

LABORATORY TESTS FOR INCREASING THE ICE-FORMING EFFICIENCY OF AD1 CRYSTALLIZING AGENT WITH THE ADDITION OF ZINC OXIDE NANOTUBES

Research article

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Abstract

At present, the redistribution of moisture in the direction necessary for man can be carried out on a large scale by artificially inducing precipitation. In this regard, scientists around the world are developing new projects to artificially increase precipitation. Projects carried out in different countries differ significantly, but most of these projects use pyrotechnic compositions containing silver iodide (AgI), which are equipped with anti-hail products. In the current state of active influences, the issue of developing new, more effective reagents is topical. This is confirmed by the fact that the average consumption of anti-hail products per 100 thousand hectares of protected territory in the period from 1967 to 1988 was 1107 pcs., and with the transition to the use of anti-hail products "Alazan-5" and "Alazan-6", equipped with more effective compositions, the consumption decreased to 531 pcs. A promising direction in the issue of increasing the ice-forming efficiency of the reagent is the use of various chemical additives to the main pyrotechnic composition of AD-1. It is proposed to use finely ground zinc powder as such an additive. Zinc oxide at a temperature of 906.2 °C begins to boil and turn into steam, which contributes to the formation of zinc oxide nanotubes during the combustion of the fuel charge of anti-hail missiles. The generation of ice-forming aerosol during rocket seeding of clouds is carried out at temperatures from 700 to 1400 °C.

Keywords: active influences, precipitation, statistical methods, redistribution of precipitation.

ЛАБОРАТОРНЫЕ ИСПЫТАНИЯ ПОВЫШЕНИЯ ЛЬДООБРАЗУЮЩЕЙ ЭФФЕКТИВНОСТИ КРИСТАЛЛИЗУЮЩЕГО РЕАГЕНТА АД-1 С ДОБАВКАМИ НАНОТРУБОК ОКСИДА ЦИНКА

Научная статья

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Аннотация

В настоящее время перераспределение влаги в нужном для человека направлении может быть осуществлено в больших масштабах путем искусственного вызывания осадков. В связи с этим ученые всего мира разрабатывают новые проекты по искусственному увеличению объема осадков. Проекты, реализуемые в разных странах, существенно отличаются друг от друга, но в большинстве из них используются пиротехнические составы, содержащие йодид серебра (AgI), которые оснащаются противоголовыми средствами. При нынешнем состоянии активных воздействий проблема разработки новых, более эффективных реагентов является актуальной. Это подтверждается тем, что средний расход противоголовых препаратов на 100 тыс. га охраняемой территории в период с 1967 по 1988 год составлял 1107 шт., а с переходом на применение противоголовых препаратов "Алазань-5" и "Алазань-6", снаряженных более эффективными составами, расход снизился до 531 шт. Перспективным направлением в вопросе повышения льдообразующей эффективности реагента является использование различных химических добавок к основному пиротехническому составу АД-1. В качестве такой добавки предлагается использовать мелкоизмельченный порошок цинка. Оксид цинка при температуре 906,2 °C начинает кипеть и превращаться в пар, что способствует образованию нанотрубок оксида цинка при сгорании топливного заряда противоголовых ракет. Образование льдообразующего аэрозоля при ракетном засеивании облаков происходит при температурах от 700 до 14000 °C.

Ключевые слова: активные воздействия, пиротехнический состав, реагент, льдообразующие частицы, цинк, наночастицы.

