Flow boiling of FC-72 from a screen laminate extended surface matrix

B. Holland, N. Ozman & R.A. Wirtz
Dept. of Mechanical Engineering, University of Nevada, Reno, NV, 89557, USA

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ABSTRACT: An investigation is conducted to assess the thermal performance of multi-layered screen laminates when used as extended surface matrices (ESM’s) in vertical up-flow boiling. A dielectric coolant (FC-72) is used as the working fluid. Four specimens are constructed having different mesh-geometries and/or number of layers. Channel Reynolds numbers are varied from 2700 to 8500 and ESM base superheats are varied from 0 °C to 50 °C. Results indicate that devices equipped with this technology can tolerate steady heat fluxes up to 140 W/cm² (based on the base area of the ESM) with corresponding ESM base superheats below 50°C. Reynolds number has a small effect on performance at low surface temperatures and a moderate effect at higher surface temperatures. Total capacity of the ESM (the product of heat flux and base area) increases approximately linearly with the thickness. A feature of this technology is that it greatly extends the working range over a bare surface.

1 INTRODUCTION

Motivation - The rapidly increasing use of electronics in military hardware is resulting in unprecedented thermal energy management needs. Future combat systems are envisioned to have high power electrical systems for propulsion, pulsed power devices and sensor arrays. These systems all dissipate large amounts of heat and traditional thermal management technology, which is based on single-phase heat transfer, will not be adequate. Liquid-vapor phase-change heat transfer promises to meet these increasingly stringent thermal management requirements because: the boiling process leads to relatively large heat fluxes at modest temperature rises, and more uniform surface temperatures can be maintained. Several comprehensive reviews have been published in recent years on boiling phenomena and phase-change heat transfer including those by Mudawar (2001), and Pioro et al. (2004a, 2004b).

A reticulated-filament open-cell structure, consisting of group-interconnected and purposely oriented thermally conductive ligaments, can be configured to have wide ranging porosity (ε) and a large specific surface area (β). When deployed as heat exchanger matrices, these structures produce high ntu-values (number of transfer units) because of the large specific surface area inherent to the media. Examples of structures with the above described characteristics are: laminations of orthogonal-weave and diamond weave fine-wire screen [Tong and London, 1957; Park et al, 2002; Xu and Wirtz, 2003, 2005]; three-filament stacked weaves [Wirtz et al, 2003] and box lattice
structures [Balantrapu et al, 2005; Sarde et al, 2006]. These structures can be configured to have a very large specific surface area ($\beta$), in excess of 50,000 m$^{-1}$. Effective thermal conductivities ($k_e$) can approach 78% of base material values. Pore size can range from O(1 µm) to O(1 cm) or larger. Thin layers can be bonded to a plane surface, giving rise to a highly convoluted surface morphology. Monolithic open-pore structures can be assembled.

The goal of this study is to assess the thermal performance of multi-layered screen laminates when used as extended surface matrices (ESM's) in vertical up flow boiling. Experiments are performed using FC-72 at near atmospheric conditions and 10 °C subcooling.

*Screen laminates* - Screens are woven on a loom. "Warp" filaments are those which emanate directly from the loom frame while "Shute" filaments are woven transverse to the warp filaments. The screen is characterized by the filament material, type of weave, wire counts (mesh numbers) in the two principal directions, $M_x$ and $M_y$, and the wire diameters in the two principal directions, $d_x$ and $d_y$ as shown in Fig. 1. The pore size is a measure of the open area as indicated in the figure. Woven metal-filament screens are commercially available with $0.0005" \leq d \leq 0.120"$ and $2\text{ in}^{-1} \leq M \leq 2800\text{ in}^{-1}$ (see footnote 1). Multi-layered screen laminate ESM's are constructed by bonding layers of wire-filament screen together to form a single monolithic structure.

![Figure 1. Definition of wire cloth parameters.](image)

### 2 EXPERIMENTAL SETUP AND PROCEDURE

For this work, nickel-coated, copper filament plain weaves with $M_x = M_y = M$ and $d_x = d_y = d$ are used. Relevant properties for the prototype screen laminates are given in Table 1.

