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AIRCRAFT AND ROCKET ENGINE THEORY

Boiling Heat Transfer of Different Liquids on Microstructured Surfaces

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Abstract—The results of an experimental study of heat transfer on microstructured surfaces are presented. The surfaces studied have been obtained by deforming cutting and have different structural shapes and sizes. Recommendations are given for the use of the surfaces studied in boiling of different liquids.

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The effective cooling systems of microelectronic equipment are required for reliability and safe operation of avionics, measuring and computing systems. The current trend in microelectronic equipment design is the increase of the specific heat fluxes in cooling systems of chips. The first step in choosing the type of a cooling system and its design is to define and quantify the heat that is generated and the amount required to be removed or the total given heat flux (or heat release) of an electronic component. Another objective is meeting the requirements for both weight and dimensional characteristics. A cooling system should be placed within the specific dimensions of the electronic equipment without leading to a sharp increase in its weight. It is always necessary to strike a balance between the optimum weight and dimensional parameters of the cooling systems while maintaining their structural simplicity. The most appropriate cooling systems are the natural convection cooling systems, since they do not require additional power to pump a refrigerant and have no moving parts, and they are both reliable and quiet. The cooling systems should also ensure smooth and reliable cooling for an extended time.

Electronic equipment developed for on-board systems of aircraft, satellites, spacecraft and missiles should be developed with account for the complex forms of attachment points, cramped space, and small dimensions while ensuring a safe and efficient heat dissipation. Cooling systems for electronic devices and their operational reliability are usually determined by the level of heat transfer coefficient and the maximum allowable temperature of the device. These two parameters allow us to select the appropriate method of cooling.

Currently, the most widely used cooling systems for electronic devices are the following:

1) air free-convection cooling systems and radiation;

2) forced air cooling systems;

3) immersion or free convection cooling by immersion into dielectric fluids, including cryogenic fluids or freons;

4) cooling under reflux in a dielectric fluid, including jet cooling;

5) forced water cooling systems;

6) open evaporation systems;

7) water chillers;

8) systems using the Peltier cells (thermoelectric cooler).

To develop the efficient, reliable and compact cooling systems 1–4 and 6, it is necessary to improve heat transfer and critical heat fluxes in boiling of different liquids. At present, air cooling systems 1 and 2 contain heat pipes that permit removing the considerable heat fluxes from small surfaces and transporting them into zones, where there are no limitations for the development of the heat transfer surface, when heat is released into the environment. Liquid-cooling and evaporative systems 3, 4 and 6, as well as the thermal stabilization systems in the form of heat pipes necessitate a significant increase in heat transfer coefficient for removing the large heat fluxes from the relatively small chip area. This problem can be solved by using the boiling liquids within the cooling systems. Despite the high heat transfer coefficients due to an intense phase transformation process during boiling, the intensity of heat transfer should be further increased even on smooth surfaces.

Increased heat transfer from the wall to the liquid at boiling can be achieved by formation of specific microstructures on the heat transfer surfaces in order to increase the intensity of the formation and detachment of bubbles [1–14].

Microstructured surfaces are the heat exchange surfaces with small-scale deformations that are obtained by their treatment and comparable in geometric parameters to roughness. Development of the structured surfaces for intensification of the boiling process is based on the following basic rule, namely, on the creation of a large number of nucleation sites or traps for vapor bubbles upon the surface, which expedites the initiation of boiling or results in boiling at lower temperature heads.

Microstructured surfaces are effective for the intensification of heat transfer processes upon the enhanced boiling surface, which is obtained by both deforming and cutting, which is a combination of both undercutting and flanged surface layers of the heat exchange surface [8].

Experimental studies were performed on a setup according to the technique [9–11]. Studies were conducted using the samples of different material thicknesses from 0.2 to 0.5 mm and a length of the working (ribbed) part of 115 mm and a width of 5–7 mm. Stock for manufacture of finned or ribbed plates were 0.5 mm thick sheets of VT1-00 titanium, 12Kh18N9Ti, 12Kh18N10T stainless steel of 0.2 mm thick, and AISI 1020 high carbon steel of 0.3-0.35 mm thick (table).

