Method for calculating the critical heat flux at pool boiling on structured surfaces

A V Stupakova and A V Dedov
National Research University “MPEI”
Russia, 111250 Moscow, Krasnokazarmennaya, 14
StupakovaAV@mpei.ru

Abstract. A method of the critical heat flux enhancements at pool boiling using rough structures of various regular and irregular geometries is investigated. The experimental data are compared, and the critical heat flux is calculated since the V. V. Yagov model, which considers the additional inflow of liquid into the evaporation zone due to the action of capillary forces in the porous space. Based on the comparison of experimental and calculated data, it is concluded that the model is not universal for all microstructured surfaces. Recommendations for the calculation are given.

1. Introduction
When using nucleate boiling as a method of heat removal, there are restrictions on the heat flux removed, associated with the occurrence of a boiling crisis – the transition from nucleate boiling to film boiling, which leads to a sharp increase in the surface temperature, its burnout and destruction. When vaporization occurs on a solid surface, three phases interact: liquid, vapor, and solid. The heat transfer coefficient, critical heat fluxes (CHF), and boiling heat transfer depends both on the physical properties of the used fluids and on many geometric and physico-chemical characteristics of the heat-releasing wall. A promising way to increase the critical density of the heat flux at boiling is to produce a microstructured surface, which can increase the CHF by 2-3 times compared to a smooth surface. The result depends on a combination of many causes, and experimental verification of the proposed structures is necessary. Over the past decade, many works have been carried out, in which boiling and the crisis of heat transfer on surfaces structured by various technologies have been studied. An overview of the state of the problem of heat transfer intensification and critical heat loads during boiling in a large volume is presented in [1]. Comparison of the results [1] shows a large range of values, the lack of calculation methods. In this paper, we analyze the results of increasing the CHF obtained on various structured surfaces and calculate the CHF according to the model proposed in [2].

2. Review research
When using microstructured surfaces, the roughness is small enough to change the consistent pattern of single-phase heat transfer. Technologies for obtaining new variants of rough structures are currently being developed, which have known in advance the geometric characteristics and physico-chemical properties. The main goal in the development of structured surfaces is to create many vaporization centers on the surface, which will lead to boiling at lower temperature pressures or to an earlier onset of boiling.
In [3], the study of the deformation-cut surfaces is carried out. This technology is a mechanical processing of metal on standard metalworking apparatus. During the study, it was found that surfaces with multidimensional texture are characterized by a great heat transfer coefficients up to 9 times, and CHFs up to 4 times. For surfaces with a three-dimensional structure, the maximum values of heat transfer i enhancements are obtained.

In [4], horizontally oriented microstructural surfaces were used. Surfaces was with a circular cross-section pins with a surface development coefficient R in the range from 1.79 to 5.94. The CHF was increased up to 2 times.

In [5], a study of CHF on pool boiling of ethanol on horizontal microstructured surfaces with structures in the form of columns and cavities was performed. It is revealed that such surfaces can increase the number of centers of vaporization, thereby reducing the overheating of the wall and increasing the heat flux. The enhancements of heat transfer coefficient and CHF on microstructured surfaces was from 3 to 5 times in comparison with smooth surfaces.

In [6], the study of the maxima of the CHF enhancement with a change of the surface pin density was carried out. The effect of different distance between the pins on the pool boiling was studied. The CHF increases with a decrease in the step between the pins, and then decreases sharply after reaching a critical value.

In [7], an increase in heat transfer on pool boiling and CHF was studied with an increase in the surface development coefficient from 1 to 4. 12 samples were made with a structure in the form of microcylinders with different geometric dimensions (height, diameter, pitch). The result was that the heat transfer coefficient increased by 1.5 times, and the CHF by 1.5-2 times compared to a smooth surface. A critical gap size is found when analyzing the capillary flow velocity on a structured surface, which limits the CHF.

In [8], the study of the intensification of heat transfer during the boiling of acetone at atmospheric pressure on a horizontal heat-generating surface was carried out. Seven heated surfaces were made, which were divided into 3 classes. One class is a smooth surface, the next is a surface with open microchannels, and the last class is a surface with two-dimensional micropores. The optimal geometrical parameters of the micro-surfaces was found, which provides the maximum heat transfer and the CHF enhancements among the three two-dimensional test sections.

In [9], irregular microstructured surfaces with a FeCrAl layer on a metal substrate were produced by sputtering. For the first time, a significant increase in CHF was achieved using all types of surfaces. The greatest increase in CHF up to 1.6 times was observed for the deposition layer deposited for 1 hour at a substrate temperature of 150 degrees. The increase in CHF was explained by an increase in the roughness coefficient r at the micro-scale. This could influence reducing the re-wetting interval with FeCrAl-layered heaters.

In [10], pool boiling is experimentally investigated on thin homogeneous porous coatings using different diameters of copper particles, different manufacturing methods, and characteristics of particles (solid or porous) with a coating thickness of 3 to 5 particle diameters. The results obtained show that the critical heat flux for all coatings is approximately 1.8 times higher than on a smooth surface. It is assumed that the presence of a thin homogeneous porous coating affects the hydrodynamic (macroscale) stability in such a way that the area of the steam channels increases.