Introduction

The output of active ice-forming nuclei depends on many factors: composition formulation, design features of the aerosol generator; reagent dispersion conditions, etc. these factors determine the dispersity of the formed aerosol, which determines its structure and ice-forming activity. An increase in dispersity leads to an increase in the number of particles per unit mass of the reagent, however, small particles exhibit ice-forming activity at very low temperatures or under conditions of significant supersaturation of water vapor, which is not found in clouds. The formation of a large aerosol leads to the production of an aerosol active in the required temperature range (from -5 to -10 °C) without supersaturation of water vapor, but as the particles become larger, the yield from 1 gram of the composition decreases. To compensate for this, the formulation of crystallizing reagents provides for the formation of an ice-forming aerosol containing a core of combustion products, on the surface of which there are inclusions of AgI. This ensures the production of sufficiently large particles with a minimum consumption of AgI deposited on their surface. Formulations with ultra low AgI content ($\leq 0.5\%$) give a spectrum of fine particles whose ice-

forming efficiency is affected by dispersion conditions. An increase in the content of AgI leads to an increase in the yield of active ice-forming nuclei and an increase in the stability of their ice-forming efficiency, but this does not mean that the yield of ice-forming nuclei increases in proportion to the content of AgI [1], [2], [3], [4]. Due to the fact that most active exposure projects use pyrotechnic compositions containing from 2 to 20% silver iodide, in recent years, research efforts have been directed to explore the possibilities of using the reserves of existing reagents based on AgI. The presence of such possibilities is indicated by the fact that the ice-forming efficiency of pyrotechnic compositions based on silver iodide strongly depends on the production technology of the compositions, on the dispersion of the components included in the composition, on the terms and conditions of storage of pyrotechnic products, etc. Therefore, increasing the efficiency of pyrotechnic compositions is mainly achieved by experimental selection of components for each particular pyrotechnic product. Thus, in particular, finely ground zinc powder is introduced into experimental pyrotechnic compositions, which, in combination with silver iodide, leads to the formation of ice-forming particles with a crystal lattice closer to that of ice. During the combustion of the fuel charge of anti-hail missiles, zinc oxide begins to boil and turn into steam, which contributes to the formation of zinc oxide nanoclusters. Molecular clusters of zinc oxide are polynuclear complex compounds based on a framework of zinc atoms surrounded by ligands. The choice of zinc is due to the fact that the ice-like structure of zinc, like that of AgI, promotes the adsorption of H₂O molecules on its surface.

Materials and methods of research

Like most metals, zinc oxidizes in air, and a dense protective film of oxidized metal compounds forms on the metal surface. This film prevents the penetration of oxygen deep into the metal and thus stops further oxidation of the metal. The boiling point of zinc is 906.2 °C, and in the process of its thermal decomposition, many active atoms are formed, which create aggregates in the form of nanoclusters. Zinc interacts with water and hydrogen sulfide when the temperature rises, releasing hydrogen; and when strongly heated, it reacts with many gases: gaseous chlorine, fluorine, iodine. At temperatures below 200 °C, in addition to zinc oxide, there is zinc peroxide ZnO₂. Above 200 °C, only ZnO is stable [5], [6]. Zinc oxide nanoclusters belong to hydrophilic clusters; they can sorb the molecules of the environment on their surface, so they are surrounded by a shell. On the surface of a zinc oxide nanocluster, there can be up to several layers of H₂O molecules, which leads to the formation of a surface water film with its subsequent freezing when the critical thickness is reached. In such a film, microvolumes with oriented H₂O molecules are formed, which acquire an ice-like structure upon supercooling. At a sufficient size, these microvolumes serve as nuclei for ice crystals. "Multiphase" zinc oxide nanoparticles do not have standard interfaces; the concept of a phase or aggregate state is inapplicable to them. Phase diagram of the Zn–O system. The complete phase diagram of the Zn–O binary system has not been constructed. There are separate data on some parts of the phase diagram, its (T-x) cross-sections and phase transition in ZnO under the influence of external pressure [7]. In [8], the (T-x)-section of the phase diagram of the Zn–O system for the condensed state was first proposed (see Fig. 1).

