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Model of droplets generation during homogeneous condensation of water vapor in the atmosphere on neutral and charged centers

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The paper considers homogeneous condensation of water vapors of moist air in the atmosphere taking place during generation of clouds and mists. A method for calculation of a radius of water droplet generated and parameters of liquid inside it is proposed. Peculiarities of homogeneous condensation taking place on centers with electric discharges are investigated. It is shown that the electric discharge leads to the electric pressure establishment at the droplet border and thus to the change in droplet radius as well as the pressure inside it.

Keywords: droplet radius, Laplace pressure, surface tension, heat and mass transfer during condensation, droplet on a charged center.

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Introduction

The problem of the formation of water droplets in various conditions, and especially in the atmosphere, is of great interest both for understanding ongoing processes and for developing methods of influencing them: the formation of rain and hail, the propagation of electromagnetic and sound waves, etc. Let's take a closer look at the problems of water condensation at altitudes from 1 to 3(5) km above the sea level. As a rule, the main results are based on observational data. Their main task was, among other things, the desire to obtain a droplet size distribution function (DF). However, the evaporation and condensation processes themselves and the effect of electric fields on them were of no less interest. This task can cover both the formation of fog and clouds and their dispersion.

The problem of droplet formation can be divided into two parts: the formation of droplets due to condensation of water vapor in the atmosphere as the temperature drops and the further interaction of droplets with each other and the surrounding environment. In our opinion, the case of bulk condensation, and especially homogeneous condensation, has not been studied sufficiently.

Both processes have different characteristic times. It can be assumed that the condensation process occurs in a shorter period of time, after which other mechanisms of droplet growth begin to prevail. The estimate of the time of homogeneous condensation obtained in this work can be used to analyze the droplet size distribution function that occur when droplets collide with each other and with air molecules.

It was suggested in Ref. [1], that growth of small droplets mainly occurs due to condensation, while larger droplets (of the order of $50\,\mu$m and more) grow mainly due to coagulation. But how to determine the characteristic size upto which condensation prevails? For example, generally, it is difficult to determine the minimal size for which vapor condensation is more significant from the experimental data [2] (Fig. 1), which can be used to find the initial number of droplets in the atmosphere. The difficulty of determining the minimal droplet size is attributable to both the various kinds of interference that exist in the atmosphere and the accuracy of the instruments used to determine the droplet size. Therefore, the problem of particle size distribution is discussed to a greater extent in the literature. Since it is necessary to rely on DF for a more detailed analysis of experimental data, it is worth dwelling on well-known works devoted to its formulation and analysis for fogs and clouds.

Extensive literature is devoted to these problems [2–7].

Apparently, one of the first fairly fundamental works devoted to the formation of fog was the work of Schumann [6], who, based on the ideas of Smolukhovsky [8], proposed an integro-differential equation for the droplet size distribution function:

$$\frac{dn}{dt} = -n\int_0^\infty f(u,v)n(u)du + \frac{1}{2}\int_0^v f(u,v-u)n(u)n(v-u)du. \tag{1}$$

Here $n(v,t)$ — the time-dependent droplet volume distribution function; t — time; $f(u,v)$ — the frequency of collisions of droplets with volume v with droplets with

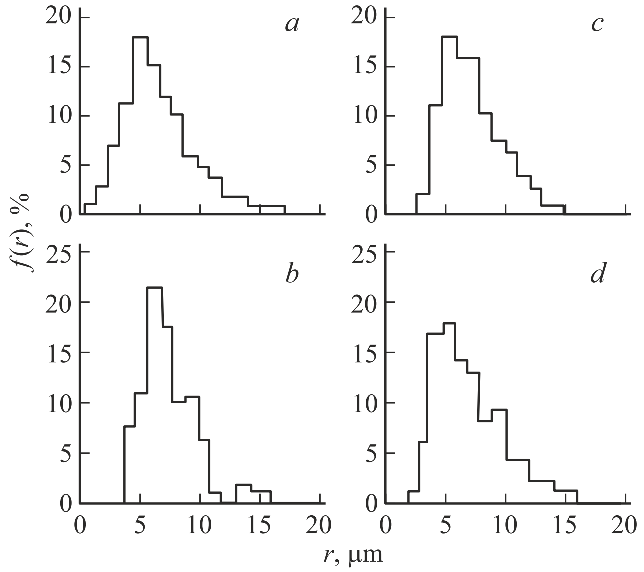

Figure 1. Experimental curves for the distribution density of cloud droplets of various shapes by size: a — the total number of measured droplets $N = 17\,269$, $r_1 = 6.8\,\mu$m; b — $N = 1029$, $r_1 = 7.6$; c — $N = 2469$, $r_1 = 7.1$; d — $N = 722$, $r_1 = 6.7$ [2] (r_1 — the value of the droplet radius corresponding to the DF peak).

volume u, related to the unit concentration of droplets of each size.

