Pool boiling on surfaces with mini-fins and micro-cavities

Robert Pastuszko, Magdalena Piasecka
Department of Mechanics, Kielce University of Technology, Al. 1000-lecia P.P. 7, 25-314 Kielce, Poland
tmprp@tu.kielce.pl

Abstract. The experimental studies presented here focused on pool boiling heat transfer on mini-fin arrays, mini-fins with perforated covering and surfaces with micro-cavities. The experiments were carried out for water and fluorinert FC-72 at atmospheric pressure. Mini-fins of 0.5 and 1 mm in height were uniformly spaced on the base surface. The copper foil with holes of 0.1 mm in diameter (pitch 0.2/0.4 mm), sintered with the fin tips, formed a system of connected perpendicular and horizontal tunnels. The micro-cavities were obtained through spark erosion. The maximal depth of the craters of these cavities was 15 – 30 µm and depended on the parameters of the branding-pen settings. At medium and small heat fluxes, structures with mini-fins showed the best boiling heat transfer performance both for water and FC-72. At medium and high heat fluxes (above 70 kW/m² for water and 25 kW/m² for FC-72), surfaces with mini-fins without porous covering and micro-cavities produced the highest heat transfer coefficients. The surfaces obtained with spark erosion require a proper selection of geometrical parameters for particular liquids – smaller diameters of cavities are suitable for liquids with lower surface tension (FC-72).

Nomenclature

\( d \) – diameter, mm
\( h \) – height (depth), mm
MF – mini-fin
MFP – mini-fin with porous covering
\( p \) – pitch, mm
\( q \) – heat flux, kW/m²
\( s \) – width of space between mini-fins, mm
SE – spark erosion
\( w \) – width, mm

Greek symbols
\( \alpha \) – heat transfer coefficient, kW/m²K
\( \delta \) – thickness, mm

Subscripts
\( p \) – pore
\( tun \) – tunnel

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1. Introduction

The growing demand for miniaturization entails seeking ever better cooling technologies that will prevent mechanical and electronic components from temperature overshoot. The limiting of operating temperatures has a significant effect on both durability of the device and safety of its users. The highest heat flux at a small temperature difference between the heating surface and the working fluid and a small heat removal surface can be obtained through a phase change accompanying boiling and condensation processes. Pool boiling from specially prepared surfaces helps obtain an additional increase in the heat transfer coefficient, which, in relation to the heat exchanger, translates to higher values of the overall heat transfer coefficient.

A brief review in [1] presents earlier studies on the enhancement of boiling heat transfer from electronic components by the use of surface microstructures. The authors suggested that most of these surfaces were effective in decreasing the wall superheating and enhancing the nucleate boiling heat transfer. In [2] the authors considered many techniques (from 1st to 4th generation) developed to enhance convective heat transfer. Compound enhancement, involving simultaneous application of several techniques, is considered 4th generation heat transfer technology. Rainey and You [3] analyzed pool boiling from plain and micro-porous pin fins in saturated FC-72. For the plain fins, the heat transfer enhancement was significant only for fins of up to 5 mm in height. The fins with a microporous layer provided higher heat transfer coefficients over the plain fins. FC-72 pool boiling on square pin fin arrays was studied experimentally by Guglielmini et al. [4]. Their surfaces had 3 or 6 mm long fins, uniformly or non-uniformly spaced on the base surface. They pointed out that the effect of fin thinning out on the heat transfer coefficient was negligible at low heat fluxes, but became evident at high heat fluxes. For uniformly spaced fins, the heat transfer rate increased with a decrease in fin width and spacing. Pastuszko [5] presented complex experimental investigations of boiling heat transfer on structured surfaces covered with perforated foil. Experimental data were discussed for two kinds of enhanced surfaces formed by joined horizontal and vertical tunnels: tunnel structures (TS) and narrow tunnel structures (NTS). The experiments were carried out with water, ethanol and R-123 at atmospheric pressure. The TS and NTS surfaces were manufactured from 0.05 mm thick perforated copper foil sintered with the mini-fins. The mini-fins were formed on the vertical side of the 5 mm high rectangular fins and horizontal inter-fin surface. The investigations showed that for NTS with the narrowest tunnels (0.6 mm), the pores with the smallest diameter were most advantageous. Pastuszko [6] conducted experimental investigations of pool boiling heat transfer on mini-fin arrays covered with porous structure. Plain mini-fins and mini-fins with a copper wire net (mesh structure) were investigated. The wire mesh with aperture of 0.32, 0.4 and 0.5 mm, sintered with the fin tips, formed a system of connected perpendicular horizontal tunnels. Tunnel width was 0.6 – 1.0 – 1.5 mm and its depth (i.e. mini-fin height) was 0.5 or 1.0 mm. Structures with mini-fins of 1 mm in height showed the best boiling heat transfer performance for water at all used heat fluxes and at the medium and highest heat fluxes for FC-72. For FC-72 at high heat fluxes (above 30 kW/m² for shorter micro-fins and 50 kW/m² for higher micro-fins), surfaces with plain micro-fins showed the highest heat transfer coefficients.

