Perspectives and problematic issues in the development of heat transfer enhancement methods at boiling and evaporation

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Abstract. The paper presents an analysis of modern methods of heat transfer intensification and critical heat flux increase during boiling and evaporation using micro-nanostructuring of surface. Special attention is paid to the analysis of such promising methods of modifying heat-transfer surfaces as the application of combined microstructured surfaces/coatings by SLM/SLS (3-D printing), the organization of structures with contrast wettability on the micro-scale. The conclusions formulated on the basis of generalization of results of complex research on studying of heat transfer, transitional and crisis phenomena at boiling in the conditions of free convection, at evaporation and boiling in flowing down films and in thin horizontal layers of liquids at use of various types of microstructuring of heat-transfer surfaces are presented.

1. Introduction
The significant increase in the number of studies on heat transfer at boiling and evaporation every year is explained by emergence and development of new highly efficient and integrated experimental and theoretical research methods, significant advances in materials science, including in the field of nanotechnology, the development of high-current electronics, and solution of new large applied problems. The development of new experimental methods makes it possible to obtain deeper and more complete information about the features of the heat transfer mechanism at boiling and evaporation, study the dynamics of evaporation of a liquid microlayer, non-stationary heat transfer in a vicinity of individual vaporization sites, obtain data for numerical simulation of the growth of individual bubbles, study the relationship of structure formation parameters with local and integral heat transfer, the development of crises, etc. One of the most promising methods for intensifying heat transfer and increasing critical heat fluxes during evaporation and boiling is the use of various micro- and nanostructured surfaces and hydrophobic/hydrophilic coatings. The search for optimal surface structures is aimed at further improving the efficiency of equipment for various purposes, which uses boiling or evaporation regimes. The practical significance of the results of such studies is associated, in particular, with the determination of the boundaries of the optimal and emergency regimes of operation of various types of heat exchangers, including non-stationary conditions of heat exchange.

In the 1970s, researchers developed and registered patents for a number of boiling surfaces, such as Thermoexcel-E [1], GEWA-T [2], etc. (see [3]). Processing methods, and the enhanced surfaces obtained with their help continue to be improved. In 1997, Thors et al. registered a patent for the Turbo-BIII surface, which turns out to be 70% more efficient than the earlier version of this type of surface, Turbo-B [4]. Approximately at the same time (in 1996), the first patent of Zubkov and Ovchinnikov [5] appeared, and in 2007 and 2013, there were the joint patents of Thors and Zubkov [6,7], which described
the technology of surface microprocessing using the so-called deformational cutting method (MDC). Starting from [8, 9], attempts have been made to create the models that describe boiling of liquid on artificial sites of structured coatings, but at the moment, this area is still being developed. Despite the large number of thematic works, there is still a need for further research on boiling enhancement using microstructured surfaces, especially for falling liquid films.

Not many works are devoted to the study of heat transfer intensification using mesh coverings. In [10], the possibility of intensifying the process of heat and mass transfer during the evaporation of falling films of water was shown. The results of test apparatus performance indicated evaporation rates up to 3-fold higher using the mesh promoter than without it (at water inflow rates of 0.72-1.00 g/s and fixed carrier gas inflow rate of 2.44·10⁻³ m³/s). In [11], the dielectric fluorocarbon PF 5060 was used. The experiments were carried out at pool boiling, as well as under geometrically limited conditions, when the mesh was covered with a plate of glass or polycarbonate. The largest increase in heat transfer coefficient at boiling reached 4 times as compared with a smooth surface for a mesh containing of 20 wires/cm. In [12], heat transfer intensification was investigated using the thin metal meshes with different numbers of layers (from 1 to 4) at pool boiling. Alcohol was used as a working fluid. The authors achieved a significant enhancement of boiling heat transfer (about 8 times) and a significant decrease in the temperature drop. It is shown that the use of the 4th layer of the mesh affects heat transfer. Some models presented in the paper do not describe adequately the experimental data obtained by the authors.

