Sub-Atmospheric Pressure Pool Boiling of Water on a Screen Laminate-Enhanced Extended Surface

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Abstract

Pool boiling experiments are conducted to investigate the heat transfer performance of screen laminate-enhanced extended surfaces in water at reduced pressures. Screen laminations of varying pore hydraulic diameter and specific surface area fine wire screen are bonded to an extended surface (fin). The fins have a 1 cm² base cross section area, a 5 deg taper with heights of 1 cm and 2/3 cm. Pool temperatures are held at the saturation temperature for water at pressures of 0.2, 0.3, 0.5 and 1.0 atm. Boiling performance of a vertical and horizontal fin orientation is investigated. The 4 layer screen laminate enhanced fin with a 10K superheat sustains base heat fluxes of up to 140 W/cm² at 1.0 atm, and up to 132 W/cm² at 0.2 atm. These extended surfaces outperform screen laminates enhanced plane surface by up to 4 fold. A reduction in saturation pressure reduces the boiling performance for all laminates. Vertically oriented fins outperform horizontal fins.

Keywords

Pool boiling, screen laminate, extended surface, enhanced surface, reduced pressure

Nomenclature

\[ A_b = \text{fin base cross section area} \ [\text{cm}^2] \]
\[ \beta = \text{specific surface area} \ [\text{1/cm}] \]
\[ d = \text{wire filament diameter} \ [\text{mm}] \]
\[ \varepsilon = \text{porosity} \]
\[ D_h = \text{pore Hydraulic Diameter} \ [\mu m] \]
\[ \Delta T_{\text{sat}} = \text{Superheat} (T - T_{\text{sat}}) \ [K] \]
\[ \Delta T_{\text{sat,b}} = \text{Base superheat} \ [K] \]
\[ M = \text{mesh number} \ (\text{wire filaments per mm}) \]
\[ N = \text{number of mesh layers} \]
\[ q''_b = \text{fin base heat flux} \ [W/cm^2] \]
\[ T_{\text{sat}} = \text{Pool saturation temperature} \ [\text{°C}] \]
\[ x = \text{Distance} \ [\text{cm}] \]

1. Introduction

Historically the power dissipated from a microprocessor has increased with its computing performance. Processor power levels have tracked Moore’s Law such that they have doubled every 36 months [1]. Single phase heat transfer is not adequate for the high thermal loads generated. Liquid-vapor phase heat transfer is an attractive alternative that can meet these demands. It has been shown that vapor phase heat transfer, nucleate boiling and liquid phase heat transfer can coexist on an extended surface, thereby increasing the operating superheat beyond that which is normally associated with the burnout condition. [2]

Nucleate pool boiling on enhanced extended surfaces in water at reduced pressures is investigated. Fin surface enhancements will not only increase the heat transfer surface area, but they are important in promoting bubble nucleation. Water is the working fluid in this study due to its high value of latent heat of vaporization and its environmentally safe characteristics. Also the saturation temperatures at reduced pressures are relevant to cooling electronics [3].

Many surface and area enhancements are proven to improve heat transfer. Haley and Westwater investigated the optimum fin shape in order to obtain nucleate boiling over the entire surface of a fin. They conclude that an annular spine achieves this [2]. McGillis and Carey used a pin fin type array to increase boiling performance at reduced pressures in water. They conclude that smaller fin gaps are most effective; there is a fin height such that performance does not increase; and, fins can increase the Critical Heat Flux (CHF) [4]. Fins that have surface enhancements may further improve boiling heat transfer as seen by Nakayama et al. In this case microfins are attached to the tip of an extended surface which increased boiling heat transfer in a dielectric field [5].

Screens were observed to improve boiling heat transfer as early as 1937 when Jacob bonded a screen onto a heated surface [6]. Gerlach and Joshi use screen mesh soldered to the heater surface as an enhancement in pool boiling in flourinert PF5060. They conclude that the unconfined wire mesh improves heat flux and increases CHF [8]. Li and Peterson use screen laminates, similar to those investigated in this paper, on a horizontal surface to increase boiling heat flux [7].

