A CAPILLARY-PUMPED LOOP HEAT PIPE WITH MULTI-LAYER MICROSTRUCTURED WICKS

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Abstract: We report the design, analysis, and preliminary testing of microstructured copper wicks for a novel capillary-pumped loop heat pipe. The heat pipe design is a key component in an integrated pump-heat sink that dissipates over 1000 W with an overall thermal resistance less than 0.05 °C/W. Microstructured wicks with sintered copper particle sizes of 5 - 150 µm were fabricated within copper tubing and permeabilities of 9.5x10^{-14} - 1.5x10^{-11} m² and maximum capillary pressures of 100 - 850 Pa have been achieved. Additionally, multi-layered microstructured wicks have been fabricated that simultaneously allow for high permeability and high capillary force. This work is a critical step towards developing new high-performance thermal management solutions for commercial, defense, and space applications.

Keywords: Loop Heat Pipe, Capillary Wick, Heat Exchanger, Sintering, Microstructure

INTRODUCTION
Thermal management is a critical bottleneck for high-power systems, such as phased-array radar and microwave and digital electronics, where performance and reliability are dictated by the ability to dissipate heat efficiently. Fluidic-based cooling solutions have commonly been incorporated using traditional large-scale air-cooled fin-fan arrays and pumped liquid-based cooling [1-3], but have suffered from system inefficiencies and limited performance characteristics.

The current work focuses on developing a novel high-power cooling unit comprised of a complex capillary-pumped loop heat pipe with an integrated blower. The pump-heat sink (Fig. 1) is 10 cm x 10 cm x 10 cm and consumes less than 33 W of electrical power while dissipating over 1000 W of heat with a thermal resistance of less than 0.05 °C/W. The design consists of a series of rotating blades used to force air between parallel condenser plates (~2.5 mm thick) of the capillary-pumped loop heat pipe with a single evaporator layer at the bottom. The integrated design utilizes a stack of rotating blades interdigitated between 18 thermal stator plates, each of which is a condenser chamber of a capillary-pumped loop heat pipe. A single evaporator layer is located at the bottom of the unit, which is in contact with the heat source, and connected to the thermal stator plates via vertical pipes. A low-profile radial-flux permanent magnet motor is mounted on top and drives the rotors on a single shaft running through the condenser plates. Air enters the top through an axial intake and is drawn radially outward between the condenser plates.

The heat pipe is an important component of the system needed to create a near isothermal heat sink and to minimize the overall thermal resistance. Figure 2 shows a schematic of the cross-section of the device and Fig. 3 shows a schematic detailing the multi-layered wicking structure. The working fluid (water) evaporates in the primary evaporator wick; the vapor travels through vertical pipes to the condenser layers where it is convectively cooled to the liquid phase and then wicked back into the evaporator.

Fig. 1: Schematic of the 10x10x10 cm integrated pump-heat sink device.
The successful operation of the heat pipe relies on efficient wicking of the water through the complex stacked geometry. Various wick sizes are necessary to create high driving pressures in the evaporator and low permeabilities in the fluid transport sections. Additionally, the condensers require adequate capillary force to withstand the tendency of gravity to flood the lower layers with liquid from the higher layers. A two-level wick design in the condenser sections will enable the device to be insensitive to orientation. The 1 µm pore primary wick in the evaporator provides a large capillary pressure to overcome viscous losses, while the ~100 µm (large-pore) wick provides a high-permeability path for liquid flow and the ~10 µm (small-pore) wick provides a high burst pressure to prevent backflow.

**Fig. 2:** Cross-section schematic of the integrated pump-heat sink showing the capillary-pumped loop heat pipe.

**Fig. 3:** Cross-section schematic of the dual-layer wick structures within the condenser and evaporator sections.

**MICROSTRUCTURED COPPER WICKS**

Five sizes of spherical copper particles were used to fabricate the microstructured wicks as shown in Table 1 and in the scanning electron micrographs (SEMs) in Fig. 4. While the smallest particles (sample E) were commercially available, the larger powders were sieved to achieve the respective sizes. Powder sample E has been selected for the fine condenser wick and the various larger powders were investigated to determine the optimal coarse wick.

The powders were loose-sintered in a 150 mm diameter tube furnace (HTF55667C, Lindberg-Blue) with a heating rate of 20 °C/min. To minimize shrinkage, the smaller particles were sintered at lower temperatures and times. A reducing atmosphere of 5% H₂, 95% N₂ was employed in positive pressure to remove existing oxidation on the particles and prevent oxidation during heating. The wicks were fabricated in copper tubes with an inner diameter of 4.8 mm. As the copper particles sinter, they bind to the tube and form a plug.

