

This paper considers the effect of structural parameters and saturation pressure on the intensity of heat transfer from boiling on porous structures made of copper metal fibers. The study involved changing the structural and geometric characteristics of porous samples and saturation pressure. The study regime parameters were chosen based on the conditions of operation of steam chambers, namely the horizontal orientation of the work area, the capillary transport of the heat carrier to the work area.

It was determined that reducing saturation pressure from 0.1 MPa to 0.012 MPa leads to a reduction in heat transfer by 15–20 % depending on the parameters of porous structures. This pattern has been explained in this paper by the increased detachable diameters of steam bubbles that thus overlap part of the capillary structure's vaporization area, which leads to a decrease in the values of the discharged heat flux at the same temperature gradient values.

The influence of values of the porosity and diameters of fibers, which the samples of a capillary structure were made from, was ambiguous. The parameter chosen for generalizing the data obtained was an effective diameter of the samples' pores, which is a more general characteristic.

The generalization of the experimental data has demonstrated that the efficiency of heat transfer increases with an increase in the effective diameter of pores in the examined range from 20 to 90 μm . Estimation dependences have been built to determine the intensity of heat transfer under sub-atmospheric pressures for metal-fibrous porous structures at a deviation of up to $\pm 30\%$.

It turned out that the resulting dependences could be used to determine the intensity of heat transfer by the examined powder structures under the sub-atmospheric pressure conditions. Applying these dependences would make it easier to design thermal stabilization systems based on steam chambers

Keywords: *vaporization, heat exchange intensity, capillary structure, saturation pressure, steam chamber*

HEAT TRANSFER INTENSITY AT WATER BOILING ON THE SURFACE OF A CAPILLARY STRUCTURE UNDER SUB-ATMOSPHERIC PRESSURE

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1. Introduction

Current development of electronic equipment is aimed at reducing the size of electronic components while increasing their processing power. This leads to an increase in specific heat fluxes, and, as a result, the difficulty of maintaining optimal temperature modes of electronic equipment operation.

Very often, two-phase heat-transfer systems, such as heat pipes or steam chambers, are used in thermal stabilization systems, which are subject to the same compactness requirements as the electronic part. That, in turn, further complicates the design and development of efficient heat discharge systems.

As one knows, most two-phase heat-transfer devices use porous structures. They act as a capillary pump to transport the heat carrier from the heat discharge zone to the heating zone. They also increase the intensity of heat transfer in the heating zone by developing the heat exchange surface and creating favorable conditions for the emergence of additional steam-forming centers. Powder, mesh, and groove porous

structures have become common. Despite some shortcomings, their large-scale use is due to the ease of manufacture. On the other hand, employing other types of structures might make it possible to expand the range of working parameters of heat-transfer systems. Metal-fiber capillary structures (MFCS) are among these types of porous structures that have a series of advantages over powder ones. This is, first of all, the high porosity and small hydraulic resistance when a heat carrier moves.

Studying the processes taking place inside two-phase systems that use metal-fiber structures makes it easier to design them and improve their efficiency. Thus, determining the numerical heat intensity values for MFCS with different structural and geometric parameters would make it possible to devise procedures for calculating two-phase heat-transfer devices. Such characteristics should be determined experimentally under conditions as close as possible to the functioning of steam chambers and heat pipes.

The constant increase in the scattering capacity of modern electronic devices renders relevance to the task of

designing effective systems for maintaining the specified temperature modes in electronic equipment. First of all, it is a search for such parameters of capillary structures that could provide for the highest intensity of heat transfer in a heating zone, both in heat pipes and steam chambers.

2. Literature review and problem statement

As one knows, saturation temperature, the parameters and type of porous structure affect the intensity of heat transfer at boiling. Paper [1] reports an analysis of the effect of saturation pressure on the intensity of heat transfer at boiling on a flooded surface with different coatings. It has been shown that reducing saturation pressure from 200 kPa to 20 kPa leads to a 20–45 % reduction in heat exchange, depending on the heat flux. The authors of [2] obtained qualitatively similar results for the freon R113, which also showed a 30–40 % reduction in heat transfer when saturation pressure changes from 341 kPa to 102 kPa. Paper [3] describes the effect of the type of porous structure (mono- and bi-porous) on the intensity of heat transfer at boiling on a flooded surface. The authors report the results about the use of bi-porous structures that could increase the intensity of heat exchange by 25–35 %. In the cited works, the studies were conducted under boiling conditions in large volumes, which do not fully correspond to the working conditions for two-phase heat-transfer systems. In such heat-transfer devices, the vaporization process takes place in porous structures saturated with heat carrier.