There are two types of collisions in the author's approach: collisions of droplets of a given volume with other droplets of different sizes, which cause droplets of a given volume to disappear, and collisions of droplets of different sizes, which lead to the formation of droplets of a given radius. Firstly, the author of Ref. [6] considered in his approach the collision frequencies to be the same and constant. And secondly, the total number of droplets varies according to the law

$$\frac{dN}{dt} = -\frac{K}{2}N^2,$$

$$N = \frac{N_0}{1 + (1/2)KN_0t}, \tag{2}$$

where K is the coagulation constant, N_0 is the initial number of nuclei droplets per unit volume.

As a result, the following equation is obtained from (1):

$$\frac{dn}{dt} = -KnN + \frac{1}{2}K\int_0^v n(u)n(v-u)du. \tag{3}$$

The author of Ref. [6] obtained the following solution to the equation (3) using the expression for N (2), as well as a number of transformations:

$$n = \frac{N_0^2}{V\left(1 + \frac{KN_0t}{2}\right)^2}\exp\left(-\frac{N_0v}{V(1 + KN_0t/2)}\right), \tag{4}$$

where V is the volume of liquid (in all the droplets) in unit volume.

It should be noted once again that in this approach it is necessary to know the collision frequencies and the nature of the change in the total number of particles.

Firstly, this non-stationary solution contains an unknown value N_0. Secondly, although formally it is a solution, but the expression (4) gives an incorrect result about the number of small-radius droplets per unit volume with a size tending to zero. Schumann in his study [6] relied on experimental data form [9] and compared them not with the calculation results using formula (4) obtained by solving equation (3) but with the values of the function multiplied by the volume occupied by a particle, that is, by r^3, in dimensionless form:

$$y = x^5\exp\{5(1 - x^3)/3\},$$

where y — the reduced DF probability density of droplets with a size in the range $r + dr$ (r — the droplet radius), scaled to its expression at $r = r_m$; $x = r/r_m$ — reduced radius, r_m — the value of the droplet radius corresponding to the DF peak.

This is probably why work Ref. [6] did not find a significant response from other researchers. More serious attempts to return to this problem were made in Ref. [5,7,10–13]. These studies are based on the kinetic equation for DF, given in Ref. [10] without derivation:

$$u\frac{\partial f}{\partial x} + \frac{\partial}{\partial r}(\dot{r}f) = \frac{I}{\rho}\delta(r - r_*). \tag{5}$$

Here u — the longitudinal projection of velocity, x — the longitudinal coordinate, δ — delta function, r_* — the radius of the nucleus of critical size, $\dot{r}$ — the rate of change of the droplet radius.

Apparently, kinetic equation (5) was applied for the first time to the condensing gas problem in Ref. [11,12]. It takes into account the change of the radius of the particles and includes the source of droplet formation. The derivation of the basic kinetic equation is briefly described in Ref. [5].

The authors of Ref. [10–12] have shown that the initial equation admits an analytical solution in the case when the droplet growth rate does not depend on their size. Then the equation can be reduced to a system of ordinary differential equations for the DF moments.

The method of moments is applied in more complex situations, using the well-known approach to solving the Boltzmann equation

$$\Omega_k = \int_{r_*}^{\infty} r^k f\,dr\ (k = 0,\ 1,\ 2).$$

Further more detailed studies were based on equation (5) using the method of moments to solve it but differed in the expression for the nucleation rate. For the gas flow and in relation to vapor condensation, it was considered by Sternin in [5], and then by Korzenstein and colleagues in [13–15], who developed the proposed algorithm for solving equation in (5) by the method of moments.

It should be noted that, unlike the approach in Ref. [6], this approach does not take into account droplet collisions but only the creation of droplets and the change of their radii over time. An attempt to partially account for the process of droplet collisions is made in Ref. [14], where the first equation in the initial system was supplemented by a summand in accordance with Ref. [16].

A more detailed consideration of the problem of determining DF may be the subject of a separate study.

Let us repeat the purpose of the work, which is to consider the homogeneous condensation of water vapor in moist air, the effect of an electric field on it, to find the characteristic times of this process and the total initial number of particles per unit volume, as well as the characteristic radius of the formed droplet.

