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IMPROVING THE HEAT TRANSFER CHARACTERISTICS OF MINIATURE TWO-PHASE THERMOSYPHONS WITH NANOFLUIDS BASED ON UKRAINIAN NATURAL ALUMOSILICATES

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In order to improve the heat transfer characteristics of miniature thermosyphons, a study of the processes of heat transfer by them using water and nanofluids as heat carriers was carried out. A water mixture based on nanoparticles of Ukrainian natural aluminosilicate – attapulgite with the addition of 0.1 % carbon nanotubes was used as nanofluids. The data of the study of the maximum heat flow and the minimum thermal resistance of copper thermosyphons with an internal diameter of 5 mm and a length of 700 mm are presented. Orientation of thermosyphons in space: vertical. The length of the heating zone varied from 50 mm to 200 mm, with the same amount of heat-carrier. The fill factor varied from 0.44 to 1.93.

A comparison was performed of the heat transfer capabilities of thermosyphons with water and with a nanofluid with a mass concentration of 0.5 %. It has been shown that nanofluid thermosyphons transmit 53 % more heat flow compared to water, and thermal resistances are reduced by 25 %.

The influence of the concentration of nanoparticles on the heat transfer characteristics of thermosyphons is shown. Nanofluids with concentrations (0.1 %, 0.5 %, 0.7 %) showed the same level of thermal resistances, with an increase in maximum heat flows compared to distilled water. Thus, when compared with the lowest concentration (0.1 %), the use of 0.5 % nanofluid gives an advantage of up to 40 %, and 0.7 % – an advantage of up to 51 %. This is explained by the appearance of a specific porous structure of anisometric nanoparticles on the heating surface, which contributes to the appearance of additional centers of vaporization during boiling and improves the heat transfer characteristics of thermosyphons.

Thus, the use of such thermosyphons with nanofluids when cooling elements of electronic equipment could improve their functional characteristics

Keywords: miniature thermosyphon, nanofluids, concentration, filling factor, heat flow, thermal resistance

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1. Introduction

The current state of development of electronic equipment is associated with a decrease in weight and size characteristics and an increase in their functional capabilities. This leads to an increase in the temperature level of its elements and their possible failure. Therefore, there is an urgent task of maintaining the given temperature mode of operation of such small-sized electronic devices. At the same time, it should be taken into account that the specific heat fluxes on the surfaces of such elements can reach significant values, which cannot be removed by traditional methods (radiators with air cooling). One of the possible ways of removing large heat flow densities from small-sized electronic devices is the use of two-phase evaporation-condensation systems. Such cooling systems include thermosyphons, heat pipes, steam chambers, pulsating and contour heat pipes, etc. It is thermosyphons, in addition to ease of manufacture, low cost, and reliability, which are characterized by lower thermal resistance than heat pipes due to the absence of a capillary structure in them. Various liquids are used as heat carriers in thermosyphons. Depending on the given temperature range, it can be water, alcohols, freons, etc. However, in some cases, thermosyphons with ordinary heat-carriers are not able to remove significant heat flows from electronic devices. The appearance of so-called nanofluids as heat carriers in thermosyphons has made it possible to improve their heat transfer characteristics.

The term nanofluid is used to refer to a colloidal solution consisting of a carrier liquid and dispersed nanoparticles with characteristic sizes from 1 to 100 nm. Solid nanoparticles are usually particles of chemically stable metals and their oxides. Nanofluids based on carbon nanotubes are also often used. Their feature is that the diameter varies from one to several nanometers, and the length can reach tens, hundreds, and even thousands of microns [1, 2].

At the same time, such substances are characterized by unique thermal and electrical properties. For example, the thermal conductivity of nanofluids increases compared to the base fluid. It also depends on the properties of microparticles and their configuration [3–6].

It is known that when using a nanofluid as a heat carrier in power equipment, it is possible to increase the specific densities of heat flows [7]. The main mechanism for increasing heat flows is not so much an increase in thermal conductivity of the working fluid [8] but an intensification of the boiling process due to the formation of roughness and a porous structure on the heating surface [9, 10].

At the same time, there is a problem of increasing the heat transfer characteristics of miniature thermosyphons, which, with small dimensions, would be able to remove significant heat flows with minimal thermal resistance at the same time. Limiting the dimensions of such systems affects the heat exchange process due to the intervention of capillary forces, as well as the forces of inertia and gravity. Therefore, the intensity of heat transfer in the evaporation and condensation zones is much lower compared to the large volume. There are still no criteria by which it would be possible to determine when the influence of limited space begins to affect the internal processes of heat transfer in miniature thermosyphons. The use of nanofluids of different concentrations as heat carriers in order to improve their heat transfer capabilities will help determine ways to create effective miniature cooling systems. It is to solve these problems that the use of nanofluids as a heat carrier in thermosyphons can help. For the successful and effective implementation of such cooling systems based on miniature thermosyphons with nanofluids as heat carriers, it is necessary to thoroughly study the processes occurring in them. This will make it possible to improve the heat transfer characteristics of miniature cooling systems. Therefore, research in this area is important and necessary for practical application.