Table

No. of surface	Material	Height of fins, μm	Fin pitch, μm	Interfin gap, μm	Angle of declination, deg	Dimple depth, mm	Dimple diameter, mm	Knurling pitch, μm	Groove width, μm
1–2	12Kh18N9T	-	-	-	-	-	-	-	-
3	12Kh18N9T	-	-	-	-	1	2	-	-
4	12Kh18N9T	-	-	-	-	0.5	1	-	-
5	VT1-00	95	40	15	87	-	-	-	-
6	VT1-00	310	160	63	87	-	-	-	-
7	VT1-00	200	120	46	87	-	-	-	-
8	VT1-00	230	90	35	87	-	-	-	-
9	VT1-00	220	60	22	87	-	-	-	-
10	AISI 1020	420	350	-	90	-	-	318	140
11	12Kh18N10 T	150	160	50	90	-	-	-	-
12	12Kh18N10 T	90	160	50	90	-	-	-	-
13	VT1-00	200	200	30–40	60	-	-	-	-
14	12Kh18N10 T	200	160	50	90	-	-	-	-
15	AISI 1020	340	240	-	75	-	-	318	140
16	12Kh18N10 T	200	160	50	90	-	-	-	-

Studies of heat transfer were performed in boiling of distilled water (bidistillate), 96% ethanol, 60% aqueous glycerol solution D98, S11 antifreeze, and 0.05% aqueous solution of Al_2O_3.

Experimental data were obtained at an atmospheric pressure of 0.1 MPa. Heat flux was varied from 10 to 1200 kW/m^2. In the investigated range of the heat flux there were observed the modes of convection, the surface and developed nucleate boiling, and the boiling crisis. Investigations were carried out in boiling of saturated liquids.

The experiments showed that the application of the relief-like surfaces obtained by the method of deforming by cutting improves the heat transfer rate at the boiling as compared with the smooth patterns. Levels of heat transfer enhancement were determined at q = idem.

The results of the test runs at boiling liquid on the smooth surface are shown in Fig. 1. The experimental results for nucleate boiling of water (Figs. 1 and 2a, points 1) and the results of calculations by the dependences $\alpha = 3q^{0.7}p^{0.15}$ [12] (Fig. 1, line A) and $\alpha = 3.4q^{2/3}p^{0,18}/(1-0.0045p)$ [13] (Fig. 2a, line B) differ by 10– 30%.

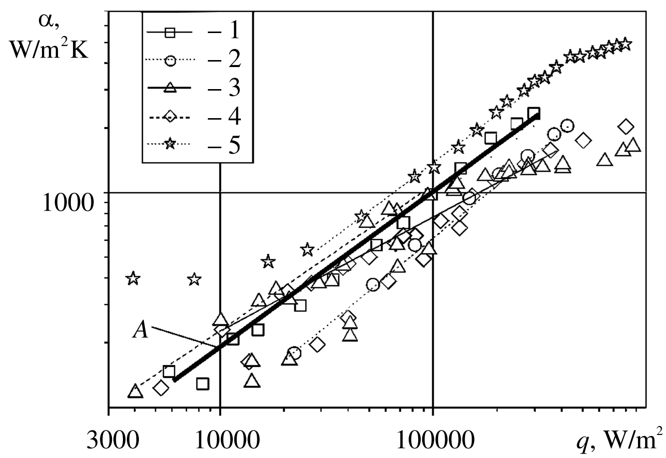

Fig. 1. Comparison of boiling heat transfer of different liquids on smooth surfaces for various liquids: (*1*) distilled water; (*2*) 96% ethanol; (*3*) 60% aqueous D-98glycerin solution; (*4*) antifreeze S11; (*5*) 0.05% Al_2O_3 + distilled water (designation in the table).

Use of 0.05% Al_2O_3 powder additives in distilled water enhanced the heat transfer by 30–40% (Fig. 3). As noted in [14], in boiling of nanofluids, including H_2O with the addition of Al_2O_3, the enhancement of heat transfer is due to an increase in nucleation sites by precipitation and growth of submicron microstructures on the boiling surfaces.

Experimental data on boiling heat transfer of various liquids in a large volume of water on the surfaces with different geometry are shown in Figs. 2 and 3. The effect of the surface roughness geometry of horizontal surfaces on the heat transfer is shown. Boiling curves have been constructed according to the data obtained with both increasing and decreasing the thermal load (hysteresis curve of boiling water has not been practically observed).

The presence of microroughness demonstrate the previously set objectives of achieving the higher heat transfer coefficients at a given temperature difference between the wall and the liquid with the beginning of nucleate boiling at a lower temperature difference between the hot wall and the liquid (Fig. 3).

The greatest enhancement of boiling heat transfer in water and 96% ethanol was achieved with surfaces nos. 10 and 15 (Fig. 4). These surfaces are with the three-dimensional columnar micro-roughness. Enhancement of boiling heat transfer in water was from 5 to 20 times, depending on the level of heat flux and from 1.3 to 23 times at reflux using 96% ethanol as compared with the smooth surface (Fig. 4). The presence of small intercostal gaps provides leakage of fluid to the nucleation sites, and the large size of the lateral grooves provides the vapor output. In boiling of the more viscous 60% aqueous solution of D-98 glycerol, heat transfer was enhanced by a factor of 1.1–3 in comparison with the smooth surface.

