The design of an extended length helium pulsating heat pipe experiment

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Abstract. Pulsating heat pipes, also known as PHPs, are passive two-phase heat transfer devices capable of moving heat at cryogenic temperatures with high effective thermal conductivities around two orders of magnitude higher than copper. A recent Helium Pulsating Heat Pipe experiment demonstrated a surprising phenomenon, where Helium PHPs of different lengths (300 mm and 1000 mm) displayed the same thermal conductance at equal heat loads. The purpose of this research is to experimentally characterize this apparent length-independence and determine the size limits for Helium PHPs. An experimental approach is developed where three additional Helium PHP experiments will be conducted with the same operating parameters as the original experiment except with extended adiabatic lengths – 1.25 m, 1.5 m, and 1.75 m. All PHPs considered in this study are in the vertical orientation and are bottom-heated. This will give five complete sets of data from which the influence of length on helium pulsating heat pipes’ performance may be analysed. This paper serves as a work-in-progress report describing the experimental design and fabrication of these Helium PHP experiments.

1. Background and Motivation
Pulsating heat pipes (PHPs) are passive two-phase thermal transport devices esteemed for their excellent ability to transport heat. Their construction consists simply of capillary tubing, typically stainless steel, wrapped into a serpentine path parallel to itself and connecting at both ends as seen in Figure 1, although other similar configurations also exist. The capillary tubing is sized to match with the working fluid’s properties in a way such that the inner diameter is small enough to induce a plug-slug flow regime through a dominating surface tension force. In the evaporator, where a heat load is introduced, the liquid sections vaporize causing the vapor plugs to expand, which drives the fluid through the pipes. The reverse phase change happens simultaneously in the condenser section, where the heat is extracted by a cooling source, such as a cryocooler. In between the evaporator and condenser is the adiabatic section, where the fluid is shuttled adiabatically from one end to the other by the thermally induced driving forces generated in the two end sections. Moreover, this unique flow regime allows PHPs to transfer...
heat more effectively than traditional conductors, with effective conductivities up to 2.5 orders of magnitude larger than high purity copper.

Pulsating heat pipes have been an active area of thermal research since their invention in the 1990s by Akachi [1] for various working fluids and temperature ranges. Cryogenic working fluids, such as nitrogen, hydrogen, and helium, have received significant interest in the cryogenic engineering field with potential applications in the aerospace, superconducting electric power, defense, and medical industries. Experimental investigations of helium pulsating heat pipes have been ongoing for several research groups, including the Key Laboratory of Cryogenics from the Chinese Academy of Sciences [2,3,4], where helium PHPs of varying fill ratios (FR) and inclination angles were tested, along with a study on the number of turns. Optimal combinations of the FR and heat load were found for various inclination angles using a helium PHP with a 100 mm adiabatic length, resulting in a maximum effective thermal conductivity of around 16 kW/m-K, which occurred at a 90-degree angle (vertically oriented). A different set of experiments compared six 8-turn PHPs in parallel to a single 48-turn PHP, all with adiabatic lengths of 100 mm and a fill ratio of around 70%. A single 8-turn configuration displayed a maximum effective conductivity of 15600 kW/m-K, larger than the 48-turn configuration at 12300 kW/m-K. Likewise, Pfotenhauer et al. [5] studied the effect of the vertical-to-horizontal aspect ratio of L-shaped helium PHPs. All adiabatic lengths were 1 m, and five aspect ratios from 4:1 to 1:4 were tested. The best thermal conductivity achieved was around 220 kW/m-K occurring at a 4:1 vertical-to-horizontal ratio. Fonseca et al. [6,7,8] from the University of Wisconsin tested two helium PHPs with different adiabatic lengths and varying initial fill ratios. A 300 mm PHP was found to have an optimal fill ratio of 70% and a maximum effective conductivity of 50 kW/m-K, while a 1000 mm PHP was found to have an optimal fill ratio of 58% and a maximum effective conductivity of 150 kW/m-K.

**Figure 1.** A schematic of a PHP showing the three sections divided by thermal boundary type, as well as the common serpentine flow path.

Fonseca’s experiments reveal an apparent length independence of helium pulsating heat pipes and serve as the primary motivation for this work. Despite displaying significantly different effective thermal conductivities, the two PHPs had the same conductance. In other words, for a given heat load, the PHPs had the same end-to-end temperature difference regardless of their length. This phenomenon is shown more explicitly with Fonseca’s experimental data in Figure 2. Accordingly, the objectives of this work are (1) to characterize the performance of helium pulsating heat pipes as a function of adiabatic length, and (2) to determine the limits of the length independence for the conductance of helium pulsating heat pipes.
2. Experiment Plan and Design

2.1. Experiment Plan
This work will directly extend Fonseca’s experiments by adding three additional helium PHP experiments to the original two, with all parameters constant except the adiabatic length, which will be varied. The configuration consists of 14 parallel tubes, 0.5 mm ID and 0.8 mm OD capillary tubing, and vertical orientation. The three adiabatic lengths to be tested are 1.25 m, 1.5 m, and 1.75 m. Testing will begin at a low liquid fill ratio for each PHP, around 20%. The evaporator heat load will be incremented, and measurements of temperatures and pressures at each end of the PHP will be recorded upon reaching a steady-state, until the PHP fails to operate. This process will be repeated for increasing fill ratios up to around 80%, which will allow an optimal fill ratio to be determined for each PHP. Moreover, temperatures will be measured with Lake Shore Cernox CU-1030 thermometers at several locations along the length of each PHP, specifically on the evaporator and condenser plates. Two pressure taps will measure the condenser and evaporator section pressures with Omega PX419-050A5V transducers, which, combined with temperature measurements, will allow the thermodynamic state of the fluid at each end to be known. Finally, heaters will be placed on the evaporator section and the condenser section to provide a heat load and temperature control respectively.