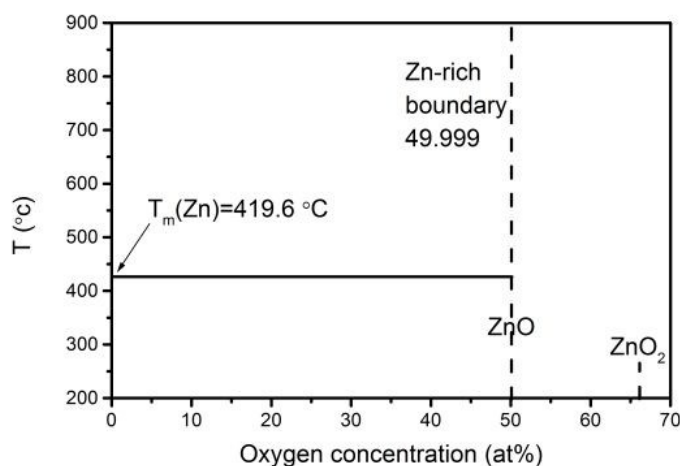
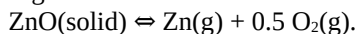


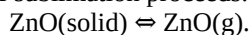
Figure 1 - (T-x)-section of the phase diagram of the binary system Zn–O at a pressure of 0.1 MPa

Note: *L* denotes the solubility of oxygen in Zn at different temperatures. $T_m(\text{Zn})$ – melting point of zinc (419.6 °C)

When heated, zinc oxide dissociates according to the reaction:



Simultaneously with this process, the process of sublimation proceeds:

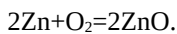


The study of zinc oxide evaporation by high-temperature mass spectrometry using platinum and quartz effusion chambers showed that in the temperature range of 1200-1450K, the vapor over ZnO(solid) consists of Zn atoms(g) and O₂(g) molecules, while ZnO(g) molecules were found only at temperatures above 1500 K [9]. At 1540 K, the composition of the gas-vapor phase over ZnO consists of 99.94% of zinc oxide dissociation products: Zn(g) and O₂(g). In the presence of an excess of zinc vapor, the evaporation rate of zinc oxide sharply increases (by a factor of 108-1010) [9]. The authors of [10] explain the

increase in the evaporation rate of ZnO in the presence of Zn vapor by the interaction of zinc with trace amounts of H₂O and CO₂, which leads to the formation of H₂ and CO, which reduce zinc oxide.

Some results of studies of ZnO nanostructures obtained in a dry and wet chamber

Previously, glass slides are installed at the bottom of the cloud chamber, which are covered with lids. A certain amount of the prototype (zinc) is placed on the graphite substrate of the reagent sublimation device. The large chamber is cooled to a predetermined temperature, and an artificial cloud environment is created in the chamber using an ultrasonic steam generator. A current of the order of 100-120 A is applied to the contacts of the graphite substrate, the substrate is heated to temperatures of 1200-2000 °C and zinc is sublimated. After that, the air in the chamber is mixed by fans. In the chamber, under the influence of high temperature, zinc interacts with oxygen to form ZnO oxide nanoparticles:



Next, zinc oxide nanostructures are deposited on glass slides, which are removed from the chamber and examined under an optical and electron microscope. During the sublimation of zinc in a dry chamber, zinc oxide nanoparticles are formed in the form of nanotubes with a diameter of about 30-50 nm and a length of several microns. Figure 2 shows a hollow nanostructure obtained in a dry chamber.