Thus, it can be noted that at present there are not so many results on the study of the capillary-porous or mesh coatings effect on heat transfer at evaporation, and available research is mainly devoted to pool boiling. That is also true for the studies of effectiveness of microstructured boiling surfaces. At the same time, such studies are necessary, since the falling films have a number of well-known advantages in comparison with heat transfer at pool boiling, as well as specific features (bubbles driftage, drop entrainment, influence of film velocity, and contribution of evaporation from the free surface even in the boiling regime) that distinguish them from pool boiling. There is a wide variety of different physical and chemical methods for creating micro- and nanostructured surfaces and porous coatings, such as sintering, electrochemical deposition, lithography, thermal (plasma) sputtering, etching, nanofluid boiling, physical and chemical deposition from the gas phase, etc. Using these methods it is possible to create a wide range of different micro and nanoporous coatings, micro-nanostructures with different geometry (nanotubes, micro-nanofibers, micro-nanoparticles), etc. A detailed review of the above methods, as well as the results of the study of the influence of modified surfaces and porous coatings, developed using these methods, on the intensity of heat transfer and critical heat fluxes in boiling is presented in a recently published review and paper [13, 14].

This paper presents the results of an experimental study of the effect of different types of coatings on heat transfer enhancement at evaporation and boiling. For each of the coating types (MDC-microstructures, microstructured capillary-porous or mesh coatings), characteristic parameters were varied.

2. The influence of the surface structuring type on heat transfer in falling films of refrigerant mixture.

The authors of [15, 16] consider the influence of enhanced surfaces on heat transfer during evaporation and boiling of a falling laminar-wave liquid film. A mixture of R114/R21 refrigerants was used as a test fluid. The liquid film flowed on the outer surface of vertically-oriented cylinders. To intensify the evaporation process, the authors used the mesh coatings with variable mesh sizes, whereas the surfaces with variable characteristics of microstructure obtained by deformational cutting were used to enhance boiling. The authors of the papers [15, 16] make a conclusion about the studied types of structured surfaces, most effective for enhancement of heat transfer in different regimes. It is shown that the mesh coatings intensify heat transfer at evaporation twice as compared to a smooth surface; the microstructured coatings with partly-closed micropores obtained by deformational cutting allow fourfold heat transfer intensification at boiling (see figure 1).
Figure 1. Comparison of boiling data for MDC-surfaces and Gewa-series surfaces [17].

The increase in the heat transfer coefficient in evaporation regime on the meshed structures, apparently, is due to the change in hydrodynamics of the wave flow of the film caused by capillary forces. In the regime of nucleate boiling \( (q > 1 \cdot 10^4 \text{ W/m}^2) \), a noticeable increase in heat transfer coefficients in comparison with a smooth surface is not observed for the studied mesh coatings.

3. Heat transfer and crisis phenomena at pool boiling on the surfaces with microstructured capillary-porous coatings. Quenching by falling liquid film of extremely overheated plate with microstructured coatings.

One of the promising ways to intensify heat transfer and increase the critical heat flux in boiling is the use of microstructured capillary-porous coatings, created, for example, by the method of directional plasma spraying [18]. As can be seen from the experimental results [19-21] carried out at pool boiling and boiling under the conditions of film flows for various liquids, this method also makes it possible to significantly intensify heat transfer. It is important to emphasize that the most brightly specific properties of such high-intensity heat transfer are manifested in non-stationary heat release conditions. The results of experimental studies [19, 21, 22] show that on surfaces with such microstructured capillary-porous coatings with non-stationary (step-wise or periodic pulse) heat release, a sharp increase in the critical heat flux, the transition time to the film boiling regime at pool boiling, a sharp decrease in the propagation velocity of the heat-releasing surface drying zones at the development of crisis phenomena in the flowing liquid films are observed.

The main objective of many studies of quenching is to find a way to reduce the total time of the transient process. Work [22] presents the results of an experimental study of rapid cooling of a superheated vertical copper plate with a plasma-deposited structured capillary-porous coating. The working liquid was liquid nitrogen on the saturation line at atmospheric pressure. The thickness of the heated copper plate is 2.5 mm; the height and the width are 55 and 80 mm, respectively. The three-dimensional capillary-porous coating on this surface was applied also by directional plasma spraying [18]. Figure 2 presents a photograph of a plate with a plasma-deposited capillary-porous coating. In this method, powder of the material to spray is fed into a high-temperature plasma jet. The powder heats up, melts, and is directed to the substrate in the form of a two-phase flow at a certain inclination angle. It is possible to apply coatings with maximum open porosity (up to 80%) and high adhesion and homogeneity degree. The coating with an average thickness of 0.57 mm and a porosity \( \varepsilon = 53\% \) was used. A bronze powder containing 89% of copper, 9% of aluminum, and 2% of manganese was sprayed. In figure 2 it
can be seen that the coating is crests and troughs distributed practically uniformly and oriented mainly in one direction. It is shown in [22] that the presence of a structured capillary-porous coating on the surface reduces the total cooling time of the plate more than threefold.

