Investigation of the bubble structure of hail droplet nuclei

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Abstract. The paper is devoted to the study of the bubble structure of hail droplet nuclei at different temperatures and Nusselt numbers. On the basis of laboratory studies, equations are obtained that allow the measured values of the arithmetic mean diameter and the concentration of air inclusions in the droplet nuclei of hail to determine the temperature at which they were formed. The effect of changes in the Nusselt number on the bubble structure of hail droplet nuclei analyses in the article. The results of estimating the temperature and the Nusselt number at the level of formation of drop nuclei of natural hailstones that fell on 7.06.2012 are presented. For calculations, previously obtained data on the arithmetic mean diameter and concentration of air inclusions in the droplet nuclei of hailstones were used. The paper presents the results of comparing the formation temperatures of natural droplet nuclei, calculated from the bubble structure according to Tlisov's data and according to our data, is 2.3 °C. The maximum difference between our data and the List data is 2 °C.

1. Introduction
Great importance for determining the level of droplet nuclei formation and for the qualitative interpretation of the structure of hailstones is the study of the bubble structure of the nuclei and layers of hailstones. The processes of formation of air bubbles in hailstones occur under the influence of various mechanisms that determine the conditions of crystallization. So, for example, during the crystallization of droplet nuclei, as the crystallization front progresses, the main part of the molecules dissolved in air goes from the crystallized part of the droplet into the liquid part. It leads to the supersaturation of the liquid part of the droplet with air, when the supersaturation reaches 20-30 fold values, bubble formation occurs. Some of them are captured by the moving crystallization front and are included in the ice, while the other part dissolves back into water with increasing pressure inside the liquid core (Henry's law). The pressure build-up inside the liquid core occurs as long as the mechanical strength of the formed ice is able to hold this pressure.

2. Results of laboratory studies of the bubble structure of droplet nuclei at different temperatures and different values of the Nusselt number
The process of formation of cracks and their healing during the crystallization of drops occurs many times. The process of formation of air inclusions in transparent layers of hailstones differs from the considered mechanism. In this case, the water layer on the hailstones begins to crystallize from the surface of the previous layer or the hail nucleus, and the bulk of the released bubbles leave the hailstone. In this case, there are no processes of intensive formation of bubbles and their reverse dissolution in water. In the dry growth mode, the formation of bubbles can be observed by the
mechanism of crystallization of micron droplets, as well as the result of trapping air between coagulating droplets on a growing hail.

In the literature, there are a large number of works devoted to laboratory studies of the dispersion of air inclusions in artificial nuclei and layers of hailstones [1-3,4-12]. In these studies, it was shown that the characteristics of air inclusions in graupel nuclei and hailstone layers depend on many parameters, such as water content, temperature, pressure, and the spectrum of droplets and crystals, and this did not allow us to find an unambiguous analytical relationship between the conditions of formation and the characteristics of air bubbles.

For droplet nuclei, a more or less correct method was found, namely, the restoration of the temperature levels of crystallization of nuclei droplets by the bubble structure. The authors [1, 2] studied the dispersion of air inclusions in frozen water droplets in a thermal chamber and found that the arithmetic mean diameter of air inclusions is related to the ambient temperature at which large droplets crystallize. The analytical expression of this relationship has the form:

$$d = A/(t_\infty - 2)$$

where $d$ is the arithmetic mean diameter of the bubbles, microns; $t$ is the ambient temperature at which the droplets crystallized, °C; $A$ is a constant value equal to 400 according to [1] and 493 according to [2]. In [5], the authors, citing theoretical calculations taking into account the results of experiments [4, 11], point out to the possibility of two significant errors in determining the temperature level of crystallization of germinal droplets from the dispersion of air inclusions in them; this is a change in crystallization conditions at high water contents and at reduced pressure. Errors associated with water content can be practically avoided [16] by choosing for analysis those nuclei, after which growth proceeded in a dry mode. Studies of the effect of pressure reduction on the crystallization rate and bubble size were carried out in [11, 12]. In experiments [7], millimeter droplets with a decrease in pressure from 1 atm to 0.1 atm froze 5 times faster. Experiments on the crystallization of a large volume of water [12] showed that a decrease in pressure at the same crystallization rates promotes an increase in the average size of bubbles and a decrease in their concentration. In [3], to clarify the effect of pressure on the arithmetic mean diameter of air inclusions, experiments were carried out on the crystallization of large millimeter droplets in a thermal vacuum chamber. Crystallization of the droplets was carried out in the temperature range -2 to -15 °C at fixed pressures of 720, 500, 300 mm Hg. Art.

$$Nu = 2 + 0.456 Re^{0.55} Pr^{1/3}$$

where $Re = \Delta W d/\gamma$ is the Reynolds number, $Pr = (10^9/(1.1r^3 - 1200r^2 + 322000r + 1.3\cdot10^9))$ – Prandtl number, $W$ – air flow velocity, $d$ – chamber diameter, $\gamma$ – dynamic viscosity of the medium, $t$ – temperature in the chamber.

