A two-condenser pulsating heat pipe for use as a passive thermal disconnect in redundant cryocooler implementations

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Abstract. A proof-of-concept, two-condenser nitrogen pulsating heat pipe (PHP) for use as a passive thermal switch in applications with redundant cryocooler installations is developed and tested. The PHP design comprises two independent PHP condensers, each thermally linked to an independent cryocooler cold head, with the two associated PHP evaporators attached to a common cold plate heat load. The design allows the cold plate heat load to be continuously cooled when one cryocooler is non-operating. This is accomplished by leveraging the thermal isolation provided by dryout in the PHP associated with the non-operating cryocooler to limit the parasitic load on the common cold plate (and therefore on the remaining operating cryocooler) from the ambient environment. Mechanical actuation is not required as the PHP thermal switch is fully passive. Instrumentation is included in the proof-of-concept device to measure the heat loads and effective thermal conductivities of each PHP. The design of the system is presented in detail, along with preliminary measurements of PHP heat loads and PHP effective thermal conductivities in states of both pulsating advection and dryout.

1. Background

Cryogenic systems with redundant cryocoolers are an appealing option to achieve the high operational reliability desired in many applications, especially spaceflight missions where cryocooler repair or replacement is difficult or impossible. Systems implementing redundant cryocoolers, however, must also reliably handle the potentially debilitating parasitic heat load intrinsic to the thermal conduction path between a non-operating high temperature cryocooler and the low temperature cooling load. One possible route to avoid such catastrophic parasitic loads is to use a pulsating heat pipe (PHP) to thermally link each of the redundant cryocoolers to a common cooling load, relying on PHP dryout to act as a thermal switch and insulate the cooling load from a non-operating cryocooler.

Pulsating heat pipes [1][2] are heat transfer devices typically consisting of a hot plate (the evaporator) and a cold plate (the condenser), connected by a multi-pass closed-loop serpentine tube containing a two-phase fluid, as shown in Figure 1. Energy is transferred from the evaporator to the condenser by a non-equilibrium, pseudo-steady oscillating flow of fluid plugs and vapor bubbles, allowing highly effective heat transfer within the device. Fluid motion in the PHP requires no mechanical power input, being induced by transient pressure differences caused by local evaporation (driven by heat inputs at the evaporator) and local condensation (driven by heat removal at the condenser).
PHPs are mechanically passive devices with no moving parts, and therefore offer high reliability. PHPs, however, suffer from dryout of the working fluid with critical heat input [3]. Dryout is caused by excessive evaporation of the working fluid, starving the PHP of liquid and preventing the pulsating plug flow which is the dominant energy transfer mechanism between the evaporator and condenser plates. When this occurs in a PHP, advection is halted in the device, leaving conduction via the working fluid gas and tube walls as the only thermal path between the evaporator and condenser. With proper device design this dryout conduction can be smaller than the effective conduction during pulsating advection by several orders of magnitude, allowing a dry PHP to act as a thermal insulator. The application of a critical heat load to a PHP in a pulsating advective state therefore activates a thermal break by triggering the dryout condition, allowing the PHP to function as a passive thermal switch. Removal of the critical heat load can restore pulsating advection and revive the thermal link.

In the application of a redundant cryocooler system, a PHP thermal switch can be actuated passively and reliably with the introduction of a parasitic heat load at the PHP condenser from a non-operating cryocooler. Prior work has shown that, in a multi-evaporator common-condenser PHP configuration, the thermal resistance caused by dryout in one of the PHP evaporators provides sufficient isolation to allow continued pulsating advective operation of the remaining non-dry evaporators in the system [4]. A redundant cryocooler implementation requires a slight design variation from this prior work; instead, a multi-condenser common-evaporator design is used in the present device. Figure 2 is a schematic showing the redundant cryocooler setup utilizing independent PHPs as the thermal connection between the cold plate and cryocooler heads. With both cryocoolers operating, each of the associated PHPs are in the pulsating advective state, functioning as highly efficient energy transport elements.
conductive thermal links between the cryocooler heads and the common cold plate. With one of the cryocoolers non-operating, the parasitic heat from the non-operating cryocooler causes dryout in the associated PHP. This activates the thermal switch and insulates the cold plate from the high temperature non-operating cryocooler, limiting the parasitic load and allowing the remaining active cryocooler to maintain the temperature of the common cold plate.

