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Recommendations for the heat transfer assessment for natural convection boiling of microfinned surfaces

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Abstract. The paper presents the generalized correlations for the heat transfer coefficients for natural convection boiling of microfinned surfaces based on the experimental measurements.

Introduction
The microfinned surface elements on the flat horizontal plate produced by the deforming cutting method is one of the most effective ways of heat transfer intensification for natural convection boiling [1, 2]. The deforming cutting method is a simple and no waste technology. It was revealed that for the two- and the three-dimensional microstructured surfaces for the element height of 90-750 µm, element thickness of 25-320 µm, and longitudinal gap width of 40-500 µm the heat transfer coefficients is growing up to a factor of 9, and the critical heat flux magnitudes are rising up to a factor of 4.1. The maximal values of the heat transfer intensification were observed for the three-dimensional surface elements. The results of studying the heat transfer enhancement for these surfaces for the boiling of the distilled water, 98% ethanol, and 60% water solution of the glycerin are presented in [3, 4].

1. Research results
In the studied range of the heat flux \( q = 4 \cdot 10^3 \div 2 \cdot 10^6 \) w/m\(^2\) were observed the convective, surface, and bubble boiling regimes. The experiments were carried out for the boiling of a saturated fluid. Before the running the experiments the degasification of the working fluid and the artificial grinding of the studied surfaces was made. During the process of the grinding for the studied elements, the working fluid was boiled for several times. The experimental for each type of the surface elements were duplicated and the duration of the experimental investigation for one type of the surface element was 2-3 days.

The generalization of results of the boiling of the distilled water [1-4] for the microfinned surfaces (Fig. 1 and Table 1) was made according to the model \( \frac{Nu}{Nu_0} = f(K_g, K_r) \), where \( K_g = q \cdot l_0/(r \cdot \rho' \cdot v') \) is a dimensionless criterion, which constitutes as a scale for the velocity of the vapor phase. This quantity was used as a scale for the velocity of the fluid particles due to the vaporization processes. The generalization of the experimental results by the dimensionless factors like \( h/\Delta, F/F_0 \) has not been successful [2-4]. Therefore, the generalization was made by using the criterion \( K_v = (h/l_0) \Delta/l_0 \delta/(s-u)/l_0 \), where as a linear scale was used the Laplace constant \( l_0 = \sqrt{\epsilon/(g \cdot (p' - \rho'))} \) proportional to the bubble diameter. The use of the capillarity constant as a linear
scale allows to define the type of type of the structure: cell or the capillary [5]. The use of the radius of a vapor bubble as a characteristic dimension \( R_s = 2 \cdot \sigma \cdot T_f / (r \cdot \rho \cdot \Delta T) \) was recommended by Jagov [6]. This was not changed the type of the dependence, however allowed to obtain the acceptable generalization.

Table 1. Parameters of studied boiling surfaces made by the deforming cutting method