Compared to powdered porous structures, MFCS have several advantages. This is, first of all, the lack of closed pores, high porosity (up to 92–96 %) and permeability ($10^{-11} \text{ m}^2 \dots 10^{-09} \text{ m}^2$) [4–6]. In addition, inside MFCS, owing to the wide distribution of pores for diameter, there is a fairly high capillary pressure in the range of 1,000 Pa to 10,000 Pa. At the same time, the permeability is much higher than that of powder structures [7]. Another advantage is the flexibility of the design (stable mechanical parameters after the device bends) [8].

One of the most important advantages of porous structures is the increase in the intensity of heat transfer during vaporization [9, 10] of the relatively smooth surfaces.

Paper [9] reports research into the heat transfer at boiling on small surfaces. It is argued that coating such surfaces with porous structures, depending on the parameters, significantly increases the intensity of heat transfer. The comparison is given regarding boiling on smooth surfaces. Work [10] shows that the values of heat transfer ratios increase with the decrease in the size of the pores of bi-porous structures. The range of diameters of pores ranged from 5 to 30 μm , which, for most types of porous structures, is the lower threshold. Thus, the data given in the cited work provide more scientific value than engineering. Paper [11] addresses the effect of the surface state on the intensity of heat transfer at boiling on mesh structures. The authors showed that the change in the roughness and surface structure of the mesh leads to an increase in the limit heat fluxes by 25 % with a simultaneous increase in heat transfer ratios to 20 %. The reported data were obtained under atmospheric pressure; that excluded the influence of factors associated with changes in saturation pressure, such as the detachable diameter of steam bubbles.

The scientific literature describes the effect of MFCS parameters on the intensity of heat transfer at boiling under

high volume conditions at different pressures. The vaporization processes that occur in most two-phase systems are carried out under the conditions of saturation of the porous structure under sub-atmospheric pressures.

The heat carrier in MFCS moves from the condensation zone to the heating zone of a heat pipe due to capillary forces. At the same time, the forces of gravity can both help the movement of the heat carrier and create additional resistance. Thus, it was shown in [12] that the intensity of heat transfer increases when the liquid's film flows along slit channels with capillary-porous walls. The conditions for the film's motion were close to the conditions occurring in heat pipes. However, a mesh was used as a capillary structure, whose properties are significantly different from those in MFCS. In addition, the film of liquid flowed mainly due to the forces of gravity as the capillary forces were very small. Work [13] shows that the use of mesh porous structures in heat exchange equipment increases its performance by up to 18 %.

There are hardly any studies that take into consideration the conditions of capillary recharge and saturation pressure in MFCS. In order to better understand the processes taking place, and, as a result, to improve the efficiency of heat-transfer systems, such research is proving to be an important task.

Such research could help in the development and design of two-phase systems for various purposes.

3. The aim and objectives of the study

The aim of this study is to determine the effect of regime and structural factors on the efficiency of heat exchange at boiling under conditions as close as possible to the working conditions of heat pipes and steam chambers. This would simplify the design and manufacture of two-phase systems, as well as thermal stabilization systems in general.

To accomplish the aim, the following tasks have been set:

- to determine the effect of saturation pressure and the parameters of porous structures on the efficiency of heat exchange in capillary transport;
- to derive generalizing dependences that would make it possible to calculate the intensity of heat exchange at boiling on porous structures;
- to determine the extent of influence of the type of porous structure on the efficiency of heat exchange at boiling under capillary transport conditions.

