the bottom of the apparatus.

4. The velocity of particles on the axis of the gravitational jet can be calculated by the known formula for the outflow of ideal liquid from the hole, and the difference between measurements and calculation increases with increasing height, but it does not exceed 5% for h/d = 182.
5. The profile of particle velocity in the cross-section of the gravitational jet varies from almost uniform in the near zone (h/d~30) to the bell-shaped jet in the far zone (h/d = 182). The degree of turbulence over the cross-section of the gravitational jet is almost uniform and varies from (10-15)% in the near zone to (5-7)% in the far zone of the jet.
6. In the central zone of the jet, a peculiar dust column is formed, which precesses around the jet axis with increasing height amplitude. The opening angle of the gravitational jet is much smaller than that of an ordinary turbulent jet. As the height increases, the area of the jet cross-section increases, and the gradient of particle concentration decreases.
7. The spectral function of particle velocity pulsations varies slightly with wave numbers $K < 10$. In the range $10 < K < 100$, it decreases in accordance with $K^{-5/3}$ dependence, characteristic of isotropic turbulent flows.

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