![Figure 2](image)

Figure 2. Experimental data from Fonseca [6,7,8] showing (a) the effective thermal conductivity and (b) the effect conductance of the two helium PHPs with different lengths at their respective optimal fill ratios.

2.2. Experiment Design
A testing rig for vertically oriented PHPs up to 1.75 m long was designed and modelled in CAD software. Due to the cryocoolers 2nd stage cooling power of only 1 W at 4 K, it is crucial to minimize the parasitic heat load on the 2nd stage. Sources of heat leak include conduction along wires and plumbing, and radiation. Therefore, several aspects of the experiment were intentionally designed to mitigate excess heat load on the cryocooler. Furthermore, the experiment’s geometries were designed to integrate into the pre-existing geometries of the vacuum chamber and the cryocooler. Careful measurements of each were taken and translated into 3D models. Figure 3 displays large-scale pictures of the complete assembly, showing how the experiment is mounted to the cryocooler and fits within the vacuum chamber. Furthermore, the primary components of the experiment are the thermal radiation shield, heat exchangers, internal valves structures, a thermal interface, and the pulsating heat pipe. Figure 4 shows these features in more detail. The radiation shield consists of two aluminum discs 254 mm in diameter, attached radially at each end of a curved sheet of aluminum 2.16 m long. The top disc is thermalized by the first stage of the cryocooler, along with the valve structures and heat exchangers that are attached to the disc. Two heat exchangers are clamped to both sides of the thermal shield top disc and serve to reduce the conduction heat load through the copper fill line tubing and to pre-cool the helium entering the PHP during the filling process. Thermal simulations were completed to estimate an
appropriate heat exchanger length. Subsequently, the two fill line pipes connect to internal needle valves, which isolate the PHP fluid from the rest of the plumbing during operation. The valves hang from aluminum cradles attached to the top shield disc and are controlled from outside of the dewar through low-conductivity stainless steel valve stems. Finally, the PHP is connected to the cryocooler’s second stage with an interface geometry designed to limit thermal resistance between the cold head and the condenser.

Figure 3. Two angles of the full experiment geometry showing all components in the context of the vacuum chamber. The chamber is 1.82 m in diameter with a depth of 3 m, and the experiment is mounted.

Figure 4. Two images showing the experimental component’s geometries in more detail, such as the radiation shield, heat exchangers, internal valves, and the PHP condenser section. The plumbing between components is not modelled.

Several components’ geometries were dependent on thermal and structural constraints, such as minimizing the 2nd stage heat load, and so were guided by thermal simulations. Such components include the thermal interface, radiation shield, and pre-cooling heat exchangers. For example, the radiation shield material and thickness were carefully selected to ensure an appropriate temperature gradient due
to the shield’s long length of over 2 m. To accomplish this, an extended surface numerical thermal model was built to predict the shield’s temperature profile, the results of which are shown in Figure 5. However, an acceptable end-to-end temperature difference could not be achieved without including a multilayer insulation (MLI) model. Therefore, a modified version of the Lockheed equation [9] was used to estimate the effect of MLI. The model estimates a 12 K temperature difference with MLI for a 0.8 mm thick 1100 series aluminum shield. Using the model’s predicted shield profile, the estimated radiation heat load to the second stage hardware is 0.5 mW, which is small enough to be neglected.

Figure 5. The results of the radiation shield thermal model. A temperature difference of around 12 K was achieved with the MLI model parameters shown.

3. Progress
Fabrication of the experiment is currently in progress, and the current state of the experiment can be seen in Figure 6. All parts, including the first PHP, have been built and connected to their respective places on the cryocooler and vacuum chamber. In addition, all thermometer wiring and external plumbing have been built, and the vacuum chamber has been tested to a vacuum pressure of 0.65 mTorr.

Figure 6. The current state of the experiment. The radiation shield and first PHP are also complete, but are not included in this picture.
4. Future Work
The following fabrication and assembly components are yet to be completed on the experiment before starting the first pulsating heat pipe test: The internal plumbing, a data acquisition system, and thermometer calibration. Upon collecting adequate data from the first PHP, a comparison will be made with the helium PHP experiments from Fonseca [6,7,8]. This process will be repeated for each vertical PHP experiment iteration. Additionally, a test rig for horizontally oriented helium PHPs of increasing adiabatic length will be fabricated upon completing the vertical experiments. Data from these proposed experiments will provide insight into the exciting phenomenon of length-independent helium pulsating heat pipes.

5. References
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