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Settling dynamics of a cluster of monodispersed drops

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The results of an experimental study of the gravitational settling dynamics of a cluster of monodispersed drops are presented. A new method is proposed for obtaining a cloud of monodispersed drops with regulated values of their size and volume concentration.The qualitative picture of the deformation of the initial spherical cluster into a prolate spheroid in the process of settling and the velocity settling of the center of mass of the cluster are determined.

Keywords: Cluster of monodispersed drops, volume concentration, gravitational settling, cluster deformation, velocity settling.

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A number of processes in nature and various engineering applications involve the formation of a liquid-drop aerosol cloud and its evolution in the course of gravitational settling. Examples of this include the production of precipitation from thunderstorm clouds, spread of toxic components of the security fuel load in separation of spent stages of liquid-propellant rockets, emergency aviation fuel discharge, and discharge of water into a body of fire from a plane or a helicopter fitted with specialized gate systems.

Experimental quantitative data on the variation of shape and velocity of settling of a drop cluster in the course of its gravitational settling are needed in order to evaluate the efficiency of mathematical models of these processes [1–3].

The determination of particle concentration values at the boundaries between settling regimes („impermeable", „partially permeable," and „permeable" clouds [4]) is one of the key issues in simulation of the motion of a drop cluster. Published data do not allow one to estimate unambiguously the boundary values of drop concentration in a cluster, since the results obtained in different studies vary widely [4–6].

In the present study, the procedure and results of investigation of the effect of the initial volume concentration of drops on the velocity of settling of a cluster in free fall in the atmosphere are reported.

The scheme of the experimental setup [7] with support *1* and supply vessel *2*, which contains the studied liquid, secured to it is shown in Fig. 1, *a*. A total of 60 coaxial capillaries *3* are positioned vertically in the lower part of vessel *2*. The upper part of supply vessel *2* is connected to electropneumatic valve *4* and compression micropump *5*. Electropneumatic valve *4* is connected to the lower part of tank *6* with the studied liquid. The upper part of tank *6* with the studied liquid is connected to compressed air cylinder *7*. Pressure gage *8* is used to monitor the pressure in tank *6*. Compression micropump *5* is connected to the liquid supply system via back valve *9*. Control system *10* with a voltage generator ensures actuation of electropneumatic valve *4* and compression micropump *5* in accordance with the experimental program. Drop cluster visualization system *11* includes video camera *12* (Nikon D600), which records the initial position of a formed cluster, and two machine vision cameras *13* (MER2-502-79U3C) for recording the evolution of this cluster in the course of its settling.

In experiments, compressed air from cylinder *7* was fed into tank *6* with the studied liquid. When electropneumatic valve *4* was open, the examined liquid entered supply vessel *2*. Stable identical drops (Fig. 1, *b*) formed in this case at the tips of capillaries *3*. With electropneumatic valve *4* closed, compression micropump *5* produced pressure pulse p_1, which induced stable separation of the entire drop cluster from capillaries, in vessel *2* (Fig. 1, *c*). Drop separation pressure p_1 was determined experimentally.

Medical needles of different gauges (21G–30G) were used to alter the drop diameter within the $D = 1.8-2.6$ mm range. Two methods for experimental determination of the size of an individual drop (video recording of a sedimenting drop and weighing [8]) were used. When the weighing method was applied, a receiving tank (not shown in Fig. 1, *a*) was mounted additionally on electronic scales. The diameter of a spherical drop was calculated in this case in accordance with the following formula:

$$D = \sqrt[3]{6M/(\pi\rho_l N)}, \qquad (1)$$

where M is the total mass of N drops measured by weighing and ρ_l is the liquid density. The spread of drop diameter values determined using the above two methods did not exceed 1%. The error of determination of the size of a cluster and the velocity of settling of its center of mass did not exceed 4%.

