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Heat Transfer during the Boiling of Liquid on Microstructured Surfaces. Part 1: Heat Transfer during the Boiling of Water

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Abstract—Results from an experimental investigation of heat transfer on microstructured surfaces obtained using the deforming cutting method and having different design shapes and sizes are presented. Heat transfer enhancement by a factor of up to 9 as compared with that on a smooth surface is obtained. Principles for constructing physical models of boiling enhancement are given.

Keywords: pool boiling, heat transfer coefficient, enhancement of heat transfer
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Development of modern technologies generates the need of achieving significantly higher heat transfer coefficients for removing high specific heat fluxes from relatively small areas. This problem can be solved by using the boiling of liquids in cooling systems. Despite the fact that considerable heat transfer coefficients are obtained due to an intense phase transformation process during boiling even on smooth surfaces, there is a need to achieve still higher enhancement of heat transfer.

Heat transfer from a wall to liquid during boiling can be enhanced using different means, namely:

(i) by selecting a suitable working fluid the physical parameters of which allow higher heat transfer coefficients to be obtained;

(ii) by using boiling during the motion of cooling agent; and

(iii) by shaping a microstructure on the heat-transfer surface for enhancing the generation and separation of bubbles.

Microstructured surfaces are understood to mean heat-transfer surfaces with small-scale deformations obtained as a result of subjecting these surfaces to processing or applying coatings and commensurable in their geometrical parameters with roughness. The roughness of such surfaces is small for changing the intensity of single-phase heat transfer; therefore, they are used primarily for boiling processes. The fundamental principle behind the development of structured surfaces for enhancing the boiling process consists in creating a large number of nucleation sites or traps of steam bubbles on the surface, due to which earlier commencement of boiling or boiling at lower temperature differences is obtained. This is especially important for the boiling of liquids that have good well surface wetting properties, e.g., freons, organic and cryogenic liquids, and liquid alkali metals.

The following requirements are imposed on the modern boiling heat-transfer surfaces for development of cooling systems:

(i) Nucleate boiling must begin at smaller differences of temperatures between the hot wall and liquid; i.e., narrower boundaries must be obtained between natural convection and nucleate boiling.

(ii) Higher heat-transfer coefficients must be obtained at the preset difference between the temperatures of wall and liquid.

(iii) A higher critical heat flux identifying the commencement of burnout must be achieved.

In paper [1] written by M. Jakob and W. Fritz, which one of the first works on heat transfer enhancement during nucleate pool boiling achieved through the use of microroughened surfaces with square milled slots and a rough surface obtained by means of a sandblasting machine, the heat transfer coefficients were increased by factors of 7–13 and 1.3–4, respectively. Such results were confirmed by the investigations carried out by C. Corty and A.S. Foust [2], which obtained a heat transfer enhancement ratio during pool boiling on a surface with granular roughness up to 4. That significant enhancement of heat transfer on structured surfaces can be obtained and that the superheating of liquid on a wall can be decreased by an order of magnitude was reported in the works of A.E. Bergles [3], J.R. Thome [4], R.L. Webb [5], S. Yilmaz and J.W. Westwater [6], as well as in the works of many other researchers. Recent years have seen an increased interest in studying the characteristics of boiling with a nanorelief [7, 8]. It was found that the use of nanorelief applied on a heat-transfer surface facilitated a decrease of separating bubble diameter by as much as