2. Experiment Design
The experiment facility constructed for this work implements the two-condenser redundant cryocooler system described in Figure 2. Isometric and profile views of the experiment system CAD assembly, with annotations for important components, are shown in Figure 3. The setup is built around two Gifford-McMahon cryocoolers – a Cryomech AL125 and a Cryomech AL60, rated for 120W and 60W, respectively, at 80K. A custom designed dewar cover plate supports the cryocoolers and includes passethrougs for electrical wires and PHP filling lines. Each cryocooler cold head is attached to an independent PHP condenser plate via a custom designed conduction heat meter. The heat meters are copper bars of known length and cross-sectional area, with platinum resistance temperature sensors (Lakeshore Cryotronics model PT-102, two-point calibration at 77K and 273.15K, 4-wire measurement) installed near each end of the meter. To account for the significant changes in thermal conductivity of copper over the temperatures of interest in this experiment, the heat meters are calibrated over a range of loads (0-12W) at two approximate temperature ranges (60K-85K and 285K-300K). This allows heat measurements both when the cryocoolers are operating (near 77K) and non-operating (near 290K). The heat meter temperatures nearest the condensers are each controlled independently via LabVIEW-based PID loops coupled to sets of electric resistance heaters (TE Conductivity model HSA50R75J) attached to the cryocooler cold heads. Like all subassemblies comprising thermal conduction paths in this experiment facility, the heat meter to cryocooler connections and heat meter to PHP condenser connections are mated with thermal vacuum grease (Apiezon N Cryogenic High Vacuum Grease) and mechanically fastened with machine screws.

The custom designed PHPs are fabricated from stainless steel tubing and milled copper condenser and evaporator plates. The tubing (Microgroup model 304H17S) has an inner diameter of 1.08 mm and outer diameter of 1.47 mm, with the inner diameter selected to be safely less than the critical diameter of approximately 2 mm required for two-phase slug/vapor flow with the nitrogen working fluid [5][6]. The tubing sections are custom bent to the design dimensions and joined together with a copper sleeve and silver braze. A brass tee connects a filling line to each PHP fluid loop, also with silver braze, while zinc chloride flux (Harris Stay-Clean Liquid Flux) and soft solder are used to join the stainless-steel PHP tubing assemblies to each copper evaporator and condenser plate. Except for the filling tube paths the PHPs are identical designs, having adiabatic section lengths of 254 mm, condenser section lengths of 102 mm, and evaporator section lengths of 102 mm. The evaporator and condenser plates are each 6.5 mm in thickness. Each PHP is vertically oriented and has an independent fluid loop consisting of 20 turns. Figure 4 shows images and CAD assembly views of the completed PHP assemblies along with important dimensions and temperature sensor locations. Again, the temperature sensors are platinum resistance temperature sensors (Lakeshore Cryotronics model PT-102, two-point calibration at 77K and 273.15K, 4-wire connection).

Three copper connector bars serve as the mechanical and thermal link between the two PHP evaporator plates. Both PHP evaporators are exposed to a thermal load distributed equally amongst three electric resistance heaters (TE Conductivity model HSA255R6J), one mounted on each of the three connector bars. With this geometry, both PHPs are bottom heated. Electrical power is provided by a programmable DC power supply and is measured with a calibrated current shunt and potential divider.

An aluminum radiation shield (not shown in Figure 3), thermally sunk to the AL125 cryocooler cold head, encapsulates the entirety of the PHP and heat meter assemblies. Note that the heat load from this shield bypasses the AL125 heat meter. Multilayer insulation (MLI) covers the exterior of the heat shield. To reduce the radiation load through the AL125 heat meter when the AL60 is non-
operating, MLI is placed between the two opposing condenser plates (one at approximately 77K and the other at 290K when the AL60 is non-operating) as indicated in Figure 3.

![Figure 3. Experiment facility CAD assembly in an isometric view (left) and profile view (right). Heat meter temperature sensor locations indicated with black circles.](image)

3. Results and Analysis

Preliminary data are presented for operation with the PHPs each filled with nitrogen at a fill ratio of 40 percent and the cryocoolers and PHPs in one of two different states described in Table 1. For each of these cryocooler states, the data cover a range of applied evaporator heat loads. This allows measurement of the heat loads and effective thermal conductivity for each PHP as a function of applied evaporator load for each cryocooler state.

| State | AL125 Cryocooler Status | AL125 PHP Condenser Temperature $T_{\text{AL}125,\text{PHP,COND}}$ | AL60 Cryocooler Status | AL60 PHP Condenser Temperature $T_{\text{AL}60,\text{PHP,COND}}$ |
|-------|--------------------------|-------------------------------------------------|------------------------|-------------------------------------------------|
| 1     | Operating                | ~70K                                            | Operating              | ~70K                                            |
| 2     | Operating                | ~70K                                            | Non-operating          | ~290K                                           |
Figure 4. Images of the assembled PHPs (left) and CAD view showing temperature sensor locations as black circles and important dimensions in millimeters (right).

