Performance Comparison of Long-Distance Helium Pulsating Heat Pipes with Varying Adiabatic Lengths

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ABSTRACT

An experimental study of long-distance helium pulsating heat pipes (PHP) is performed, where the thermal performance of two 7-turn PHPs with different adiabatic lengths (1.25 m and 1.5 m) are compared for fill ratios between 40% and 60%. For each PHP, the effective conductivity within this fill ratio range was not strongly affected by the fill ratio and displayed a logarithmically increasing conductivity with heat load up until dry-out. Despite this, the fill ratio did affect the heat load at which dry-out occurred. The two PHPs are then compared using effective conductance instead of conductivity, revealing similar performance independence associated with the adiabatic length prior to phase change. Finally, for one combination of adiabatic length and fill ratio, adiabatic tube temperatures and thermodynamic states are analyzed, which gives insight into potential flow characteristics and performance-abating phase change. The best performance observed for the 1.25 m PHP was 319.2 kW/m-K at 0.51 W, with a fill ratio of 54.11%, while the best performance observed for the 1.5 m PHP was 328.3 kW/m-K at 0.33 W, with a fill ratio of 45.56%.

INTRODUCTION

Pulsating Heat Pipes (PHP), also known as Oscillating Heat Pipes (OHP), are a unique variant of heat pipe that have gained research interest in the past decade for their improved performance and lower mass when compared to traditional heat pipes and thermal links. Like other heat pipes, PHPs utilize the flow of a two-phase fluid to transfer heat and are entirely thermally driven, although they lack a wicking structure. The construction of a PHP is simple: a long capillary tube traverses a specified length several times while turning at each end, then connecting to form a close loop. This general shape is displayed in Figure 1, although other variations are possible. Figure 1 also shows the three sections of a PHP defined by their heat flow direction. The evaporator picks up a prescribed heat load, the condenser deposits the heat picked up in the evaporator to a cooling source, and the adiabatic section experiences no heat transfer with the surroundings and serves as a passage for the fluid to move between the other two sections.

The inner diameter of the capillary tube is one of the most critical design parameters of a PHP and should be sized such that the Bond number of the working fluid is less than 2. When this condition is met, the surface tension force between the fluid and the tube walls is strong enough to overcome the buoyancy force experienced by vapor bubbles, which causes bubbles to become trapped between

Cryocoolers 22, edited by R.G. Ross, Jr., J.R. Raab and S.D. Miller

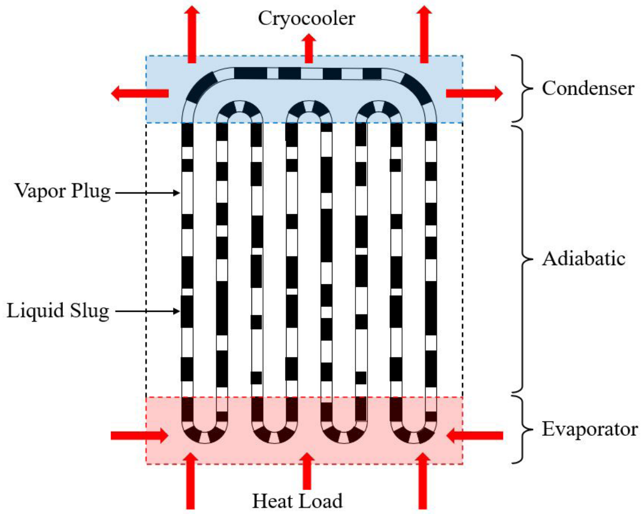
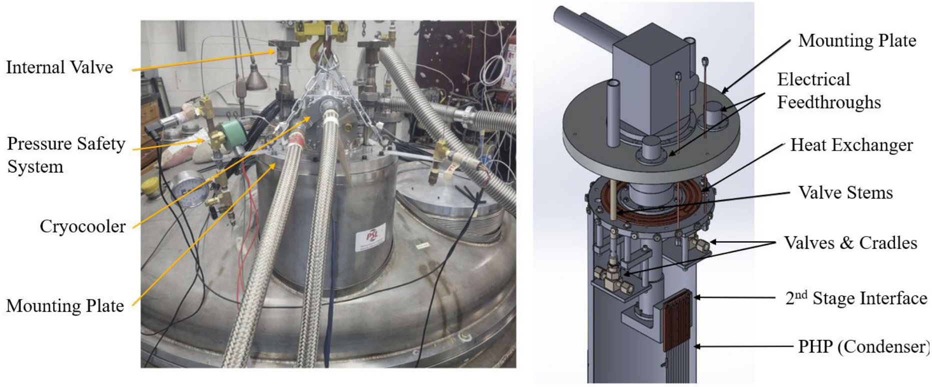


