Visualization of pool boiling on plain micro-fins and micro-fins with sintered perforated foil

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Abstract. The paper presents visualization investigations of boiling heat transfer over enhanced structures. The experiments were carried out for two kinds of enhanced surfaces: an array of 0.5 mm high micro-fins without covering (plain micro-fins designated as MF) and the surfaces made by sintering micro-fin tops with the copper perforated foil (MF+F). Pool boiling data at atmospheric pressure were obtained for saturated water, ethanol, FC-72 and Novec-649. Visualization studies aimed at identifying nucleation sites and determining the diameter and frequency of departing bubbles. Different pool boiling mechanisms were observed for the plain micro-fins and micro-fins covered with the porous structure.

1. Introduction

For any theoretical description of boiling on surfaces with fins, from the initiation to the developed pool boiling and to the boiling crisis, it is essential that the phenomena that occur within a confined area are identified. Thus, the pool boiling analysis requires identification of the sites of vapor bubble nucleation, growth and departure and liquid supply to the tunnels as well as determination of departing bubble diameters and frequency.

Jaikumar and Kandlikar [1] focused on the effect of the inter-fin channel width on the effectiveness of the fins and on the mechanisms of heat transfer from open micro-channel surfaces. The surfaces had three coating configurations identified as sintered-throughout, sintered-fin-tops, and sintered-channels. The experiment was performed for water at atmospheric pressure for three inter-fin channel widths, 300 μm, 500μm and 762μm. High speed camera images showed that on the sintered-throughout surfaces, bubbles nucleated mostly inside the inter-fin channels. In the case of the sintered-fin-tops surface, the high speed images suggested that the wider channels had a longer flow length and the liquid was unable to feed to the nucleation sites located on the fin tops. On the sintered-channel surface, the jet impingement on the fin tops was found to contribute to liquid feed into the channels.

In [2,3,4], the authors used two types of copper samples: a solid copper interconnected microchannel net and a porous interconnected microchannel net. The samples were tested with water as the working fluid at atmospheric pressure. Visualization, run for both surface types, focused on the bubble growth rate and on the influence of the heating surface area on bubble diameter. The diameter of departing bubble decreased as the liquid subcooling increased at both low and high heat fluxes. However, liquid subcooling was shown to hardly affect the bubble growth regime. Bubble growth was induced by the inertia regime and the heat transfer-controlled regime at low heat fluxes. The growth regime is only governed by the inertia regime at high heat fluxes because the bubble diameter grows nearly linearly with time.

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Cooke and Kandlikar [5] used visualization to evaluate water boiling in channels etched on silicon chips. Analysis of the fast video camera images (1000 – 2000 frames per second) demonstrated that compared with the smoother surfaces of micro-fin faces, increased porosity of etched microchips was the major factor in the increased number of nucleation sites present at the bottom of the microchannels. The bubbles moved towards the tops of the micro-fins where they attached themselves to the surface and experienced a rapid growth in volume. The same authors [6] obtained different pool boiling images from copper surfaces with larger microchannels, 197 $\mu$m and 375 $\mu$m wide and 335 and 400 $\mu$m deep, respectively, at the heat flux of about 200 kW/m$^2$. The nucleation was shown to occur outside the bottom of the channels, and the growing bubble having no contact with the micro-fin face contacted only the edges of the neighboring micro-fins.

Moita et al. in [7,8] presented their findings from the qualitative and quantitative analyses of pool boiling heat transfer from a silicon chip with a microstructure and with HFE 7000, HFE 7100, ethanol and water as the working fluids. The authors aimed at estimating the heat transfer coefficient between the heating surface and the working fluid and at determining, with the use of a fast camera, the diameter of departing bubbles, departure frequency and the number of nucleation sites. The relation between bubble nucleation density and heat transfer coefficient was also discussed.

Nimkar et al. [9] conducted experiments for FC 72 at atmospheric pressure. The paper examined the effect of inter-cavity spacing and convective plumes from a heat source located below the test heater on the nucleate boiling performance, bubble nucleation parameters, active site density, and CHF for a vertically oriented test surface with micro-pyramidal cavities immersed in saturated FC 72. The photography was used to record and quantify the bubble departure frequency, the departure diameter, the active site density, and to observe the effect of interaction between neighboring nucleation sites.

The Kielce University of Technology has long been conducting visualization studies of pool boiling with water, ethanol and FC-72 for structures with subsurface tunnels [10] and for flow boiling of refrigerants in minichannels [11,12]. Research devoted to the surfaces with micro-fins covered with perforated foil was reported in [13,14]. Preliminary images for boiling FC-72 on surfaces with 1 mm high micro-fins covered with foil with pores 0.3 mm in diameter at superheats of 3.6 and 6.1K were reported by Pastuszko and Wójcik [14].