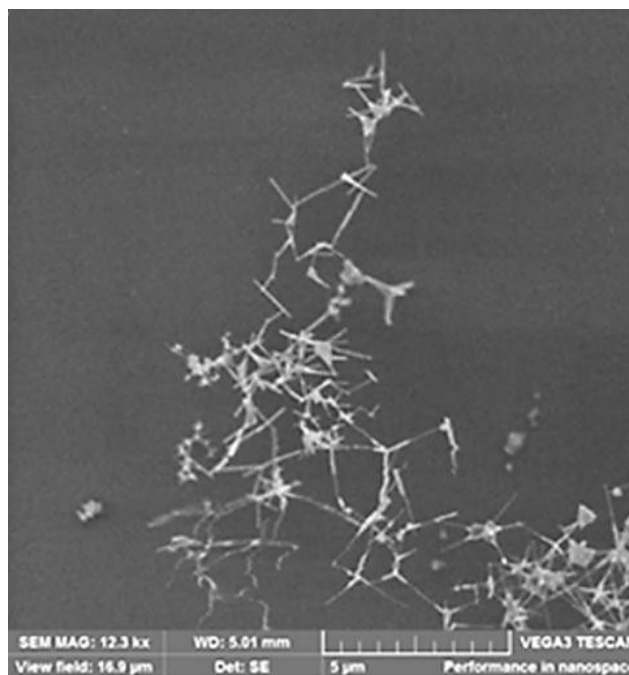


Figure 2 - Zinc oxide nanostructure obtained in a dry chamber

When zinc is sublimated in the presence of water vapor, hollow nanostructures (up to 300 μm in size) are formed, the formation of which depends on the water content in the chamber. At low water content, nanostructures are formed in large quantities, and disappear with increasing water content. Zinc oxide nanostructures consist of nanotubes, the dimensions of which are 1-5 nm. Figure 3 shows a photograph of a zinc oxide nanostructure taken with a TESCAN electron microscope.

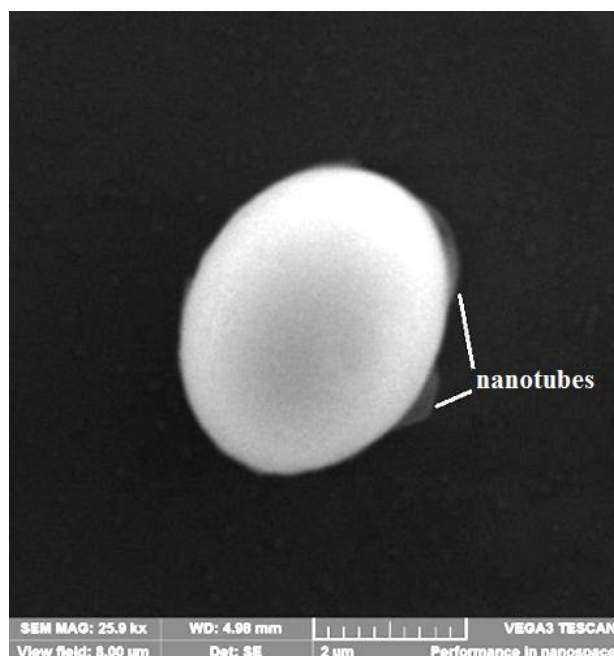


Figure 3 - Nanostructure of zinc oxide obtained in water vapor

As can be seen from the figures, hollow ZnO nanostructures obtained by sublimation of zinc oxide in the presence of water vapor, as well as in a dry chamber, consist of the same elements – zinc oxide nanotubes. An analysis of the literature data shows that the properties of water strongly depend on the nanotube diameter. When the nanotube diameter changes from 1.05 to 1.52 nm, the phase transition temperature of water changes from +13 to +138 °C [7], [8], [9]. It should be noted that zinc oxide nanoclusters belong to hydrophilic clusters; they can sorb the molecules of the environment on their surface, so they are surrounded by a shell. On the surface of a zinc oxide nanocluster, there can be up to several layers of H₂O molecules, which leads to the formation of a surface water film with its subsequent freezing when the critical thickness is reached. In such a film, microvolumes with oriented H₂O molecules are formed, which acquire an ice-like structure upon supercooling. With a sufficient size, these microvolumes serve as nuclei for ice crystals [1], [11]. For each sample, the yield of crystallization nuclei was calculated according to the method [11].