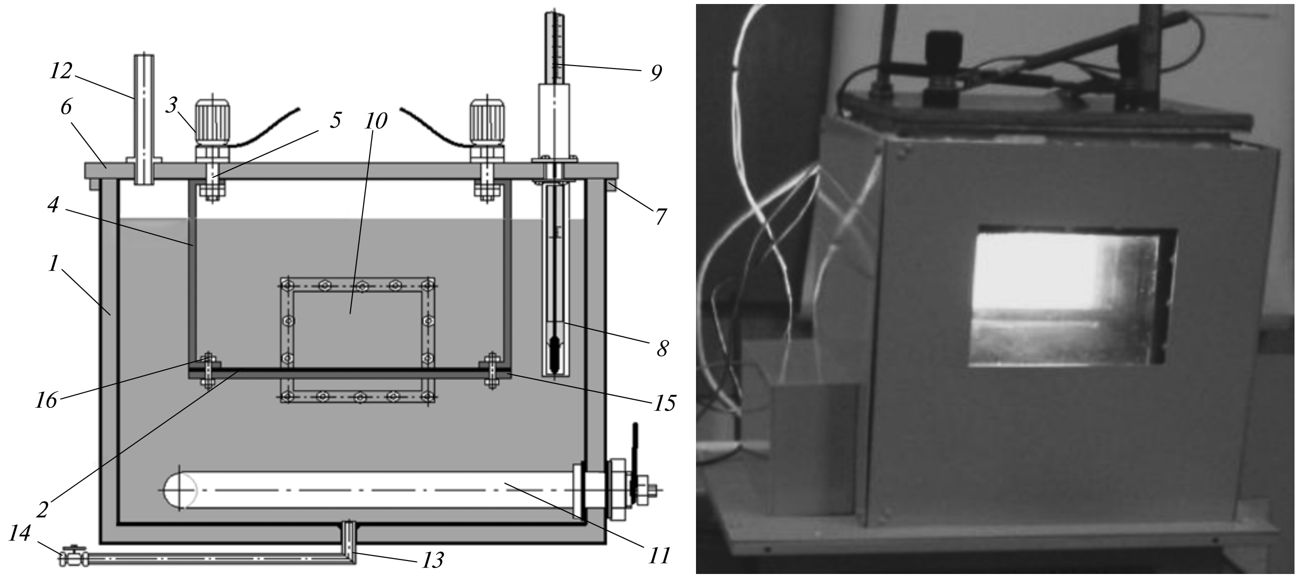

Fig. 1. Schematic design and external view of the experimental setup.

a factor of 3, increase of the number of nucleation sites by as much as factor of 25, and increase of bubble separation frequency by a factor of 3 to 5 as compared with smooth surfaces. Quite a number of studies of boiling on structured surfaces were carried out in Russia, among which the works of M.A. Styrikovich [9], Yu.A. Kuzma-Kichta [10–12], S.A. Kovalev [10, 13], M.D. Diev [14], L.L. Vasil'ev [15], V.M. Polyaev [16], I.Z. Kopp [17], L.I. Roizen [18], A.V. Borishanskaya [19], and of many other researchers are worthy of noting.

By subjecting a surface to special treatment (mechanical processing, formation or application of coatings) it is possible to create open cavities (half-closed recesses), which "capture" steam bubbles on the surface and facilitate further vaporization in liquids having small surface tension forces. The mechanism of phase transformation on such structured surfaces differs from "usual' boiling. Specific features of such process and its different models are described in the works of Xin, Ayub, Wong, Nakayama, Webb, and Chen, a review of which is given in [20]. In view of the fact that heat-transfer surfaces have a large number of varied geometrical parameters, and that optimization of boiling heat transfer involves a large number of operating parameters, researchers and engineers have to deal with intricate problems, and a need arises to carry out further extensive experiments in this field.

The modern methods for obtaining boiling surfaces can be subdivided into those implying development of disordered and ordered structures. Disordered structures can be obtained by spraying powders, by sintering powders or fibers, by applying composite coatings, also on a glue base, by abrasive treatment, chemical etching, applying different kinds of electrolytic coatings, etc. Ordered structures are obtained by subjecting surfaces to cutting, pressure treatment, and their combination. Assembled constructions with attached elements are also used.

In this work, we studied ordered structures obtained by a combined use of methods for cutting and plastic deformation (bending) of the surface layers of a heat-transfer surface. This technique was called a deforming cutting method and is used not only for making different types of heat-transfer surfaces [21, 22] but also for obtaining filtering tubes, microscreens, capillary structures, for strengthening surfaces, for restoring the sizes of parts, etc.

THE EXPERIMENTAL SETUP AND MEASUREMENT PROCEDURE

The experiments were carried out at a setup (Fig. 1) consisting of a thermally insulated vessel made in the form of boiling chamber *1* with sizes $150 \times 250 \times 200$ mm filled with doubly distilled water. Asbestos heat-insulating packing is placed between the boiling chamber's double walls. Chamber *1* contains plate *2*, on which boiling enhancement was studied. The experimental plates were heated by passing electric current through them. The power supply voltage was applied to sample *2* from terminals *3* through 3-mm thick and 20-mm wide flat copper current leads *4*. The current leads are secured on electrically insulating textolite cover *6* by means of threaded joint *5*. Cover *6* is furnished with sealing collar *7*. The experimental plate was placed with respect to cover *6* and vessel *1* so as to achieve the best visibility of its working surface. Experimental plate *2* is attached to 30-mm wide and 6-mm thick supporting textolite plate *15* and is pressed to the current leads through threaded joint *16*. Pocket *8* of thermometer *9* is attached to the cover. During the experiments, thermometer *9* was installed into pocket *8* so

