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Settling and evaporation of a cloud of bidispersed drops in heated air

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The results of an experimental study of the dynamics of gravitational settling and evaporation of cloud of the bidispersed drops in heated air are presented. The qualitative picture of the cloud settling and the its evaporation characteristics in the temperature range 473–633 K was obtained. A comparison with the characteristics of settling and evaporation of single drops was made. The sizes of single drops correspond to the ones of the drops from the cloud.

Keywords: cloud of bidispersed drops, gravitational settling, heated air, evaporation velocity, experimental study.

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The study of the characteristics of settling and evaporation of a cloud of drops with controlled values of their sizes and volume concentration is of interest in experiments into the interaction of drops during collisions [1], evaporation in a high-temperature medium [2], and other physical processes characterizing the motion of gas-droplet media. The majority of published papers on the characteristics of motion and evaporation are focused on single drops, streams of successively moving drops, or clouds of polydispersed drops forming when liquid is atomized by nozzles [3–5]. The results of experimental studies into the patterns of motion and evaporation of a bidispersed cloud of drops provide a detailed insight into the mechanisms of individual „elementary" processes and allow one to evaluate the validity of models characterizing them and, consequently, enhance the reliability of developed physical and mathematical models and computer codes for calculation of two-phase flows with deformable particles of a dispersed phase [1].

In the present study, we report on the procedure and results of an experimental study of the patterns of settling and evaporation of a cloud of bidispersed drops in free fall in heated air.

A setup including a device for producing a cloud of bidispersed drops, a heater, and equipment for visualizing the settling process and measuring the drop mass was used in experiments. The device for production of drops [6] features two cylindrical chambers with working liquid that are separated by a partition. It allows one to form two horizontal drop layers via two sets of capillaries (Vogt Medical injection needles) of different diameters that are distributed evenly on the bottom covers of the chambers.

In the course of experiments, the excess pressure in each of chamber was raised slowly to the levels of Δp_1, Δp_2 providing a given time for drop formation during liquid flow through the capillaries; when stable drops formed at the ends of capillaries, the pressure in the chambers was reset to zero. Pressure pulses were induced to ensure simultaneous separation of drops of each layer from the capillaries in the chambers.

The Tate formula was used to calculate the diameters of capillaries that ensure the production of drops of given diameters $D_i (i = 1, 2)$ [7]:

$$d_i = \frac{\rho g D_i^3}{3.6\sigma}, \tag{1}$$

where d_i is the internal (for non-wetting liquids) or external (for wetting liquids) diameter of the capillary; ρ, σ are the density and the surface tension coefficient of liquid; and g is the gravitational acceleration.

The mass flow rates providing a given drop formation time were calculated in advance to determine the values of Δp_1 and Δp_2:

$$G_i = \frac{m_i}{t_i}, \tag{2}$$

where m_i is the mass of drops with diameter D_i and t_i is the time of drop formation at the end of the capillary.

The value of $t_i = 50\,\mathrm{s}$ was chosen according to the criterion of zero disturbing influences exerted on a drop during its slow formation from liquid entering through the capillary. According to [7], the deviation of the measured diameter of a forming drop from the one calculated using the Tate formula does not exceed 0.5% at formation time $t_i \sim 1$ min.

Volumetric flow rate of liquid Q through the capillary is specified by the Poiseuille formula [8]:

$$Q = \frac{\pi r^4 \Delta p}{8\mu l}, \tag{3}$$

where r is the internal capillary radius, μ is the coefficient of dynamic viscosity of liquid, and l is the capillary length.

Mass flow rate of liquid G through the capillary is given by the formula

$$G = \rho Q = \rho \frac{\pi r^4 \Delta p}{8\mu l} = \frac{\rho S^2 \Delta p}{8\pi\mu l}, \tag{4}$$

where S is the cross-sectional area of the capillary channel.