Figure 1. A schematic showing the general PHP shape, the three PHP sections distinguished by heat flow direction, and the train of plugs and slugs in the tube.

distinct liquid sections. For example, an inner tube diameter of 0.5 mm is sufficient for helium to meet the Bond number criterion. In the ideal PHP operating state, phase change in the evaporator and condenser sections cause expansion and compression of the fluid, respectively, which results in an oscillating pressure condition that drives the train of plugs and slugs from end to end. This principle implies that the fluid flow within a PHP is thermally driven, and no external flow control devices are necessary, including a wick. However, depending on several parameters such as heat load, number of turns, and fill ratio (liquid volume fraction), the working fluid in a pulsating heat pipe can span several flow regimes and phases, which makes predicting their behavior difficult.

Helium pulsating heat pipes, in particular, would be an excellent augmentation to 4 K cryocoolers. Integration with helium PHPs could extend the cooling distance of a cryocooler without significantly compromising the temperature at which the cooling power is lifted. Furthermore, since PHPs are composed mostly of small capillary tubes, they are more flexible and lightweight than other thermal links. The space community is interested in cryogenic PHPs as candidates for spreading cooling power to large liquid fuel containers and large space telescopes. Additionally, helium PHPs could aid cryocoolers in cooling superconducting magnets from a distance to limit cryocooler performance degradation resulting from the strong magnetic field.

While the first PHP design was developed more than 30 years ago by Akachi [1], experimental research interest in cryogenic PHPs has grown significantly in the past decade. For example, parametric studies concerning the fill ratio, orientation, and the number of turns have been performed for helium PHPs at the Chinese Academy of Sciences' Key Laboratory of Cryogenics [2,3] that generated important results such as the existence of the optimal number of turns. In one study, a 4-turn helium PHP with an adiabatic length of 100 mm displayed a performance of 15.65 kW/m-K at 0.27 W with a fill ratio of 70.8% [3]. Likewise, long-distance PHP experiments using nitrogen as the working fluid have been performed at the IRFU CEA-Saclay Laboratory [4,5]. An 18-turn, horizontally oriented, meter-long nitrogen PHP was tested at a fill ratio of 50%, and displayed a maximum conductivity of around 86 kW/m-K at 15 W [4]. Another experiment from the same group assessed an 18-turn nitrogen PHP with an adiabatic length of 3 m, where temporary operation with conductivities up to 350 kW/m-K was observed [5]. Numerous helium pulsating heat pipe experiments also have been undertaken at UW-Madison [6-8]. Of particular interest is a study that showed two helium PHPs with different adiabatic lengths (0.3 m and 1 m) displayed nearly identical conductances when operated at their respective optimal fill ratios [6-8]. The present project is motivated by the supposed length-independent performance of helium PHPs observed by Fonseca, Pfotenhauer, and Miller [6-8].



(a) (b)

Figure 2. A picture of the experimental facility, consisting of the test rig mounted to the vacuum chamber (a), and a CAD diagram of the test rig's components (b).