4. The study materials and methods

To solve the tasks set, a field experiment was chosen as the main method of research. An experimental installation (Fig. 1) was designed, which consists of an airtight body with a heater installed inside. To reduce the outflow of heat from the heater to the body, a fluoroplastic sleeve is used. In addition, the fluoroplastic was chosen for reasons of ensuring the tightness of the internal volume of the chamber. The body has a thermocouple sealed input, as well as terminals for a capacitor, a vacuum meter, and a refueling port. The capacitor is made in the form of a tubular heat exchanger. It was used to regulate the saturation temperature by changing the temperature and flow rate of the coolant. The body of the chamber was thermally insulated to reduce heat losses to the environment.

The heater includes a copper block hosting the cartridge heating elements inside. Their total capacity is 1,200 W. Also inside the heater and the chamber are the copper-constantan thermocouples, which control the heat flux and saturation temperature.

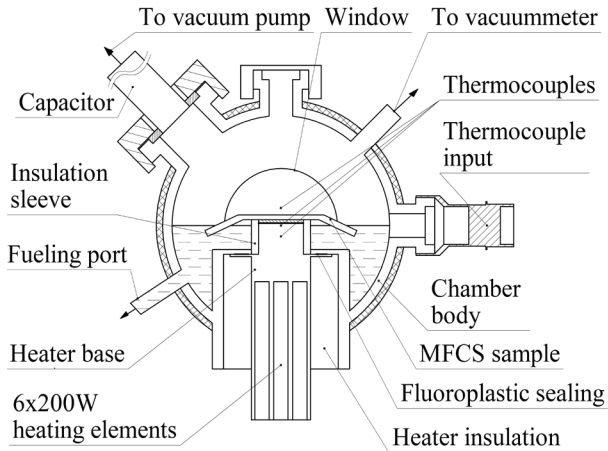


Fig. 1. Experimental installation design

The experimental sample (Fig. 2) is a 54-mm-diameter MFCs disk with a baked copper substrate: diameter, 20.4 mm; thickness, 0.5 mm. The tests were conducted for samples with thicknesses of 0.3 and 0.5 mm, made from baked copper fibers. 27 samples were produced in total, with fiber diameters of 10 to 50 μm, and with a fiber length of 3 mm. The porosity of the samples ranged from 64 to 85%. Samples 1–7 were made of fibers with a diameter of fibers of 50 μm; 9–15 – 30 μm; 17–21 – 20 μm; 24–27 – 10 μm.

The samples are listed in Table 1.

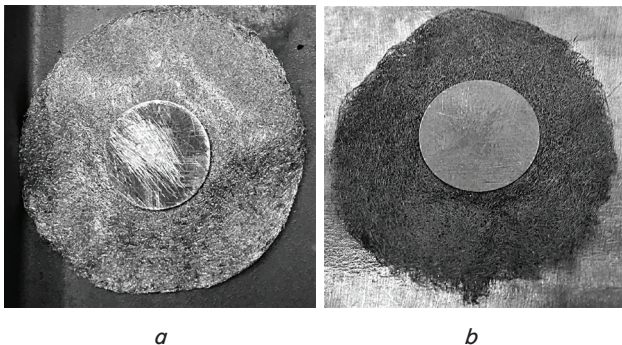


Fig. 2. General view of samples: a – before oxidation; b – after oxidation

This structure of the sample allows for its rapid installation on the work surface, as well as avoiding the soldering on the capillary structure itself. On the other hand, such a structure partially imitates the design of the heat pipe, that is the substrate plays the role of a wall to which the structure is baked.

A sample of the porous structure was soldered to the heater by the solder Sn60Pb40. To prevent contamination of the sample and the chamber environment, the soldering process took place without the use of flux. The wettability of the sample was ensured by pre-oxidation according to the procedure given in work [14]. Oxidization was also carried out to ensure the independence of the surface of the sample on the temperature of soldering. After the sample was soldered, the internal volume of the chamber was pumped out with the

2NVR-5DM vacuum pump and filled with distilled water. The heater was turned on, and the sample was boiled for 2 hours. At the same time, the working liquid was degassed. During the experiment, the saturation temperature was controlled by a capacitor of the heat exchanger, as each increase in the heater power resulted in an increase in the pressure that must be compensated for by condensation in the heat exchanger. After the experiment, the chamber was opened and the experimental sample was dismantled. The thickness of the porous structure was then re-measured.