The relation for Δp_i follows from (4):

$$\Delta p_i = \frac{8\pi\mu l_i}{\rho S_i^2} G = \frac{8\pi\mu l_i}{\rho S_i^2} \frac{m_i}{t_i}. \quad (5)$$

The values of amplitude $P_i \geqslant 10\Delta p_i$ and duration $\Delta t_i = 70$ ms of pressure pulses for each chamber ensuring stable and simultaneous separation of each layer of drops were determined in the course of test experiments.

A setup similar to the one discussed in [9] was used to determine the patterns of evaporation of a cloud of bidispersed drops in heated air. A heater consisting of a ceramic tube with an internal diameter of 250 mm and a height of 1 m was positioned in the cluster settling region. Wire nichrome spirals connected to a power source were mounted on the inner surface of the heater. Thermal insulation was provided by thin sheet steel covering the outer surface of the heater; asbestos gaskets were installed at the heater inlet and outlet. A receiving container mounted on a VK-150.1 analytical laboratory balance with an error of ± 10 mg was positioned in the lower part of the setup.

The equipment for visualizing the process of drop cloud settling and measuring its settling velocity included two high-speed MER2-502-79U3C video cameras with a framing rate of 450 fps installed at different distances from the region under study. One of the cameras had a shooting field of 10×10 cm that allowed us to estimate the size of drops. The other camera was focused on the region of drop cloud settling and was used to determine experimentally the settling velocity of the center of mass of monodispersed drop clusters via frame-by-frame processing of video records in CorelDRAW with an error of $\sim 4\%$.

This setup was used to perform a series of experiments into the dynamics of settling and evaporation of a cluster of bidispersed drops of distilled water. Droplets of controlled sizes $D_1 = 2.9$ mm, $D_2 = 3.7$ mm were formed using 21G and 16G medical injection needles, respectively.

The dynamics of settling and the characteristics of evaporation of single drops with their diameters corresponding to the examined bidispersed cloud were studied for comparative analysis. The sizes and evaporation characteristics of single drops were determined experimentally by measuring the mass of 200−300 identical drops that passed through the heater at a given temperature. The velocity of single drops and the dependence of the distance traveled on time were found by solving the drop settling equation numerically [9].

Figure 1 presents a qualitative pattern of formation and gravitational settling of a bidispersed cloud of drops at different distances x from the lower layer of drops (plane $B-B$ in Fig. 1). It follows from Fig. 1 that two layers of monodispersed drops form in planes $A-A$ and $B-B$ at the initial moment of time (Fig. 1, *a*). Following separation of drops from the capillaries, a cloud of bidispersed drops forms at distance $x \approx 1.5$ cm (Fig. 1, *b*), which starts to stratify into two separate monodispersed clusters at distance $x \approx 5.0$ cm (Fig. 1, *c*). When the cloud is divided into