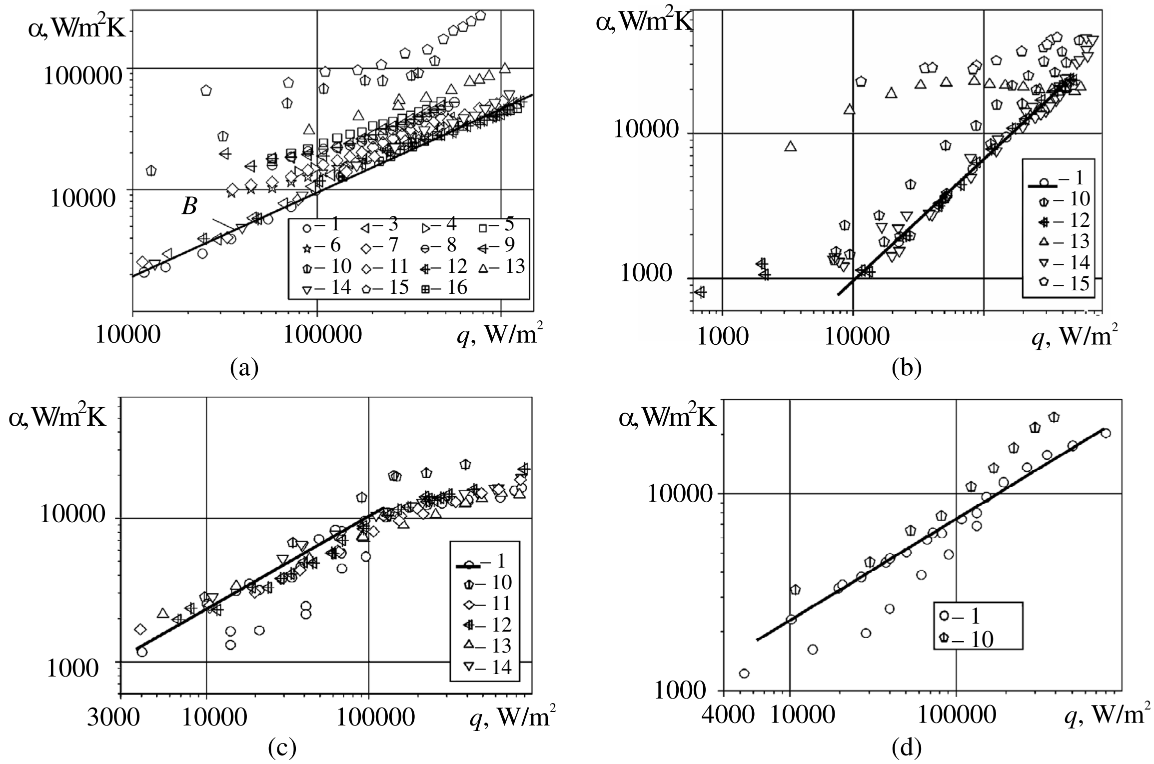

Fig. 2. Boiling heat transfer in a pool of different liquids on various-shaped surfaces: (a) distilled water; (b) 96% ethyl alcohol; (c) 60% aqueous D-98 glycerol solution; (d) S11 antifreeze (designation in the table).

