Experimental Demonstration and Characterization of a Ceramic Sintered Wick Heat Pipe Evaporator

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As electrified aircraft propulsion (EAP) matures and power electronics, electric machines, and batteries achieve higher power density, the thermal management of these devices becomes ever more critical. In this paper, a heat pipe made from a dielectric ceramic material is proposed, which enables its use in the thermal management of a high frequency filter inductor for an EAP power electronics application. The manufacturing process for the sintered powder wick was developed and its performance characterized. The heat pipe is further experimentally demonstrated via an open evaporator test and shown to behave analogous to a constant conductance heat pipe.

I. Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$A_c$</td>
<td>cross sectional area, m$^2$</td>
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<tr>
<td>$\beta$</td>
<td>diameter ratio</td>
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<tr>
<td>$D$</td>
<td>diameter, m</td>
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<tr>
<td>$d_p$</td>
<td>spherical particle diameter, m</td>
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<tr>
<td>$\varepsilon$</td>
<td>porosity</td>
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<tr>
<td>$g$</td>
<td>gravitational acceleration, m/s$^2$</td>
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<td>$h$</td>
<td>wetted height, m</td>
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<tr>
<td>$h_{eq}$</td>
<td>equilibrium height, m</td>
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<tr>
<td>$\Delta h_{lg}$</td>
<td>enthalpy of vaporization, J/kg</td>
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<tr>
<td>$Q$</td>
<td>heat load, W</td>
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<tr>
<td>$R$</td>
<td>thermal resistance, K/W</td>
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<td>$\theta_c$</td>
<td>contact angle, °</td>
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<tr>
<td>$k$</td>
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</tr>
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<td>permeability, m$^2$</td>
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<td>$\Delta p_t$</td>
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<tr>
<td>$\rho$</td>
<td>density, kg/m$^3$</td>
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<tr>
<td>$\sigma$</td>
<td>liquid-vapor surface tension, N/m</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature, °C</td>
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4 Process Engineer.
II. Introduction

With the increased specific power required of electrified aircraft propulsion (EAP) components, such as power electronics, electric machines, and batteries, the thermal management system becomes increasingly important due to higher heat fluxes and the temperature sensitivity of these devices. New materials or techniques for thermal management can be an enabling technology for further improvement in the specific power and efficiency of these devices. In these applications, the push to higher fundamental frequencies and higher switching frequencies has worsened problems such as eddy current losses in the vicinity of these devices. Relatively, the increased power density makes simple cooling schemes such as air cooling inadequate. Therefore, direct liquid cooling is pursued as one alternative; however, it has its own drawbacks such as added weight (large fluid volumes), the need for pressure containment, and complexity. Heat pipes are commonly employed in the thermal management of electronics. A heat pipe is a passive device that transports heat through evaporation and condensation of a fluid and capillary action in a wick which moves the liquid from a condenser (cold interface) to the evaporator (attached to the device to be cooled). Heat pipes have an envelope that serves as the pressure vessel, the wick which is either grooved or made from a porous medium such as screens or sintered powder, and the vapor space which moves the evaporated fluid from the evaporator to the condenser. Historically, heat pipes are almost exclusively made from metals and as such, in high frequency electrical devices, may incur eddy current losses due to the proximity of high frequency magnetic fields. If a heat pipe could be made from a dielectric material, it could be used for thermal management in applications where high frequency magnetic fields are present. Polymers are one class of candidate materials but suffer from very poor thermal conductivity. Another class of dielectric materials with good thermal conductivity are technical ceramics. A potential advantage of ceramic heat pipes in more conventional electronics thermal management is that the material may have good thermal expansion match to semiconductor substrates, which could eliminate the need for a separate insulation layer in the design of semiconductor components; thereby, improving thermal management. In very high temperature applications, the use of ceramic material for the heat pipe could enable use of corrosive working fluids, or the use in challenging environments without the need for special coatings.