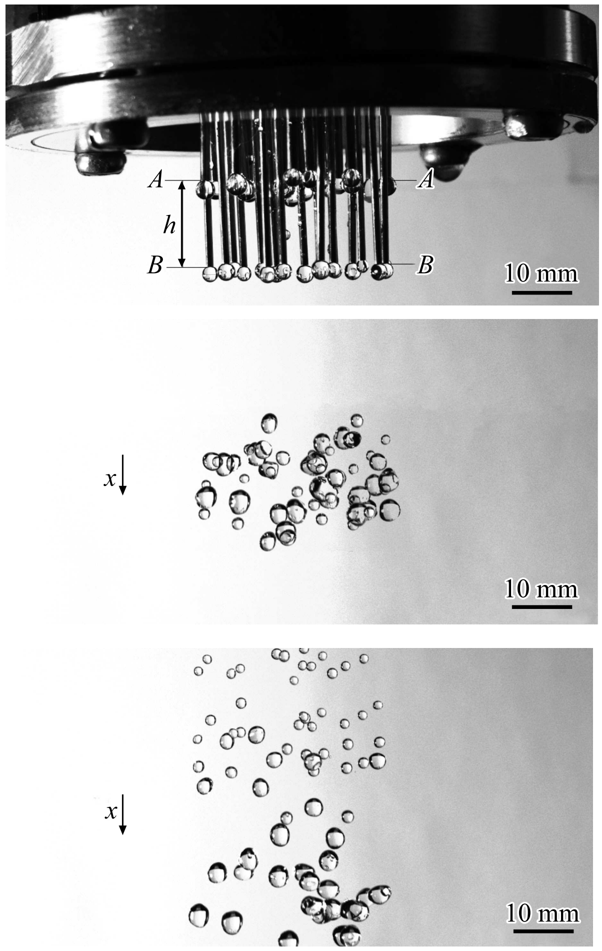

Figure 1. Qualitative pattern of formation and gravitational settling of a bidispersed drop cloud (20 drops 3.7 mm in diameter and 20 drops 2.9 mm in diameter). *a* — Formation of two drop layers in planes $A-A$ and $B-B$ ($x \approx 0$ cm); *b* — motion of the bidispersed drop cloud ($x \approx 1.5$ cm); *c* — stratification of the bidispersed cloud into two monodispersed clusters ($x \approx 5.0$ cm).

two clusters, the concentration of drops in each of them decreases, and their further settling proceeds in the „blow-through" cloud regime [10] at the velocity of a single drop with its diameter equal to the diameter of drops in the cluster (Fig. 2).

The intensity of drop evaporation in the cloud was estimated based on the evaparation rate W of drops passing through the heater with a varying average temperature inside its cavity. Evaporation rate W was calculated as [9]

$$W = \rho \frac{\Delta R}{t}, \Delta R = R_0 - R_k = R_0 \left[1 - \sqrt[3]{1 - \Delta m} \right],$$

$$\Delta m = \frac{m_0 - m_k}{m_0},$$

where ΔR is the drop radius reduction from R_0 to R_k due to evaporation; m_0, m_k are the drop masses before and after heating; and Δm is the relative change in mass of a drop during evaporation.

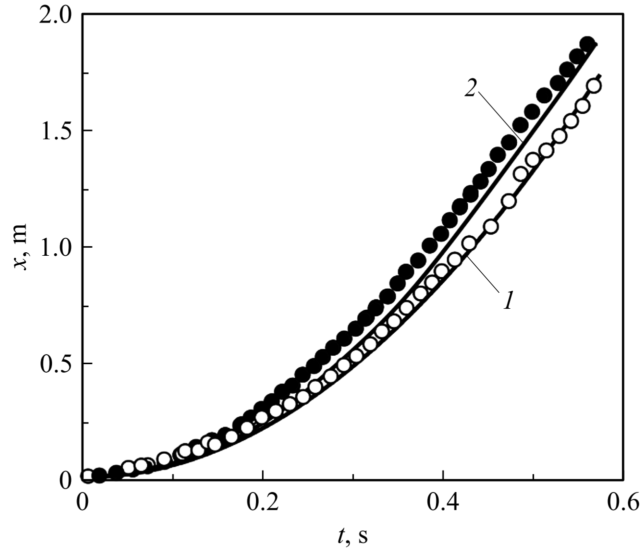

Figure 2. Dependences of the distance traveled on time. *1, 2* — Calculated dependences $x(t)$ for single drops with a diameter of 2.9 and 3.7 mm, respectively. Open and filled circles represent the measured values for the center of mass of a cluster of monodispersed drops with a diameter of 2.9 and 3.7 mm, respectively.