As for the effect of constant electric fields from external sources on condensation on charged particles, their significant impact can take place at field strengths significantly exceeding the voltage at which an electrical breakdown of air develops. Therefore, such fields can hardly be realized under the conditions under which the problem of homogeneous condensation is being considered. It is shown that with real-world fields, the impact on the process is small. The impact of alternating electric fields with fluctuations of the order of radio frequency (from 100kHz to 10MHz) is of interest. Variable fields can lead to parametric oscillation of individual droplets, but this task requires a separate special analysis.

1. Homogeneous condensation: the radius of a droplet and the pressure inside it

Analyzing the nature of condensation of moist air in clouds of the Earth's atmosphere and in mists, it can be assumed that the condensation process proceeds in two stages: the first stage, which occurs during τ_1, is accompanied by the formation of droplets of the same size, evenly spaced in the volume of condensation. The formed droplets interact with the surrounding air and with each other, which leads to the determination of the size of the droplets during τ_2, and that is well observed in many experiments. This time τ_2 exceeds the time τ_1, and the first stage is considered in this part of this study.

The homogeneous condensation implies the process inside a large volume of humid air, as a result of which droplets of the same size are formed. It is believed that homogeneous condensation takes place in a gas mixture containing steam when complexes (clusters [17]) are formed in it as a result of fluctuations — clusters of molecules. The process of homogeneous condensation should be described in more detail within the framework of the kinetic theory of cluster formation from water molecules. In this approach, it is necessary to take into account how a growing cluster containing n molecules is formed from individual water molecules, taking into account the fact that its destruction can take place because of the interaction of the cluster with the surrounding air. Some of such accumulations can reach a critical size in supersaturated steam, and then they become nuclei, which further grow to liquid droplets [18]. These processes occur at the earliest stage of water droplet formation, so in the future we will first neglect the analysis of the initial stage of water cluster growth, and limit ourselves to the final stable state when droplets of the same radius are formed. There is a large number of papers [19–22] devoted to the formation of various kinds of clusters that contain a small number of particles. The papers of F.M.Kuni et al. [23,24] consider various aspects of condensation (homogeneous and heterogeneous) of supersaturated steam in a volume, including relaxation to a stationary process, droplet growth to critical sizes in the case when the steam source has constant power, as well as the effect of the form of nucleation centers, the presence of surfactants, etc. on condensation. The purpose of this paper is to analyze droplets that already contain a significantly larger number of particles than the various clusters in the works known to the authors [19–22]. Thus, we will limit ourselves to the final result of the formation of a droplet of radius r_d, without considering the processes occurring during its growth from a certain fluctuating size r_{00} to the size r_d.

Let's consider the case when the temperature of the humid air has dropped to a certain value, leading to complete condensation of water vapor. The main task of this part of the work is to determine the radius of the formed droplets, their number per unit volume, the liquid parameters (pressure and density) inside the droplet and the characteristic time of the homogeneous condensation of water vapor in the air.

Let's start with the fundamental picture related to the use of the well-known Laplace equation for the pressure jump at the phase boundary:

$$\Delta p = \frac{2\sigma}{r}, \tag{6}$$

where Δp — pressure difference in the condensed droplet and in the surrounding humid air, [Pa]; σ — surface tension, [N/m].

It can be seen from equation (6) that the pressure and density in a liquid droplet depend on its radius in an isothermal medium at a known ambient pressure. The smaller the radius under constant conditions, the greater the internal pressure. This yields different density from the real equation of state for the liquid, which is usually not taken into account in publications on this topic.

We will assume that droplets of the same size r_d formed from moist air as a result of homogeneous condensation.

Unfortunately, it is impossible to use equation (6) directly, because the radius of the droplet and the pressure inside it are unknown.

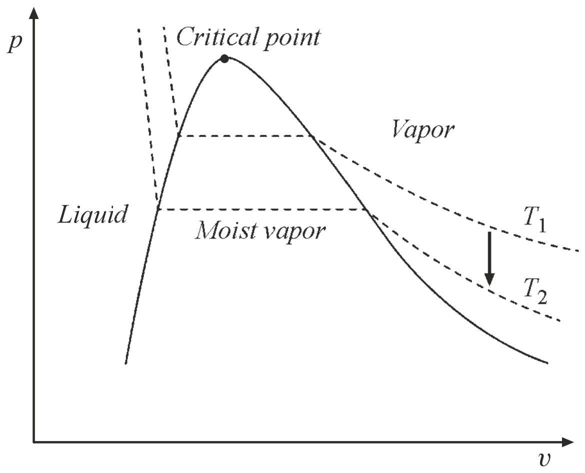

Figure 2. Phase diagram for water in pressure–specific volume coordinates.

