Investigation of transport properties of porous coatings from nanoparticles of aluminum oxide

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Abstract. In this work, coatings of nanoparticles of aluminum oxide are investigated. Photos were obtained using an electron and optical microscope. A method is proposed for the formation of a coating of nanoparticles with and without agglomerates. The transport properties of nanoparticles of aluminum oxide, silicon carbide, titanium oxide and diamond have been investigated. The effect of agglomerates of nanoparticles on the rise of liquid has been determined.

1. Introduction
About one fourth of the earth's surface area is permafrost. The soil in the permafrost regions has been at temperatures below 0 °C for more than a thousand years. During the construction of various heat-generating structures, such as residential buildings and industrial facilities, the soil begins to thaw and deform. Due to deformation, the foundations of structures are destroyed, which leads to disasters and material damage. In the Russian Federation, on the territory of the permafrost regions, there are strategic reserves of precious metals, fresh water, oil and gas. Extraction and development of new fields requires the installation of soil cooling systems - thermal stabilizers. The main task of thermal stabilizers or seasonal cooling devices is to prevent soil melting. However, in the construction of extended objects, it is necessary to use composite horizontal or vertical thermal stabilizers, where the problem of reducing thermal resistance at the junction, as well as transport of liquid and intensification of heat transfer inside the device is urgent. The thermal resistance of the heat stabilizer depends on the characteristics of the joint, the surface structure of the evaporator, the material and orientation of the pipes and the heat carrier [1]. To improve the transport of liquid from the lower generatrix to the upper one, it is proposed to form a porous coating of nanoparticles on its surface in a slightly inclined tube of the evaporator of the thermal stabilizer. The deposition of nanoparticles on the surface of the evaporator of the thermal stabilizer will lead to an improvement in heat transfer and a decrease in thermal resistance [2,3].

To improve the height of the capillary rise of a liquid, various methods are used, one of which is the formation of a layer of nanoparticles with a microstructure in the evaporator. In [4, 5], the technology of obtaining a coating from nanoparticles using the processes of evaporation of a colloidal liquid with the addition of nanoparticles of aluminum oxide is described. It is shown that this technology can increase the rise of liquid in the layer of nanoparticles by 100%.

In [6], a study of the effect of nanoparticles on the thermal efficiency of a heat pipe is presented. It was found that a mixture of nanoparticles in water with the addition of a surfactant increases the efficiency. This effect did not manifest itself when the nanoparticles were abandoned and led to the appearance of dry spots, which increased the thermal resistance.
In [7], the analysis of the effect of nanoparticles on the thermal resistance of a thermosyphon was carried out. It is shown that the use of a solution of nanoparticles as a working fluid makes it possible to reduce the thermal resistance of the device.

The study of the effect of nanoparticles on heat transfer was carried out in [8]. It is shown that the use of a nanoparticle coating in a copper evaporator makes it possible to improve the heat transfer during evaporation by more than 100%.

Surface wetting was studied in [9]. The coating was obtained on the surface of an aluminum-magnesium alloy using a pulsed laser of nanosecond duration. Samples of substrates were abraded and polished prior to application. An X-ray analysis of the surface shows an increase in the amount of oxygen on the coating, which contributes to the contact angle hysteresis. The proposed coating retained stable properties for up to 120 days, after which the contact angle decreased.

The study of the properties of coatings from nanoparticles of aluminum oxide is shown in [13-14]. To improve the transport of the coolant in the evaporator of the thermosyphon, coatings of nano- and microparticles are used in the evaporator.

According to the known data, it can be said that at present there are various methods for intensifying the heat exchange during evaporation, which makes it possible to reduce the thermal resistance of the thermosyphon. It is necessary to study the properties of porous coatings, the effect on liquid capillary rise and improve these properties.

2. Obtaining nanoparticles of aluminum oxide

The nanoparticles used in this work were obtained under three different conditions. In the first case, a chemical method was used for the preparation of a sol with transfer to a gel to obtain nanoparticles of a given size. In the second and third cases, the thermal decomposition of aluminum sulfate was used. The difference consisted in the use of cellulose for the third case.

