The influence of the electric field on the crystallization of water droplets in the air flow

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Abstract. A technique has been developed for experimental modeling of the crystallization of water droplets in the air stream. It is shown that the electric field affects the crystallization of droplets. A multiple regression equation is obtained, which connects the time of complete freezing of droplets in the air flow with their size and medium temperature. The obtained results can be useful in laboratory and theoretical modeling of the mechanisms of freezing of droplets and in the implementation of methods for the active influence on thundercloud clouds and fogs.

Introduction

The first studies of the influence of the electric field on the freezing of supercooled water droplets were carried out in 1861 by Dyufo. He put a drop of distilled water in a mixture of oils and chloroform so that the density of the mixture was equal to the density of water. When discharged Rumkorfa coil through a drop of its sudden freezing occurred. Subsequently, the study of the influence of the electric field on the crystallization of supercooled water droplets has been applied in the study of sedimentation processes. Despite the large amount of research carried out in this area, many issues related to the formation and growth of hail remain insufficiently studied to date. These include the conditions for the formation of nuclei of hail and their subsequent growth in the clouds. It turned out that in many cases the hail nuclei are frozen drops. Electrical forces can directly affect the state of droplets, leading them to crystallization at higher temperatures than in the absence of these forces. On the other hand, electric forces can affect the rate at which active nuclei of crystallization hit the surface of droplets, which can lead to an increase in the probability of droplet crystallization at a given supercooling temperature [1].

Modern methods of influencing gradation are based on the creation of additional artificial hail germ. The formation of artificial germs occurs either when the reagent particles get inside the cloud droplets that are in the warm part of the cloud, or when they are subsequently raised to negative temperatures and hardening.

Therefore, the study of the temperature change process of water droplets that are suspended in the air flow is relevant today. But research into the mechanisms of crystallization of droplets (hail formation) encounters fundamental difficulties, which consist in the fact that direct experiments inside hail clouds are still associated with solving complex scientific and technical problems and are fraught with danger to the life of a researcher. Therefore, to restore the picture of the process of formation and growth of hail applied laboratory tests in a wind tunnel.
Materials and research methods
An experimental facility has been developed at the High-Mountain Geophysical Institute (Russia, Nalchik), with which it is possible to simulate the free-flow (drooping) of droplets [2, 3, 4]. The installation diagram is shown in Figure 1.

![Figure 1](image1.png)

**Figure 1.** Scheme of the experimental setup: 1 - working tube, 2 - nozzle, 3 - stabilization chamber, 4 - electric heater, 5 - air cooler, 6 - fan, 7 - metal mesh, 8 - cellular partition

The experimental setup is a partially closed wind tunnel operating at normal atmospheric pressure. Its main elements are: a fan, a stabilization chamber, a cooling machine, an electric heater, a nozzle, a measuring section and measuring devices. Air is sucked through the pipe by the fan and is fed into the air cooler. The cooled air passes through the electric heater, stabilization chamber, nozzle and enters the working tube. The nozzle inlet and outlet are shielded with metal grids to eliminate air turbulence. A drop is placed in the working tube.

A schematic diagram of the measuring section of the installation, on which laboratory modeling of the influence of an electric field on the crystallization process of supercooled water droplets was carried out, is shown in Figure 2.

![Figure 2](image2.png)
**Figure 2.** Measuring station experimental setup: 1 - working tube, 2 - capacitor plates, 3 - high voltage source (IVN), 4 - thermocouple, 5 - self-recording potentiometer (KSP-4), 6 - photo or video camera

The working tube is fixed to the plates of a flat capacitor, to which high voltage is supplied from the IVN source. The temperature in the working volume is recorded using a thermocouple, the signals from which are recorded on a recorder - potentiometer KSP - 4. Observation of the experiment is carried out using a photo or video camera.