Table 1

Parameters of MFCs experimental samples

Sample No.	Thickness, mm	Porosity, %	Fiber diameter, μm
1	0.3	64	50
2	0.31	75.8	
3	0.31	80	
4	0.3	84.7	
5	0.5	66	
6	0.43	75.7	
7	0.46	79.1	
9	0.3	66	30
10	0.3	75.8	
11	0.3	79.4	
12	0.3	84.1	
13	0.47	65	
14	0.51	75.5	
15	0.5	79.5	
17	0.31	66	20
18	0.32	76	
29	0.3	81.2	
19	0.3	84.4	
20	0.5	66	
21	0.5	74.5	
24	0.31	76.7	
25	0.31	84.5	10
27	0.51	74.7	

Our experimental studies were conducted at saturation temperatures of 50, 65, and 100 °C.

The resulting temperature data were processed according to the following procedure:

1. Average temperatures and their differences were calculated. After that, according to the Fourier law, we determined the heat flux delivered to the experimental sample.

$$Q_{delivered} = \frac{\lambda}{\delta} \cdot F_s \cdot \Delta T_{1-2},$$

where λ is the heat conductivity of the heater material, W/(m·K); δ is the distance between thermocouples T₁ and T₂, m; F_s is the cross-sectional area of contact spot, m².

2. Heat flux losses are calculated by the Fourier law for a cylindrical wall:

$$Q_{losses} = \frac{2 \cdot \pi \cdot l \cdot \lambda (T_3 - T_4)}{\ln\left(\frac{r_2}{r_1}\right)},$$

where l is the length of the top of the insulation, m; λ is the thermal conductivity of the insulation material, W/(m·K);

T_3 and T_4 are the temperatures of the inner and outer wall of the insulation, °C; r_2 and r_1 are the internal and external radii of the insulation, m.

3. The difference between the heat flux supplied and the value of the loss was accepted as the true value of the heat flux; this value was accepted for further calculations of the heat transfer factor under the Newton-Richman law:

$$\alpha = \frac{Q_{delivered}}{F_s(t_o - t_{sat})}$$

where t_o is the MFCS sample's base temperature, °C; t_{sat} is the vapor temperature (saturation temperature), °C.

The temperature at the base of the sample was also determined by the law of Fourier for a multi-layered wall. At the same time, the contact resistance of soldering was adopted as a perfect thermal contact.

4. The thickness of the solder layer was determined after the experiment, on the detached sample, using a micrometer.

To verify our results, tests were carried out on a smooth surface, involving two samples of MFCS whose parameters the closest to the literary data. The results of the comparison showed an alignment with the literary data [9]. The discrepancy in the data did not exceed 10 % in terms of heat transfer rates.

5. Results of studying the effect of structural and regime parameters on the intensity of heat exchange

5.1. The effect of pressure and porous structure parameters on heat transfer intensity

Below are the results of our study in dimensionless coordinates, namely $Nu=f(Re)$, where the Nu and Re numbers are determined as follows:

$$Nu = \frac{\alpha \cdot D_{eff}}{\lambda_f}$$

$$Re = \frac{w_{vapor} \cdot D_{eff}}{\nu}$$

where α is the experimental heat transfer ratios, $W/m^2 \cdot K$; D_{eff} is the effective diameter of the pores of a capillary structure, m; λ_f is the Fluid thermal conductivity factor, $W/m \cdot K$; w_{vapor} is the rate of vaporization; ν is the coefficient of kinematic viscosity of the liquid, m^2/s .

The rate of vaporization was determined from the following dependence:

$$w_{vapor} = \frac{q}{r \cdot \rho''}$$

where q is the heat flux density, W/m^2 ; r is the specific heat of vaporization, J/kg ; ρ'' is the density of steam, kg/m^3 .

Fig. 3 shows the data acquired at a saturation temperature of 100 °C.

The graphic representation indicates that the inclination angle of the curves for different samples is different. In these coordinates, the inclination angle of the curve characterizes the efficiency of the MFCS sample performance. The chart demonstrates that the greatest efficiency of heat exchange

was obtained for high-porous samples. In addition, with the reduction of fiber diameter, the efficiency of heat exchange is reduced by 10–35 % depending on the values of porosity. These changes have been observed to depend on the effective diameter of the pores of the capillary structure, which increases the inclination angle of the curve.

