Advances and Unsolved Issues in Pulsating Heat Pipes

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Pulsating (or oscillating) heat pipes (PHP or OHP) are new two-phase heat transfer devices that rely on the oscillatory flow of liquid slug and vapor plug in a long miniature tube bent into many turns. The unique feature of PHPs, compared with conventional heat pipes, is that there is no wick structure to return the condensate to the heating section; thus, there is no countercurrent flow between the liquid and vapor. Significant experimental and theoretical efforts have been made related to PHPs in the last decade. While experimental studies have focused on either visualizing the flow pattern in PHPs or characterizing the heat transfer capability of PHPs, theoretical examinations attempt to analytically and numerically model the fluid dynamics and/or heat transfer associated with the oscillating two-phase flow. The existing experimental and theoretical research, including important features and parameters, is summarized in tabular form. Progresses in flow visualization, heat transfer characteristics, and theoretical modeling are thoroughly reviewed. Finally, unresolved issues on the mechanism of PHP operation, modeling, and application are discussed.

INTRODUCTION

Evolution in the design of the heat pipe—a type of passive two-phase thermal control device—has accelerated in the past decade due to continuous demands for faster and smaller microelectronic systems. As modern computer chips and power electronics become smaller and more densely packed, the need for more efficient cooling systems increases. The new design of a computer chip at Intel, for instance, will produce localized heat flux over 100 W/cm², with the total power exceeding 300 W. In addition to the limitations on maximum chip temperature, further constraints may be imposed on the level of temperature uniformity in electronic components. Heat pipes are a very promising technology for achieving high local heat-removal rates and uniform temperatures on computer chips.

True development of conventional heat pipes (CHP) began in the 1960s; since then, various geometries, working fluids, and wick structures have been proposed [1]. In the last 20 years, new types of heat pipes—such as capillary pumped loops and loop heat pipes—were introduced, seeking to separate the liquid and vapor flows to overcome certain limitations inherent in conventional heat pipes. In the 1990s, Akachi et al. [2] invented a new type of heat pipe known as the pulsating or oscillating heat pipe (PHP or OHP). The most popular applications of PHP are found in electronics cooling because it may be capable of dissipating the high heat fluxes required by next generation electronics. Other proposed applications include using PHPs to preheat air or pump water. This review article will describe the operation of pulsating heat pipes, summarize the research and development over the past decade, and discuss the issues surrounding them that have yet to be resolved.

Pulsating heat pipes, like conventional heat pipes, are closed, two-phase systems capable of transporting heat without any additional power input, but they differ from conventional heat pipes in several major ways. A typical PHP is a small meandering tube that is partially filled with a working fluid, as seen in Figure 1 [3]. The tube is bent back and forth parallel to itself, and the ends of the tube may be connected to one another in a closed loop, or pinched off and welded shut in an open loop (see Figure 1a and 1b). It is generally agreed by researchers that the closed-loop PHP has better heat transfer performance [4, 5]. For this reason, most experimental work is done with closed-loop PHPs. In addition to the oscillatory flow, the working fluid can also be circulated in the closed-loop PHP, resulting in heat...
transfer enhancement. Although an addition of a check valve (see Figure 1c) could improve the heat transfer performance of the PHPs by making the working fluid move in a specific direction, it is difficult and expensive to install these valves. Consequently, the closed-loop PHP without a check valve becomes the most favorable choice for the PHP structures. Recently, PHPs with a sintered metal wick have been prototyped by Zuo et al. [6, 7] and analyzed by Holley and Faghri [8]. The wick should aid in heat transfer and liquid distribution. There has also been some exploration into pulsating heat pipes in which one or both ends are left open without being sealed (see Figure 1d) [9–11].

Like a CHP, a PHP must be heated in at least one section and cooled in another. Often the evaporators and condensers are located at the bends of the capillary tube. The tube is evacuated and then partially filled with a working fluid. The liquid and its vapor will become distributed throughout the pipe as liquid slugs and vapor bubbles. As the evaporator section of the PHP is heated, the vapor pressure of the bubbles located in that section will increase. This forces the liquid slug toward the condenser section of the heat pipe. When the vapor bubbles reach the condenser, it will begin to condense. As the vapor changes phase, the vapor pressure decreases, and the liquid flows back toward the condenser end. In this way, a steady oscillating flow is set up in the PHP. Boiling the working fluid will also cause new vapor bubbles to form. The unique feature of PHPs, compared with conventional heat pipes, is that there is no wick structure to return the condensate to the heating section, and therefore there is no countercurrent flow between the liquid and the vapor. Due to the simplicity of the structure of a PHP, its weight is lower than that of conventional heat pipe, which makes PHP an ideal candidate for space application.

Research on PHPs can be categorized as either experimental or theoretical. While experimental studies have focused on either visualizing the flow pattern in PHPs or characterizing the heat transfer capability of PHPs, theoretical examinations attempt to analytically and numerically model the fluid dynamics and/or heat transfer associated with oscillating two-phase flow. The existing experimental and theoretical research and their parameters are summarized in Table 1. The table lists the primary investigators, reference number, and the year the study was published, followed by the details of the modeling and/or experiment: theoretical approaches, major assumptions, the material used to manufacture the PHP, the geometry and configuration of the flow channel, number of parallel channels, inclination angles, channel diameters, the working fluids tested, the charge ratios that they were tested at, range of heat transferred by the PHP, a summary of the conclusions drawn by the investigator, and other significant comments. This article also presents the principles of operation, flow visualization, heat transfer, and modeling, as well as a discussion of the unresolved issues in PHP research.

**PRINCIPLES OF OPERATION**

Although simple in their construction, PHPs become complicated devices when one tries to fully understand their operation: the thermodynamics driving PHP operation, the fluid dynamics governing the two-phase oscillating flow, heat transfer (both sensible and latent), and the physical design parameters of the PHP must all be considered.

**Thermodynamic Principles**

Heat addition and rejection and the growth and extinction of vapor bubbles drive the flow in a PHP. Even though the exact features of the thermodynamic cycle are still unknown, Groll and Khandekar [12] described it in general terms using a pressure/enthalpy diagram as seen in Figure 2. The temperature and vapor quality in the evaporator and condenser are known, or can be assumed, so the state at the outlets of the evaporator and condenser are known. Starting at the evaporator inlet, point A on the P-h diagram, the processes required to get to point B on the diagram can be simplified to heat input at a constant pressure combined with isentropic pressure increase due to bubble expansion. As one travels through the adiabatic section from the evaporator to the condenser, the pressure decreases isentropically. The thermodynamic process between the condenser’s inlet and outlet are complicated, but can be simplified to constant pressure condensation with negative isentropic work. An isenthalpic pressure drop in the adiabatic section completes the cycle. Because of the numerous assumptions made in this description, thermodynamic analysis is insufficient to study PHPs.

**Fluid Dynamic Principles**

Fluid flow in a capillary tube consists of liquid slugs and vapor plugs moving in unison. The slugs and plugs initially distribute themselves in the partially filled tube. The liquid slugs are able to completely bridge the tube because surface tension forces overcome gravitational forces. There is a meniscus region on either end of each slug caused by surface tension at the solid/liquid/vapor interface. The slugs are separated by plugs...
<table>
<thead>
<tr>
<th>Investigator</th>
<th>Theoretical approaches</th>
<th>Investigator</th>
<th>Theoretical approaches</th>
<th>Sample text</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akachi et al. [2]</td>
<td>None N/A</td>
<td>Maezawa et al. [27]</td>
<td>None N/A</td>
<td>Thermal resistance is independent of heat input and inclination angle if the number of turns is greater than 80.</td>
</tr>
<tr>
<td>Miyazaki and Akachi [28]</td>
<td>Differential relationship between propagation wave of ( \Delta p ) and oscillatory flow ( \Delta \alpha ) excited by each other.</td>
<td>Miyazaki and Akachi [48]</td>
<td>None N/A</td>
<td>Wave equation of pressure was derived.</td>
</tr>
<tr>
<td>Miyazaki and Arikawa [49]</td>
<td>None N/A</td>
<td>Nishio [29]</td>
<td>None N/A</td>
<td>measured wave velocities fairly agreed with Eq. (14).</td>
</tr>
<tr>
<td>Gi et al. [4]</td>
<td>None N/A</td>
<td>Toffan</td>
<td>None N/A</td>
<td>Flow visualizations</td>
</tr>
<tr>
<td>Investigator (year)</td>
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<td>Open/closed loop</td>
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<tr>
<td>Hosoda et al. [19] (1999)</td>
<td>Numerical solution of 1-D liquid and vapor flow.</td>
<td>Thin liquid film, pressure loss at bends, and viscous dissipation are neglected.</td>
<td>Glass</td>
<td>Closed</td>
</tr>
<tr>
<td>Lee et al. [15] (1999)</td>
<td>None</td>
<td>N/A</td>
<td>Brass, acrylic</td>
<td>Closed</td>
</tr>
<tr>
<td>Zuo et al. [6] (1999)</td>
<td>Oscillatory flow modeled similar to mechanical vibration with viscous damping.</td>
<td>Vapor is an ideal gas. Laminar liquid flow. Heat transfer is neglected.</td>
<td>Sintered and plate copper</td>
<td>Closed</td>
</tr>
<tr>
<td>Zuo et al. [7] (2001)</td>
<td>Mass, momentum, and energy equations of 1-D transient two-phase flow are solved using SIMPLEC scheme.</td>
<td>Liquid and vapor phases are at local equilibrium. Convection dominate in axial direction.</td>
<td>Copper</td>
<td>Closed</td>
</tr>
<tr>
<td>Dobson and Hams [9] (1999)</td>
<td>Explicit finite difference scheme is used to solve equations for motion and heat transfer.</td>
<td>Vapor is an ideal gas. Incompressible liquid. No heat transfer in liquid.</td>
<td>Copper</td>
<td>Unlooped with open end</td>
</tr>
<tr>
<td>Author(s)</td>
<td>Type of Study</td>
<td>Material</td>
<td>Diameter</td>
<td>Orientation</td>
</tr>
<tr>
<td>-------------------</td>
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</tr>
<tr>
<td>Dobson [11]</td>
<td>None</td>
<td>Stainless steel</td>
<td>Open Circular</td>
<td>46</td>
</tr>
<tr>
<td>Kiseev and Zolkin [43]</td>
<td>None</td>
<td>Stainless steel</td>
<td>Open Circular</td>
<td>46</td>
</tr>
<tr>
<td>Lin et al. [31] (2001)</td>
<td>None</td>
<td>Copper</td>
<td>Open Circular</td>
<td>40</td>
</tr>
<tr>
<td>Tong et al. [20] (2001)</td>
<td>None</td>
<td>Pyrex glass</td>
<td>Closed Circular</td>
<td>14</td>
</tr>
<tr>
<td>Shafii et al. [13] (2001)</td>
<td>Mass, momentum, and energy equations for each liquid slug and vapor plug are solved.</td>
<td>N/A</td>
<td>Open/ closed Circular</td>
<td>4</td>
</tr>
</tbody>
</table>