2. Literature review and problem statement

Paper [11] investigates the use of aqueous nanofluid with copper oxide particles (d_{np}=30·10^{-9} m). It has been proven that in the case of using a nanofluid compared to water, it was possible to achieve a significant improvement in heat transfer and an improvement in the isothermality of the thermosyphon wall, with a simultaneous decrease in its temperature. Also, the values of the maximum heat flow in the heating zone for samples with nanofluid increased by 120 % compared to water. It was found that there is an optimal mass concentration of copper oxide nanoparticles in the base fluid, which is 1.0 %, at which maximum heat flows were observed. But in the work, the study was carried out at one filling factor (50 %) and the length of the thermosyphon did not exceed 350 mm. It is not entirely clear how the indicators of the heat transfer characteristics of thermosyphons will change for other geometric parameters.

At the same time, similar effects are described in works [12–14]. Thus, in [12], a study of the heat transfer characteristics of thermosyphons of different internal diameters filled with two types of working fluids (distilled water mixed with silver nanofluids 0.5 % by mass and pure water) was conducted. It was shown that thermosyphons with silver-based nanofluids transmitted significantly higher maximum heat fluxes than thermosyphons with pure water. The dependence of the influence of the inner diameter of the thermosyphon and the saturation temperature on the maximum heat flows was recorded. When these parameters were increased, the maximum heat fluxes increased significantly. However, the study was conducted for 50 % charging of the heating zone with a heat-carrier and a constant concentration of silver nanoparticles (0.5 %) in water. Therefore, it is not known what the heat transfer characteristics of thermosyphons will be at other filling parameters and concentration of nanoparticles in the liquid.

In work [13], the issue of thermal improvement of the productivity of thermosyphon heat pipes using iron oxide - nanofluid as a working fluid is considered. Deionized water with diluted iron oxide nanoparticles was used as the base liquid. The mass concentration was 2 % and 5.3 %. Research was conducted at two angles of inclination of the thermosyphon heat pipe, 45° and 90° (vertical). It was shown that the more iron oxide nanoparticles were dispersed in the working fluid, the higher the heat transfer characteristics of such a device compared to water. With the vertical location of the thermosyphon heat pipe (90°), the characteristics were improved than at 45°. However, this conclusion is not very consistent with previous studies of thermosyphons when the angle of inclination is changed, where the reverse nature of the influence of the angle of inclination on the maximum heat flow is asserted.

Also, in [14], along with an increase in the critical heat flow, a decrease in the thermal resistance of thermosyphons when used as a heat-carrier with iron oxide nanoparticles compared to distilled water is noted.

However, work [15] shows the opposite effect. Acid-treated carbon nanotubes have been shown to increase both surface tension and water wettability. The changed interphase properties cause a modification of the boiling mechanism, which is characterized by an increase in the diameter of the bubbles, a tendency to coalescence, a decrease in the density of active nucleation sites and the frequency of separation. Deterioration of operational characteristics when using water-based nanofluid and carbon nanotubes led to high temperature in the heating zone and increased thermal resistance.

In [16], the total thermal resistance of a closed two-phase thermosyphon was investigated using pure water and various aqueous nanofluids with Al_2O_3, CuO, and laponite clay nanoparticles. The mechanism of blocking of active cavities by agglomerates of nanoparticles is described, as a result of which the number of active centers of vaporization decreases. The worst results were demonstrated by nanofluid with laponite clay. Due to its use, thermal resistance has increased by 55 % compared to water.

However, it is interesting to note that the use of nanofluids based on clay minerals as a heat carrier for energy systems has proven very successful [17].

Thus, such mutually exclusive and contradictory research results show that the topic of using nanofluids as heat carriers in thermosyphons is not sufficiently elucidated. This especially applies to the influence of the mass concentration of nanoparticles in the base fluid on the efficiency of heat transfer by miniature thermosyphons. There is also an unsolved problem of using nanofluids with different thermophysical properties of nanoparticles in thermosyphons. It is not entirely clear how the filling factor affects the maximum heat fluxes and thermal resistance of miniature thermosyphons when using nanofluids as heat carriers.

3. The aim and objectives of the study

Our research aimed to improve the efficiency of heat transfer processes by miniature thermosyphons using nanofluids based on Ukrainian natural aluminosilicates with the addition of carbon nanotubes as heat carriers. This could make it possible to – the heat transfer characteristics of thermosyphons for cooling electronics.

To achieve the goal, the following tasks must be solved:

– to find out the effect of using the above-mentioned nanofluid instead of water on the thermal resistance of miniature two-phase thermosyphons;

– to determine the influence of the filling factor on the heat transfer characteristics of miniature thermosyphons with nanofluids;

– to determine the influence of the concentration of nanoparticles in the base liquid on the maximum heat flows and the minimum thermal resistance of miniature thermosyphons.

4. The study materials and methods

The object of our research is physical phenomena and processes of heat transfer in miniature closed evaporative-condensation cooling systems. The subject of the study is the determination of the influence of regime and geometric factors on the processes of evaporation and condensation in miniature two-phase thermosyphons with different heat carriers.

