

# Micro Physical Model for Glaciogenic Particles in Clouds for Precipitation Enhancement

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**Abstract:** The detailed microphysical model is presented for the cases of injection the glaciogenic particles inside natural clouds; nowadays glaciogen aerosols are solid  $CO_2$  or liquid  $N_2$ . The model includes calculation for quantity of ice crystals that are forming in the overcooled areas, and effect for water droplets grow in a far zone near glaciogen. The comparison with common  $AgI$  is presented and discussed.

**Keywords:** Atmosphere, Clouds, Precipitation Enhancement, Glaciogens

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## 1. Introduction

Concentrations of the greenhouse gases are tightly increasing together with average planet temperature [1], so broader usage of active methods for atmosphere purification and precipitation enhancement seems appropriate mechanism for climate normalization. The developments of methods for the stimulation of precipitation inside natural clouds are based on the fact that a typical cloud can contain thousands and up to millions of tons of water. In addition to it, the sum of  $CO_2$  and water vapor in atmosphere put together the 95% in a mass of greenhouse gases now. Today's atmospheric carbon dioxide levels are the highest in comparison with last times in human history; the  $CO_2$  concentration was not be confined higher then 280 ppm in 100 years ago. Incoming pollution in atmosphere are studied carefully today [2, 3]. The  $CO_2$  input exceeds natural capacities for a process, so we have fast evident accumulation of  $CO_2$  in a free atmosphere. In view of the changes to the climate apart from global warming, we have more hot and arid summers last years, the record-setting hurricane seasons in ocean and etc. The development of technical methods for free atmosphere purification is very important today's world and mitigation approach is necessary in order to combat the imminent dangers related to climate changes. Rains in industrial regions from the middle of last Century to today have led to

soil deterioration up to  $pH = 3 - 4$  [4]. Therefore, different systems that are designed to work in precipitation regimes are necessary for atmosphere, soil and climate recovery. The idea of weather modification by precipitation enhancement was generated some time ago by Langmuir [5], but now is the time for the development of the similar ideas aimed at the man-made purification of the free atmosphere; one effective way is further wide development of the methods of precipitation enhancement. Resent approach [6] incorporates the possibility of stepwise  $CO_2$  purification in areas of the free atmosphere by spraying of alkaline compounds inside the clouds via an airplane. The alkali causes significantly increases of the  $CO_2$  solubility in rain droplets during their gravitational fall to provide the effective carbon transport to the ground, because concentrations of carbon ions in water are  $[HCO_3^-]$  and  $[CO_3^{2-}]$ , they increased in 10 and 100 times accordingly by each unit of  $pH$ . This future technology can really compensate for annual carbon emission by method application at 0.1% of planet surface [7, 8]. Motivation for rains usage, control and modification is obvious.

Today methods for precipitation enhancements have been developed in different countries around the world with wide practice [9, 10]. The most popular current technologies for precipitation stimulation are those that involve the sprinkling of hygroscopic or glaciogenic particles [11, 12]. At present time, the hygroscopic particles should be imported by the

airplane into special lowest part of natural convective clouds usually, where rising air flows exist with high velocity only in power cloud, which is difficult in reality. And besides, great number of such experiments with hygroscopic particles didn't bring any results, especially in seaside areas and hot seasons [13]. New glaciogen substances are necessary for development.

The new microphysical model is proposed here for the cases of injection the glaciogenic particles in natural clouds. The solid  $CO_2$  or liquid  $N_2$  are used as glaciogenic substances in clouds to enhance precipitation [14, 15]. The methods for precipitation enhancement into 'cold' clouds were developed in a cold climate in Moscow during last years [16], and series of experiments are performed in St Petersburg [17], so the glaciogenic substances are commonly used in Russia. Outlined in this paper is the temperature analysis in vicinity or further zones around flying glaciogenic particles. The influence for cloud medium is considered. Comparison of both considered glaciogens and *AgI* substance is performed.