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<tr>
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<th>Parallel channels</th>
<th>Inclination angle (°)</th>
<th>$D$ (mm)</th>
<th>Working fluid</th>
<th>Charge ratio $q$ (W)</th>
<th>Conclusions and comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shafii et al. [14] (2002)</td>
<td>Thin film evaporation and condensation were solved to get latent heat transfer coefficient.</td>
<td>N/A</td>
<td>Water</td>
<td>Open/ closed</td>
<td>Circular</td>
<td>4</td>
<td>—</td>
<td>1.5, 3.0</td>
<td>Water</td>
<td>64.21–89.5</td>
<td>0–119</td>
</tr>
<tr>
<td>Cai et al. [17] (2002)</td>
<td>None</td>
<td>N/A</td>
<td>Quartz, copper</td>
<td>Closed, open</td>
<td>Circular</td>
<td>12, 50</td>
<td>45, 0</td>
<td>2.4, 2.2</td>
<td>Ethanol, water, acetone, ethanol, ammonia</td>
<td>50, 40–60</td>
<td>100–600</td>
</tr>
<tr>
<td>Khandekar et al. [16] (2002)</td>
<td>None</td>
<td>N/A</td>
<td>Aluminum/ glass, copper/ glass</td>
<td>Closed</td>
<td>Rectangular, rectangular, circular</td>
<td>12, 12, 10</td>
<td>0–90</td>
<td>2.2×2, 1.5×1, 2.0</td>
<td>Water, ethanol</td>
<td>10–70</td>
<td>25–70</td>
</tr>
<tr>
<td>Khandekar et al. [56] (2002)</td>
<td>Artificial Neural Network (ANN) is used to predict PHP performance.</td>
<td>Copper</td>
<td>Closed</td>
<td>Circular</td>
<td>10</td>
<td>90</td>
<td>2</td>
<td>Ethanol</td>
<td>0–100</td>
<td>—</td>
<td>ANN is trained by experiments. Effects of diameter, number of turns, length, inclination angle, and fluid properties are not in the model.</td>
</tr>
<tr>
<td>Khandekar et al. [24] (2002)</td>
<td>None</td>
<td>Glass/ copper</td>
<td>Closed</td>
<td>Circular</td>
<td>10</td>
<td>0, 45, 90</td>
<td>2</td>
<td>Water, ethanol</td>
<td>0–100</td>
<td>5–15</td>
<td>Effect of gravity is negligible. Bubble formation and collapse are discussed.</td>
</tr>
<tr>
<td>Author(s)</td>
<td>Year</td>
<td>Description</td>
<td>Material(s)</td>
<td>Diameter</td>
<td>Length</td>
<td>Heat Transfer Coefficient</td>
<td>Temperature Difference</td>
<td>Amplitude</td>
<td>Frequency</td>
<td>Notes</td>
<td></td>
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<tr>
<td>Ma et al. [32] (2002)</td>
<td></td>
<td>Liquid slug oscillation is described by the balance of thermally driven, capillary, frictional, and elastic restoring forces. Heat transfer in evaporator is modeled as convective boiling in a tube.</td>
<td>Copper</td>
<td>Open Circular</td>
<td>4</td>
<td>0</td>
<td>1.67</td>
<td>Acetone</td>
<td>—</td>
<td>5–20</td>
<td>Minimum onset temperature difference is 15°C. Range of operational temperature difference is studied. Model underpredicts temperature drops.</td>
</tr>
<tr>
<td>Zhang and Faghri [10] (2002)</td>
<td></td>
<td>Evaporation and condensation on thin film left behind by liquid slug is solved.</td>
<td>N/A</td>
<td>Open Circular</td>
<td>1</td>
<td>0</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Overall heat transfer is dominated by sensible heat transfer. Frequency and amplitude are not affected by surface tension.</td>
</tr>
<tr>
<td>Zhang et al. [52] (2002)</td>
<td></td>
<td>Liquid–vapor pulsating flow in a U-shaped miniature tube is investigated.</td>
<td>N/A</td>
<td>Open Circular</td>
<td>2</td>
<td>−90</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>The amplitude and frequency of oscillation were correlated to the heat transfer coefficients and temperature difference.</td>
</tr>
<tr>
<td>Zhang and Faghri [53] (2003)</td>
<td></td>
<td>Liquid–vapor pulsating flow in PHP with arbitrary number of turns is investigated.</td>
<td>N/A</td>
<td>Open Circular</td>
<td>Any</td>
<td>−90</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Amplitude and circular frequency decrease by decreasing the lengths of the heating and cooling sections. Increasing the charge ratio resulted in a decrease of amplitudes and an increase of circular frequency.</td>
</tr>
<tr>
<td>Charoensawan et al. [34] (2003)</td>
<td></td>
<td>None</td>
<td>N/A</td>
<td>Copper</td>
<td>Closed Circular</td>
<td>10–46</td>
<td>0, 90</td>
<td>1.0, 2.0</td>
<td>Water, ethanol, R-123</td>
<td>50</td>
<td>200–1100</td>
</tr>
<tr>
<td>Investigator (year)</td>
<td>Theoretical approaches</td>
<td>Assumptions</td>
<td>Materials</td>
<td>Open/ closed loop</td>
<td>Flow path geometry</td>
<td>Parallel channels</td>
<td>Inclination angle (°)</td>
<td>D (mm)</td>
<td>Working fluid</td>
<td>Charge ratio</td>
<td>q (W)</td>
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</tr>
<tr>
<td>Khandekar et al. [23] (2003)</td>
<td>None</td>
<td>N/A</td>
<td>Pyrex, glass</td>
<td>Closed</td>
<td>Circular</td>
<td>20–58</td>
<td>0, 90</td>
<td>2</td>
<td>R-123</td>
<td>50</td>
<td>5,000–70,000 W/m²</td>
</tr>
<tr>
<td>Khandekar et al. [33] (2003)</td>
<td>None</td>
<td>N/A</td>
<td>Copper</td>
<td>Closed</td>
<td>Circular</td>
<td>10</td>
<td>0, 90</td>
<td>2</td>
<td>Water, ethanol, R-123</td>
<td>0–100</td>
<td>5–65, 5–60, 5–25</td>
</tr>
<tr>
<td>Khandekar and Groll [21] (2004)</td>
<td>None</td>
<td>N/A</td>
<td>Glass/copper</td>
<td>Closed</td>
<td>Circular</td>
<td>2</td>
<td>0, 90</td>
<td>2</td>
<td>Ethanol</td>
<td>0–100</td>
<td>14.8–74.4</td>
</tr>
<tr>
<td>Rittidech et al. [3] (2003)</td>
<td>None</td>
<td>N/A</td>
<td>Copper</td>
<td>Open</td>
<td>Circular</td>
<td>38–84</td>
<td>0</td>
<td>0.55, 1.05, 2.03</td>
<td>Ethanol, Water, R-123</td>
<td>50</td>
<td>2,000–12,000 W/m²</td>
</tr>
<tr>
<td>Rittidech et al. [35] (2005)</td>
<td>None</td>
<td>N/A</td>
<td>Copper</td>
<td>Open</td>
<td>Circular</td>
<td>16 per PHP, 32 PHPs</td>
<td>—</td>
<td>2</td>
<td>Water, R-123</td>
<td>50</td>
<td>1460–3504 (Total)</td>
</tr>
<tr>
<td>Authors</td>
<td>Type</td>
<td>Material</td>
<td>Pressure</td>
<td>Angle</td>
<td>Temperature</td>
<td>Fluids</td>
<td>Performance Notes</td>
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<tr>
<td>Liang and Ma [54] (2004)</td>
<td>None</td>
<td>N/A</td>
<td>Circular</td>
<td>0</td>
<td>1, 2, 5</td>
<td>Water</td>
<td>Vapor bubble is considered as gas spring. Vapor bubbles are uniformly distributed. Isentropic bulk modulus generates stronger oscillations than the isothermal bulk modulus.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gu et al. [44] (2004)</td>
<td>None</td>
<td>Aluminum</td>
<td>Closed</td>
<td>Rectangular</td>
<td>96</td>
<td>1 × 1</td>
<td>R114</td>
<td>50-60</td>
<td>14–5.9</td>
<td>PHP performed better in microgravity than normal or hyper gravity. New equation of critical diameter in microgravity is developed.</td>
<td></td>
</tr>
<tr>
<td>Riehl [36] (2004)</td>
<td>None</td>
<td>Copper</td>
<td>Open</td>
<td>Circular</td>
<td>13</td>
<td>0, 90</td>
<td>1.5</td>
<td>Acetone, ethanol, isopropyl, alcohol, methanol1, water</td>
<td>Performance is better when operating in a horizontal orientation. Better performances were obtained when acetone was used in vertical orientation and methanol was used on horizontal orientation.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zhang et al. [5] (2004)</td>
<td>None</td>
<td>Copper</td>
<td>Open and closed</td>
<td>Circular</td>
<td>6</td>
<td>90</td>
<td>1.18</td>
<td>FC-72, ethanol, water</td>
<td>Open loop PHP did not work. A minimum heat input is necessary to initiate pulsating flow. Closed loop PHP. Optimum charge ratio is 70% for all three fluids.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sakulchangsatjatai et al. [51] (2004)</td>
<td>None</td>
<td>N/A</td>
<td>—</td>
<td>Open and closed</td>
<td>—</td>
<td>—</td>
<td>0.66, 1.06, 2.03</td>
<td>Heat flux increases with decreasing evaporator length, and increasing latent heat and number of turns. Correlation to predict heat transfer characteristics was proposed.</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Katpradit et al. [37] (2005)</td>
<td>None</td>
<td>Copper</td>
<td>Open</td>
<td>Circular</td>
<td>10, 20, 30</td>
<td>0, 90</td>
<td>0.66, 1.06, 2.03</td>
<td>Model is same as Shafii et al. (2001). The predicted heat transfer rate is compared to experimental results in literature.</td>
<td></td>
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<th>Inclination angle (°)</th>
<th>$D$ (mm)</th>
<th>Working fluid</th>
<th>Charge ratio $q$ (W)</th>
<th>Conclusions and comments</th>
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</thead>
<tbody>
<tr>
<td>Xu et al. [25] (2005)</td>
<td>None</td>
<td>N/A</td>
<td>Glass/copper</td>
<td>Closed</td>
<td>Circular</td>
<td>8</td>
<td>90</td>
<td>2</td>
<td>Water, methanol</td>
<td>10, 30</td>
<td>Flow circulation was observed. Flows in some channels are in the opposite direction of bulk circulation. Both startup and steady thermal oscillations were studied. Oscillation flow at low heating power displays random behavior and becomes quasi-periodic at high heat power.</td>
</tr>
<tr>
<td>Xu and Zhang [41] (2005)</td>
<td>None</td>
<td>N/A</td>
<td>Copper</td>
<td>Closed</td>
<td>Circular</td>
<td>8</td>
<td>90</td>
<td>2</td>
<td>FC-72</td>
<td>70</td>
<td>10–25.6</td>
</tr>
<tr>
<td>Holley and Faghri [8] (2005)</td>
<td>Mass, momentum and energy equations are solved for PHP with sintered copper wick and varying channel diameter.</td>
<td>Liquid is incompressible. Neglecting losses at bends. Saturated vapor with negligible flow friction.</td>
<td>—</td>
<td>Circular</td>
<td>24</td>
<td>0</td>
<td>1.397, 1.568</td>
<td>Water</td>
<td>40, 55, 70</td>
<td>100–400</td>
<td>Minimal temperature difference and fluctuation appear at operating temperature between 120°C and 160°C. At 100 W, the temperature difference can be reduced from 42°C to 25°C for the nanofluid OHP as opposed to the pure water OHP.</td>
</tr>
<tr>
<td>Cai et al. [40] (2006)</td>
<td>None</td>
<td>N/A</td>
<td>Stainless steel, copper</td>
<td>—</td>
<td>Circular</td>
<td>24</td>
<td>0</td>
<td>1.397, 1.568</td>
<td>Water</td>
<td>40, 55, 70</td>
<td>100–400</td>
</tr>
<tr>
<td>Ma et al. [45] (2006)</td>
<td>None</td>
<td>N/A</td>
<td>Copper</td>
<td>Closed</td>
<td>Circular</td>
<td>24</td>
<td>90</td>
<td>1.65</td>
<td>Nanofluid (water with diamond nanoparticles)</td>
<td>50</td>
<td>5–336</td>
</tr>
<tr>
<td>Study Reference</td>
<td>Methodology</td>
<td>Fluids</td>
<td>Channel Shape</td>
<td>Channel Size</td>
<td>Pressure Difference</td>
<td>Operating Temperature</td>
<td>Prandtl Number</td>
<td>Karman Number</td>
<td>Modified Jacob Number</td>
<td>Bond Number</td>
<td>Kutateladze Number</td>
</tr>
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<td>-----------------</td>
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<tr>
<td>Ma et al. [55]</td>
<td>Laplace transformation was used to solve the ODE that accounts for the balance of thermally driven, frictional, and elastic restoring forces.</td>
<td>Water, acetone</td>
<td>Circular</td>
<td>1.65</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charoensawan and Terdtoon [38] (2007)</td>
<td>Nondimensional empirical correlation for heat transfer of PHP is proposed. Four dimensionless numbers are identified.</td>
<td>Copper</td>
<td>Closed</td>
<td>Circular</td>
<td>10, 22, 32, 52</td>
<td>0</td>
<td>1, 1.5, Water</td>
<td>30, 50, 80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qu et al. [39] (2007)</td>
<td>None</td>
<td>Copper</td>
<td>Closed</td>
<td>Square, triangle</td>
<td>16</td>
<td>90, –90</td>
<td>1, 1.5</td>
<td>Water</td>
<td>25–40</td>
<td>7.3–33.3 W/cm²</td>
<td>PHP with triangle channel performs better than that with square channel. PHP with 1.5 mm channel performs better than that with 1 mm channel.</td>
</tr>
<tr>
<td>Khandekar and Gupta [42] (2007)</td>
<td>Heat conduction in the radiator plate is solved using FLUENT. The contribution of PHP is modeled using an effective thermal conductivity.</td>
<td>Aluminum</td>
<td>Closed</td>
<td>Circular</td>
<td>22</td>
<td>90, 0</td>
<td>Water</td>
<td>50</td>
<td>20–62.5</td>
<td>Embedded PHP can be beneficial only if the conductivity of the plate is low.</td>
<td></td>
</tr>
</tbody>
</table>
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Figure 2 Thermodynamics of a PHP [12].