This paper deals with moist air, the humidity of which is less than unity and equals to S_1 (the ratio of the partial pressure of water vapor at a given temperature to the saturation pressure). Suppose there was a temperature change from T_1 to T_2 ($T_2 < T_1$). Let's consider the process of formation of liquid droplets in a volume. There may be different processes, but we will focus on one when the water vapor contained in the air at a temperature of T_1 has fully or partially condensed into a liquid droplet at a temperature of T_2. It is necessary to determine the radius of the droplet and the parameters of the liquid inside it. As a result of condensation, liquid from a certain volume of radius r_M is collected into a droplet and can be located on the isotherm T_2 (Fig. 2) at pressures higher than the saturation pressure at T_2. It is assumed that all available moisture has passed into the liquid during condensation (when the residual humidity S_L satisfies the inequality $S_L/S \ll 1$). Let's estimate the size of the region r_M from which the water has collected into a single drop. Since the mass of liquid enclosed in a droplet is equal to the mass of water vapor in a volume of radius r_M, it is possible to write the following equation:

$$\frac{4}{3}\pi r_d^3 \rho_d = \frac{4}{3}\pi r_M^3 \rho_V,$$

where ρ_d is the density of liquid in a drop, ρ_V is the density of vapor in a certain region.

Thus, the relationship between the size of the droplet and the region of moist air from which all moisture is accumulated into the droplet due to diffusion is as follows:

$$\frac{r_d}{r_M} = \left(\frac{\rho_V}{\rho_d}\right)^{1/3}.$$

However, the above considerations still do not allow using equation (6) directly, since a new value has appeared — the characteristic size of the region from which moisture condenses (accumulates) into a drop. The final solution requires to take into account the time it takes for vapors to condense from the region r_M into a droplet of the final radius r_d, and the fact that condensation releases heat, which should be removed, i.e. there are two characteristic times: the time of motion of the condensation wave and the time of discharge of condensation heat from region r_M to outside. Therefore, for further discussion, we assume that the time of motion of the wave front of the condensation phase transition is equal to the time of condensation heat dissipation.

It is possible to determine the time of motion of the condensation wave front τ_c by solving the one-dimensional Stefan problem. This is the time it takes for the phase boundary to travel the distance from r_M to r_d. Then, considering that the radius of the humid air region is much larger than the radius of the water drop, we obtain

$$\tau_c = \frac{r_M^2}{a_V}. \tag{7}$$

Here a_V is the of thermal diffusivity, of moist air, which consists of the thermal diffusivity of dry air and water vapor.

Heat is released during condensation, therefore, in order for the formed droplet to be at a temperature of T_2, this heat shall be removed in a certain characteristic time τ_{qc}:

$$Q_c = h_{LG}\frac{1}{\tau_{qc}}\frac{4}{3}\pi r_M^3 \rho_V.$$

Here h_{LG} is the heat of the phase transition.

Let's estimate the time it takes for the heat of condensation $Q = q_c S_M = q_c 4\pi r_M^2$ to be removed from the region with a radius of r_M. The condensation heat flux rate can be represented in terms of the condensation heat transfer coefficient α and the temperature difference between the source air and the cooled air: $q_c = \alpha(T_1 - T_2)$.

Since bulk condensation is considered, there is practically no data on the heat transfer coefficient in the literature.

According to [25], the heat transfer coefficient for droplet condensation can be 40–100 kW/(m^2·K).

The empirical formula for the heat transfer coefficient is given in Ref. [26]

$$\alpha = T_s^{0.8}(5 + 0.3\Delta T), \tag{8}$$

where T_s is the saturation temperature equal to T_2; $\Delta T = T_1 - T_2$.

It should be noted that formula (8) is valid for pure water vapor. In the present problem, the medium is a mixture of dry air and water vapor, so the resulting values of the heat transfer coefficient will be somewhat overestimated. To account for differences in the composition of the medium, it is necessary to introduce an absolute correction factor less than one, which is not used here.