Table 1 - Ice forming component test results AD-1 at different temperatures

Temperature, °C	Reagent AD-1, g	Specific output, g ⁻¹
-6.8	0.01	6.5E11
-7.0	0.01	5.3E12
-7.2	0.01	5.3E12
-7.3	0.01	2.1E12
-7.5	0.01	3.2E12
-8.2	0.01	3.3E12
-8.7	0.01	1.3E12
-9.4	0.01	1.6E12
-9.7	0.01	6.4E12
-9.8	0.01	2.3E12
-10.2	0.01	1.2E12
-10.6	0.01	1.2E12
-11.9	0.01	5.7E12
-13.4	0.01	4.4E12

In laboratory studies, finely dispersed zinc powder was used, which was introduced into the initial pyrotechnic composition AD-1 in relation to its total mass – 3%, 6% and 9%, respectively. It was found that the experimental reagent AD-1 with the addition of zinc in the amount of 6% of the total mass of the pyrotechnic composition has the highest activity. The test results are presented in table 2.

Table 2 - Average values of the yield of crystallization nuclei of the ice-forming component of AD-1 with the addition of zinc (6%) at different temperatures

Temperature, °C	Reagent AD-1+Zn(6%)	Specific output, g ⁻¹
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-5.0	0.00052	1.8E13
-4.2	0.00052	1.2E13
-3.4	0.00052	1.0E13
-2.2	0.00052	1.2E13
-2.0	0.00052	4.0E12
-1.6	0.00052	4.7E12
-1.1	0.00052	9.0E12
-1.0	0.00052	6.6E12
-11.2	0.01	9.0E13
-10.6	0.01	5.4E13
-10.4	0.01	1.4E14
-10.2	0.01	6.3E13
-10.0	0.01	6.0E13
-9.6	0.01	5.2E13
-7.5	0.01	6.9E13

Table 3 presents the results of laboratory studies of the ice-forming efficiency of the AD-1 composition with various mass concentrations of zinc.

Table 3 - Specific yield of AD-1 reagent particles with addition of zinc

t, °C	-11	-9	-7	-5
C _{Zn} , %	Specific output, g- ₁	Specific output, g- ₁	Specific output, g- ₁	Specific output, g- ₁
0	3.2 x 10 ¹²	2.7 x 10 ¹²	2.5 x 10 ¹²	6.5 x 10 ¹¹
1	8.8 x 10 ¹²	7 x 10 ¹²	5.6 x 10 ¹²	1.2 x 10 ¹²
2	1.5 x 10 ¹³	1.2 x 10 ¹³	8.2 x 10 ¹²	4.5 x 10 ¹²
3	2.8 x 10 ¹³	2.2 x 10 ¹³	1.1 x 10 ¹³	7.2 x 10 ¹²
4	4.6 x 10 ¹³	3.6 x 10 ¹³	1.6 x 10 ¹³	9.5 x 10 ¹²
4.7	6.5 x 10 ¹³	5.2 x 10 ¹³	2.5 x 10 ¹³	1.1 x 10 ¹³
5	7.0 x 10 ¹³	5.9 x 10 ¹³	3.0 x 10 ¹³	1.3 x 10 ¹³
5.5	7,3 x10 ¹³	6,2 x10 ¹³	3,3 x10 ¹³	1,5 x10 ¹³
6	7.5 x 10 ¹³	6.3 x 10 ¹³	3.4 x 10 ¹³	1.6 x 10 ¹³
6.6	6.5 x 10 ¹³	5.2 x 10 ¹³	2.5 x 10 ¹³	1.4 x 10 ¹³
7	5.2 x 10 ¹³	4.3 x 10 ¹³	1.9 x 10 ¹³	1.0 x 10 ¹³
8	3.4 x 10 ¹³	3.0 x 10 ¹³	1.4 x 10 ¹³	7.2 x 10 ¹²
9	2.2 x 10 ¹³	1.9 x 10 ¹³	1.0 x 10 ¹³	5.3 x 10 ¹²

The specific yield of reagent particles depending on the concentration of zinc oxide is shown in figure 4.