The following drop settling equation was solved numerically to perform a comparative analysis of the velocities of settling of a drop cluster and an individual drop:

$$m\frac{du}{dt} = mg - C_D(\mathrm{Re})\frac{\pi D^2}{4}\frac{\rho u^2}{2}. \qquad (2)$$

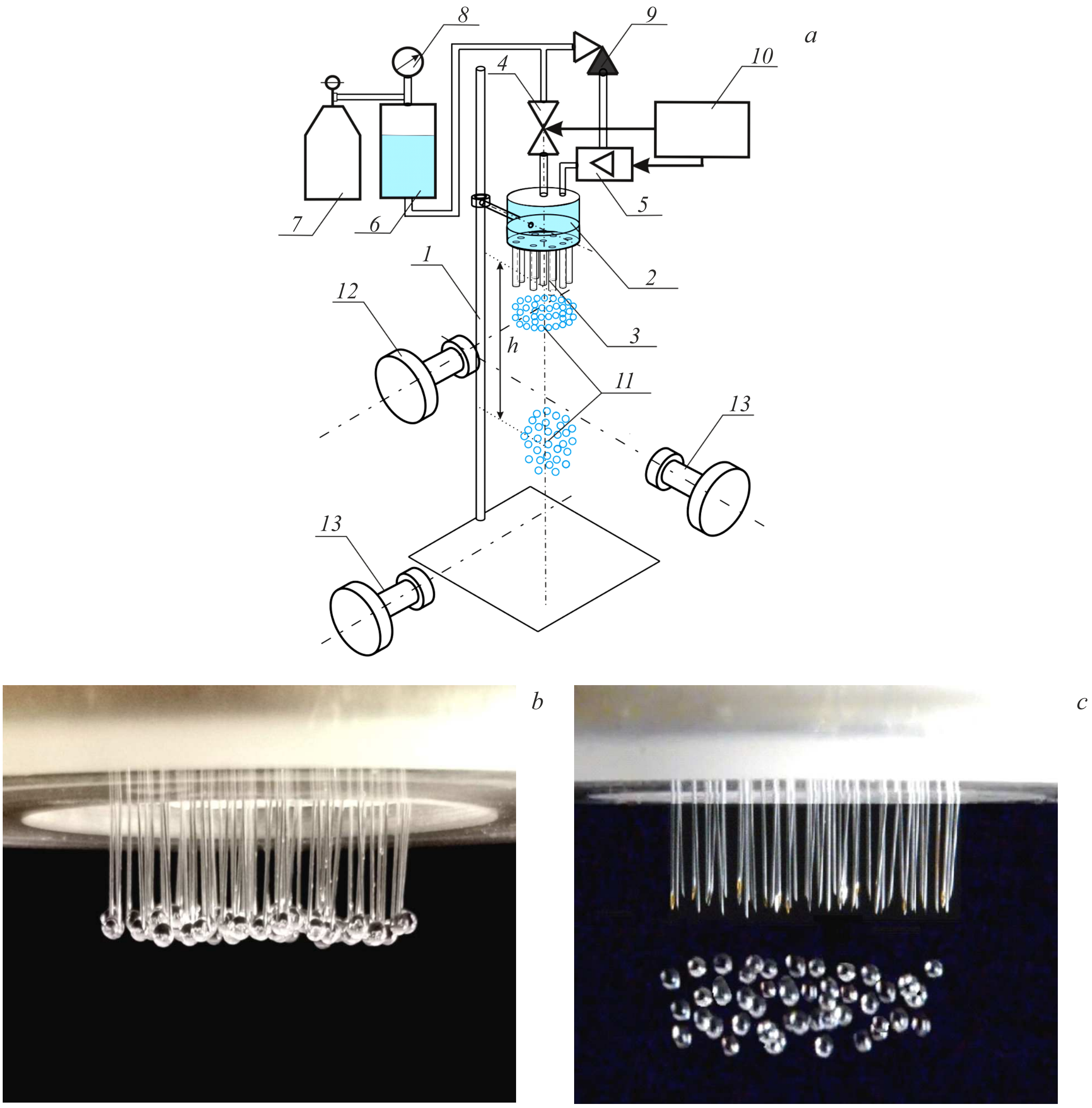

Figure 1. Diagram of the experimental setup for examination of the settling dynamics of a cluster of monodispersed drops (a) and photographs of drops formed at the tips of capillaries (b) and the forming drop cluster (c).