As a research hypothesis, the statement that the increase in the heat transfer capacity of thermosyphons with nanofluids as heat carriers is ensured by the presence of deposition of nanoparticles on the heat exchange surface is accepted. This increases the number of vaporization centers and increases the intensity of heat transfer. An experimental study with statistical processing of the results was chosen as the method.

To test the hypothesis, copper thermosyphons with a total length of 700 mm were selected. The inner diameter was 5 mm, the wall thickness was 0.5 mm. The length of the condensation zone was fixed and was 200 mm. Heating took place with the help of a multi-section heater of different lengths (from 45 mm to 200 mm). Thus, by changing its length, a change in the filling factor was achieved. The filling factor is the ratio of the liquid volume V_l to the internal volume of the heating zone V_{ev} of the thermosyphon ($F_r=V_l/V_{ev}$). With the same internal diameter d_{in}, the filling factor was determined as the ratio of the filling height of the heat-carrier h_l to the length of the heating zone L_{ev} ($F_r=h_l/L_{ev}$). The height of filling with heat-carrier for all thermosyphons was the same and was 88±1 mm.

The geometric characteristics of the studied thermosyphons are given in Table 1.

Table 1

Geometric characteristics of thermosyphons

Inner diameter, d_{in} mm	Overall length, l_Σ, mm	Length of the heating zone, l_{ev}, mm	Condensation band length, l_c, mm	Fill factor, $F_r=L_l/L_{ev}$	Heat-carrier
5.0	700	44; 100; 150; 200	200	1.93; 0.88; 0.59; 0.44	Water
5.0	700	44; 100; 150; 200	200	1.93; 0.88; 0.59; 0.44	Nanofluid 0.1 wt%
5.0	700	44; 100; 150; 200	200	1.93; 0.88; 0.59; 0.44	Nanofluid 0.5 wt%
5.0	700	44; 100; 150; 200	200	1.93; 0.88; 0.59; 0.44	Nanofluid 0.7 wt%

The experimental bench (Fig. 1) was an installation for researching the heat transfer characteristics of evaporation-condensation systems.

The studied sample 1 was placed and fixed in a laboratory tripod. A multi-section nichrome heater 2 was wound on the heating zone of the sample, which was powered by a laboratory autotransformer 5 from the network through a voltage stabilizer 6. The outer surface of the heater was covered with a layer of basalt fiber (with a preliminary calculation of the effective thickness of the insulation layer). The power supplied to the heater was monitored using wattmeter 4. Heat removal from the experimental sample was performed using a tube-in-tube heat exchanger 3, where the heat-carrier was supplied through rotameter 8 from the pressure tank 7.

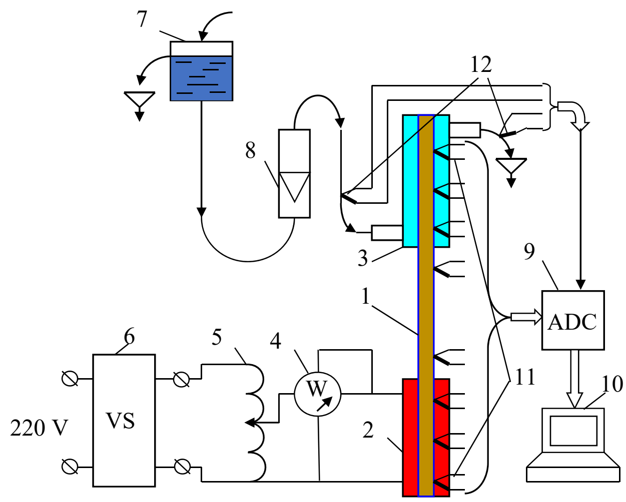

Fig. 1. Scheme of an experimental bench for the study of heat transfer characteristics of evaporative-condensing systems

The temperature of the surface of thermosyphons and cooling water at the inlet and outlet of the heat exchanger was controlled using copper - constantan thermocouples 11, 12 with an absolute error of ±0.1 °C. The signal from the thermocouples was transmitted using an analog-to-digital converter (ADC) 9 to a personal computer (PC) 10. Next, the information was stored, and further data processing was carried out.

The temperature of the cooling water at the inlet to the condenser was maintained at 20±1 °C. Water consumption was constant $4{,}9\cdot10^{-3}$ kg/s±$0{,}1\cdot10^{-3}$ kg/s and was controlled by rotameter 8.

The total thermal resistance of thermosyphons was determined as the ratio between the difference in average temperatures in the heating and condensation zones to the transmitted heat flow:

$$R=\frac{\overline{T}_{ev}-\overline{T}_c}{Q_{out}}. \tag{1}$$

The electrical power supplied to the heating zone of thermosyphons is not equal to the power transmitted along its length to the condensation zone due to heat removal through the insulation. Therefore, the heat flow transmitted along the length of the thermosyphon was calculated according to the following dependence:

$$Q_{out} = G \cdot C_p \left(T_{out} - T_{in}\right), \quad (2)$$

where G is the flow of water that cooled the condensation zone, kg/s; C_p – specific heat capacity of water, J/kg·K; T_{out}, T_{in} – water temperatures after leaving the condenser and before entering the condenser, °C.

The calculation of the errors of the heat flow, which is removed, did not exceed 5 %, and the thermal resistance did not exceed 7 %.