Figure 3 Liquid slug in a PHP [13].

of the working fluid in the vapor phase. The vapor plug is surrounded by a thin liquid film trailing from the slug.

Figure 3 shows the control volume for one liquid slug in a PHP and the forces acting on it [13]. Motion of the ith liquid slug within the PHP with an inner diameter of $D$ and cross-sectional area of $A$ can be described by the simplified momentum equation given by [13,14]:

$$\frac{d m_{i\ell}}{dt} = \left[ p_{v_i} - p_{v(i+1)} \right] A - \pi D L_{i\ell} \tau$$  \hspace{1cm} (1)

where $m_{i\ell}$, $v_{i\ell}$, and $L_{i\ell}$ are the mass, velocity and length of the ith liquid slug, respectively. The difference between vapor pressures of the ith and the $(i+1)$th vapor plug, $p_{v_i} - p_{v(i+1)}$, are the driving force for the oscillatory flow. The shear stress, $\tau$, depends on whether the liquid flow is laminar or turbulent.

Heat Transfer Principles

In order to properly evaluate total heat transfer in a pulsating heat pipe, the radial heat transfer between the pipe wall and the working fluid, the evaporative heat transfer, and the condensation heat transfer must all be considered. As the liquid slugs oscillate, they enter the evaporator section of the PHP. Sensible heat is transferred to the slug as its temperature increases, and when the slug moves back to the condenser end of the PHP, it gives up its heat. Latent heat transfer generates the pressure differential that drives the oscillating flow. The phase change heat transfer takes place in the thin liquid film between the tube wall and a vapor plug and in the meniscus region between the plug and slug, which requires complex analysis.

Physical Parameters Affecting PHP Design

The parameters that affect PHP performance are numerous and include the following.

Geometric Parameters of the Flow Channel

The inner diameter must be small enough that surface tension forces dominate gravitational forces and distinct liquid slug and vapor plugs can form. The theoretical maximum inner diameter for a capillary tube occurs when the square of the Bond number equals 4. The ratio between gravitational force and surface tension force is known as the Bond number, which is defined as:

$$Bo = \frac{g (\rho - \rho_v) D^2}{\sigma}$$  \hspace{1cm} (2)

which can be rearranged to show that the maximum inner diameter of a PHP is:

$$D_{\text{crit}} = \frac{2}{\sqrt{g(\rho - \rho_v)}} \left( \frac{\sigma}{g} \right)$$  \hspace{1cm} (3)

Cross-sectional geometry can affect flow patterns. Sharp edges can create capillary channels that disrupt the normal slug flow and cause stratified or annular flow. Stratified flow causes the PHP to act as a series of interconnected gravity-driven thermosyphons, and the fluid flow will not pulsate. This greatly decreases the heat transfer capability of the PHP [15,16]. Circular cross-sections do not pose any such challenges to flow in the PHP.

