Sedimentation dynamics of a polydisperse cluster of solid particles in a viscous fluid

V A Arkhipov, S A Basalaev, N N Zolotorev, K G Perfilieva and A S Usanina

National Research Tomsk State University, 36 Lenina Avenue, Tomsk 634050
Russian Federation

E-mail: k.g.perfiljeva@yandex.ru

Abstract. Methods and results of experimental studies of the gravitational sedimentation of a consolidated polydisperse system of solid spherical particles in a viscous fluid are presented. The overall picture of motion of the consolidated system of bi-disperse solid spherical particles is obtained. The motion regularities (the cloud evolution, sedimentation rate, and drag coefficient) of a set of solid spherical particles under various flow regimes are investigated. The gravitational sedimentation of monodisperse and bi-disperse consolidated systems of spherical particles in the viscous fluid is compared.

1. Introduction

The motion regularities of a consolidated dispersed system of particles are among the fundamental problems of classical hydrodynamics of two-phase flows [1]. Interest in the problem of the motion of a concentrated particle cloud is associated with a wide range of applications of the results obtained. The processes of gravitational sedimentation of the cloud particle are of practical importance in environmental problems (cleaning of water bodies from pollution), in coal industry (water suppression of dust in coal mines), in heat-and-power engineering (combustion of sprayed fuels), in chemical technology (precipitation columns), and in a number of other branches of engineering and technology [2].

The process of sedimentation of a cluster of solid particles in a field of gravity depends on a number of parameters, such as the size and shape of particles, the physicochemical properties of the fluid and solid particles, the initial concentration of particles in the cloud, and the motion regime [3]. The method of incorporation of particles into the fluid also affects the regularities of particle sedimentation.

In [4], a setup and method for studying the sedimentation of the monodisperse cluster of solid particles in a viscous fluid were proposed. The method was based on the incorporation of the monodisperse set of solid particles into the fluid according to two methods, which provide the particle motion in the regimes of a blown, non-blown, and partially blown cloud. In the present work, a modified method for studying the gravitational sedimentation of a polydisperse cluster of solid particles in the viscous fluid is presented [5].

2. Block diagram of the experimental setup

To study the gravitational sedimentation of a polydisperse cluster of solid particles, an experimental setup shown in figure 1 was used.
Figure 1. Block diagram of the setup used for studying the particle cloud sedimentation comprising fixed hemispherical shell 1; movable hemispherical shell 2; particles 3; axis 4; bearings 5; cell 6; viscous fluid 7; nozzle 8; valve 9; water tank 10; drain tube 11; generator 12; tank 13 with the viscous fluid; valve 14; nozzle 15; and video camera 16.

The instrument operates as follows. The container consisting of the fixed 1 and movable 2 waterproof hemispherical shells is used. The polydisperse portion of solid spherical particles 3 is introduced into the container. The movable shell is rigidly connected to the axis 4 installed in bearings 5 and can be rotated. After filling the container with particles, it is closed by rotating the shell and placed into the cell 6 with the viscous fluid 7. Water is introduced from the tank 10 through the nozzle 8 with the valve 9. When the container is filled completely, the excess water is substituted through the drain tube 11. Particles are mixed with water in the container upon the exposure to ultrasonic vibration from the UZGM-10-22MS generator 12. Mixing particles with water provides uniform distribution of polydisperse particle cluster in the cavity of the spherical container, since the low dynamic viscosity coefficient of water allows the mixing process to be intensified by ultrasonic vibration. Water is substituted gradually during mixing over a period of (3÷5) minutes by viscous fluid introduced into the container from tank 13 through valve 14 and nozzle 15. Gradual substitution of water from the container by the viscous fluid provides maintaining of the uniform particle distribution in the container cavity until complete substitution of water by the fluid with the dynamic viscosity coefficient corresponding to the viscosity of the fluid in the cell. The particle mobility decreases with increasing viscosity of the fluid in the container, which contributes to maintaining a uniform distribution of particles. Excess viscous fluid is substituted from the container through the drain tube. After complete substitution of
water by the viscous fluid, the container is opened by 180 degree rotating the movable shell. Wherein, the spherical cloud of particles began to precipitate in the cell with the fluid.