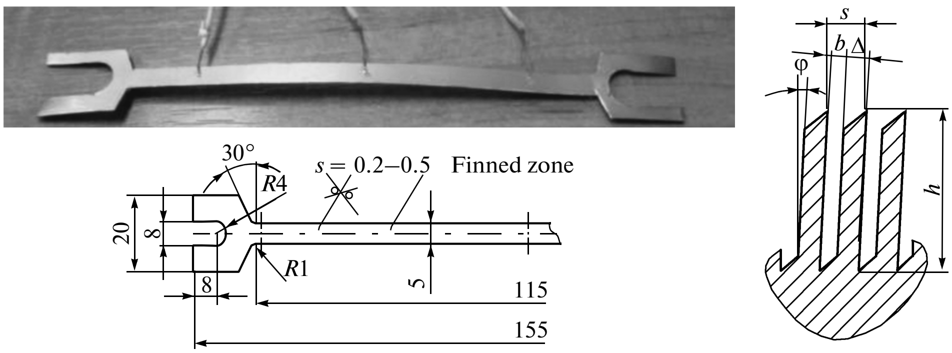

Fig. 2. Geometric shape of the sample, location of the finned zone and thermocouples, and the sizes of fins.

that the mercury reservoir was at the same level with experimental plate *2*. Thus, the temperature of water immediately in the plate *2* location zone was measured.

The chamber body has two windows *10*: one made of opal glass for lighting and the other of transparent glass for observing the boiling process.

The water was heated to the boiling temperature using tubular electric heater *11*, the thermal power of which was adjusted during the experiment. Steam generated during boiling was cooled on the wall of a condenser connected to the cavity of chamber *1* through sleeve *12* located in the vessel's upper part. The produced condensate flowed back into the chamber. The condenser also served for maintaining the saturation conditions in the working chamber.

The chamber was filled with water and emptied through drain sleeve *13* in the vessel's lower part with valve *14* held in the open position. When the installation was in operation, valve *14* was held in the closed position. The layer of liquid above the experimental plate had a height of 60–80 mm.

The parameters characterizing the water heating process, which was organized by using a guard heater and an experimental heater, were adjusted by means of a power unit and a control unit. The power unit comprised autotransformers (installed on a welded frame's front panel) for varying the voltage applied to the experimental heater and to the guard tubular electric heater, two switches for connecting and disconnecting the power supply voltage applied to the experimental heater and guard tubular electric heater, amperemeters for monitoring the current during the sample heating process, voltmeters for determining the voltage drop across the sample, and millivoltmeters for measuring the thermal e.m.f. of Chromel–Copel thermocouples on the sample surface, and indicating fixtures.

The water temperature t_w was measured in the course of experiments using a mercury thermometer with the measurement range from 50 to 100°C and scale division of 0.1°C.

The heat-transfer coefficient α, W/(m^2 K) was calculated from the formula

$$\alpha = Q/(F\Delta t),$$

where $Q = I\Delta U$ is the heat flux releasing on the plate, W; I is the current fed to the plate, A; ΔU is the voltage drop across the plate, V; F is the plate surface area between the current leads (the product of plate width by the plate length between the current leads without taking into account the increase of surface area as a result of finning), m^2; and $\Delta t = \overline{t}_{wl} - t_w$ is the difference between the average temperature of sample surface and the water temperature, K.

THE STUDIED SUBJECTS

The geometrical shape and sizes of the samples are shown in Figs. 2 and 3 and listed in Table 1. The investigations were carried out on samples made of different materials with a thickness from 0.2 to 0.5 mm, test (finned) portion length equal 115 mm and width of 5–7 mm. The sample length was selected so as to have unobstructed view of the boiling surface through the sight window, and the sample's test portion thickness and width were selected so as to obtain the required heat fluxes at the heat-transfer surface. For obtaining reliable electric contact between the samples and current-carrying busbars and minimal removal of heat from the surfaces to the busbars, the area of the corresponding edges of samples was increased. A microrelief was applied on the straight narrow part of the sample.

Sheets made of Grade VT1-00 titanium with a thickness of 0.5 mm, Grades 12Kh18N9T and 12Kh18N10T stainless steel with a thickness of 0.5 mm, and Grade AISI 1020 carbon steel with a thickness of 0.30–0.35 mm (see Table 1) were used as billets for fabricating finned plates. These materials were selected because (a) fins with a high-quality shape can be obtained on the surface of titanium plates and (b) the used materials had relatively high resistivity, which is quite important since the samples were heated in the experiments by passing electric current through them.

