Heat transfer on microstructured surfaces with pool boiling of various liquids

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Abstract. Recommendations for predicting heat transfer coefficients and critical heat fluxes are developed on the basis of available experimental data on heat transfer and critical heat fluxes for boiling of different liquids on microstructured surfaces realized by deformed cutting method. Microstructured surfaces allow intensifying heat transfer 1.1 to 6 times. Due to the variable wettability of microstructured surface elements, critical heat fluxes increase over 4 times. The proposed criteria equations allow predicting heat transfer coefficients with an error of 30%, and critical heat fluxes with an error of 30–35%. The equations are of interest for designing cooling systems for microelectronic devices, heat and mass transfer devices, boiling zones of heat pipes and thermosyphons, etc.

1. Introduction

Liquid cooling systems are currently used for cooling the heat loaded elements of power electrical equipment and microelectronics. In these systems, the liquid boils directly on the electronic components. For this purpose, they are placed directly in the liquid coolant. And to increase the reliability of cooling systems, critical heat fluxes have to be increased.

Methods of heat exchange enhancement during pool boiling are traditional [1]: influence on internal mechanisms of the process (increase of vaporization centers, wettability control, increase of liquid inflow into microlayer evaporation zone, etc.); and increase/development of the heat-exchange surface.

Nowadays the great majority of works are focused on searching and applying new technologies of surface structuring and boiling process control [1, 2]. The main results of these works only demonstrate the effect without any detailed description of the investigated process for different coolants and conditions of experiments. Modern surface structuring technologies have been developed. They allow controlling the heat exchange during boiling, thus reducing the temperature head of the beginning of boiling, increasing the values of critical thermal head, and intensifying the heat transfer coefficient.

One of the methods for obtaining effective microstructured boiling surfaces is the deformation cutting technology [3,4]. This method is based on the process of partial cut allowance and targeted...
plastic deformation of the undercut surface layer. The resulting chips are not completely separated from the workpiece, maintaining a bond with it on its narrow side. The set of undercut surface layers, keeping their connection with the workpiece, form on the treated surface of a part of the developed macro relief. The technology has high productivity and a wide range of standard sizes of the resulting macro-relief and can be implemented both on specialized and unified metal-cutting equipment.

The selection of geometrical parameters of microstructured surfaces allows controlling the wettability of the surface and the inflow of liquid into the evaporation zone. The wetting angle affects the formation of the steam bubble [1]. The increase of the edge angle (wetting property deterioration) reduces the temperature head corresponding to the boiling beginning and intensifies the heat output. Improvement of wettability promotes the liquid inflow into the zone of intensive evaporation and increases critical heat fluxes. The combination of these factors allows for simultaneous heat transfer intensification and increases critical heat fluxes.

2. General correlations for heat transfer coefficient

Only surfaces obtained by deforming cutting were used to generalize data on pool boiling heat transfer of liquids heated to saturation temperature. All surfaces were divided into two groups (Fig. 1): surfaces with 2-D relief (microribs); and surfaces with 3-D relief (micro-pin structures).

The generalization was performed using the polynomial regression method:

\[
\frac{\alpha}{\alpha_0} = f_1(K_q(\theta/90),(h/l_0),(\Delta/l_0),(\delta/l_0))
\]

where \( \alpha \) is the heat transfer coefficient on a microstructured surface, \( \alpha_0 \) is the heat transfer coefficient on a smooth surface, \( K_q \) is the dimensionless criterion - the scale of the average liquid velocity caused by the vaporization process \( K_q = q_0/(r\rho''v'') \), \( l_0 \) is the Laplace constant proportional to the tear-off diameter of the bubble. \( l_0 = \sqrt{\frac{\sigma}{g(\rho' - \rho''')}} \), \( \rho' \) and \( \rho'' \) are the liquid and vapour densities, \( v' \) is the fluid kinematic viscosity coefficient, \( r \) is the latent heat of vaporization, \( \sigma \) is the surface tension coefficient; and geometrical parameters \( \theta, h, \Delta, \delta \) are shown in Fig. 2.

![Figure 1](image)

(a) Surfaces for pool boiling obtained by deforming cutting method:
   a – surfaces with 2-D relief (microribs), b – surfaces with 3-D relief (micro-pin structures).