The paper [23] presents results of a computational experiment simulating rapid cooling by falling liquid nitrogen film of an overheated vertical copper plate with a structured capillary-porous coating. A dynamic pattern of the running quench front was obtained; it correlates satisfactorily with that observed in the experiments. The features of the heat transfer and quench front dynamics in the transient process are studied. The maximum density of the heat flux carried away into the liquid turned out to exceed by far that in quasi-stationary conditions. The presence of capillary-porous coating significantly affects the dynamics of quenching and temperature fields and makes it possible sharply to reduce the total quenching time. Initialization of a quench front on a plate with a structured capillary-porous coating occurs at a temperature much higher than the thermodynamic limit of liquid overheating. The reliability of the numerical simulation results was confirmed via direct comparison with experimental data on the variation of the plate temperature (see figure 3), as well as on the velocity and geometry of the quench front.

**Figure 2.** Magnified image of plate with plasma-deposited structured capillary-porous coating.

**Figure 3.** Variation of temperature of coated and uncoated plate in transient process. Numerical simulation results in comparison with experimental data for plate with microstructured capillary-porous coating.

4. Heat transfer at evaporation/boiling in thin horizontal liquid layer on microstructured surfaces. 3D printing technology.

In recent years, research on the development of methods for the use of additive 3D printing technology (selective laser melting/SLM/SLS sintering) to create effective heat and mass transfer equipment has been actively developing. The main advantage of SLM/SLS technology is the ease of manufacturing complex parts and coatings of specified geometries, which eliminates the need for subsequent processing. At the same time, there is very limited literature on the use of SLM/SLS technology for manufacturing structured surfaces to enhance heat transfer at boiling (there are no known works on intensification of heat transfer in evaporation regimes when structuring the surface by the SLM/SLS method). In the last 3 years, the authors of works [24, 25], when conducting experiments on heat transfer enhancement during boiling for the first time used the technology of SLM/SLS for applying microribs, creating microcavities and porous structures on the heat-transfer surface. Using FC-72 as a working
fluid at atmospheric pressure, the authors of these works, according to their experimental data, achieved almost a 3-fold increase in the heat transfer coefficient and a 6-fold increase in the critical heat flux compared to a smooth surface. In contrast to the above, the authors of work [26], in the experiments on water boiling under conditions of saturation and underheating on structured surfaces (cavities of various forms with a characteristic size of about 1 mm) also created by the SLM/SLS method, have not received any intensification of heat transfer. When using caverns with a certain predetermined shape in the experiments of the authors [26], even regimes with a significant decrease in the heat transfer coefficient were found. This comparative example shows the importance of systematic complex research of the degree of influence of microstructuring of the heat-transfer surface for different liquids at varying reduced pressure with a subsequent comparative analysis. It is obvious that the choice of characteristic scales and microstructures/structures when modifying the heat-emitting surface should take into account their dependence on the type of liquid, regime parameters and a number of other factors due to the peculiarities of the hydrodynamic regime of heat transfer (pool boiling of liquid, boiling and evaporation in the flowing liquid films or in the thin horizontal layers of liquid).

The characteristic results of the experimental study of heat transfer and CHF during boiling of n-dodecane on a microstructured capillary-porous surface are presented. The surface is coated using a 3D laser printer [27, 28] (see figure 4). The dependence of the heat transfer coefficient on the heat flux density under different pressures and liquid layer heights is studied. The obtained experimental data were compared with the values obtained in [29] for evaporation/boiling regimes on a smooth surface.

**Figure 4.** Heating surface of the experimental facilities. The photograph of the microstructured capillary-porous coating (3D printing technology).

Scale – 1 mm.

**Figure 5.** The regime of bubble boiling. The relation of the heat transfer coefficient to the heat flux density. Coloured symbols correspond to the data on the coated surface.

Figure 5 presents data on heat transfer coefficients on the smooth surface and on the surface with a capillary-porous coating for two heights of the liquid layer ($h = 1.4$ and $1.7$ mm) at different pressures (P, KPa). As shown in figure 5, the heat transfer coefficients at boiling are 3-5 times higher on the capillary-porous coating compared with the uncoated surface. Heat transfer intensification is higher for the lower pressure.