The maximum capillary pressure (MCP) that can be sustained across the wick interface is related to the effective pore radius (r_eff) by the Young-Laplace relation [4]

$$\Delta P_{\text{max}} = \frac{2 \sigma \cos \alpha}{r_{\text{eff}}}$$

(1)

where $\sigma$ and $\alpha$ are the surface tension of the liquid and the contact angle, respectively. The pressure drop for flow through the wick is related to the permeability ($k$) and flow rate ($Q$) by Darcy’s Law [4]

$$\Delta P = \frac{\mu l}{A_{cs} k} Q$$

(2)

where $\mu$, $l$, and $A_{cs}$ are the viscosity of the fluid, flow length, and cross sectional area of the porous media, respectively. Equations (1) and (2) were used to characterize the effective pore size and permeability from experimental data.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Particle Size (µm)</th>
<th>Sintering Temp. (°C)</th>
<th>Sintering Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>120-140</td>
<td>850</td>
<td>30</td>
</tr>
<tr>
<td>B</td>
<td>75-100</td>
<td>850</td>
<td>30</td>
</tr>
<tr>
<td>C</td>
<td>40-90</td>
<td>850</td>
<td>30</td>
</tr>
<tr>
<td>D</td>
<td>0.5-150</td>
<td>850</td>
<td>30</td>
</tr>
<tr>
<td>E</td>
<td>5-15</td>
<td>700</td>
<td>15</td>
</tr>
</tbody>
</table>

**Table 1:** Sintered wick samples and fabrication details
TESTING AND RESULTS

Figure 5 shows a schematic of the experimental setup used to characterize the permeability and MCP for each sample. A pressurized reservoir was used to drive water through a flow meter (L-5CCM-D, Alicat Scientific) and then the wick. A regulator controlled the driving pressure, and a differential pressure transducer (FDW1AT, Honeywell) measured the pressure drop through the wick.

![Fig. 5: Experimental setup for determining capillary pressure and permeability through the sintered wicks.](image)

Permeability

Figure 6 shows characterization results of flow rate as a function of driving pressure for each sample. Table 2 lists the permeabilities determined using Equation (2). In general, larger particle sizes lead to higher flow rates for a given pressure drop. The inclusion of a wider range of particle sizes, however, adversely affects the permeability. Sample D, with particle sizes ranging from 0.5 - 150 μm shows a higher flow resistance than A and B. The smaller particles in sample D fill the voids between the larger particles, which reduces the permeability. Large particles, sieved to a narrow range, result in the highest permeability (sample A).

![Fig. 6: Flow rates through sintered wicks as a function of driving pressure for various samples.](image)

Maximum Capillary Pressure

The MPC was measured by introducing water to the samples and slowly increasing the backside pressure until the liquid penetrates through the wick. The measured MCPs of the wicks are tabulated in Table 2 based on an assumed advancing contact angle of 84° [4].

![Fig. 4: SEM images of various sintered copper wicks.](image)
Table 2: Sintered wick characterization results

<table>
<thead>
<tr>
<th>Sample</th>
<th>Particle Size (μm)</th>
<th>Permeability (m²)</th>
<th>Capillary Press. (Pa)</th>
<th>Eff. Pore Size (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>120-140</td>
<td>1.5E-12 +/-7.5E-13</td>
<td>98 +/-37</td>
<td>155</td>
</tr>
<tr>
<td>B</td>
<td>75-100</td>
<td>8.3E-12 +/-2.3E-12</td>
<td>303 +/-214</td>
<td>50</td>
</tr>
<tr>
<td>C</td>
<td>40-90</td>
<td>3.6E-12 +/-1.3E-12</td>
<td>380 +/-195</td>
<td>40</td>
</tr>
<tr>
<td>D</td>
<td>0.5-150</td>
<td>9.1E-13 +/- (NA)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>E</td>
<td>5-15</td>
<td>9.3E-14 +/- (NA)</td>
<td>770 +/-43</td>
<td>20</td>
</tr>
</tbody>
</table>

FABRICATION OF DUAL-LAYER WICKS

To fabricate a dual-layer planar wick structure, as shown in Fig. 3, the MCP of a coarse high-permeability wick was increased by completely filling the surface voids with finer particles. A graphite mold was first filled with the 40 - 90 μm powder, and then refilled at the surface with the 5 - 15 μm powder. The excess was scraped off of the surface. The powder was sintered at 850 °C for 30 minutes with the procedure described above.

Figure 7 shows a cross-sectional SEM of the dual-layer wick. The fine powder fills the surface to a depth of approximately 1.5 times the diameter of the coarse powder. The results suggest that adding a powder of intermediary particle size between the two layers more effectively fills interstitial voids. This results in a thinner fine wick layer and higher permeability.

CONCLUSION

Successful operation of the capillary-pumped loop heat pipe with vertically stacked condensers requires a wick structure capable of supplying high capillary pressure while maintaining high permeability. This work investigates the effect of mixing various particle sizes on maximum capillary pressure and permeability. The inclusion and addition of smaller particles to a coarse wick shows an increase in the maximum capillary pressure, but with a decrease in permeability. In addition, a dual layer wick was fabricated by filling the inter-particle voids at the surface of a coarse wick. Filling the surface with a fine wick creates high surface capillary forces while maintaining high bulk permeability. This work serves as the basis for developing high-permeability high-capillary-pressure dual-layered wicks in planar condenser sections of a capillary-pumped loop heat pipe.

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