## 2. Temperature Analysis

To intensify the precipitation enhancement in a clouds the glaciogen initiators are used. Such initiators include solid carbon dioxide or drops of liquid nitrogen with the temperature  $-79^\circ\text{C}$  or  $-196^\circ\text{C}$  correspondingly. Each glaciogen particle is evaporated inside the cloud that locally lowers the temperature around itself. In supercooled region near particles with temperature  $T \sim -40^\circ\text{C}$  and lower a homogeneous condensation begins and facilitates formation of a great number of ice crystals,  $N$ . The smallest ice crystals scattered in different directions with their rapid condensation growth due to initial water reserve of the cloud. At the same time, ice crystals collide with other droplets while moving, this process lowers the temperature of the cloud droplets with increase their condensation grow. Let's consider the area of the temperature field around the moving particle. An initial glaciogenic particle has a radius  $x_0$  with a few mm typically for  $CO_2$ , but it is decreases due to further evaporation. The surrounding spherical cooled volume located around, its radius is  $x_1$ , for details of this system refer to Figure 1. There  $T_0$  is the particle surface temperature, and  $T_1$  is surrounding temperature. The radii for glaciogen particle are  $x_0 = 2, 3$  or  $4$  mm in practice, but typical cloud droplets radii are  $r = 1 - 10$   $\mu\text{m}$ . Firstly, the stationary influence to Cloud in cooling area with  $T_1 < T < T_0$  is considered, note the droplet radii are  $r \ll x_0$ . The stationary heat equation in cylindrical coordinates are considered to describe the temperature fields in cooling area  $x_0 < x < x_1$ :

$$\frac{d^2T}{dx^2} + \frac{1}{x} \cdot \frac{dT}{dx} = 0 \quad (1)$$

The boundary conditions are:

$$T(x_0) = T_0; T(x_1) = T_1 \quad (2)$$

The solution together with boundary equations describes the temperature fields in cooling area  $x_0 < x < x_1$ :

$$\begin{aligned} T(x) &= C_1 \ln x + C_2 \\ C_1 &= \frac{T_0 - T_1}{\ln(x_0 / x_1)} \\ C_2 &= T_0 - (T_0 - T_1) \frac{\ln(x_0)}{\ln(x_0 / x_1)} \end{aligned} \quad (3)$$

The temperature was calculated in cooling zone around glaciogen particles of solid  $CO_2$  or liquid  $N_2$  then their radii are  $x_0 = 4, 3$  or  $2$  mm. Results of calculations according to stationary model (1-3) are presented at Fig.2a. The calculations accuracy is the temperature difference up to level of  $T(x_1) - T_1 = 0.5^\circ\text{C}$ . The radial cooling zone could be the  $x_1 = 50$  mm around glaciogens with radius  $x_0 = 4$  mm. All distances,  $x$ , are measured in radial direction from the center of coordinates according to the scheme of Figure 1.

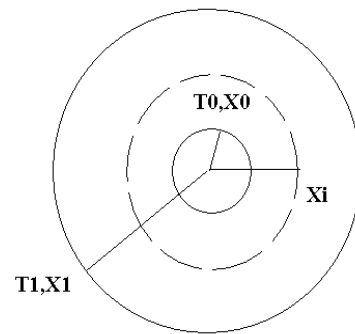


Figure 1. The scheme of the cooled volume around glaciogen particle.

However, this stationary model can't be applied or it has specific cases for realization, there is a proof below. Firstly, high speed,  $V$ , of falling glaciogenic particle provide a small time for action in surrounding, this fact conflicts to the stationary model utilization correctly. Let's consider this topic more carefully. The particle falling velocity  $V$  is determined usually by equality of gravity force  $F_g = mg = 4\pi\rho_p x_0^3 g / 3$  with the force of air resistance  $F_a$ . The fall velocity can be here approximated roughly using the stationary speed of droplet gravitation sedimentation, where  $g$  is the gravitational acceleration according to the following formulas:

$$F_g = F_a, mg = \rho_a \pi x_0^2 V^2 C_{Re} / 2 \quad (4)$$

here particle mass is  $m$ ,  $g$  is acceleration of gravity, the  $\rho_p$ ,  $\rho_a$ , are the density of solid (or liquid) particle and air respectively, and coefficient,  $C_{Re}$ , depends of Reynolds number,  $C_{Re} = 0.6 - 1$ . The fall velocity  $V(x_0)$  can be approximated roughly using the stationary speed of droplet gravitation sedimentation according to the following formulas:

$$V(x_0) \approx \sqrt{2x_0 g \rho_p / \rho_a} \quad (5)$$

The minimal acting time,  $t_1$ , in cooling zone is equal to the

diameter of this zone ( $2x_0$ ) divided to velocity from (5) of the flying particle. The time could be defined as follows  $t_1 \approx 2x_0 / [\sqrt{g\rho_p / \rho_a} \cdot \sqrt{2x_0}] = 10^{-2} \sqrt{2x_0}$ , there  $x_0$  is measured in meters, so  $t_1 = 6 - 9$  ms. Our physical model propose the plume after flying glaciogen particle that is formed by vaporized supercooled molecules with the same low temperature. It is necessary to introduce the time,  $t_2$ , for the plume living and action. The time  $t_2$  determines the diffusion time for glaciogenic molecules motion from the zone of plum that has the same radius as  $x_0$  according to our assumption. The diffusion motion of supercooled molecules from the center of plum is performed according to known diffusion/thermal solutions for length [20], as followed:

$$x_0 \approx \sqrt{D \cdot t_2} \quad (6)$$

The complete acted time is the sum:

$$\begin{aligned} t &= t_1 + t_2 \\ t_1 &\approx x_0^{0.5} (2g\rho_p / \rho_a)^{0.5} \\ t_2 &\approx x_0^2 / \chi \approx x_0^2 / D \end{aligned} \quad (7)$$

The plum in the central area has the same temperature as glaciogenic particle's temperature,  $T_0 = -196$  °C or  $-79$  °C. The time of action with account of supercooled molecules plume was calculated as  $t_2 = 0.2 - 0.8$  sec then glaciogen particle radii are  $x_0 = 2 - 4$  mm. The  $\chi$  is a thermal diffusivity,  $\chi \approx 0.2$  cm<sup>2</sup>/s. The model of the plume is illustrated by the falling water droplets in the study [21], and is confirmed by realistic numerical values in further calculations at present work. Let's return to the result of stationary model of cooling zone at Fig. 2a to show its further development. The time,  $t = t_{st}$ , for implementation of the model (1-3) should be in agreement with equation (6) where thermal wave length is  $x_l$ , so  $t_{st} \approx x_l^2 / D$  and  $t_{st} > 100$  seconds. As a result, we get necessary time too long in comparison with [21] for stationary model implementation. The comparison of necessary time with acted time in equation (6) gives  $t_{st} \neq t$ , so the stationary modal can't be used. Physically, it means that cooled evaporated molecules from glaciogen cannot reach far cooled distance at Fig.2a.

The interpretation for zone of influence of the moving particle should be changed. Non-stationary heat equation in cylindrical coordinates and its solution with the same boundary conditions (2) have the forms:

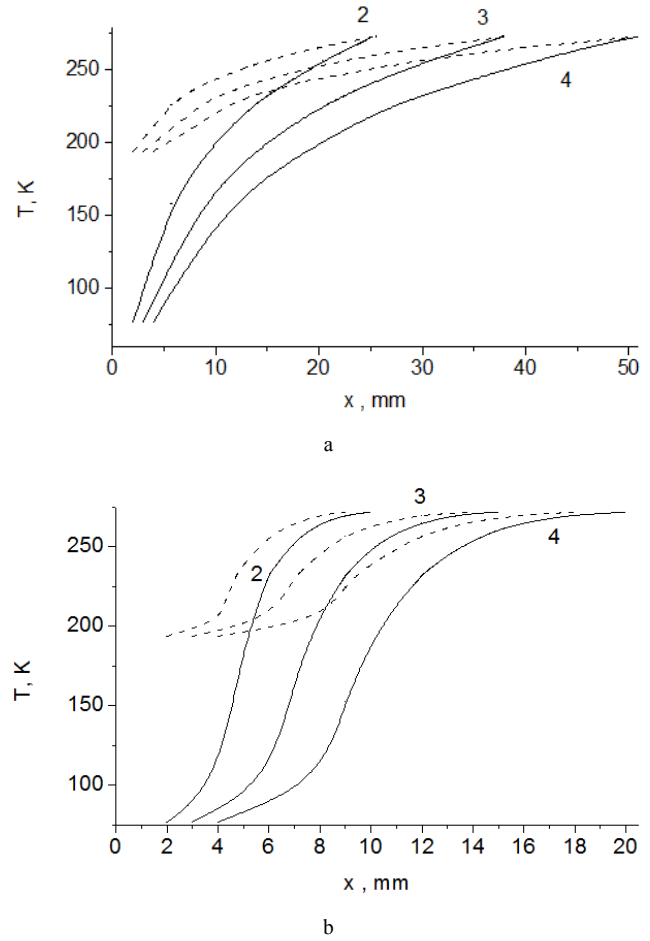
$$\begin{aligned} \frac{\partial T}{\partial t} &= \chi \left( \frac{\partial^2 T}{\partial x^2} + \frac{2}{x} \frac{\partial T}{\partial x} \right) \\ T(x, t) &= T_1 - T_0 \cdot \operatorname{erfc} \left[ \frac{x - x_0}{2\sqrt{\chi t}} \right] \end{aligned} \quad (8)$$

There  $\chi$  is a thermal diffusivity. The complementary error function for the argument,  $A(x) = (x - x_0) / (2\sqrt{\chi t})$ , could be calculated as simplest approximation of function  $\operatorname{erfc}(A(x)) \sim$

$\exp(-A^2(x))$  with the similar results to the next one. The next possible presentation [19] was used here to get more accuracy in far cooled zones up to  $x_l$ , as follow:

$$\operatorname{erfc}(X) \approx \pi^{-1/2} \left( \frac{x - x_0}{2\sqrt{\chi t}} \right)^{-1} \exp \left[ -\frac{(x - x_0)^2}{4\chi t} \right] \quad (9)$$

The acting time  $t$  was calculated according to (7) here. Result calculations of the cooling zone according to non-stationary model (8-9) are presented at Figure 2b.



**Figure 2.** Calculations of the temperature in cooling zone of the glaciogen particles of CO<sub>2</sub> (dashed lines) and N<sub>2</sub> (solid lines); the graphs titles 2, 3 or 4 correspond to appropriate radius of glaciogen particle  $x_0$ . The (a) corresponds to stationary model (1-3), but the (b) corresponds to non-stationary model (7-9).

As can be seen from Fig.2b the temperature decreases in surrounding media at the distance from the center of axe at Figure 1 as follows. The distance values for complete cooled zone are  $x_l = 19$ ; 14 or 9 mm approximately near CO<sub>2</sub> solid particle with its radii  $x_0 = 4$ ; 3 or 2 mm accordingly. Similar calculations were done around N<sub>2</sub> glaciogens with a radii  $x_0 = 4$ ; 3 or 2 mm, the zones of influence are  $x_l = 20$ ; 15 or 10 mm accordingly. The limit distances with temperature  $T_i = -40$ °C were calculated to separate two cooling regimes into surrounding media according to considered mechanisms of cooling influence. We suppose that if  $T_i < T < T_0$  the

homogeneous condensation predominates, but then  $T_i > T > T_l$  the host water droplets in cloud will increased in their sizes. The supercooled zone is located near glaciogen particle then  $x_i < x < x_0$ , but far cooled zone has radial location at distance  $x_i > x > x_l$ . Calculations were done with taking into account  $x_0$ , the results limit distances are  $x_i^{CO_2} = 9.50$ ; 7.15 or 4.76 mm for  $CO_2$  glaciogen with  $x_0 = 4$ ; 3 or 2 mm. The zones limits are  $x_i^{N_2} = 12.05$ ; 9.05 or 6.02 mm for liquid  $N_2$  with its droplet radii  $x_0 = 2, 3, 4$  mm correspondingly. All mentioned values of distances  $x_0, x_i, x_l$  are measured from the center of coordinates according to the scheme of Figure 1.