EXPERIMENTAL CONFIGURATION

An experimental facility was constructed to house vertical helium pulsating heat pipe experiments for PHPs with adiabatic lengths up to 1.75 m. This facility consists of a test rig mounted to a large vacuum chamber with a diameter of 2 m and a height of 3 m. A picture of the test facility and a CAD model of the experiment's internal components are shown in Figure 2. The test rig links a Sumitomo SHI RDK-415D2 cryocooler to the chamber via a sealing plate. The cryocooler has a cooling power of 1.5 W at 4 K at its second stage. Moreover, several notable components are connected to both stages of the cryocooler within the vacuum chamber. For example, a cold valve, heat exchanger, and radiation shield are thermally anchored to the first stage. The cold valve, which can be controlled from outside the vacuum chamber, can isolate the fluid in the PHP from the warmer fluid in the heat exchanger and fill plumbing. Next, the heat exchanger pre-cools room temperature helium gas before entering the PHP at the second stage, expediting the cool-down process and reducing heat leak through the internal plumbing components. Finally, a 2 m long aluminum radiation shield fixed to the first stage encloses the PHP and intercepts thermal radiation from room temperature. In addition, a 20-layer MLI blanket covers the radiation shield, further reducing the radiation heat transfer to the shield and, therefore, the PHP. These test rig components were designed and analyzed by thermal modeling, with the goal of minimizing the heat leak to the second stage components.

The PHPs tested in this experimental study have 14 parallel tubes (7 turns) made from 0.5 mm ID 304 stainless steel capillary tubing, soldered to thin copper plates at the ends serving as the condenser and evaporator sections. The two PHPs tested had the same evaporator/condenser length (90 mm) but different adiabatic lengths (1.25 m and 1.5 m). Both PHPs tested are vertically oriented and bottom-heated. Furthermore, data are presented for fill ratios between 40% and 60%, which has been identified as the optimal range for the 1.25 m PHP. Additionally, several temperature and pressure sensors are placed strategically on the PHPs. First, temperature sensors are mounted on both the evaporator and condenser ends for performance calculations. Next, three temperature sensors each are placed on adjacent tubes in the adiabatic section, equally spaced along the adiabatic length. These measurements are made using Cernox CX-1050-CU-HT-1.4L temperature sensors. Finally, pressures are measured at each end of the PHPs using Omega PX419-050A5V pressure transducers. The sensor placements are shown in Figure 3.

RESULTS

Each PHP was tested with a step-wise increasing heat load. Starting from zero, the prescribed heat load is incrementally increased by 20 mW until significant degradation of the PHPs' performance

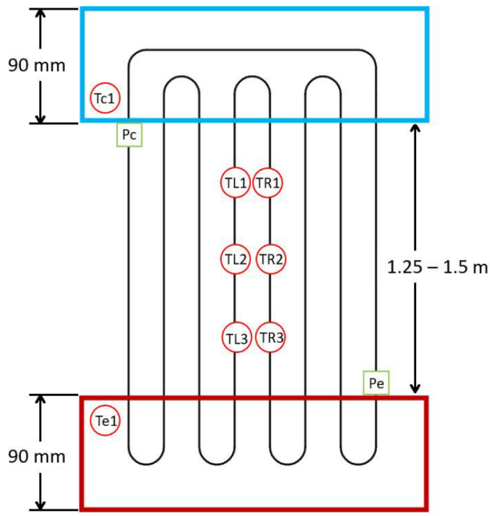


Figure 3. Temperature and pressure sensor placements on the PHPs. The diagram is not to scale, nor shows the actual number of turns for the PHPs tested.

is observed. Pressure and temperature measurements were recorded over a period of 15 minutes for each heat load. Figure 4 shows the average effective conductivities for several fill ratios between 40% and 60% for both PHP lengths. The effective conductivity can be determined via Equation (1) using the measured evaporator and condenser temperatures along with the known heat load applied by a resistive heater.