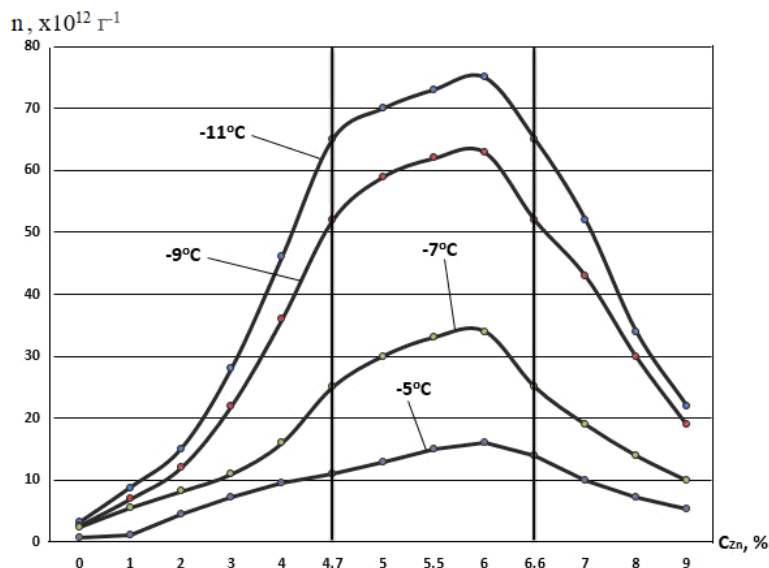


Figure 4 - Dependence of the specific yield of ice-forming particles on concentrations of zinc in pyrocomposition AD-1 for different temperature levels

The graph shows that the maximum yield of ice-forming particles is provided in the zinc concentration range of 4.7-6.6 wt. %. The corresponding area on the chart is marked with vertical lines. Numerous experiments have established that when finely dispersed zinc powder is added to the composition of the initial ice-forming fuel AD-1 in a ratio of 6% to the total mass of the composition, it increases the yield of ice-forming particles in the temperature range from 0 to -14 °C. The increase in the yield of active ice-forming particles in the temperature range under study is explained by the fact that during the thermal decomposition of zinc oxide, many active atoms are formed, which create aggregates in the form of ZnO nanoclusters. They are the basis on which water molecules are stacked, forming ice crystals. Thus, the addition of finely ground zinc powder to the main pyrotechnic composition provides a significant increase in the ice-forming efficiency of the reagent in the temperature range from 0 to -14 °C. In determining the effectiveness of crystallizing reagents, environmental cleanliness is of great importance. Proposed as an additive to the main pyrotechnic composition, zinc oxide powder has been known for its antibacterial properties since time immemorial [12]. It was used during the reign of the pharaohs, and historical records show that zinc oxide was used in many ointments to treat injuries and boils as early as 2000 BC [13]. It is still used in sunscreens, as an additive, as a photoconductive material, LEDs, transparent transistors, solar cells, memory devices, cosmetics and catalysts [7], [14].

Conclusion

The obtained results of laboratory tests showed that the presence of finely dispersed zinc powder in the composition of the initial ice-forming fuel AD-1 in relation to the total mass of the composition of 6% sharply increases the yield of ice-forming particles in the entire range of accepted temperatures. At the same time, the yield of ice-forming particles at a temperature of minus 12 °C increases by almost an order of magnitude, and in the temperature range from minus 2 °C to minus 4 °C, it almost doubles. It was found that the ice-forming properties of zinc oxide nanoclusters depend on the environmental conditions where sublimation is performed. During sublimation in a dry chamber, zinc oxide clusters with a diameter of about 30-50 nm are formed [11]. During sublimation in a large cloud chamber in the presence of water vapor and at negative temperatures, zinc oxide clusters are formed with sizes from 50 nm to 10 μm, which have a hollow structure and consist of many nanotubes with a diameter of 1-5 nm. Nanoclusters formed during sublimation in a dry chamber do not have ice-forming properties, while nanoclusters formed during sublimation of zinc in the presence of water vapor have good ice-forming properties, with a specific yield of up to 10¹³ g⁻¹. On the basis of the original ice-forming fuel AD-1, a method has been developed for obtaining an effective pyrotechnic composition for equipping meteorological rockets designed for active impact on thunderclouds in order to artificially increase liquid precipitation and combat hail. This composition can also be used in the creation of promising ground-based generators for active influence on supercooled fogs in order to provide favorable meteorological conditions for the operation of spaceports, airports and road communications.