Working Fluid Properties

- **Surface tension.** Higher surface tensions will increase the maximum allowable diameter and also the pressure drop in the tube. Larger diameter will allow improved performance, but an increased pressure drop will require greater bubble pumping and thus a higher heat input to maintain pulsating flow.
- **Latent heat.** A low latent heat will cause the liquid to evaporate more quickly at a given temperature and a higher vapor pressure; the liquid slug oscillating velocities will be increased and the heat transfer performance of the PHP will be improved.
- **Specific heat.** A high specific heat will increase the amount of sensible heat transferred. Because the majority of the total heat transfer in a PHP is due to sensible heat, a fluid with a high specific heat is desirable.
- **Viscosity.** A low dynamic viscosity will reduce shear stress along the wall and will consequently reduce pressure drop in the tube. This will reduce the heat input required to maintain a pulsating flow.
The rate of change in pressure with respect to temperature at saturated conditions \((dp/dT)_{sat}\). This property affects the rate at which bubbles grow and collapse with respect to changes in temperature. At a high value of \((dp/dT)_{sat}\), the difference between vapor pressures in the evaporator and condenser will be increased and the performance of a PHP will be improved by enhanced oscillatory motion of liquid slugs.

**Charge Ratio**

The charge ratio is the volume of the working fluid divided by the total internal volume of the PHP. If the charge ratio is too low, there is not enough liquid to perpetuate oscillating slug flow and the evaporator may dry out. If the charge ratio is too high, there will not be enough bubbles to pump the liquid, and the device will act as a single phase thermosyphon. Charge ratios ranging from 20% to 80% will allow the device to operate as a true pulsating heat pipe. An optimal charge ratio exists for each particular PHP setup; for many typical experiments (circular cross-section in a planar array with less than 20 parallel channels), the optimum charge ratio is around 40%.

**Number of Turns**

The number of turns in the PHP may affect thermal performance and may negate the effect of gravity. By increasing the number of turns, there are more distinct locations for heat to be applied. The fluid within each turn may be either liquid or vapor, the heating of which creates differences in pressure at each turn. It is these pressure differences that drive the pulsating flow. If a PHP only has a few turns, it may not operate in the horizontal or top heat modes, but a PHP with many turns can operate at any orientation because of the perturbations in each turn.

**PHP Configuration**

A PHP may have open loop, closed loop, or open-ended configurations. An open loop PHP has both ends sealed off. The ends of a closed loop PHP are connected to one another, such that the working fluid can circulate. An open-ended PHP has one or both ends unsealed (see Figure 1). In general, closed loop PHP offer the best performance because circulation of the working fluid increases the fluid velocity and likewise the sensible heat transferred.

**Inclination Angle**

PHP performance may or may not change with inclination angle. The dependence on orientation may be coupled to the number of turns. Experimental results have shown that performance is generally better in a vertical orientation, and some PHPs with only a few turns do not operate at horizontal orientations. Other experiments, usually using PHPs with many turns (greater than 40 turns), have shown that performance is independent of inclination angle. Also, analysis by Shafii et al. [13], has shown the effect of gravity to be negligible. For this review, the following convention will be followed regarding inclination angle: vertical bottom heat mode = 90°, horizontal heat mode = 0°, vertical top heat mode = −90°.

**Size and Capacity of Evaporator and Condenser**

These parameters can affect the overall heat transfer of the PHP and could change the flow patterns within the heat pipe. Below a particular onset heat flux from the evaporator, the fluid in the PHP will not pulsate. Also, if the condenser can not dissipate enough heat, it will limit the maximum heat transfer from the PHP.

**FLOW PATTERNS**

The pressure difference created by evaporation/boiling in the heating section and condensation in the cooling section push the liquid slugs to move from the heating section to the cooling section. The motion of the liquid slugs will lower the vapor pressure in the heating section and increase the pressure in the cooling section. This reversed pressure difference will push the liquid slug back to the heating section, and oscillatory flow is initiated and sustained. When the liquid slug moves away from the heating section, there will be a liquid film left behind, and it is widely believed that evaporation and condensation on the film are the mechanisms that result in the pressure change in the vapor phase [9, 10, 11, 14, 17, 18]. The pressure difference between the heating and cooling sections is the driving force of oscillatory motion. In addition, vapor bubbles collapsing due to condensation [13] or generation and growth of vapor bubble [17, 19] may also occur. Because the total volume of a PHP is fixed, the collapse of a vapor bubble must be simultaneously compensated by the generation of vapor bubbles or growth of a vapor plug/bubble elsewhere [12].

For the case that the PHP has closed-loop and the heat flux at the heating section is high, the liquid slugs move from heating section to the cooling section at a relatively high velocity. The inertia of the liquid slugs may be large enough so that the liquid slug can pass the cooling section and enter the next heating section; consequently, the flow pattern in the PHP may change from oscillatory flow to circulating flow.

Gi et al. [4] performed the flow visualization experiment on a PHP made from a Teflon tube strung between hot and cold water jackets. The PHP has 20 parallel channels, is filled with R142b, and was videotaped with an 8 mm camera to record the flow. The description of the flow patterns does not adequately explain what was observed, and little information can be derived from the flow visualization portion of the experiment. Hosoda et al. [19] performed flow visualization of a glass PHP using water as the working fluid. The observed flow indicated that the vapor bubbles propagate in the evaporator and migrate in an oscillatory
fashion to the condenser, where the vapor plugs are either reduced in size or are condensed completely to extinction. Flow visualization of a PHP made of brass and acrylic was performed by Lee et al. [15]. The PHP had rectangular flow channels as opposed to the usual circular cross-section. The flow observed was very different from results of other flow visualization experiments: the fluid did not circulate in the traditional vapor plug/liquid slug arrangement, but rather bubbles flowed along the flow channel and liquid returned to the condenser as stratified, liquid slug arrangement, but rather bubbles flowed along the flow channel and liquid returned to the condenser as stratified, rivulet flow. Perhaps the rectangular cross-section did not allow for proper capillary flow. The most active oscillation was observed at 90° inclination angle, and with charge ratios ranging from 40–60%.

Tong et al. [20] visualized the flow patterns of a closed loop glass PHP filled 60% with methanol. The PHP was tested at inclination angles of 0 and 90°. In the vertical orientation (90°), the flow stalled due to stratified flow returning liquid to the evaporator and trapping it there. The vapor plugs oscillated during startup, but circulation in the PHP was achieved with the vapor plugs traveling from one parallel channel to the next. The circulation velocity increased as the heat input increased, and the fluids circulated both clockwise and counterclockwise. The direction of circulation was due to uneven vapor distribution at startup. Cai et al. [17] built a PHP made of quartz and filled with ethanol, and used high-speed video to record the flow pattern. The video showed the propagation of bubbles in the liquid, some of which moved to the cooled section of the PHP and condensed to extinction. Other bubbles grew large enough to become fully developed vapor plugs with a thin liquid film along the wall. Local dryout was observed in the evaporator, but liquid soon returned to the evaporator from the condenser.

Most studies reveal that circulation occurs in a closed-loop PHP and contributes to better performance of the PHP [4, 12, 20–23]. In order for the liquid slugs to be pushed by the vapor plugs to generate the oscillation or circulation in the PHP, the ideal flow pattern is capillary slug flow, in which liquid slugs and vapor plugs alternatively exist in the PHP. Khandekar et al. [24] reported experiments using a closed-loop glass PHP with water and ethanol as the working fluid. The effects of gravity were noticeable, as this PHP had only 10 parallel channels. They also observed that when liquid slugs pass the U-bends in the heating section, a small amount of liquid would always be left behind, and the boiling of this liquid significantly contributes to the overall heat transfer of the PHP. As heat flux increases, Groll and Khandekar [12] reported that the oscillating slug flow may change to directional slug flow, and ultimately to directional annular flow (see Figure 4). The direction that the flow takes is arbitrary for a given experiment, but once it is established, it remains fixed and does not turn around. Khandekar and Groll [21] studied a two-phase glass loop with only two parallel channels filled with ethanol. As heat is increased, the flow proceeded from slug flow with small amplitude oscillation to larger amplitude oscillation, to slug flow with occasionally reversing circulation, until one leg transitions to annular flow at high power inputs. The two-phase loop did not operate at horizontal orientation. The photographs of the representative flow patterns in a PHP obtained by Khandekar et al. [23] are shown in Figure 5. The slug-annular transition depends not only on the heat input, but also the geometrical constructional features and inclination angles of the PHP.

Xu et al. [25] visualized flow in a closed-loop glass PHP charged with methanol or water by videotaping at 125 frames per second. The fluid circulated during testing but also exhibited a phenomenon called “local flow direction switch,” which involves the flow in some of the channels to go the opposite direction of bulk fluid circulation. For methanol, it was observed that the bubble displacement followed a quasi-sine wave. When water was used, the bubble displacement exhibited a quasi-rectangular oscillating motion. This difference was attributed to the difference in latent heats of vaporization.

The flow patterns in PHPs can be summarized below:

- The oscillatory slug flow driven by the pressure difference between the heating and cooling sections is the dominant flow pattern in PHPs.
- For closed-loop PHP, the oscillatory slug flow may be combined with circulation of working fluid.
- As heat flux in a closed-loop PHP increases, the circulation of working fluid may suppress oscillatory flow, and the flow pattern can change to circulating slug flow. At even higher heat flux, the directional slug flow will change to directional annular flow.