In a general case, when the effective diameter of pores increases, the resistance of steam bubble discharge decreases. That leads to an increase in the frequency of detachment and, as a result, to an increase in the number of active sites of vaporization over a certain period.

In addition, the increase in the heat flux supplied over time leads to a partial drying of the MFCS sample. As a result, the liquid begins to actively evaporate from thin films. This process is carried out until the porous structure can provide for the required amount of liquid for evaporation.

The study reported in [15] has linked the efficiency of heat transfer to the activation of new vaporization sites and the reduction in the thickness of the liquid's film. Reducing the thickness of the film, which evaporates from the surface of the fibers of MFCS, leads to an increase in the efficiency of vaporization. Based on the data obtained, we can conclude that the parameters described above vary in different ways for different samples.

A similar pattern was observed for the saturation temperatures of 65 °C (Fig. 4) and 50 °C (Fig. 5).

The range of inclination angles in the experimental data is smaller at boiling under sub-atmospheric pressure. This is due both to the change in the thermal properties of the working fluid and to the fact that when the pressure decreases the detachable diameter of the vapor bubbles increases. That is, the increase in the detachable diameter of the steam bubble leads to that the steam phase takes up more volume in the porous structure. Thus, the number of active vaporization sites (VVs) decreases over a certain period.

On the other hand, it is difficult for steam bubbles to be discharged through the layers of porous structure, due to the increase in the ratio of surface tension and viscosity of the liquid. As a result, the role of effective pore diameter begins to diminish. This is also evident by the growth in the grouping of data received. That is, to describe the data, it is necessary to take into consideration the effective diameter of the pores of MFCS samples. Values for effective pore diameters of MFCS samples were taken from [16].

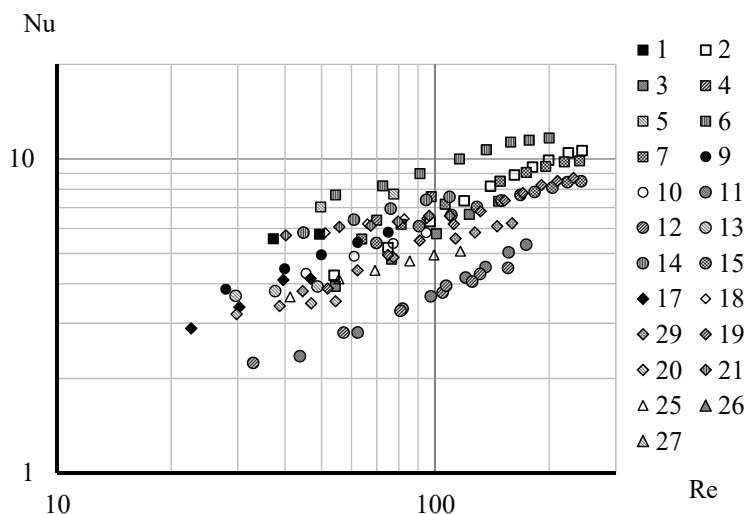


Fig. 3. Heat transfer efficiency dependence on Re for the samples of metal-fiber capillary structures at a saturation temperature of 100 °C

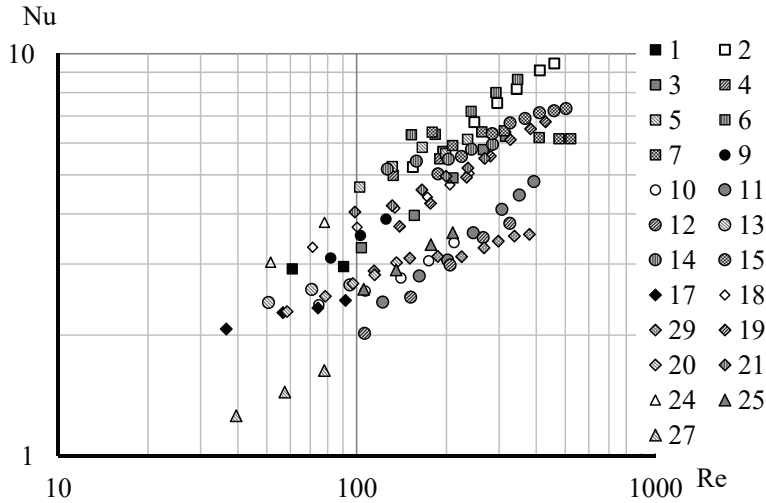


Fig. 4. Heat transfer efficiency dependence on Re for the samples of metal-fiber capillary structures at a saturation temperature of $65\text{ }^{\circ}\text{C}$