Note that smallest radius  $x_0 = 2$  mm is more real for liquid nitrogen droplets for realization in practice. Considered zone's boundary  $x_i$  around glaciogen particle is shown by dashed circle in scheme Fig. 1.

Let's estimate the dynamics of falling glaciogenic particles. Using formulas (5) and (15) for glaciogen evaporation, we estimated the living time of falling glaciogenic particle  $t_f$  up to its evaporation. The values are  $t_f \approx 180$  sec for  $CO_2$  particles, and  $t_f \approx 28$  sec for  $N_2$  liquid substance according to Figure 3. The current falling velocity and complete living way could be estimated from Fig. 3.

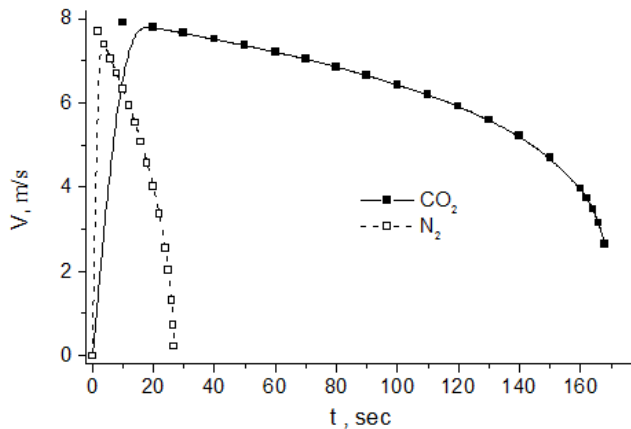


Figure 3. The speed and time for the falling evaporated  $CO_2$  particle or a  $N_2$  droplet taking into account its evaporation by Langmuir equation (15).

### 3. Resulting Number of Ice Crystals for Different Glaciogens

Firstly we consider the supercooled zone near glaciogen particles. Let's calculate the number of these crystals,  $N$ . The water droplets in clouds can be in supercooled state without its crystallization up to the low temperatures  $\sim -40^\circ C$  [12], only a narrow central supercooled zone near glaciogenic particle has sue condition for fast homogeneous crystallizations. Water droplets with small radii  $r < r_k$  should have sublimation and ones with bigger sizes have time for their condensation grow. The predominant mechanism here is a fast homogeneous condensation of water vapor with its fast crystallization into a large number of ice crystals. The most authors believe the start of homogeneous condensation correspond to oversaturation level  $s(T) \approx 3 - 6$ . The topic was studied in a science literature with details [22-26]. The

critical radius [18] for possibility to grow for water droplets can be calculated using the following formula taking into account:

$$r_k(T) = 2\sigma M / [\rho_w E T \ln(s(T))] \quad (10)$$

where  $\sigma$  is a water's surface tension, water molar mass is  $M$ , the  $E$  is a universal gas constant We assumed that droplets with  $r = r_k$  have fast crystallization in supercooled area.

Let's calculate the water in this area to build the number of ice crystals in supercooled zone. The initial typical value for supersaturation in local medium was considered as typical cloud value  $s_0 = 0.01$ , for example. It provides the water vapor amount  $W_v$  as follows:

$$W_v = \frac{P_0(1+s_0)}{P_{atm}} \cdot \frac{N_L}{N_A} M \quad (11)$$

Taking into account real pressure of water vapor/air and combination of Loschmidt,  $N_L = 2.68 \cdot 10^{25}$ , and Avogadro,  $N_A = 6.022 \cdot 10^{23}$ , constants, we obtain the resultant water mass in a water evaporated molecules  $W_v \approx 5$  g/m<sup>3</sup>. The total fast evaporation of initial cloud droplets was suggested in supercooled zone, so liquid water content  $W$  was added in further estimations, for example  $W = 1$  g/m<sup>3</sup>. The total water content to produce ice crystals will be  $W_w = W_v + W$ . Other vapor reorganization in medium was neglected here due to long necessary diffusion time. So the crystals number can be calculated by dividing of water vapor amount given by equation (11) to the ice crystals with critical radius  $r_k(T)$  from (10).