**HEAT TRANSFER PERFORMANCES**

Although evaporation/boiling in the heating section and condensation in the cooling section play roles on the overall heat transfer in a PHP, heat transfer from the heating section to the cooling section by the liquid slugs via sensible heat is dominant when the flow pattern in the PHP is slug flow [13, 14, 26].
Therefore, the heat transfer performance of a PHP with slug flow will never be as good as an equivalent heat pipe or thermostyphon, which is based on pure phase change heat transfer. Groll and Khandekar [12] pointed out that the term pulsating “heat pipe” seemed apparently a misnomer because most of heat is transferred by the latent heat in the heat pipe. With increasing heat flux, evaporation of the thin liquid film, formed (left) by the liquid slug sweeping in the U-bends in the heating section, may play an important role, and the contribution of latent heat to the total heat transfer may be increased. At a higher heat flux, the flow pattern becomes directional annular flow. In this case, the heat is transferred mostly by evaporation and condensation of the liquid film, and the heat transfer capacity becomes comparable to a conventional heat pipe. Under this circumstance, Groll and Khandekar [12] questioned the name “pulsating” heat pipe because it really does not represent the dominant flow pattern. Therefore, the role of sensible heat and the flow pattern in a PHP largely depend on the heat flux: at a lower heat flux, the contribution of sensible heat on the overall heat transfer is dominant and the flow pattern is pulsating flow; at higher heat flux the latent heat becomes dominant on the overall heat transfer and the flow pattern becomes directional annular flow.

Because the closed-loop PHP is thermally more favorable, the majority of the experimental works have focused on the closed-loop PHPs (see Table 1). Akachi et al. [2] tested a particular type of PHP known as the Kenzan Fin, which had as many as 500 turns packed closely together in a cylindrical array and was charged with R142b. It was concluded that a minimum number of turns (as many as 80 turns in this setup) are necessary to make the Kenzan Fin’s operation independent of inclination angle. Maezawa et al. [27] performed experiments with an open looped copper PHP with 40 turns and charged with R142b or water. The PHP operated with very low thermal resistance for all inclination angles when it was charged 50% with R142b. When water was used as the working fluid, it did not perform successfully in top heat mode (inclination angle = −90°) when the heat input rate was greater than 800 W. Chaotic analysis of temperature oscillation in the experimental PHP showed that the oscillation is non-periodic. Miyazaki and Akachi [28] tested a closed loop copper PHP filled with R142b, with 60 parallel channels, at three different inclination angles and with varying charge ratios. Charge ratio was seen to have a significant effect on PHP operation. While the charge ratio for bottom heat mode can vary widely, the optimized charge ratio for top heat mode is 35%. They also found that the heat transfer limitations that usually exist in traditional heat pipes were not encountered in the PHP. Gi et al. [4] concluded that the heat transfer performance for a closed-loop PHP is better than the closed-end PHP because the circulation of the working fluid in the closed-loop PHP enhances heat transfer. Nishio [29] reported experiments with glass PHPs with several different working fluids, inner diameters, and charge ratio. It was found that the heat transfer coefficient between the tube wall and the working fluid is independent of the temperature difference between the evaporator and the condenser, ΔT, for charge ratios from 30–80%. For the four fluids tested (i.e., water, soapsuds, ethanol, and R141b), water performed the best at a charge ratio of 30%.

While most PHPs consist of a smooth walled tube and do not contain an internal wick structure, as in a conventional heat pipe, it is noteworthy that Zuo et al. [6] has developed a prototype PHP with a sintered copper wick covering the inner wall of each channel. The wick provides more nucleation sites for boiling the working fluid, and it also distributes liquid evenly, reducing the local temperature fluctuation. Thermal imaging showed the PHP to be nearly isothermal during testing and was capable of transferring heat at thermal resistances as low as 0.16°C/W at an optimum charge ratio of 70%. Their results showed that the pulsating flow of the working fluid significantly enhanced the heat transport capability over the conventional heat pipes.

Lin et al. [30] built an open loop planar PHP with an evaporator in the middle of the parallel channels and a condenser on either end, which was different from the structures studied.
by most researchers. Acetone was the working fluid, and PHP performance was measured by thermal conductance. When the PHP was operating at the vertical position at low heat rates (less than 600 W), the condenser above the evaporator transferred more heat than the condenser below the evaporator. This PHP setup operated better at horizontal than vertical, and the optimum charge ratio was 38%. Lin et al. [31] used the same experimental setup from their previous study to test two fluorocarbon fluids, FC-72 and FC-75. The prototype PHP was originally designed for use with acetone, and thus the inner diameter (1.75 mm) was greater than the critical diameter given by the bond number relation for the working fluids. This led to evaporator dryout at charge ratios less than 40%. At a charge ratio of 50%, the PHP was capable of dissipating 2040 W of heat. Unlike the previous experiment with acetone, PHP performance with the fluorocarbon fluids was independent of orientation.

Cai et al. [17] built a second PHP made out of copper and had an evaporator in the middle with a condenser on either end. Water, acetone, ethanol, and ammonia were used as working fluids, with charge ratios ranging from 40–80%. Working fluids with lower latent heats had larger gradients for the temperature difference between the evaporator and condenser as a function of heat input, but the amplitude of temperature fluctuations is smaller, and the frequency of the fluctuations are higher. Therefore, fluids with low latent heats are recommended for PHP to promote oscillatory motion. Ma et al. [32] constructed an open-looped copper PHP that used acetone as the working fluid. The experiment recorded the temperature along the PHP as the heat input was increased from 5 to 20 W. Oscillation of the working fluid only occurred in a certain range of power input. A minimum onset temperature difference is required to initiate oscillation, and a range of ΔT exists where steady state motion is possible.

Khandekar et al. [16] fabricated a closed-loop PHP with rectangular flow channels machined into an aluminum plate and a glass tube PHP. The metal PHP did not operate at an inclination angle of 0°, but operated as a thermosyphon rather than a PHP at 90° orientation. Thermographs of the glass PHP showed that a temperature difference exists from one parallel channel to the next (inter-tube). It is hypothesized that some minimum inter-tube temperature difference is required for PHP operation.

Khandekar et al. [33] experimentally studied the performance of a closed-loop copper PHP with a 2 mm diameter and 10 parallel channels. To maximize heat transfer, each working fluid had a slightly different optimum charge ratio (water = 30%, ethanol = 20%, and R-123 = 35%) due to differences in surface tension, latent and specific heats, and the value of dp/dT sat. The small number of turns in the PHP setup did not allow for operation at horizontal orientation. Charoensawan et al. [34] performed parametric experimental investigations on closed-loop PHPs with varying numbers of parallel channels, evaporator and condenser lengths, and inner diameters. Three working fluids (water, ethanol, and R-123) were tested at a charge ratio of 50%, at both 0° and 90° orientations. Results show that gravity has a significant effect on PHP performance unless the PHP has a certain critical number of turns. There is a critical number of turns below which the PHP does not operate at horizontal orientation. If the critical diameter is exceeded, the PHP will cease to function properly. Making the correct choice of working fluid can enhance PHP performance, but fluid choice is affected by several parameters, especially inner diameter due to differences in the surface tension and the latent heat of each fluid. Khandekar et al. [23] performed visualizations and proposed a semi-empirical model based on 248 experimental data from [34]. The maximum achievable heat flux for a given closed-loop PHP with a charge ratio of 50% can be obtained from the following correlation:

\[
q'' = \frac{q}{2\pi DNLe} = 0.54[\exp(\beta)]^{0.48}Ka^{0.47}Pr_\ell^{0.27}Ja^{-1.43}N^{-0.27}
\]

(4)

where \( q \) is heat transfer rate (W), \( D \) is inner diameter of the PHP (m), \( N \) is number of turns, \( L_e \) is the length of the evaporator section (m), \( \beta \) is the inclination angle measured from horizontal axis, and \( Pr_\ell \) is the liquid Prandtl number. The Karman and Jakob numbers are defined as

\[
Ka = \frac{\rho_e (p_{sat,e} - p_{sat,c})D^2}{\mu_e^2 L_{eff}}
\]

(5)

\[
Ja = \frac{c_p,e(T_{sat,e} - T_{sat,c})}{h_{te}}
\]

(6)

where \( p_{sat,e} \) and \( p_{sat,c} \) are the saturation temperatures in the evaporator and condenser, respectively. The effective length can be found by \( L_{eff} = (L_e + L_c)/2 + L_a \). Equation (4) can be used to predict maximum heat transfer in a PHP with an accuracy of ±30%.

Rittidech et al. [3] studied heat transfer characteristics of closed-end copper PHPs with different inner diameters (0.66, 1.06, and 2.03 mm). The lengths of evaporator, adiabatic, and condenser sections were equal and changed to 15, 10, and 5 cm. The number of turns varied from 19 to 42. The PHPs were charged with water, ethanol, or R123 at a charging ratio of 50%. They proposed the following correlation for Kutateladze numbers to predict the heat flux for a closed-end PHP at horizontal orientation.

\[
Ku_0 = \frac{q''}{\rho_v h_{te} \left[ \sigma g(p_e - p_v)/\rho_v^2 \right]^{1/4}}
\]

\[
= 0.0052 \left[ \left( \frac{D^{4.3} L_{e}}{L_{e}^{4.4}} \right)^{N^{0.5}} \left( \frac{p_e}{p_v} \right)^{-0.2} Pr^{25} \right]^{0.116}
\]

(7)

where \( L_e \) is the total length of the PHP tube and \( D^{4.3} L_{e}^{0.1}/L_{e}^{4.4} \) is a dimensionless variable that indicates the size of the PHP. The standard deviation for Eq. (7) was ±30%. Rittidech et al. [35] proposed to use a closed-end PHP as an air preheater for energy thrift in a dryer. The experiment applies the waste heat from the dryer exhaust to the evaporator section of 32 copper PHPs (each PHP has 8 turns), and the PHPs reject the heat from the condenser section to the incoming air. The PHPs are made of copper tube with an inner diameter of 2 mm and charged with water and R123 at a charging ratio of 50%. The following correlation for
a vertical closed-end PHP was proposed following Rittidech et al.'s [3] approach:

$$K_{u0} = 0.0067 \left( \frac{D^{3.1} L^{0.1}}{L_c^{3.2}} \right) N^{0.9} \left( \frac{\rho_v}{\rho_t} \right)^{-0.1} \left( \frac{\omega \mu_v^4}{\sigma^2 \rho_v} \right)^{0.175}$$