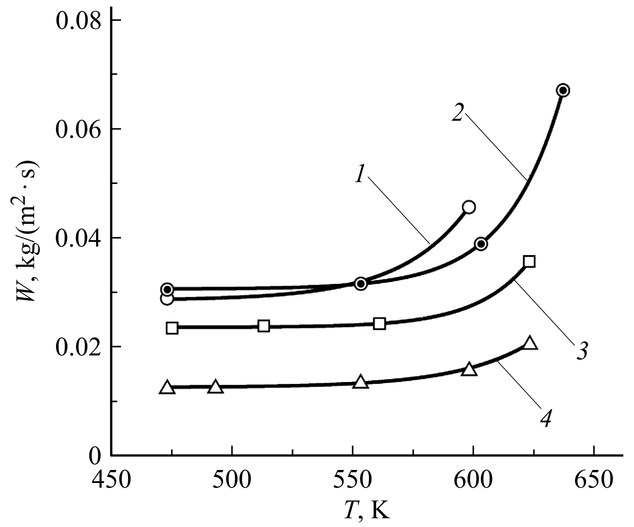

Figure 3. Experimental dependences of the drop evaporation rate on the air temperature in the heater. *1* — Single drop with a diameter of 2.9 mm, *2* — single drop with a diameter of 3.7 mm, *3* — bidispersed cloud (20 drops 3.7 mm in diameter and 20 drops 2.9 mm in diameter), and *4* — monodispersed cluster (40 drops with a diameter of 2.9 mm).

Equivalent drop radius $R_e = \sqrt[3]{0.5(R_1^3 + R_2^3)}$ was used as R_0 for a bidispersed cluster. The time of passage through the heater 1 m in length was determined in accordance with the plots (Fig. 2).

Figure 3 shows the dependence of the evaporation rate for single drops and mono- and bidispersed clusters on the air temperature in the heater. Quantitative data on the evaporation rate for single drops and its dependence on temperature are consistent with the results of studies [11,12] conducted under similar conditions. It follows from Fig. 3 that the evaporation rates for single drops 2.9 and 3.7 mm in diameter differ insignificantly within the temperature range of 475–600 K. The intensity of evaporation of a cluster of monodispersed drops is significantly lower than that of a single drop. This effect has also been noted in [4] and is apparently associated with the presence of a layer of water vapor between drops in the cluster. The effect of vapor on the rate of evaporation of the bidispersed cloud is less pronounced (Fig. 3) than the corresponding effect for the monodispersed cluster. The evaporation rate for the bidispersed cluster (curve *3* in Fig. 3) calculated based on the results of direct measurements of Δm is higher than the corresponding values for the monodispersed cluster (curve *4* in Fig. 3), that may be attributed to collision of drops of different sizes in the process of settling, their coagulation, fragmentation, and formation of secondary drops [1]. These processes may affect both the settling rate of the resulting polydispersed drops and the velocity of their evaporation.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] A.A. Shraiber, Itogi Nauki Tekh. Kompleksn. Spets. Razdely Mekh., **3**, 3 (1988) (in Russian).

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

[3] R.S. Volkov, S.A. Kerimbekova, P.A. Strizhak, Tech. Phys. Lett., **48**, 142 (2022). DOI: 10.1134/S1063785022040137.

[4] 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).

[5] S.A. Kerimbekova, R.S. Volkov, P.A. Strizhak, Tech. Phys. Lett., **49** (10), 41 (2023).
DOI: 10.61011/TPL.2023.10.57056.19676.

[6] V.A. Arkhipov, S.A. Basalaev, N.N. Zolotorev, V.I. Romandin, S.N. Polenchuk, *Sposob polucheniya oblaka bidispersnykh kapel'*, Patent Appl. No. 2024111059 (filed on April 23, 2024) (in Russian).

[7] A. Adamson, *Physical Chemistry of Surfaces* (Wiley, 1976).

[8] L.G. Loitsyanskii, *Mekhanika zhidkosti i gaza* (Nauka, M., 1973) (in Russian).

[9] V.A. Arkhipov, S.A. Basalaev, A.I. Konovalenko, K.G. Perfil'eva, Tech. Phys. Lett., **46** (6), 610 (2020). DOI: 10.1134/S1063785020060176.
[10] V.G. Khorguani, Kh.M. Kalov, Izv. Akad. Nauk SSSR. Fiz. Atmos. Okeana, **11** (3), 278 (1975) (in Russian).
[11] V.I. Terekhov, V.V. Terekhov, N.E. Shishkin, K.Ch. Bi, J. Eng. Phys. Thermophys., **83** (5), 883 (2010). DOI: 10.1007/s10891-010-0410-7.
[12] G.V. Kuznetsov, P.A. Kuybin, P.A. Strizhak, High. Temp., **53** (2), 254 (2015). DOI: 10.1134/S0018151X15020133.

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