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

[1,2]Bryant Mueller

[2]Dr. John Pfotenhauer

[2]Dr. Franklin Miller

[1]Presenting author

[2]University of Wisconsin - Madison

Pulsating heat pipe (PHP) background[1,2,3]

PHPs are heat transfer devices comprised of

- a (typically) closed-loop, serpentine tube filled with a two-phase working fluid
- an evaporator section, condenser section, and adiabatic section

Operating principles

- heat input at evaporator and removal at condenser
- energy transferred from evaporator to condenser via transient, oscillating slug/plug flow
- surface tension must be dominant force to achieve slug/plug flow (tube diameter < critical diameter)
- fluid driven by thermally-induced, transient pressure gradients from cyclic evaporation and condensation

Key features

- excellent heat transfer characteristics
- mechanically passive (mechanical pump not required)
- operation in microgravity environment possible
- dryout in either condenser or evaporator can cause thermal isolation

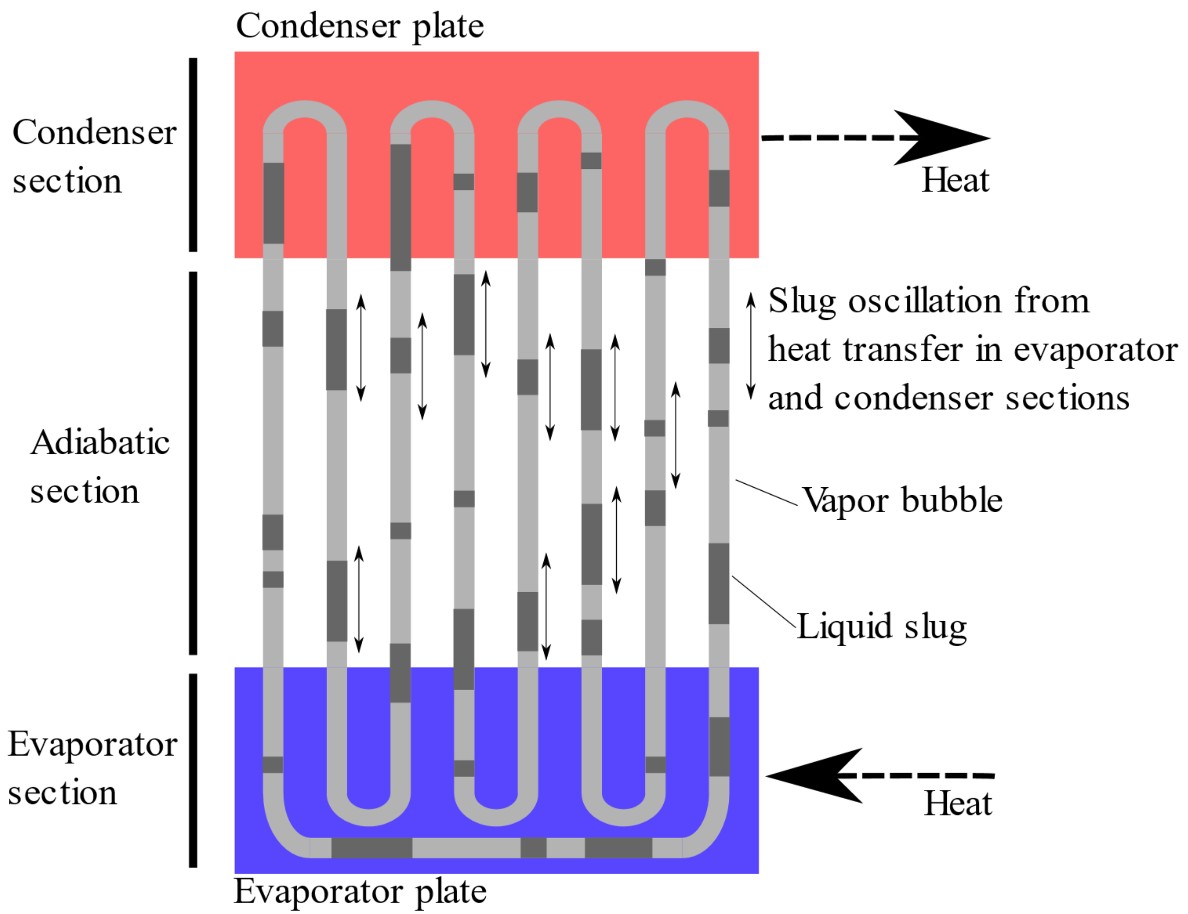

Figure 1. Schematic of a typical pulsating heat pipe (PHP)