(8)

where $\omega$ is the frequency of oscillation motion of vapor plug that is defined as the frequency of simple harmonica motion, $\omega = \sqrt{g \ell / \rho_v L_t}$. Equation (8) has a standard deviation of ±30%. It was concluded that the PHP could be applied to reduce energy consumption in the drying process. Riehl [36] tested an open loop PHP with 13 parallel channels made from copper tubing with an inner diameter of 1.5 mm, in vertical and horizontal orientation, and at a charge ratio of 50% for acetone, ethanol, isopropyl alcohol, methanol, and water. The results showed that an onset heat input exists to drive oscillation, and each working fluid gave a different onset heat input. The best performing fluid at the vertical orientation was acetone, and at the horizontal orientation, methanol was best. Zhang et al. [5] experimentally studied both open and closed copper PHPs using FC-72, ethanol, and water as working fluids. The open-loop PHP did not perform successfully due to having too few turns. For a closed-loop PHP, this study verified that a minimum heat input is necessary to initiate pulsating flow, and that the thermo-physical properties of the working fluid affect that onset heating power. Khatipradit et al. [37] proposed a correlation to predict the critical heat flux (at which dryout occurs) of a closed-end PHP based on experiments for variety of working fluids, inner diameters, evaporator/condenser lengths, and number of parallel channels. The correlations to predict critical heat flux, $q'_{cr}$, for horizontal and vertical heat modes are, respectively:

$$K_{u0} = 53680 \left( \frac{D}{L_c} \right)^{1.17} \omega^{14.17} \beta_0^{-0.66}$$

(9)

and

$$K_{u0} = 0.0002 \left( \frac{D}{L_c} \right)^{0.92} \omega^{-0.212} \beta_0^{0.295} \left[ 1 + \left( \frac{\rho_v}{\rho_t} \right)^{0.25} \right]^{13.06}$$

(10)

where $K_{u0}$ and $K_{u90}$ are Kutateladze numbers for horizontal and vertical orientations defined using critical heat fluxes, $q'_{cr}$. The Jakob number, $Ja$, and the Bond number, $Bo$, are same as those defined in Eqs. (6) and (2). Equations (9) and (10) provided empirical correlations that can be used to predict the heat transfer limit of the PHP at different orientations.

Charoenasawan and Terdtoo [38] developed the following empirical correlation to predict the thermal performance of a horizontal closed-loop PHP:

$$K_u = 2.13 \times 10^{-7} \Phi_t^{0.73} (Ja^*)^{0.38} \delta_0^{-0.84} \kappa_{0.58} (k_c / k_o)$$

(11)

where the Kutateladze number, $K_u$, Bond number, $Bo$, and Karman number, $Ka$, are the same as those defined in Eqs. (7), (2), and (5), respectively. The modified Jakob number is defined as

$$Ja^* = \frac{\phi c_p, \Delta T}{(1 - \phi) h_t}$$

(12)

where $\phi$ is the filling ratio, $k_c / k_o$ in Eq. (11) is the ratio of thermal conductivities of the coolant at the required temperature and the ambient air at 25°C. Equation (11) was obtained by correlating 98 sets of experimental data for water and ethanol, and the standard deviation (STD) was ±30%.

Qu et al. [39] studied mini PHP with square and regular triangle cross-sections. The sides of the squares and triangles vary between 1 and 1.5 mm. The PHPs had eight turns and were made of copper. The filling ratio varied from 20 to 40%. With the same length of the side, the thermal resistance of the PHP with the regular triangle channel is smaller than those with the square channel. For the same capillary structure, the thermal resistance of the PHP with the 1.5-mm channel is smaller than that with the 1-mm channel.

Cai et al. [40] presented an experimental investigation of heat transfer characteristics of PHPs versus operating temperature. The PHP with 12 turns is made of stainless steel or copper and charged with water at three filling ratios: 40%, 55%, and 70%. They found that minimal temperature difference and fluctuation appear at operating temperatures between 120 and 160°C. Xu and Zhang [41] studied startup and steady thermal oscillation of a closed-loop copper with four turns and charged with FC-72. Two types of startup processes were observed: the sensible heat receiving startup process with fluid stationary inside, accompanying an apparent temperature overshoot at lower heat power, and the sensible heat receiving process without fluid motion inside, incorporating a smooth oscillation transition period with oscillation flow at high heating power. In addition, oscillation flow at low heating power displays random behavior and become quasi-periodic at high heat power. Khandekar and Gupta [42] investigated embedded PHP in an alumina plate subject to natural convection and radiation. Semicircular grooves were milled on the radiator base plate and the closed-loop PHP with a 2 mm inner diameter and 11 turns is embedded in the grooves. They concluded that embedded PHP can be beneficial only if the conductivity of the plate is low.

Because the successful operation of PHPs depends on surface tension, not gravity, the performance of an ideal PHP should be independent from the operation mode. Kiseev and Zolkin [43] experimentally investigated the effects of acceleration and vibration on the heat transfer performance of the closed-end PHP with acetone as the working fluid and a charge ratio of 60%. There was an increase in the evaporator temperature by about 30% as the acceleration varied from -6 g to +12 g. Gu et al. [44] experimentally investigated the heat transfer performance of a PHP made of a thin aluminum plate with small internal channels charged with R-114 under normal to high gravity (1–2.5 g) and reduced gravity (∼±0.02 g). The experiments for reduced gravity were performed aboard a parabolic aircraft, Falcon 20, which can provide low gravity conditions (∼±0.02 g) for 15–20 seconds. The results showed that the performance of
a PHP under reduced gravity is better than that at normal to hypergravity.

Ma et al. [45, 46] charged nanofluids (HPLC grade water containing 1.0 vol.% 5–50 nm of diamond nanoparticles) into a closed-loop copper PHP with 12 turns and found that nanofluids significantly enhance the heat transport capability. When the nanofluid is charged to the PHP, the temperature difference between the evaporator and the condenser can be significantly reduced. For example, when the power input added on the evaporator is 100 W, the temperature difference can be reduced from 42°C for the pure water PHP to 25°C for the nanofluid PHP. The heat transport capability in a nanofluid PHP depends on the operating temperature. They also found that when the operating temperature increases, the thermal resistance is significantly decreased.

Chiang et al. [47] studied the performance of PHPs constructed of multiport extruded aluminum tubing with square or triangular cross-sections. The effects of types of working fluid (ethanol and acetone), fluid fill ratio, orientation, PHP dimension, and inner structures on the performance of the PHP are investigated. They also charged nanofluid (formed by dispersing 0.5% vol. of diamond into ethanol) into the PHPs with 26 ports, and slight but consistent improvements on the performance were obtained.

**MODELING**

Because slug flow is the primary flow pattern in PHPs, most existing efforts on modeling have focused on slug flow. Miyazaki and Akachi [28] proposed a simple analytical model of self-excitation oscillation based on an oscillating feature observed in the experiments. The reciprocal excitation of pressure oscillation due to changes in the heat transfer rate caused by the oscillation of the void fraction was investigated. Oscillation of the void fraction is out of phase behind the pressure oscillation by π/2. This model indicates that an optimal charge ratio exists for a particular PHP. If the charge ratio is too high, the PHP will experience a gradual pressure increase followed by a sudden drop. Scarce charging will cause chaotic pressure fluctuation; however, proper charging will generate a symmetrical pressure wave.

Miyazaki and Akachi [48] derived the wave equation of pressure oscillation in the PHP based on the self-excited oscillation, in which the reciprocal excitation between pressure oscillation and void fraction was assumed:

\[
\frac{\partial^2 p}{\partial t^2} = c^2 \frac{\partial^2 p}{\partial x^2}
\]

(13)

where the wave velocity is

\[
c = \sqrt{\frac{q_e^{\text{sat}} R_T T_0}{4\pi L \alpha_0 \rho_r \nu (h_{lv} - R_T T_0)}}
\]

(14)

where the subscript 0 denotes the equilibrium point, and L is the length of a turn. The progressive wave for a closed-loop channel and the standing wave for a closed-end channel can be obtained from Eq. (14). Miyazaki and Arikawa [49] investigated the oscillatory flow in the PHP and measured the wave velocity, which was fairly agreed with the prediction of [48].

Hosoda et al. [19] reported a simplified numerical model of a PHP, in which temperature and pressures are calculated by solving the momentum and energy equations for two-dimensional, two-phase flow. However, the thin liquid film that surrounds a vapor plug on the tube wall and the friction between the tube and the working fluid were neglected. Experimental results were used as initial conditions for the model. The numerical results for pressure in the PHP are higher than the experimental results, but the model does show that propagation of vapor plugs induced fluid flow in the capillary tubes.

Zuo et al. [6, 7] attempted to model the PHP by comparing it to an equivalent single spring-mass-damper system, and the parameters of the system are affected by heat transfer. The fluid displacement was described by

\[
\frac{d^2 x}{dt^2} + \left(\frac{8 \mu_1 P \varphi}{\rho_1 D A} \right) \frac{dx}{dt} + \frac{2A^2 R_T T_{\text{sat}}}{(L/2)A \rho_1 (1 - \varphi)/\rho_e^2}
\]

\[
\times \left[ \frac{LA \rho_1 (1 - \varphi)}{2} + \frac{q_e}{h_{lv}} \right] x = 0
\]

(15)

where P is the flow channel perimeter, A is the cross-sectional area, D is diameter, \( \varphi \) is the charge ratio, L is the flow channel length, and \( q_e \) is heat transfer rate (W). The second and third terms in Eq. (15) represent the viscous damping term and the spring stiffness term. It can be seen that the spring stiffness increases with increasing time, and therefore the amplitude of oscillation must decrease with increasing time; this is in contradiction with steady oscillations observed in PHP operation. Wong et al. [50] modeled an open-loop PHP by considering it as a multiple spring-mass-damper system, but the flow was modeled under adiabatic conditions for the entire PHP. A sudden pressure pulse was applied to simulate local heat input into a vapor plug.