Figure 5 plots the heat loads measured at both the AL125 and AL60 cryocooler heat meters \(Q_{AL125,HM}\) and \(Q_{AL60,HM}\), respectively) as a function of the applied evaporator heat load \(Q_{APPLIED,EVAP}\) for both cryocooler states. \(Q_{TOTAL,HM}\) – the sum of \(Q_{AL125,HM}\) and \(Q_{AL60,HM}\) – is also shown, which for state 1 (both cryocoolers operating) agrees very well with \(Q_{APPLIED,EVAP}\) over the measurement range. Since the entire load applied at the evaporator must conduct through the two heat meters, this agreement is expected by energy balance and provides additional validation of the heat meter calibrations.

In state 2 (with the AL60 non-operating), \(Q_{TOTAL,HM}\) is no longer in agreement with \(Q_{APPLIED,EVAP}\) as the AL60 condenser plate (at ~290K) radiates substantially to the surrounding radiation shield (at ~70K). This heat \(Q_{AL60,HM,RAD}\) conducts through the AL60 heat meter – from the AL60 cold head to the AL60 condenser plate – yet bypasses the AL125 heat meter because the heat shield load is attached directly to the AL125 cold head. The parasitic load on the AL125 evaporator through the dry AL60, \(Q_{AL60,PHP}\), must therefore be computed in this state via energy balance on the AL125 PHP as the difference between \(Q_{APPLIED,EVAP}\) and \(Q_{AL125,HM}\). Using this method, the parasitic load \(Q_{AL60,PHP}\) is about -1.3W (negative heat indicates flow into the evaporator from the cryocooler cold head) and essentially invariant with changes in applied evaporator load. The AL60 heat meter measurement \(Q_{AL60,HM}\) – the sum of the parasitic load \(Q_{AL60,PHP}\) through the dry AL60 PHP and the radiative load \(Q_{AL60,HM,RAD}\) from the AL60 PHP condenser plate to the shield – is also constant (at about -3.8W) with variations in applied evaporator heat load. Since \(Q_{AL60,HM,RAD}\) can be assumed constant over these conditions as the temperatures of the AL60 PHP condenser plate and radiation shield do not change substantially, this implies that the parasitic load \(Q_{AL60,PHP}\) through the AL60 PHP is also constant with changes in \(Q_{APPLIED,EVAP}\). This confirms with a second independent analysis that the parasitic load on the AL125 PHP evaporator is invariant with \(Q_{APPLIED,EVAP}\). Finally, note that the parasitic load \(Q_{AL60,PHP}\) on the AL125 PHP evaporator through the dry AL60 PHP is about 1/8 of the capacity of the AL125 PHP demonstrated in Figure 5 (the actual maximum capacity is higher and has not been explored in this preliminary data set), and about 1/40 the available capacity of the AL125 cryocooler after discounting for the heat shield load. This shows that the AL60 PHP is successfully acting as a thermal switch with
the AL60 non-operating, insulating the evaporator assembly from the hot AL60 PHP condenser plate and allowing the AL125 PHP to continue cooling the evaporator load. Note that with proper design consideration (such as increasing the overall PHP length), the parasitic load on the AL125 evaporator could be reduced substantially in magnitude from the approximately -1.3W measured in this experiment, allowing reductions in the parasitic load to cooling capacity ratios reported above.

Figure 5. Heat measurements through the AL125 heat meter \(Q_{\text{AL125,HM}}\), AL60 heat meter \(Q_{\text{AL60,HM}}\), and total through the heat meters \(Q_{\text{TOTAL,HM}}\) over a range of applied evaporator heat loads \(Q_{\text{APPLIED,EVAP}}\) in state 1 (upper panels). Heat measurements through the AL125 heat meter \(Q_{\text{AL125,HM}}\), AL60 heat meter \(Q_{\text{AL60,HM}}\), and parasitic AL125 evaporator load through the AL60 PHP \(Q_{\text{AL60,PHP}}\) over a range of applied evaporator heat loads \(Q_{\text{APPLIED,EVAP}}\) in state 2 (lower panels). See table 1 for state definitions. Both PHPs at 40 percent fill ratio. Positive heat indicates flow from the PHP evaporator to the cryocooler cold head and negative heat indicates flow from the cryocooler cold head to the PHP evaporator.