There are numerous passive and active methods for boiling heat transfer enhancement – this article focuses on the comparison of boiling efficiency of extended surfaces with and without a perforated covering and the surface with micro-cavities.

2. Experimental stand

Figure 1 presents the diagram of the measurement stand for determining boiling curves. Its main module is constructed in a similar way to the modules described in [5,6].
The heat flux was determined based on the temperature gradient in the upper part of the heating cylinder, with the assumed one-dimensional heat conduction.

Temperature superheat, heat flux and boiling heat transfer coefficient for MF and MFP surfaces were related to the level of the mini-fins base.

The estimated uncertainties were as follows:
- low heat flux (2 kW/m²): heat flux ±35%, heat transfer coefficient ±40%,
- high heat flux (550 kW/m²): heat flux ±1.2%, heat transfer coefficient ±2.2%.

3. Investigated structures
Square copper samples with the side of 26.5 mm and three types of structural surfaces were used (Figures 2, 3):
- the surface with micro cavities, unevenly distributed and obtained by spark erosion (denoted as SE),
- copper 0.5 and 1.0 mm high mini-fins spaced with pitches of 3.5 and 2.0 mm (denoted as MF),
- surfaces manufactured by sintering mini-fin tips with a copper perforated foil – 112 mini-fins arranged in a system of tunnels intersecting at right angles (denoted as MFP).

For MF and MFP, the tunnel width in one direction was constant (1.5 mm at the pitch of 3.5 mm); in the perpendicular direction, the width of 0.6 and 1.5 mm was used at the pitch of 2 mm (Figure 3).

The SE surfaces with micro-cavities were obtained by spark erosion, using electric-etcher and branding-pen (arcograph). The height and depth of the craters of these cavities depend on the parameters of branding-pen settings. Two surfaces for the study were obtained by spark erosion caused by different electrodes’ polarity which determines the occurrence of decremental or incremental treatment. Figure 2 shows the photos (a, d), cross-sections of the whole area (b, e) and a fragment of the cross-section (c, f) of the area employed in the study. Images were obtained by Nikon Eclipse MA 200 microscope coupled with Nikon DS-Fi1 digital camera and NIKON NIS 3 digital analyzer (resolution of 0.34 μm/pixel). The SE-B surface has more shallow craters, almost 15 μm deep, while the craters in the second surface (SE-C) do not exceed the depth of 30 μm.