Shafii et al. [13] developed a theoretical model to simulate the behavior of liquid slugs and vapor plugs in both closed- and open-loop PHPs with two turns (see Figure 6). The model solves for the pressure, temperature, plug position, and heat transfer rates. The most significant conclusion is that the majority of the heat transfer (95%) is due to sensible heat, not due to the latent heat of vaporization. Latent heat serves only to drive the oscillating flow.

Sakulchangsatjatai et al. [51] applied Shafii et al.'s model to model closed-end and closed-loop PHPs as oscillating two phase heat and mass transfer in a straight pipe and neglects the thin liquid film between the vapor plug and the pipe wall.

Zhang et al. [52] analytically investigated oscillatory flow in a U-shaped miniature channel—a building block of PHPs. A significant difference between this model and other mathematical models is the nondimensionalizing of the governing equations. Flow in the tube is described by two dimensionless
parameters, the non-dimensional temperature difference and the evaporative and condensation heat transfer coefficients. It was found that the initial displacement of the liquid slug and gravity have no effect on the amplitude and angular frequency of oscillation. Also, the amplitude and frequency of oscillation are increased by increasing the dimensionless temperature difference. The amplitude and frequency of oscillation were correlated to the heat transfer coefficients and temperature difference. Zhang and Faghri [53] investigated oscillatory flow in a closed-end pulsating heat pipe with an arbitrary number of turns (see Figure 7). The results showed that for a PHP with few turns (i.e., fewer than six) the amplitude and frequency of oscillation are independent of the number of turns. The motion of the vapor plugs is identical for odd-numbered plugs once a steady state has been reached. Even-numbered plugs also exhibit identical motion. Odd- and even-numbered plugs have the same amplitude, but they are out of phase by \( \pi \). As the number of turns is increased above six, the odd- and even-numbered plugs no longer show identical oscillation. Each plug lags slightly behind the next; however, each plug is still separated by \( \pi \) from the next one (see Figure 8).

Dobson and Harms [9] investigated a PHP with two open ends. The open ends are parallel and point in the same direction. These ends are submerged in water, while the evaporator section is coiled and attached to a float so that it is out of the water. The evaporator is heated and the oscillatory fluid motion produces a net thrust. A numerical solution of the energy equation and the equation of motion for a vapor plug is presented to predict the plug’s temperature, position, and velocity. Oscillatory motion in the PHP generated a net average thrust of 0.0027N. Heat transfer due to sensible heat was not taken into account. Recently, Dobson [11, 18] proposed to use the open-ended PHP in conjunction with two check valves to pump water, but the maximum attainable mass flow rates are on the order of mg/s—hardly enough to irrigate fields. An improved model for liquid slug oscillation that considered pressure difference, friction, gravity, and surface tension was also presented.

Zhang and Faghri [10] proposed models for heat transfer in the evaporator and condenser sections of a PHP with one open end by analyzing thin film evaporation and condensation (see Figure 9). The liquid film thicknesses in the evaporator and condenser sections respectively satisfy

\[
\frac{d}{dx} \left( \sigma K - p_d \right) = \frac{3 \mu_\ell}{2 \pi R \rho_\ell \delta_3} \left[ \dot{m}_{\ell, in} - \frac{2 \pi R k_\ell (T_h - T_c)}{h_\ell'} \right] + \frac{1}{\delta} \int_0^x \frac{1}{\delta} dx
\]

\[
\frac{\sigma h_{\ell'} \rho_\ell}{3 \mu_\ell} \left[ \delta^3 \left( \frac{d^3 \delta}{dx^3} + \frac{1}{(R - \delta)^2} \frac{d \delta}{dx} \right) \right] = k_\ell (T_v - T_c) \int_0^x \frac{1}{\delta} ds
\]
where $K$ is the curvature, $p_d$ is the disjoining pressure, $R$ is the radius of the PHP, $\dot{m}_{l,in}$ is the mass flow rate of the liquid film at $x = 0$ (see Figure 9a), and $T_h$, $T_c$, and $T_e$ are the temperatures of the heating section, cooling section and vapor phase, respectively. Phase changes over this film drive oscillatory flow in the PHP. Heat transfer in the evaporator is the sum of evaporative heat transfer in the thin liquid film and at the meniscus. Heat transfer in the condenser is similarly calculated and sensible heat transfer to the liquid slug is also considered. It is found that the overall heat transfer is dominated by the exchange of sensible heat, not by the exchange of latent heat. Shafii et al. [14] further developed their earlier numerical model [13] by including an analysis of the evaporative and condensation heat transfer in the thin liquid film separating the liquid and vapor plugs. Both open- and closed-loop PHPs are considered, and they display similar results. As can be seen from Figure 10, the total heat transfer is due mainly to the exchange of sensible heat ($\sim 95\%$). Total heat transfer slightly increases as surface tension of the working fluid increases. The total heat transfer significantly decreased with decreasing heating section wall temperature. Increasing the diameter of the tube resulted in higher total heat transfer. Liang and Ma [54] presented a mathematical model describing the oscillation characteristics of slug flow in a capillary tube. In addition to the modeling of oscillating motion, numerical results indicate that the isentropic bulk modulus generates stronger oscillations than the isothermal bulk modulus. While it demonstrates that the capillary tube diameter, bubble size, and unit cell numbers determine the oscillation, the capillary force, gravitational force, and initial pressure, distribution of the working fluid significantly affects the frequency and amplitude of oscillating motion in the capillary tube. By performing a force balance of the thermally driven, capillary, frictional, and elastic restoring forces on a liquid slug, the oscillating motion is analytically described by Ma et al. [32, 55]. Pressure differences between the evaporator and the condenser are related to the temperature difference between the evaporator and the condenser by the Clapeyron-Clausius equation. The temperature difference between the evaporator and the condenser of a PHP is utilized as a driving force of the oscillating motion. With frictional and restoring forces considered but the gravitational force neglected, the equation that governs the motion of the working fluid in an oscillating heat pipe can be found as

$$
(L_f \rho_f + L_v \rho_v) A \frac{d^2 x}{d\tau^2} + \left[ (f_l \cdot Re_f) \left( \frac{\mu_f L_f}{2 D_h} \right) 
+ (f_v \cdot Re_v) \left( \frac{\mu_v L_v}{2 D_h} \right) \right] \cdot A \frac{dx}{d\tau} + \frac{A \rho_v RT}{L_v} x
= \left( \frac{Ah_{l,v,c}}{T_e} \right) \left( \frac{\Delta T_{\text{max}} - \Delta T_{\text{min}}}{2} \right) [1 \cos(\omega \tau)]
$$

where $L_f$ and $L_v$ are the length of liquid and vapor, $\Delta T_{\text{max}}$ and $\Delta T_{\text{min}}$ are the maximum and the minimum temperature differences between the condenser and the evaporator sections, and $f_l$ and $f_v$ are friction coefficients for liquid and vapor phases, respectively. Ma et al. [55] obtained the exact solution of Eq. (18) using Laplace transformation. Oscillating motion depends on charge ratio, total characteristic length, diameter, temperature difference between the evaporator and condenser sections, working fluid, and operating temperature. The mathematical model underpredicted the temperature difference between the evaporator and condenser when compared to experimental results [32].

Holley and Faghri [8] presented a numerical model for a PHP with a sintered copper capillary wick with flow channels that have different diameters. The effects of the varying channel diameter, inclination angle, and number of parallel channels are presented. When one channel was of a smaller diameter, it induced the circulation of the fluid which in turn increased the heat load capability of the PHP. The modeled PHP performed better in the bottom heat mode (smaller temperature differential) than the top heat mode. Varying the mean Nusselt number had little effect on the PHP performance. As the number of parallel channels increases, the PHP sensitivity to gravity decreases and its heat load capability increases.

Khandekar et al. [56] used an Artificial Neural Network (ANN) to predict PHP performance. The ANN is of the fully connected feed forward configuration and is trained using 52 sets of experimental data from a closed-loop PHP. The ANN is fed the heat input and fill ratio of each data set and calculates the effective thermal resistance of the PHP. The ANN model learned
to predict thermal performance for this type of PHP but neglects many parameters that affect PHP performance, including tube diameter, number of parallel channels, length of the PHP, inclination angle, and properties of the working fluid. If the ANN had more input nodes with which to consider these parameters, it would be a more effective model, though even then it would require considerably well organized experimental data for the ANN to learn from.

Khandekar and Gupta [42] modeled heat transfer in a radiator plate with PHP embedded using a commercial package FLUENT. However, oscillatory flow and heat transfer of the PHPs were not modeled. The contribution of PHPs on the heat transfer in the radiator plate was considered using an effective thermal conductivity obtained from experiment.

**UNRESOLVED ISSUES AFFECTING PHP PERFORMANCE**

In spite of significant efforts in the last decade, no comprehensive tools exist to aid engineers in designing a PHP. This is because either the issue remains uninvestigated properly or they have been studied and conflicting results were found. Also, the diversity of experiments and analyses make them difficult to compare directly. Nonetheless, the following issues require further investigation:

**Sensible Heat vs. Latent Heat**

Analyses by Zhang and Faghri [10] and Shafii et al. [13, 14] conclude that the majority of the overall heat transfer (greater than 90%) in a PHP is due to the exchange of sensible heat. Also, Groll and Khandekar [12] showed that for ethanol the ratio of sensible enthalpy to total enthalpy is greater than 98% for the range of charge ratios in which PHPs operate. On the other hand, the role of latent heat becomes important when the flow pattern becomes annular directional flow. Further experimental evidence is needed to reveal the roles of sensible and latent heats under different conditions.