Конфликт интересов

Не указан.

Рецензия

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Conflict of Interest

None declared.

Review

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Список литературы / References

1. Абшаев А.М. Руководство по организации и проведению противорадовых работ / А.М. Абшаев, М.Т. Абшаев, М.В. Бареева и др. — Нальчик: Печатный двор, 2014. — 499 с.
2. Vonnegut B. Experiments with Silver-Iodide Smokes in the Natural Atmosphere / B. Vonnegut // Bull. Amer. Meteor. Soc. — 1950. — Vol. 31. — 65 p.

3. Никандров В.Я. Искусственные воздействия на облака и туманы / В.Я. Никандров. — Л.: Гидрометеиздат, 1959. — 191 с.
4. Закинян Р.Г. Кинетика роста льда на поверхностях предметов различных форм, помещенных в поток переохлажденного аэрозоля / Р.Г. Закинян // Материалы V научно-технической конференции СК ГТУ. — Северо-Кавказский горно-металлургический институт, 2001. — С. 20.
5. Жариков В.А. Основы физико-химической петрологии / В.А. Жариков. — М.: МГУ, 1976. — 420 с.
6. Внукова Н.Г. Наноматериалы и нанотехнологии / Н.Г. Внукова, Г.Н. Чурилов // Учебное пособие по лабораторному практикуму. — Красноярск: СФУ, 2007. — С. 103.
7. Özgür Ü. Comprehensive Review of ZnO Materials and Devices / Ü. Özgür, Ya.I. Alivov, C. Liu et al. // J. Appl. Phys. — 2005. — Vol. 98. — DOI: 10.1063/1.1992666.
8. Wriedt H.A. The O-Zn (Oxygen-Zinc) System / H.A. Wriedt // J. Phase Equilib. — 1987. — Vol. 8. — № 2. — P. 166-167.
9. Казенас Е.К. Испарение оксидов / Е.К. Казенас, Ю.В. Цветков. — М.: Наука, 1997. — 543 с.
10. Anthrop D.F. Sublimation and Thermodynamic Properties of Zinc Oxide / D.F. Anthrop, A.W. Searcy // J. Phys. Chem. — 1964. — Vol. 68. — P. 2335-2342.
11. Khuchunaev B.M. Researches of ice-forming efficiency of products of sublimation of pyrotechnic compositions consisting of silver iodide agi particles and zinc oxide nanotubes / B.M. Khuchunaev, Kh-M.Kh. Baysiev, S.O. Gekkieva et al. // IOP Conference Series Materials: Science and Engineering. — 2021. — DOI: 10.1088/1757-899X/1083/1/012097.
12. Roselli M. Zinc Oxide Protects Cultured Enterocytes from the Damage Induced by Escherichia coli / M. Roselli, A. Finamore, I. Garaguso et al. // Journal of Nutrition. — 2004. — № 133. — P. 4077-4082. — DOI: 10.1093/jn/133.12.4077.
13. Sawai J. Quantitative Evaluation of Antibacterial Activities of Metallic Oxide Powders (ZnO, MgO and CaO) by Conductimetric Assay / J. Sawai // J Microbiol Methods. — 2003. — № 54. — P. 177-182.
14. Patent 20050191257 A1 United States. Dry Deodorant Containinga Sesquiterpene Alcohol and Zinc Oxide / Brahms J., Mattai J., Jacoby R. et al.; Current Assignee: Colgate Palmolive Co. — № 10/789,153; filed: 27.02.2004; published: 01.09.2005. — 17 p.