Here, m and u are the mass and the velocity of settling of a drop, g is the gravitational acceleration, ρ is the air density, and $C_D(\mathrm{Re})$ is the dependence of the drag coefficient [9,10] on Reynolds number $\mathrm{Re} = \rho u D/\mu$, where μ is the dynamic viscosity of air,

$$C_D(\mathrm{Re}) = \begin{Bmatrix} \frac{24}{\mathrm{Re}}, & \mathrm{Re} < 0.3 \\ \frac{24}{\mathrm{Re}}(1 + 0.189\mathrm{Re}^{2/3}), & 0.3 \leqslant \mathrm{Re} \leqslant 700 \\ 0.44, & \mathrm{Re} > 700 \end{Bmatrix}.$$

In addition to calculations, measurements of the velocity of settling of an individual drop were performed via visualization. Distilled water was the liquid studied in experiments. Caps were put on a fraction of capillaries in order to examine the influence of drop concentration on the cluster settling dynamics. The number of drops in a cluster and the initial distance between their centers were varied in these experiments.

Figure 2 presents a qualitative picture of evolution of the shape of a monodispersed drop cluster in the course of its settling. The diameter of drops in a cluster was $D = 2.3$ mm, and the distance between neighboring capillaries was $l_0 = 3.4$ mm. Distance h travelled by a cluster was measured from the tips of capillaries to its center of mass (Fig. 1, a). It follows from Fig. 2 that a drop cluster undergoes deformation in the process of settling: a plane drop layer transforms, in sequence, into a cylinder, a sphere, and a prolate spheroid with axes a and b (Fig. 2). The characteristic dimensions of a drop cluster varied along its trajectory of motion to distance $h = 1.8\,\mathrm{m}$ in the following way. At height $h \approx 0.1\,\mathrm{m}$, a spherical cluster with a diameter of approximately 40 mm formed. Characteristic cluster size a increased monotonically in the course of settling from 40 mm to a stationary value of 140 mm; at distance $h \approx 1.0\,\mathrm{m}$, a further increase in a was observed. Cluster height b increased monotonically from 40 to 355 mm.

The cluster expanded in volume in the process; consequently, the mean distance between drop centers in a cluster also increased: $l \geqslant l_0$. Let us analyze the mechanism of cluster expansion by examining the dependence of dimensionless parameter $k = l/D$ on distance h (Fig. 3, a). Volume concentration C of drops in a cluster decreases when this cluster expands in volume in the process of settling:

$$C = nV/V_c, \tag{3}$$

where n is the number of drops, $V = \pi D^3/6$ is the drop volume, and $V_c = \pi a^2 b/6$ is the cluster volume.

The relation for determining the increase in mean distance between drop centers in a cluster in the course of settling may be derived from the expression relating mean distance l between the centers of neighboring particles to the volume concentration of spherical particles [11]:

$$l = D\sqrt[3]{\pi/6C}. \tag{4}$$

Note that the pattern of variation of characteristic cluster size a in the process of settling is similar to the variation of parameter k with h (Fig. 3, a). This type of dependence $k(h)$ is apparently induced by the dynamics of variation of distance l between drop centers and, consequently, by the change in volume concentration of drops that depends on the cluster volume. Since the cluster shape is that of a prolate spheroid, its volume is proportional to the square of horizontal axis length (characteristic size a), and the variation of this axis length in the course of settling exerts a significant influence on the cluster volume. This effect may be associated with the dominant influence of the velocity of a sedimenting cluster on its midsection area $S_m = \pi a^2/4$.

Figure 3, b presents the dependences of velocity of settling $u(h)$ of a drop cluster ($D = 2.3\,\mathrm{mm}$) at different values of parameter k and the variation of velocity of settling of an individual drop with the same diameter calculated in accordance with Eq. (2).

It can be seen from Fig. 3, b that the velocity of settling of the center of mass of a cluster with the dimensionless parameter value set initially to $k = 1.5$ exceeds the velocity of motion of an individual drop („partially permeable“ cloud regime). As the initial value of parameter k increases, the motion velocity of the center of mass of a cluster decreases; at $k = 3.0$, it becomes virtually equal to the velocity of motion of an individual drop („permeable“ cloud regime). The calculated values of the mean distance between centers of drops and their initial volume concentration C_0 are $l = l_0 = 3.4\,\mathrm{mm}$, $C_0 = 0.23$ at $k = 1.5$ and $l = 6.6\,\mathrm{mm}$, $C_0 = 0.13$ at $k = 3.0$. It should be noted that initial drop concentration C_0 was calculated for a plane layer of drops formed at the tips of capillaries. In the event of drop separation and formation of a cluster, the concentration of drops in it decreases abruptly at distance $h = 5\,\mathrm{cm}$; past this point, the drop concentration decreases monotonically and smoothly.

