Characterizing Helium Pulsating Heat Pipes

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A series of experiments and modeling activities have been carried out over the past few years at the University of Wisconsin – Madison with a helium pulsating heat pipe (PHP). This report describes the results of various methods used to characterize the behavior of the PHP, including developing correlations of the heat flux $q''$ at the evaporator end in terms of dimensionless parameters such as the Karman number ($K_a$), Jacob number ($J_e$), and Prandtl number ($Pr$), and exploring the use of CFD tools such as ANSYS Fluent to visualize the internal 3D behavior of the two-phase flows. These combined efforts, along with other published reports, provide both physical understanding and design tools for future applications of helium pulsating heat pipes.

1. Introduction

During the past 20 plus years, the behavior of pulsating heat pipes (PHPs) has been investigated by multiple research groups around the world due to the simplicity of their construction and their amazing ability to effectively transfer heat away from a source and deposit it at a heat sink. A significant amount of development has taken place using room temperature fluids, and multiple review articles summarizing these activities have been written [1-3]. In the past 10 years the research has extended into the cryogenic regime and includes fluids such as nitrogen, neon, hydrogen and helium [4-6]. Thermal management for superconducting magnets and space systems presents compelling reasons to utilize PHPs in these cryogenic systems, and it is anticipated that they will become increasingly recognized as a valuable component in the cryogenic system design process.

At the University of Wisconsin – Madison, a significant effort has been devoted to helium-based PHPs. This report provides a survey of recent data and methods being used to characterize the behavior of the helium PHP, and describes our progress utilizing thermodynamic considerations, modeling efforts both with a spring-mass-damper approach and with CFD analyses, and empirical correlations based on relevant non-dimensional parameters.

The subsequent sections begin with a short discussion regarding helium’s fluid properties related to PHP behavior, before going on to provide a brief description of the PHP test rig at UW-Madison, and finally, presenting a sample of tools being utilized to characterize and explore the performance of the helium PHP.

2. Properties

In addition to the potential application of PHPs for superconducting magnets and space systems, our interest in the helium PHP also grows out of the observation that various fluid properties related to the behavior of a PHP set helium apart from most other fluids. A comparison between a few of the significant properties for helium and nitrogen is provided in Table 1. Within this set of properties, those of nitrogen are similar to many room temperature fluids. Perhaps of most importance is the very small viscosity of helium, a factor of 100 times smaller than that of nitrogen. In that the pressure driven motion is dependent on the slope of the saturation line, helium’s slope at the normal boiling point (nbp) is significantly higher than that for nitrogen. Both of these observations would lead one to expect the PHP motion to be more vigorous for helium. The ratio of the volumetric heat capacity of
the fluid at its normal boiling point to that of the stainless-steel wall at the same temperature, for the same length of the tube (hcratio), is large for helium, while less than one for nitrogen. This would suggest that while shuttle heat transfer along the walls may contribute to the heat transfer in a PHP for other fluids, it is probably insignificant for helium.

| Fluid | Tnbp (K) | Tc (K) | \( \frac{P_{\text{liquid}}}{P_{\text{vapor}}}_{\text{nbp}} \) | \( \frac{\Delta P}{\Delta T}_{\text{nbp}} \) | \( \frac{K\Delta a}{K} \) | \( \mu_\ell (\text{Pa} \cdot \text{s}) \) | hcratio |
|-------|---------|-------|----------------|----------------|----------------|----------------|---------|
| Helium | 4.22    | 5.2   | 7.4            | 101            | 3.2e-6          | 24             |
| Nitrogen | 77.33   | 126   | 175            | 12             | 1.6e-4          | 0.64           |

3. UW-Madison PHP test rig

Many features and details of the PHP test rig at UW-Madison have been reported elsewhere [6]. For the purposes of this report it is helpful to repeat here that the PHP is composed of a stainless-steel capillary with inner and outer diameters of 0.5 mm and 0.8 mm respectively. The capillary tube is wound back and forth between the condenser and evaporator regions, and finally closing back upon itself, forming 21 loops. These are grouped into 3 identical sets of 7 vertically oriented loops all connected in series, but with each set of 7 loops mounted on three individual plates fastened to the condenser at the top end and to three individual sets of heated copper plates at the evaporator end. The lengths of the condenser and evaporator sections are 90 mm and 30 mm respectively while the length of the adiabatic section has been set at 300 mm and 1000 mm for two different sets of measurements.