Distilled water and aqueous nanofluid based on previously purified natural aluminosilicate - attapulgite (Ukraine) with the addition of 0.1 % carbon nanotubes (CNTs) were used as heat-carriers. Nanofluids were obtained by ultrasonic dispersion of the corresponding nanopowders in a solution of anionic surfactant on a UZDN-2T disperser at a frequency of 22 kHz and a power of 500 W. The average particle size according to the data of the analysis on the laser correlation spectrometer ZetaSizer NANO-ZS (Malvern Instrument, UK) was 300–400 nm.

The initial mass concentration of nanoparticles of the dispersed phase (aluminosilicate+CNT) in water was 0.5 %. In order to study the influence of the concentration of nanoparticles on the heat transfer characteristics of thermosyphons, samples of nanofluid with an increased concentration (0.7 %) and with a reduced concentration (0.1 %) were prepared. Thermosyphons with the same mass and dimensional characteristics were filled with the indicated nanofluids. The experimental study was carried out with stepwise heat supply to the heating zone. The increase in heat flow occurred after the stabilization of heat transfer processes in thermosyphons. The experiment ended with the occurrence of crisis phenomena, which was accompanied by a sharp increase in temperature in the heating zone. The testing methodology for all thermosyphons remained constant, which made it possible to conduct a comparative analysis and determine the influence of decisive factors on the heat transfer characteristics of thermosyphons.

In addition, in order to compare and determine the expediency of using nanofluids, a similar sample of a miniature closed two-phase thermosyphon with distilled water as a heat-carrier was manufactured and tested. It was this sample that acted as a reference and comparisons were performed relative to it.

5. Results of investigating the influence of the use of nanofluids on the heat transfer characteristics of thermosyphons

5. 1. The effect of using a nanofluid instead of water on the thermal resistance and maximum heat fluxes of miniature two-phase thermosyphons

One of the main heat transfer characteristics of evaporation-condensation systems (heat pipes, thermosyphons) is the value of the minimum thermal resistance $R_{\min}$ and the maximum heat flow transmitted $Q_{\max}$. These parameters depend on many factors. First of all, on the geometric characteristics of the thermosyphons (inner diameter, length of the heat exchange zones, and total length), on the amount of filled heat-carrier (filling factor F_r), as well as the thermophysical properties of heat-carriers.

The start of heat transfer in the thermosyphon is connected with the activation of the steam generation centers in the heating zone. When the heat flow is brought to this zone along the inner wall, a thermal boundary layer is formed in the liquid. Its thickness, depending on the geometric parameters of the thermosyphon, can be proportional to its inner diameter. And then almost the entire heat-carrier can be in an overheated (metastable) state relative to the saturation temperature. Activation of the first vaporization center leads to the appearance of a bubble, which, after detaching from the surface, grows in volume and can reach the inner diameter of the thermosyphon. As a result, part of the superheated liquid is ejected by such a steam bubble from the heating zone to the condensation zone. At the same time, the temperature in the heating zone drops sharply, and in the condensation zone it rises. Such a phenomenon as "geyser boiling" [18, 19] depends both on the type of liquid and the amount of refueling, and on the mode parameters. Our studies showed that there is an area of heat flows in which the temperature pulsations of the thermosyphon wall occur. Basically, this area lies in the range of initial heat flows, when the conditions for activation of at least one center of vaporization are created in the heating zone of the thermosyphon (Fig. 2).

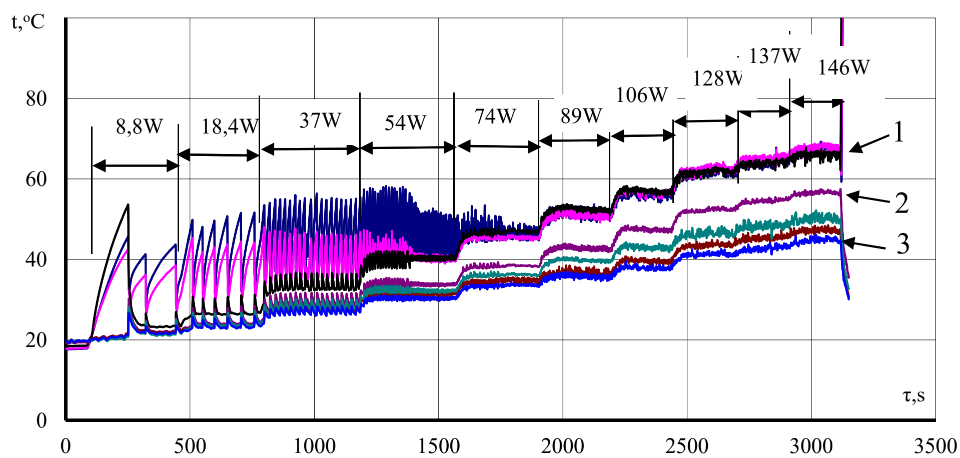

Fig. 2. Dependence of the temperature of the thermosyphon wall with an inner diameter of $5.0 \cdot 10^{-3}$ m on time when the heat flow changes (F_r=0.44) (water heat-carrier based on a mixture of carbon nanotubes and attapulgite (0.5 %)): 1 – heating zone; 2 – adiabatic zone; 3 – condensation zone

An increase in the heat flow leads to a gradual decrease in the amplitude of pulsations, which is associated with an increase in the number of active centers of vaporization and an increase in the pressure in the thermosyphon. At the same time, the separation diameters of the bubbles decrease, and their number increases, which helps decrease the thickness of the thermal boundary layer. And the ejection of part of the heat-carrier from the heating zone to the condensation zone stops.