| №  | Material       | h·10⁻⁶, m | w·10⁻³, m | \( \delta \cdot 10^{-6}, \) m | \( \phi, ^{\circ} \) | u·10⁻⁹, m | s·10⁻³, m | m·10⁻⁶, m | z·10⁻⁶, m | n·10⁻⁶, m | k·10⁻⁶, m |
|----|----------------|-----------|-----------|-----------------------------|-------------|-----------|-----------|-----------|-----------|-----------|-----------|
| 1-2 | 12X18H9T       | Smooth plate |           |                             |             |           |           |           |           |           |           |
| 5   | BT1-00         | 95        | 40        | 25                          | 3           | 0         | 0         | 0         | 0         | 0         | 0         | 15        |
| 6   | BT1-00         | 310       | 160       | 97                          | 3           | 0         | 0         | 0         | 0         | 0         | 0         | 73        |
| 7   | BT1-00         | 200       | 120       | 74                          | 3           | 0         | 0         | 0         | 0         | 0         | 0         | 46        |
| 8   | BT1-00         | 230       | 90        | 55                          | 3           | 0         | 0         | 0         | 0         | 0         | 0         | 35        |
| 9   | BT1-00         | 220       | 60        | 38                          | 3           | 0         | 0         | 0         | 0         | 0         | 0         | 22        |
| 10  | AISI1020       | 420       | 350       | 170                         | 0           | 140       | 318       | 0         | 0         | 0         | 0         | 180       |
| 11  | 12X18H9T       | 150       | 160       | 110                         | 0           | 0         | 0         | 0         | 0         | 0         | 0         | 50        |
| 12  | 12X18H9T       | 90        | 160       | 110                         | 0           | 0         | 0         | 0         | 0         | 0         | 0         | 50        |
| 13  | BT1-00         | 200       | 200       | 160                         | 30          | 0         | 0         | 0         | 0         | 0         | 0         | 40        |
| 14  | 12X18H9T       | 200       | 160       | 110                         | 0           | 0         | 0         | 0         | 0         | 0         | 0         | 50        |
| 15  | AISI1020       | 340       | 240       | 170                         | 15          | 140       | 318       | 0         | 0         | 0         | 0         | 70        |
| 16  | 12X18H9T       | 200       | 160       | 110                         | 0           | 0         | 0         | 0         | 0         | 0         | 0         | 205       |
| 17  | AISI1020       | 420       | 350       | 145                         | 20          | 120       | 320       | 0         | 0         | 0         | 0         | 205       |
| 18  | 316L           | 300       | 70        | 26                          | 7           | 0         | 0         | 0         | 0         | 0         | 0         | 10        |
| 19  | BT1-00         | 550       | 250       | 150                         | 10          | 0         | 0         | 0         | 0         | 0         | 0         | 100       |
| 20  | AISI1020       | 570       | 350       | 140                         | 10          | 180       | 320       | 0         | 0         | 0         | 0         | 205       |
| 21  | AISI1020       | 480       | 240       | 105                         | 20          | 120       | 320       | 50        | 100       | 50        | 135       |
| 22  | BT1-00         | 300       | 250       | 140                         | 0           | 0         | 0         | 0         | 0         | 0         | 0         | 110       |
| 23  | BT1-00         | 360       | 200       | 115                         | 25          | 0         | 0         | 0         | 0         | 0         | 0         | 85        |
| 24  | BT1-00         | 360       | 200       | 115                         | 25          | 0         | 0         | 15        | 95        | 30        | 85        |
| 25  | BT1-00         | 200       | 100       | 65                          | 7           | 0         | 0         | 0         | 0         | 0         | 0         | 10        |
| 26  | 316L           | 500       | 400       | 200                         | 10          | 0         | 0         | 0         | 0         | 0         | 0         | 200       |
| 27  | 316L           | 400       | 400       | 200                         | 10          | 0         | 0         | 0         | 0         | 0         | 0         | 100       |
| 28  | 316L           | 400       | 400       | 200                         | 10          | 300       | 600       | 0         | 0         | 0         | 0         | 100       |
| 29  | 316L           | 400       | 400       | 200                         | 7           | 300       | 600       | 20        | 50        | 10        | 100       |
| 30  | BT1-00         | 500       | 400       | 200                         | 10          | 0         | 0         | 0         | 0         | 0         | 0         | 200       |
| 31  | 316L           | 450       | 320       | 200                         | 5           | 70        | 320       | 0         | 0         | 0         | 0         | 250       |
| 32  | 316L           | 300       | 100       | 95                          | 0           | 0         | 0         | 0         | 0         | 0         | 0         | 5         |
| 33  | 316L           | 350       | 80        | 75                          | 0           | 0         | 0         | 0         | 0         | 0         | 0         | 5         |
| 34  | 316L           | 350       | 325       | 320                         | 0           | 75        | 300       | 0         | 0         | 0         | 0         | 5         |
| 35  | 316L           | 320       | 225       | 220                         | 0           | 75        | 300       | 0         | 0         | 0         | 0         | 5         |
| 36  | 316L           | 800       | 450       | 200                         | 5           | 0         | 0         | 0         | 0         | 0         | 0         | 250       |
| 37  | 316L           | 300       | 200       | 120                         | 0           | 125       | 300       | 0         | 0         | 0         | 0         | 5         |
| 38  | 316L           | 220       | 300       | 220                         | 5           | 50        | 300       | 0         | 0         | 0         | 0         | 50        |
| 39  | 316L           | 375       | 300       | 300                         | 0           | 50        | 300       | 0         | 0         | 0         | 0         | 105       |
| 40  | 316L           | 500       | 500       | 150                         | 5           | 50        | 325       | 150       | 50        | 10        | 200       |
Figure 1. Shapes of the microfinned surfaces.