The supercooled area  $x_i$  near glaciogenic particle was calculated as a function of glaciogen initial radius  $x_0$  and can be obtained from Figure 2b then  $T < 233$  K. To get the rate of crystals production near glaciogen particle we use the time of diffusion motion,  $t_i$ , of molecules to form cooling zone. This time is  $t_0 \approx (x_0^2/D)$  obtained from equation (6). To begin with, the total number of ice crystals that are produced per second,  $N/t_i$  in s<sup>-1</sup>, could be calculated as a sum taken across all of supercooled zone inside glaciogen and at its temperature  $T = -79^\circ C$  for  $CO_2$  or  $T = -196^\circ C$  for  $N_2$ , as follows:

$$N_{x_0} = \frac{W_w 4\pi x_0^3 / 3}{t_0 \rho_w 4\pi r_{k,x_0}^3 / 3} \quad (12)$$

The calculated values for  $N_{x_0}$  are presented at Table 1 in row 1 for glaciogenic particles with radius  $x_0 = 4$  mm for solid  $CO_2$  particle and for liquid  $N_2$  droplet.

At the next step we incorporate wider supercooled zone  $x_i$  with the temperature  $T_i < T < T_0$  near glaciogen particle taking into account data at Figure 2b with  $x_i$  being a radius around glaciogen particles with appropriate local temperature  $T = -40^\circ C = 233$  K. The cooling zone for homogeneous condensation here was considered inside radial zone  $x_i < x < x_0$  and during time  $t_i = (x_i - x_0)^2 / D$ . Taking into account mentioned larger zone for homogeneous condensation we obtain the following equation:



$$N_{xi} \approx \frac{W_w x_i^3}{2\rho_w t_i} \left[ r_{k,x0}^{-3} + r_{k,xi}^{-3} \right] \quad (13)$$

Calculations of this number  $N_i$  of the ice crystals are performed according to the formula (13) and presented for at rows 2-4 of the Table 1 for a glaciogen radii  $x_0 = 4; 3$  or  $2$  mm correspondingly.

**Table 1.** Calculations (12-14) of producing of ice crystals numbers,  $N$ , near glaciogens.

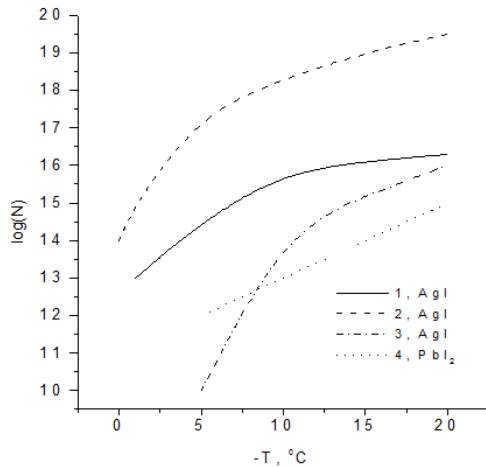
Crystals numbers, $N/s; N$	Solid $CO_2$	Liquid $N_2$
1) $N_{x0}, s^{-1}; x_0 = 4\text{mm}$ (eq.12)	$1.6 \cdot 10^{17}$	$2.5 \cdot 10^{18}$
2) $N_{xi}, s^{-1}; x_i$ then $x_0 = 4\text{mm}$ , (13)	$6.2 \cdot 10^{17}$	$8.3 \cdot 10^{18}$
3) $N_{xi}, s^{-1}; x_i$ then $x_0 = 3\text{mm}$	$4.7 \cdot 10^{17}$	$6.2 \cdot 10^{18}$
4) $N_{xi}, s^{-1}; x_i$ then $x_0 = 2\text{mm}$	$3.2 \cdot 10^{17}$	$4.2 \cdot 10^{18}$
5) $N_f; x_i$ then $x_0 = 4\text{mm}$ , (14)	$1.1 \cdot 10^{20}$	$2.3 \cdot 10^{20}$
6) $N_f/g, g^{-1}$	$4.2 \cdot 10^{20}$	$8.7 \cdot 10^{20}$