As a result, the expression for the cooling time can be written as

$$\tau_{qc} = h_{LG}\frac{r_M \rho_V}{3\alpha\Delta T}. \tag{9}$$

Calculated data for liquid droplets and radius of the humid air region from which water condenses

α, kW/(m^2·K)	Pressure inside the droplet P_d, MPa	ρ_d, kg/m^3	r_d, μm	r_M, μm
10.27	0.1206	999.95	4.4	248.6
40	0.219	1000	1.13	63.8
70	0.318	1000	0.64	36.5
100	0.418	1000.1	0.45	25.5

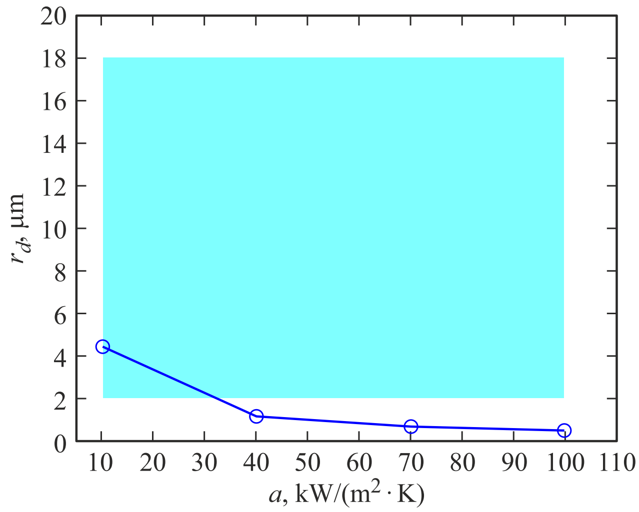

Figure 3. The dependence of the droplet radius on the heat transfer coefficient of droplet condensation and the range of prevailing droplet sizes in clouds and mists (continuous area).

It should be borne in mind that radiation can also affect the removal of condensation heat, but a separate analysis will be devoted to this.

The above assumption is used to obtain the final results that times (7) and (9) are equal in the process of homogeneous condensation: $\tau_c = \tau_{qc}$.

Using the real equation of state [27], we find the droplet radius, pressure, and density in a droplet of liquid at a temperature of T_2.

The listed parameters are found using the iteration method:

$$P_d^{(i+1)} = P_a + \frac{2\sigma}{r_M}\left[\left(\frac{\rho_V}{\rho_d}\right)^{-\frac{1}{3}}\right]^{(i)},$$

where P_a — ambient air pressure, P_d — pressure in a droplet of water.

A more detailed calculation using the equation of state of water [27] was performed in Ref. [28]. The calculations also used the real equation of state $P_d = P_s + a_0^2(\rho_d - \rho_s)$, where P_s, ρ_s — pressure and density at the saturation line; a_0 — the speed of sound in water. As a result, the values of the radius, density of water, and pressure inside the droplet were obtained for air at an altitude of 1000 m at a certain temperature (see table, Fig. 3).

The radius values obtained are within the range of the observed droplet sizes from [2,3,9,29].

As a result, knowing the initial humidity of the air at a known temperature, it is possible to estimate the droplet radius, and therefore the initial number of droplets per unit volume, which will be needed later when discussing the distribution of drops by size. It is also possible to calculate the time of the homogeneous condensation process, which is very important for estimating the initial formation of droplets.

2. Effect of electric fields on homogeneous condensation in atmosphere

When water vapor condenses on charged particles, there can be at least two extreme cases: when the charge is located on the surface of a sufficiently large solid particle, and then the condensed liquid is in the form of a certain layer, the thickness of which may be less than the radius of the particle. Another case is when the charge is concentrated on a solid particle with a very small radius (approximately 10^{-8} m), which is many times smaller than the radius of a liquid droplet formed during homogeneous condensation. Futher on, let's focus on the second case.

Let us consider the effect of electric fields on the condensation process. There are several mechanisms of such influence. The first is the effect of static electric fields created by charged particles, the second is the effect of electric fields from external objects, such as charged clouds and the earth, and the third is the effect of alternating electric fields.

Let us consider in more detail the results of homogeneous condensation when it occurs on an initial particle of radius r_{00} carrying an electric charge eZ (this may be a charged speck of dust). Still, without considering the processes that take place during condensation and lead to the formation of a liquid particle of radius $r_d \gg r_{00}$, we limit ourselves to the final state, comparing it with the final state in the absence of charge.