**Research results and discussion**

Experiments were carried out to study the process of freezing of water droplets in the air stream. In the course of the experiment, drops of distilled water with a size of 3 ÷ 6 mm were suspended in the working area of the wind tunnel. The drops were kept by the air flow, the speed of which reached 6 ÷ 9 m / s. The air flow temperature over the wetted thermometer was 7.5 ÷ 18.75 °C. The dependence of the drop freezing temperature on time was investigated. In fig. 3a shows a typical view of the curve, obtained on the basis of the study of droplets larger than 3 mm in the wind tunnel in the absence of an electric field.

![Figure 3](image)

**Figure 3.** Dependence of the drop freezing temperature on time: curve (a) - in the absence of an electric field; curve (b) - in the presence of an electric field; 1 - cooling a drop of water; 2 - hardening; 3 - cooling a frozen drop

The dependence obtained in the course of our experiments during the crystallization of a drop of double-distilled water with a diameter of 3.86 mm in the presence of an electric field is shown in Fig. 1 b. For such a droplet with an average duration of complete freezing of droplets of 67 s, the average time of the onset of freezing was 10 minutes.

In Fig. 3, three areas can be distinguished, which reflect the following physical processes: cooling of the liquid phase, solidification and cooling of the solid phase. During the time of complete hardening, the time from the onset of freezing (formation of an ice crust) to the complete freezing of water is taken.

From Fig. 3, it can be seen that the cooling processes (section 3) and solidification (section 2) in the absence (curve a) and the presence (curve b) of the electric field in both experiments almost coincide.
Section 1 is determined fairly accurately. When the drop is cooled, due to dendritic crystallization, an ice crust is formed on the drop with a thickness determined by the formula:

$$
\Delta r = \frac{R \, c_w (T_{cr} - T_w)}{3 \, L_{ph,t}},
$$

(1)

where $c_w$ - is the heat capacity of water; $T_w$ - water subcooling temperature; $T_{cr}$ - crystallization temperature (phase transition); $L_{ph,t}$ - latent heat of phase transition; $R$ - the radius of the solidified particle. At this moment, the latent heat of the phase transition is released, and the temperature of the drop sharply (stepwise) rises to $0^\circ C$. The duration of this moment is about 1 s and less, in other words, it is much less than the time of complete hardening of the drop.

Determining the end of the process of solidification causes are difficulties. Visually determine the point at which solidification ends and the drop begins to cool is not always possible due to the opacity of the resulting ice crust. In addition, the resulting ice particle begins to oscillate long before it is completely solidified. The change in temperature occurs smoothly. The observed bending of the temperature curve corresponds to a time interval of $10 \div 20$ s, and therefore the end of the drop solidification becomes somewhat uncertain. The problem of hardening a drop of water is reduced to the problem of hardening the ball under boundary conditions of the third kind, where the temperature of the wet thermometer of air flow is taken as the medium temperature, and the heat transfer coefficient is taken as a generalized heat transfer coefficient, which takes into account the heat transfer from the particle and is found from the experiment. As a result, a method was developed for processing experimental data, according to which the following formula is used to determine the total solidification time for water droplets in a wind tunnel:

$$
\tau_0 = \frac{\rho_i \cdot L_{ph,t}}{6 \lambda_i (T_{cr} - T_w)} \left( R - \frac{2 \lambda_i R}{\alpha^2} \right) \left( 1 + \frac{c_i (T_{cr} - T_w)}{L_{ph,t}} \right) \left( 1 + \frac{c_w (T - T_{cr})}{L_{ph,t}} \right),
$$

(2)

where $c_i (T_{cr} - T_w) / L_{ph,t}$ - is the criterion of Stephen; $1 + c_w (T - T_{cr}) / L_{ph,t}$ - is a factor that takes into account the drop cooling before solidification; $L_{ph,t}$ - heat of solidification; $T_w$ - water subcooling temperature; $T_{cr}$ - crystallization temperature (phase transition); $\lambda_i$ - is the thermal conductivity coefficient of the thermocouple material; $\alpha^2$ - generalized heat transfer coefficient; $\rho_i$ - ice density; $c_i$ - mass heat capacity of ice; $c_w$ - heat capacity of water; $T$ - temperature of the hardened drop.