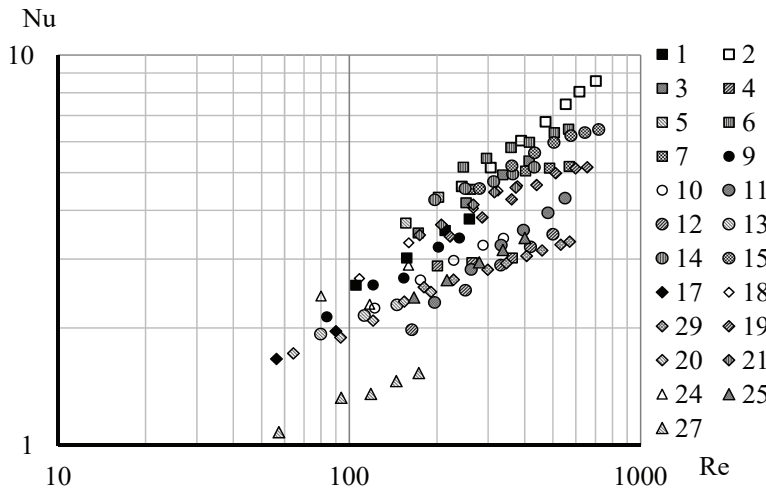


Fig. 5. Heat transfer efficiency dependence on Re for the samples of metal-fiber capillary structures at a saturation temperature of $50\text{ }^{\circ}\text{C}$

5. 2. Generalization of the data obtained

The result of analyzing the experimental data employing the theory of similarity is the derived criterial dependences in the form $Nu=f(Re)$. They take the following form:

$$Nu_{100\text{ }^{\circ}\text{C}} = Re^{50 \cdot D_{eff}^{0.5}} \tag{1}$$

$$Nu_{65\text{ }^{\circ}\text{C}} = Re^{15 \cdot D_{eff}^{0.4}} \tag{2}$$

$$Nu_{50\text{ }^{\circ}\text{C}} = Re^{5 \cdot D_{eff}^{0.31}} \tag{3}$$

These generalizing formulas describe 80 % of the experimental data with a maximum deviation not exceeding $\pm 30\%$. The application range of these dependences is within the limits of the effective pore diameter D_{eff} values from 20 to 90 μm , with Re numbers from 50 to 500, for the saturation temperatures of $50\text{ }^{\circ}\text{C}$ and $65\text{ }^{\circ}\text{C}$. For a saturation temperature of $100\text{ }^{\circ}\text{C}$, the range of Re numbers is 30 to 300.

5. 3. The effect of a capillary-porous structure on heat exchange intensity

We have investigated the effect of sub-atmospheric pressures on samples of powder porous structures whose parameters are given in Table 2.

Table 2
Parameters of the examined samples of powder structures

Sample	Thickness, mm	Porosity	Particle size, μm	Pore D_{eff} , μm
SP1	0.3	54.5 %	120–200	46.5
SP2	0.3	55.1 %		
SP3	0.5	56.2 %		

When investigating the samples of a porous structure from baked powder, it was found that the nature of the effect of saturation pressure on the efficiency of heat transfer is similar to the samples made from a metal felt. In addition, it was determined that dependences (2), (3) describe the efficiency of heat transfer for powder structures under sub-atmospheric pressures at a deviation not exceeding $\pm 30\%$ (Fig. 6). Under atmospheric pressure, the Nu 's values, calculated from (1), were on average 40 to 45 % lower than those obtained during the experiment.

This deviation may be due to the fact that the process of steam bubble discharge from porous structures differs depending on their type. When the pressure decreases, the difference decreases due to the growth of detachable diameter, and the influence of the type of porous structure is reduced. This assumption should be tested for other types of porous structures.