The fill ratio, defined as the volume of saturated liquid in the PHP at the starting temperature of 2.9 K divided by the total volume of the PHP, has been varied between 20% and 80%. For each fill ratio the total heat applied at the evaporator end (equally divided between the three evaporator plates) is ramped in a step-wise fashion from 0 to 0.84 watts incrementing by 0.024 watts and holding the heat constant for ~ 12 minutes at each step. Subsequently the heat is ramped back down to zero in the same fashion. Cernox® thermometers mounted on the copper plates at the condenser and evaporator ends record the temperatures with a resolution of +/- 50 mK at a variety of sampling rates. Additionally, independent pressure measurements at the condenser and evaporator ends are also gathered throughout the heating ramps.

4. Characterization tools

Four different methods are being used to explore and characterize the behavior of the helium PHP. These include a thermodynamic state analysis, two different modeling efforts, and an empirical heat transfer correlation.

4.1 Thermodynamic considerations

As has been extensively discussed in a recent publication [7], the use of a temperature, specific-volume diagram can be helpful to explain the thermal behavior of the PHP as the heat load is increased. Noting that the overall specific volume of the PHP is effectively constant once the valve connected to the supply gas is closed (typical operation), one finds that the overall thermodynamic quality of the two-phase mixture within the PHP will either increase or decrease as the average temperature is increased depending on whether the overall specific volume is respectively larger or smaller than the critical specific volume of the fluid. Figure 1 displays two sets of time dependent temperature data gathered with the 1000 mm adiabatic configuration, and during a heater ramp-up when the initial fill ratio is 20% and 80%. Also shown are the corresponding T-\( v \) diagrams and effective conductance of the PHP, defined by the ratio of the heat applied at the evaporator end to the temperature difference between the evaporator and condenser ends. Here one may notice that for the 20% fill ratio, the significant temperature rise at the evaporator end corresponds to the fluid at that end of the PHP extending into the superheated region, while the fluid at the condenser end remains as a saturated liquid. The corresponding conductance peaks while both ends are still inside the two-phase region and falls significantly as the fluid in the evaporator becomes increasing vapor. When the fill ratio is 80%, smaller temperature excursions are recorded when the fluid in the evaporator extends outside the vapor dome and into the subcooled liquid range. Again, the fluid at the condenser end
remains as a saturated liquid. Interestingly, a further increase of heating drives the fluid at the evaporator end into the supercritical range, and although the PHP continues to operate, its thermal conductance decreases significantly. When the fill ratio is 58%, the corresponding specific volume is very close to the critical specific volume, the temperatures at both ends are well behaved up to the maximum heat load of 0.84 watts, and the conductance achieves its maximum value (compared to that with any other fill ratio) of 1.1 W/K.

One of the more surprising results from the helium PHP data is observed when comparing the conductance data gathered with the optimum fill ratio condition for the 300 mm adiabatic configuration and the 1000 mm adiabatic configuration. The conductance data, shown in figure 2 reveals that even though the distance between the evaporator and condenser for these two sets of data are different by more than a factor of 3, the same heat applied to the evaporator end produces the same temperature difference between the evaporator and condenser, up to the value for which the fluid in the evaporator end extends into the superheated region. To date we have only taken measurements with these two lengths for the adiabatic section, but it will certainly be of interest to explore this feature for longer lengths of the adiabatic section.
4.2. Modeling
Two different efforts to characterize the PHP behavior via numerical modeling have been pursued. One of the primary objectives for both modeling efforts has been to illuminate the reason for the experimentally observed relatively slow thermal and pressure oscillations. In particular, the measured data reveal spatially large-scale thermal oscillations with a period of ~ 8 seconds, so that the temperatures in the three different evaporator plates oscillate out of phase with each other, but with similar magnitude and identical frequency.