The particle cloud sedimentation is visualized using shooting through transparent cell walls with two Citius C 100 high-speed digital video cameras 16 in two views with a shooting rate of (50÷100) frames per second. Video is processed using a computer receiving the information from the cameras.

3. Experimental results

To study the gravitational sedimentation of steel balls \( \rho_p = 7748 \text{ kg/m}^3 \) in the size range \( D_p = (1÷3) \text{ mm} \), more than 300 series of experiments were performed. PMS-10000 silicone oil \( (\rho_l = 979 \text{ kg/m}^3, \mu_l = 10.84 \text{ Pa} \cdot \text{s}) \) was used as a viscous fluid.

The container opening time was chosen based on the condition of minimum cloud deformation during the opening period. The distance traveled by the particle during sedimentation over time \( \tau_2 \) is

\[
\Delta l = u \cdot \tau_2,
\]

where \( u \) is the particle sedimentation rate.

Let us formulate the condition of minimum cloud deformation as inequality

\[
\Delta l \leq 0.025 D_c,
\]

where \( \Delta l \) is the cloud boundary displacement due to the particle sedimentation and \( D_c \) is the container diameter.

Condition (2) means that the cloud boundary displacement \( \Delta l \) does not exceed 2.5% of its diameter.

In the viscous fluid, the stationary sedimentation rate of a single particle is defined as follows [6]:

\[
u = \frac{(\rho_p - \rho_l) D_{\text{max}}^2}{18 \mu_l} g,
\]

where \( \rho_p \) is the particle material density; \( \rho_l \) is the fluid density; \( D_{\text{max}} \) is the diameter of the largest particle in the cloud; and \( \mu_l \) is the dynamic viscosity coefficient of the fluid; and \( g \) is the acceleration of gravity.

The condition for determining the container opening time

\[
\tau_2 \leq \frac{0.45 D_c \mu_l}{(\rho_p - \rho_l) D_{\text{max}}^2 g}.
\]

can be obtained after substitution of equation (3) into equations (1) and (2).

The initial volume concentration of particles in the container is defined by the formula

\[
C_0 = \frac{V_p}{V_c},
\]

where \( V_p = \frac{\pi}{6} \sum_{i=1}^{n} N_i D_i^3 \) is the total volume of particles and \( V_c = \frac{\pi D_c^3}{6} \) is the container volume.

The initial concentration of particles can be varied in a wide range by changing the container diameter \( D_c \), the number \( n \) of particle fractions, and the diameter \( D_i \) and number \( N_i \) of particles of each of the fractions.

Video frames of gravitational sedimentation of the bi-disperse system of solid spherical particles (balls with \( D_1 = 1 \text{ mm} \); \( N_1 = 35 \); \( D_2 = 3 \text{ mm} \); \( N_2 = 35 \)) with the initial volume particle concentration \( C_0 = 0.28 \) from the container with a diameter \( D_c = 15 \text{ mm} \) are shown in figure 2.
Figure 2. Video frames of gravitational sedimentation of the bi-disperse system of solid spherical particles.

Analysis of the results of the sedimentation visualization has shown that motion of the consolidated system of bi-disperse particle systems is similar to the motion of the monodisperse cluster [4]. The gravitational sedimentation can be also divided into four stages: the sphere motion, the spheroid formation and motion, the spheroid deformation, and the spheroid decay. In most of the performed experiments, the fourth stage of motion of a group of particles occurred immediately after the spheroid formation and motion.

According to the results of the experiments, the main differences between the motion of the polydisperse particle cluster and the monodisperse one were analyzed. It was established that the decay stage of the polydisperse particle spheroid was delayed in time as compared with the monodisperse system depending on the percentage ratio of particles with different diameters. This is due to the fact that fine particles contribute to maintaining the integrity of the entire spheroid. The substitution of fine particles from the consolidated polydisperse particle system during the stage of formation and motion of the spheroid and the stage of deformation of the spheroid was noted. Duration of each stage of the cluster deformation increases with increasing the fluid viscosity and decreasing the density and mean particle diameter in the polydisperse cluster.