$$k_{eff} = \frac{\dot{Q}L}{NA_c(\bar{T}_E - \bar{T}_C)} \tag{1}$$

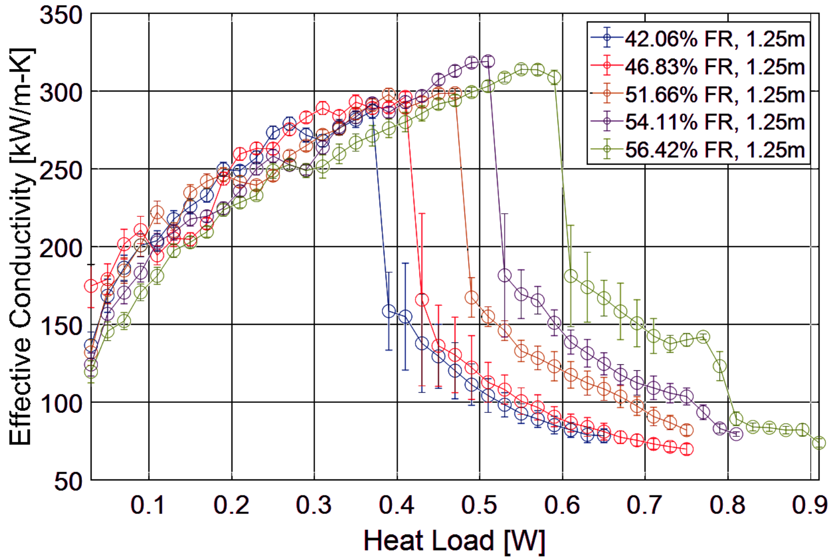
Fill ratios between 25% and 85% have been tested for the 1.25 m PHP. The fluid in the evaporator section of the PHP will either become superheated or supercritical at low heat loads if the fill ratio is too low or high, respectively. The more common superheated condition in the evaporator is often referred to as dry-out. Both phase change scenarios significantly diminish the PHP's performance, so 40% to 60% has been identified as the optimal range for the 1.25 m PHP. Unlike the 1.25 m PHP, a complete spectrum of fill ratios has yet to be tested with the 1.5 m PHP. Therefore, the data currently available is presented for the 1.5 m PHP. The fill ratios tested so far for the 1.5 m PHP fall within the optimal range for the 1.25 m PHP, but this does not guarantee these tests are within the optimal range for the 1.5 m PHP. Moreover, since the experimental error of the temperature measurements is small compared to the observed temperature oscillations, the error bars in Figures 4-6 represent the average oscillation amplitude.

When comparing PHPs with different adiabatic lengths, the effective conductivity is less valuable as it depends on the length and, therefore, is inflated when considering longer devices. Instead, the effective conductance, calculated in Equation (2), is a more useful performance parameter for comparison as it neglects geometric aspects and only considers the overall thermal resistance. Figure 5 compares the conductance of the 1.25 m and 1.5 m PHPs for all fill ratios. Likewise, Table 1 summarizes each test's maximum conductivity, conductance, and heat load (prior to performance degradation).

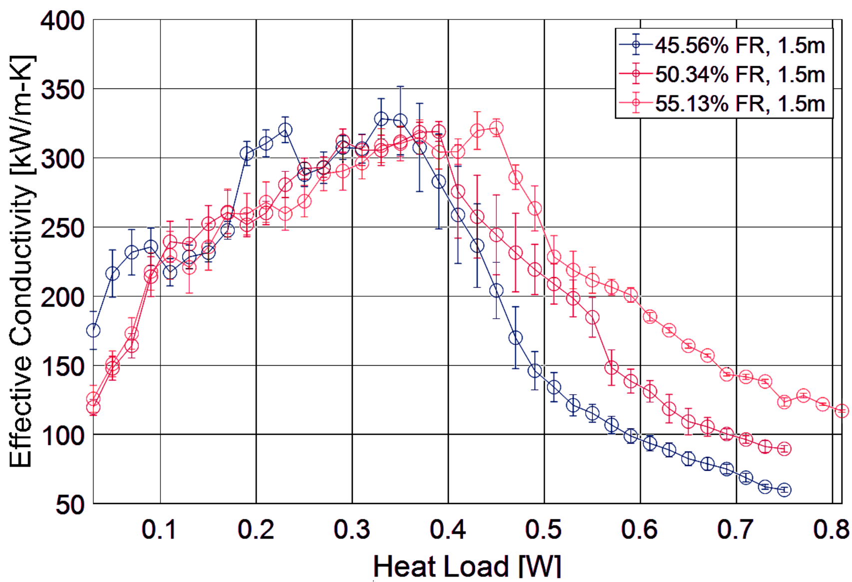
$$C_{eff} = \frac{\dot{Q}}{(\bar{T}_E - \bar{T}_C)} \tag{2}$$