Table 1 shows the values of Re and Nu at different air flow rates. As can be seen, the value of Re is greater than the critical 2320 for Re and 20 for Nu. Therefore, the flow in the wind tunnel, accompanied by intense mixing of air with pulsations of velocities and pressures, along with the main vertical movement of air, transverse movements and rotational movements are observed.

**Table 1.** The value of the Reynolds and Nusselt numbers for different values of the air flow velocity in the chamber.

| Air flow velocity, m/s | Reynolds number | Nusselt number |
|------------------------|----------------|---------------|
| 8                      | $1.3\cdot10^3$ | 228           |
| 10                     | $1.7\cdot10^3$ | 263           |
| 12                     | $2\cdot10^3$   | 288           |

Table 2 shows the results of the experiments.
Table 2. Results of experiments on the study of the bubble structure of droplet nuclei of hail.

| n  | t, °C | W, m/s | d, microns | N, mm⁻³ | Nu |
|----|-------|--------|------------|---------|----|
| 1  | -3    | 8      | 105        | 326     | 228|
| 2  | -3    | 10     | 99         | 412     | 269|
| 3  | -3    | 12     | 96         | 478     | 288|
| 4  | -3    | 8      | 107        | 328     | 228|
| 5  | -3    | 10     | 96         | 410     | 269|
| 6  | -3    | 12     | 98         | 486     | 288|
| 7  | -3    | 8      | 102        | 322     | 228|
| 8  | -3    | 10     | 97         | 404     | 269|
| 9  | -3    | 12     | 94         | 481     | 288|
| 10 | -3    | 8      | 108        | 320     | 228|
| 11 | -3    | 10     | 97         | 403     | 269|
| 12 | -3    | 12     | 95         | 481     | 288|
| 13 | -3    | 8      | 103        | 327     | 228|
| 14 | -3    | 10     | 98         | 411     | 269|
| 15 | -3    | 12     | 94         | 480     | 288|
| 16 | -3    | 8      | 106        | 328     | 228|
| 17 | -3    | 10     | 98         | 410     | 269|
| 18 | -3    | 12     | 95         | 516     | 288|
| 19 | -6    | 8      | 48         | 350     | 228|
| 20 | -6    | 10     | 42         | 444     | 269|
| 21 | -6    | 12     | 30         | 510     | 288|
| 22 | -6    | 8      | 51         | 355     | 228|
| 23 | -6    | 10     | 39         | 440     | 269|
| 24 | -6    | 12     | 33         | 510     | 288|
| 25 | -6    | 8      | 52         | 357     | 228|
| 26 | -6    | 10     | 43         | 449     | 269|
| 27 | -6    | 12     | 29         | 516     | 288|
| 28 | -6    | 8      | 47         | 360     | 228|
| 29 | -6    | 10     | 41         | 447     | 269|
| 30 | -6    | 12     | 32         | 515     | 288|
| 31 | -6    | 8      | 48         | 359     | 228|
| 32 | -6    | 10     | 44         | 439     | 269|
| 33 | -6    | 12     | 28         | 520     | 288|
| 34 | -6    | 8      | 46         | 354     | 228|
| 35 | -6    | 10     | 37         | 440     | 269|
| 36 | -6    | 12     | 29         | 550     | 288|
| 37 | -9    | 8      | 40         | 398     | 228|
| 38 | -9    | 10     | 34         | 479     | 269|
| 39 | -9    | 12     | 30         | 540     | 288|
| 40 | -9    | 8      | 39         | 394     | 228|
| 41 | -9    | 10     | 42         | 475     | 269|
| 42 | -9    | 12     | 31         | 548     | 288|
| 43 | -9    | 8      | 39         | 387     | 228|
| 44 | -9    | 10     | 34         | 472     | 269|
| 45 | -9    | 12     | 29         | 548     | 288|
| 46 | -9    | 8      | 39         | 394     | 228|
As can be seen in figures 1 and 2, and from table 1, with an increase in the Nusselt number, i.e. with an increase in convective heat transfer, the arithmetic mean diameter of air inclusions decreases and their concentration increases. The analytical characteristics of the type of communication of air inclusions in the ice from the Nusselt number and the crystallization temperature based on earlier results and taking into account the form of curves in figure 1. can be found in the form:

\[ \begin{align*}
    d &= A/|t - 2| + 0.1Nu \\
    N &= 171 + B(t + 3) + B_1((0.1Nu - 2)/1.2 - 2) \\
\end{align*} \]

where \( d \) is the arithmetic mean diameter of air inclusions, \( t \) is the droplet crystallization temperature, \( Nu \) is the Nusselt number, and \( N \) is the concentration of air inclusions, \( A, A_1, B, B_1 \) – constant coefficients \( A=595, A_1=11, B=12, B_1=27 \). To compare the results of determining the temperature level of the formation of droplet nuclei with the above data, we assume that as a result of measuring the arithmetic mean diameter, a value of 50 microns was obtained.

Figure 1. Change in the arithmetic mean diameter of air inclusions in frozen droplets as a function of the crystallization temperature at the values of the Nusselt number (228, 268, 288).
Then the temperature of the droplet nucleus according to the List's formula is $t = -6 ^\circ C$, according to [2] $t = -7.90 ^\circ C$, according to our formulas at $\text{Nu}=228$, $t = -6.30 ^\circ C$, at $\text{Nu}=288$, $t = 5.50 ^\circ C$, at $\text{Nu}=400$, $t = -4.60 ^\circ C$, at large values of $\text{Nu}$, the discrepancy in determining the temperature can be significant. As can be seen from the figures, the determination of the crystallization temperature of droplet nuclei by empirical formulas without taking into account the heat transfer of the droplet with the environment can lead to significant errors, because the characteristics of air inclusions depend on both temperature and turbulent heat transfer.

![Figure 2](image)

**Figure 2.** Changes in the concentration of air inclusions in droplet nuclei at different temperatures and different values of the Nusselt number.

### 3. Results of the study of the bubble structure of natural hail nuclei

The results of the study of the bubble structure of natural hail nuclei on June 7, 2012, hail with a diameter of up to 50 mm was observed in the area of the village of Shalushka (the Kabardino-Balkarian Republic). Samples of hailstones were collected and their sections were examined. The arithmetic mean diameters of air particles and their concentrations were measured. A total of five hailstones were examined. We used these data to determine the temperature depending on the heat transfer of the droplet with the environment. Table 3 shows the measured values of the concentrations and the arithmetic mean diameter of the air inclusions in the five droplet nuclei and the values of the crystallization temperature and the Nusselt number calculated from them using the system of equations (2) at the level of their formation.

| n | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| $d$, microns | 63 | 76 | 53 | 64 | 45 |
| $N$, mm$^{-3}$ | 393 | 279 | 390 | 255 | 333 |
| $t, ^\circ C$ (according to our data) | $-4.5$ | $-5.3$ | $-5$ | $-6$ | $-8$ |
| $t, ^\circ C$ on[1] | $-4.3$ | $-3.5$ | $-5.5$ | $-4$ | $-7.8$ |
| $t, ^\circ C$ on[2] | $-5.8$ | $-4.5$ | $-7.3$ | $-5.7$ | $-8.9$ |
| Nu | 280 | 30 | 170 | 100 | 45 |
As can be seen from the table, the level of formation of droplet nuclei in this hail process was in the temperature range from \(-4.5\) °C to \(-8\) °C. At this temperature range, the Nusselt number varied from 30 to 280. In table 3, for comparison, the results of determining the temperature of the formation of droplet nuclei from the bubble structure according to [1] and [2] and according to our data are 2.30 S. The maximum difference between our data and the List's data, as can be seen from the table, is 2 °C, the maximum difference in determining the temperature from the data [1] and [2] is equal to \(-1.70\) S. Obviously, the temperature calculated from [1] is always less than from [2], since the coefficient in [1] is 400, and in [2] is 493.

4. Conclusions
Conclusions based on laboratory studies, solution of equations, which allows the measured values of the arithmetic mean diameter and concentration of air inclusions in the droplet hail nuclei to determine the temperature at which the droplet hail nuclei were formed, taking into account the heat transfer of the droplet with the surrounding environment.

The analysis of the results of the experiments shows that the determination of the crystallization temperature of the droplet nuclei by empirical formulas without taking into account the heat transfer of the droplet with the environment can lead to significant errors, since the characteristics of air inclusions depend on both temperature and turbulent heat transfer.

The results of the study of sections of hailstones that fell on 7.06.2012 showed that the droplet nuclei were formed in the temperature range from \(-4.5\) °C to \(-8\) °C on an ascending trajectory, at this level the Nusselt number varied from 30 to 280.

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