Previous examples of ceramic heat pipes include SiC for use with high temperature working fluids [1]. Sintered ceramic wicks were also previously developed for use in loop heat pipe evaporators [2] and dual-use loop heat pipes or capillary pumped loops [2], [3]; however, the small pore size (<10 µm) in these examples makes them largely unsuitable for conventional heat pipes. Ceramic wicks consisting of alumina and silica fibers have also been considered for capillary pumped loop systems [4]. Aluminum oxide (Al₂O₃), also known as alumina is a common ceramic that can be manufactured by powder sintering and additive manufacturing, making it a good candidate material to produce a sintered ceramic wick in line with conventional metal heat pipe sintered wicks. Another benefit is that alumina is a dielectric and has a moderate thermal conductivity of approximately 25 W/m-K. This concept was previously presented in [5], whereby a manufacturing process for a spherical Al₂O₃ powder wick was demonstrated for a water heat pipe. The work presented in this paper details the additional experimentation of that manufacturing process and a preliminary thermal test involving the evaporator.

III. The Application of Ceramic Heat Pipes for Inductor Cooling

While the proposed dielectric ceramic heat pipe can be used in several demanding scenarios, the original application that prompted its development was a high frequency inductor used to filter the output of a power electronics converter. This inductor was required to be small, lightweight, and extremely efficient (the target efficiency goal for the entire converter was 99%). The magnetic field in the immediate vicinity of the inductor would cause eddy current losses if a more conventional metal heat pipe were used to couple the inductor to a cold plate (or if the inductor were directly thermally coupled to the cold plate). Therefore, to maintain efficiency and have good thermal transport capability by liquid cooling, it was proposed to couple this inductor to a cold plate using a heat pipe manufactured from a thermally conductive, yet dielectric, material. Thus, ceramics were chosen. Aluminum oxide (Al₂O₃) was chosen for its wide commercial availability and moderate thermal properties. The proposed system, showing just the ceramic evaporator of the heat pipe integrated with the filter inductor, is shown in Fig. 1. The heat pipe sizing and theoretical performance of this system were previously presented in [5]. This nominal heat pipe design had a 40 mm outer diameter, 2 mm thick wick, 50 mm evaporator section, and 200 mm overall length. When wicking against gravity, the heat pipe was analytically predicted to adequately cool the 120 W of inductor loss while keeping the hotspot temperature in the inductor winding to approximately 172°C – well below its maximum temperature limit of 240°C.
A key part of the development effort was the sintering of the wick [5]. Conventional ceramic powder sintering usually uses ceramic particles <10 µm in size as smaller particles have higher surface energy, thereby making sintering easier. Densification occurs as the surface energy of the grains is reduced through the formation of a single solid. To have an appropriately performing wick, a powder size over an order of magnitude larger than conventional ceramic sintering powders was required, and therefore special processing. However, the wick also requires only minimal sintering – enough to thermally and structurally couple the particles, but not so much as to severely impact the porosity. The Al₂O₃ powder used in the manufacturing of the wick was previously tested and confirmed to have a mean particle diameter (D50) of 120 µm, a D10 of 92 µm, and D90 of 159 µm. After various trials, the process used for all the following test articles was sintering at 1650°C with the addition of 5 wt% talc content to the powder mix. The talc is what enabled liquid phase sintering of the spherical 120 µm Al₂O₃ powder. Scanning electron microscope (SEM) images of the sintered wick are shown in Fig. 2.

IV. Characterization Testing

The alumina powder sintered at Ceramco was characterized for pore-size distribution and porosity with Galwick as the test fluid. The results of this test, which are shown below in Table 1, indicate a porosity of 42%. This is in line with the micrographs indicating high porosity. The pore size ranges from 13 µm to 57 µm, with an average pore diameter of 29 µm. The bubble point diameter, which is used in the maximum capillary pressure estimation, is 57 µm. The pore size distribution is plotted in Fig. 3. The measured porosity from the capillary flow method is within the expected range for loose random packing of spherical particles, indicating that there was likely only very little volume
reduction from sintering the powder wick. This is confirmed by the SEM imagery of the sintered wick samples shown in Fig. 2.

