Progress of cryogenic pulsating heat pipes at UW-Madison

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Abstract. Space agencies continuously require innovative cooling systems that are lightweight, low powered, physically flexible, easily manufactured and, most importantly, exhibit high heat transfer rates. Therefore, Pulsating Heat Pipes (PHPs) are being investigated to provide these requirements. This paper summarizes the current development of cryogenic Pulsating Heat Pipes with single and multiple evaporator sections built and successfully tested at UW-Madison. Recently, a helium based Pulsating Heat Pipe with three evaporator and three condenser sections has been operated at fill ratios between 20 % and 80 % operating temperature range of 2.9 K to 5.19 K, resulting in a maximum effective thermal conductivity up to 50,000 W/m-K. In addition, a nitrogen Pulsating Heat Pipe has been built with three evaporator sections and one condenser section. This PHP achieved a thermal performance between 32,000 W/m-K and 96,000 W/m-K at fill ratio ranging from 50 % to 80 %. Split evaporator sections are very important in order to spread cooling throughout an object of interest with an irregular temperature distribution or where multiple cooling locations are required. Hence this type of configurations is a proof of concept which hasn’t been attempted before and if matured could be applied to cryo-propellant tanks, superconducting magnets and photon detectors.

1. Introduction

Pulsating Heat Pipes (PHPs) or Oscillating Heat Pipes (OHPs) were firstly designed and proposed by Akachi [1, 2] in the 1990s. PHPs are of great interest because they exhibit high heat transfer rates compared to solid thermal straps, display small temperature differences between the evaporator and condenser section, and are more flexible and easier to construct than conventional heat pipes.

Many room temperature PHPs have been developed using fluids such as water and ethanol. A summary of these experimental results are tabulated in [3] and [4]. Due to their high thermal performance, room temperature PHPs could be considered as an alternative method of cooling CPU chips or other electronic devices. Rittedech et al. [5] constructed a PHP that provided cooling for a Pentium 4 CPU generating 44.5 W of electric heat at 53 ºC.

Unlike room temperature PHPs, only a few cryogenic PHPs have been tested [6-15]. These cryogenic PHP’s have been tested with helium [6-9] and nitrogen [10-15] as working fluids. Since cooling surfaces of cryocoollers are localized and small, PHPs with multiple sections attached to the cold finger could be used as thermal spreaders to cool remote hot spots or to provide cooling to large surface areas. This concept could be used to cool down superconducting magnets, cryo-propellant tanks and avoid the usage of more than one cryocooler in these distributed cooling systems. Thirty percent of the helium consumed in 2016 was used to cooling magnetic resonance imaging devices (MRIs) by submerging the superconducting magnets in liquid helium [16]. Due to the high cost of helium, closed cooling systems such as PHPs coupled to cryocoollers could be an alternative cooling method for MRI systems. This reduction in helium consumption could make MRI systems more affordable.
2. Experimental Apparatus

2.1 PHP Configuration and Sensor Measurements

The stainless steel 304 capillary tubing used for both helium and nitrogen PHPs have an inner and outer diameter of 0.5 mm and 0.8 mm, respectively. As shown in Figure 1-a, the helium based PHP is divided into three sub-PHP sections (PHP1, PHP2 and PHP3) but connected to each other in series using copper unions. The advantage of having multiple PHPs connected in series is to distribute the cooling load of a cryocooler to multiple heat spots; there, could minimize the amount of cryocoolers required to cool down a large surface area. This figure also shows the actual configuration and attachment to the RDK-408A2 cryocooler. Each evaporator section is divided into two subsections in order to apply uneven heat loads and observe any thermal performance changes, but for this paper only, the data for even heat loads will be reported. The evaporator sections are made of copper-110 grade plates with a width, length and thickness of 76.2 mm, 30 mm and 4.75 mm, respectively. While the condenser section is also made of the same material and thickness, but with a width and length of 69.2 mm and 90 mm, respectively. It is important to note that 0.8 mm grooves were machined on both sections and soldered to the capillary tubing in order to ensure good thermal contact. Each evaporator section contains a 10 W heater, model kal-10, and a germanium temperature sensor model GR-200A (T2, T3, T5, T6, T7, and T10). A Cernox® sensor model CX-1050 (T1) was attached to the condenser section of PHP1. While the other condenser sections PHP2 and PHP3, have a germanium sensor model GR-200A, T9 and T4 respectively. The Cernox® sensor was calibrated and purchased from Lake Shore Cryotronics with an uncertainty of ±3.79 mK from a temperature range of 1.4 K to 10 K. The germanium sensors were later calibrated with respect to the calibrated Cernox® sensor, achieving a total uncertainty of ±4.51 mK at a range of 2.7 K to 10 K. Note, all heaters are connected to the back side of the evaporator plate. Copper achieves high thermal conductivities and low specific heats at cryogenic temperatures around 4.2 K; therefore a temperature difference of 16 mK was estimated from the center to one of the ends of the evaporator section, which makes it possible to assume an isothermal distribution when the heaters were used.

