Calculation of critical heat fluxes at boiling on microstructured surfaces

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Abstract. A method for increasing the critical heat flux at boiling by applying porous structures of various regular geometries to a smooth surface is considered. The analysis of experimental data and calculation of the critical heat flux based on the model of V.V. Yagov, which considers the additional inflow of liquid into the evaporation zone due to the action of capillary forces in a porous space. Comparison of experimental and calculated data allows us to conclude that this model is not suitable for all microstructured surfaces.

1. Introduction
Nucleate boiling is one of the most effective ways of heat removal from surfaces. There are also some limitations for exhaust heat flux associated with the occurrence of the crisis of boiling heat transfer. In fact, when evaporation on a solid surface the interaction of the three phases: liquid, vapor and solid. Heat transfer and critical heat flux (CHF) at boiling depend on the physical properties of the boiling liquid, and by a few characteristics of the heat-transfer wall. A promising way to increase the critical heat flux at boiling is the production of a structured surface. A surface modification allows to increase CHF in 2-3 times in comparison with a smooth surface. The effectiveness of the surfaces depends on a combination of many factors necessary experimental verification of the proposed structures. Over the last decade, many papers which investigated the boiling crisis and heat transfer on structured surfaces. The comparison of the results of [1] shows large variability, the lack of calculation methods. In the present work the analysis of the results of CHF obtained on a regular structured surface at pool boiling, the calculation of CHF according to the model proposed in [3].

2. Review of completed researches
Microstructured surfaces - heat exchange surfaces, with small-scale deformations obtained during their processing and / or coating, comparable in geometry to roughness. In this case, the roughness is small for changing the intensity of single-phase heat transfer. The porous layer on the surface can be created in various ways, and currently there is a development of technologies for producing new variants of porous structures with previously known geometric characteristics and physicochemical properties. The development of structured surfaces to intensify the boiling process is based on the basic rule - the creation of many centers of vaporization on the surface, which leads to an earlier start of boiling.

In [2], the surfaces were obtained by the method of deforming cutting. This technology is simple, non-waste, is a metal machining on standard metalworking equipment. The study revealed that these
surfaces with two- and three-dimensional structures are characterized by a significant increase in heat transfer coefficient (HTC) - up to 9 times, and CHF - up to 4.1 times. The maximum values of heat transfer intensification were obtained for surfaces with a three-dimensional structure.

In [4], boiling was studied on horizontally oriented, well-defined microstructural surfaces in order to systematically investigate the role of increasing surface development on CHF. For the study, microstructured surfaces were made in the form of columns with a circular cross section with a surface development (increase) coefficient in the range from 1.79 to 5.94. An increase in CHF up to 2 times was obtained.

In [5], CHF was studied during the boiling of ethanol on horizontal microstructured surfaces in the form of microcolumns and microcavities. It was established that microstructures can increase the number of centers of vaporization at low heat fluxes, thereby reducing wall overheating and increasing heat flux. Experimental results show that microstructures increase the heat transfer coefficient and CHF in comparison with smooth surfaces from 3 to 5 times.

In [6], a study was made of the maxima of the increase in CHF with a change in the density of the surface texture. Textured surfaces in the form of microcolumns with a width of 10 μm and a height of 12 μm were studied, and the effect of different values of the distance between the columns on the boiling crisis was compared. The data presented in the article show that first the CHF increases with decreasing step between the micro columns, and then decreases sharply after reaching the maximum value.

In [7], a study was conducted of increasing boiling heat transfer and CHF with an increase in the surface development coefficient from 1 to 4.4. 12 samples with a structure in the form of micro cylinders with various geometric dimensions (height, diameter, pitch) were made. The result of the study was that the HTC increased by 1.5 times, and CHF by 1.5-2 times compared with a smooth surface. However, when analyzing the capillary flux velocity on a structured surface, a critical gap size is found that limits the CHF. The critical gap size is discussed analytically and compared with experimental data.

In [8], a study was conducted of boiling heat transfer intensification of acetone at atmospheric pressure on a horizontal surface. It was made 7 working surfaces, which were divided into 3 types. The first type is a smooth surface, the second is a surface with open microchannels evenly spaced, and the third is a surface with evenly spaced 2D micropores. The result of the study was that the optimal step between the micro-dimensions was found, which provides the best heat transfer characteristics and the greatest CHF among the three 2D surfaces.

In fig. 1. presents the results of the considered works in the form of the dependence of the ratio $q_{cr,sur}$ on a structured surface to $q_{cr}$ on a smooth surface on the surface development coefficient $r$. On average, the increase in the critical heat flux varies from 1.1 to 2.3 times. The maximum increase in the
critical heat flux to 3.5–4 times was recorded in [5] on a structure in the form of microcolumns and microcavities. Moreover, the relative increase in CHF exceeds the surface development coefficient.

