Laboratory studies of the graupel nuclei formation and the processes of their further growth in a liquid droplet medium

B M Khuchunaev1,*, A B Khuchunaev1
1Federal State Budgetary Institution «High-mountain Geophysical Institute», 2 Lenin Avenue, Nalchik, 360030, Russia
*E-mail: buzgigit@mail.ru

Abstract. The article presents a set of equipment for studying the growth of graupel nuclei and the growth of graupel particles. It was established in the work that the growth parameters as mass, the rate of mass growth have extreme values from −5 °C to −12 °C. It was found that at the initial stage of hail formation, two growth modes are observed: first, the growth of ice particles occurs due to the diffusion of water vapor; second, the growth of ice particles occurs as a result of crystal aggregation. The calculated values of the density of ice formed during the diffusion of water vapor vary from 0.9 to 0.97 g/cm³, in the second case from 0.2 to 0.6 g/cm³. A significant increase in the growth rate of hail occurs during the translational-rotational movement of the air flow in the wind tunnel. The article shows that with an increase in water content, the growth rate of hailstones increases. When the water content reaches approximately one gram per cubic meter there is a sharp decrease in the growth rate. With a further increase in the water content, the growth rate increases. The sharp decrease in the growth rate is most likely due to the fact that at a water level of about one gram per cubic meter, the nuclei are saturated with moisture and the ice density increases, and this leads to a decrease in the rate of hail growth.

1. Introduction
The growth of crystals due to the diffusion of water vapor and the formation of graupels, as well as its further growth in the liquid droplet medium, play an important role in the formation of precipitation in both natural and seeded clouds. Many field studies have been conducted to understand this process [1-5]. Field research has a number of limitations. To study the growth of precipitation particles, it is impossibility of continuous observation and it is difficulty to determine the dependence of the growth parameters on the characteristics of the environment.

2. Equipment and methodology
A set of equipment was used to study the mechanism of graupel formation and its growth in a liquid droplet medium: these are a cloud chamber, an automated optical system for determining the concentration and size of ice crystals, a steam generator, a device for sublimating reagents, a sampling device, a flow ultramicroscope, a Testo 425 thermal anemometer, a Lasair III 350L particle counter. The main part of the equipment is described in [6] so we will not dwell on them, we will look in more detail at the wind tunnel where the growth of graupel particles occurred.
Figure 1. Wind tunnel for studying the growth of snow graupels.

A wind tunnel for studying the growth of snow graupels (figure 1) is a transparent cylindrical truncated cone (1) with a height of 1.15 m, with an upper diameter of 0.3 m and the base of the cone 0.8 m in diameter. The angle of the cone is 6 degrees. The wind tunnel is positioned so that the base of the cone is at the top. The base of the cone is covered with a lid, there is a cylinder with a diameter of 8 cm in the middle of the lid, a fan is attached to the cylinder, tubes and meshes are installed inside the cylinder, they serve to stabilize the flow (5). The air flow in the wind tunnel is created by the fan (3). The speed in the device is regulated by changing the voltage applied to the fan. When a laminar air flow passes from a pipe with a diameter of 8 cm to a pipe with a diameter of 0.8 m, the air flow velocity drops in the wind tunnel.

In the figure 1 (on the right side) the diagram of the air flow velocities in a wind tunnel is given. The diagram of the air flow velocities in a wind tunnel is somewhat different from the classical representation that follows from the Hugoniot equation [6], and states that in subsonic gas movement, as well as in the case of an incompressible liquid, with an increase in the cross-sectional area of the pipe, the speed of movement decreases and, conversely, with a decrease in the cross-section, the speed increases. In our case, near the fan, the flow does not immediately expand, so in the widest part of the pipe, the speed is maximum. As you move away from the fan, the flow rate decreases until the diameter of the flow coincides with the diameter of the pipe, then along the pipe, the speed increases to the way down. If we consider the velocity profile along the vertical section of the pipe, then from figure. 1 (on the right side) it can be seen that the air flow velocity is maximal in the center and decreases towards the edges. For the three measurement levels (a,b,d) in the wind tunnel, this statement remains true, except for the b-level, where the central velocity is less due to the design features of the wind tunnel.

