Recommendation for prediction of pool boiling heat transfer of various liquids on microstructured surfaces

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Abstract. Recommendations for prediction heat transfer coefficients and critical heat flux according to available in the literature experimental data of heat transfer and critical heat flux for boiling different liquids on microstructured surfaces made by deformed cutting method are obtained. In the work, on available in the literature sources of experimental data on heat transfer and critical heat flux at boiling of various liquids on the microstructured surfaces made by the deforming cutting method, recommendations for prediction of heat transfer coefficients and critical heat fluxes are received. Microstructured surfaces allow to intensify the heat transfer is 1.1 to 6 times. Due to the variable wettability of microstructured surfaces elements, critical heat flux increase before 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%. In order to improve the accuracy of forecasting, the possibility of using an artificial neural network model for generalizing heat transfer coefficients is shown. Forecasting using an artificial neural network model allows us to determine the heat transfer coefficients with an error of ±20%. 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.); - 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 are only demonstration of the effect without detailed description of the investigated process for different coolants and conditions of experiments. Modern surface structuring technologies have been developed. They allow to control the heat exchange during boiling, thus reducing the temperature head of the beginning of boiling, increasing the values of critical thermal head, 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, which kept the continuity of its connection with the workpiece, forms on the treated surface of the part a 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 to control 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) allows to reduce the temperature head corresponding to the boiling beginning, to intensify the heat output. Improvement of wettability promotes the inflow of liquid into the zone of intensive evaporation and increases critical heat fluxes. The combination of these factors allows for simultaneous heat transfer intensification and increase in 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); - 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 \( \alpha \) - heat transfer coefficient on a microstructured surface, \( \alpha_0 \) - heat transfer coefficient on a smooth surface, \( K_q \) - a dimensionless criteria - the scale of the average liquid velocity caused by the vaporization process \( K_q = q \cdot l_0 / (r \cdot \rho' \cdot v') \), \( l_0 \) - Laplace constant proportional to the tear-off diameter of the bubble. \( l_0 = \sqrt{\frac{\sigma}{g(\rho' - \rho'')}} \), \( \rho' \) and \( \rho'' \) - liquid and vapour density, \( v' \) - fluid kinematic viscosity coefficient, \( r \) – vaporization latent heat, \( \sigma \) - surface tension coefficient; geometrical parameters \( \theta, h, \Delta, \delta \) shown on Fig.2.

![Figure 1. 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).](image)

There are several approaches to normalizing geometric parameters in boiling dependencies. 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 - $a_0 = 872 \frac{P_{\text{crit}}^{1/3}}{(T_{\text{crit}}^{5/6}M^{1/8})} (1+4.64(P/P_{\text{crit}})^{1.16}q^{2/3})$, $P_{\text{crit}}$ and $T_{\text{crit}}$ - critical pressure and critical temperature of the coolant, $M$ - molecular weight of the coolant.

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 is 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 has been obtained for calculation of 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-D relief (micro rib) (Fig.3):

$$\frac{a}{a_0} = 6 K_q^{-0.2}(9/90)_{0.554}(h/l_0)^{0.190}(\Delta/\delta)_{0.201}(\delta/l_0)^{-0.394}$$

Equation (1) describes experimental points with a 30% deviation at a confidence probability of 0.95. Equation (1) is valid in the range $q=3800-2.17106$ 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), $\Delta/\delta=0.002-1.29$ (relative distance between micro-rib element. Fig.2), $\delta/l_0=0.01-1$ (relative thickness of the micro-rib profile. Fig.2), $Pr=1.75-35.7$, $F/F_0=1.66-9.75$ (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.