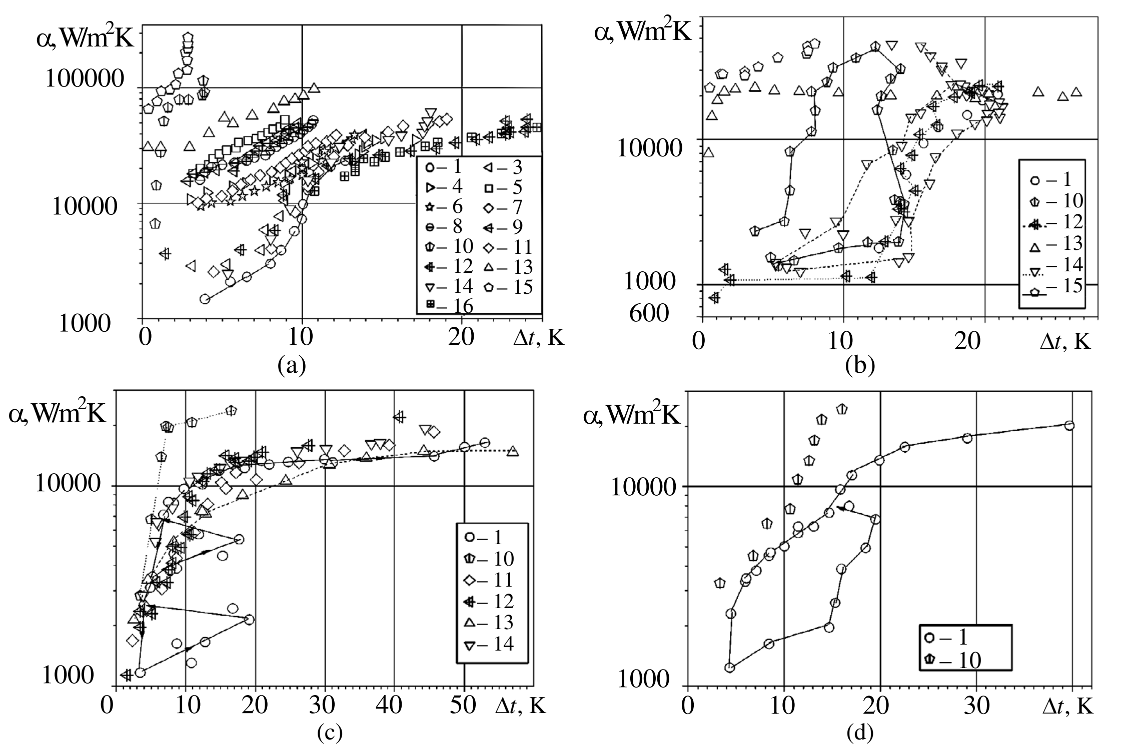

Fig. 3. The intensity of the boiling heat transfer of various liquids in a pool, depending on the temperature difference between the various-shaped surfaces: (a) distilled water; (b) 96% ethyl alcohol; (c) 60% aqueous D-98 glycerol solution; (d) S11 antifreeze (designation in the table).