A further increase in the heat flow leads to a gradual increase in temperature in all zones of the thermosyphon. The transition from bubbling boiling mode to film boiling led to a sharp increase in temperature in the heating zone and the thermal resistance of the thermosyphon increased rapidly. In Fig. 2, this was observed at Q=146.3 W.

The use of nanofluid as a heat carrier in miniature thermosyphons showed a significant increase in maximum heat flows. Figures 3–5 show the dependences for different filling factors F_r=0.44, 0.59, and 0.88. The comparison was made with thermosyphons that were filled with water and nanofluid.

Thus, the use of an aqueous nanofluid based on a mixture of carbon nanotubes and attapulgite, in comparison with water, at F_r=0.44, led to an increase in the maximum transmitted heat flux by approximately 53 % (Fig. 3).

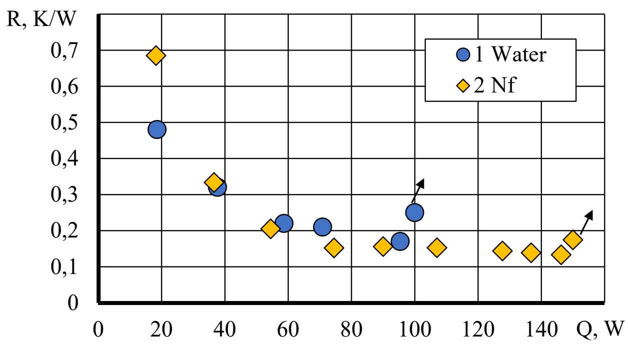

Fig. 3. Dependence of thermal resistance on the transmitted heat flow for F_r=0.44: 1 – miniature thermosyphon with water; 2 – miniature thermosyphon with a water heat-carrier based on a mixture of carbon nanotubes and attapulgite (0.5 %)

It is important to note that as an improvement in transmission characteristics, not only an increase in heat flux was recorded but also a simultaneous decrease in thermal resistance by 23 %, albeit slightly. The initial operating modes, in this case from 20 W to 30 W, are characterized by modes of undeveloped boiling, a larger error of determination, and a large amplitude of temperature fluctuations. In addition, the operation of thermosyphons under these modes (not optimal) is not advisable. From the point of view of system optimization, it would be more expedient for such small thermal loads to switch to thermosyphons with a smaller diameter, which would work under the "minimum thermal resistance mode". Thus, it would be possible to reduce the total mass and dimensions while not losing in terms of heat transfer.

Due to the transition from water to an aqueous heat-carrier with a mixture of attapulgite nanoparticles and carbon nanotubes at F_r=0.59, it was possible to increase the maximum transferred heat flow by 22 % (Fig. 4). At the same time, as in the case of F_r=0.44, a decrease in thermal resistance by approximately 25 % was recorded in parallel.

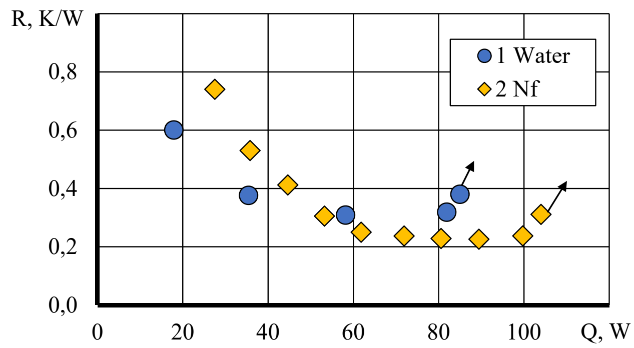

Fig. 4. Dependence of thermal resistance on the transferred heat flow for F_r=0.59: 1 – miniature thermosyphon with water; 2 – miniature thermosyphon with a water heat-carrier based on a mixture of carbon nanotubes and attapulgite (0.5 %)

For F_r=0.88, the nature of the change in heat transfer characteristics is identical to that shown in Fig. 3, 4. However, this leads to an increase in heat flow compared to water by 47 %, and a decrease in thermal resistance by 25 % (Fig. 5).