Denotation and parameters of the investigated surfaces are shown in Table 1.
Table 1. Denotation and dimension of the analyzed structures.

| sample code       | $\delta$ | $s$  | $h$  | $w_{sn}$ | $p_{sn}$ | $d_p$ | $p_p$ |
|-------------------|----------|------|------|----------|----------|-------|-------|
| MF-0.5-0.6        | 2        | 1.5  | 0.5  | 0.6      | 2.00     | -     | -     |
| MFP-0.5-0.6-0.1   | 2        | 1.5  | 0.5  | 0.6      | 2.00     | 0.1   | 0.2/0.4 |
| MF-1.0-1.5        | 2        | 1.5  | 1.0  | 1.5      | 2.00     | -     | -     |
| MFP-1.0-1.5-0.1   | 2        | 1.5  | 1.0  | 1.5      | 2.00     | 0.1   | 0.2/0.4 |
| SE-B              | -        | -    | max. 0.015 | -        | -        | max. 0.15 | irregular |
| SE-C              | -        | -    | max.0.030 | -        | -        | max. 0.40 | irregular |

Figure 2. SE-B surfaces (a-c) i SE-C (d-f): photos (a, d), cross-section of the whole area (b, e) and a fragment of cross-section (c, f), magnification of 200 x.
4. Results

4.1. Water boiling

Figure 4 presents boiling curves for water with heat flux increasing and decreasing, for three kinds of surfaces. At small heat fluxes, that is, below 70 kW/m², the highest heat transfer coefficients were obtained from the surface with low mini-fins (0.5 mm), with perforated foil. In comparison with ES-B surface, heat transfer coefficients obtained by this surface were up to three times higher in the heat flux range of 20 – 60 kW/m².

In the range of 70 – 300 kW/m², the highest heat transfer intensification (enhancement) was obtained from the surface without the foil and with higher mini-fins. This can be explained by the fact that at the high heat flux, the foil did not suppress intense vapor generation and release, and wide spaces ensured both the flow of sufficient amount of liquid between the mini-fins and the effective vapor release. The maximum value of the obtained heat transfer coefficient exceeded 20 kW/m²K. At 300 kW/m², the heat transfer coefficient for MF-1.0-1.5 is more than two times higher than \( \alpha \), with the same mini fins but covered with the perforated foil. The surface obtained through the spark erosion (SE-c) is suitable for producing highest heat transfer coefficients at the heat flux of about 500 kW/m².
Figure 4. Boiling heat transfer data for water, $q^+$ - increasing heat flux, $q^-$ - decreasing heat flux.

The effect of SE-B aging after a three-month submersion in distilled water was also presented in the discussed chart (Figure 4). A 5% increase in the heat transfer coefficient can be observed for heat fluxes between 60 – 600 kW/m$^2$, which fits the error range for determining $\alpha$ for small and medium heat fluxes.

4.2. FC-72 Boiling

Figure 5 shows that in the case of FC-72 boiling, the highest heat transfer coefficients at low heat fluxes ($q < 10$ kW/m$^2$) are provided by surfaces with 0.5 mm high mini fins without the covering. At higher heat fluxes ($10 < q < 25$ kW/m$^2$) 1 mm high mini fins with additional perforated foil covering give best results. For heat fluxes higher than 25 kW/m$^2$, spark-eroded surfaces with cavities of smaller dimensions (ES-B) seem most suitable. Small dimensions of the foil pores are not able to ensure the inflow of liquid to spaces between mini-fins, which results in low effectiveness of the surface with foil-covered mini-fins for medium and high heat fluxes.

5. Conclusions

The measurements allow drawing tentative conclusions with reference to the surface geometry that produces the highest increase in heat transfer coefficients for individual boiling liquids:

- The surfaces with the proposed arrangement of pores (holes) or cavities make it possible to provide a large number of nucleation sites. This leads to a substantial intensification of the heat flux transferred from the investigated surfaces.
- A surface with 1.0 mm high mini fins provides the most effective boiling heat transfer intensification for water at heat fluxes higher than 70 kW/m$^2$.
- The use of an additional covering with holes of 0.1 mm in diameter is reasonable for boiling of water at the heat flux lower than 70 kW/m$^2$.
- Spark-eroded surfaces require a proper selection of geometrical parameters for particular liquids – smaller dimensions of cavities are suitable for liquids with lower surface tension (FC-72) at heat fluxes above 25 kW/m$^2$. 
Figure 5. Boiling heat transfer data for FC-72, $q^+$ - increasing heat flux, $q^-$ - decreasing heat flux.

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