There are several approaches to normalizing geometric parameters in boiling dependences. For example, it is proposed to choose the initial diameter of the steam bubble as the defining size. However, analysis has shown that the most profitable is to use \( l_0 \). This primarily depends on the boiling model - the calculation through the initial diameter of the steam bubble more describes the increase of the centers of vaporization and their exit from the microstructure elements, and \( l_0 \) describes the control of wettability and increase of liquid inflow into the micro-layer evaporation zone. It is recommended to accept the equation of Borishansky –
\[ \alpha = 872P_{\text{crit}}^{1/3}(T_{\text{crit}}-36M^{1/3})(P/P_{\text{crit}})^{0.1}(1+4.64(P/P_{\text{crit}})^{1.16})^{2/3}, \]

\( p_{\text{crit}} \) and \( T_{\text{crit}} \) are the critical pressure and critical temperature of the coolant, and \( M \) is the molecular weight of the coolant.

**Figure 2.** Geometric parameters of the surface microstructure.

Generalization of experimental data presented in Table 1 and Fig. 1 was carried out for geometric parameters of surfaces with 2-D relief (micro-rib) and regime parameters of pool boiling. The material of the surfaces was stainless steel, copper, titanium. Thickness of surfaces No. 1-23 is 0.2-0.3 mm. During generalization of more than 730 experimental points, dependence was obtained to calculate heat transfer coefficient at pool boiling water, ethanol, 60% of glycerine water solution, freons R113 and R123, Novec 649 refrigerant in big volume on boiling surfaces with 2 heat transfer coefficient at

\[ \alpha/\alpha_0 = 6 K_q^{-0.2}(\theta/90)^{0.554}(h/l_0)^{0.190}(\Delta/l_0)^{0.201}(\delta/l_0)^{-0.394} \]  

(1)

**Figure 3** Pool boiling heat transfer coefficients for surfaces with 2-D relief (micro ribs). Indication of points shown in table 1. \( \bar{\alpha} = \alpha/\alpha_0 \), \( A = 6 K_q^{-0.2}(\theta/90)^{0.554}(h/l_0)^{0.190}(\Delta/l_0)^{0.201}(\delta/l_0)^{-0.394} \)

**Figure 4** Pool boiling heat transfer coefficients for surfaces with 3-D relief (micropins). Indication of points shown in table 2. \( \bar{\alpha} = \alpha/\alpha_0 \), \( A = 3.2 K_q^{-0.2}(\theta/90)^{1.64}(h/l_0)^{0.393}(\Delta/l_0)^{0.08}(\delta/l_0)^{0.18} \times (u/l_0)^{-0.47}(s/l_0)^{0.47} \)

Equation (1) describes experimental points with a 30% deviation at a confidence probability of 0.95. Equation (1) is valid in the range of \( q = 3800-2.17106 \text{ W/m}^2, K_q = 5-11500, \theta/90 = 0.72-1, h/l_0 = 0.09-1.45 \) (relative height of micro-ribs. Fig.2), \( \Delta/l_0 = 0.002-1.29 \) (relative distance between micro-rib element. Fig.2), \( \delta/l_0 = 0.01-1 \) (relative thickness of the micro-rib profile. Fig.2), \( Pr = 1.75-35.7 \), and \( F/F_0 = 1.66-9.75 \) (increase in heat exchange area).

Geometric parameters of surfaces with 3-D relief (micro-pin structures) and regime parameters of pool boiling, for which the generalization of experimental data was carried out, are shown in Table 2.
and Fig. 2. The material of surfaces is stainless steel, copper, titanium. Thickness of surfaces No. 1-23 is 0.2-0.3 mm.

Table 1. Geometric parameters of surface with 2-D relief (micro ribs)

