Design and Operation of a Cryogenic Nitrogen Pulsating Heat Pipe

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Abstract. We report the design, experimental setup and successful test results using an innovative passive cooling system called a “Pulsating Heat Pipe” (PHP) operating at temperatures ranging from 77 K to 80 K and using nitrogen as the working fluid. PHPs, which transfer heat by two phase flow mechanisms through a closed loop tubing have the advantage that no electrical pumps are needed to drive the fluid flow. In addition, PHPs have an advantage over copper straps and thermal conductors since they are lighter in weight, exhibit lower temperature gradients and have higher heat transfer rates. PHPs consist of an evaporator section, thermally anchored to a solid, where heat is received at the saturation temperature where the liquid portion of the two-phase flow evaporates, and a condenser where heat is rejected at the saturation temperature where the vapor is condensed. The condenser section in our experiment has been thermally interfaced to a CT cryocooler from SunPower that has a cooling capacity of 10 W at 77 K. Alternating regions of liquid slugs and small vapor plugs fill the capillary tubing, with the vapor regions contracting in the condenser section and expanding in the evaporator section due to an electric heater that will generate heat loads up to 10 W. This volumetric expansion and contraction provides the oscillatory flow of the fluid throughout the capillary tubing thereby transferring heat from one end to the other. The thermal performance and temperature characteristics of the PHP will be correlated as a function of average condenser temperature, PHP fill liquid ratio, and evaporator heat load. The experimental data show that the heat transfer between the evaporator and condenser sections can produce an effective thermal conductivity up to 35000 W/m-K at a 3.5 W heat load.

1. Introduction

Figure 1 shows a schematic of a pulsating heat pipe PHP were the change in volume of the vapor bubbles and liquid slugs form the necessary oscillatory movement to transfer heat from the evaporator to condenser section. In recent years, the University of Wisconsin–Madison has designed a Helium based PHP which resulted in an effective thermal conductivity $k_{eff} = 2,393 \text{ W/m-K}$ at oscillations periods of 21 sec [1].

Mito and Natsume [2] have successfully operated a PHP using hydrogen, neon and nitrogen, achieving effective thermal conductivities of 500-3,000 W/m-K, 1,000-8,000 W/m-K and 10,000-18,000 W/m-K respectively. In addition, the Institut Nanosciences et Cryogenie INAC [3], were able to operate a helium PHP between inclination angles of 0° and 40°, achieving a maximum heat transfer of 145 mW using a cold source at 4.2 K.

Space agencies have been looking for new innovative ways to integrate passive cooling systems in order to minimize mass and power consumptions. Hence, the ‘Experimental Setup’ section below
describes the design for a modular nitrogen PHP that could be easily tested in a parabolic microgravity flight and thereby compare its performance with the ground testing data presented in the Results section.

![Figure 1. Schematic of a PHP/OHP [4].](image)

2. Experimental Setup and Engineering Design

Table 1 and figure 2 shows the major components of the experiment. The nitrogen PHP operates inside a 20 cm vacuum nipple with a total length of 33 cm.

| Main Components: |
|------------------|
| 1) 20 cm OD Vacuum Nipple. |
| 2) PHP heat at Evaporator. |
| 3) PT-103 temperature casing at evaporator. |
| 4) Evaporator Section. |
| 5) Thermal Jacket: Cu 110 Grade. |
| 6) Wire Support Tensors. |
| 7) Condenser Section. |
| 8) Thermal Bus: from cryocooler to condenser. |
| 9) Vacuum and temperature feedthrough flange. |
| 10) AL 6061 Circular Supporting Plates. |
| 11) Supporting Wires for condenser and evaporator sections. |
| 12) Threaded rod to fix circular supports (10). |
| 13) PT-103 temperature casing at condenser. |
| 14) SSL support tubes for circular support. Bolted from bottom flange to circular support. |
| 15) Sunpower CT cryocooler. Nominal operation: 10 W at 77 K. |
| 16) Support Structure for cryocooler. |
Figure 2. PHP major components.

Figure 3-a, shows the actual experimental setup where a 3.8 L nitrogen tank supplies the necessary charge of gas to the PHP. On the atmospheric side, the nitrogen tank is connected to a 6.35 mm copper tube that extends to a KF 25 gas feed-through on the vacuum chamber’s top flange. Inside the vacuum chamber, the gas feed-through lines are reduced to the same capillary tubing size and connected to the evaporator section via a 1/8” VCR T fitting. The vacuum chamber is connected to the pumping system using a KF-25 bellows. This system is composed of a mechanical pump in series with a turbo-molecular pump. A second evacuation line and valve was installed in order to provide the option to evacuate and purge the nitrogen tank directly. The nitrogen tank was connected to a KF-25 four way cross. A high purity N\textsubscript{2} supply-line was connected to another port of the four-way cross in order to fill the nitrogen tank if needed. Finally a pressure transducer was installed on top of the nitrogen tank. A simplified schematic of the gas plumbing is seen in figure 3-b. All results presented this paper were performed with the nitrogen tank valve opened.

