Enhancement of critical heat fluxes at pool boiling on structured surfaces

I A Khaziev, A V Dedov and S D Fedorovich
National Research University "MPEI", Russia, 111250 Moscow, Krasnokazarmennaya, 14
dedovav@mpei.ru

Abstract. A comparison of experimental data on heat transfer and CHF at pool boiling on structured surfaces is performed. An analysis of the CHF increase depending of the surface development is performed. New experimental data on the Leidenfrost temperature on structured surfaces are obtained. Beam technologies for surface modification are presented. Experimental data on CHF at R-113 pool boiling on structured surfaces are presented.

1. Introduction
Lately, the number of studies on the problems of boiling heat transfer has been on the rise from year to year. A significant part of such works is devoted to the experimental study of the individual processes that make up the pool boiling heat transfer. The new tools enable obtaining information about parts of the mechanics, studying the dynamics of the evaporation of the microlayer of the fluid in the vicinity of the individual centers of vaporization, obtaining data for closing equations in a numerical simulation of the growth of individual bubbles, etc. Many papers are related to the problems of enhancement of boiling heat transfer. A significant part of the methods for the enhancement of boiling heat transfer is related to the surface modification and creation of structures, both regular and irregular multiscale, using a variety of methods. Structuring the heat transfer surface creates the possibility of greatly increasing the heat transfer surface while creating artificial vaporization centers and intensifying the flow of fluid into the evaporation zone. This paper analyzes the results of the increase in the CHF obtained precisely in laboratory experiments, and presents its own data at pool boiling.

2. Boiling Heat Transfer on a Surface with Regular Structures
A typical way of presenting data on the comparative enhancement of heat transfer and CHF at pool boiling is by means of boiling curves. Fig. 1 presents the results of a study [1] obtained at pool boiling of water at atmospheric pressure on SiO$_2$ surfaces modified by ion etching to create regular pin structures of heights 10 and 20 μm, diameters 5 and 10 μm, and pitches 5, 10 and 15 μm. The studied surfaces are shown as well. In the experiments of [1], a typical experimental method was used: a layer of copper was sprayed onto the backside of the sample and used for soldering the sample to a heat-conducting rod. The temperature gradient was used to determine the heat flux and the temperature of the base of the sample. The heat flux was determined on the basis of the cross-sectional area of the sample (unmodified surface). Fig. 1 shows a similar view of the boiling curves for both the modified surfaces and the smooth one. Differences in the form of a sharp vertical growth $q$ at almost constant overheating are observed only
for individual surfaces. The excess of the CHF values obtained on the structured surfaces compared to the smooth one makes up from 1.9 times (surface S1) to 2.4 times (surface S6). In [1], an increase in the effective contact line of the three phases on modified surfaces proportional to the coefficient of the surface increase was cited as the reason for the CHF increase. If the data in Fig. 1 is recalculated for the actual heat transfer surface, the boiling curves will diverge noticeably, and the highest CHF value for the modified surface will roughly correspond, within the error range, to the CHF value for the smooth one. The relative increase in heat transfer and the CHF will not be proportional to the development of the surface.

A sufficient number of results similar to those of [1] were obtained for silicon surfaces with a regular structure, for example, in [2–5]. A regular relief in the form of the ribs forming mini-channels on the surface (height 180 to 275 μm, thickness 100 and 200 μm, pitches 100 and 200 μm) was examined in [2]. The object of the study was the pool boiling of water at atmospheric pressure in the state of saturation. The authors presented the results in the form of a comparison of the boiling curves obtained for different samples. When calculating the heat flux, both the area of the base of the work area and the real (wetted) surface area were used. Comparison of the data presented in [2] allows us to conclude that when the actual heat transfer area is taken into account, the developed surfaces mostly do not show any HTC increase compared to the smooth ones, and the divergence between the boiling curves obtained for the different surfaces remains. The relative increase in heat transfer is not proportional to the development of the surface.