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

**Figure 3** - Pool boiling heat transfer coefficients for surfaces with 2-D relief (micro ribs). Indication of points shown in table 1.

$$\overline{a} = \frac{a}{a_0}, \quad A = 6 K_q^{-0.2}(9/90)_{0.554}(h/l_0)^{0.190}(\Delta/\delta)_{0.201}(\delta/l_0)^{-0.394}$$

**Figure 4** - Pool boiling heat transfer coefficients for surfaces with 3-D relief (micropins). Indication of points shown in table 2.

$$\overline{a} = \frac{a}{a_0}, \quad A = 3.2 K_q^{-0.2}(9/90)_{1.64}(h/l_0)^{0.95}(\Delta/\delta)_{0.08}(\delta/l_0)^{0.18} \times (u/l_0)^{-0.47}(s/l_0)^{0.47}$$
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, μm | Δ, μm | δ, μm | u, μm | s, μm | 0, ° | Regime parameters |
|------|-----|-------------------------------|-------|-------|-------|-------|-------|------|------------------|
| [4-7] | 1   | Distilled water               | 95    | 15    | 15    | -     | -     | 87   | P=10^3 Pa T=373 K |
|      | 2   |                               | 310   | 63    | 97    | -     | -     | 87   |                  |
|      | 3   |                               | 200   | 46    | 74    | -     | -     | 87   |                  |
|      | 4   |                               | 230   | 55    | 74    | -     | -     | 87   |                  |
|      | 5   |                               | 220   | 38    | 55    | -     | -     | 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=10^3 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   | 55    | 65    | -     | -     | 83   |                  |
|      | 16  |                               | 500   | 200   | 200   | -     | -     | 80   |                  |
| [8]  | 17  | Freon R113                    | 310   | 33    | 182   | -     | -     | 80   | P=10^3 Pa T=320 K |
| [9,10]| 18  | Ethanol                       | 90    | 50    | 110   | -     | -     | 90   | P=10^3 Pa T=351.5 K |
|      | 19  |                               | 200   | 50    | 110   | -     | -     | 90   | P=10^3 Pa T=351.5 K |
|      | 20  | 60% glycerin water solution   | 200   | 50    | 110   | -     | -     | 90   | P=10^3 Pa T=381 K |
|      | 21  |                               | 90    | 50    | 110   | -     | -     | 90   | P=10^3 Pa T=381 K |
| authors | 22  | Distilled water               | 300   | 5     | 95    | -     | -     | 90   | P=10^3 Pa T=373 K |
|      | 23  |                               | 300   | 5     | 75    | -     | -     | 90   | P=10^3 Pa T=373 K |
| [11] | 24  | Distilled water               | 400   | 300   | 300   | -     | -     | 90   | P=10^3 Pa T=373 K |
|      | 25  |                               | 300   | 300   | 300   | -     | -     | 90   | P=10^3 Pa T=373 K |
|      | 26  |                               | 200   | 300   | 300   | -     | -     | 90   | P=10^3 Pa T=373 K |
|      | 27  | Novec 649                     | 400   | 300   | 300   | -     | -     | 90   | P=10^3 Pa T=322 K |
|      | 28  |                               | 200   | 300   | 300   | -     | -     | 90   | P=10^3 Pa T=300 K |
| [12] | 29  | Freon R123                    | 1038  | 450   | 1050  | -     | -     | 90   | P=10^3 Pa T=381 K |
| authors | 30  | 60% glycerin water solution   | 200   | 50    | 110   | -     | -     | 90   | P=10^3 Pa T=381 K |

The generalization was performed using the polynomial regression method:

$$\frac{a}{a_0} = f_2 \left(K_q, \frac{(0/90)}{\theta}, (h/l_0), (\Delta/l_0), (\delta/l_0), (u/l_0), (s/l_0) \right)$$

At generalization more than 500 experimental points 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) is received:

$$\frac{a}{a_0} = 3,2 \cdot K_q^{0.2} \left(\frac{(0/90)}{\theta} \right)^{-1.64} \left(\frac{h/l_0}{0.35} \right) \left(\frac{(\Delta/l_0)_{0.08}}{\delta/l_0} \right) \left(\frac{u/l_0}{0.47} \right) \left(\frac{s/l_0}{0.47} \right)$$

Equation (2) describes experimental points with a 30% deviation at a confidence probability of 0.85. Equation (2) is fair in the range q=2400-3.5106 W/m², K_q=8.7-22030, θ/90=0.77-1, h/l_0=0.09-0.71 (relative height of micropins. Fig.2), Δ/l_0=0.002-0.3 (relative cross distance between micropin
element. Fig.2), δ/l _e_ =0.042-0.42 (relative cross thickness of the micro-rib profile. Fig.2), u/l _e_ =0.009-0.28 (relative longitudinal distance between micropin element. Fig.2), s/l _e_ =0.02-0.79 (relative longitudinal thickness of the micro-rib profile. Fig.2), Pr=1.75-7.35, F/F _p_ =2.23-4.8 (increase in heat exchange area).