DISCUSSION

Figure 4 (a) shows the effective conductivity results from the 1.25 m PHP tests at various fill ratios. Each test displayed a similar trend: As heat load increases, the conductivity increases logarithmically until a maximum heat load is reached, where the conductivity then drops precipitously



(a)



(b)

Figure 4. Effective thermal conductivities as a function of incrementing heat load of the 1.25 m PHP for fill ratios 42.06% to 56.42% (a). and the 1.5 m PHP for fill ratios 45.56% - 55.13% (b).

and exhibits increased oscillations. Interestingly, this logarithmic increase in effective conductivity with heat load is nearly independent of fill ratio, within the range of fill ratios tested. Despite this effect, the fill ratio does indeed influence the maximum heat load carried through the PHP before the drastic performance drop. As the fill ratio increases from 42.06% to 56.42%, the maximum heat load increases from 370 mW to 590 mW. A similar effect is noticeable in other helium PHP experiments [2,6,8]. The best performance observed for the 1.25 m PHP was 319.2 kW/m-K at 0.51 W, with a 54.11% fill ratio. Moreover, this 7-turn PHP can carry more than 0.5 W of heat with high

Table 1. Performance Summary for All PHP Tests.

	Fill Ratio	Maximum Conductivity [kW/m-K]	Maximum Conductance [W/K]	Maximum Heat Load [mW]
1.25 m	42.06%	287.1	0.63	370
	46.83%	293.3	0.65	410
	51.66%	298.7	0.66	470
	54.11%	319.2	0.70	510
	56.42%	314.1	0.69	590
1.5 m	45.56%	328.3	0.60	350
	50.34%	319.1	0.58	390
	55.13%	321.7	0.59	450

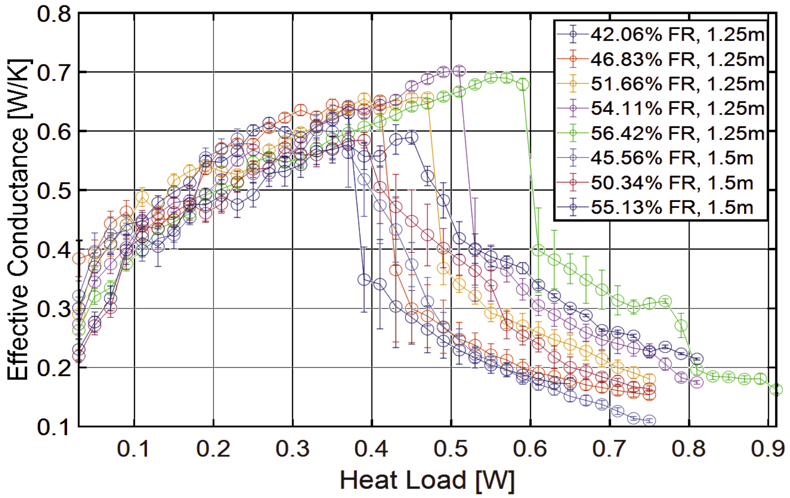


Figure 5. Effective conductance as a function of heat load for both PHP lengths (1.25 m and 1.5 m) with fill ratios between 42.06% and 56.42%.

efficiency, so one can imagine two or more 7-turn helium PHPs cooling in parallel could transfer the total cooling capacity of a typical 4 K cryocooler.

The effective conductivity results from the 1.5 m PHP are shown in Figure 4 (b), where the best performance observed was 328.3 kW/m-K at 0.33 W, with a 45.56% fill ratio. The fill ratio independent performance prior to drop-off, as seen with the 1.25 m PHP, is also noticeable with the 1.5 m PHP, with some variance emerging from the 45.56% fill ratio case. Also congruent with the 1.25 m PHP tests is the correlation of the heat load at which performance degrades with the fill ratio. As the fill ratio increases from 45.56% to 55.13%, the maximum heat load increases from 350 mW to 450 mW. Nevertheless, the two PHPs differ when considering the nature of the performance drop-offs. First, the performance drops observed for the 1.5 m PHP are significantly less drastic when compared to the 1.25 m PHP, where the performance drops occur at a specific heat load. Also, the 1.5 m PHP's performance at similar fill ratios dropped off at appreciably lower heat loads. For example, the drop-off occurred at 590 mW at a 56.52% fill ratio for the 1.25 m PHP, and at 450 mW at a 55.13% fill ratio for the 1.5 m PHP. A study of a broader range of fill ratios for the 1.5 m PHP is required to determine whether these effects arise from adiabatic length limits being reached or whether there is a more optimal range of fill ratios for a PHP of this length.