Pal and Joshi report high heat fluxes from rectangular grooved copper surfaces at reduced pressures [9]. Copper metal foam and nanostructured copper surfaces are proven to increase boiling performance as shown by Choon et al and Li et al respectively [10, 11].

This work investigates extended surfaces (fins) enhanced with 4 layer screen laminates in saturated pool boiling experiments. Surface enhanced fins are oriented vertical and horizontal. Pressures range from 0.2 to 1.0 atm. with fin heights of 2/3 cm and 1 cm.

2. Surface Enhancement

A lamination of wire mesh is an effective surface enhancement for nucleate pool boiling. These highly convoluted open cell structures have large specific surface area, and they can be configured to have a wide ranging pore size. Orthogonal plain weave wire mesh properties include the mesh number, M (wire filaments per mm) and wire filament diameter, d (mm). M and d control the porosity, \( \varepsilon \) and specific surface area, \( \beta \ (1/cm) \).
Table 1 Plain weave wire mesh properties

Table 1 shows values of these properties for laminations of 50, 80 and 145 mesh weaves. The Table shows all laminations having porosity, $\varepsilon = 43\%$. The specific surface area ranges from $100 \text{ cm}^{-1}$ to $404 \text{ cm}^{-1}$ while the pore hydraulic diameter $D_h = \frac{4\varepsilon}{\beta}$ ranges from $172\mu\text{m}$ to $43\mu\text{m}$. The goal is to determine the pore size, characterized by the pore hydraulic diameter, that will promote bubble nucleation.

In this work, the screen-laminations are cold rolled to achieve a constant value of the porosity. This makes the pore hydraulic diameter only an inverse function of the specific surface area, $\beta$. Therefore, thermal performance will be dependent on only the hydraulic diameter and number of layers that make up the lamination. Relatively large hydraulic diameters are chosen because larger pore sizes are known to be more effective at bubble nucleation at low pressures [12]. Four layers of mesh have been selected as a starting point for multilayered mesh laminates because Li and Peterson, in their experiments with pool boiling on a horizontal, screen laminate-enhanced surface found multiple layers to be optimal [7].

3. Extended Surface

In this work, test articles consist of a copper fin with a $5^\circ$ taper. The fins are 1 cm and 2/3 cm in height with a width of 3 cm and a 1/3 cm base thickness ($A_b = 1 \text{ cm}^2$). The fin surfaces are coated with a fine filament screen lamination. Figure 1 shows the assembly of the test article. The fin is initially diffusion bonded to a 125 $\mu\text{m}$ thick copper foil base-plate. After this cold rolled copper wire mesh is stacked and diffusion bonded on the fin surfaces. Cold rolling creates flat surfaces that increase bonding area between layers and to the fin surface. Diffusion bonding results in a seamless bond between the copper mesh layers and the fin surface. The copper foil base-plate/enhanced fin assembly is then silver soldered to the tip of a heat flux gauge/heater block (HFG). The heater block supplies the thermal load to the test article while four evenly spaced thermocouples measure the temperature profile of the HFG. A linear curve fit of the temperature profile gives the heat flux and the test article base temperature. The HFG is insulated with potted silicone.

The test articles surfaces are identified by, $xxMyyyyd-N$, where $xxM$ is the mesh number (inch$^{-1}$), $yyyyd$ is the wire filament diameter, $d$ (in thousandths of an inch) and $N$ is the number of layers in the screen laminate surface.