The capillary wicking behavior of a sintered alumina wick strip shaped sample was measured at the Wichita State University, in Dr. Gisuk Hwang’s laboratory. The sample was 50 mm long and 6 mm wide. The capillary rise method, which is based on the Washburn formulation, was employed. In this method, the sample is partially submerged in acetone and the rise of liquid into the wick is observed optically and recorded. This capillary rise against gravity quickly penetrates the sample, which indicates a trend of increasing reliability with sample length. The estimated maximum capillary pressure for a given contact angle is calculated by (1), and the non-linear differential equation derived from Darcy’s law, as shown in (2), is used to model the 1-D rate of rise in the test sample. The time-dependent meniscus height \( h \) (m) is related to the permeability and maximum capillary pressure \( p_{c,max} \) (Pa), which in-turn is related to the minimum pore radius \( r_{eff} \) (m). A contact angle \( \theta_c \) (°) of zero is assumed. The results of this method are shown in Fig. 4. The equilibrium or maximum capillary rise \( h_{eq} \) is estimated based on the short time measurements. The best curve (least squares method) is used to find the permeability \( K \) and \( r_{eff} \). The permeability of \( 8.3 \times 10^{-12} \) m\(^2\) is about half that of the value predicted by the Karman-Cozeny correlation [6] for packed beds, which predicts \( 18 \times 10^{-12} \) m\(^2\) given 120 um diameter spherical particles and a porosity of 42%. This deviation is not surprising given the correlation is for spherical packed beds and this is a sintered wick, and the correlation is used as an approximation. The minimum meniscus radius of curvature (spherical meniscus) \( r_{eff} = 22 \) µm from the curve fit is close to half the bubbling diameter of 57 µm or 28 µm measured by the previous porometry results. With the effective radius now known, an estimate of the capillary pressure can now be done for different fluids. In this exercise, methanol will be considered as it is a candidate fluid for use in the EAP application due to its lower freezing point. Now, in considering water and methanol, we employ a conservative contact angle of \( \theta_c = 45° \) and 0°, respectively. With their properties at a 1 atm saturated liquid condition, we estimate \( p_{c,max} = 3.8 \) kPa, and 1.7 kPa, respectively.

\[
p_{c,max} = \frac{2\sigma \cos \theta_c}{r_{eff}} \tag{1}
\]

\[
\frac{dh}{dt} = \frac{1}{h \mu} \left( \frac{2\sigma \cos \theta_c}{r_{eff}} - \rho gh \right) \tag{2}
\]
The addition of talc as a sintering aid may adversely impact the thermal conductivity of the wick since it has a lower thermal conductivity than the alumina particles. First, a volume fraction calculation is made assuming the density of the alumina particles to be 3900 kg/m$^3$ and a talc density of 2700 kg/m$^3$. Because the talc is made from smaller particles and mixed with the alumina, it is assumed in the final wick form that the talc is coating the alumina particles and bridging the gaps. Therefore, a series conduction model is appropriate to estimate the solid thermal conductivity based on the volume fractions of alumina and talc. The volume fraction of talc is 7% at 5 wt% and assuming a talc (at 100°C in the fired condition [7]) thermal conductivity of 2 W/m·K, and an alumina conductivity of 25 W/m·K, the series conduction model yields an alumina-talc effective conductivity of 13.7 W/m·K. Further, assuming 42% porosity, the solid conductivity of 13.7 W/m·K, and a saturated liquid water conductivity of 0.68 W/m·K at 100°C, the Krupiczka correlation [8] predicts an effective thermal conductivity of 3.0 W/m·K. The Krupiczka results are plotted in Fig. 5 for variable talc content.