![Figure 1](image-url)

**Figure 1.** The dependence of the relative increase in CHF on the surface development coefficient.

### 3. Calculation of CHF at boiling

Most of the studies on the effect of porous coatings on the critical heat flux value are exclusively empirical studies. A theoretical consideration of the problem of increasing the thermal efficiency during boiling on a porous surface of regular structure was carried out in [3], where the contradictions of the hydrodynamic model of the crisis were analyzed and a different approach to creating a theory of the boiling crisis was proposed, namely, the approach connecting the crisis with an irreversible increase in the area of dry spots on the heating surface. The boiling crisis occurs when the influx of liquid into the intensive evaporation zone, caused by the gradient of the surface curvature of the liquid macro film, does not compensate for its evaporation at the dry spot boundary. In the framework of this model, the influence of microcoating is introduced through a change in the capillary pressure gradient and the conditions of fluid flow in the macro film. When boiling occurs on a structured surface, a capillary pressure gradient in microchannels is added to the pressure gradient due to the curvature of the meniscus of the film. The final equation [3] for the relative increase in CHF has the form:

$$\frac{q_{cr,\text{surf}}}{q_{cr}} = (1 + \frac{k_1 (\frac{\sigma}{\rho g})^{0.4} (\frac{\mu}{\Delta \rho})^{0.8}}{(a+s)^2}), \tag{1}$$

where $q_{cr}$ - CHF on the base (smooth) surface; $q_{cr,\text{surf}}$ is the CHF on a structured surface, $k_1$ is the empirical coefficient (in [3], the calculations according to (1) were compared with the results of [6] and the value $k_1 = 7.5 \cdot 10^4$ was selected), $a$ and $s$ are geometric parameters of the surface structure: $a$ - characteristic size (for example, width or diameter), $s$ - step between microroughnesses.
Using the geometric parameters of the surface structure, one can express the coefficient of surface development (increase in area):

\[ r = \frac{\pi ah}{(a+s)^2}, \]

where \( h \) is the height of the structure.

For the studies considered above, where a pool boiling was studied at atmospheric pressure on surfaces with a regular structure, the relative increase in the CHF was calculated using formula (1). A comparison of the calculated values depending on the surface development coefficient (2) is shown in Fig. 2. Compared to fig. 1, the data scatter is smaller; single surfaces with a high relative CHF are distinguished.

![Figure 2](image-url)

**Figure 2.** Dependence of the relative increase in CHF on the surface development coefficient.

Figure 3 shows the ratio of experimental data \( q_{cr, exp} \) to those calculated by formula (1) \( q_{cr, cal} \), depending on the surface development coefficient.
Based on Fig. 3, it can be noted that there are points at which the experimental value differs significantly from the calculated value. In this case, most of the calculated values coincide with empirical data or vary within the error range; for these microstructures, formula (1) can be used for theoretical analysis to assume the value of the critical heat flux on a certain structure. For example, for structures in the form of bayonet microribs from [2], for microcolumns and microchannels from [8] with a moderate surface development coefficient, for microcylinders from [7] with 4 < r < 5, for [6] with microcolumns.

Formula (1) is not suitable for the theoretical prediction of the CHF obtained in [5], since a very small part of the calculated CHF values coincides with the experimental values. Of the 34 structures considered in [5], only 2 microstructures show reasonable agreement with the calculation according to (1). The remaining experimental data on the CHF are several times higher than the calculated ones.

4. Conclusion
The task of improving CHF using microstructured coatings is discussed in the paper. The geometric parameters of the microstructured coatings determine the conditions of motion of liquid and vapor in the porous space. Not only characteristic sizes but also the number of potential centers of vaporization, play an important role in the intensification of boiling heat transfer. Surface with well-developed microstructure provides many potential centers of vaporization, and therefore have higher coefficients of heat transfer in comparison with a technically smooth surface. However, the structure of the too large thickness cause a complex counter flow of liquid and vapor, and have a tendency to ”steaming” - the phenomenon when the steam generated does not have time to leave the structure, and the liquid does not have time to run to the centers of vaporization. Therefore, these surfaces show a deterioration of heat transfer and CHF.

The calculation according to formula (1) for six studies was performed, in which the values of the CHF obtained on regular microstructures with different characteristic sizes and the pitch between microroughnesses were presented. Comparing the results of calculations and experimental data on the CHF, we can conclude that it is possible to use (1) to summarize the results of most studies. For concrete
regular structures — a microstructured surface with edges, micro columns with a square section and a round section, as well as for structures in the form of microchannels, the best data correspondence on surfaces with a moderate surface development coefficient is obtained.

Acknowledgments
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5. References
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