3. Cryocooler

A CT SunPower cryocooler was attached to one side of the 0.25 m flanges using a 50 KF connector. The cold tip of the cryocooler was thermally anchored to the PHP core via a copper braided thermal bus in order to assure flexibility and avoid any damage due to vibration from the cryocooler. The cryocooler has a cooling power equal to 10 W at a temperature of 77 K.
4. PHP Core
As shown in figure 4, the pulsating heat pipe is comprised of 3 major sections: the evaporator, adiabatic and condenser sections. The evaporator section was made of copper 110 grade with an ID = 50 mm, OD = 65 mm and $L_e = 70$ mm. In addition, the evaporator includes a 50 ohm heater with a maximum power dissipation of 10 W. The condenser section is also made of copper 110 grade with an ID = 25.4 mm, OD = 65 mm and $L_c = 70$ mm and is thermally attached to the cryocooler via the thermal bus. The condenser and evaporator section are soldered to stainless steel 304 capillary tubing with dimensions of 0.5 mm ID and 0.8 mm OD, and the region between these two section is called the adiabatic section, where $L_a = 80$ mm. As shown in figure 4, the 20 capillary tubing loops are bent around equally circumferentially space 4 mm shoulder screws. It is of interest to note that in order to safeguard against adverse deformation, the capillary tubing was bent while containing water that was frozen with LN2. After the water was warmed back to room temperature, it was drained and the capillary tubing was heated to remove any remaining water.

As previously mentioned, the capillary tubing was soldered to the evaporator and condenser section to increase the thermal contact. A general purpose zinc chloride flux (Stay Clean®) was applied to the capillary to remove all oxides allowing it to be soldered to the copper sections. The final construction of the PHP core is shown in figure 5.

5. Thermal Jacket and Support Structure
As shown in figure 2, a copper thermal jacket, 0.002 inches thick, OD = 141 mm and $L=305$ mm, encloses the PHP core and was also thermally anchored to the cryocooler’s cold tip. The thermal jacket was rolled and attached to two aluminum circular supports. These two circular supports are positioned 131 mm apart from each other using ¼” - 20 threaded rods, see figure 5 above. In addition, the circular
support closest to the cryocooler is sustained by 4 stainless steel tubes with dimensions of OD = 9.525 mm, ID = 9.017 mm and L = 152 mm, item 14 of figure 2. These supporting tubes are bolted to the 10 inch flange, which is at room temperature. The heat conduction through these 4 tubes was designed and minimized to be $Q_{\text{rod}} = 0.5$ W, assuming the temperature of one end of the tubes is 300 K and the other is 85 K, this last temperature is the nominal operating temperature of the thermal jacket.

As shown in figure 6, a supporting structure was designed similar to the spokes of a bicycle wheel. Stainless steel 304 wires are tensioned at the $\frac{1}{4}''$ -20 threaded rods to the condenser and evaporator sections, in which each section has 8 wires. These wires have a diameter and length of 0.77 mm and 7 cm respectively. An advantage of using thin wires is to reduce the heat conduction between the support structure/thermal jacket and the PHP core. The total heat conduction of the wires was calculated by assuming that the operating temperature of the thermal jacket and PHP core are 85 K and 77 K, giving a $\Delta T = 8$ K, and total number of wires $N = 16$, resulted in $Q_{\text{wire}} = 6.9$ mW.

![SSL Wires 1/4-20 Threaded Rod](image)

**Figure 6.** PHP core support structure.

6. Multilayer Insulation Blankets

A MLI blanket with 7 layers was placed at the inner surface of the vacuum chamber and another 14 layer MLI blanket was wrapped around thermal jacket, see figure 7-a and figure 7-b. With this MLI configuration, the effective emissivity was calculated to be $e^* = 0.002$, resulting in an estimated radiation load to the thermal jacket of $Q_{\text{rad}} = 174$ mW.

![Vacuum Chamber](image)  
 ![Thermal Jacket](image)

**Figure 4.** a) MLI on vacuum chamber. b) MLI around thermal jacket.
7. Thermometers
A total of 5 lakeshore platinum RTDs, model PT-103, measure the temperature of the experiment. A copper casing was built for each thermometer and placed at the cold tip of the cryocooler, top endplate of thermal jacket, thermal bus and evaporator and condenser sections. A 1.65 mm hole was drilled in the copper casing and the PT sensors were placed inside with Apiezon® N thermal grease.

8. Measurements and Discussion
Figure 8-a shows the cooldown curve of the experiment starting at an initial temperature of 300 K. It can be observed that the nitrogen PHP takes 12 hours to reach a steady state temperature of 80 K. Since the evaporator section is thermally anchored to the condenser section via the capillary section, the thermal resistance initially is very high \( R = 438 \text{ K/W} \), and most of the cooling of the evaporator is due to the radiation to its surroundings. Before cooling down and turning on the cryocooler, the capillary tubing is initially filled with nitrogen at a pressure \( P = 170 \text{ kPa} \). It can also be seen that the evaporator cools down faster as liquid is formed in the condenser section.