<table>
<thead>
<tr>
<th>Mesh Number (cm$^{-1}$/in$^{-1}$)</th>
<th>Wire Diameter (mm)</th>
<th>Number of Layers</th>
<th>Surface Coating</th>
<th>Lamination Thickness, t (mm)</th>
<th>Porosity</th>
<th>Compression Factor</th>
<th>$k_{\text{eff}}$ (W/mK)</th>
<th>$\beta$ (m$^2$/m$^3$)</th>
<th>$D_h$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.016</td>
<td>5</td>
<td>Nickel plate</td>
<td>2.4</td>
<td>0.72</td>
<td>0.96</td>
<td>50</td>
<td>2700</td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>over solder</td>
<td>3.9</td>
<td>0.71</td>
<td>0.91</td>
<td>52</td>
<td>2900</td>
<td>0.98</td>
</tr>
<tr>
<td>50</td>
<td>0.009</td>
<td>5</td>
<td>Nickel plate</td>
<td>4.6</td>
<td>0.63</td>
<td>1.10</td>
<td>60</td>
<td>6500</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td></td>
<td>7.4</td>
<td>0.61</td>
<td>0.92</td>
<td>69</td>
<td>7500</td>
<td>0.30</td>
</tr>
</tbody>
</table>

1 In the United States, weaves are traditionally designated in British Gravitational units (inches).
The table shows the two mesh numbers, $M$ that were investigated (20 in$^{-1}$ and 50 in$^{-1}$), wire diameters $d$ (0.016 in and 0.009 in), number of layers $N$ (five and ten), surface coatings, compression factor $cf$, lamination thickness, $t$ porosity $\varepsilon$, effective thermal conductivity $ke$, specific surface area $\beta$, and the pore hydraulic diameter $D_h$. The compression factor accounts for wire-filament interleaving when the screens are stacked together to form the laminate, and the pore hydraulic diameter is a measure of pore size. Equations for calculating each of these parameters for plain-weave screen laminates were derived by Xu and Wirtz (2002). The table shows that the lamination thickness varied in four steps from 2.4 mm to 7.4 mm. Relative to the course-weave laminations, the fine-weave laminations have approximately: 13% lower porosity, 35% greater effective thermal conductivity, a 2.4-fold larger specific surface area and 65% smaller pore size.

The naming convention that will be used in this paper to identify the laminates is: mesh number (in$^{-1}$)/wire diameter (in)/number of layers. For example, M20/d016/N5 represents the 20-mesh, 0.016 inch diameter wire, five-layer lamination.

Figure 2 shows the implementation of the screen lamination/calorimeter in the vertical up-flow channel. The lamination, of thickness, $t$ spans the channel of width, $H$ and depth, $w$ (into the page). For this study $H = 9.5$ mm, $w = 50.8$ mm and $t$ varies by laminate (Table 1). The right channel wall (and lateral walls) are of Teflon, $L = 29$ mm. A transparent polycarbonate cover plate (left channel wall) allows the flow to be visually monitored and photographed.

![Figure 2. Implementation of screen laminate.](image)

Fluid approaches the laminate at velocity $V_{in}$, temperature $T_{in}$ and pressure $P_{in}$ after passing through a flow straightener. The inlet temperature and pressure are measured approximately 4 cm below the laminate. Temperature is measured using an exposed-junction T-type thermocouple; and, pressure is measured using a 0 – 103 kPa absolute pressure transducer. The inlet velocity, $V_{in}$ is determined from a flow rate measurement. Condensate flow is characterized in terms of two Reynolds numbers: The mesh Reynolds number

\[ \text{Re} = \frac{\rho V D_h}{\mu} \]  

where $V = V_{in} / \varepsilon$ is the pore average velocity and $D_h = 4\varepsilon / \beta$ is the pore hydraulic diameter, and the channel Reynolds number
An amount of heat \( q \) enters the base of the screen laminate ESM from a calorimeter that is buried in the Teflon channel wall. The calorimeter consists of a copper heater block and thin fin of thickness, \( t \) and width, \( w \). Cartridge heaters in the copper block provide the heat load. Thermocouples in the copper fin allow for the determination of the ESM base heat load, and base temperature, \( T_b \).

The calorimeter fin temperature is measured at two axial locations, \( T_1 \) and \( T_2 \) a distance \( \Delta y = 10 \text{ mm} \) apart. Each temperature (\( T_1 \) and \( T_2 \)) is measured twice: once from the left edge of the calorimeter fin and once from the right edge of the calorimeter fin, then averaged. The temperatures are measured using 1.6 mm sheathed, ungrounded T-type thermocouples at a depth of 0.64 cm in from the edges of the copper fin. Analysis of conduction in the calorimeter fin/Teflon wall allows for determination of \( T_b \) and \( q \) [Holland, 2006]. The heat loss, \( q_{loss} \) is typically 3% of ESM heat load, \( q \).

Prototype construction - The 20-mesh screen laminates were reflow soldered using 95/5 Tin/Antimony solder paste (\( k_s = 67 \text{ W/m/K} \)) [Park, 2001]. Soldering ensures that wire intersections and the individual layers are in good thermal contact. A section of laminate is cut from a larger specimen and ground flat. The laminate is then reflow soldered to the end of the calorimeter using 95/5 Tin/Antimony solder. The interfacial resistance between the calorimeter and laminate is assumed to be small enough to neglect when calculating ESM base temperature because care was taken to ensure the bonding surfaces were flat prior to soldering and the solder joint is very thin.