In laboratory modeling, it is important that the model corresponds to real atmospheric conditions, and the principles of similarity theory are usually used to clarify this issue. In our case, the ratio of the similarity of velocity and size in the air flow is satisfied, since the particle size and flow velocity correspond to real conditions. As for the geometric dimensions in aerodynamic research, it is accepted
that the dimensions of the wind tunnel are an order of magnitude larger than the size of the object under study. Thus, it is possible to study the growth of particles up to 8 mm in the proposed wind tunnel. The sequence of the experiment is as follows. First, water vapor is launched into the cooled chamber (the amount of water vapor is regulated by the start-up time). After stirring the mixture of air and water vapor, turn on the wind tunnel fan. After two or three minutes the wind tunnel fan is turned off to complete the experiment, and the grown graupel particles fall on the substrate with transformer oil. The concentration and size of the droplets were measured by the Lasair III 350L particle counter, and the water content in the chamber is calculated from this data. The mass of the graupel was determined by the diameter of the droplet, which is formed after the graupel melts in the transformer oil.

3. Results of the study the growth of graupel nuclei

The analysis of the experimental data shows figure. 3 that there are two maxima of the growth rate-this is near the temperature −4 °C and about −12 °C, the maximum growth is 0.185 mg/s at a temperature of −11.8 °C and a water content of 1.1 g/m³. It should be noted that in [8] studying the growth rate of ice crystals, we also obtained two maxima, but only one near −6 °C and the second about minus 14.5 °C. This is most likely due to the fact that in our experiments, the growth of graupels occurs due to two mechanisms: the diffusion of water vapor and as a result of crystal aggregation. The growth of crystals occurs only due to the diffusion of water vapor in the experiments [8]. Experiments show that with increasing water content, the growth rate increases.

![Figure 2. The dependence of the growth rate of graupels on the temperature.](image)

4. Results study of hail growth on drip and graupel nuclei

An experimental study of the growth of hail on drip and graupel nuclei was carried out using the above-described equipment. Prior to the experiment, a hail nucleus with a diameter of 2-3 mm was suspended on a rubber thread, micron-sized droplets were launched into the chamber, cloud samples were taken in parallel, a fan was turned on, and a cloud medium flow to the nucleus was created. The growth of hail was observed using a video camera and the process of hail growth was recorded. In the following video, the material was used to determine the change in the size of hailstones

$$\frac{dR}{dt} = \frac{\pi}{3} \int_0^R \left[ \frac{(R + r)}{R} \right]^2 \left[ V(r) - V(r) \right] r^3 E(R, r),$$  \hspace{1cm} (1)
where \( R \) is the radius of the nucleus, \( r \) is the radius of cloud droplets, \( V(R), V(r) \) is the rate of fall of hailstones and cloud droplets, respectively, \( n(r) \) is the number of particles with radius \( r \). \( E(R, r) \) is the hailstone capture coefficient of cloud droplets.

After simple transformations, we obtain for the conditions of growth of hailstones in the chamber:

\[
\Delta R = \left( E[R, r] / 4 \rho_k \right) W,
\]

(2)

where \( W \) is the velocity of the air flow in the chamber. With the growth of hailstones, its density differs from the density of water, to take this into account, we introduce a coefficient

\[
K = E(R) \rho_B / \rho_L ,
\]

(3)

let's call it the growth factor. When the density of the hailstone layer tends to the density of water, \( K \) tends to the value of the capture coefficient. The lower the density of the hails

\[
K = 4 \Delta \rho_k / W q \Delta t .
\]

(4)

In the figure 3 shows a diagram of the dependence of the growth rate on the water content in the chamber.

As can be seen from the figure, there is a pretty good relationship between the growth rate and the water content in the chamber, the coefficient of determination is 0.98. As can be seen from the above material, the rate of growth of hailstones on the droplet nucleus depends on the water content, with increasing water content, the growth coefficient increases.

![Figure 3. The dependence of the growth rate of hailstones on the drop nuclei on the water content in the chamber.](image)

When hailstones grow in a liquid-droplet medium on a graupel nucleus at high humidity and relatively high temperatures, the graupel is impregnated with moisture, sometimes the geometric size of the hail decreases. In the 4 is a photo of artificial graupel.