Figure 5 displays a comparison between the two PHPs for all fill ratios tested, using effective conductance as the performance parameter. Curiously, the previously mentioned logarithmic

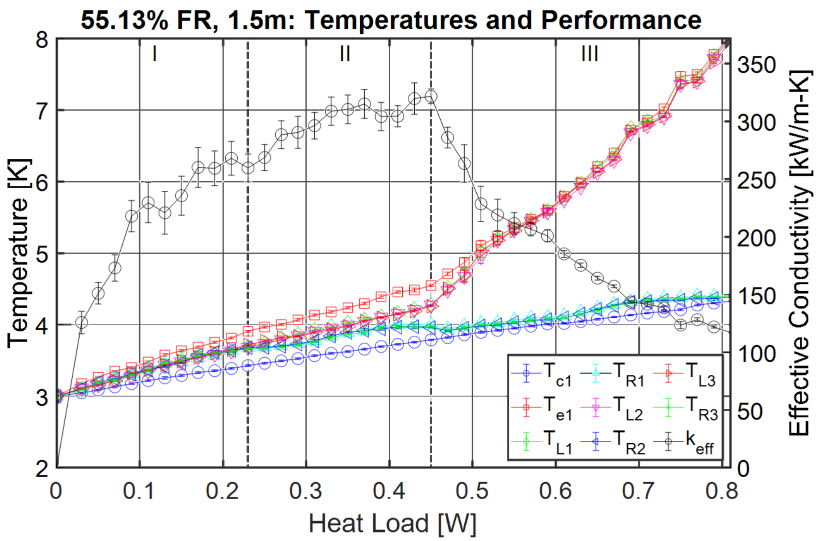


Figure 6. Adiabatic, condenser, and evaporator temperature trends with increasing heat load for the 1.5 m PHP with a 55.13% fill ratio, overlayed with the resulting effective conductivity of this configuration.

performance rise with increasing heat load is also evident in this comparison, despite a significant difference in the PHPs' lengths. Indeed, PHP conductance was not strongly dependent on either fill ratio or length prior to performance degradation within this fill ratio range. Both the adiabatic length and fill ratio did, in fact, strongly influence the heat load at which degradation occurred. This observation suggests that the heat transfer mechanisms are similar despite variations in multiple parameters.

Although the thermal performance of a heat pipe is the most important result, performance calculations involve only the evaporator and condenser temperatures. A closer look at temperatures measured on the adiabatic section, along with pressure measurements, gives some insight into flow characteristics and causes of thermal performance degradation. Figure 6 displays the average temperatures of the evaporator, condenser, and the adjacent adiabatic tubes at each heat load tested, along with the effective conductivity for the following PHP configuration: 1.5 m adiabatic length with a 55.13% fill ratio. It is noteworthy that at every applied heat load, both adiabatic tubes were nearly isothermal along their length. Three regions can be defined from trends in the adiabatic tube temperatures. In region I (0 mW – 230 mW), the adjacent adiabatic tube temperatures match. There are a few possible explanations for this observation. First, the plugs and slugs in the adiabatic section could be oscillating in place, with some variation of shuttle heat transfer being the dominant mechanism. In contrast, a circulatory flow regime is also possible in region I if only latent heat is transferred to the fluid in the evaporator and condenser. Next, the adiabatic tube temperatures diverge in region II (230 mW – 450 mW). This difference in adjacent tube temperatures may indicate the onset of a circulatory flow regime with the cold tubes containing fluid moving from the condenser to the evaporator, and the adjacent hot tubes containing fluid moving in the opposite direction. Despite this difference, the effective conductivity in region II continues the same trend with increasing heat load as in region I. Finally, in region III (450 mW – 800 mW), a more aggressive divergence in adiabatic tube temperatures is observed, and a significant drop in effective conductivity occurs.