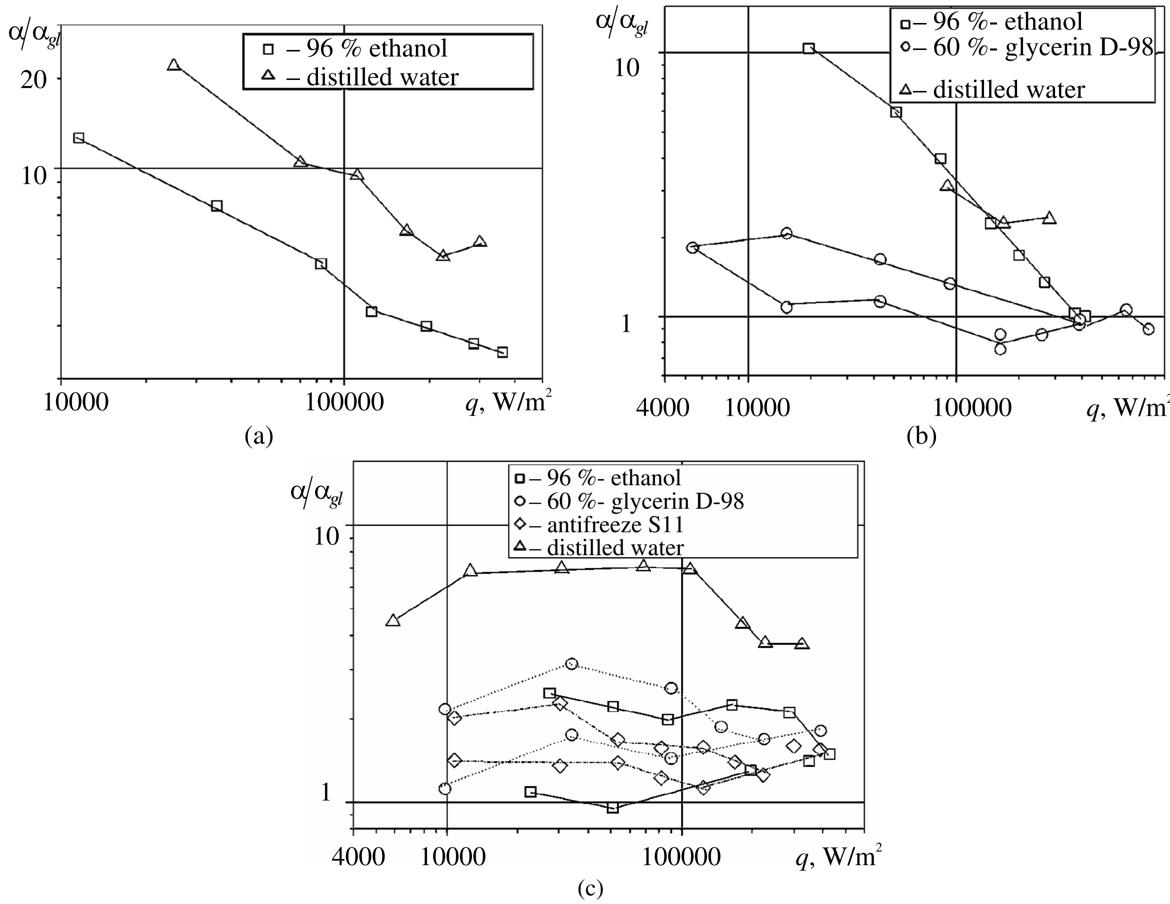

Fig. 4. Comparison of boiling heat transfer enhancement of various liquids on different types of microstructured surfaces: (a) surface no. 15; (b) no. 13; (c) no. 10 (designation in the table).

A high level of boiling heat transfer was shown on surface no. 13 (Figs. 3 and 4) having solid fins, the ends of which were horizontally bent to form microchannels. Such surfaces are close in enhancement mechanisms to porous coatings. Boiling heat transfer on this surface was enhanced 2.5–3 times for water, 10 times for 96% ethanol, and two times for the D-98 60% aqueous glycerol solution.

Analysis of the experimental data obtained for surface nos. 5–9, 11, 12, 14, and 16 with two-dimensional microfins showed that the level of heat transfer enhancement in boiling water depends on to the height of microribs, the width of gaps between microribs, the position of fins, and the angle of the ribbing to the vertical edges. The boiling heat transfer of water on the micro-ribbed surfaces nos. 5–9 was enchanced by a factor 1.2 to 2.5 throughout the entire density range of heat fluxes. In boiling of 96% ethanol, 60% aqueous solution of D-98 glycerin, and S11 antifreeze, practically no heat transfer enhancement on these surfaces was observed (Figs. 2b–2d). Based on the results obtained it was concluded, that with an increase in the absolute size, namely, the gap between the ribs (fin pitch), the level of heat transfer enhancement decreases.

On surfaces nos. 3 and 4 with macroroughness of spherical recesses, the heat transfer enhancement in water boiling was minimal, it was enhanced by a factor of 1.2.

As is seen from Figs. 2–4, the best data on the intensity of the heat transfer enhancement were obtained for surfaces nos. 10 and 15 with columnar structure. For surface no. 13 "steaming" can be observed beneath the porous curved edges, boiling on the outer sides of the ribs and the typical distribution of the heat transfer coefficient as a function of the surface overheating and heat flux density. This is particularly evident in boiling of 96% ethanol (Figs. 2b and 3b).

Comparison of heat transfer enhancement for different surfaces and liquids is shown in Fig. 4. It can be noted that the greatest heat transfer enhancement on the surfaces investigated takes place in boiling of water. Therefore, these surfaces are most effective in water cooling systems of microprocessor equipment, water heat pipes, and water thermosyphons. For other fluids, it is necessary to select the geometric parameters of microstructured surfaces, depending on the capillary constant of a particular fluid.

To substantiate the mechanisms of heat transfer enhancement on the surfaces, we carry out video filming of boiling process in the course of these experiments. Visualization of water boiling for surfaces nos. 1, 3, and 9 is given in [9–11].

In the absence of mathematical models, the empirical criteria can be used for calculating the heat transfer and critical heat fluxes on the surfaces being investigated. This requires systematization and processing of experimental data. An attempt to generalize the experimental data on heat transfer obtained in this work was made in [10]. It is imperative to increase further the array of experimental data, involve the available data from the literature, and generalize these data.

Thus, the experimental study was made and the data array was formed on boiling heat transfer for various saturated liquids at a pressure of 0.1 MPa under free convection on the microstructured surfaces of different structure with sizes of fin elements from 50 to 420 μm obtained by deforming and cutting.

It has been established that the most suitable substance for investigating the microgeometry of boiling surfaces is water. The highest heat transfer enhancement in the case of boiling of water (from 3 to 20 times) is attained on the surfaces with three-dimensional columnar and channel structures. For two-dimensional microfins the enhancement of heat transfer does not exceed 2.5 times. The decrease in the distance between fins and their thickness increase the heat transfer rate. Thus, the objectives for further studies and selection of effective microstructures on boiling surfaces have been formulated.

The results obtained from this study are the basis for generalizing and obtaining the dependences for the calculation of heat transfer coefficients at boiling of different saturated liquids at a pressure of 0.1 MPa under free convection on microstructured surfaces of different structures.

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