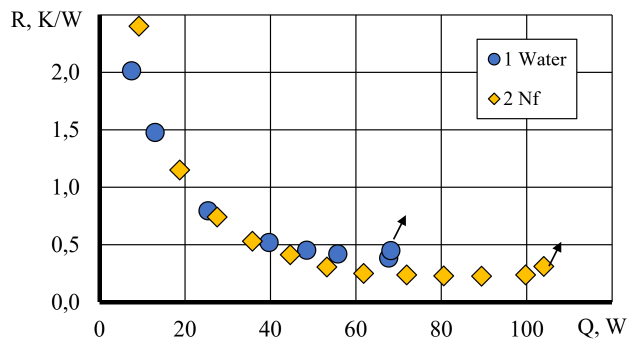

Fig. 5. Dependence of thermal resistance on the transmitted heat flow for F_r=0.88: 1 – thermosyphon with water; 2 – thermosyphon with a water heat-carrier based on a mixture of carbon nanotubes and attapulgite (0.5 %)

5. 2. Influence of the filling factor on the heat transfer characteristics of thermosyphons with nanofluids

Experimental data showed that with an increase in the filling coefficients, a decrease in the maximum heat fluxes is observed for both water and nanofluid (Fig. 6). Moreover, in comparison with water, at almost all F_r, the use of thermosyphons with nanofluids increased the maximum heat flows by almost two times.

The change in transfer properties (maximum heat flow transmitted by the system) with an increase in the filling factor is reversed. That is, the larger the filling factor (smaller heating zone), the smaller the heat flow the cooling system is able to transfer. This is explained by a simultaneous increase in the specific heat flow (heat flow density), with a decrease in the area of the inlet. That is, the drying of the heating zone occurs with smaller heat flows, under conditions of equality of the height of the heat-carrier filling L_l=const, and a decrease in the length of the heating zone L_{ev}.

To understand the nature of this change, it is important to recall the procedure of changing the fill factor. As mentioned above, when d_{in}=const, the filling factor is defined as the ratio of the filling height of the heat-carrier L_l to the length of the heating zone L_{ev}.

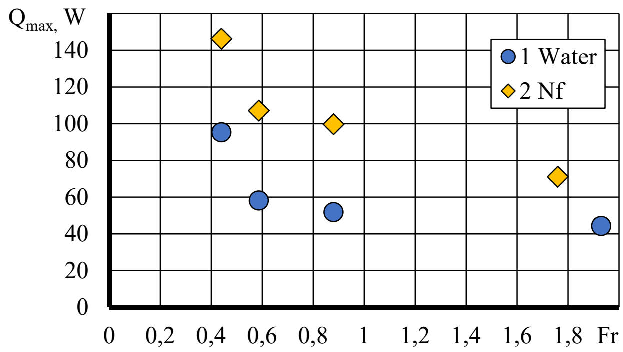

Fig. 6. Dependence of the maximum transferred heat flow on the filling factor: 1 – thermosyphon with water; 2 – thermosyphon with a water heat-carrier based on a mixture of carbon nanotubes and attapulgite (0.5 %)

It follows from this that the change in the filling factor can occur by varying the mass (as a result of the height) of the filling, and by changing the length of the heat supply zone. In this work, the change was achieved by using a multi-section heater and changing the length of the supply zone. Fig. 7 shows the change in the filling factor of the thermosyphon when the heat flow is supplied by heaters of different lengths. In this case, the heat transfer characteristics of the investigated thermosyphons can be used for cooling systems of electronic equipment elements with specific dimensions.

However, when using thermosyphons with different mass of filling with heat-carriers and a constant length of the heating zone (L_{ev}=const), the opposite pattern is observed. An increase in the filling factor leads to an increase in maximum heat flows and a decrease in the thermal resistance of thermosyphons [21].

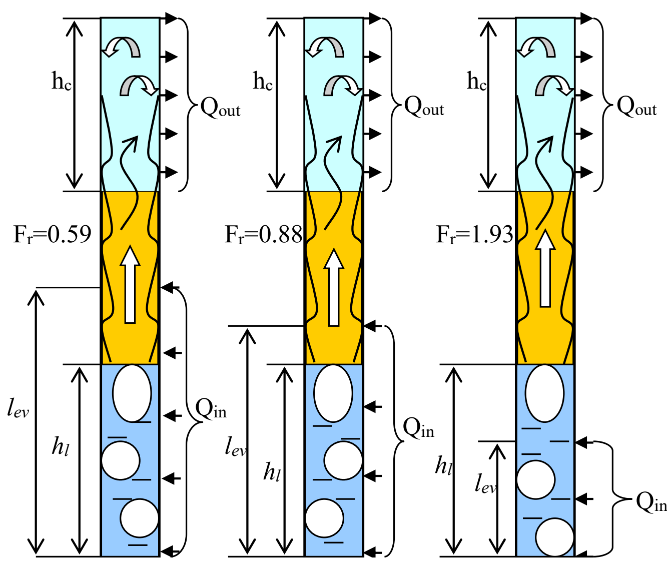

Fig. 7. Scheme of operation of a thermosyphon with an inner diameter of $5\cdot10^{-3}$ m at different F_r (h_l=const)

It is important to note that in this case, when comparing the dependence of the heat flow on the filling factor, the curve for the nanofluid over the entire studied range of Fr is higher than the curve for water. This indicates an obvious advantage of using nanofluids (an aqueous nanofluid with a mixture of carbon nanotubes and attapulgite nanoparticles) in terms of heat flows that can be transferred by the system, compared to ordinary distilled water.