| Ref. | №  | Liquid            | h, D, δ, u, s, 0, ° | Regime parameters |
|------|-----|-------------------|---------------------|-------------------|
| [4-7]| 1   | Distilled water   | 95 15 15 - - 87    | P=10⁸ Pa T=373 K  |
|      | 2   |                   | 310 63 97 - - 87   |                   |
|      | 3   |                   | 200 46 74 - - 87   |                   |
|      | 4   |                   | 230 35 55 - - 87   |                   |
|      | 5   |                   | 220 22 38 - - 87   |                   |
|      | 6   |                   | 150 50 110 - - 90  |                   |
|      | 7   |                   | 90 50 110 - - 90   |                   |
|      | 8   |                   | 200 50 110 - - 90  |                   |
|      | 9   |                   | 200 50 110 - - 90  |                   |
| [2]  | 10  | Distilled water   | 300 44 26 - - 83   | P=10⁸ Pa T=373 K  |
|      | 11  |                   | 300 110 140 - - 90 |                   |
|      | 12  |                   | 360 85 115 - - 90  |                   |
|      | 13  |                   | 500 200 200 - - 80 |                   |
|      | 14  |                   | 360 85 115 - - 65  |                   |
|      | 15  |                   | 200 35 65 - - 83   |                   |
|      | 16  |                   | 500 200 200 - - 80 |                   |
| [8]  | 17  | Freon R113        | 310 33 182 - - 80  | P=10⁸ Pa T=320 K  |
| [9,10]| 18  | Ethanol           | 90 50 110 - - 90   | P=10⁸ Pa T=351.5 K |
|      | 19  |                   | 200 50 110 - - 90  | P=10⁸ Pa T=381 K  |
|      | 20  | 60% glycerin      | 200 50 110 - - 90  | P=10⁸ Pa T=381 K  |
|      | 21  | water solution    | 90 50 110 - - 90   | P=10⁸ Pa T=381 K  |
| authors | 22  | Distilled water   | 300 5 95 - - 90    | P=10⁸ Pa T=373 K  |
|      | 23  |                   | 300 5 75 - - 90    | P=10⁸ Pa T=373 K  |
| [11] | 24  | Distilled water   | 400 300 300 - - 90 | P=10⁸ Pa T=373 K  |
|      | 25  |                   | 300 300 300 - - 90 | P=10⁸ Pa T=373 K  |
|      | 26  |                   | 200 300 300 - - 90 | P=10⁸ Pa T=322 K  |
|      | 27  | Novec 649         | 400, 300 300 - - 90| P=10⁸ Pa T=322 K  |
|      | 28  |                   | 200 300 300 - - 90 | P=10⁸ Pa T=322 K  |
| [12] | 29  | Freon R123        | 1038 450 1050 - - 90| P=10⁸ Pa T=300 K  |
| authors | 30  | 60% glycerin      | 150 50 110 - - 90  | P=10⁸ Pa T=381 K  |
| water solution |      |                   |                     |                   |

The generalization was performed using the polynomial regression method:

\[
\alpha/\alpha_0 = f_2 (K_\infty, (\theta/90), (h/l_0), (\Delta/l_0), (\delta/l_0), (u/l_0), (s/l_0))
\]

At generalization of more than 500 experimental points we received the dependence for calculation of coefficient of pool boiling heat transfer: water, ethanol, 60 % of a water solution of glycerine, freons R11, R113, R123, R134a on surfaces with a 3-D relief (micropin structures) (Fig.4):

\[
\alpha/\alpha_0 = 3.2 K_\infty^{0.2} (\theta/90)^{-1.64} (h/l_0)^{0.35} (\Delta/l_0)^{0.08} (\delta/l_0)^{0.18} (u/l_0)^{0.47} (s/l_0)^{0.47}
\]

Equation (2) describes experimental data with a 30% deviation at a confidence probability of 0.85. Equation (2) is fair in the range of \( q = 2400-3.5106 \) W/m², \( K_\infty = 8.7-22030 \), \( 0.90 = 0.77-1 \), \( h/l_0 = 0.09-0.71 \) (relative height of micropins. Fig.2), \( \Delta/l_0 = 0.002-0.3 \) (relative cross distance between micropin
elements. Fig.2), δl₀=0.042-0.42 (relative cross thickness of the micro-rib profile. Fig.2), u/l₀=0.009-0.28 (relative longitudinal distance between micropin elements. Fig.2), s/l₀=0.02-0.79 (relative longitudinal thickness of the micro-rib profile. Fig.2), and Pr=1.75-7.35, F/F₀=2.23-4.8 (increase in heat exchange area).

Table 2. Geometric parameters of a surface with 3-D relief (micropins)