Figure 6 plots the effective thermal conductivity for each PHP as a function of applied evaporator heat load. The effective thermal conductivity for the PHPs are calculated according to Equations 1 and 2, where \(Q_{\text{AL125,PHP}}\) and \(Q_{\text{AL60,PHP}}\) are heat flows through the respective PHPs, \(d_{\text{PHP,TUBE,OD}}\) is the outer diameter of the PHP tubing listed in the prior section, \(L_{\text{ADIABATIC}}\) is the adiabatic section length from Figure 4, \(T_{\text{AL125,PHP,EVAP}}\) is the AL125 PHP evaporator temperature, \(T_{\text{AL125,PHP,COND}}\) is the AL125 PHP condenser temperature, \(T_{\text{AL60,PHP,EVAP}}\) is the AL60 PHP evaporator temperature, and \(T_{\text{AL60,PHP,COND}}\) is the AL60 PHP condenser temperature. The PHP evaporator and condenser temperatures are evaluated from mean of the three temperature sensors on each evaporator and condenser plate shown in Figure 4. Note that for state 1 (AL125 and AL60 operating), \(Q_{\text{AL125,PHP}}\) and \(Q_{\text{AL60,PHP}}\) are simply the heat meter measurements for the respective cryocooler from Figure 5, \(Q_{\text{AL125,HM}}\) and \(Q_{\text{AL60,HM}}\). For state 2 (AL125 operating and AL60 non-operating), \(Q_{\text{AL125,PHP}}\) is again \(Q_{\text{AL125,HM}}\), but \(Q_{\text{AL60,PHP}}\) is the parasitic load on the AL125 PHP evaporator via the dry AL60 PHP, defined previously as the difference between \(Q_{\text{APPLIED,EVAP}}\) and \(Q_{\text{AL125,HM}}\).

\[
k_{\text{EFF,AL125}} = \frac{|Q_{\text{AL125,PHP}}|}{\pi \left(\frac{d_{\text{PHP,TUBE,OD}}}{2}\right)^2 \frac{L_{\text{ADIABATIC}}}{T_{\text{AL125,PHP,EVAP}} - T_{\text{AL125,PHP,COND}}} |T_{\text{AL125,PHP,EVAP}} - T_{\text{AL125,PHP,COND}}|}
\]
The effective conductivities for the PHPs in pulsating advection in Figure 6, in general, increase monotonically with heat load through the PHP. This behavior is consistent with reported measurements on other PHPs [7][8][9]. For the dry AL60 PHP associated with state 2, the effective thermal conductivity is smaller than observed in the pulsating advective state by over two orders of magnitude and has no significant dependence on applied evaporator heat load. This again demonstrates that the AL60 PHP is, as designed, successfully acting as a passive thermal switch when the AL60 is non-operating.

Figure 6. Effective thermal conductivity of the AL125 PHP $k_{\text{EFF,AL125PHP}}$ over a range of AL125 PHP heat loads $Q_{\text{AL125,PHP}}$ (left panels) and AL60 PHP $k_{\text{EFF,AL60PHP}}$ over a range of AL60 PHP heat loads $Q_{\text{AL60,PHP}}$ (right panels). Data shown for state 1 (upper panels) and for state 2 (lower panels). Corresponding conductance (UA) values shown on the right vertical axes. See table 1 for state definitions.

The ratio of effective conductivity of the AL60 PHP in state 1 (AL60 operating) to that in state 2 (AL60 non-operating) is shown as a function of the heat load through the AL60 PHP in Figure 7. Here the effective conductivity in state 2 is considered a constant at the mean of the values shown in the lower right panel of Figure 6. In state 1 the conductivity varies with the load carried by the AL60 PHP, as shown in the upper right panel of Figure 6. The ratios range from about 200 to about 850, depending on load, again illustrating the insulating ability of the dry AL60 PHP imposed with a large temperature difference (approximately 220K) between the condenser and evaporator.
4. Conclusion and Future Work
Preliminary data obtained from the two-condenser redundant cryocooler system built for this project demonstrates the feasibility of using PHPs as thermal switches in cryogenics applications. The effective conductivity and associated parasitic load of a dry PHP – induced by the high temperature non-operating cryocooler attached to the PHP condenser– are measured and shown to be sufficiently small as to allow a redundant operating cryocooler with an independent PHP to continue cooling the common cold plate load.

Future work on this experiment setup will focus on expanding the data set over a range of PHP fill ratios beyond the 40 percent presented here. Additionally, the two independent PHP fluid loops will be reconfigured into a single common loop and the performance compared with the independent loop configuration. Such a design is less complex from a piping and filling perspective and perhaps more desirable for some applications. Finally, an additional system will be designed and built to replicate the experiment with helium as the PHP working fluid.

5. References
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