An analysis of the [1–2] data allows us to draw a simple conclusion about the ambiguous effect of the degree of surface development on the increase in both heat transfer and the CHF during boiling. Slight differences in some indicators of such geometry show better comparative results. It is important that the surface structure has a size comparable to the characteristic boiling dimensions (thickness of the macro-layer of the fluid, radius of a viable bubble), which are determined by the properties of the fluid and the characteristics of its state.

A separate area of application of research efforts concerns the possibility of achieving an increase in both boiling heat transfer and CHF on a structured surface compared to a smooth one, taking into account the actual heat transfer surface. Several such studies are worthy of a mention. The greatest surface development was obtained using nanomaterials with a high aspect ratio. So, for example, in study [3], regular Si pin structures with a height of 8–32 μm, diameter of 4–120 μm, and pitch of 7–205 μm were covered with a metallized virus of tobacco mosaic (weaving of cylindrical rods 300 nm long with 18 nm diameters), which developed the surface 57-fold (the contribution of the microstructure was 6.4 times while the remaining increase was due to the nanostructure). For this sample, the CHF increased by 3.2 times (for a similar surface without a nanostructure, it increased by 2.7 times) compared to the smooth surface. For structures with a large pin pitch during the surface development by 1.03–1.45 times, the obtained increase in the CHF was 1.8–2 times, respectively. The application of a nanostructure slightly increased the CHF but resulted in a loss compared to a smooth surface, taking into account the development of the surface. In [3], the increase in CHF was explained by an increase in the influx of fluid into the evaporation zone due to capillary forces.

The effect of the minimum size of the surface structure was shown in [4]. The Si surfaces were modified by the photolithographic method. A regular structure was created in the form of ribs of heights 0.3 to 1.5 μm, thickness 5.2 to 7.5 μm, and pitch 4.8 to 7.5 μm. The surface was developed by 1.11 to 1.55 times. SiO$_2$ oxidization with a thickness of 125 nm was performed on some samples. Boiling curves for all surfaces were obtained. The course of some of the curves is identical to the boiling curve of a smooth surface; for SiO$_2$-coated surfaces with height of the ribs exceeding 1 μm, heat transfer showed improvement. The increase in the CHF, calculated taking into account the development of the surface, was in the range of 0.75–1.6 times the values corresponding to a flat surface. An increase in CHF was observed for high ribs protruding beyond the microlayer of the fluid and thus increasing the contact line of the three phases.
Results similar to those of [1–5] were obtained not only for silicon samples characterized by good thermal conductivity and almost perfectly smooth surfaces, but for metal surfaces with a regular structure as well. For example, in [6], boiling of water on a copper surface with a regular structure in the form of ribs was studied. The rib height was 0.4 mm, the thickness was 0.2 mm, and the pitches were 300, 500, and 762 μm. A copper porous coating was applied to the surface. Several surfaces of the same type were used, on which the coating was applied to the tops of the ribs, to the entire ribbed surface, and to the entire surface except for the tops of the ribs. Boiling curves were obtained for all the surfaces, and an analysis of the HTC and CHF data was performed in the form of a comparison of boiling curves for surfaces with the same porous coating but different rib pitches and for smooth surfaces. The data were recalculated for the actual (wetted) heat transfer surface, the drawback of which is the use of differing wall temperatures determined by the temperature gradient in the heating block. When using the transverse sectional area, the temperature of the top of the rib is recounted (in an unknown way), while for the actual surface, the temperature at the base of the rib is recounted. Significant increase in HTC and CHF for structured surfaces compared to the smooth one was obtained, determined by the type of application of the porous coating and the pitches of the ribs. In [6], the increase in HTC and CHF was explained by the creation of conditions for separating the paths of fluid influx and steam escape. Even with the actual heat transfer surface taken into account, an increase in the CHF reached 30%.

