Visualization and thermal resistance of a sintered wicks structure evaporator in a two phase loop thermosyphon

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Abstract
A prototype two-phase loop thermosyphon (TPLT) was built and tested for thermal performance. This experimental study simultaneously investigated the evaporator resistance and flow visualization in operating the TPLT under sub-atmospheric pressure. To facilitate the visualization of flow regime in the evaporator, a transparent glass window was attached to the evaporator. Evaporators with 1-mm-thick sintered copper powder wicks (average diameter, 100 μm) were used. Temperature distribution and evaporator resistance were measured while increasing the input power in a series of 11 steps (20, 60, 100, 120, 140, 160, 180, 200, 220, 240, and 260 W) until the sintered wicks reached completely dried out. Temperature fluctuations and instabilities in the vapour and liquid lines were observed. Heat leakage from the evaporator and intermittent motion in the flow regime were significant factors in generating the implicit boiling instability. As the input power was increased, onset of pool boiling, nucleate boiling, as well as slug and bubbles were observed successively when the liquid level was above the surface of the wicks. When the net input power reached 236 W, the water film suddenly receded toward the wick surface. The process of the meniscus receding during the film evaporation, and the dynamics from the initial condition until dryout on the sintered copper wicks were observed and documented.

Key words: Visualization, Two phase loop thermosyphon, Evaporator resistance, Sintered powder wick, Meniscus receding

1. Introduction
Packaging and thermal management of electronic equipment has created demand for new and reliable methods for electronic cooling. Because of increased power levels and the miniaturization of electronic devices, typical cooling techniques such as conduction and forced or natural convection are unable to cool such a high heat flux. The increased integration of electronic systems requires improved cooling technology. Thermosyphon cooling is an alternative cooling technology for dissipating high heat flux. A thermosyphon is a two-phase heat transfer device with highly effective thermal conductivity. When heat is applied to the evaporator, the saturated liquid boils and evaporates. The heat from the evaporator section is released into the condenser section, which is positioned above the evaporator to ensure that the condensate returns under the influence of gravity. Loop thermosyphons improves the heat transfer efficiency of single-tube thermosyphons. The design reduces the collision of condensed liquid and gas, which flow in opposite directions. An advanced loop thermosyphon comprises an evaporator (where the liquid boils) and condenser (where the vapour condenses back to liquid) that are connected by a riser and downcomer. Loop thermosyphon cooling is among the most promising technologies because it can dissipate high heat fluxes with minimal difference in temperature (Kang, et al., 2010). Loop thermosyphons have many industrial applications because of their simplicity, high heat transfer capability, and passive nature. These loops have received extensive attention from academic and technical researchers (Franco, A and Filippeschi, S., 2012). The evaporation resistance of loop thermosyphons is critical
to their overall thermal performance. The evaporation resistance is influenced by many parameters, including heat flux, wick properties (e.g., type, thickness, porosity, and permeability), and the kind and filling ratio of working fluid. Because of experimental difficulties, limited studies on evaporation resistance measurement have been conducted under realistic sub-atmospheric pressure. Khodabandeh (2005) studied the heat transfer coefficient of a loop thermosyphon evaporator at a reduced pressure of 0.1. The tested evaporators were fabricated from small blocks of copper with vertical channels. Chang et al. (2012) devised and examined a highly efficient sub-atmospheric copper-water loop thermosyphon using a multi-channel evaporator with an enhanced boiling surface. With an enhanced boiling surface, the boiling heat transfer rate was elevated while suppressing the instabilities because of higher nucleation density and bubble frequency (Khodabandeh, R. and Furberg, R., 2010).

Kang et al. (2010) enhanced the boiling surface in the evaporator by using sintered copper wick structures to reduce the heater surface temperature. Compared with a wickless evaporator, the temperature of an evaporator with 1-mm-thick wicks was reduced by approximately 10% at a heat load of 150 W (Kang, et al., 2010).

This study comparatively examined the boiling flow structure, onset of pool boiling, pool boiling, film evaporation, and dryout of an operational loop thermosyphon by employing flow visualization and conducting thermal performance tests under sub-atmospheric conditions while incrementally increasing the heat input.