The total number of ice crystals,  $N_f$ , in a trajectory of gravitation fall of glaciogenic particle can be estimated by multiplication of  $N_{xi}$  to fly time  $t_f$ . The complete fly time presented at Fig. 3, so the complete number of ice crystals  $N_f$  can be calculated according to following formula:

$$N_f = t_f N_{xi} \quad (14)$$

The value  $N_f$  is listed at the 5<sup>th</sup> column of the Table 1 then particle radii are equal to 4 mm. The values in the last row of the Table 1 were obtained by dividing the previous data (5 row) to the particle initial weight  $4\pi\rho_0^3\rho_p/3$ , so data at 6<sup>th</sup> row represent the complete crystals number  $N_f$  per 1 gram of glaciogen,  $N_f/g$ .

The results of Table 1 suggest that the particles of liquid nitrogen are more effective, but they act only inside smaller cloud layer due to fast evaporation. For a physical description, the further collisions of ice crystals are useful. The moving ice crystals will collide with the water droplets with radius  $r$  inside cloud, this collision can cause fast crystallization in overcooled droplets with resulting fast droplet condensation grow.



**Figure 4.** Theoretical limit of ice crystals,  $N$  per 1 gram of  $AgI$  or  $PbI_2$  [26]. The graph 1 correspond to  $m = 1, \varepsilon = 0$ ; the graph 2 differs from (1) by cooled  $AgI$ ; the graph 3 differs from (1) by  $m = 0.996, \varepsilon = 0.014$ ; the graph (4) presents the best experimental data for  $PbI_2$ .

Let's compare obtained data from calculations for both  $CO_2$  and  $N_2$  with activity of widespread traditional glaciogens for precipitation enhancement, the  $AgI$  and  $PbI_2$ . In the monograph [26] the resultant ice forming properties of silver and lead iodide aerosols are investigated in details. Particular attention is given to determine of aerosol ice-forming activity limit, appropriate formulas and calculations were presented for these cases. The theoretical results for number of produced ice crystals are presented for  $AgI$  using at Fig.4. The theory predicts that  $AgI$  glaciogen activity depends strongly on wetting parameter  $m$  and the magnitude of deformation obtained at crystallization,  $\varepsilon$ .

Theoretical values are presented with comparison to work [26] which gives similar values from the 12 experimental studies from different groups. The best results were obtained in laboratory chambers at temperature  $T = -5^\circ\text{C} \div -15^\circ\text{C}$ , so values differ from theoretical limit within 10%. Note, that the best graph (2) was calculated for cooled molecules of  $AgI$  such conditions were possible in experimental chambers only, because in reality the  $AgI$  is a part of artillery shell with high temperature as a result. In experiments the  $AgI$  or  $PbI_2$  reagents were mixed with explosive substance in the central part (5 – 10%) of the artillery shell. The artillery shells with reagent in the central part blow up in a cloud in experiments, and reagent evaporates with formation of mono molecules or clusters [27, 28].

## 4. Water Droplets Increment in far Cooled Zone

Note that for considered here glaciogens ( $CO_2$  and  $N_2$ ) there are additional cooling effects for surrounding media in a extended zone, but  $AgI$  or  $PbI_2$  do not exhibit such effect due to principal difference of action. Firstly, large numbers of ice crystals are forming. The other effect is the additional fast grow of water droplets in extended zones surrounding moving glaciogen particle, there is  $T_l < T < T_i$ . The appropriate cooling far zone is created by glaciogen particle, this zone changes in time during particle evaporation with appropriate changes on its size and fall velocity, see Fig.2b. ice crystals cannot appear here because supersaturation is low, but host cloud droplets that are located here will have fast condensation grow due to additional temperature decrease  $T(x)$ . The condensation increment of the radius of usual water droplets trapped in far zone on the basis of the ratio of the Langmuir [18] as follows:

$$d_w^2 \approx \frac{8DMp_b[s(T)]}{ET(t)\rho_w} t + d_w^0 \quad (15)$$

here new diameter of water droplet is  $d_w = 2r$ ; its initial diameter is  $d_w^0$ , the water density is  $\rho_w$ , water molar mass is  $M$ , the  $E$  is a universal gas constant, the saturated water vapor pressure is  $p_b$ . The supersaturation near water droplet due to decreased temperature is  $s(T)$  given by equation (16). The

supersaturation function depends on surrounding temperature as follows:

$$s(T) = \ln(p(T)/p_b) \quad (16)$$

The pressure  $p(T)$  of saturated water vapor near water droplet increases according to low temperature in cooled zone, it can be determined on the basis of the relation [18]:

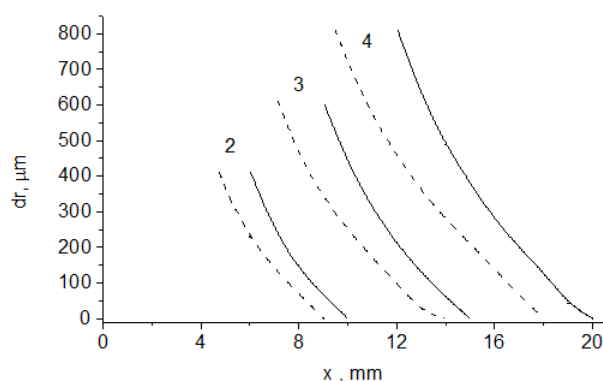
$$\ln[p(T)] = A - B/T(x) \quad (17)$$

here the coefficients are  $A=21.18$  and  $B=5367$  for CGC system. Then a water droplet is located in the zone of influence  $x_l < x < x_i$  at the scheme of Fig.1, a supersaturation  $s(T)$  near water droplet has strong increase. An appropriate super saturation  $s(T)$  near water droplet can be presented as follows:

$$s(x) \approx B(T_x^{-1} - T_1^{-1}) \quad (18)$$

Maximal value is  $s_{max} \approx 8$  near  $CO_2$  glaciogen particle then  $T_{x0} = -79^\circ C$ , or  $s_{max} \approx 50$  near  $N_2$  then  $T_{x0} = -196^\circ C$ . Next we determine the variable temperature in a field of influence of glaciogen particle during movement according to equation (9). Resulting relations for temperature (9) and associated supersaturation function from equation (18) were introduced according to increment formula (15) to get water droplet increments. Alternative scenario is using temperature and distance of cold extended zone near glaciogen directly at the Figure 2b. We use the equation (7) for affecting time  $t$  taking into account of supercooled molecules after flight of glaciogen particle. The equations were used for approximate calculations, then the initial radius in (15) correspond to the typical cloud droplet size,  $d_w^0 = 10 \mu m$ , but further calculation indicates a low sensitivity to initial droplet size. The resulting form for a water droplet increment is as follow:

$$r_w \approx 0.5\sqrt{d_w^2 - d_0^2} \quad (19)$$



**Figure 5.** The increment of water droplets in cooled zone of glaciogen, then  $0 > T > -40^\circ C$ . The graph enumeration 2; 3 or 4 correspond to the glaciogen's radius  $x_0 = 2; 3$  or  $4$  mm accordingly. The solid graphs correspond to  $N_2$  influence, the dashed ones to  $CO_2$ .

The corresponding results are given at Figure 5 and show great values for increment of water droplets in extended zone near glaciogen particles flying in clouds. One can see from

Figure 5 the significant influence of a cooling reagent in a distant zone onto observed water droplets. In particular, if initial radius of glaciogen is  $x_0 = 4$  mm, the radius of water droplets increases up to  $r = 810 \mu m$  in the vicinity of that zone. The influence of a distant zone on the environment of a cloud is enormous, considering the big extent of a zone influence is 20 or 18 mm for liquid nitrogen or solid ice respectively.

## Conclusion

The solid  $CO_2$  or liquid  $N_2$  glaciogen particles can be applied in cold or warm clouds. Appropriate models and formulas for complete actions are presented and justified by corresponding calculations describing utilization of solid  $CO_2$  or liquid  $N_2$  glaciogens. These substances are no expansive, they exhibit ecological safety and high efficiency in utilization. The comparison with common  $AgI$  reagent was considered for efficiency of ice crystal production.

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