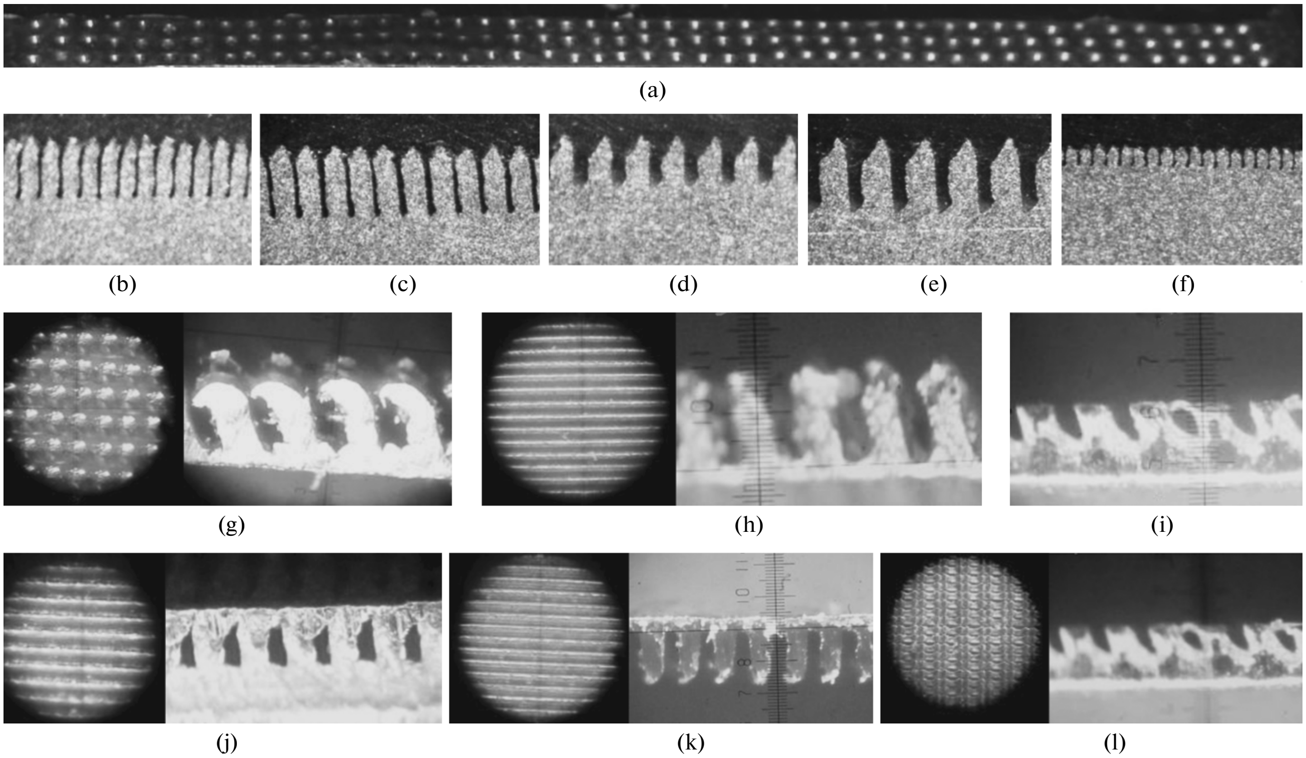

Fig. 3. Appearance (top view and metallographic sections) of the studied boiling surfaces. (a) 3D roughness in the form of spherical dimples; (b)–(f), (h), (i), and (k) 2D roughness in the form of conducting fins; (g) and (l) 3D roughness in the form of pin-shaped dissipating fins; and (j) 2D roughness in the form of microchannel structure formed by bent conducting fins.

The samples were fabricated from 20-mm wide plates with a microrelief preliminary applied on them. The specific feature connected with processing these billers was that the sample's heated segment had to be made with its lateral sides parallel to each other and rectilinear with accuracy of ±0.1 mm. Such accuracy had to be ensured in order to exclude narrowing and, as a consequence, local overheating of the surface that might introduce errors during temperature measurements. The sample's shape was obtained from the billet by subjecting it to electroerosion treatment or on a grinding machine according to a template.

The sample surface temperature was measured using three Chromel-Copel thermocouples (with the conductors 0.2 mm in diameter) (see Fig. 2). The junction of one thermocouple was near the sample's transverse symmetry axis, and the junctions of the two end thermocouples were at a distance of 40 mm from the sample edges. Each junction of the thermocouple was welded to the sample surface. The free ends of the thermocouples were taken out through a hole in the vessel cover, which was sealed during the experiment. All wires of the thermocouples were insulated from each other and from the liquid by means of PVC tubes.