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>temperature, °C</td>
</tr>
<tr>
<td>$Q$</td>
<td>input power, W</td>
</tr>
<tr>
<td>$Q_{net}$</td>
<td>net input power, W</td>
</tr>
<tr>
<td>$R$</td>
<td>evaporator thermal resistance, °C/W</td>
</tr>
<tr>
<td>$t$</td>
<td>experiment test time, sec.</td>
</tr>
<tr>
<td>$P_{sat}$</td>
<td>saturation pressure, torr</td>
</tr>
</tbody>
</table>

**Subscripts**

- $m$: heater lower position
- $u$: heater upper position
- $s$: heater surface
- $v$: vapor line
- $l$: liquid line
- $c$: cooling jacket
- $\text{in}$: inlet
- $\text{out}$: outlet

2. Experimental methods

Figure 1 shows a schematic of the two-phase loop thermosyphon (TPLT) design used in this study. The TPLT comprised an evaporator, condenser, vapour line, and liquid line. When heat was applied to the evaporator, the liquid vaporizes and moves through the vapour line to the condenser where the heat is removed. Subsequently, the vapour condensed into the evaporator via the liquid line, and the cycle repeats. The evaporator comprised a 12-mm-high stainless steel chamber and 5-mm-high copper bottom plate with sintered copper powder wicks to enhance the boiling process. The steam chamber and bottom plate were joined by a heat-resistant O-ring and hex-head screws.

The bottom plate comprised a circular sintered powder wick structure (diameter, 35 mm; thickness, 1.0 mm). The size of the sintered powder was between 50 and 150 μm, and the porosity was approximately 51.671%. Figure 2 shows a scanning electronic microscopy (SEM) image of the sintered copper. A glass window was installed above the steam chamber to observe the fluid boiling in the bottom plate. The condenser comprised six vertical smooth copper tubes (OD, 6 mm; length, 81 mm). The condenser was fabricated using acrylic and copper plates with an inlet and outlet for cooling water. The inner diameters of the vapour and liquid lines were 6 and 3 mm, respectively, and the tube wall thickness was 1.5 mm. The evaporator and condenser were linked by the vapour and liquid lines.
The experimental apparatus comprised a heater, power supply, cooling water thermostat, flow meter, temperature acquisition instruments, high-speed camera, and personal computer. A DC power source was used to supply power to the heater. The heater was composed of a copper rod with a thermal conductivity of 385 W/m·K. The area of the heater was $31 \times 31$ mm. The temperature of the lower position $T_m$ and the upper position $T_u$ of the heater was measured using two thermocouples (PT-100). The temperatures at $T_m$ and $T_u$ were retrieved using a computer software system. With a
given heat transfer area, heat transfer distance, heat conduction coefficient of the copper rod, conception of Fourier Law, and ASTM-5470 D, the net input power $Q_{net}$ and surface temperature $T_s$ between the heater and loop thermosyphon can be obtained, as shown in Fig. 3 (Chen, et al., 2013). Two T-type thermocouples (diameter, 0.3 mm) were inserted into the inlet and outlet of the condenser to measure the temperature of the circulating cooling water at the inlet $T_{c,in}$ and outlet $T_{c,out}$. Four thermocouples were attached to the tube wall of the vapour and liquid lines to measure the temperature of the vapour ($T_{v,in}$ and $T_{v,out}$) and liquid ($T_{l,in}$ and $T_{l,out}$). The temperature measurement uncertainty was 0.1 °C. The flow rate of the cooling water was set at 0.18 L/min, and its temperature was maintained at 26 °C.

After evacuating and charging the system, the system input power was increased in a series of 11 steps (20, 60, 100, 120, 140, 160, 180, 200, 220, 240, and 260 W). Each power level was maintained until a steady system state was reached before increasing the power. The steady state was determined based on the stabilization of the heater surface temperature $T_s$. The transient and steady experimental data were recorded by a temperature acquisition instrument (imc SPARTAN-L) at 5-s intervals to evaluate the performance of the thermosyphon. Furthermore, the evaporator boiling mechanism was observed by high-speed camera (Phantom M310, 16 000FPS).