In the atmosphere, at different altitudes, starting from the Earth's surface and up to tens of kilometers, there are various charged particles on which water vapor condenses. Some of these particles are produced by cosmic rays, which produce ionization of various kinds of solid and gaseous inclusions. These can be individual molecules, clusters consisting of groups of molecules of different or the same grade, or solid dust particles. In addition, charging can be caused by the solar radiation exposure of solid particles with various kinds of metal inclusions. Photoemission takes place under the direct action of solar radiation: free electrons escape into the surrounding space, and the particles acquire a positive charge. In turn, electrons can „stick" to various atoms (for example, oxygen) that have a high affinity for an electron. Thus, charged particles can be present in large quantities in the atmosphere. The list of particles, the mechanisms of charge formation on them and their maintenance in the atmosphere is a separate topic [2,30–33]. Therefore, the present work assumes the presence of particles charged both positively and negatively. Here, the main focus is on the pressure that is created by the electric field of the charged center.

Let us consider the problem with the condition that condensation centers of small radius r_{00} are present in water vapor, carrying a charge $Q = eZ$ (e — electron charge, Z — number of charges). The particle radius should be of the order $0.1-0.01\,\mu$m. At the same time, it cannot accumulate too many charges Z. Since the charges have the same sign, repulsive forces arise between them, leading to the breaking of the particle on which they have accumulated.

The charged center creates a radial electric field around itself. Let's assume that a droplet with a radius of r_d has already formed on this center.

The radial part of the electric field induction vector remains constant when passing through the boundary of media, therefore, the following relations are valid:

$$D_d(r_d) = D_a(r_d),$$

$$E_d\varepsilon_0\varepsilon_d = E_a\varepsilon_0\varepsilon_a.$$

Then, the electric field strength abruptly changes at the boundary of the droplet

$$E_a = \frac{eZ}{4\pi\varepsilon_0\varepsilon_a r_d^2},$$

$$E_d = \frac{eZ}{4\pi_0\varepsilon_d r_d^2}, \tag{10}$$

where ε_0 — electrical constant; ε_d, ε_a — relative permittivity of water and air.

The electric field creates pressure, which contributes to and affects the Laplace jump on the droplet surface. Since the electric pressure is related to the electric field strength as $P_j = \varepsilon_0\varepsilon_j E^2/2$ ($j = d,\ a$), according to (10), the pressure is proportional to the square of the voltage, and therefore to the square of the electric charge of the condensation center. Expressions for the electrical pressure in the air and inside the droplet:

$$P_{dE} = \frac{(eZ)^2}{32\pi^2\varepsilon_0\varepsilon_d r_d^4},$$

$$P_{aE} = \frac{(eZ)^2}{32\pi^2\varepsilon_0\varepsilon_a r_d^4}.$$

As mentioned above, the pressure created by the electric field does not depend on the sign of the charge carried by the condensation center.

The presence of an electric field leads to a modification of the Laplace jump. The equilibrium condition on the droplet surface, taking into account the electric field, has the form

$$\Delta P_{hd} - \Delta P_E = \frac{2\sigma}{r_{de}},$$

where ΔP_{hd} — the pressure difference in the droplet and in the surrounding atmosphere; $\Delta P_E = P_{aE} - P_{dE}$ — the electrical pressure difference between the surrounding air and inside the droplet; r_{dE} — the radius of the droplet formed during condensation in the presence of an electric field created by a charged condensation center.

Next, we will evaluate the effect of the electric field on the radius of the formed droplet.

The number of charges Z that can be accumulated on the condensation center is selected as a variable parameter. A preliminary assessment showed that $Z \sim 10^4$ is necessary for the effect of the electrical pressure difference to be noticeable.

It is chosen for calculations that the relative permittivity of water inside a droplet is $\varepsilon_d = 80$ and the relative permittivity of ambient air is $\varepsilon_a = 1$.

The analysis is performed by considering the dependence of the parameters on the number of charges Z and condensation heat transfer coefficient α.

First, we calculate the electric fields that occur outside and inside the droplet. Due to the large difference in the dielectric permittivity of the media, the external field exceeds the internal field by two orders of magnitude. Figure 4 shows the values of the external electric field strength as more significant than the breakdown field

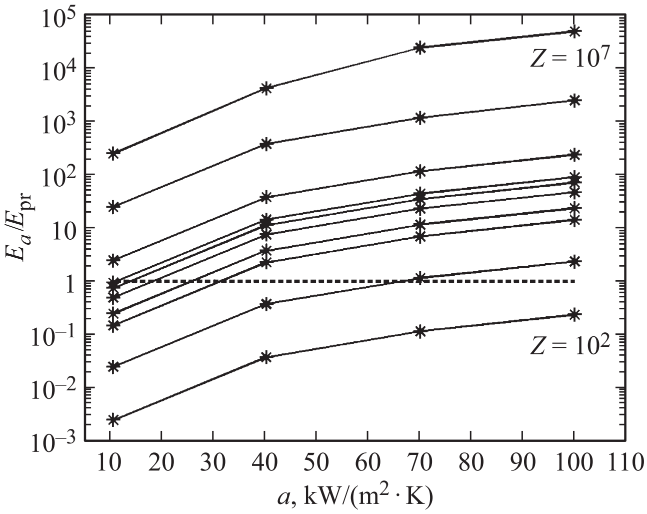

Figure 4. The relative electric field strength that occurs in atmospheric air at different heat transfer coefficients of droplet condensation and the number of charges at the condensation center; attributed to breakdown strength.