The objectives of the present study were to understand the boiling phenomena for plain micro-fins and micro-fins with porous covering arrays and to verify the assumptions for the theoretical model.

### 2. Test surfaces

Two structural surfaces were used (Fig. 1):

- 0.5 mm high plain micro-fins (designated as MF),
- enhanced surfaces made by sintering micro-fin tops with the copper perforated foil (denoted as MFP).

Both specimens, square in shape and with a side of 26.5 mm, were made from copper and had 104 micro-fins 1.4 x 2.0 mm$^2$ in cross-section and 0.5 mm in height. The MFP surface was fabricated by sintering the base MF surface with the copper perforated foil – forming a tunnel-pore structure. Denotation and the other parameters of the investigated surfaces are shown in Table 1.

### Table 1. MF/MFP surface codes and specifications.

| Sample code | $\delta$ mm | $h$ mm | $w_{1\text{mm}}$ mm | $p_{\text{fin}}$ mm | $d_p$ mm | $p_{p1}/p_{p2}$ mm |
|-------------|-------------|--------|---------------------|-------------------|---------|-------------------|
| MF-0.5-0.6  | 2           | 0.5    | 0.6                 | 2.00              | -       | -                 |
| MFP-0.5-0.6-0.3 | 2   | 0.5    | 0.6                 | 2.00              | 0.3     | 0.4/0.6           |
Figure 1. a) view of MF-0.5-0.6 sample, b) dimension symbols c) view of MFP-0.5-0.6-0.3 sample

3. Experimental setup

The diagram of the measurement stand for external visualization is presented in Figure 2. It is a modified version of the set-up described in [14]. The main stand module consists of a cylindrical vessel (3), filled with working fluid, and placed over the investigated sample (5). The sample is soldered to a 170 mm long cylindrical copper bar (13) 45 mm in diameter.

Figure 2. Schematic diagram of the external visualization system: 1 – digital/ high speed camera; 2 – boiling liquid; 3 – glass vessel; 4 – condenser; 5 – investigated sample; 6 – lights; 7 – data logger; 8 – dry-well calibrator; 9 – PC; 10 – autotransformer; 11 – wattmeter; 12 – insulation; 13 – copper bar with cartridge heater.
The cylinder diameter corresponds to the diagonal of the sample base. A 1000 W electric cartridge heater, 19 mm in diameter and 130 mm in length, is installed into the bar.

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

Visualization images were obtained using two high speed cameras: a digital monochrome PHOT MV-D1024-160-CL (Photonfocus) at a resolution of 1024x1024 pixels and an EX-FH20 (Casio) at a resolution of 480x360 at the recording speed of 210 fps.

Selected thermodynamic parameters of four working fluids used in the experiments, at the saturation temperature, are summarized in Table 2.

| Parameters at $p=101.3$ kPa | Water | Ethanol | FC-72 | Novec-649 |
|-----------------------------|-------|---------|-------|-----------|
| $T_{sat}, ^\circ$C           | 100   | 78.3    | 56.4  | 49.0      |
| $\rho_l$, kg/m$^3$           | 959   | 757     | 1602  | 1513      |
| $\rho_v$, kg/m$^3$           | 0.597 | 1.43    | 13.24 | 13.42     |
| $\mu_l$, Pa s               | $2.8\cdot10^{-4}$ | $4.4\cdot10^{-4}$ | $4.3\cdot10^{-4}$ | $4.5\cdot10^{-4}$ |
| $c_{pl}$, J/kgK             | 4220  | 723     | 1103  | 1103      |
| $i_{lv}$, kJ/kg             | 2251  | 963     | 94.9  | 88.0      |
| $\lambda_l$, W/mK           | 0.68  | 0.169   | 0.055 | 0.059     |
| $\sigma_l$, N/m             | 0.0589 | 0.0177 | 0.0081 | 0.0108 |

4. Boiling heat transfer coefficients

Examples of boiling curves are shown in Figs 3 and 4. Some of the experimental data were derived from [14]. For boiling water, the use of micro-fins covered with perforated foil considerably increases (doubles when compared with plain fins) the value of the maximum heat flux. Heat transfer coefficients for the plain surface and for the surface with smooth micro-fins are similar.

Plain micro-fins have a beneficial effect in pool boiling with FC-72 (Fig. 4). If the surface is aged, the heat transfer coefficient shows a twofold increase in comparison with the micro-fins with the foil covering and more than fourfold increase in comparison with the plain surface.