4. Experiment Facility

The test chamber is a 3.5 liter cubical cell with 3 polycarbonate windows for visualization as seen in Fig. 2. The test article is mounted into a side wall of the tank with the fin surfaces in vertical orientation. The tank is also rotated to where
the test article is mounted from the bottom so the fin is horizontal orientation, with the fin structure pointing up. A vacuum controller maintains system pressure while a pressure transducer verifies the pressure within the test cell. Excess water vapor is condensed and returned to the tank by reflux condensers that are attached between the test cell and the vacuum controller. Mounted to the test cell is an immersion heater to maintain the pool at saturation temperature. Four type-T thermocouples measure the pool temperature, and two more measure vapor temperature above the pool. These, in conjunction with pool pressure, are used to determine non-condensable gas content. Non-condensable gas content for the experiments reported here is less than 5.0 PPM. Steinke and Kandlikar show that boiling is not affected for gas content below 5 ppm [13].

Once the test article is mounted into the tank wall, water is boiled at reduced pressure (0.2 atm) for an hour to remove any dissolved air. The pressure is then adjusted for the current experiment and the test article heater is turned on. The auxiliary heater and the test article are left on to increase pool temperature to saturation temperature and to boil-in the screen-laminate surface. After an hour of boiling, data acquisition is initiated.

First dissolved gas content is determined by turning off the heaters, sealing the tank and taking pressure and temperature data for 5 min. Once this is achieved and dissolved gas content is in the correct range (< 5ppm) the boiling experiment starts.

The data acquisition program controls the power levels and acquires data to determine the uncorrected surface heat flux and surface temperature. The power levels are held constant for 5 min before collecting 100 seconds of steady state data and a 4 sec video. The calculated average heat flux and the temperature of the HFG tip are saved to a data file. Raw data from the experiment is also written to a separate data file. The power levels are automatically increased (boiling curve) to a predetermined maximum power level then reduced (cooling curve) until the program is completed.

Videos of boiling are used to assess the effectiveness of the boiling surface. Views of both sides of the fin are seen in vertical oriented experiments and only the front side for horizontal fin orientation. Two views are useful in the determination of the uniformity of boiling between sides. The coalescent frequency of bubbles departing and coalescing as it slides vertically across the surface is also determined.

5. Experimental Protocol

Fabrication of test articles leaves an oxide layer on the surface and is removed chemically before every experiment.

A 200 fps camera with a 72 mm telecentric lens records bubble dynamics. A ring light mounted to the lens illuminates the test article. Figure 3 is a plan view that shows the orientation of the video system in relation to the test article. As seen in the figure a front view and an edge view of the fin structure are achieved by placing a mirror at 45° opposite the fin tip. This results in a projected front view with rear and front edge views transposed.

Figure 3 Imaging system schematic.

Figure 4 Heat flux and superheat
Data Reduction and Uncertainty

Figure 4 shows the placement of the thermocouples in the HFG and a representative temperature distribution. The heat flux and HFG tip temperatures are calculated online using a linear curve fit to the 4 TC’s over the 1 cm distance x (cm). The exploded view of the solder joint and copper foil with corresponding temperature drops are seen at the right in Fig. 4. Corrections to the heat flux and the fin-base temperature, due to the solder joint and the copper foil are calculated offline. The thermal resistance for the solder joint between the HFG tip and the copper foil is estimated to be 1.0 [cm·K/W]. The thermal resistance across the copper foil is estimated to be 1.5 [cm·K/W].

Uncertainties in the results are calculated through a Monte Carlo uncertainty propagation simulation. Table 2 shows that, assuming 2σ uncertainties in location and temperature of ±0.05 mm and ±0.25 K, the 2σ uncertainty of the base heat flux is ±6.9 W/cm² while the base superheat 2σ uncertainty is ±2.1 K for nominal values of $q''_b = 75$ W/cm² and $\Delta T_{sat} = 10$ K. The uncertainty of the dissolved gas for nominal values of 1.0 ppm is ±0.6 ppm as seen in Table 2.