Thus, a qualitative picture of deformation of a compact monodispersed drop cluster in the process of gravitational

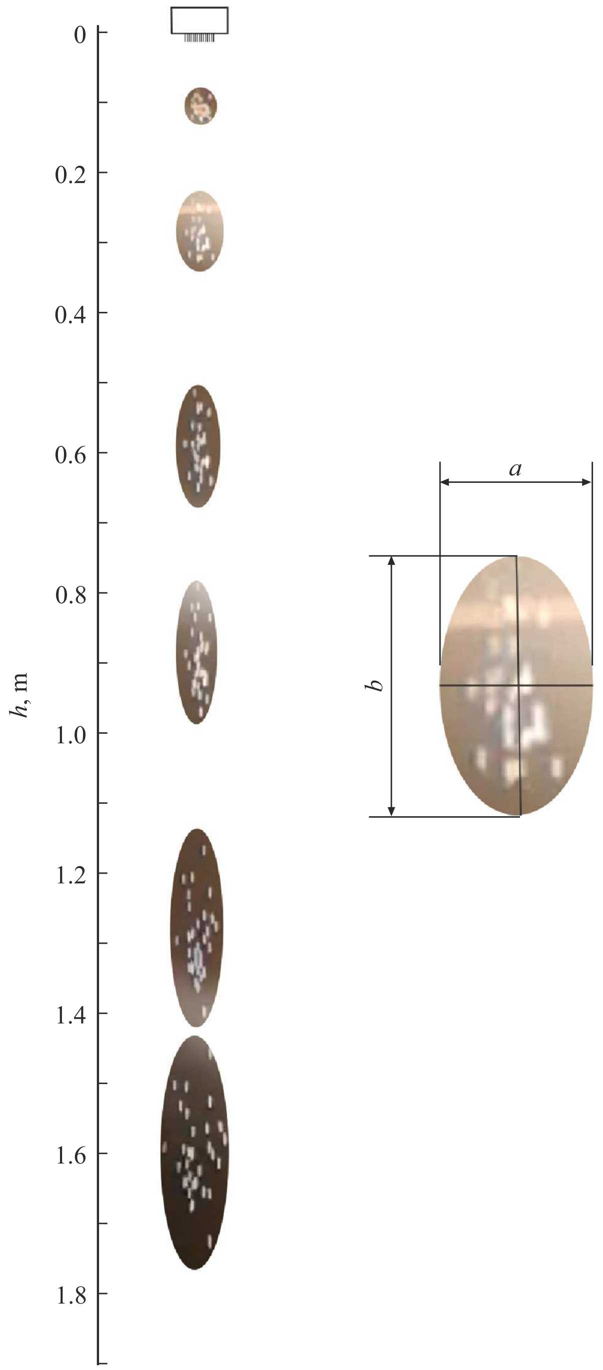

Figure 2. Video sequence visualizing the process of gravitational settling of a monodispersed drop cluster ($D = 2.3\,\mathrm{mm}$).