To exclude boiling of water on the smooth (lower nonfinned) surface of the sample and to avoid temperature measurement errors caused by steam bubbles periodically generated at the thermocouple welding locations, the surface was covered by a layer of epoxy glue and a layer of silicon sealant, and glued to a textolite substrate. The layers of glue and sealant served to ensure additional strength of the connection of thermocouples with the sample. The 6-mm thick textolite substrate protected the plates from being damaged and deformed during the experiment and served to decrease heat losses on the opposite nonfinned side of the plate.

As was already mentioned, the experimental boiling surfaces were heated by passing electric current through them. The configuration of finned elements has certain specific features with respect to the flow of current and heat propagation. The boiling surface has the shape of a rectangle in its plan view, and fins can be arranged both along its long and short sides. Therefore, the electric current passed in the plate's longitudinal direction may cause release of Joule heat only in the base part of fins (transverse ones) and concurrently in fins themselves (longitudinal ones); i.e., these elements can either dissipate or release heat. Almost all studies of boiling on finned surfaces are carried out for the first case, which is a traditional one. In the present study, we primarily investigated heat-releasing microfins, i.e., 2D fins the generatrices of which coincided with the direction of electric current, the heating of which over the height can be regarded as uniform. Heat-dissipating microfins were those with a 3D con-

Table 1. Parameters of the studied plates

Nos. of samples (Figs. 4, 5)	Type of surface, external view (Fig. 3)	Material	Fin height h, μm	Fin pitch s, μm	Interfin gap b, μm	Fin inclination angle φ, deg	Depth of indents, mm	Diameter of indents, mm	Knurling pitch, μm	Groove width, μm
1, 2	Smooth	12Kh18N9T	–	–	–	–	–	–	–	–
3	*a*	12Kh18N9T	–	–	–	–	1	2	–	–
4	*a*	12Kh18N9T	–	–	–	–	0.5	1	–	–
5	*b*	VT1-00	95	40	15	3	–	–	–	–
6	*c*	VT1-00	310	160	63	3	–	–	–	–
7	*d*	VT1-00	200	120	46	3	–	-	–	–
8	*e*	VT1-00	230	90	35	3	–	–	–	–
9	*f*	VT1-00	220	60	22	3	–	–	–	–
10	*g*	AISI 1020	420	350	–	0	–	–	318	140
11	*h*	12Kh18N10T	150	160	50	0	–	–	–	–
12	*i*	12Kh18N10T	90	160	50	0	–	–	–	–
13	*j*	VT1-00	200	200	30–40	30	–	–	–	–
14	*k*	12Kh18N10T	200	160	50	0	–	–	–	–
15	*l*	AISI 1020	340	240	–	15	–	–	318	140
16	*k*	12Kh18N10T	200	160	50	0	–	–	–	–

figuration, i.e., fins arranged in a discontinuous manner along the flow of electric current through them, and the distribution of temperatures in them is typical for finning.

The influence of the direction of electric current in microfins on boiling surfaces was numerically investigated in the works of M.D. Diev and D.N. Morskoi. It has been found that if current flows along the fins, Joule heat is released in them uniformly, and almost no heat is released in fins if current flows in the transverse direction.

The data for samples Nos. 5–9 (see Table 1) were obtained by the scientific team led by Diev.

STUDY RESULTS

The experimental data were obtained for distilled water at atmospheric pressure. Heat flux density was varied from 10 to 1200 kW/m^2. Convection, surface and developed nucleate boiling, and burnout modes were observed in the studied range of heat flux density. The investigations were carried out in a boiling mode when the temperature of liquid in the boiling chamber in the zone of samples was in the range 97.5–99.3°C.

It was noted during the experiments that a change occurs in the heat transfer intensity during long-term operation of plates with liquid periodically boiling up on their surface; i.e., a "break-in" process of the surface takes place. Experiments from a series of seven boil-ups on the surfaces showed that the level of heat transfer on the surface decreases after four boil-ups (possibly, due to destruction of oil microfilm on the surface and carryover of microparticles and air bubbles from the interfin space), after which it remains almost constant (in experiments carried out on individual plates for 14 days with a duration of 3 h a day). All results were obtained on broken-in plates.

According to the results of experiments, use of surfaces with a relief obtained by means of the deforming cutting method makes it possible to achieve more efficient boiling heat transfer as compared with that in smooth samples.

Figures 4 and 5 show the experimental data on heat transfer for pool boiling of water on surfaces with different geometries. The effect the roughness geometry of horizontal surfaces has on heat transfer is shown. The boiling curves were constructed for a growing heat load (almost no hysteresis in the boiling curve was observed).