3. Boiling Heat Transfer on a Surface with Irregular Structures

Surfaces with irregular structure are usually metallic. The most widespread are formed from such structuring methods as electrochemical deposition, selective laser melting, ion and plasma spraying, short duration exposure to a laser beam, and application of nanoparticles. Among studies focused on these methods, [8–17] are worthy of note. Despite the variety of technologies, the final result is a porous layer formed on the surface, which has physicochemical properties different from the original surface, where characteristic asperities are 10¹–10³ μm in height and of a very complex shape. The estimates of the surface development using femtosecond laser radiation in [8] show values of 3–8 times with the heights of the asperities fluctuating between 9 and 55 μm. For a number of structured surfaces of complex shape, in which the asperities have several characteristic scales¹, it is impossible to reliably estimate the increase in the surface area. For surfaces with the heights of asperities ~ 10 μm, which is typical for technical surfaces, taking into account the increase in area does not seem reasonable. The combination of changes in the physicochemical properties of surfaces, primarily wettability, the
presence of a porous layer leading to the effect of capillary forces and gas absorption, and the
correspondence of the scale of asperities to the characteristic dimensions determining boiling (radius of
a viable bubble, thickness of the evaporating microlayer of fluid under the bubble), leads to the increase
in HTC and CHF of structured surfaces, compared to smooth ones. In some papers [6, 9, 12, 15, 16],
new effects were noted; the wall temperature decreased during boiling, which is called “boiling
inversion”. The tasks of the enhancement of heat transfer and the CHF do not always coincide. Heat
transfer enhancement is considered a decrease in the temperature superheat at the identical heat flux on
different surfaces, leading to a formal increase in the HTC, while the CHF may be lower. For highly
porous surfaces, the presence of dissolved gases promotes boiling with very low wall overheating. If the
CHF of structured surfaces exceeds values characteristic of smooth ones, then the following main
scenarios are presented, shown in Fig. 2. Lines 1 and 2 are rather arbitrarily offset relative to the boiling
curve for a smooth surface (points in Fig. 2), and reflect the following main trends: line 1 – there is no
significant enhancement of heat transfer while the CHFs increase; line 2 – there is considerable heat
transfer enhancement, usually when exceeding the CHF for a smooth surface. From line 2, the following
are likely: a – inversion of the boiling curve; b – continuation of the boiling curve without changes; c –
decrease in the heat transfer intensity. The position of line 2 in the area of low superheat is determined
by the porosity of the surface; a significant decrease in the initial superheat is characteristic of surfaces
resulting from deposition or sintering of particles. The course of the boiling curve is determined by the
structure of the surface: for example, in studies [6, 15], for all structured copper surfaces, all the
variations have been implemented in Fig. 2 (with the exception of 2–c in [15]) using different methods
of surface modification.

Line 1 characterizes the possibility of extending the “ordinary” boiling curve to the higher area q,
obtained in [7, 14], line 2–a [8, 9, 12, 15], line 2–b [7–8, 10–12, 15, 17], line 2–c [7, 12, 14, 17]. The
increase in HTC and CHF for all lines is, according to [7–17], owed to the following reasons:
– changes in the surface wettability after processing [10–12, 15, 17],
– an increase in the contact line of the three phases and evaporation of the microlayer [13, 15],
– activation of additional centers of vaporization [7–9, 12, 15],
– separation of the paths of fluid influx and steam escape [9, 14, 16],
– the impact of capillary forces [7, 10, 15].

Apparently, all the assumptions are valid, and the course of lines 1 and 2 determines the dominant
mechanism. From the point of view of practice, an increase in the CHF is the most desirable, as the
HTCs are sufficient with nucleate boiling. An increase in the HTC, to the detriment of the operating
temperature range of the wall, is disadvantageous. Surface modification resulting in line 1 seems to be the
most desirable [15].