In regimes of non-blown and partially blown cloud, the sedimentation of the spherical particle cloud can be considered as the sedimentation of the sphere with a diameter $D_s$, whose density $\rho_s$ is defined by the equation

$$\rho_s = \rho \frac{1}{D_s}$$
\[
\rho_s = \frac{\rho_p \left(NV_p\right) + \rho_l \left(V_s - NV_p\right)}{V_s} = C_0 \left(\rho_p - \rho_l\right) + \rho_l,
\]

(6)

where \(N\) is the number of particles in the cloud and \(V_s = \pi D^3/6\) is the volume of the particle cloud.

The equation of motion of the sphere can be represented as

\[
\rho_s V_s \frac{du_s}{dt} = V_s \left(\rho_s - \rho_l\right) g - C_D S_M \frac{\rho_l u_s^2}{2},
\]

(7)

where \(u_s\) is the sedimentation rate of the particle cloud; \(g\) is the acceleration of gravity; \(C_0\) is the particle cloud drag coefficient; \(S_M = \pi D^2/4\) is the area of the cloud midsection. In the stationary regime (\(du_s/dt = 0\)), the formula defining the drag coefficient

\[
C_D = \frac{2V_s \left(\rho_s - \rho_l\right) g}{S_M \rho_l u_s^2},
\]

(8)

follows from equation (7).

Taking into account the ratio for the density of the particle cloud (6), the formula (8) takes the form

\[
C_D = \frac{4}{3} \cdot \frac{gD_s}{\rho_l u_s^2} C_0 \left(\rho_p - \rho_l\right),
\]

(9)

The drag coefficient is determined from the experimentally measured values of the parameters in (9).

Regression analysis of the experimental data on the drag coefficient \(C_D\) of the particle cloud showed that the highest determination coefficient was obtained for the dependence of \(C_D\) on the dimensionless complex \(\Pi = Re_s \cdot C_0\). The dependence for the drag coefficient of a set of particles moving in partially blown cloud regimes can be represented as an empirical formula (the determination coefficient \(R^2 = 0.93\))

\[
C_D = 13.5 \left(Re_s \cdot C_0\right)^{-0.9},
\]

where \(Re_s = \frac{\rho_l u_s D_s}{\mu_s}\).

From the analysis it follows that the drag coefficient of the aggregate of solid spherical particles increases in the range \(C_D = 6 \pm 8000\) with decreasing the dimensionless complex in the range \(\Pi = 1.1 \pm 8.1 \cdot 10^{-4}\).

We note that the drag coefficients are obtained under the assumption that the cloud size, shape, and speed are constant during the sedimentation. Analysis of the effect of the expansion and change of the cloud shape on the sedimentation characteristics, in particular, on the sedimentation rate, will allow the obtained dependence for the drag coefficient to be clarified.
Conclusion
A modified method for studying the gravitational sedimentation of the polydisperse cluster of solid particles in the viscous fluid was presented.

Video frames of gravitational sedimentation of the bi-disperse system of solid spherical particles were obtained.

A comparative analysis of the results of experiments on studying the sedimentation of polydisperse and monodisperse particle system was performed.

It was shown that motion of the consolidated polydisperse system of solid spherical particles was similar to the motion of the monodisperse cluster of particles.

It was established that the decay stage of the polydisperse particle spheroid was delayed in time compared with the monodisperse system depending on the percentage ratio of particles with different diameters.

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References
[1] Brounstein B I 1977 *Hydrodynamics, mass and heat transfer in disperse systems* (Leningrad: Chemistry) p 279 [in Russian]
[2] Romankov P G and Kurochkina M I 1982 *Hydromechanical processes in chemical technology* (Leningrad: Chemistry) p 288 [in Russian]
[3] Khorguani V G 1966 *AS USSR. Atmosphere and ocean physics* 2 (4) 394–401
[4] Arkhipov V A and Usanina A S 2017 *Fluid Dynamics* 52 (5) 666–77
[5] Arkhipov V A, Basalaev S A, Perfilieva K G and Maslov E A 2018 *Method of studying the sedimentation of a spherical polydisperse cloud of solid particles in a viscous fluid* Application on Patent RU 2018142185 [in Russian]
[6] Arkhipov V A and Usanina A S 2014 *Motion of Dispersed-Phase Particles in a Carrier Medium: a Textbook* (Tomsk: Publishing house TSU) p 252 [in Russian]