In the background experiments, when there was no constant or alternating electric field, the average value of the freezing temperature was $-14.5^\circ C$, which is typical for distilled water. In the presence of a constant electric field, the freezing temperature increased. As a result, the mean, median, and mode of freezing temperature shifted to higher temperatures compared with background experiments. It is noted that the range of the frequency spectrum of the freezing point of the droplets increases, which may be explained by the variation of the electric field strength in the experiments.

It should be noted that the temperature jump in the presence of a constant electric field is $(2 \div 4) 0^\circ C$ higher than in its absence. And the waiting time for the onset of hardening is also less than in the presence of an electric field. Those under the influence of an electric field, the drop hardens at high temperatures and faster than in its absence.

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The obtained results found a qualitative agreement with the data of studies conducted by V.N. Filatkin et al. [5] and T.N. Gromova and others [6] in a different range of droplet sizes.

Figure 4 shows the average waiting time for the moment of the onset of freezing as a function of temperature according to the results of our laboratory experiments.

\[ T = -2 \cdot 10^{-11} \tau^4 + 3 \cdot 10^{-8} \tau^3 + 1 \cdot 10^{-5} \tau^2 - 0.0569 \tau + 15.531. \]  

(3)

It turned out that the time dependence of the freezing point \( T \) of a drop \( \tau \) is described by a polynomial function:

Based on the statistical processing of the experimental data, a multiple regression equation was obtained, which relates the time when levitating water droplets completely freeze from the diameter \( d \) and temperature of the medium \( T \):

\[ t = -0.417 + 2.3 \cdot 10^{-2} d - 0.188 T. \]  

(4)

The correlation coefficient of the equation matters \( R = 0.934 \), and the coefficient of determination is \( D = 0.869 \). As is known, the closer \( D \) to 1, the stronger the dependence, in our case, between the time of complete freezing and the diameter of the drop and the temperature of the medium, the relationship is strong.

**Summary**

The paper obtained results that are useful in theoretical and laboratory modeling of the mechanisms of formation and growth of hailstones:
temperature-time dependence of the duration of crystallization of levitating water droplets in the air flow in the absence and presence of an electric field;

- the equation of multiple regression, connecting the time of complete freezing in the air stream of droplets, their size and temperature of the medium.

Particular attention is the result of the displacement of the freezing point of the drop in the region of higher temperatures by (2 ÷ 4) 0 C in the presence of an electric field. What can be used in questions of active influence of crystallizing reagent on thundercloud clouds and fogs.

References

[1] Muchnik V M 1974 Physics of thunderstorms (Moscow, Gidrometeoizdat).
[2] Grigorieva V A, Zorina V M 1982 Heat and mass transfer. Thermomechanical experiment (Reference book, Moscow, Energoizdat).
[3] Tlisov M I, Balkarova S B, Kalov R Kh 2003 Laboratory modeling of the influence of the electric field on the process of crystallization of raindrops (Collection of scientific papers of the 5th Russian conference on atmospheric electricity, Vladimir) 1 226-229.
[4] Fedorov V G, Babaki B S, Erkin M A 1990 The influence of the electric field on heat and mass transfer (Electronic processing of materials) 1 30-31.
[5] Filatkin V N, Tlisov M I, Pilin I I 1991 Theoretical and experimental studies of heat transfer processes during the nucleation, growth and melting of hailstones (Proceedings of the HMG1 (High-Mountain Geophysical Institute)) 80 50-68.
[6] Gromova T N, Pershina T A et al. 1975 Identification of Particles Emitted When Water Droplets Freeze (Proceedings of the MGO) 356 18-27.