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

| Ref. | №  | liquid                       | 3-D geometrical parameters | Regime parameters |
|------|-----|------------------------------|---------------------------|------------------|
| [4,7] | 1   | Distilled water              | h, μm 180, Δ, μm 170, δ, μm 140, u, μm 178, s, μm 90 | P=10^5 Pa, T=373 K |
|      | 2   |                              | 340, 70, 170, 140, 178, 75 |                  |
| [2]  | 3   | Distilled water              | h, μm 205, Δ, μm 145, δ, μm 120, u, μm 200, s, μm 70 | P=10^5 Pa, T=373 K |
|      | 4   |                              | 570, 210, 140, 180, 140, 80 |                  |
|      | 5   |                              | 480, 135, 105, 120, 200, 70 |                  |
|      | 6   |                              | 400, 200, 200, 300, 300, 80 |                  |
|      | 7   |                              | 400, 200, 200, 300, 300, 83 |                  |
| authors | 8   | Distilled water              | h, μm 120, Δ, μm 200, δ, μm 250, u, μm 70, s, μm 85 | P=10^5 Pa, T=373 K |
|      | 9   |                              | 350, 5, 320, 225, 75, 90 |                  |
|      | 10  |                              | 320, 5, 320, 225, 75, 90 |                  |
|      | 11  |                              | 300, 80, 120, 175, 125, 90 |                  |
|      | 12  |                              | 220, 80, 220, 250, 50, 85 |                  |
|      | 13  |                              | 375, 5, 300, 250, 50, 90 |                  |
|      | 14  |                              | 500, 350, 150, 275, 50, 85 |                  |
| [9,10]| 15  | Ethanol                      | h, μm 180, Δ, μm 170, δ, μm 140, u, μm 178, s, μm 90 | P=10^5 Pa, T=351.5 K |
|      | 16  |                              | 340, 70, 170, 140, 178, 75 |                  |
|      | 17  | 60% glycerin water solution  | h, μm 180, Δ, μm 170, δ, μm 140, u, μm 178, s, μm 90 | P=10^5 Pa, T=381 K |
|      | 18  |                              | 340, 70, 170, 140, 178, 75 |                  |
| [13] | 19  | Freon R11                    | h, μm 250, Δ, μm 365, δ, μm 250, u, μm 460, s, μm 90 | P=10^5 Pa, T=297 K |
|      | 20  | Freon R123                   | 540, 250, 365, 250, 460, 90 | P=0.9-10^5 Pa, T=300 K |
|      | 21  | Freon R134a                  | 540, 250, 365, 250, 460, 90 | P=3-10^5 Pa, T=277.5 K |
| [12] | 22  | Freon R123                   | 750, 320, 280, 10, 830, 90 | P=0.9-10^5 Pa, T=300 K |

### 3. General correlations for critical heat flux

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:

\[ q_{\text{crit}}/q_{\text{crit0}} = f_1 (\theta /90, l/h, l, \Delta /l, \delta /l, Pr) \]
\[ q_{\text{crit}}/q_{\text{crit0}} = f_2 (\theta /90, l/h, l, \Delta /l, \delta /l, u /s, Pr) \]

where \( q_{\text{crit}} \) is the critical heat flux when liquid is pool boiling on a microstructured surface, \( q_{\text{crit0}} \) 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 \( q_{\text{crit0}} \). They can be estimated using the dependence for Kutateladze critical heat flux: \( q_{\text{crit0}} = 0.13 \sqrt{\rho c} \sqrt{g \sigma (\rho - \rho^*)} \) 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 has been obtained for calculation of 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):
\[ q_{\text{crit}} / q_{\text{crit0}} = 14.4 \left( \theta / 90 \right)^{1.36} \left( h / l_0 \right)^{0.33} \left( \Delta / l_0 \right)^{0.26} \left( \delta / l_0 \right)^{0.43} \text{Pr}^{2/3} \]  