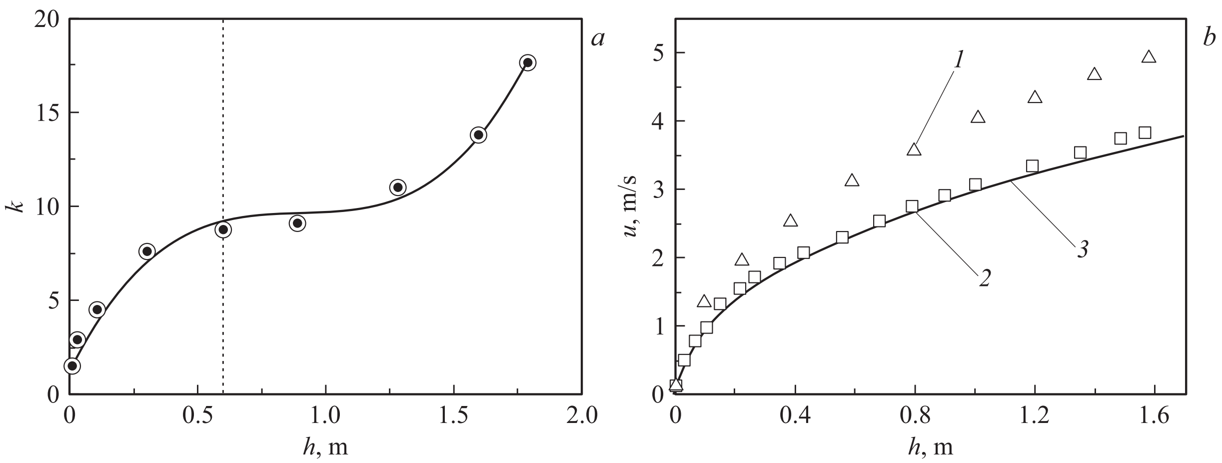

Figure 3. Dependences of parameter k (a) and the velocity of settling (b) on distance travelled. *1* — velocity of the center of mass of a cluster ($k = 1.5$), *2* — velocity of the center of mass of a cluster ($k = 3.0$), and *3* — velocity of settling of an individual drop ($D = 2.3\,\mathrm{mm}$).

settling was established based on experimental data. The dependence of the settling velocity of the center of mass of a cluster on the initial drop concentration was determined. It was demonstrated that the dependence of the settling velocity of the center of mass of a cluster on the distance travelled gets closer to the corresponding dependence for an individual drop as the drop concentration in a cluster decreases.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] V.A. Arkhipov, S.A. Basalaev, O.V. Matvienko, K.G. Perfil'eva, A.S. Usanina, *Generatsiya i evolyutsiya zhidko-kapel'nogo aerozol'nogo oblaka v pole sily tyazhesti* (Izd. Tomsk. Univ., Tomsk, 2022) (in Russian).

[2] O.V. Vysokomornaya, G.V. Kuznetsov, P.A. Strizhak, *Isparenie i transformatsiya kapel' i bol'shikh massivov zhidkosti pri dvizhenii cherez vysokotemperaturnye gazy* (Izd. Sib. Otd. Ross. Akad. Nauk, Novosibirsk, 2016) (in Russian).

[3] V.I. Terekhov, M.A. Pakhomov, *Teplomassoperenos i gidrodinamika v gazokapel'nykh potokakh* (Izd. Novosib. Gos. Tekh. Univ., Novosibirsk, 2008) (in Russian).

[4] V.G. Khorguani, Kh.M. Kalov, Izv. Akad. Nauk SSSR. Fiz. Atmos. Okeana, **11** (3), 278 (1975) (in Russian).

[5] S. Soo, *Fluid Dynamics of Multiphase Systems* (Blaisdell, 1967).

[6] I.M. Vasenin, N.N. D'yachenko, K.E. Elkin, R.K. Narimanov, J. Appl. Mech. Tech. Phys., **45** (6), 788 (2004). DOI: 10.1023/B:JAMT.0000046025.09468.9a.

[7] V.A. Arkhipov, S.A. Basalaev, N.N. Zolotorev, S.N. Polenchuk, V.I. Romandin, K.G. Perfil'eva, A.S. Usanina, *Sposob polucheniya kompaktnogo klastera monodispersnykh kapel' zadannogo razmera*, RF Patent No. 2795373 published on May 3, 2023 (in Russian). https://www1.fips.ru/ofpstorage/Doc/IZPM/RUNWC1/000/000/002/795/373/%D0%98%D0%97-02795373-00001/docment.pdf

[8] V.A. Arkhipov, S.A. Basalaev, A.I. Konovalenko, K.G. Perfil'eva, Tech. Phys. Lett., **46** (6), 610 (2020). DOI: 10.1134/S1063785020060176.

[9] R.I. Nigmatulin, *Dinamika mnogofaznykh sred* (Nauka, M., 1987), Vol. 1 (in Russian).

[10] G.I. Kelbaliyev, Theor Found Chem. Eng., **45** (3), 248 (2011). DOI: 10.1134/S0040579511020084.

[11] J.H. Conway, N.J.A. Sloane, *Sphere packings, lattices and groups* (Springer, N.Y., 1988). DOI: 10.1007/978-1-4757-2016-7.

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