The thermal resistance of the evaporator can be expressed as follows Eq. (1):
\[ R = \frac{(T_s - T_{v,in})}{Q_{net}} \]  

where \( T_s \) is the heater surface temperature, \( T_{v,in} \) is the temperature of the inlet vapour, and \( Q_{net} \) is the net input power. The uncertainty analysis of the thermal resistance was calculated based on the following Eq. (2):

\[
w(R) = \left[ \left( \frac{\partial R}{\partial T_s} w(T_s) \right)^2 + \left( \frac{\partial R}{\partial T_{v,in}} w(T_{v,in}) \right)^2 + \left( \frac{\partial R}{\partial Q_{net}} w(Q_{net}) \right)^2 \right]
\]

where \( w(Q_{net}) \), \( w(T_s) \), and \( w(T_{v,in}) \) are uncertainties of the net input power, heater surface temperature, and vapour line inlet temperature, respectively. The uncertainty of the experiment was calculated at 1.63%–3.21%.

3. Results and discussion

3.1 Temperatures, input power and thermal resistance measured with time

Figure 4 shows the heater temperature \( T_s \), vapour line inlet temperature \( T_{v,in} \), evaporator thermal resistance \( R \), and saturated pressure corresponding to \( T_{v,in} \) at various net input powers \( Q_{net} \) with time at a 1-mm-thick wick. As anticipated, the heater temperature was consistently higher than the vapour line inlet temperature. The thermal resistance decreased as the input power increased. The variations in thermal resistance at an input power of 18 W (1.9 W/cm\(^2\)) were higher than others because of an intermittent generation of vapour bubbles at this stage (Chen, et al., 2013). While the input power was increasing from 18 to 54 W (1.9 to 5.6 W/cm\(^2\)), a marked drop in thermal resistance (from 0.45 to 0.2 °C/W) was observed because the incremental increase in input power was three times greater than at any other time. At an input power of 54 W (5.6 W/cm\(^2\)), the intermittently generated vapour bubbles transferred into a sustained and stable mode, and the thermal resistance of evaporator gradually stabilized. As shown in Fig. 4, dryout occurred when the input power was 236 W (24.6 W/cm\(^2\)), and this was attributed to a lack of liquid flowing back into the evaporator where the heater surface and evaporator temperature was 83.5 °C and 67.5 °C, respectively, and the thermal resistance of the evaporator was 0.07 °C/W.

![Fig. 4 Heater temperature, vapour line inlet temperature, pressure, input power and thermal resistance with time.](image_url)

Figure 5 shows that the temperature fluctuations were more prominent in \( T_{v,in} \) and \( T_{v,out} \) because the motion of the vapour flow was more intermittent. The temperature of the liquid line inlet \( T_{l,in} \) and cooling water outlet \( T_{c,out} \) were initially constant before increasing after applying an input power of 60 W when the liquid began boiling. The figure also shows that before the onset of boiling, the temperature of the liquid line outlet \( T_{l,out} \) increased because of the heat conduction from the evaporator. The temperature of the liquid line outlet \( T_{l,out} \) appeared to decrease when the condensate started flowing into the liquid line after the onset of boiling. On average, the liquid line outlet \( T_{l,out} \) was...
approximately 2 °C higher than that of the liquid line inlet $T_{\text{l,in}}$ after 3000 s because the heat leaking from the evaporator to the liquid line preheated the working fluid prior to entering the evaporator. The temperature fluctuations in $T_{\text{l,out}}$ were higher when the input power was above 200 W because of the steadier supply of condensate. The combination of heat leakage from the evaporator and intermittent motion of the vapour and liquid flow were factors in generating the implicit boiling instability.

3.2 Visualization observed from onset of pool boiling to dryout

The visualization focused on the wick structure of the evaporator because the major phenomena occurred in this area. Initially, the liquid level was approximately 6 mm above the wick surface. Figure 6 shows the top view of the wick surface and a line graph denoting the increasing heater temperature. Initially, the liquid level was approximately 6 mm above the wick surface. Figure 6(a) shows that after applying an input power of 18W (1.9 W/cm$^2$), the liquid continued to rise in temperature until bubbles appeared on the wick surface (heater surface temperature, 43.4 °C). Figure 6(b) shows bubbles that rose from isolated nucleation sites in the boiling range of the pool nucleate. As the power and temperature were increased, increasingly more sites were activated. Fig 6(c) shows that successive bubbles merged into slugs and relatively continuous vapour columns when $T_s = 69.5$ °C; and some areas of the wick surface remained visible. In the film boiling regime (Fig. 6(d)), a vapour film blanketed the entire wick surface. With increasing heat load, the amount of evaporated water was more than the returning condensate, and the liquid level continued to decline. When the water receded to the surface of the wick, the film evaporation happened, and only a few bubbles were observable (Fig. 6(e)). When the liquid level dropped below the surface of wicks, the evaporator resistance decreased until $T_s$ increased suddenly, and partial dryout occurred (Fig. 6(f)). Figure 7, 8, and 9 show a series of images from top view and diagrammatic side view representations of bubble nucleation, bubble formation, and film evaporation, respectively. The observation was carried from the top of the glass, so that the phenomenon of inside the wick could not be seen. The schematic side view images of inside the wick were hypotheses based on the corresponding video.