5. 3. Influence of nanoparticle concentration on heat transfer characteristics of miniature thermosyphons

In addition to the basic composition of working heat-carrier, namely an aqueous nanofluid with a mixture of carbon nanotubes and attapulgite particles with a mass concentration of 0.5 %, heat-carriers with an increased (0.7 %) and reduced (0.1 %) content of nanoparticles were prepared. The mass and dimensional characteristics of the system, the test bench, heating and cooling conditions for the new samples remained the same as for the sample with a concentration of 0.5 %. The unification of research conditions was created in order to make a correct comparison and determine the influence of the concentration of nanoparticles on the heat transfer characteristics of the system.

F_r=0.44 (Fig. 8) and 0.59 (Fig. 9) were chosen as the heat carrier filling coefficients under investigation.

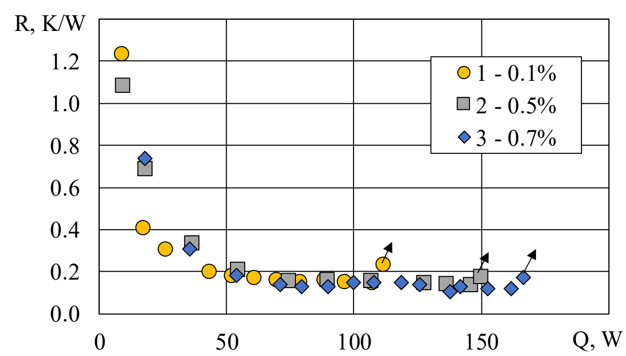

Fig. 8. Influence of nanoparticle concentration on heat transfer characteristics for F_r=0,44: 1 – 0,1 %; 2 – 0,5 %; 3 – 0,7 %

Arrows in Fig. 3–5 and Fig. 8–9 indicate the beginning of crisis phenomena, that is, the onset of the transition to the film boiling regime. At the same time, there is a significant and uncontrollable increase in thermal resistance due to an increase in temperature in the heating zone. During film boiling, the flow of steam to the condensation zone decreases and the heating zone dries out. In fact, this is the moment when the cooling system stops performing its functions, and without taking appropriate measures (turning off, switching to a mode with less heat generation, etc.), the device fails due to overheating of the wall in the heating zone.

For the above F_r=0.44, the thermal resistance for samples with a concentration of 0.1 %, 0.5 %, and 0.7 % is practically unchanged, but with an increase in the concentration of nanoparticles, a significant increase in the transmitted heat flux is observed. Thus, for concentrations of 0.1 %, the maximum heat flow was 107.3 W, for 0.5 % – 141.7 W, and for the highest concentration (0.7 %), the value reached 161.9 W. Thus, compared to the least concentrated working fluid (0.1 %), an increase to 0.5 % led to an increase in heat flow by 40 %, and to 0.7 % by 51 %. It should be emphasized that the addition of even the smallest investigated concentration of nanoparticles to the base fluid (0.1 %) led to an increase in the maximum heat flow up to 12.5 %, and a decrease in thermal resistance up to 13 % compared to water.

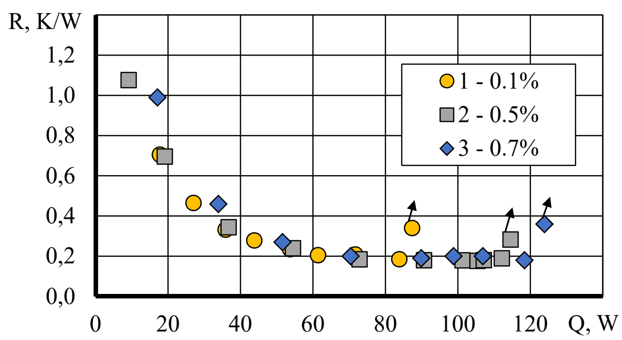

Fig. 9. Influence of nanoparticle concentration on heat transfer characteristics for F_r=0,59: 1 – 0,1 %; 2 – 0,5 %; 3 – 0,7 %

For F_r=0.59, the thermal resistance situation remains identical to F_r=0.44, that is, its minimum value is in the same range, within the measurement error, for all three studied concentrations. Along with this, a significant increase in the maximum heat flow is also recorded: water – 58.5 W; 0.1 % nanofluid – 83.8 W; 0.5 % nanofluid –112.1 W, and 0.7 % nanofluid – 118.4 W.

Based on these data, it can be stated that an increase in the mass concentration of nanoparticles in the base liquid leads to an increase in the heat transfer characteristics of miniature thermosyphons.

6. Discussion of results of investigating the influence of the use of nanofluids on the heat transfer characteristics of thermosyphons