4.2.1 Mass-spring-damper model
In the first modeling effort, the mass-spring-damper approach utilized by Gürsel et al [8] for room temperature fluids has been applied for the helium PHP. Additional features have been incorporated including heat exchange with the PHP wall, use of an explicit equation of state for helium, and the capabilities of the ordinary differential equation solver ODE 45 in Matlab. Full details of this model, along with results for the time dependent temperature oscillations in the PHP will be presented in a forthcoming publication. Here it is relevant to mention that the results also demonstrate spatially large-scale oscillations with a period of around 2-3 seconds.

4.2.2 CFD models
The second modeling effort utilizes the CFD software package ANSYS-Fluent and takes advantage of its two-phase fluid flow modeling capabilities. Space does not allow a full description of the various numerical sanity checks that have been carried out, except to mention that grid and time-step insensitivity conditions are satisfied. In addition, the two-phase volume-of-fluid (VOF) approach is used with reasonable, consistent values for the evaporation-condensation frequency numbers associated with the Lee model.

Results with a variety of PHP configurations have been obtained. In all of these, the evaporator and condenser lengths are fixed at 10 mm and 20 mm respectively, while the adiabatic length varies between 20 mm and 200 mm and the number of turns varies between 2 and 5. A snapshot of the results from a case with a 50 mm adiabatic section and 5 turns is shown in figure 3 along with a record of the time dependent spatially averaged temperatures in the evaporator and condenser regions. The CFD results display the time dependent growth and collapse of bubbles in the capillary tube as well as the system-wide motion of the warm vapor plugs and cooled liquid slugs. Although the geometry depicted here is not an exact match to the experimental lengths, the time dependence of the large-scale temperature oscillations is similar. The CFD results provide an insight into the flow conditions as well as the evaporating and condensing features that produce the slow thermal oscillations observed in the experiments.

4.3 Correlations
Following the approach presented by Khandekar et al [9], we have combined the data from 450 runs of the helium PHP test rig and developed a non-dimensional correlation for the allowed heat load, q, at the evaporator end in terms of the dimensionless Karman (Ka), Jacob (Ja), Prandtl (Pr), Bond (Bo) number, and scaled length (Lr) values:

$$\frac{q}{\rho D} = \frac{a^{c_4} K a^{c_2} J a^{c_3} P r^{c_4} L r^{c_5} B o^{c_6}}{C_7}$$

(1)
Figure 3. a) Snapshot of CFD results for a 5-turn helium PHP with a 50 mm adiabatic length. Scale shows gas volume fraction from 0 (saturated liquid) to 1 (saturated vapor). The condenser, evaporator regions are at the top, bottom of the figure respectively. b) Time dependent evaporator and condenser temperatures corresponding to the model displayed in a).

Here \( q \) is the heat load (watts), \( D \) and \( L_e \) are respectively the capillary diameter and evaporator length (m), \( L_r \) is the ratio of the adiabatic to total length, and \( C_i \) are the fitting coefficients. Values for the six coefficients for each of the three separate 7-loop PHP sections are shown in Table 2. Variations among the three sections are presumed due to the slightly different interconnections between them.

Table 2: Fit coefficients for non-dimensional correlation, eq. (1)

| PHP#  | \( C_1 \) (W/m\(^2\)) | \( C_2 \) | \( C_3 \) | \( C_4 \) | \( C_5 \) | \( C_6 \) | \( C_7 \) (W/m\(^2\)) |
|-------|--------------------------|--------|--------|--------|--------|--------|--------------------------|
| PHP1  | 1528.64                  | 6.0332E-2 | -6.4466E-2 | 1.6453E-1 | 2.2017E-1 | 2.3726E-2 | -2506.86                 |
| PHP2  | 1363.75                  | 6.1087E-2 | -6.4705E-2 | 1.6635E-1 | 2.2685E-1 | 5.6270E-2 | -2233.24                 |
| PHP3  | 2409.32                  | 4.1589E-2 | -4.3025E-2 | 1.1161E-1 | 1.5565E-1 | 3.3534E-2 | -3343.63                 |

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