3.2.1 Pool boiling on sinter wicks

Figure 7 shows a schematic of the onset of the boiling liquid and the corresponding photograph of the sintered wicks. The first bubbles started forming at the interspaces of the wicks and heating surface; the liquid was slightly superheated and the bubbles condensed before reaching the wick surface. Therefore, no bubbles were observed forming on the wick surface (Fig. 7a). As the excess temperature increased, bubble inception eventually occurred on the wick surface. When the input power increased, a 0.2 mm bubble was observed (Fig. 7b). The size of the sintered powder was between 50 and 150 μm, so the diameter of the bubble released from a hole in Fig.7 is smaller than it of commonly known. The inertia of the liquid caused the bubble to grow (Fig. 7c), and the vapour bubble became separated from the
sintered wick when its diameter expanded to 0.5 mm (Fig. 7d). The bubble grew from 0.2 to 0.6 mm in 1.4 s (Figs. 7b–7e). After the inertia forces dissipated, the bubble began to collapse. Figs. 7e and 7f show that a 0.6 mm bubble collapsed within approximately 0.1 s. The fluid motion in this mode of boiling was governed by natural convection currents, and the heat transfer from the heating surface to the fluid was by natural convection.

![Fig. 7](image)

Fig. 7 Series of images from top view and diagrammatic side view representations of bubble nucleation in sintered wick at 11,000 fps.
3.2.2 Film evaporation

Figure 8 shows a schematic and photograph of the bubble formation as the water film receded. When the input power reached a critical value, the water film suddenly receded toward the wick surface, and the menisci further receded toward the inside of the wicks. The corresponding bubble formation at the same position was photographed using a high-speed camera within 1578 ms. Figs. 8a–8c show that the number and size of the bubbles on the wick cavities decreased. The absence of cavity bubbles may have resulted from the high evaporation rate of the liquid film and high disjoining pressure, which may increase the boiling superheat (Lin, et al., 1995). The augmentation of the area of liquid film evaporation coupled with the thinner film resulted in the lowest thermal resistance of 0.07 ºC/W in this study (Fig. 4). Finally, the menisci receded and wick surfaces dried out during the evaporation on the sintered copper wick (Fig. 8d). Figure 9 shows a series of images from the top view and diagrammatic representations of the film evaporation when the water film receded to the wick surface. Initially, a 0.2-mm-diameter bubble was observed forming on the wick pore, and few large bubbles were generated and trapped inside the pores. The bubble on wick surface directly evaporated, and the bubble departure process was not directly observed during the evaporation process. The time for the bubble to nucleate, expand, and burst was very brief. Figure 9 shows that it took approximately 9 ms to evaporate a 0.2-mm-diameter bubble.

![Fig. 8](image1.png)

Fig. 8 Series of images from top view and diagrammatic side view representations of bubble formation with water film receding at 11,000 fps.