In [11], provides a fundamental understanding of the underlying mechanisms of boiling intensification using various nanomodifications of structures. Some nanostructures resulted in a 2.6-fold increase in CHF compared to smooth surfaces. Several methods of applying deformations to the surface have been studied. Some methods give an increase in CHF, and some a decrease. This analysis led to the conclusion that you need to use several methods at the same time to get even better results.

In [12], numerous studies of heat transfer during boiling of freon R-113 on specially created modified surfaces were carried out. It was found that the increase in the heat transfer coefficient and the critical heat flux is not proportional to the surface development coefficient. As an explanation for the growth of CHF, it was suggested that the possibility of evaporation of the micro-layer of liquid under the bubble remains due to the non-isothermal heating surface and the additional inflow of liquid.
into the evaporation zone. An increase in the CHF of up to 25% was obtained, for this purpose, a simple technology of surface modification by an electron beam was used.

Figure 1. The CHF enhancements $q_{cr,mod.}/q_{cr,sm.}$ from the surface development coefficient for regular structures (experimental data from the above articles).

Figure 2. The CHF enhancements $q_{cr,mod.}/q_{cr,sm.}$ from the surface development coefficient for irregular structures (experimental data from the above articles).

Figure 1-2 shows the results of the studies [3–11] in the form of the CHF enhancements as the function on the surface development coefficient $R$. The CHF enhancement varies from 1.1 to 3.5 times. The maximum CHF enhancement up to 3-4 times was in [5] on the structure in the form of micro-columns and micro-cavities, in [12] on some surfaces, as well as in [11].

3. Calculation method
Most of the research on the effect of surface structuring on the value of the CHF in the vast majority of cases is experimental research. The theoretical consideration of pool boiling CHF enhancement on a structured surface with regular geometry is carried out in [2]. In [2] the contradictions of the
A hydrodynamic model of the CHF are analyzed. The different way to developed of the boiling crisis theory is proposed. The crisis conditioned by irreversible increase of the dry spots on the heating surface. The CHF occurs when the liquid inflow into the area of intense evaporation, caused by the gradient of the curvature of the liquid macrofilm surface, does not compensate for its evaporation at the boundary of the dry spot. In developing this model, the effect of micro-coating is introduced through a change in the capillary pressure gradient and the flow conditions of the liquid in the macrofilm. At boiling on a structured surface, a capillary pressure gradient in the microchannels is added to the pressure gradient due to the curvature of the meniscus of the film. The final equation [2] for the CHF relative enhancement has the form:

$$\frac{q_{cr, mod}}{q_{cr}} = 1 + k_1 \left( \frac{\sigma}{\rho G} \right)^{0.4} \left( \frac{\mu}{\lambda \rho G} \right)^{0.8} (a + s)^2,$$  \hspace{0.5cm} (1)$$

where $q_{cr}$ – CHF on a smooth surface; $q_{cr, mod}$ – CHF on a structured surface, $k_1=7.5 \cdot 10^{-4}$ the empirical coefficient, $a$ - the characteristic size (for example, width or diameter), $s$ - the step between the micro-roughnesses.

To calculate the projected increase in CHF, an analysis of the various structures was carried out separately. For structures with regular morphology, it was necessary to determine the characteristic size. It is concluded that for structures in the form of columns (in the cross section of which a square, rectangle, circle, or polygon, as well as for spherical recesses), the width or diameter is taken as the characteristic size. And for micro-edges or micro-channels, the height of the deformation is taken as the characteristic size. For structures with irregular morphology, some articles initially gave the average values of the necessary parameters, but for some it was necessary to calculate them according to the structure profile. As well as for micro-ribs with regular morphology, the average height of deformations was chosen as the characteristic size.

Using the geometric parameters of the surface structure, the surface development coefficient can be expressed:

$$r = \pi ah(a + s)^2,$$  \hspace{0.5cm} (2)$$

where $h$ is the height of the structure.

For the above works, where the study of pool boiling at atmospheric pressure on surfaces with regular and irregular structures was performed, the relative increase in CHF was calculated using the formula (1) [13]. Figure 3-4 shows a graph of the dependence of the ratio of experimental data to those calculated by formula (1) on the surface development coefficient.

Based on figure 3-4, there are points showing the discrepancy between the experimental and calculated values. At the same time, most of the calculated values coincide with the empirical data or vary within the margin of error. For these structures, the formula (1) can be used for the theoretical prediction to assume the value of the critical heat flux on a certain surface. For example, for structures in the form of bayonet micro-ribs from work [3], for micro-cavities and micro-channels from work [5] with a moderate surface development coefficient, for micro-cylinders from work [11] with $4 < R < 5$, for work [6] with micro-columns.

The CHF data obtained in [8] is not calculated using formula (1). From the 34 CHF value considered in [8], only 4 microstructures have reasonable agreement with the calculation according to (1). The rest of the experimental data on CHF are several times higher than the calculated ones. Such structures require careful study and reflection.