5. Visualization investigation results

5.1. Water boiling

For boiling water, nucleation of vapor bubbles at a few pores is observed on the surface with micro-fins and porous covering (Fig. 5) at small heat fluxes ($q \approx 27$ kW/m$^2$). An increase in heat flux activates subsequent nucleation sites. The departing bubbles have similar diameters for heat fluxes ranging between 27 and 85 kW/m$^2$. At higher heat fluxes, the bubbles strongly tend to coalesce. The nucleation occurs in the pores over the inter-fin space.
5.2. Ethanol boiling

Figure 6 shows the growth and departure of a single vapor bubble at \( q \approx 27 \) kW/m\(^2\). For ethanol boiling, the bubbles on MFP surfaces coalesce intensively even at small superheats.

5.3. FC-72 boiling

For FC-72 boiling, activation of most pores at small heat fluxes (\( q = 5 \) kW/m\(^2\)) can be observed on the surface with plain micro-fins (Fig. 7). Small diameters of departing bubbles result from low surface tension of the working fluid (about 0.01 N/m). The bubbles grow in the spaces between micro-fins.
5.4. Novec 649 boiling
Low surface tension and low heat of evaporation ensure pool boiling intensity at heat fluxes of 3 kW/m² (Fig. 8). The diameters of departing bubbles are similar to those for FC-72 boiling.

6. Diameters and frequencies of departing bubbles
Macrophotography sequences used in qualitative and quantitative analyses (Fig. 6) were obtained with the use of a PHOT MV-D1024-160-CL fast speed camera at a recording speed of 308 fps. The diameters of departing bubbles and frequencies of departure were determined as an average value of 8 - 10 nucleation sites for the minimum of 30 subsequent vapor bubbles. These parameters were measured at a constant heat flux.

Figures 9 and 10 show the diameters and frequencies as a function of heat flux for two samples, MFP-0.5-0.6-0.3 and MF-0.5-0.6, and different working fluids. For the MFP surface, the bubble diameter and frequency of departure increases with increasing heat flux. For tunnel-pore structures, as the nucleation mechanism is different from that occurring on plain surfaces, the relation used for calculating the departing bubble diameter is based on the buoyancy force and surface tension balance relative to the pore diameter [14]. The departing bubble diameter can be written as:

\[
d_b = \left( \frac{6 \sigma d_p}{g (\rho_f - \rho_v)} \right)^{1/3}
\]  

(1)

The experimental measurements (Fig. 9a) show that the diameters of departing bubbles have values close to those calculated from equation (1) for boiling Novec and FC-72. For water and ethanol, the experimental values of the diameters are higher than those calculated, which may be a result of vapor bubble coalescence at the moment of departure as their diameter exceeds the pore pitch value by several times. On the MF surface (Fig. 10) the frequencies of bubble departure increase slightly with increasing heat flux for Novec and FC-72, and the diameters of departing bubbles take nearly constant values. Above 30 kW/m², the vertical coalescence occurs, i.e., the bubbles coalesce and form the so called vapor columns.
7. Conclusions

The visualization experiments allow drawing the following conclusions:

- In the four boiling liquids investigated on micro-fins with perforated foil, active pores are present only in the foil above the inter-micro-fins spaces.
- In liquids with higher surface tension (water, ethanol), vapor bubbles have a strong tendency to coalesce at the moment of departure.
- The theoretical relation for calculating diameters of bubbles departing from tunnel-pore surfaces holds only for boiling FC-72 and Novec-649.
- In liquids with low surface tension (FC-72, Novec-649), on surfaces with micro-fins covered with perforated foil, the frequency of bubble departure increases quickly with increasing heat flux.
- Constant values of the diameters of departing bubbles and a minor increase in departure frequency at increased heat fluxes can be observed on surfaces with plain micro-fins (MF).
Nomenclature

c
specific heat, J/kgK

d
 diameter, m

f
 frequency, Hz

h
 micro-fin height, m

i
 enthalpy, J/kg

p
 pitch, m

q
 heat flux, W/m²

s
 gap between fins, m

w
 width, m

α
 heat transfer coefficient, kW/m²K

δ
 thickness, m

ΔT
 wall superheat related to the horizontal perforated foil level, K

λ
 thermal conductivity, W/mK

μ
 dynamic viscosity, Pa s

ρ
 density, kg/m³

σ
 surface tension, N/m

Subscripts

d
 departing bubble

l
 liquid

p
 pore

sat
 saturation

tun
 tunnel

v
 vapor

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