The sintered wick samples were tested for the effective thermal conductivity using the ASTM E1530 guarded heat flow meter (GHFM) method. This test method covers a steady-state technique for the determination of thermal resistance of materials with thicknesses less than 25 mm. A sintered wick disk-shaped sample (50 mm diameter and 4 mm thick) was tested for thermal conductivity in air at 25°C. The test yielded an effective through-plane thermal conductivity of 1.33 W/m·K. Another sample was initially tested with the transient plane source method, but this yielded a seemingly non-physical thermal conductivity result over an order of magnitude higher, close to the expected range of thermal conductivity for fully dense Al$_2$O$_3$. As a result, the GHFM method was used instead. In the heat pipe application, the liquid filling the wick pores will result in a higher effective thermal conductivity (as opposed to air),
as shown with the below experimental and compared to the Krupiczka thermal conductivity correlation [8] for loosely packed particles (not sintered). The measured effective conductivity is over three times higher than the packed bed correlation, indicating that the sintering process significantly improves the effective thermal conductivity. This is as expected due to the thermally conducting bridges created between particles that can be seen in Fig. 2, given that the Krupiczka correlation is used here as a conservative estimate for thermal conductivity.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Predicted Effective Conductivity (W/m-K)</th>
<th>Measured Conductivity (W/m-K)</th>
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<tr>
<td>Air</td>
<td>0.34</td>
<td>1.33</td>
</tr>
<tr>
<td>Water</td>
<td>3.0</td>
<td>Not Tested</td>
</tr>
<tr>
<td>Methanol</td>
<td>1.4</td>
<td>Not Tested</td>
</tr>
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</table>

Table 2. Thermal conductivity predictions based on Krupiczka correlation and the measured porosity of 42%, compared to the measured thermal conductivity by GHFM with air filled pores.

V. Evaporator Testing

After the basic performance characteristics were determined (the rate of rise behavior, the porosity and pore size, and the thermal conductivity), a combined next step test was planned. While a heat pipe is a device with no mass transfer to the surroundings, a simplified test can be conducted where the heat pipe evaporator is open to atmosphere and relies solely on the enthalpy of vaporization and mass flow to the ambient environment to reject heat. A benefit of this approach is that a heat pipe open to atmosphere will enable knowledge of the temperature at the liquid-vapor interface so long as the evaporator container is insulated and the input heat flux high enough. In this particular test, water is used, so the saturation temperature at the inner diameter of the evaporator is approximately 100°C for all tests conducted. A closed heat pipe test is a significantly more difficult experiment since it would require a vacuum pump, charging equipment, the system to be well-sealed, and the determination of a good charge mass. As a result, this open evaporator test is a good first step towards determining the combined capillary pumping performance, the effective thermal conductivity of the wick when a fluid is present, and the maximum heat load limit of the evaporator.

The basic open heat pipe concept is shown in Fig. 6, where the outside of the flexible heater is insulated such that heat must travel into the wick and evaporate liquid. The heaters cover 50 mm of the axial length of the evaporator. Affixed to the outer wall of the evaporator at various locations are calibrated special limits type T thermocouples bonded with thermally conductive epoxy. TC1 and TC6 are bonded to the ceramic wall at the edges of the heaters, while TC4 and TC13 are bonded to the wall in between the two heating elements. TC16 is placed directly in the liquid bath to measure the incoming liquid temperature, while TC8 is suspended in the vapor space to measure the vapor

![Fig. 6](image-url) (a) Open evaporator cylindrical test to determine capillary heat load limit of the heat pipe when operating at a saturation temperature of 100°C. (b) Thermocouple locations marked in orange.
temperature. TC1, TC4, and TC6 are in the same angular plane, while TC13 and TC14 are offset from TC4 in opposite angular directions by approximately +/- 45 degrees. A calibrated current transducer and voltage taps at the heater leads provide the measurement of electrical power and therefore heat input to the experiment.

Two test articles 80 mm long and 47 mm in diameter were manufactured with 1 mm and 2 mm thick wicks, respectively. Photographs of the 2 mm thick wick evaporator are shown in Fig. 7. The evaporator test article was manufactured by taking a stock alumina tube, filling it with the alumina and talc powder mixture, and then sintering. Subsequently, the wick was core-drilled to a rough size and then ground to final dimensions. On one end, the wick and the stock alumina tube are flush. Some contamination from the grinding swarf is present (black marks). At the end of the wick, there is a small gap between the wall and the rest of the wick; however, it appears this gap is only present here as more in-depth particles are bridging this gap.