($E_{pr} = 3$ MV/m). The dependence is constructed for the four obtained values of the heat transfer coefficient (see table). The horizontal line corresponds to the breakdown voltage in the atmosphere at a given pressure. Isolines with the same value Z are marked. At high Z, the electric field should significantly exceed the breakdown field, which is not realized in the atmosphere.

Figure 5 shows how the difference in electrical pressure changes with respect to the hydrodynamic Laplace jump as the number of charges increases. Figures 6, 7 show the changes of pressure in the droplet and the droplet radius.

The calculation of the radii of a liquid droplet is performed similarly to the scheme in the previous section

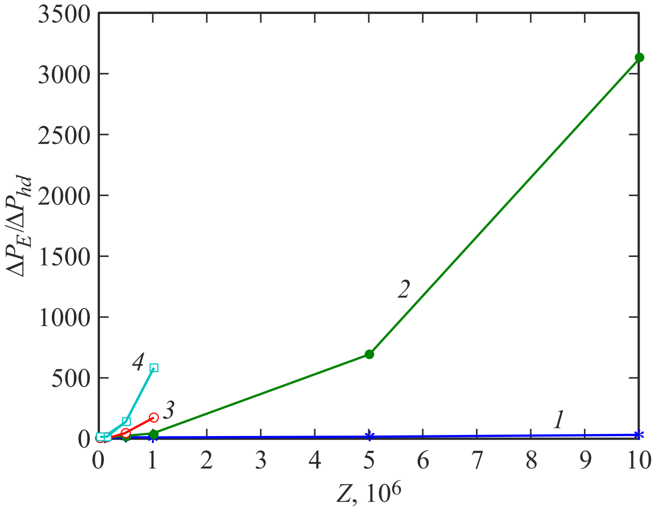

Figure 5. Relative electrical pressure with different heat transfer coefficients during condensation and charge numbers at condensation center: *1* — $\alpha = 10.27$, *2* — 40, *3* — 70, *4* — 100 kW/(m^2·K).

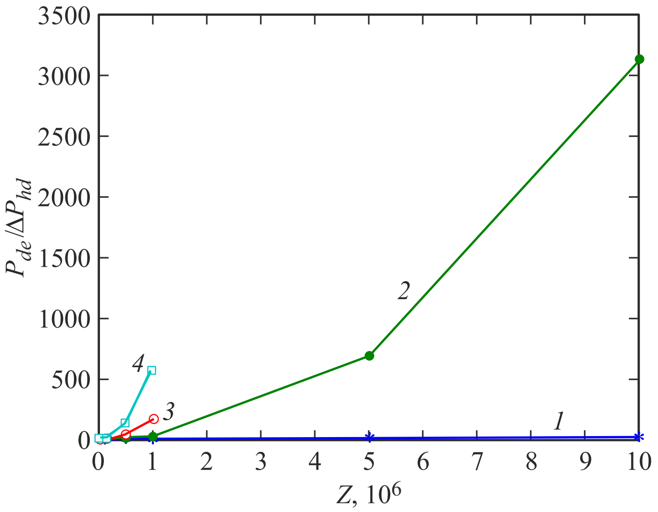

Figure 6. Relative pressure in a liquid droplet with different heat transfer coefficients during condensation and charge numbers at condensation center: *1* — $\alpha = 10.27$, *2* — 40, *3* — 70, *4* — 100 kW/(m^2·K).