Список литературы на английском языке / References in English

1. Abshaev A.M. Rukovodstvo po organizacii i provedeniyu protivogradovyh rabot [Guidelines for organizing and carrying out anti-hail works] / A.M. Abshaev, M.T. Abshaev, M.V. Berekova et al. — Nalchik: Pechatnyi dvor, 2014. — 499 p. [in Russian]
2. Vonnegut B. Experiments with Silver-Iodide Smokes in the Natural Atmosphere / B. Vonnegut // Bull. Amer. Meteor. Soc. — 1950. — Vol. 31. — 65 p.
3. Nikandrov V.Ya. Iskusstvennye vozdejstviya na oblaka i tumany [Artificial Influences on Clouds and Fogs] / V.Ya. Nikandrov. — L.: Gidrometeizdat, 1959. — 191 p. [in Russian]
4. Zakinyan R.G. Kinetika rosta l'da na poverhnostyah predmetov razlichnyh form, pomeshchennyh v potok pereohlazhdenного aerolya [Kinetics of Ice Growth on the Surfaces of Objects of Various Shapes Placed in a Stream of Supercooled Aerosol] / R.G. Zakinyan // Materialy V nauchno-tehnicheskoy konferencii SK GTU [Proceedings of the V Scientific and Technical Conference NC STU]. — North Caucasian Mining and Metallurgical Institute, 2001. — P. 20. [in Russian]
5. Zharikov V.A. Osnovy fiziko-himicheskoy petrologii [Fundamentals of Physical and Chemical Petrology] / V.A. Zharikov. — Moscow: Moscow State University, 1976. — 420 p. [in Russian]
6. Vnukova N.G. Nanomaterialy i nanotekhnologii [Nanomaterials and Nanotechnologies] / N.G. Vnukova, G.N. Churilov // Uchebnoe posobie po laboratornomu praktikumu [Textbook for laboratory practice]. — Krasnoyarsk: SFU, 2007. — P. 103. [in Russian]
7. Özgür Ü. Comprehensive Review of ZnO Materials and Devices / Ü. Özgür, Ya.I. Alivov, C. Liu et al. // J. Appl. Phys. — 2005. — Vol. 98. — DOI: 10.1063/1.1992666.
8. Wriedt H.A. The O-Zn (Oxygen-Zinc) System / H.A. Wriedt // J. Phase Equilib. — 1987. — Vol. 8. — № 2. — P. 166-167.
9. Kazenas E.K. Isparenie oksidov [Evaporation of Oxides] / E.K. Kazenas, Yu.V. Tsvetkov. — М.: Nauka, 1997. — 543 p.
10. Anthrop D.F. Sublimation and Thermodynamic Properties of Zinc Oxide / D.F. Anthrop, A.W. Searcy // J. Phys. Chem. — 1964. — Vol. 68. — P. 2335-2342.
11. Khuchunaev B.M. Researches of ice-forming efficiency of products of sublimation of pyrotechnic compositions consisting of silver iodide agi particles and zinc oxide nanotubes / B.M. Khuchunaev, Kh-M.Kh. Baysiev, S.O. Gekkieva et al. // IOP Conference Series Materials: Science and Engineering. — 2021. — DOI: 10.1088/1757-899X/1083/1/012097.
12. Roselli M. Zinc Oxide Protects Cultured Enterocytes from the Damage Induced by Escherichia coli / M. Roselli, A. Finamore, I. Garaguso et al. // Journal of Nutrition. — 2004. — № 133. — P. 4077-4082. — DOI: 10.1093/jn/133.12.4077.
13. Sawai J. Quantitative Evaluation of Antibacterial Activities of Metallic Oxide Powders (ZnO, MgO and CaO) by Conductimetric Assay / J. Sawai // J Microbiol Methods. — 2003. — № 54. — P. 177-182.
14. Patent 20050191257 A1 United States. Dry Deodorant Containinga Sesquiterpene Alcohol and Zinc Oxide / Brahms J., Mattai J., Jacoby R. et al.; Current Assignee: Colgate Palmolive Co. — № 10/789,153; filed: 27.02.2004; published: 01.09.2005. — 17 p.