The capillary heat load limit of the evaporator can now be estimated assuming the saturated properties of liquid water at 100°C, the maximum pore diameter of 57 μm from Table 1, and the apparent permeability of $8.3 \times 10^{-12}$ m$^{-2}$ from Section IV. Assuming a conservative contact angle of 60° between the wick and water, the predicted heat load limit is 225 W for the 1 mm thick wick and 439 W for the 2 mm thick wick.

To confirm the basic functionality of the 1 mm thick wick evaporator article, it was tested in a petri dish with no insulation in two cases: 1) completely dry and 2) with water to confirm wicking and evaporating functionality. The dry case functions as a control to confirm the wick is wetting, and to rule out convection as the primary mechanism for heat rejection in the next stage of performance testing. The evaporator was tested open to air to allow for thermal imaging for qualitative comparisons, samples of which are shown in Fig. 8. The thermal images were taken assuming a uniform emissivity of 0.9, which is not accurate for all materials (e.g., polyimide) involved, and a background temperature of 21°C – hence the merely qualitative nature of these measurements.

![Fig. 7](Left) Ceramic heat pipe evaporator test article, 2 mm thickness wick sample shown. (Right) Full evaporator with solid alumina case shown before attachment of flexible heaters and thermocouples.

![Fig. 8](a) Evaporator operating open to air in dry condition rejecting 19 W of heat via natural convection only. (b) Dry case with thermal/optical composite image. (c) Thermal/optical composite image of evaporator wicking in pool of water rejecting 40 W of heat.
In the dry case, the steady-state heat rejection was 19 W and the temperature measured near TC13 and within the crosshairs was 108.6°C (vs 112°C measured via infrared). In the wetted case, the steady-state heat rejection was 40 W, and the actual temperature measured by thermocouple TC13 near the crosshairs was 86.4°C. The peak temperature in the wetted case was lower than the 1 atm saturation temperature (100°C) because this test was open to atmosphere, so the actual temperature at the wick inner diameter was at some point between the dew point in the room and below 86°C. In comparing the wetted case to the control dry case, it was observed that over double the heat load was rejected at a lower temperature difference to ambient; thereby, indicating that water was wicking against gravity and evaporating near the heaters. This is further confirmed qualitatively by the thermal images in Fig. 8. In the dry case, the whole evaporator is more isothermal further from the heaters. In the wetted case, there is a sharp contrast in the temperature profile at the lower boundary of the heating elements. This is analogous to the expected behavior in a real heat pipe: the adiabatic section of the heat pipe should be mostly isothermal and intermediate to the condenser and evaporator temperatures.

The evaporator with a 1 mm thick wick was placed in the enclosed, thermally insulated beaker on a hot plate (the test configuration illustrated in Fig. 5) and was tested at variable heat loads to capture the overall thermal resistance and the heat load limit of the evaporator. It should be noted that prior to turning on the heaters, the beaker first is warmed up close to the saturation temperature using the hot plate. The transient characteristics of the test for a single data point are shown in Fig. 9, with the temperature difference between the 100°C saturation temperature and the actual measurement plotted.

![Fig. 9 Transient temperature response relative to 100°C saturation temperature are shown for a representative data point.](image)

The test results of several heat load test points are shown in Fig. 10, where the three hottest temperatures are plotted against input heat load with linear fits. The measurements at TC16 and TC8, while not shown, have confirmed that the water saturation temperature was 100±0.5°C by direct measurement of both the liquid pool (TC16) and vapor space (TC8), respectively. This figure, therefore, confirms the evaporator is able to operate up to approximately 70 W of heat load. Testing at higher heat loads up to the expected limit of 225 W for this article was precluded by the unexpectedly high temperatures.