Figure 5 shows a graph of the dependence of the ratio of CHF on a modified surface to CHF on a smooth surface from the surface development coefficient for both regular and irregular structures.
Figure 3. Dependence of $q_{cr,exp.}/q_{cr,dep.}$ on the surface development coefficient for regular structures.

Figure 4. Dependence of $q_{cr,exp.}/q_{cr,dep.}$ on the surface development coefficient for irregular structures.

The generalization of the data is made by approximating the polynomial function $f(R)$ and its equation is obtained $f(R) = -0.03R^2 + 0.22R + 0.81$. Thus, it is possible to predict the CHF value on the structured surface for some structures.
4. Conclusion
The problem of increasing CHF due to the use of microstructured surfaces is considered. The conditions for the movement of liquid and vapor in a porous space are determined by the geometric parameters of microstructured coatings. The characteristic size and number of potential centers of vaporization play a key role in the intensification of heat transfer during boiling. Surfaces with a developed microstructure provide a greater number of potential centers of vaporization, and therefore have higher heat transfer coefficients in comparison with technically smooth surfaces. At the same time, structures that are too thick cause complex counter-flows of liquid and tend to "steaming". The resulting steam does not have time to leave the structure while the liquid does not have time to be brought to the centers of vaporization. Thus, the surface is burned. Therefore, such surfaces show a deterioration in heat transfer and CHF.

The calculation according to the formula (1) was performed for ten works, in which the values of CHF obtained on both regular and irregular microstructures with different geometric parameters were presented. Comparing the results of calculations with experimental data on CHF it can be concluded that it is possible to use formula (1) to generalize the results of most studies. For specific regular structures (microstructured surface with ribs, micrololumns with square and circular cross-sections, as well as structures in the form of microchannels and microcavities), the best fit of the data is observed at moderate surface development coefficients. Irregular structures also show a good correspondence between experimental and calculated data but require more careful study. Based on the comparison of experimental and calculated data, it is concluded that this model is not universal for all microstructured surfaces. During data comparison, it was suggested that it is possible to predict the value of CHF on various structured surfaces using the generalizing function f(R).

Acknowledgements
This research was supported by the Russian science Foundation (grant 19-19-00410).
References

[1] Dedov A V 2019 A Review of Modern Methods for Enhancing Nucleate Boiling Heat Transfer (Review) Thermal Engineering Volume 66, Issue 12, 1 p. 881-915

[2] Sukomel L A, Yagov V V 2017 Possibilities of increasing critical heat fluxes during boiling on surfaces with porous coatings (review) Vestnik MPEI, Pages 55-67

[3] Schelchakov A V, Khakimzyanov R R 2014 Heat transfer on microstructured surfaces during boiling water under conditions of free convection. Pages 263-266

[4] Kuang-Han Chu, Ryan Enright, Evelyn N Wang 2012 Structured surfaces for enhanced pool boiling heat transfer American Institute of Physics 5 p

[5] Lining Dong, Xiaojun Quan, Ping Cheng 2013 An experimental investigation of enhanced pool boiling heat transfer from surfaces with micro/nano-structures International Journal of Heat and Mass Transfer

[6] Navdeep Singh Dhillon, Jacopo Buongiorno, Kripa K Varanasi 2015 Critical heat flux maxima during boiling crisis on textured surfaces Nature Communications p 189-196

[7] Seol Ha Kima, Gi Cheol Leeb, Jun Young Kang, Kiyofumi Moriyamaa, Moo Hwan Kima,c, Hyun Sun Park 2015 Boiling heat transfer and critical heat flux evaluation of the pool boiling on micro structured surface International Journal of Heat and Mass Transfer p 1140-1147

[8] Xianbing Ji, Jinliang Xu, Ziwei Zhao, Wolong Yang 2013 Pool boiling heat transfer on uniform and non-uniform porous coating surfaces Experimental Thermal and Fluid Science p 198-212

[9] Gwang Hyeok Seo, Gyoondong Jeun, Sung Joong Kim 2016 Enhanced pool boiling critical heat flux with a FeCrAl layer fabricated by DC sputtering International Communications in Heat and Mass Transfer 102 p 1293-1307

[10] Hwang G-S, Kaviany M 2006 Critical heat flux in thin, uniform particle coatings International Journal of Heat and Mass Transfer 49 p 844–849

[11] Md Mahamudur Rahman, Emre Ölçeroğlu, Matthew McCarthy 2014 Role of Wickability on the Critical Heat Flux of Structured Superhydrophilic Surfaces Langmuir №30 p 11225-11234

[12] Dedov A V, Khaziev I A, Laharev D A & Fedorovich S D 2021 Study of Nucleate Pool Boiling Heat Transfer Enhancement on Surfaces Modified by Beam Technologies Heat Transfer Engineering, DOI: 10.1080/01457632.2021.1896834

[13] Stupakova A V, Dedov A V 2020 Calculation of critical heat fluxes at boiling on microstructured surfaces Journal of Physics: Conference Series, 1683(2), 022098