Analyzing the data of those studies in which boiling inversion was obtained (line 2–a), the following
can be noted: the surface consists of irregular asperities with a scale of 10¹–10² μm; correlation between
the size of the structure and its surface material is observed; the experiments were conducted under
conditions of heating the work surface with thermal conductivity. Non-isothermality of the heat transfer
surface and temperature distribution along the asperities is an essential condition [8]. The results for
structures of the same size but of different thermal conductivity are obtained in the form of either line
2–a or line 2–b. In some ways, the task is similar to the possibility of cooling individual protrusions
during film boiling on the surface of heated bodies, which leads to a sharp increase in the cooling rate
[18]. A possible explanation for the heat transfer enhancement is as follows: the contact line of the three
phases has a complex geometry, and the microlayer of the fluid from which evaporation into a bubble
occurs repeats this geometry. With an increase in the heat flux density, an increase in temperature occurs
along individual peaks of the asperities, leading to a significant growth of the mass of fluid evaporating
into a bubble. Intense local heat effluent appear, and the average surface temperature may drop. An
important methodological feature of [8–9, 12, 15] is the determination of the heat flux and wall
temperature based on the measured temperature distribution in the heat-conducting rod. The use of three
temperature values for specifying the function and determining the gradient leaves open the issue of the
reliability of the values at low wall superheat, as well as specifies the thickness of the sample with the
asperities of the scale of $10^2$–$10^3$ μm. An indirect confirmation of the possibility of lowering the wall temperature during boiling is the experiments [19] where similar results were obtained at flow boiling in the channels.

![Figure 2. Typical boiling curves of structured surfaces (lines 1 and 2); the points are the boiling curve on a smooth surface](image)

One of the assumptions that dominate in the literature on the causes of significant enhancement of boiling heat transfer on a number of structured surfaces is the assumption in [16] about the “ordering” of the process by separating the paths of the fluid influx and steam escape, enhancing macro-convection, which leads to a highly effective self-supporting boiling configuration. The possibility of creating such configurations was shown in [20–21], where alternating zones with different thermal conductivities on a smooth copper surface resulted in significant enhancement of both the HTC and CHF. Due to the non-isothermality and redistribution of the heat flux on the surface, it is possible to double the values of the CHF. In our own opinion, the key increase factor is the preservation of the possibility of evaporation of the microlayer of fluid under the bubble, due to the non-isothermality of the heating surface and the influx of fluid into the evaporation zone, rather than the enhancement of macro-convection. To check the laws of the assumptions about the optimal geometry of zones with different heat conductivity [20] and to study the inversion of boiling on micro-structured surfaces [8–9, 12, 15], it is necessary to conduct experiments not only at atmospheric pressure but at a wide range of pressures as well [22].

4. The Study of Pool Boiling on Structured Surfaces

Surface modification is a concomitant phenomenon in a number of physical experiments and in some technologies. Various studies of the interaction of particle beams with the surface, carried out as part of the development of technologies for protecting the first wall and the diverter of the ITER reactor, have led to the modification of the surfaces under study (aluminum, stainless steel, tungsten, etc.). A relief of
the microstructure appears on the surface. Another example is the technology of hardening of metal surfaces when exposed to a laser, electron or plasma beam [23]. In this technology, a pre-nanocarbon coating can be applied to the surface, which is introduced into the surface layer using radiation fluxes. Impact of increased beam energy leads to a relatively regular microscale surface structuring. To study the possible enhancement of heat transfer and the CHF of such surfaces, a collection of samples was gathered. The samples were transformed into working sections in the form of cylindrical plates with a diameter of 30 mm and a thickness of 1–3 mm. Fig. 3 shows photographs of the surfaces of some of the samples. Table 1 shows the characteristics of some of the samples used, the results of measurements of the contact angle, and the Leidenfrost temperature for water.

Surfaces (1–9) in Table 1 have a microstructure in the form of irregular (1, 3, 5–7) and relatively regular (2, 4, 8–10) irregularities, combining, among other things, modified and unmodified sections (8). Surface 10 of Table 1 was obtained from a PLM installation [24] of our department by exposure to helium plasma on a sample for 3 hours at a surface temperature of 850 °C and an energy flux of 180 kW/m². The surface has a relatively regular structure in the form of cones with a solution angle of 20°, a height of up to 12 μm, and a base diameter of 3 μm (Fig. 3f). The surface of the cones has a developed porous structure (Fig. 3c). At the bases of the cones, the surface has a highly porous spongy structure with a characteristic pore size of 100 nm.