It follows from Fig. 5 that higher coefficients of heat transfer at a preset difference of wall and liquid temperatures can be obtained, and the onset of nucleate boiling at smaller differences of temperatures between the hot wall and liquid can be achieved if the boiling surface has microughness.

Figure 4 shows the results of test experiments (points *1*) for the boiling of water on a smooth surface. These results differ by 10% from the results of calculation (curve *2*) carried out using the Labuntsov dependence $\alpha = 3q^{0.7}p^{0.1}$.

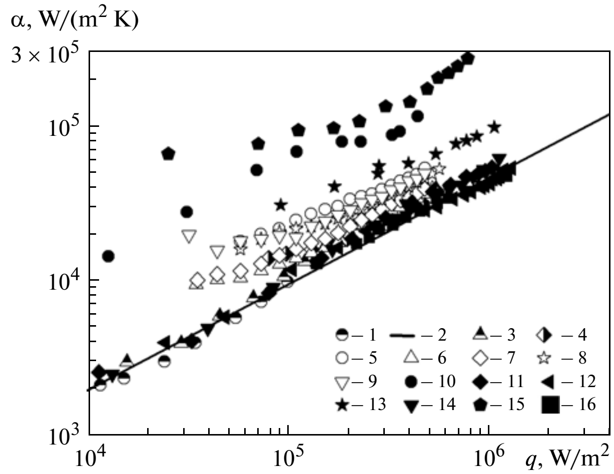

Fig. 4. Heat transfer during pool boiling of water on surfaces of different geometries. (1)–(16) are the numbers of samples (see Table 1).

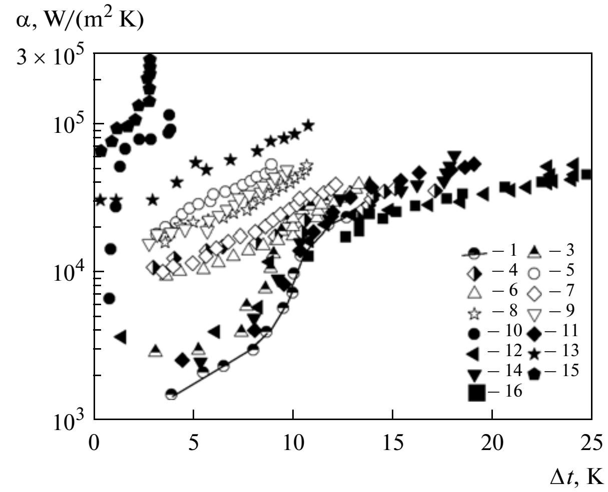

Fig. 5. Intensity of heat transfer during pool boiling vs. the difference of temperatures for surfaces with different geometries. (1)–(16) are the numbers of samples (see Table 1).

The levels of heat transfer enhancement were determined at the same value of q = idem (according to the data of Fig. 4). The term "enhancement" is used here taking into account the increase of surface area as a result of applying a microstructure (the ratio of which was in the range from 2.1 to 8.3 for samples Nos. 5–12 and 14–16) and the change in the hydrodynamic pattern of boiling on a microcapillary surface. With the heat-transfer coefficients calculated taking into account the development of surface, their values turn to be smaller than those for a smooth surface.

The highest enhancement of heat transfer is typical for the surfaces of samples Nos. 15 and 10 with 3D roughness in the form of bars, the ratio of which is from 4.5 to 9 depending on the heat flux density. Small interfin gaps facilitate leak-in of liquid to nucleate sites, and significant sizes of transverse grooves facilitate removal of steam [4, 20].

A high level of heat transfer enhancement was also observed on the surface of sample No. 13 with continuous fins, the ends of which are bent horizontally and form microchannels. These surfaces are close to porous coatings in the mechanisms of heat transfer enhancement. The enhancement ratio of heat transfer from such surface was equal to 2.5–3 in the entire range of heat flux densities.

An analysis of the study results obtained for the surfaces of samples Nos. 5–9, 11, 12, 14, and 16 with 2D microfins showed that the heat transfer enhancement ratio depends on the height of microfins, gap width between microfins, and fin inclination angle with respect to a vertical plane.

The data shown in Fig. 6 testify that at q = 250 kW/m^2, the enhancement ratio α/α_{sm} of heat transfer for samples Nos. 11, 12, and 14 having similar types of surfaces with heat-releasing microfins (s, b, φ, Δ = const, where $\Delta = s - b$ is the fin thickness) increases with increasing the relative fin height h/Δ from 0.82 to 1.82 (h increases from 90 to 200 μm) in the range from 1.17 to 1.26. As to the relative heat-transfer area F/F_{sm}, it increases more significantly: from 2.125 to 3.5, i.e., by a factor of 1.65.