As you can see from the picture 5, with an increase in water content, the growth coefficient increases, when the shelf life reaches about 1 g/m³, the growth coefficient decreases abruptly, with a further increase in water content, the growth coefficient continues to grow. This phenomenon is not observed with the growth of droplets. The abrupt decrease in the growth coefficient is most likely due to the fact that at water levels of about 1 g/m³, the ice density increases, and some of the water has time to absorb into the inner layers of the growing hailstone.
Figure 4 shows the results of a study of the growth of hailstones on graupel nuclei. The results of the experiments show that with the growth of hail on graupel nuclei, a clear relationship between the growth coefficient and water content is not observed. This is due to the fact that the graupel captures large droplets that do not have time to crystallize, and are pulled into the hailstone under the action of capillary forces. At low water levels, the growth coefficient takes a value of slightly more than three. This is due to the fact that with such growth, ice with a density of 0.2 - 0.4 g/cm³ is formed.

With an increase in water content, the graupel begins to absorb water and the growth coefficient becomes negative, or the growth is insignificant. In some cases, at high water levels, a decrease in the radius of the hailstones indicates that the crystallization rate does not ensure the crystallization of all the water captured by the hailstones, some part of the water is absorbed into the hailstone, the other part can leave the hailstone.
The amount of saturated water is commensurate with the mass captured from the cloud environment. Sections of artificial hailstones show the presence not crystallized water in the pores of ice. The results of the experiments show that the coagulation growth of hailstones depends on the water content and on the substrate on which the growth occurs. Even at subzero temperatures, there may be periods of time in which the size of the hailstone decreases, this is due to the melting of the upper layer. The results of the experiments show that the process of hail growth in a liquid-droplet medium and due to the diffusion of water vapor is a very long process, and is unlikely to be realized in pure form in hail clouds. Apparently, an important role in the formation of hail and precipitation is played by the aggregation of crystals and their further impregnation and growth due to coagulation with large cloud droplets. Despite the fact that the mechanism of formation of large millimeter droplets in clouds is not completely clear, their presence in hailstones is shown on the basis of field studies of natural hailstones [10].

5. Conclusions
1. Equipment and methods for laboratory research of education have been created.
2. It is shown that the growth rate of nuclei has two maxima: one about minus four, the second about minus twelve degrees.
3. The results of the experiments show that the coagulation growth of hailstones depends on the water content and on the type of embryo on which the growth occurs. With the growth of hail on graupel nuclei, it is possible to impregnate the cereal with water and temporarily reduce the size of the hail.
4. The results of the experiments show the process of hail growth in a liquid-droplet medium due to the diffusion of water vapor is a very long process and is unlikely to be realized in pure form in hail clouds.

References
[1] Pruppacher H R and Klett J D 1978 Microphysics of Clouds and Precipitation (Boston: D. Reidel Publishing Company) p 714
[2] Dovgalyuk Yu A and Pershina T A 2005 Atlas of Snowflakes (St. Petersburg: Hydrometeoizdat) p 140
[3] Brief chronology of observations of snow crystals 2008 (Electronic resource. Internet portal)
[4] Chukin V V, Melnikova I N, Nguyen T T, Nikulin V N, Sadykova A F and Chukina A M 2015 Diagnostics of ice cores in clouds according to the instrument Modern problems of remote sensing of the Earth from space 4(12) 133–142
[5] Nevzorov A N and Shugae V F 1992 Observation of the early stage of the evolution of the ice phase in supercooled clouds Meteorology and hydrology 1 81–92
[6] Khuchunaev B M, Khuchunaev A B, Panaetov V P, Stepanova S I and Teunova N V 2013 Laboratory modeling of the growth of graupel nuclei of hail (News of the Kabardin-Balkar scientific center of RAS) 1(51) 71–75
[7] Kraiko A N 2007 Short Course of Theoretical Gas Dynamics (Moscow: MIPT) p 300
[8] Tsuneya Takahashi, Tatsuo Endoh, Gorow Takahama and Norihiko Fukuta 1991 Vapor diffusional growth of free-falling snow crystals between −3 and −23 °C J. Journal of the Meteorological Society of Japan 69(1) 15–31
[9] Rogers R R 1979 A Short Course in Cloud Physics ed. Mazina I P (Leningrad: Hydrometeoizdat) p 231
[10] Tlisov M I, Khuchunaev B M and Shapovalov A V 2007 The concept of drip nuclei in the method of preventing the formation of large hail Bulletin of higher education institutes. North Caucasus region. Natural sciences 2 107–111