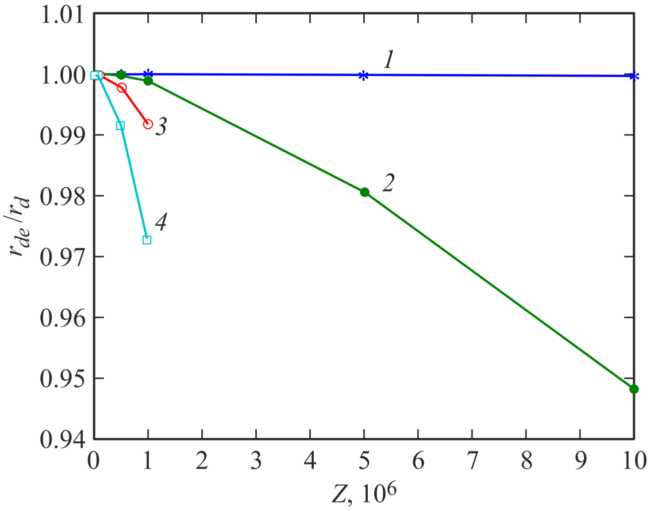

Figure 7. Relative radius of a liquid droplet with different heat transfer coefficients during condensation and charge numbers at condensation center: *1* — $\alpha = 10.27$, *2* — 40, *3* — 70, *4* — 100 kW/(m^2·K).

in the absence of an electric field. Now the iterative calculation formula is supplemented by the difference in electrical pressures. As a result, after several iterations we obtain the values of the radii of liquid droplets depending on the number of charges on the particle using the already obtained values of the radius of the humid air region from which the droplet condenses, and the same estimates of the heat transfer coefficient in case of droplet condensation. Changes of the droplet radius and pressure in it are obtained.

The results of the calculations show that the droplet radius in case of homogeneous condensation on charged particles depends on in practice two parameters: the number of charges and the heat transfer coefficient. However, a significant effect of charge at the same heat transfer coefficients occurs at $Z > 10^4$.

It follows from the calculations performed that the droplet radius practically does not change for a charge value from zero to the order of $1.6 \cdot 10^{-16}$ C, but the pressure of the liquid inside the droplet increases. Considering charges of greater importance does not make practical sense due to the fact that, as noted earlier, this can lead to the development of an electrical breakdown of the air.

When the electric field changes from zero to certain values, the presence of a charge leads to an increase in electric pressure, therefore, from the Laplace jump condition, the pressure of the liquid inside the droplet should increase, which is observed in calculations.

It also follows from the calculation results that the charge sign does not affect the condensation conditions. However, the effect of the electric field on diffusion was not taken into account in this consideration, when calculating the r_M region from which the moisture contained in the air is collected in a droplet. If we consider that water molecules have a dipole moment $d = 61 \cdot 10^{-29}$ C/m, then the presence of an electric field from a charged particle affects the motion of molecules towards the condensation center. In an electric field, a force acts on a molecule, which is equal to $\mathbf{F} = d\nabla E$. Therefore, this force leads to repulsion from the condensation center in case of a negatively charged condensation center, and it leads to attraction to the condensation center in case of a positively charged condensation center. The impact of the charge sign on the process of homogeneous condensation can actually be observed in some cases in [34]. Taking this into account may lead to a change of the value of the radius r_M, since the convective component will also be affected along with the diffusion component. This impact is not taken into account in this study, so the result is that the characteristics of homogeneous condensation do not depend on the sign of the charge. The authors reserve a more detailed analysis of this process for the future.

The impact of α in the framework of the proposed model of equilibrium droplet formation is related to the equality of the times of the condensation wave and heat release, depending on the heat transfer coefficient.

The condensation processes on charged particles discussed in this section may be relevant to the analysis of the stability of the boundary of a charged cloud, studied in Ref. [35].

There are papers that study the impact of electric fields on the displacement of the phase equilibrium of droplets in an electric field. However, these effects can also occur in electric fields significantly higher than the field of electrical breakdown, and therefore are not considered here. The analysis of the effect of alternating electric fields on the droplet parameters, which requires further more detailed analysis, is of greater interest.

Conclusion

Homogeneous condensation of water vapor from moist air occurring at electrically neutral centers and homogeneous condensation at charged centers were considered. The calculation of the parameters (radius, density, and pressure) of the formed condensate droplet was based on the hypothesis that the time of heat removal of the phase transition and the time of movement of the condensation wave of water vapor are equal. The values of pressure and density inside a droplet of water in a volume of moist air at an altitude of 1000 m were calculated. The proposed mechanism of homogeneous condensation can be applied at other altitudes, and in particular, it may be useful for predicting the formation of fogs near the earth's surface and near various facilities.

The effect of charge when homogeneous condensation occurs on particles carrying an electric charge was studied. The limits of the impact of the electric field on the parameters of homogeneous condensation were shown. It is found that the droplet radius decreases depending on the particle charge, and the pressure inside the droplet increases with the an increase in the number of charges and regardless of the charge sign.

Conflict of interest

The authors declare that they have no conflict of interest.

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