As shown in Figure 1-b, the nitrogen PHP was constructed of the same type of capillary tubing as the helium experiment but with a circular shaped configuration in order to maximize a total of 42 turns (21 turns on each side, 7 on each evaporator). The adiabatic section was set to a length of 80 mm. The condenser and evaporator sections were made of copper 110 with an inner diameter, outer diameter and length of 55.8 mm, 67.8 mm and 70 mm, respectively. It is important to note, that the critical diameter, \( D_{crit} \), calculated and plotted in [13], for nitrogen is 2 mm for saturation pressure ranging from 100 kPa to 300 kPa, but during this experiment the PHP was able to operate successfully with a diameter of 0.5 mm, ensuring a slug flow and achieving high effective thermal conductivities. It can also be observed in Figure 1-b, that the evaporator section was split into three identical units. Each unit contains four heaters, model Kal 10, connected in series to ensure a uniform temperature distribution. In addition, each evaporator was equipped with one platinum RTD, model PT-103, centered at the outer diameter. The condenser section contains one PRT (directly aligned with PRT on section 2) and the fifth thermometer was attached as close to the cold head as possible. A complete description of the dewar used and the support structure for the N\(_2\) PHP is given by Fonseca [13].
2.2 Filling process

Figure 2 shows a general schematic of the experimental apparatus. Both the helium and nitrogen PHP experiments contain two pressure sensors model Endevco 8510B-500. The first pressure sensor (Supply Pressure Sensor) is connected to the Gas Supply in order to calculate the initial mass of the system. While the second pressure sensor (PHP Pressure Sensor) is coupled at the gas-line connecting the Gas Supply and PHP’s capillary tubing. A group of PHP valves are used in order to conduct refilling and purging/evacuations procedures if needed. One difference between both PHP experiments, but not shown in Figure 2, is that for the nitrogen based PHP, the gas-line refilling the capillary tubing is located at the evaporator section instead of the condenser section due to the fact that the evaporator section was closer to the gas feedthrough. Future tests will be conducted to verify if the PHPs performance behaves differently depending on the location of the refilling line.

A Sumitomo cryocooler model RDK-408A2 and Sunpower CT cryocooler were attached to the condenser section for the helium and nitrogen experiments, respectively. The RDK cryocooler can reach 4.2 K at 1 W while the CT cryocooler could not operate at the manufacturer’s specifications of 77 K at 10 W, reaching only 77 K at 5 W.

Before turning on the cryocooler, it is important to initiate the purging process in order to evacuate any impurities inside the capillary tubing that could clog the flow. Therefore, all lines
connecting to the PHP were pressurized to 150 kPa using the working fluid and evacuated to a pressure of $10^4$ torr; this was performed 5 times.

### 2.3 Initial Filling Ratio

In order to calculate the initial filling ratio $f_{\text{liq}}$, all component volumes $V_i$, temperature $T_i$ and pressure $P_i$ connecting the Gas Supply tank to the capillary tubing should be known. Using temperature and pressure sensors, the masses in each volume $V_i$ after opening the Supply Valve can be calculated and summed in the form of

$$m_o = m_1(T_1, P_1, V_1) + m_2(T_2, P_2, V_2) + \ldots + m_N(T_{PHP}, P_{PHP}, V_{PHP}) = \sum_{i=1}^{N} m_i$$  \hspace{1cm} (1)

where $m_o$ is the initial mass in the Gas Supply tank before opening Supply Valve and filling the entire PHP and $m_i$ are all masses occupying its corresponding volume $V_i$, this includes the PHP volume $V_{PHP}$ and the gas supply volume $V_{tank}$. Mass $m_N$ is the mass of the PHP. The initial mass $m_o$ can be calculated using the ideal gas law

$$m_o = \frac{P_o V_{tank}}{R T_o}$$  \hspace{1cm} (2)