Linear fits are inserted into this plot for thermocouples TC4, TC6, and TC13 – these fits have $R^2$ values of 0.89, 0.80, and 0.85, respectively. TC4 and TC13, which were offset angularly, exhibited similar temperature readings over the test range. TC6, which was located on the ceramic wall at the edge of a heater, exhibited considerably cooler temperatures perhaps because it was in less direct proximity to the heaters, and had a more controlled application of thermal epoxy when it was bonded on. At the maximum heat load tested of 70 W, TC6 outputted an unexpectedly high measurement. This could be indicative of partial dry-out, which would typically occur at the physically highest location in the heat pipe – this is where TC6 is located.

The apparent thermal resistance in the heat pipe was higher than expected. Using the test data (heat and temperature), the known thickness and thermal conductivity of the solid wall, an estimate of the apparent thermal conductivity of the wick can be made. When averaged across all the test results, the apparent effective thermal conductivity of wick is 0.59 W/m-K, which is below even the thermal conductivity of saturated liquid water at 100°C (0.68 W/m-K). The
uncertainty on the empirical thermal conductivity measurement by uncertainty propagation considering the heat input, thermocouple accuracy, and wick thickness tolerance totals approximately to 15%; however, this does not explain the discrepancy from the expected value of 3.0 W/m-K by calculation in Table 2. This measurement is also lower than the effective thermal conductivity of the wick test sample in air by GHFM (Table 2). This is seemingly non-physical, as saturated liquid water has approximately 20 times the thermal conductivity of air. The current suspected explanation lies in how the thermocouples are bonded to the wall and surrounded by insulation. It is suspected that the thermocouples are instead measuring the temperature of the polyimide insulated flexible heaters as opposed to the actual alumina wall temperature. In this case, the temperature of the heater includes additional contact resistance and conduction through an adhesive layer, as well as the actual heater element.

To further understand the possibility of interference from the heaters in the temperature measurement as opposed to the onset of dry out, a subset of the data at lower heat loads for TC6 were plotted in Fig. 11 since TC6 is least likely to be influenced by the thermal connection to the heaters. A best fit curve ($R^2 = 0.91$) is also plotted alongside a predicted temperature curve assuming an effective thermal conductivity as measured in air in Table 2. This focus on the lower heat flux values for TC6 improves the wick thermal conductivity estimate, but not enough even to meet the effective conductivity previously measured in air. It is also possible that there is poor contact between the sintered
wick and the wall due to issues during sintering, as Fig. 7 may suggest, and our assumption that bridging occurs further from the end is incorrect. Based on the behavior shown in Fig. 10 and Fig. 11, it would appear that either the thermal interference on the thermocouple measurements from the heaters or poor thermal connection between the wick and wall are the likely explanations for this unexpectedly low apparent thermal conductivity. Because of these uncertainties, the test results are most useful in demonstrating that a wicking evaporator concept has been demonstrated with approximately constant conductance up through at least 70 W of heat load. As this was a first attempt at a ceramic evaporator, future tests may illuminate more on the causes of the thermal conductivity discrepancy, and a closed heat pipe is expected to be the next developmental step.

VI. Conclusion

The concept for a ceramic sintered wick heat pipe, which is analogous to a conventional sintered metal heat pipe, was manufactured and experimentally demonstrated. The use of a ceramic material (Al₂O₃) for both the case and wick could enable future unique applications of such a heat pipe including harsh, high temperature metal working fluids, direct attachment to high voltage devices to eliminate the electrical insulator, electronics applications where good thermal performance and CTE matching is also a concern or use in high frequency & high flux density magnetic fields where eddy current losses would be a concern. Several test articles were produced to measure the rate of rise (and therefore capillary wicking performance), thermal conductivity, pore size distribution, and porosity. An evaporator test article was produced to use water as the working fluid, and flexible heaters were employed to test the performance of the evaporator when operating at 1 atm pressure and 100°C. Initial testing of this evaporator was completed and shown to behave as a constant conductance heat pipe.

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References