| Ref. | Nº | liquid | Geometric parameters of the surface with 3-D relief (micropins) | Geometric parameters of the surface with 3-D relief (micropins) | Regime parameters |
|------|----|--------|---------------------------------------------------------------|---------------------------------------------------------------|------------------|
|      |    |        | h, µm | Δ, µm | δ, µm | u, µm | s, µm | θ₀,₀ |
| [4-7] | 1  | Distilled water | 420  | 180  | 170  | 140  | 178  | 90   | P=10³ Pa |
|      | 2  | Distilled water | 340  | 70   | 170  | 140  | 178  | 75   | T=373 K  |
| [2]  | 3  | Distilled water | 420  | 205  | 145  | 120  | 200  | 70   | P=10³ Pa |
|      | 4  | Distilled water | 570  | 210  | 140  | 180  | 140  | 80   | T=373 K  |
|      | 5  | Distilled water | 480  | 135  | 105  | 120  | 200  | 70   |               |
|      | 6  | Distilled water | 480  | 200  | 200  | 300  | 300  | 80   |               |
|      | 7  | Distilled water | 400  | 200  | 200  | 300  | 300  | 83   |               |
| authors | 8 | Distilled water | 450  | 120  | 200  | 250  | 70   | 85   | P=10³ Pa |
|      | 9  | Distilled water | 350  | 5    | 320  | 225  | 75   | 90   | T=373 K  |
|      | 10 | Distilled water | 320  | 5    | 320  | 225  | 75   | 90   |               |
|      | 11 | Distilled water | 300  | 80   | 120  | 175  | 125  | 90   |               |
|      | 12 | Distilled water | 220  | 80   | 220  | 250  | 50   | 85   |               |
|      | 13 | Distilled water | 375  | 5    | 300  | 250  | 50   | 90   |               |
|      | 14 | Distilled water | 500  | 350  | 150  | 275  | 50   | 85   |               |
| [9,10]| 15 | Ethanol   | 420  | 180  | 170  | 140  | 178  | 90   | P=10³ Pa |
|      | 16 | Ethanol   | 340  | 70   | 170  | 140  | 178  | 75   | T=351,5 K|
|      | 17 | 60% glycerin | 340  | 70   | 170  | 140  | 178  | 75   | P=10³ Pa |
|      | 18 | water solution | 420  | 180  | 170  | 140  | 178  | 90   | T=381 K  |
| [13] | 19 | Freon R11 | 540  | 250  | 365  | 250  | 460  | 90   | P=10³ Pa |
|      | 20 | Freon R123 | 540  | 250  | 365  | 250  | 460  | 90   | T=297 K  |
|      | 21 | Freon R134a | 540  | 250  | 365  | 250  | 460  | 90   | P=3.10⁵ Pa |
| [12] | 22 | Freon R123 | 750  | 320  | 280  | 10   | 830  | 90   | T=300 K  |

3. General correlations for critical heat fluxes

To generalize the data for critical heat fluxes, the surface data presented in Tables 1 and 2 were used. Generalization was carried out using the method of polynomial regression by models for 2-D and 3D surface microstructure, respectively:

\[
\frac{q_{cr0}}{q_{crit0}} = f_{1}(\theta/90, (h/l₀),(\Delta/l₀),(\delta/l₀),Pr) \\
\frac{q_{cr0}}{q_{crit}} = f_{2}(\theta/90, (h/l₀),(\Delta/l₀),(\delta/l₀),(u/l₀),(s/l₀),Pr)
\]

where \(q_{cr0}\) is the critical heat flux when liquid is pool boiling on a microstructured surface, and \(q_{crit0}\) is the critical heat flux when liquid is boiling on a smooth surface. The values obtained experimentally are taken as the critical heat flux when liquid is boiling on a smooth surface \(q_{crit}\). They can be estimated using the dependence for Kutateladze critical heat flux: \(q_{crit0}=0.13\sqrt{\rho C_p g \sigma (\rho' - \rho^\circ)}\) with recommendations on amendments to the thickness of thin-walled boiling surfaces of Gogonin [14]. It should be noted that the amount of experimental data is very limited.

During generalization, dependence was obtained for calculating critical heat flux at pool boiling of water, ethanol, 60% of glycerine water solution, freons R113 and R123, Novec 649 on boiling surfaces with 2-D relief (microribes) (Fig.5):
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Conclusion

Recommendations for predicting heat transfer coefficients and critical heat fluxes have been developed on the basis of available experimental data on heat transfer and critical heat fluxes for boiling of different liquids on microstructured surfaces, realized by deformed cutting method. Microstructured surfaces allow intensifying heat transfer 1.1 to 6 times. Due to the variable wettability of microstructured surface elements, critical heat fluxes increase over 4 times. The proposed criteria equations allow predicting heat transfer coefficients with an error of 30%, and critical heat fluxes with an error of 30-35%. The equations are of interest for designing cooling systems for microelectronic devices, heat and mass transfer devices, boiling zones of heat pipes and thermosyphons, etc.
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