Results

Figure 5 shows images of boiling on the 80M0055d-4 test article in vertical orientation. The figure simultaneously shows a projected side view and end view of the tapered fin. Note the location of the “front” surface. This boiling surface has an 8 K base superheat and a base heat flux of $q''_b = 131$ W/cm². The departing bubbles begin small at the bottom of the surface and coalesce into a large bubble as it travels upward. Coalescence occurs at a frequency of approximately 13 Hz and consequently determination of nucleation site locations is difficult. However, it is observed that the large bubble sweeps over the surface, possibly sweeping up small bubbles that form above it.

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<table>
<thead>
<tr>
<th>Nominal Values</th>
<th>2σ Uncertainty</th>
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<tr>
<td>$\Delta T_{sat,b}$</td>
<td>10 K</td>
</tr>
<tr>
<td>$q''_b$</td>
<td>75 W/cm²</td>
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<tr>
<td>Dissolved Gas</td>
<td>1.0 ppm</td>
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Table 2 Data Uncertainty
The image of boiling on the 80M0055d-4 fin at 0.2 atm. shown in Fig. 6 has an 8 K base superheat with $q_{b}'' = 95 \text{ W/cm}^2$. The bubble departure size is increased compared to 1.0 atm. experiments. The bubbles begin at the bottom of the test article and coalesce with other bubbles as it sweeps upward across the surface. This occurs at a higher frequency of 20 Hz.

The majority of the boiling appears to occur near the base of the extended surface throughout the range of superheats for all pressures. This shows that the entire height of the extended surface is not utilized due to the surface superheat decreasing as the boiling extends out from the base, suggesting that shorter fins could be utilized.

Figure 7 shows an image of a vertically oriented, 2/3 cm height, 80M0055d-4 fin at $\Delta T_{sat,b} = 8.5 \text{ K}$, $q_{b}'' = 81.9 \text{ W/cm}^2$. Notice only the back side of the fin is fully boiling.

The next higher heat flux for the same surface as fig. 7 is shown in Fig. 8 at $\Delta T_{sat,b} = 7.8 \text{ K}$, $q_{b}'' = 100.4 \text{ W/cm}^2$. Notice in this image that boiling occurs on both sides of the fin.

The graph of the boiling and cooling curve for the vertical oriented, 2/3 cm height, 80M0055d-4 fin is shown in Fig. 9. The boiling curve shows discontinuities in the data.
corresponding to the rear side ONB at $\Delta T_{\text{sat},b} = 2.3$ K, $q''_{b} = 13.2$ W/cm$^2$ and ONB of the front side corresponding to $\Delta T_{\text{sat},b} = 7.8$ K, $q''_{b} = 100.4$ W/cm$^2$ shown in Fig. 8. This delay of ONB can be attributed to temperature differences between the front and rear surfaces. Due to the discontinuous nature of the boiling curves, only cooling curves are reported in the following results presentation.

Figure 10 compares boiling performance at 1.0 atm. of 1.0 cm height surface enhanced fins with the following surface enhancements: a 4 layer 50 mesh (50M0090d-4), a 4 layer 80 mesh (80M0055d-4) and a 4 layer 145 mesh (145M0022d-4) enhanced surface. The 4 layer 50 mesh surface slightly outperforms the 4 layer 80 mesh surface up to $\Delta T_{\text{sat},b} = 4.5$ K, but the 4 layer 80 mesh outperforms 4 layer 50 mesh with increasing base superheat such that at 8 K superheat the 80M0055d-4 surface outperforms the 50M0090d-4 by 42%. The 4 layer 145 mesh surface performs equally to the 4 layer 80 mesh surface at low superheats but the 4 layer 80 mesh outperforms the 4 layer 145 mesh surface with increasing base superheat such that at 8 K superheat the 4 layer 80 mesh surface outperforms the 4 layer 145 mesh by 200%.