where $P_o$ is the initial pressure of the Gas Supply tank before opening the Supply Valve, $T_o$ is the ambient temperature and $R$ is the gas constant. In addition, the mass occupied in the PHP $m_{PHP}$ can be calculated using the following equation

$$m_N = m_{PHP} = \rho_{l,\text{sat}} V_l + \rho_{v,\text{sat}}(V_{PHP} - V_l)$$  \hspace{1cm} (3)

where $\rho_{l,\text{sat}}$ and $\rho_{v,\text{sat}}$ are the densities of the saturated liquid and vapour, respectively. $V_l$ is the volume occupied by liquid in the PHP. Equations (1) and (2) can be combined to solve for $V_l$ as

$$V_l = \frac{m_o - \left(\sum_{i=1}^{N-1} m_i\right) - \rho_{v,\text{sat}} V_{PHP}}{\rho_{l,\text{sat}} - \rho_{v,\text{sat}}}$$  \hspace{1cm} (4)

It is important to note that the gas-lines close enough to the PHP could experience condensation; therefore the temperature for these lines were assumed to be the saturation temperature at which the PHP was operating at since no thermometry devices were connected to these lines. Finally, the filling ratio $f_{\text{liq}}$ can be calculated as the ratio between the $V_l$ and $V_{PHP}$

$$f_{\text{liq}} = \frac{V_l}{V_{PHP}}$$  \hspace{1cm} (5)

### 3. Results and Discussion

#### 3.1 Helium Pulsating Heat Pipe

The helium experiment was operated at a constant condenser temperature $T_{\text{cond}}$ of 4.2 K while the heat loads at each bottom evaporator sections were gradually increased from 0 W to 0.1940 W with increments of 0.008 W. It is important to note that condenser section was temperature controlled at 4.2 K using an additional heater. For each heat load increment, a total of 500 steady state temperature data points, in a time interval of 8 min, were recorded to calculate the average temperatures. It is important to note that it took around 3 minutes for the evaporator sections to reach steady state once the heat load was increased. For these results, only the bottom evaporator heaters were used as shown in Figure 1-a. In addition, these heat loads were applied at liquid fill ratios ranging from 20 % to 80 % in order to verify the optimal thermal performance for this constant condenser temperature case. Figure 3-a and b represent the average temperature data versus heat loads at fill ratios $f_{\text{liq}}$ of 30 % and 60 %, respectively. It can be observed that at a fill ratio of 30 %, a dry-out conditions is encountered at a heat load of 0.0638 W causing the evaporator temperature to exceed the critical temperature of
He-4 (5.2 K). However, the PHP was able to operate at a steady state condition, reaching supercritical temperatures up to 18 K. Furthermore, for a fill ratio of 60 % and at the same heat loads, the critical temperature of He-4 was not exceeded, hence maintaining a two phase flow in the evaporator section. Due to the the performance of the cryocooler, only heat loads below 0.178 W per heater were applied to maintain a condenser temperature of 4.2 K. Finally, Figure 4 shows the maximum effective thermal conductivities $k_{eff}$ at different fill ratios, notice a desirable operation up to 48,000 W/m-K can be achieved between 50 % and 75 % fill ratio, but with a maximum at 60 %. Even though PHP1 shows the lowest effective thermal conductivity, it is still in the same order of magnitude to the other sections. One possibility for this discrepancy can be due to slight uneven filling ratios in each PHP section.

It is important to note that this helium PHP was operated at a vertical orientation. Dong Xu et al. [8] achieved an optimal thermal performance for their helium PHP in a vertical orientation when the condenser section was located at the top, while in a horizontal position the thermal performance was degraded drastically. Therefore, due to gravitational forces, we predict that the thermal performance of our helium PHP would decrease at a horizontal orientation, but further tests will be conducted.