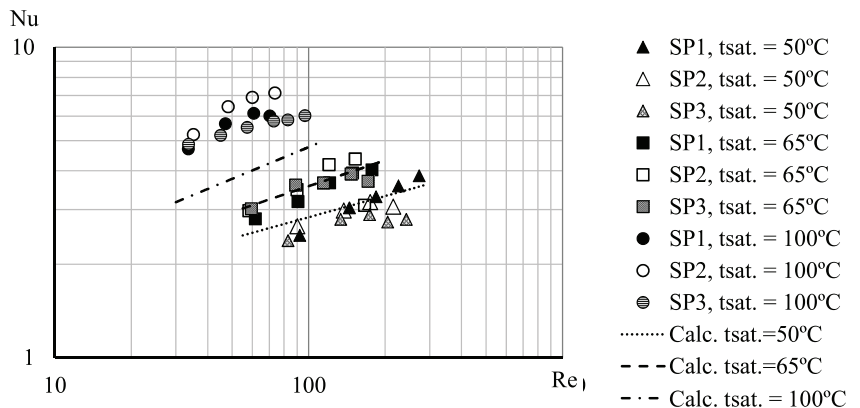


Fig. 6. Comparing the calculation based on the derived dependences with the experimental data for powder structures

6. Discussion of results of studying the intensity of heat transfer at boiling on capillary-porous structures

As a result of our study, it was determined that lowering saturation pressure leads to a reduction in the efficiency of heat transfer at boiling by 5–20 % (Fig. 3–5). This phenomenon is explained by several processes at

once. First, the intensity of heat transfer is affected by the size of the bubbles. When the pressure of saturation is reduced, the detachable diameter of vapor bubbles increases. That leads to an increase in the area of the porous structure occupied by the steam phase. This reduces the area of the surface at which the vaporization takes place. Second, with a decrease in the saturation pressure, the thermal-physical properties of a heat carrier change, which leads to the difficulty of steam exiting the porous structure. That is also facilitated by the reduction in the effective diameter of pores.

A feature of our study is the proximity to the conditions of steam chamber operation, namely a lower saturation pressure and the capillary recharge of the evaporation area.

As a result of the generalization, simplified dependences were derived to determine the effectiveness of heat transfer. These equations generalize more than 80 % of the data at a deviation of no more than 30 %. The application of equations is in the range of Re numbers from 50 to 500 under low pressure conditions, and 30 to 300 – for atmospheric pressure. This range of applicability corresponds to the region of active vaporization. These dependences do not generalize cases of convective heat exchange, boiling onset, and near-critical regions.

In addition, the results of our study are applicable only for the saturation pressure range from 0.012 MPa to 0.1 MPa. This, in a general case, is only half the working range of pressures in two-phase systems using water as a heat carrier.

Further research may be carried out towards expanding the working range of saturation pressures. In addition, research is needed using other heat carriers, which could

lead to greater use of results in the design of two-phase systems.

7. Conclusions

1. Our experimental study and the generalization of data obtained have established that a decrease in saturation pressure leads to a deterioration in the intensity of heat transfer by 5–20 % depending on the parameters of the porous sample. It has been found that reducing the effective pore diameter of the porous structure reduces the efficiency of heat transfer at boiling. In a general case, if the effective diameter is reduced from 90 to 40 μm , the intensity of heat exchange under the specified conditions can decrease by 25–40 %.

2. The generalization of data using the theory of similarity has made it possible to derive dependences that could be used to determine the intensity of heat transfer at water boiling on porous structures at capillary recharge under conditions close to those that are real for specific evaporative-condensation systems (heat pipes, steam chambers).

3. It has been determined that the reduction of saturation pressure leads to the fact that the type of porous structure has less effect on the intensity of heat transfer at boiling under capillary recharge conditions. As saturation pressure decreases, the effect of the type of porous structure on the intensity of heat transfer at boiling decreases. Thus, in the region of low pressures, the intensity of heat transfer of powder and fibrous structures is close. At atmospheric pressure, the intensity of heat transfer for powder structures is 15–20 % higher than that for fibrous structures.

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