- a – 5-9, 11, 12, 14, 16, 19, 22, 23, 26, 30, 32, 33, 36;
- b - 10, 15, 20, 31, 34, 35, 37;
- c - 13, 24, 25, 27;
- d – 17, 38, 39;
- e – 18;
- f – 21, 40;
- g - 28, 29

During the analysis of the experimental results for the average heat transfer coefficients for the natural convection boiling (Figure 2) on the two-dimensional (2D) microfinned surfaces were observed the influence of the $Kq$ criterion on the relative heat transfer coefficient $\frac{Nu}{Nu_0} \sim K_q^{-n}$, where the power of the last term is varying in the range $n=0.55-0.8$.

Figure 2. Experimental results for boiling of a distilled water for boiling on microfinned surfaces with two-dimensional fins. Notation is shown in Table 1. Line – Micheev equation (smooth surface).

During the analysis was assumed the average value of the $n=0.6$. It is deferss little from the adopted values [5,7] of the influence of a heat flux on the heat transfer coefficient for the boiling for the dependence $Nu \sim Kq^{0.7}$. This effect was observed in [5] for the boiling on the microporous surface. The difference of the power of the $Kq$ occurs due to the three different boiling regimes for the developed boiling heating. The first regime is characterized by the dramatic increase of the heat
transfer coefficient with the increase of the vaporization velocity \( K_q \). The second regime the rate of the heat flux is equal to the smooth surface \( \Delta \approx 0.7 \). With the further increase of the heat flux (\( K_q \)), for the third regime is observed the effect when the liquid is pushing aside from the microfinned surfaces. This effect is analogous to the film boiling. The heat transfer coefficient for the third regime is equal or becomes less than the magnitudes for the heat transfer coefficient of boiling for the smooth surface.

Generally, for all of three regimes explained in [5] the power \( n \) of the \( K_q \) could be different for the boiling on the microfinned and microporous surfaces. For instance, this effect could be observed for the samples №22 and №33 (Fig. 1).

The change of the wall roughness is leading to the considerable increase of the heat transfer coefficient, because the amount of evaporations centers is defined by the wall roughness [5, 7]. As the efficient evaporation centers could be used the dimples and the grooves on the surface where the liquid and the gas could be hold. This assumption allows to evaluate the influence of the dimensionless geometrical parameters of the fins on the relative heat transfer coefficient, including the relative transverse gap of the two-dimensional micro-fins \( \Delta/l_0 \). It should me mentioned that the value of the transversal gap was ranged for \( \Delta=(1-350) \times 10^{-6} \) m and was considerably lover then the value of the capillarity constant \( l_0=2.5 \times 10^{-3} \) m. Due to this fact, the capillarity effect was observed on the prospected samples. It may be noted, that for the large values of the two-dimensional structures (\( \Delta>l_0 \)) the gaps are filled by the fluid and do not participate in the boiling as the active evaporation centers. The studied values of the ratio \( \Delta/l_0 \) allows us to quantify the microfinned channels as the capillary type [8].

The experimental values of the average heat transfer coefficients for the natural convection boiling of distilled water on the two-dimensional microfinned surfaces at the atmospheric pressure could be generalized by the equation (1):

\[
\text{Nu} = 2.57 \cdot \text{Nu}_0 \cdot K_q^{-0.1} \left( \frac{\Delta}{l_0} \right)^{-0.23} \left( \frac{h}{l_0} \right)^{0.23} = 2.57 \cdot \text{Nu}_0 \cdot K_q^{-0.1} \left( \frac{h}{\Delta} \right)^{-0.23} \tag{1}
\]

The deviation of the experimental data from the equation above do not exceed \( \pm 30 \% \) with the confidence probability of 95\% (Fig. 3).