![Figure 3. Average bottom Evaporator Temperatures versus Heat Load for a) 30 % fill ratio and b) 60 % fill ratio.](image)

![Figure 4. Maximum $k_{eff}$ at Fill Ratios of 30 % to 80 %.](image)

3.2 Multiple Evaporator nitrogen Pulsating Heat Pipe

The nitrogen PHP was operated with equal heat loads on each evaporator section of 1.5 W (4.5 W total) and a condenser temperature of 89 K. This was the minimum achievable temperature at 4.5 W due to diminished cryocooler performance. The fill ratio was varied from 30 % to 90 %, but the PHP only operated properly in the range of 50 % to 80 %. Outside of this range there was inconsistent thermal communication between the evaporators and condenser along with persistent run-aways. Figure 5 shows the effective thermal conductivity of each section at various fill ratios with an optimum of 55 %. It is important to note the inflated conductivity values reported for section 2. There is only one thermometer on the condenser section and it is aligned and anchored to the same capillary
tubing where thermometer of section 2 is located. Therefore, this causes both sensors to report temperatures that are more similar to each other compared to the other sections. The PHPs ability to sustain operation under uneven heat loading was tested by varying the distribution of a 4.5 W heat load across the three sections. Starting with even heat loads of 1.5 W on each section, simultaneously, the load on section one was reduced in steps of 100 mW, the load on section three was increased in steps of 100 mW and the load on section 2 was kept constant. The PHP sustained operation until the heat loads on section one and three were 73 % different (0.7, 1.5, 2.3 W, respectively) after which a lack of thermal communication between the evaporators and condenser caused the PHP to “turn off”. Figure 6 shows the conductivity of each section as the distribution of the heat is varied. The sum of the conductivities of every section represents the total conductivity of the system for a given heat loading. Table 1 summarizes the test and shows an interesting trend. When increasing the distribution of the total heat load, the total conductivity, or sum of all three conductivities, of the system changes minimally overall. However, as the distribution of the total heat becomes more drastic, the total conductivity begins to deviate from the initial conductivity, when heat loading was even. However, as the distribution of the total heat becomes more drastic, the total conductivity begins to deviate from the initial conductivity, when heat loading was even. This shows that up to a certain limit the distribution of the heat load does not affect the overall performance of the PHP.

![Figure 5](image1.png)

**Figure 5.** Effective conductivity of each PHP section as fill ratio is varied at a constant heat load of 4.5 W.

![Figure 6](image2.png)

**Figure 6.** Effective conductivity of each PHP section as the distribution of a 4.5 W heat load is varied at a fill ratio of 70 %. 
Table 1. Summary of test in which the distribution of a 4.5 W heat load is varied across a three-evaporator nitrogen pulsating heat pipe.

| Heat Load on Section 1 [W] | Heat Load on Section 2 [W] | Heat Load on Section 3 [W] | Total Heat Load [W] | Sum of Effective Conductivity [kW/m-K] | Error from Conductivity with equal Loads | Percent Difference Between Max and Min Q |
|---------------------------|----------------------------|---------------------------|--------------------|---------------------------------------|----------------------------------------|----------------------------------------|
| 1.5                       | 1.5                        | 1.5                       | 4.5                | 152.3                                 | 0.0%                                   | 0.0%                                   |
| 1.4                       | 1.5                        | 1.6                       | 4.5                | 152.9                                 | 0.4%                                   | 6.9%                                   |
| 1.3                       | 1.5                        | 1.7                       | 4.5                | 153.8                                 | 1.0%                                   | 14.3%                                  |
| 1.2                       | 1.5                        | 1.8                       | 4.5                | 156.0                                 | 2.4%                                   | 22.2%                                  |
| 1.1                       | 1.5                        | 1.9                       | 4.5                | 152.2                                 | 0.1%                                   | 30.8%                                  |
| 1                         | 1.5                        | 2                         | 4.5                | 154.0                                 | 1.1%                                   | 40.0%                                  |
| 0.9                       | 1.5                        | 2.1                       | 4.5                | 148.4                                 | 2.6%                                   | 50.0%                                  |
| 0.8                       | 1.5                        | 2.2                       | 4.5                | 145.5                                 | 4.5%                                   | 60.9%                                  |
| 0.7                       | 1.5                        | 2.3                       | 4.5                | 123.1                                 | 19.2%                                  | 72.7%                                  |

4. Conclusions
Two distinct three evaporator PHPs using helium and nitrogen have been operated successfully and achieved maximum effective thermal conductivities of order of magnitude of 4 (10^4 W/m-K). The nitrogen PHP has the advantage of operating at saturation temperatures and pressures much lower than the critical point which guarantees a two-phase flow even when high heat loads are applied to one of the evaporator sections. In contrast, for the helium PHP, the range of operating the PHP below the critical temperature is around 2 K, therefore dry-out limitations or superheated conditions were encountered.

Acknowledgements
The authors would like to thank Sumitomo Heavy Industries and Madison Cryogenics for their support on the helium and nitrogen PHP, respectively.

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