The sol-gell technology has long been known to the scientific community, but in practice it is necessary to observe the accuracy of calculations when carrying out a chemical reaction. In this work, aluminum alkali was used to obtain a dispersion system. First, a solution of aluminum salt and potassium alkali was prepared. To stabilize the solution, a nonionic surfactant was added to it. Then, the solution was filtered with a micron filter and dried at 120 °C until water was completely removed. This method was used to obtain large particles of aluminum oxide (Fig. 1a).

The essence of the thermal decomposition method was the calcination of an aluminum salt at a temperature of more than a thousand degrees Celsius. The resulting powder was mixed in a mortar to obtain a homogeneous mass. When the particles were applied to the surface of the substrate, a layer of particles similar in structure to a sponge was formed. The typical particle size was from 1 to 10 microns.

To reduce the particle size, it was proposed to use cellulose from 100% cotton [10]. A solution of nanoparticles in water was prepared at the rate of 50 g per 400 ml of distilled water. Cellulose was impregnated with a solution of aluminum salt in water and placed in a crucible. Then carried out the drying of the resulting mass at 190 °C in a drying oven. As a result, cellulose bars were obtained with the addition of aluminum sulfate particles. The crucible was placed in a muffle furnace, where thermal decomposition of the resulting mass took place at a temperature of 1200 °C. The characteristic particle size obtained by these methods was less than 1 micrometer, and the structure was similar to many fine fibers. Experimental models were prepared for inserting a layer of nanoparticles and studying its properties. The substrates were cleaned with an abrasive, to remove the residues of which the surface was washed with an alkali solution and then with distilled water. The coating was formed in several stages. Nanoparticles were dissolved in water to obtain a solution with a mass concentration of aluminum oxide 0.01 ± 0.005%. Then the solution was stirred and passed through a thin nozzle, which is necessary to obtain a homogeneous colloidal liquid. Then, the resulting liquid was filtered using a filter with a permeability of less than 1 micrometer.

To obtain a coating, the substrate was heated to 200 °C, and then a drop of liquid was applied to it, which quickly boiled and evaporated. During boiling of the nanofluid on the substrate surface, the liquid phase was removed, and the nanoparticles were deposited on the plate and a coating was formed [11]. To strengthen the bond of the nanoparticle layer with the substrate, the latter was briefly heated to a temperature of 1000 °C.
It can be seen in the figure that the smallest particles can be obtained by thermal decomposition of cellulose with the addition of an aluminum salt. And when choosing a sol-gel method, the particles form agglomerates with a size of more than 10 micrometers.

![Figure 1](image.jpg)

**Figure 1.** Photographs of a surface coated with aluminum oxide particles. a-particles obtained by the sol-gel method, b-particles obtained by thermal decomposition of aluminum sulfate, c-particles obtained by thermal decomposition of aluminum sulfate on cellulose.

As can be seen, during the thermal decomposition of aluminum sulfate on the cellulose surface, particles are obtained with a smaller size than during thermal decomposition without deposition of aluminum sulfate. When choosing a sol-gel method, the particles formed large spherical agglomerates.

3. **Forming a layer of nanoparticles**

To improve the transport properties of the coating, a nanoparticle structure was formed, similar to the method described in [12]. To form the coating, a substrate of A85 grade aluminum was chosen.

The experiments were carried out under normal conditions and a temperature of 30 degrees Celsius. The preparation of a coating with a microstructure in the form of microtrenches was carried out by preparing a solution of nanoparticles in distilled water with a concentration of 0.01% and adding isopropanol to this solution in a ratio from 1 to 99. As a result, a mixture of dissolved nanoparticles in water and alcohol was obtained. The concentration of nanoparticles in the solution was 0.0001 ± 0.005%. To remove agglomerates and large particles (more than 1 μm), the solution was defended for an hour. To form trenches, it is necessary to use an air blower with an air flow temperature of 510 °C and a flow rate of 700 l/m. A mixture of nanoparticles was supplied to the substrate surface at a given flow rate, which spread out under the influence of the air flow and quickly evaporated. After the deposition process, a nanostructure was formed on the substrate surface, which can be seen in Figure 2. Liquid transport in such a structure occurs not only in the pores of the coating, but also in individual capillaries - microtrenches.