A temperature-specific volume phase diagram is a helpful tool when analyzing the phases and mass distribution of a PHP's fluid, and provides information about the phase change that induces the performance deterioration. Figure 7 [9] shows the predicted phase diagram of the condenser and evaporator fluid for each heat load tested (1.5 m adiabatic length and 55.13% fill ratio). Since temperature and pressure alone cannot constrain the thermodynamic state of a two-phase fluid, an assumption regarding the mass distribution of the fluid must be made. First, a group of condenser

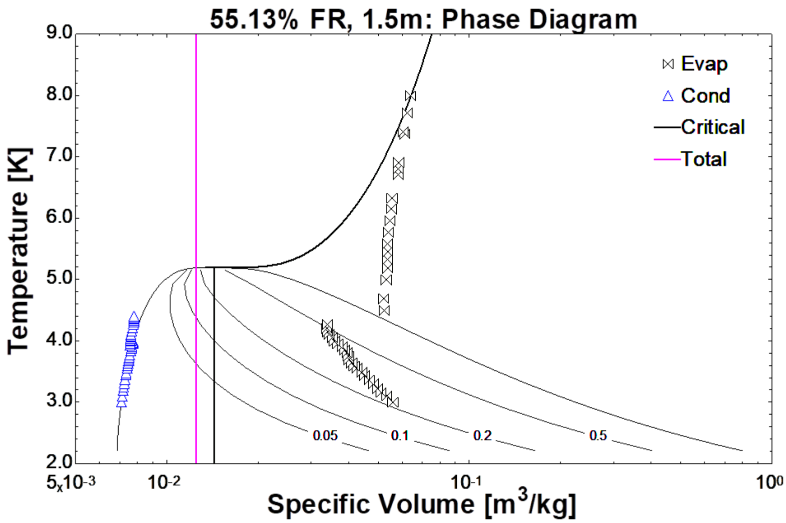


Figure 7. An estimated phase diagram of the fluid contained within the evaporator and condenser sections of the 1.5 m PHP with a 55.13% fill ratio.

data points was identified by their proximity to the saturated vapor line. For these data, it was assumed that the condenser and corresponding adiabatic tubes were filled with saturated liquid. This method enables the prediction of a two-phase state for the rest of the PHP, that is, the evaporator and corresponding adiabatic tubes. Although this assumption prevents condenser points from laying within the vapor dome, it is a decent prediction for the evaporator fluid's state since the condenser mass quality is low. For example, Figure 7 reveals a phase change at 450 mW, where the evaporator and corresponding adiabatic tubes become superheated. For this PHP configuration, this is the same heat load at which the performance drop occurs, suggesting that dry-out is the phenomenon that dictates the maximum heat load that a PHP can transfer. For other configurations, especially those with high fill ratios, the phase change that induces performance degradation can also be associated with a transition from two-phase to either subcooled or supercritical conditions in the non-condenser portion of the PHP.

CONCLUSIONS

The performances of two different 7-turn helium pulsating heat pipes with adiabatic lengths 1.25 m and 1.5 m, respectively, were determined from progressive heat load experiments and analyzed for several fill ratios. The following conclusions can be drawn from the results of these tests:

1. 7-turn helium PHPs can provide excelled heat transfer performance approaching effective thermal conductivity values of 350 kW/m-K with adiabatic lengths up to 1.5 m, carrying a considerable fraction of a typical 4 K cryocooler's capacity.
2. Helium PHPs with different adiabatic lengths (1.25 m and 1.5 m) performed similarly over a range of heat loads and fill ratios prior to phase change.
3. Fill ratio and adiabatic length primarily affected the heat load at which phase change (dry-out) occurs in the PHP, which resulted in degraded performance.

Further testing of helium PHPs with adiabatic lengths at and beyond 1.5 m is necessary to establish a more robust characterization of pulsating heat pipe performance as a function of adiabatic length and fill ratio. In addition, a more comprehensive analysis of adiabatic tube temperature trends, especially regarding transient phenomena, could give more insight into the flow characteristics of helium PHPs.

ACKNOWLEDGMENT

This work was supported by a NASA Space Technology Graduate Research Opportunities Award (80NSSC20K1177).

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