The effect of the filling factor F_r on the maximum heat flow of thermosyphons is observed to be the same for both water and nanofluid. As can be seen from Fig. 3, 4, the maximum heat flux at F_r=0.59 decreased for both water and nanofluids compared to F_r=0.44. At F_r=0.44 for the nanofluid, it was equal to about 146 W, and at F_r=0.59, its decrease to 100 W was observed. This can be explained by the fact that when F_r increased, the part of the heating zone that was not occupied by the liquid decreased. The intensity of heat exchange in this zone depended on the thickness of the condensate film returning to the heating zone. As is known [20], with small thicknesses of liquid films, heat transfer coefficients during boiling increase significantly and may exceed the intensity of heat exchange in the area where the heat-carrier is located. Therefore, the smaller the area of the heating zone on which the film of condensate is located (Fig. 7), the smaller the value of the maximum heat transmitted by the thermosyphon. Also, the heat flux density increases when the length of the heating zone decreases. And that is why film boiling occurs in the heating zone at lower values of the total heat flow. The obtained results (Fig. 3–5) can be interpreted within the limits of modern concepts [9, 10, 17]. Unlike a single-phase heat-carrier (water), the boiling of nanofluids is accompanied by the formation of porous deposits of nanoparticles on the heated surface. As a result, the roughness of the heat exchange surface increases, which contributes to an increase in the number of potential centers of vaporization. The physical mechanism responsible for increasing the critical heat flux and delaying the boiling crisis by nanofluids is the destabilization of the vapor film due to the deposition of particles on the heating surface. In this case, the presence of carbon nanotubes with high thermal conductivity in the deposits of nanoparticles leads to an increase not only in the convective component of heat transfer, but also in the conductive one. At the same time, there is a possibility of the effect of nanoparticles in the liquid on the growth and detachment of steam bubbles during intense boiling in the heating zone of the thermosyphon. Due to the turbulence of the flow, nanoparticles fall on the interphase boundary of the vapor bubble and reduce its separation diameter, as well as contribute to its separation as soon as possible. The intensity of heat transfer increases and this explains the decrease in thermal resistance of thermosyphons. The increase in maximum heat flows occurs as a result of the appearance of some non-isothermality of the heat exchange surface. And as is known [19], the appearance of elements with different thermal conductivity on the surface prevents the spread of a vapor film during a boiling crisis. Non-isothermality of the surface occurs due to the appearance on the surface of elements of carbon nanoparticles (close to graphene), the coefficient of thermal conductivity of which is much higher than that of copper.

From Fig. 8, 9, and by comparison with the data on water (Fig. 3, 4), it is possible to see an increase in the maximum heat flow due to an increase in the concentration of nanoparticles in the base liquid. It has a non-linear dependence, and the character becomes less pronounced with further growth. However, it is advisable to study higher concentrations in order to find its optimal level.

The increase in the maximum heat flow due to the increase in the concentration of nanoparticles in the nanofluid can be explained by the increase in the thickness of the porous layer on the surface of the heating zone. This porous layer arises due to the deposition of nanoparticles during the boiling of the nanofluid. The greater the concentration of nanoparticles, the greater the surface roughness. This leads to a surface relief with a greater number of potential centers of vapor formation while simultaneously promoting the rupture of the vapor film in the event of a heat transfer crisis. The intensity of heat transfer increases with a simultaneous increase in maximum heat flows. It was shown in [22] that with an increase in the roughness of the heating surface in thermosyphons, both the intensity of heat transfer increases and heat transfer occurs at increased heat flows.

In work [23], aqueous nanofluid with Al_2O_3 (0.05 %) and aqueous nanofluid with $TiSiO_4$ (0.075 %) were studied. As a result of studies of different concentrations, it was noted that for Al_2O_3 it was 0.05 %, and for $TiSiO_4$ – 0.075 %. A further increase in concentration led to a deterioration of thermal resistance and intensity of heat exchange, in comparison with the above.

Taking into account the experimental data, it should be noted that the recommended mass application levels of 0.05 % and 0.075 % [23] are not absolute for many nanofluids. The optimal concentration of nanoparticles depends on many factors (base liquid, material of nanoparticles, size and shape of nanoparticles, etc.). Therefore, for individual groups of nanoparticles and base fluids, the heat transfer characteristics of thermosyphons can differ by several times, and even by orders of magnitude.

The use of more concentrated heat-carriers and the determination of the optimal level (points of change in the trend for deterioration of thermal resistance and intensity of heat exchange) are promising and relevant stages of further research.

7. Conclusions

1. The heat transfer characteristics of miniature closed two-phase thermosyphons were investigated, in which a water nanofluid based on Ukrainian natural aluminosilicates, namely a mixture of attapulgite nanoparticles with carbon nanotubes, was used as a heat carrier.

It is shown that in the entire investigated range of heat flows, miniature closed two-phase thermosyphons with nanofluid demonstrated significantly better heat transfer characteristics than similar samples with water. Thus, due to the use of nanofluids, it was possible to increase the maximum heat fluxes transmitted to 53 % and reduce thermal resistance by 25 %.

2. Data on the influence of the filling coefficients of miniature thermosyphons on the maximum heat flows for water and nanofluids as heat carriers are given. It is shown that when the filling factor increases, the maximum heat flows decrease. Thus, with a filling factor of F_r=0.44 for a nanofluid with a concentration of 0.5 %, the maximum heat flow was equal to 146.3 W, and with F_r=0.59, it decreased to 112.2 W. However, in comparison with water, thermosyphons filled with nanofluids transmit approximately two and a half times greater heat flows.

3. The influence of nanoparticle concentrations in the base liquid on the heat transfer characteristics of miniature thermosyphons is shown. The sample with a mass concentration of 0.7 % showed the best characteristics. At the same time, although the trend of increasing maximum heat fluxes became less pronounced when going from 0.5 % to 0.7 %, the thermal resistance remained at the same level for all studied concentrations.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

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