![Figure 2](image.jpg)

**Figure 2.** Photo of a coating with micro trenches
4. Transport properties

To determine the effect of the formation of a microstructure in a layer of aluminum oxide nanoparticles, experiments were carried out to determine the maximum height of the capillary rise of a liquid. The samples were placed vertically and secured with a tripod, and the liquid was supplied to the lower base of the metal plate using a thin needle. The height of the liquid rise was determined by filming its movement over the surface of the sample.

To carry out experiments to determine the height of liquid rise, substrates of nickel of rectangular shape, with dimensions of 2 × 6 cm, were prepared. Soapy and again distilled water.

First, a colloidal solution of nanoparticles in water was prepared, which was intensively mixed. The height of the liquid rise was measured in the range of concentrations of aluminum oxide nanoparticles obtained at 1200 °C, in a solution from 1.54% to 0.021%. It was found that with an increase in the volume of the deposited nanofluid, the rise height increases. The maximum lifting height was reached at a concentration of nanoparticles in the solution of 0.067%. Therefore, for further experiments, it was chosen equal to 0.07 ± 0.005%. The height of the rise increases with increasing, but after reaching the extreme point, it begins to decline.

The first series of experiments was carried out to determine the liquid rise for particles obtained at temperatures of 950 and 1200 °C. In fig. 3 shows the measurement data of the lifting height of the liquid. It was found in the experiments that the lifting height of the liquid for coating the particles obtained at 950 °C is 15 mm higher than for the particles obtained at 1200 °C. The results agree with the data from [15] [16] for structures in the form of a microgrid and a sintered coating. The increase in liquid rise is explained by the presence of agglomerates in the layer of nanoparticles obtained at a lower temperature. The coating adheres to the substrate due to the smaller particle size, and the agglomerates provide improved liquid lift due to the larger particle size.

Figure 3. Dependence of the height of liquid rise on the estimate of the layer thickness: (1) - particles without agglomerates obtained at 1200 °C, (2) - particles with agglomerates obtained at 950 °C, (3) - liquid rise for a microporous coating [15], (4) - liquid rise on the microtexture [16].

In the second series of experiments, the effect of the nanoparticle material was studied. The transport properties of coatings made of nanoparticles of aluminum oxide, silicon carbide, titanium oxide and carbon (allotropic modification - diamond) were determined. The results of measurements of the height of the liquid rise are shown in Fig. 4. It was found that the highest rise of distilled water was obtained for a coating of nanoparticles of aluminum oxide, and the height of rise for titanium oxide particles is...
10 mm less than for particles of aluminum oxide. Silicon carbide and diamond nanoparticles raise the liquid by no more than 2 mm, regardless of the volume of the colloidal solution applied to the substrate.

**Figure 4.** Dependence of the height of rise of distilled water on the volume of applied nanofluid: 1- aluminum oxide nanoparticles obtained at 950 °C, 2- carbon nanoparticles, 3- silicon carbide nanoparticles, 4- titanium oxide nanoparticles

5. Conclusion

Technologies for obtaining a coating of nanoparticles of aluminum oxide with and without agglomerates by boiling a colloidal solution on a substrate are described. The transport properties of coatings made of nanoparticles of aluminum oxide, titanium oxide, silicon carbide, and diamond have been investigated. The highest liquid rise is observed in coatings made of nanoparticles of aluminum oxide. The low rise of the liquid in the layer of silicon and carbon particles is explained by the smaller particle size and, consequently, by the reduced porosity. To improve the transport properties, an additional microstructure can be formed in the nanoparticle layer. For example, microtrenches, in which, due to capillary effects, the rise of the liquid increases.

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