![Figure 3. Dependence of the relative heat transfer rate from the criterion \( K_q \) for the boiling of the distilled water on the surfaces with the 2D fines. Notation is shown in Table 1.](image)

The geometrical dimensionless parameters of the two-dimensional microfinned surfaces №13, №18, №23, №24-25, №27, №32-33 (Table 1) are: \( K_q=100 \pm 2 \times 10^4 \); the relative height of the fin \( h/l_0=(3.8\pm13.98) \times 10^2 \); the relative transversal gap \( \Delta/l_0=(0.2\pm7.99) \times 10^2 \); the relative gap between fins \( k/l_0=(0.199\pm3.995) \times 10^2 \); the relative thickness of the fins \( \delta/l_0=(1.04\pm7.99) \times 10^2 \).
The experimental data for the average heat transfer coefficients for natural convection boiling of the distilled water for the two-dimensional microfinned surfaces with banded elements (2D+) (Figure 4) for the atmospheric pressure could be expressed by the generalization equation (Figure 5):

\[ Nu = 2.1 \cdot Nu_0 \cdot K_q^{-0.214} (h/l_0)^{1.1} (\Delta l_0)^{0.13} \]  

(2)

The deviation of the experimental data from Equation 2 do not exceed ±30% with the confidence probability of 0.95 (Fig. 3). The experimental parameters were varied: \( K_q = 170 \div 1.5 \cdot 10^4 \), the dimensionless geometrical parameters for the samples №5-9, №11, №12, №14, №16, №30, №32-33, №36 (Table 1) were as following: the relative height of the fin \( h/l_0 = (3.6 \div 22.77) \cdot 10^{-2} \), the relative transversal gap \( \Delta/l_0 = (0.2 \div 7.99) \cdot 10^{-2} \), the relative thickness of the fins \( \delta/l_0 = (1 \div 7.99) \cdot 10^{-2} \). It should be mentioned, that the excluded samples №32 and №33 could be acceptable expressed by the Equation 1, however have the different power of the \( K_q \), and, therefore, are not shown in Figure 3.

![Figure 4](image1.png)

**Figure 4.** Experimental results for heat transfer rate for the boiling of distilled water on the surfaces with two-dimensional banded fins (2D+). Notation is shown in Table 1. Line Micheev equation.

The experimental data for the average heat transfer coefficients for natural convection boiling of distilled water on the microfinned surfaces with the three-dimensional tubular elements (3D) for the atmospheric pressure could be generalized by the equation (Figure 7):

\[ Nu = 0.9 \cdot Nu_0 \cdot K_q^{-0.3} (h/l_0)^{0.48} (\delta/l_0)^{-0.7} (s-a)/l_0)^{-0.7} (\Delta l_0)^{0.1} (u/l_0)^{-0.4} \]  

(3)

The deviation of the experimental data from Equation 3 do not exceeds ±45% with the confidence probability of 0.95. The \( K_q \) criterion was ranged in \( K_q = 30 \div 2 \cdot 10^4 \), the relative height of the fin \( h/l_0 = (8.79 \div 22.77) \cdot 10^{-2} \), the relative transversal gap \( \Delta/l_0 = (3.2 \div 13.98) \cdot 10^{-2} \), and the relative axial gap \( (s-u)/l_0 = (5.59 \div 11.98) \cdot 10^{-2} \), the relative thickness of fins \( \delta/l_0 = (4.19 \div 11.95) \cdot 10^{-2} \).
Figure 6. Experimental results for heat transfer rate for boiling of distilled water on the surfaces with three-dimensional tubular fins (3D). Notation is shown in Table 1. Line – Micheev equation.

Figure 7. Dependence of the relative heat transfer rate for boiling of distilled water on the surfaces with three-dimensional tubular fins (3D) versus criterion $K_q$. Notation is shown in Table 1.

Conclusion
In the paper are given the recommendations for increasing the heat transfer for boiling on microfinned surfaces and shown the general correlations for heat transfer coefficient for natural convection boiling on surfaces with two- and three-dimensional microfinned surfaces from the operational $K_q$ and dimensionless geometrical criteria $K_Г$.

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