**Figure 3.** Microphotographs (a–b), Photographs (d–e), and SEM images (c, f) of the Surface of the Samples: a) No. 1, Table 1; b) No. 3, Table 1; d) No. 8, Table 1; e) No. 2, Table 1; c) and f) No. 10, Table 1
Data on the characteristic parameters of irregularities were obtained using an automated microscope LEXT OLS4000. The static contact angles for all samples were measured using an automated KRUSS DSA25 unit. The measurements were performed many times, for two initial droplet volumes, in different areas of the surfaces. In order to determine the Leidenfrost temperature, the specialized unit was used [25]. Table 1 presents data on the values of the Leidenfrost temperature on smooth surfaces from [26], as well as calculated using an equation [27]. The data in Table 1 show that the impact on the surface does not change the physicochemical properties of the surface; even for aluminum, practically identical angle values were obtained (excluding surface 10 of Table 1 with highly developed porosity). Using the Leidenfrost temperature experiments to evaluate the effect of the surface modifications on heat transfer characteristics proved impossible. Firstly, due to the inaccuracy of the measurement method used, based on measuring the time of evaporation of a droplet (lifetime), and secondly, due to the significant contingency of the physicochemical properties of the surface on temperature (due primarily to oxidizability) when the surface was heated.

To study the enhancement of the HTC and CHF at pool boiling, an experimental facility was created. Pool boiling of R-113 freon took place on a horizontal work section soldered to the end of a copper cylinder heated with a cartridge heater. The temperature corresponded to the saturation state at

| №  | Material          | Processing method                             | Roughness Indicators (μm) | Contact Angle | T $_{L}$, °С Our experiments (polished [26]) | T $_{L}$, °С Calculation according to [27] |
|----|------------------|-----------------------------------------------|---------------------------|---------------|---------------------------------------------|---------------------------------------------|
|    |                  |                                               | R$_a$                     | R$_c$         | before after                                 | before after                                 |
| 1  | Copper           | Electron beam                                 | 3,11                      | 10,7          | 83,6 82,8                                   | 257                                           |
|    |                  |                                               |                           |               |                                              | (250)                                        |
| 2  | Stainless steel  | Electron beam                                 | 14,1                      | 342,0         | 82,1 82,6                                   | 232                                           |
|    |                  |                                               |                           |               |                                              | (280-310)                                    |
| 3  | Aluminum         | Plasma treatment                              | 29,5                      | 111,7         | 79,0 79,4                                   | 303                                           |
|    |                  |                                               |                           |               |                                              | (225-280)                                    |
| 4  | Steel            | Laser with nanocarbon materials               | 2,21                      | 7,43          | 87,1 84,2                                   | 263                                           |
|    |                  |                                               |                           |               |                                              | (+)                                          |
| 5  | Aluminum         | Plasma treatment                              | 20,9                      | 77,9          | 78,7 77,7                                   | 253                                           |
|    |                  |                                               |                           |               |                                              | (225-280)                                    |
| 6  | Aluminum         | Plasma treatment                              | 5,39                      | 19,0          | 82,3 100,6                                  | 276                                           |
|    |                  |                                               |                           |               |                                              | (225-280)                                    |
| 7  | Stainless steel  | Plasma treatment                              | 0,92                      | 2,75          | 82,1 82,6                                   | 265                                           |
|    |                  |                                               |                           |               |                                              | (280-310)                                    |
| 8  | Steel            | Electron beam with nanocarbon materials       | 7,40                      | 81,1          | 87,1 83,0                                   | 257                                           |
|    |                  |                                               |                           |               |                                              | (+)                                          |
| 9  | Stainless steel  | Laser with nanocarbon materials               | 1,46                      | 7,02          | 56,4 57,7                                   | –                                             |
|    | AISI 304         |                                               |                           |               |                                              | 260                                          |
| 10 | Stainless steel  | Plasma treatment on PLM                       | 6,0                       | 12,0          | 56,4 129,3                                  | –                                             |
|    | AISI 304         |                                               |                           |               |                                              | 260                                          |
atmospheric pressure maintained in the vessel. The temperature and heat flux were determined using three thermocouples with a 10 mm pitch situated on the axis of the copper cylinder, with one situated on the top surface of the cylinder. The uncertainty in the heat flux measurement did not exceed 5%, temperature ± 0.3 °C. During the experiments, preliminary boiling of freon was carried out for the purpose of deaeration. Then the temperature of freon was lowered to ~ 47° C, which was maintained at this level by regulating the voltage on the disk heater. Under such conditions, there is no volume boiling of freon. Then the voltage on the cartridge heater was changed gradually, and the readings of the thermocouples were recorded when the stationary temperature regime was reached. The voltage pitch decreased as the voltage value increased. The voltage continued to increase until an uncontrolled increase in the temperature of the top surface of the cylinder occurred (the boiling crisis was achieved). The CHF values are shown in Table 2. For a number of surfaces, an increase in CHF was not obtained. A characteristic feature was first conducting experiments to determine the Leidenfrost temperature, and then by boiling. When studying the temperature of Leidenfrost, the surfaces were heated in air to temperatures of at least 350 °C. Boiling experiments were repeated at least 3 times for each surface. No experiments were carried out for samples 9 and 10 of Table 1 to determine the temperature of Leidenfrost; the effect of aging of the surface was noted when in the first experiment the values of CHF were reached by about 15% higher than in the next two. For other samples, a similar effect was not found. Sample 10 of Table 1 shows a slight decrease in CHF, which is typical for samples with a highly porous structure.