**Optimum Charge Ratio**

It has been shown that PHPs operate correctly with charge ratios ranging from 20–80%. Also, most researchers agree that for each PHP, some optimal charge ratio exists. Unfortunately, due to the differences in PHP geometry and the properties of various working fluids, the optimum charge ratio can reside anywhere within that range. There are no robust correlations or models that can accurately predict the best charge ratio for a given PHP. The model by Zuo et al. [7] was capable of predicting the optimal charge ratio for their experimental setups within 10%, but the model was extremely simplified, and there is no proof that such a model could be applied to other PHPs.

**Gravity/Inclination Angle**

Most of the above theoretical investigations include gravity in their calculations, and they have found that its effects are dominated by surface tension forces. However, experiments show that gravity may yet play a significant role. As the inclination angle is varied from vertical to horizontal, the thermal performance of many PHPs degraded, and some did not operate at all. Other PHPs, often with many turns, were able to perform satisfactorily independent of orientation. If the inner diameter of the PHP is decreased, it may also aid in the PHP’s ability to perform at low inclination angles.

**Number of Turns**

The number of turns in a PHP and the associated flow perturbations in each turn may account for a PHP’s ability to function in the horizontal orientation. Experimental results from Rittidech et al. [3], who reported heat flux rather than heat transferred because PHP with evaporators of different sizes were compared, have shown that the heat flux decreases as the number of turns increases. It was proposed that some optimum number of turns might exist that would achieve maximum heat flux.

**Losses at Bends**

A typical simplifying assumption in many of the mathematical models is to neglect the pressure lost at each bend in the pipe. Because it has been shown experimentally that the number of turns affects a PHP thermal performance and its ability to operate at low inclination angles, it may not be totally valid to treat the PHP as a straight pipe. Perturbations at each bend may not be negligible, but including them in a numerical model greatly increases its complexity.

**Onset Heat Flux/Temperature**

PHPs are thermally driven non-equilibrium devices, and although they may be very effective heat spreaders, a temperature difference must exist between the evaporator and condenser to maintain their operation. In many cases, there was observed to be some minimum heat flux or differential temperature necessary to initiate oscillating flow. Like the optimum charge ratio, the onset heat flux was different for each experiment. Therefore, parametric investigation is required to fully understand this phenomenon.

**Evaporator Dryout**

Some investigators claim that PHPs have an advantage over conventional heat pipes because they are not limited by
evaporator dryout, but others have observed local dryout, especially at low charge ratios. The oscillating flow should quickly return liquid to the evaporator, but dryout and the associated rise in local wall temperature should still be avoided.

**Surface Tension**

One of the most important properties of the working fluid used in a PHP is surface tension. Surface tension determines the critical diameter of the PHP, pressure drop along the PHP, and affects the flow within the PHP, but conflicting conclusions have been drawn as to whether higher or lower values of surface tension improve PHP performance. Analysis by Shafi et al. [14] concluded that heat transfer increases as the surface tension of the fluid increases. However, Groll and Khandekar [12] indicate that a low surface tension is desirable because it reduces the pressure drop necessary to drive the flow.

**Capillary Wick**

Typical PHPs have no internal capillary wick structure, but Zuo et al. [6, 7] were able to achieve very high heat fluxes from a PHP with a sintered copper wick. The wick aids in the distribution of the liquid throughout the PHP and provides more nucleation sites for bubbles to form. However, except for the work by Zuo’s group and Holley and Faghri [8], little investigation has been performed in this area.

**Non-Dimensional Parameters**

Nearly all current PHP studies rely on the dimensional parameters that were already discussed, which makes the development of general design tools challenging. If PHP performance can be correlated with certain non-dimensional parameters, it would provide a better understanding of the complex phenomena governing PHP operation. Rittidech et al. [3] attempted to do so with Kutateladze and Prandtl numbers, but this correlation is limited to open-loop PHPs in the horizontal heat mode over a certain temperature range. Khandekar et al. [23] also developed a semi-empirical model based on the Reynolds, Karman, liquid Prandtl, and Jakob numbers. The resulting function is only valid for charge ratios of 50%. Zhang and Faghri’s model [53] does well to describe the motion of the two-phase flow while taking various parameters such as number of turns and charge ratio into account, but it does not predict heat transfer performance. Obviously, further investigation is required to expand such semi-empirical models.

**Numerical Simulations**

The existing theoretical models of PHPs are mainly lumped, one-dimensional, or quasi-one-dimensional, and many unrealistic assumptions are often introduced. In order to significantly advance the understanding of oscillatory flow and heat transfer in PHPs, transient evaporation and condensation of thin film, effect of surface tension, and heat transfer in directional annular flow at high heat flux must be considered. In addition, the modeling of flow pattern transition, transient evaporation/boiling, and condensation in PHPs with more advanced techniques, such as the volume of fluid (VOF) model [57, 58] to simulate 2-D/3-D two-phase flow and heat transfer, will be very helpful to obtain a more realistic description of transient flow and heat transfer in the PHPs.

**Nanofluid PHPs**

While most research on electronics cooling focuses on the enhancement of heat transfer using various techniques, very few people paid attention to the inherently low thermal conductivity of the working fluid. It was demonstrated that dispersion of a tiny amount of nanoparticles in traditional fluids, which results in nanofluids, dramatically increases their thermal conductivities. For example, a small amount (less than 1% volume fraction) of copper nanoparticles or carbon nanotubes dispersed in ethylene glycol or oil can increase their inherently poor thermal conductivity by 40% and 150%, respectively [59, 60]. Ma et al. [45, 46] demonstrated that the performance of a PHP can be significantly improved by charging nanofluids into the PHP. On the contrary, Chiang et al. [47] showed that the performance of the PHP by the addition of nanoparticle is only improved slightly. The mechanism of performance enhancement, oscillatory flow, and phase change of the nanofluids in the PHP needs to be investigated.

**COMMERCIAL AVAILABILITY AND APPLICATIONS**

Although PHPs are being studied mostly in the academic community, as indicated in this review, the commercial availability of pulsating heat pipes is limited. Thermacore, Inc. and the Rockwell Scientific Co. have done research regarding pulsating heat pipes, but do not currently manufacture PHPs as standard items. Two companies that do offer PHPs for sale are TSHeatronics Co., Ltd. of Japan and Advanced Cooling Technologies, Inc. (ACT) in the United States. TSHeatronics calls their technology Heatlane. Heatlane AL-EX is an aluminum flat plate PHP that can be formed in different configurations. The working fluids used are butane and HFC-134a. The Heatlane AL-EX can be combined with aluminum fins and used as a heat sink to cool power semiconductors, laser generators, and CPUs. A similarly finned PHP can be used as a heat absorber. Applications for aluminum Heatlanes without fins include cooling plasma screens and LCD monitors. TSHeatronics also makes a stainless steel version of their product with water as the working fluid. This style PHP has found uses in the food service industry. Applications include a rice cooker and a Sushi display case.
Stainless steel Heatlanes have also been used in fluid to fluid heat exchangers.

**CONCLUSIONS**

Since their invention, there have been a considerable number of studies relating to pulsating heat pipes, and their ability to transfer heat at very low effective thermal resistances has been proven. The work compiled here significantly increases the understanding of the phenomena and parameters that govern the thermal performance of pulsating heat pipes. Many unresolved issues still exist, but continued exploration should be able to overcome these challenges. The development of comprehensive design tools for the prediction of pulsating heat pipe performance is still lacking.

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**NOMENCLATURE**

- $A$: tube cross sectional area, m$^2$
- $B_0$: Bond number
- $c$: wave velocity, m/s
- $c_p$: specific heat at constant pressure, J/kg K
- $D$: diameter, m
- $f$: friction factor
- $g$: gravitational acceleration, m$^2$/s
- $h_{lw}$: latent heat, J/kg
- $Ja$: Jakob number
- $k$: thermal conductivity, W/m-K
- $Ka$: Karman number
- $Ku$: Kutateladze number
- $L$: length, m
- $m_{li}$: mass of the $i$th liquid slug, kg
- $m_{lt}$: liquid mass flow rate, kg/s
- $N$: number of turns
- $p$: pressure, Pa
- $P$: flow channel perimeter, m
- $Pr$: Prandtl number
- $q$: heat transfer rate, W
- $q''$: heat flux, W/m$^2$
- $R$: radius, m
- $R_g$: gas constant, J/kg-K
- $Re$: Reynolds number
- $s$: coordinate, m
- $t$: time, s
- $T$: temperature, K
- $v_i$: velocity of the $i$th liquid plug, m/s
- $x$: Coordinate, m

**Greek Symbols**

- $\alpha$: void fraction
- $\beta$: inclination angle
- $\delta$: liquid film thickness, m
- $\Delta p$: pressure change, Pa
- $\Delta\alpha$: change of void fraction
- $\mu$: dynamic viscosity, kg/m-s
- $\rho$: density, kg/m$^3$
- $\sigma$: surface tension, N/m
- $\tau$: shear stress, N/m$^2$
- $\phi$: charge ratio
- $\omega$: frequency of oscillation motion

**Subscripts**

- $a$: adiabatic
- $c$: condenser
- $e$: evaporator
- $eff$: effective
- $\ell$: liquid
- $le$: left end
- $re$: right end
- $sat$: saturation
- $t$: total
- $v$: vapor

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