**Conclusions**
Capillary-porous coatings have a significant influence on development of the transitional processes and crisis phenomena at stepwise heat release. There is degeneration of boiling crisis development at rapid heating on the such coated surfaces at the heat fluxes below the value of the CHF at steady state heat
release. Fundamentally new results on the degree of heat transfer intensification on microstructured surfaces created by the 3-D printing method are shown. Features of heat transfer and development of crisis phenomena at boiling and evaporation on the modified surfaces in thin horizontal layers of liquid are considered. The analysis shows that under these conditions the optimal parameters of capillary-porous coatings are largely determined by the thickness of the layer for a given liquid and the value of the reduced pressure.

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References
[1] Fujie K, Nakayama W, Kuwahara H and Kakizakci K 1977 U.S. Patent 4060125
[2] Saier M, Kastner H W and Klockler R 1979 U.S. Patent 4179911
[3] Webb R L 2004 J. Heat Transfer 126 1051
[4] Thors P, Clevinger N R, Campbell B and Tyler J T 1997 U.S. Patent 5697430
[5] Zubkov N N and Ovchinnikov A I 1996 European Patent EP 0727269
[6] Thors P and Zoubkov N 2007 U.S. Patent 731137
[7] Thors P and Zoubkov N 2013 U.S. Patent 8573022
[8] Nakayama W, Daikoku T, Kuwahara H and Nakajima T 1980 J. of Heat Transfer 102 451
[9] Chien L-H and Webb R L 1988 Int. J. Heat and Mass Transfer 41 2183
[10] Salvagnini W and Taqueda M A 2004 Ind. Eng. Chem. Res. 43 (21) 6832
[11] Gerlach D W and Joshi Y K 2005 In Proc. IMECE2005 82595
[12] Dąbek L, Kapjor A and Orman Ł J 2016 In Proc. AIP Conf. 1745 020005
[13] Surtsev A, Serdyukov V S and Pavlenko A N 2016 Nanotechnologies in Russia 11 (11–12) 696
[14] Surtsev A S, Serdyukov V S, Pavlenko A N, Kozlov D V and Selishchev D S 2018 Bulgarian Chemical Communications 50 (K) 36
[15] Pecherkin N I, Pavlenko A N and Volodin O A 2015 Int. J. Heat and Mass Transfer 90 (11) 149
[16] Volodin O A, Pecherkin N I, Pavlenko A N and Zubkov N N 2017 Interf. Phenomena and Heat Transf. 5 215
[17] Ayub Z H 1986 Retrospective Theses and Dissertations Paper 7979
[18] Kalita V I, Komlev D I, Komlev V S and Radyuk A A 2016 Mater. Sci. Engin. 60 255
[19] Surtsev A S, Pavlenko A N, Kuznetsoy D V, Kalita V I et al. 2017 Int. J. Heat and Mass Transfer 108 146
[20] Surtsev A S, Kuznetsoy D V, Serdyukov V S, Pavlenko A N, Kalita V I et al. 2018 Appl. Therm. Eng. 133 532
[21] Pavlenko A N, Kuznetsoy D V and Surtsev A S 2018 J. Eng. Thermophys. 27 (3) 285
[22] Pavlenko A N, Tsoi A N, Surtsev A S, Kuznetsoy D V, Kalita V I, et al. 2018 High Temp. 56 (3) 404
[23] Starodubtseva I P and Pavlenko A N 2018 J. Eng. Thermophys. 27 (3) 294
[24] Wong K K and Leong K C 2018 Int. J. Heat Mass Transfer 121 46
[25] Ho J Y, Wong K K and Leong K C 2016 Int. J. Heat Mass Transfer 99 107
[26] Kang Z. and Wang L. 2018 Experimental Thermal and Fluid Science 93 165
[27] Bayev S G, Bessmeltsev V P, Goloshevsky N V, Goryaev Ye P, Kasterov V V and Smirnov K K 2017 Proceedings of the International Scientific Conference “SibOptics - 2017” (Novosibirsk) 1 (Novosibirsk: SSUG&T) 29
[28] Zhukov V I, Pavlenko A N and Bessmeltsev V P 2018 Journal of Physics: Conference Series 1105 (012054) 5
[29] Zhukov V I and Pavlenko A N 2018 Int. J. Heat Mass Transfer 117 978