**Table 2: CHF experiments and calculation.**

| Sample number from table 1 | 2   | 5   | 8   | 9   | 10  | unmodified steel surface | Kutateladze equation |
|-----------------------------|-----|-----|-----|-----|-----|--------------------------|----------------------|
| CHF, kW/m²                  | 253 | 263 | 263 | 214 | 195 | 212                      | 210                  |

5. Conclusion
A large number of studies on boiling heat transfer have been performed on specially created modified surfaces, and new effects have been obtained. The increase in the HTC and CHF is not proportional to the surface development.

To explain the reasons for the increase in the HTC and CHF, several assumptions have been made that need justification. A possible reason may be the preservation of the possibility of evaporation of the microlayer of fluid under the bubble due to non-isothermality of the heating surface and the influx of fluid into the evaporation zone. New theoretical models for the CHF of modified surfaces are needed.

In a number of plasma and beam technologies, surface modification is a concomitant phenomenon. These surfaces do not show any incredible results in the enhancement of the HTC and CHF, but they can significantly expand the temperature range of the surfaces in heat transfer equipment. Varying the technological values may lead to obtaining the necessary surface characteristics.

Acknowledgments
This work was supported by the Russian Scientific Foundation (grant № 19-19-00410).

References
[1] Chu KH, Enright R and Wang E N 2012 Structured surfaces for enhanced pool boiling heat transfer// Appl. Phys. Lett. 100
[2] Cooke D and Kandlikar SG 2011 Pool boiling heat transfer and bubble dynamics over plain and enhanced microchannels ASME J. Heat Transfer 133.
[3] Rahman M.M, Oliceroglu M and McCarthy M 2014 Role of wickability on the critical heat flux of structured superhydrophilic surfaces Langmuir 30 11225.
[4] Zou A and Maroo SC. 2013 Critical height of micro/nano structures for pool boiling heat transfer enhancement Appl. Phys. Lett. 103
[5] Dhillon NS, Buongiorno J and Varanasi KK 2015 Critical Heat Flux Maxima During Boiling Crisis on Textured Surfaces Nature Communications 6 8247
[6] Jaikumar A and Kandlikar SG 2016 Ultra-high pool boiling performance and effect of channel width with selectively coated open microchannels Int. J. Heat Mass Transfer 95 795.
[7] Rahman M and McCarthy M 2017 Effect of Length Scales on the Boiling Enhancement of Structured Copper Surfaces J. Heat Transfer 139(11) 111508-9
[8] Kruse C, Tsubaki A, Zuhlke C, Anderson T, Alexander D, Gogos G and Ndao S. 2016 Secondary pool boiling effects Appl. Phys. Lett. 108
[9] Kruse C M, Anderson T, Wilson C, Zuhlke C, Alexander D, Gogos G and Ndao S. 2015 Enhanced pool-boiling heat transfer and critical heat flux on femtosecond laser processed stainless steel surfaces Int. J. Heat Mass Transfer 82 109
[10] Wang Y, Luo J, Heng Y, Mo D and Lyu S. 2018 Wettability modification to further enhance the pool boiling performance of the micro nano bi-porous copper surface structure Int. J. Heat Mass Transfer 119 333