The heater was set to 2 W once the evaporator and condenser sections equilibrated to 80 K and 140 kPa in order to initiate the oscillatory behavior. Figure 8-b shows the initial time traces of the temperature of the PHP. The plot shows that the initial oscillation period was \( \tau = 5.8 \text{ min} \).

At heat loads above 2 W the oscillations periods decreased dramatically, the most pronounced and frequent periods at heat loads of 2.5 W, 3 W and 3.5 W, and at a constant cryocooler temperature \( T_{\text{cryo}} = 74 \text{ K} \), were between 18 sec and 42 sec.

![Figure 8](image_url)

**Figure 8.** a) Complete time history of cooldown and PHP operation. b) PHP oscillations at 2.0 W.

The CT cryocooler can be controlled at a fixed temperature or a fixed input power. Figure 9 shows experiments runs at different heater loads, along with the associated change of pressure in the nitrogen tank. The \( \Delta T \) between the condenser and evaporator section decreases from 3.3 K to 1 K between heat loads of 2 W to 3.5 W respectively. It is important to note that for these experiment runs, the valve located between the PHP loop and the nitrogen tank remained opened, to avoid any dramatic increase of pressure in the capillary tubing if the cryocooler would malfunction or shut down.

Using the data in figure 9, the effective thermal conductivity \( k_{\text{eff}} \) and the liquid volume ratio \( f_{\text{liq}} \) (fill percentage) can be calculated using Equation (1), Equation (2) and Equation (3). The effective thermal conductivity is defined using Equation (1), where \( A_c \) is the total cross-sectional area of the capillary tubing, \( Q_{\text{cryo}} \) is heat load applied to the evaporator, \( L_{\text{eff}} \) is the adiabatic length of the PHP, and \( T_{\text{evap}} \) and \( T_{\text{cond}} \) are the mean steady state temperatures of the evaporator and condenser sections [1].
The fill percentage is calculated based on the known volumes of the supply tank, the PHP, and the gas connecting tubing \[1\]. The total number of moles \(N_{\text{total}}\), is initially calculated using the ideal gas law for the nitrogen tank at its initial pressure and temperature which were 170 kPa and 300 K respectively. Once the nitrogen tank valve is opened, the PHP and connecting lines are filled. Hence, Equation (2) can be used to determine the volume occupied by the liquid \(V_i\) in the PHP:

\[
N_{\text{total}} = \frac{P_{\text{final}} V_{\text{tank}}}{RT_{\text{amb}}} + \frac{P_{\text{final}} V_{\text{gas-lines}}}{RT_{\text{gas-lines}}} + \rho_{l,\text{sat}} V_l + \rho_{v,\text{sat}} (V_{\text{PHP}} - V_l) \quad (2)
\]

Here \(\rho_{l,\text{sat}}\) and \(\rho_{v,\text{sat}}\) are the molar densities of the saturated liquid and saturated vapor respectively, \(V_{\text{PHP}}\) is the volume of the PHP, \(V_{\text{gas-lines}}\) is the volume comprised of the connecting lines between the PHP and tank, \(T_{\text{gas-lines}}\) is the temperature of the gas lines. \(P_{\text{final}}\) is the average final tank pressure, shown in figure 9. Finally, the fill percentage can be calculated as the ratio of liquid volume to the total PHP volume:

\[
f_{\text{liq}} = \frac{V_l}{V_{\text{php}}} \quad (3)
\]

As shown in figure 10-a, the thermal conductivity rises from 5000 W/m-K to 35000 W/m-K as the heat load increases from 2 W to 3.5 W, while the fill percentage \(f_{\text{liq}}\) decreases from 46.32 % to 27.08 %. Finally, it should be noted that the effective thermal conductivity is higher at low fill percentages at a constant cryocooler cold tip of 74 K, as shown in figure 10-b.
9. Conclusions
We have successfully fabricated and tested a nitrogen PHP that was able to transfer 3.5 W of heat with a $\Delta T = 1.0$ K across an adiabatic length of 8 cm. The resulting effective thermal conductivities for this experiment were between 5000 W/m-K and 35000 W/m-K, which have the same orders of magnitude as the results presented by Mito and Natsume [2] 10,000 to 18,000 W/m-K. The CT cryocooler was only able to provide a heat lift of 5 W at 77 K instead of its designed heat lift of 10 W. This cryocooler was donated to the University of Wisconsin – Madison and its prior operation is unknown. In future work we will operate the PHP at different inclination angles, adiabatic lengths and cold tip temperatures in order to determine the PHP’s optimal performance. In parallel, we will submit a proposal to NASA Flight Opportunities Program to apply for a microgravity parabolic flight in order to demonstrate its functionality in space environments.

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