Figure 11 shows a boiling curve of a 4 layer 80 mesh enhanced plane surface [14] and a cooling curve from a 4 layer 80 mesh enhanced fin. The base superheat of the enhanced fin is compared to the surface superheat of the enhanced plane surface. The 4 layer 80 mesh fin test article at a base superheat, $\Delta T_{\text{sat},b} = 8$ K outperforms the 4 layer 80 mesh plane surface at the same superheat by 400%. This shows that the extended surface utilizes the area enhancement inherent to fins.

At reduced pressures the performance of the enhanced extended surface is reduced as seen in Fig. 12. Pressures used are 0.2 atm. ($T_{\text{sat}} = 60$ °C), 0.3 atm ($T_{\text{sat}} = 68$ °C), 0.5 atm ($T_{\text{sat}} = 82$ °C) and 1.0 atm. ($T_{\text{sat}} = 100$ °C). The 0.5 atm data shows a 3% reduction in performance; the 0.3 atm. data shows a 10% reduction in performance and the 0.2 atm. data shows a 27% reduction in performance relative to the 1.0 atm. data. The cooling curves for the 4 pressures show that the base heat flux is approximately linearly proportional to the superheat.
Figure 13 Vertical and horizontal test article orientation effects on the 80M0055d-4 1.0 cm test article in water at 0.2 atm. and 1.0 atm.

Figure 13 shows the performance dependence on the orientation of an enhanced fin. At 1.0 atm the horizontal surface (open diamond symbol) outperforms the vertical surface (closed diamond symbol) up to $\Delta T_{sat,b} = 4.5$ K. Then the vertical surface outperforms it at higher superheats. At 0.2 atm the vertical orientation (closed circle symbol) outperforms the horizontal test article (open circle symbol) by up to 30%.

The performance advantage of the vertical orientation is attributed to enhancement caused by sliding bubbles as investigated in Bayazit et. al. where the bubble enhances single phase convection as the bubble moves through the water and also because the bubble creates an evaporation microlayer that evaporates and is re-flooded by liquid trapped in front of the rising bubble [15]. The coalescence frequency for the vertical 80M0055d-4 surface is 15Hz at 0.2 atm.

The effect of reducing the fin height is shown in Fig. 14 where the 1cm tall fin performance is compared to 2/3 cm tall fin performance. The figure shows cooling curves for the vertically oriented 4 layer 80 mesh surfaces at 1 atm and 0.2 atm. At 1 atm the 2/3 cm tall fin outperforms the 1cm tall fin up to $\Delta T_{sat,b} = 6$ K then the 1cm tall fin outperforms at higher superheats. At 0.2 atm the 1cm tall fin outperforms the 2/3 cm fin by 12% at $\Delta T_{sat,b} = 8$ K. The added height of the fin increases boiling surface area at higher superheats, but at lower superheats a shorter relatively thicker fin allows for more surface area with active boiling. The reduction in pressure that reduces the boiling performance utilizes the taller fin’s boiling surface area that can be in active boiling.

8. Conclusions

The effects of changing the pore size of screen laminate surface enhancements, orientation and height of a fin in pool boiling of water at reduced pressures are investigated. The following can be concluded:

- The 4 layer 80 mesh surface enhancement, with a hydraulic diameter in the mid-range of the selected screen laminates produces the greatest increase in boiling performance. This is true for both 1.0 atm and 0.2 atm. This is attributed to utilization of the area enhancement of the fin and the increased boiling performance due to the screen laminate surfaces.
- Vertically oriented fins outperform horizontally oriented fins for reduced pressures and at higher superheats at 1.0 atm. Coalescing bubbles that sweep the fin surface may be the cause for increased heat transfer on the vertically oriented surfaces.
- The 1 cm fin height improved performance at reduced pressure and at 1.0 atm, at higher superheats. Although at lower superheats at 1.0 atm, the 2/3 cm fin is the leader. This is attributed to more of the fin surface area boiling due to reduced single phase heat transfer of the shorter fin.
- Coarse meshes augment boiling heat transfer better than fine meshes. This is contrary to Sloan et al’s findings [14].

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References