[11] Patil C, Santhanam K and Kandlikar S 2014 Development of a two-step electrodeposition process for enhancing pool boiling Int. J. Heat Mass Transfer 79 989
[12] Xu P, Li Q and Xuan Y 2015 Enhanced boiling heat transfer on composite porous surface Int. J. Heat Mass Transfer 80 107
[13] Surtsev A, Pavlenko A, Kuznetsov D, Serdyukov V, Kalita V, Komlev D, Ivannikov A and Radyuk A. 2017 Heat transfer and crisis phenomena at pool boiling of liquid nitrogen on the surfaces with capillary-porous coatings Int. J. Heat Mass Transfer. 108(A) 146.
[14] Zhang C, Zhang L, Xu H, Li P and Qian B 2019 Performance of pool boiling with 3D grid structure manufactured by selective laser melting technique // Int. J. Heat Mass Transfer. 128 570
[15] Jaikumar A, Rishi A, Gupta A and Kandlikar SG 2017 Microscale Morphology Effects of Copper–Graphene Oxide Coatings on Pool Boiling Characteristics J. Heat Transfer. 139(11) 111509-11
[16] Jaikumar A and Kandlikar SG 2017 Pool boiling inversion through bubble induced macroconvection Appl. Phys. Lett. 110 094107.
[17] Jun S, Kim J, Son D, Kim H Y and You SM 2016 Enhancement of Pool Boiling Heat Transfer in Water Using Sintered Copper Microporous Coatings Nuclear Eng. and Techn. 48 932–940
[18] Dedov A V, Zabirov A R, Sliva A P, Fedorovich S D and Yagov VV 2019 Effect of Coating on a Carbon Nanostructure on Heat Transfer with Unsteady Film Boiling High Temp. 57 (1) 63–72
[19] Belyaev AV, Varava AN, Dedov AV and Komov AT 2018 Critical heat flux at flow boiling of refrigerants in minichannels at high reduced pressure Int. J. Heat Mass Transfer. 122 732
[20] Rahman M, Pollack J and McCarthy M 2015 Increasing Boiling Heat Transfer using Low Conductivity Materials Scientific Reports 5 13145
[21] Rahman M and McCarthy M 2017 Boiling Enhancement on Nanostructured Surfaces with Engineered Variations in Wettability and Thermal Conductivity Heat Transfer Eng. 38 (14-15) 1285
[22] Dedov AV 2019 A Review of Modern Methods for Enhancing Nucleate Boiling Heat Transfer Thermal Eng. 66 (12) 881-915
[23] Bocharov GS, Dedov AV, Eletskii AV, Zaharenkov AV, Zilova OS, Nuha A and Fedorovich SD 2018 Laser Strengthening of a Steel Surface with Fullerene Coating Doklady Physics 63 (12) 489–492
[24] Budaev VP et al. 2017 Plasma device at NRU «MPEi» for testing of refractory metals and creation of highly porous materials of new generation, Problems of Atomic Science and Technology, ser. Thermonuclear Fusion, 40 (3) 23.
[25] Khaziev IA, Dedov AV and Serebryakova MO 2018 Research of the leidenfrost temperature on structured surfaces IOP Conf. Series: Journal of Physics: Conf. Series 1128 012056
[26] Bernardin J D and Mudawar I. 1999 The Leidenfrost Point: Experimental Study and Assessment of Existing Models Transactions of the ASME 121 894-903
[27] Baumeister K J, and Simon FF 1973 Leidenfrost Temperature—Its Correlation for Liquid Metals, Cryogens, Hydrocarbons, and Water” ASME Journal of Heat Transfer 95.166-173