Reflow soldering is not possible with the 50-mesh laminates because liquid solder will clog the much smaller pores. Therefore, the individual layers of the 50-mesh laminates are nickel plated to bond the wire intersections, stacked together using small wires to align the pores, clamped together, then reflow soldered to the calorimeter using 95/5 Tin/Antimony solder paste. All laminates are given a superficial coating of bright nickel after bonding to the calorimeter to ensure similar surface characteristics. Finally, all laminates are arranged such that the pores of the individual layers are aligned (within practical limits). This “inline” arrangement gives the fluid a straight path through the laminate. Details regarding prototype construction are contained in Holland [2006].

Hydraulic loop - The hydraulic loop is shown schematically in Fig. 3; and, Fig. 4 is a photograph of the test rig. The system is filled through the reservoir (1 in Fig. 4). A sight tube on the side of the reservoir allows the fluid level to be visually monitored. A magnetically-coupled pump (PC, Fig. 3) pumps the FC-72 through a small inline 40 micron filter (FLT). The fluid then passes through two flow meters (FM) of unequal capacity connected in parallel. This arrangement (high-flow/low-flow) allows for measurements ranging from 0.76 – 45 liter/min. Flow rate is controlled by throttling the valves just upstream of the flow meters. After passing through the flow meters the fluid is heated to the desired inlet temperature (\( T_{in} = T_{sat} - 10 \degree C \)) using electric tape heaters connected to power supplies. Inlet temperature is controlled by varying the voltage to the tape heaters. Pressure is controlled by throttling the valve downstream of the test section.

Raw data (temperatures and pressure) is collected with a data logger and a process controller (5d in Fig. 4). After exiting the test section a two-fluid parallel plate heat exchanger (HE, 7 in Fig. 4) connected to an external chiller is used to remove the heat generated in the test section and keep the total system pressure constant by condensing the vapor generated in the test section.
All components in the hydraulic loop are connected with brass fittings and ½” annealed aluminum tubing. In the Fig. 4, a self-illuminating borescope (8) is connected to a digital video camera (9) to photograph the boiling from above the laminate. Photographs are also taken from the front using a digital SLR camera with a shutter speed of 1/1000 sec.

3 TEST PROCEDURE

Prior to collecting data the FC-72 is boiled vigorously in the heated section for approximately 90 minutes to degas it. During this time a vent on top of the reservoir is periodically opened to allow the separated gasses to escape. The effect of dissolved gasses on boiling in FC-72 has been documented by Rainey et al. [2003]. These gasses tend to shift the boiling curve and removing them ahead of time allows better repeatability in the experiment. No effort is made to analyze the exact gas content in the FC-72. However, this procedure is consistent with procedures reported by Chang and You [1997] and Mukherjee and Mudawar [2003].

For each experiment, data is collected by varying the heat flux from high to low. This is referred to as the cooling curve [Incropera and DeWitt, 2002] and explains why there is no incipience overshoot evident in results discussed later on. Each data point is collected after the operating conditions stabilize to within a specified tolerance and the time variation of \( T_J \) is less than 0.04 \(^\circ\)C/min or a repeating oscillation is observed.

4 RESULTS

Figure 5 plots the cooling curve of a 50.8 mm wide x 2.4 mm tall (1.2 cm\(^2\)) un-enhanced Ni-plated copper surface (no ESM) for three channel Reynolds numbers. The surface is the tip of one of the calorimeters, and its’ length in the stream wise direction is the thickness of the ESM prototype. The Figure shows no Reynolds number effect for this very short surface. The critical heat flux (CHF) for the reference surface is approximately 34 W/cm\(^2\) at a superheat of approximately 14 °C. Experimentally, the CHF is taken as the highest heat flux achieved prior to observing a large increase in surface temperature for a modest increase in heat flux.
Figure 5. Surface Heat Flux vs. superheat, un-enhanced surface.

Figure 6 plots the ESM base heat flux vs. superheat (cooling curve) of ESM M20/D016/N5 for the same three channel Reynolds numbers as Fig. 5. The Figure is typical of what is observed with the three other ESM prototypes [Holland, 2006]. The effect of increasing Reynolds number is an upward shift in the curves. This effect is negligible in the single phase regime (negative superheats) and becomes more pronounced as superheat increases. The heat flux increases with increasing superheat throughout the entire range of testing, i.e. no evidence of unstable boiling conditions observed for superheats in excess of 40 °C, where an ESM base heat flux of 95 W/cm² is achieved. This is in marked contrast to the un-enhanced surface which showed instability (transitional boiling) at superheat temperatures of approximately 14 °C.