Equation (3) describes experimental points with a 35% deviation at a confidence probability of 0.8. Equation (3) is fair in the range \( \theta / 90 = 0.72 \pm 1 \), \( h / l_0 = 0.09 \pm 1.45 \), \( \Delta / l_0 = 0.002 \pm 1.29 \), \( \delta / l_0 = 0.01 \pm 1 \), \( \text{Pr} = 1.75 \pm 35.7 \), \( F / F_0 = 1.66 \pm 9.75 \). In the generalizing process the dependence for calculation of critical heat flux at pool boiling of water, ethanol, 60% of glycerin water solution on 3-D reliefsurfaces (micro-pin structures) was obtained (Fig.6):

\[ q_{\text{crit}} / q_{\text{crit0}} = 11.2 \left( \theta / 90 \right)^{2.26} \left( h / l_0 \right)^{0.35} \left( \Delta / l_0 \right)^{0.19} \left( \delta / l_0 \right)^{0.245} \left( u / l_0 \right)^{0.4} \left( s / l_0 \right)^{0.82} \text{Pr}^{2/3} \]  

Equation (4) describes experimental points with a \( \pm 30\% \) deviation at a confidence probability of 1.0. Equation (4) is valid in the range \( \theta / 90 = 0.77 \pm 1 \), \( h / l_0 = 0.09 \pm 0.71 \), \( \Delta / l_0 = 0.002 \pm 0.3 \), \( \delta / l_0 = 0.042 \pm 0.42 \), \( u / l_0 = 0.009 \pm 0.28 \), \( s / l_0 = 0.02 \pm 0.79 \), \( \text{Pr} = 1.75 \pm 7.35 \), \( F / F_0 = 2.23 \pm 4.8 \)

Figure 5. Pool boiling critical heat flux on surfaces with 2-D relief (micro ribs). Indication of points shown in Table 1.

\[ \bar{q} = q_{\text{crit}} / q_{\text{crit0}} \]

\[ B = 14.4 \left( \theta / 90 \right)^{1.36} \left( h / l_0 \right)^{0.33} \left( \Delta / l_0 \right)^{0.26} \left( \delta / l_0 \right)^{0.47} \text{Pr}^{2/3} \]

Figure 6. Pool boiling critical heat flux on surfaces with 3-D relief (micropins). Indication of points shown in Table 2.

\[ \bar{q} = q_{\text{crit}} / q_{\text{crit0}} \]

\[ B = 11.2 \left( \theta / 90 \right)^{2.26} \left( h / l_0 \right)^{0.35} \left( \Delta / l_0 \right)^{0.19} \left( \delta / l_0 \right)^{0.245} \left( u / l_0 \right)^{0.4} \left( s / l_0 \right)^{0.82} \text{Pr}^{2/3} \]

4. Possibilities of using an artificial neural network

A method of generalizing experimental data by using an artificial neural network has found wide application. A neural network was developed to generalize experimental data on the boiling of various liquids on microstructured two-dimensional surfaces. The following physical and geometric characteristics were used as input parameters: \( K_n \), \( \theta / 90 \), \( h / l_0 \), \( \Delta / l_0 \), \( \delta / l_0 \) for 565 experimental points. An artificial neural network model is implemented in the MatLab software package. The log-sigmoid function is used as the activation function.

To create a neural network, it is necessary to divide the experimental data into a training and test sample, with volumes of 80% and 20% of all experimental points, respectively. The neural network trains the model from a training sample, and then compares the values with the test sample. The "reverse propagation of Bayesian regularization" model was chosen as the learning model. This training model generalizes a small sample of data more accurately than standard training models, but requires more computing and time resources. The standard error was selected as the quality criterion for the training model. The best value was achieved on 571 training epochs.

The dependence of the values obtained as a result of the neural network operation \( \alpha / \alpha_0 \) on the experimental data \( \alpha / \alpha_0 \) showed that the correlation coefficient is \( R=0.92 \) for the training sample,
The proposed criteria equations allow predicting heat transfer coefficients with an error of 30%, and critical heat flux with an error of 30-35%.

In order to improve the accuracy of forecasting, the possibility of using an artificial neural network model for generalizing heat transfer coefficients is shown. Forecasting using an artificial neural network model allows us to determine the heat transfer coefficients with an error of ±20%.

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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