![Fig. 9](image2.png)

Fig. 9 Series of images from top view and diagrammatic side view representations of film evaporation when water film recedes to the wick surface at 16,000 fps.
Table 1 shows the main results of the thermal measurements during dryout. This study measured temperatures and calculated the thermal resistance at 5 s intervals. The first sudden jump in R from 0.074 to 0.083 °C/W occurred when $t$ was between 13,375 and 13,380 s, at which point $Q_{net}$ dropped from 236.3 to 232.6 W. Figure 10 shows the corresponding sequential images of the evaporation process for the sintered wick at 236 W. From the video, it is easy to distinguish whether the surface of the wick is wet or dry. But sometimes it is difficult to distinguish which part of the wick is wet or dry from the pictures. As shown at time $t$, a large part of the upper wicks was exposed, some exposed surface were light reflecting and only few of the wick surfaces and pores were wetted. Circle the apparent wetted surface and wetted pore were to illustrate and compare. As $T_s$ increased, the water film receded, surface and pore became partially wetted, as can be seen at $t + 15$ and $t + 41$ ms. At $t + 118$ and $t + 143$ ms, the water film receded to the lower wick with the wick surface exposed. The video shows a small amount of vapour streaming out from the wick pores. At $t + 184$ ms, dryout extended to the wick surface. The water film could no longer be observed after the heat flux approached the critical value because of the lack of condensate flowing back to the evaporator.

Table 1 Thermal performances of evaporator during dryout.

<table>
<thead>
<tr>
<th>$t$ (sec.)</th>
<th>$Q$ (W)</th>
<th>$T_s$ (°C)</th>
<th>$T_{v, in}$ (°C)</th>
<th>$R$ (°C/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13355</td>
<td>235.2</td>
<td>83.7</td>
<td>66.0</td>
<td>0.075</td>
</tr>
<tr>
<td>13360</td>
<td>235.2</td>
<td>83.7</td>
<td>66.3</td>
<td>0.074</td>
</tr>
<tr>
<td>13365</td>
<td>235.7</td>
<td>83.7</td>
<td>66.3</td>
<td>0.074</td>
</tr>
<tr>
<td>13370</td>
<td>236.3</td>
<td>83.6</td>
<td>66.0</td>
<td>0.075</td>
</tr>
<tr>
<td><strong>13375</strong></td>
<td><strong>236.3</strong></td>
<td><strong>83.6</strong></td>
<td>66.1</td>
<td><strong>0.074</strong></td>
</tr>
<tr>
<td><strong>13380</strong></td>
<td><strong>232.6</strong></td>
<td><strong>84.4</strong></td>
<td>65.0</td>
<td><strong>0.083</strong></td>
</tr>
<tr>
<td>13385</td>
<td>228.3</td>
<td>85.3</td>
<td>65.4</td>
<td>0.087</td>
</tr>
<tr>
<td>13390</td>
<td>226.2</td>
<td>85.9</td>
<td>65.9</td>
<td>0.088</td>
</tr>
<tr>
<td>13395</td>
<td>223.6</td>
<td>86.7</td>
<td>65.3</td>
<td>0.096</td>
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<tr>
<td>13400</td>
<td>216.2</td>
<td>88.5</td>
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<tr>
<td>13405</td>
<td>209.8</td>
<td>90.2</td>
<td>65.8</td>
<td>0.116</td>
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<tr>
<td>13410</td>
<td>206.7</td>
<td>91.2</td>
<td>64.7</td>
<td>0.128</td>
</tr>
</tbody>
</table>

Fig. 10  Sequential images of evaporation process for sintered wick at 236W at 11,000 fps.
4. Conclusion

Evaporator resistance measurement and flow visualization were simultaneously performed for sintered copper powder wicks while operating a TPLT under sub-atmospheric pressure. This study successfully observed the formation of the onset of pool boiling, nucleate boiling, slug and bubble formation, film boiling, and meniscus receding process during the film evaporation and dryout on sintered copper wicks.

The main findings are summarized as follows:

- The evaporator resistance decreased in conjunction with incremental increases in the input power and along with water recession until a minimal thermal resistance of 0.07 °C/W and maximal value of 236 W were reached.
- A combination of heat leakage from the evaporator and intermittent motion of the vapour and liquid flow were factors in generating the implicit boiling instability.
- With increasing input power, the water film receded to the wick surface, and then the film evaporation happened. The bubbles on the wick surface directly evaporated, and the time for the bubbles to nucleate, expand, and burst was very short (9 ms).
- When the input power reached a critical value, the water film suddenly receded toward the wick surface, and the menisci receded further because of the lack of water flowing back. At this point, the thermal resistance began increasing because of the partial dryout of the sintered wicks.
- Future studies should concentrate on applying a compensation chamber to the TPLT to prevent the heat leaking from the evaporator toward the condenser, and providing continuous operation when the evaporator would normally experience dryout.

References