Tung and Dhir have identified the different heat transfer regions that can occur during flow boiling in a volumetrically heated porous media:

1. **Sub-Cooled Liquid Region** Single phase heat transfer heats sub-cooled liquid to Tsat.
2. **Two-Phase Region** The two-phase region begins when nucleation initiates on porous media elements. Before all of the liquid is evaporated, most of the interstitials will be occupied by vapor, and liquid droplets carried with the vapor may experience intermittent contact with porous media elements.
3. **Transition Region** Unstable, intermittent (non-equilibrium) boiling of entrained droplets and single phase vapor heat transfer.
4. **Superheated Vapor Region** Stable, single phase solid-vapor heat transfer (dry-out)

Figure 7 shows how we think these four regions will arrange themselves in a porous fin. With sufficient wall superheat, the region near the heated wall, (4) could experience dry-out, with a vapor sheet above the dry-out region. Further from the wall, (3, 2) nucleate and transitional boiling obtains, with a two-phase exit flow. Even further out from the heated wall, the RFM temperature drops to near Tsat so nucleation is inhibited and single phase (liquid) heat transfer obtains.

Figure 8 shows the M50/d009/N10 screen laminate at three key superheats. The left-hand images were taken by photographing the laminate from the side through the polycarbonate cover (shown in Fig. 2). The white band in those images is a layer of silicone sealant on the calorimeter.
fin, about 2 mm thick. Above that is the black Teflon y = 0 wall. The right-hand images were taken by photographing the laminate from above using the borescope camera (shown in Fig. 4). The solid black line represents the Teflon channel wall, y = 0.

The upper views show the laminate at a superheat of 3.3 °C. The ESM base heat flux is 33.3 W/cm². Isolated bubbles characteristic of partial nucleate boiling are observed and boiling occurs from roughly 1/8th of the ESM surface area.

The middle images show the laminate at a superheat of 13.9 °C (near CHF for the reference surface). The ESM base heat flux is 61.4 W/cm², roughly twice the un-enhanced surface heat flux. Now bubbles are coalescing to form columns and fully developed nucleate boiling is observed. Boiling coverage increases to approximately 3/8ths of the exposed area.

The lower views show the laminate at a superheat of 22.6 °C with an ESM base heat flux of 82.7 W/cm². Now the characteristics of transitional boiling are observed. Note what appears to be a vapor sheet in the edge view. Boiling coverage has increased to roughly 5/8ths of the exposed area.

Figure 9 shows the boiling curve for four screen laminate ESM’s compared to the pool boiling curves of Nakayama’s surface-enhanced stud [Nakayama et al, 1984] and Rainey and You’s surface-enhanced square pin fins [2000]. The Figure shows that the highest performance was achieved with the M50/d009/N5 laminate followed closely by the M50/d009/N10 laminate. The fine-mesh screen laminate ESM’s are shown to achieve a base heat flux in excess of 100 W/cm² with a superheat of 30°C. The two 20-mesh laminates showed nearly the same performance and overlap the results of Rainey and You for superheats greater than 10 °C. All four laminates and Rainey and You’s enhanced fins have similar slopes for superheats greater than 10 °C. Analysis of the data shows that ESM base heat flux is proportional to $\Delta T_{sat}^{4.3}$. 

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Figure 7. Boiling regimes in a porous fin.

Figure 8. Visualizations of boiling regimes for M50/d009/N10 laminate.
Figure 10 shows the effect of thickness on the heat transfer rate per unit channel width $w$, at a fixed superheat and constant channel Reynolds number. Values were linearly interpolated and marked with the 2-sigma confidence intervals. Also shown is a least squares linear fit. As the graph shows there is an approximately linear relationship between the ESM base heat transfer rate and ESM thickness. (Pearson’s linear correlation coefficient = 0.984.) This relationship persists (approximately) at other superheats suggesting that a “ballpark” estimate of performance requires knowing only the thickness of the laminate.

5 CONCLUSION

In conclusion we observe that multi-layered screen laminate ESM’s such as those studied in this work can effectively enhance heat transfer over an unenhanced surface in terms of both surface temperature and heat flux. Of the laminates tested the M50/d009/N5 had the highest performance. Results indicate that devices equipped with this technology can tolerate steady heat fluxes up to 140 W/cm$^2$ (based on the base area of the heat sink) with corresponding surface temperatures below 100°C and no evidence of boiling instability. The boiling regimes suggested by Tung and Dhir (1983) are found in boiling from a porous ESM. Reynolds number has a small effect on performance at lower ESM base superheats and a moderate effect at superheats. At superheats greater than 10 °C the heat flux is proportional to $\Delta T_{sat}^{1.3}$ for the screen laminate ESM’s tested. Total capacity (the product of heat flux and base area) of the devices increases approximately linearly with thickness.

ACKNOWLEDGEMENT/DISCLAIMER

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