The surfaces of samples Nos. 14 and 16 have the same shape and sizes of microfinning, but sample No. 14 has longitudinal heat-releasing fins, whereas sample No. 16 has transverse heat-dissipating fins. It was noted that the heat-transfer coefficients on sample No. 14 were by 8–50% higher than those on sample No. 16, depending on the level of heat fluxes. A numerical assessment showed that the average efficiency factor of fins on the surface of sample No. 16 is 0.78 and that of fins on the surface of sample No. 14 is 1.0. The heat transfer on the surface of sample No. 16 of the same type with heat-dissipating fins with the relative height h/Δ = 1.82 (h = 200 μm) has the same level as that on the surface of sample No. 12 with heat-releasing fins with the heighth/Δ = 0.82 (h = 90 μm).

The heat transfer enhancement ratio on the microfinned surfaces of samples Nos. 5–9 was from 1.2 to 2.5 in the entire range of heat flux densities.

Based on the results obtained on samples Nos. 5–9, an attempt was made to analyze the effect the width of interfin gap has on heat transfer. For samples Nos. 5–9, variation of all the main geometrical parameters is typical. We see from Table 2 that the relative fin height h/Δ has an inversely proportional effect as compared with samples Nos. 11, 12, and 14. Attempts to determine the effect the interfin gap width b/h and the relative fin width Δ/b have on the level of heat transfer were not met with success. However, it can be seen from Table 2 that the absolute size of interfin gap b (the fin pitch s) has an effect (Fig. 7): as its value

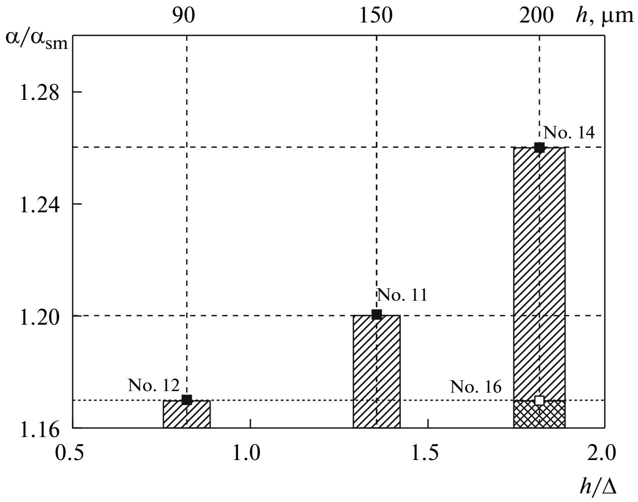

Fig. 6. The effect the height of microfins has on the heat transfer enhancement ratio at $q = 250$ kW/m^2. $s = 160$ μm, $b = 50$ μm, $\Delta = 110$ μm, $\Delta/b = 2.2$, $s/b = 3.2$; $\varphi = 0$.

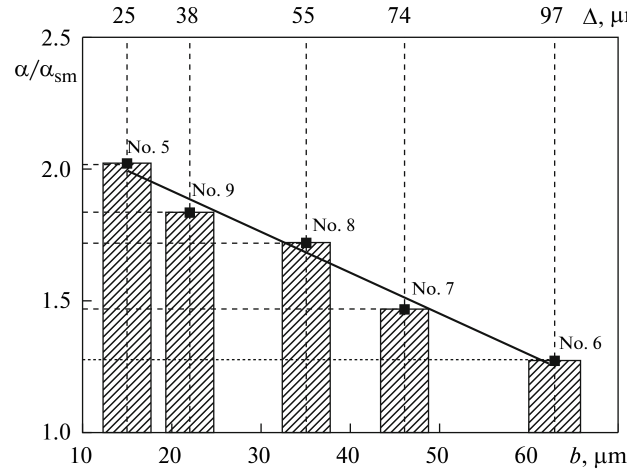

Fig. 7. The effect of intefin gap width on the heat transfer enhancement ratio at $q = 250$ kW/m^2.

increases, the heat transfer enhancement ratio decreases. In this case, the heat-transfer area decreases, but it was not possible to reveal how the heat-transfer area F/F_{sm} influences the heat-transfer coefficient (see Table 2).

The enhancement of heat transfer on the surfaces of samples Nos. 3 and 4 with macroroughness composed of spherical dimples is minimal and does not exceed a factor of 1.2.

Video recording of the boiling process on the samples was carried out during the experiments, the results of which showed that nucleate boiling emerges on the surfaces of samples Nos. 5–15 at smaller temperature differences. The nucleate sites grow in number, the separating bubbles have smaller diameters, microbubbles remain in the intefin space as the boiling process develops, and the bubble separation frequency increases. This is especially the case on the surfaces of samples Nos. 10, 13, and 15, the separating bubbles on which have a drastically smaller diameter, and their separation occurs at higher frequency.

The results from the performed investigations allow us to substantiate the optimal conditions for using these intensifiers and the mechanisms governing heat transfer enhancement.

THE PHYSICAL PRINCIPLES FOR ENHANCEMENT OF BOILING HEAT TRANSFER ON MICROSTRUCTURED SURFACES

Enhancement of boiling heat transfer on microstructured surfaces opens the way for making cooling systems and heat-transfer equipment essentially more compact [20]. The enhancement ratio of heat transfer on tubes with straight fins with a height of 0.06–2 mm reaches 2–4, and that on tubes with porous coating or deformed fins with a small height reaches 10 or more as compared with a smooth tube. Higher critical heat fluxes and a smaller level of superheating required for the onset of nucleate boiling are also important parameters for practical use.

The enhancement of heat transfer is connected with a change in the hydrodynamic pattern of boiling and partially with increasing the heat-transfer surface area. Vaporization occurs both on the upper edges of fins (pins) and in interfin spaces (pores). Hence, heat

Table 2. Analysis of the effect the design parameters of boiling surfaces have on heat transfer enhancement at $q = 250$ kW/m^2

Increase of heat transfer α/α_{sm}	No. of sample (Figs. 4, 5)	Fin thickness Δ, μm	Interfin gap b, μm	Fin height h, μm	Fin inclination angle φ, deg	Relative fin height h/Δ	Relative width of interfin gap b/h	Relative fin width Δ/b	Increase of heat-transfer area F/F_{sm}
2.02	5	25	15	95	3	3.8	0.16	1.67	5.75
1.84	9	38	22	220	3	5.8	0.10	1.72	8.33
1.72	8	55	35	230	3	4.2	0.15	1.57	6.11
1.47	7	74	46	200	3	2.7	0.23	1.61	4.33
1.28	6	97	63	310	3	3.2	0.20	1.54	4.87

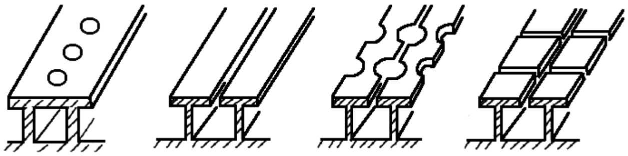

Fig. 8. Prospective shapes of boiling surfaces.

removal during vaporization takes place within the confines of interfin gaps and at the top edges of fins, and also by the liquid flowing under the effect of capillary forces in the interfin gaps and heated on the top edges of fins. The effectiveness of the above-mentioned factors depends on the geometry of enhanced surface and on its determining sizes.

At low heat fluxes liquid fully fills all interfin gaps, part of which become afterwards active nucleation sites. As heat fluxes grow, steam bubbles are generated at active nucleation sites in interfin gaps. The liquid residing between these sites is "sucked" into the interfin space under the effect of capillary forces and propagates over the interfin gaps, thus moving toward active nucleation sites. As heat fluxes grow further, steam fully fills the interfin gaps, and steam bubbles grow on the upper edges of fins; i.e., fins as if pierce the steam layer.

According to the existing ideas of M.D. Diev about the mechanisms governing the boiling on microroughened surfaces [14] and the experimental data obtained by S. Yilmaz, N.-H. Kim, and other researchers [6, 23], who noted heat transfer enhancement by more than a factor of 10, 2D and 3D microreliefs with one of the shapes shown in Fig. 8 may be among prospective boiling heat-transfer surfaces. Roughnesses with microcapillary gaps containing cavities with exits for steam of sufficiently large cross section are very efficient both for heat transfer enhancement and for increasing critical heat loads. In all likelihood, pulsating boiling in such kind of pores at which Diev pointed out concurrently ensures efficient evaporation from the surface of liquid films inside the pores and efficient removal of steam from them. In this study, the surface of sample No. 13, close in design to the proposed intensifiers, had the highest heat-transfer characteristics; however, the finning parameters need optimization.

Thus, the performed investigations have shown that heat-transfer surfaces obtained by the new resource saving method for shaping them in the form of 2D and 3D microfinned surfaces and channel structures make it possible to achieve essentially enhanced heat transfer during the boiling of liquids. The highest enhancement of heat transfer is typical for surfaces with 3D bar and channel structures: by a factor of 3 to 9. The heat-transfer enhancement ratio for 2D microfins is up to 2.5. Decreasing the interfin distance and fin thickness facilitates heat transfer enhancement.

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