PHPs as passive thermal disconnects

Dryout in a PHP

- complete evaporation of liquid (local or global) within a PHP tube
- caused by excessive heat input into the system
- loss of primary heat transfer mechanism (slug/plug flow)
- results in thermal isolation of dry section[4]

Dryout as a passive thermal disconnect mechanism

- dryout at the condenser can thermally isolate the evaporator from the excessive load
- evaporator can remain cold and operational, cooled via another heat route

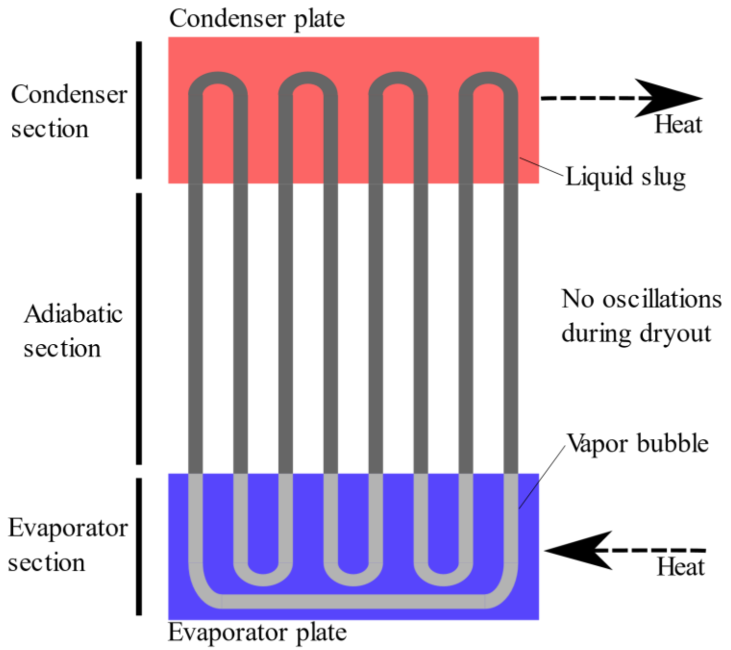

Figure 2a. Illustration of dryout from excessive evaporator heat load

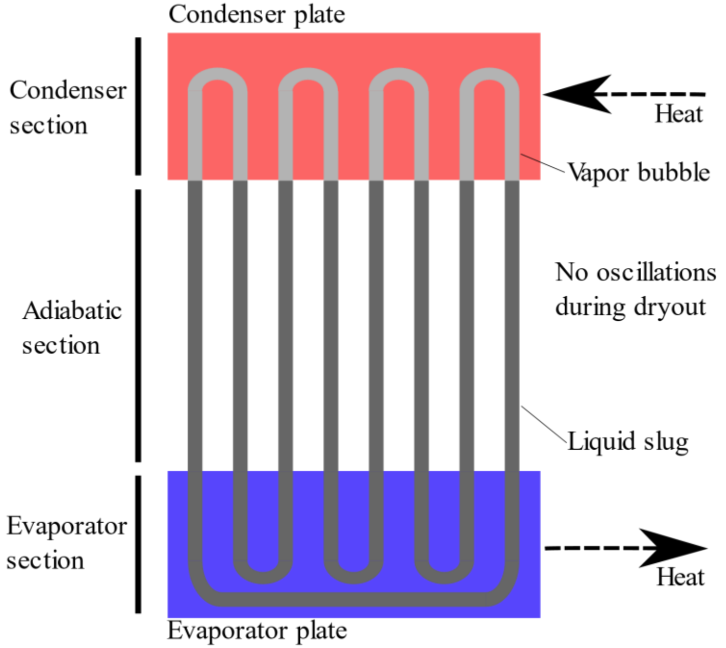

Figure 2b. Illustration of dryout from excessive condenser heat load

PHPs as passive thermal disconnects with redundant cryocooler setups

Redundant cryocooler implementations

- reliability improvements for systems inaccessible for maintenance
- continuous cooling during replacement / swap of a single cryocooler

Passive thermal disconnect requirements

- high thermal conductivity when the cryocooler is operational
- low thermal conductivity when cryocooler is non-operational (to limit parasitic load on the cold plate)
- passive operation / no work inputs / no mechanically actuated components
- automatic activation of thermal break with excessive heat input from a non-operational cryocooler cold head (causes dryout in associated PHP condenser section)

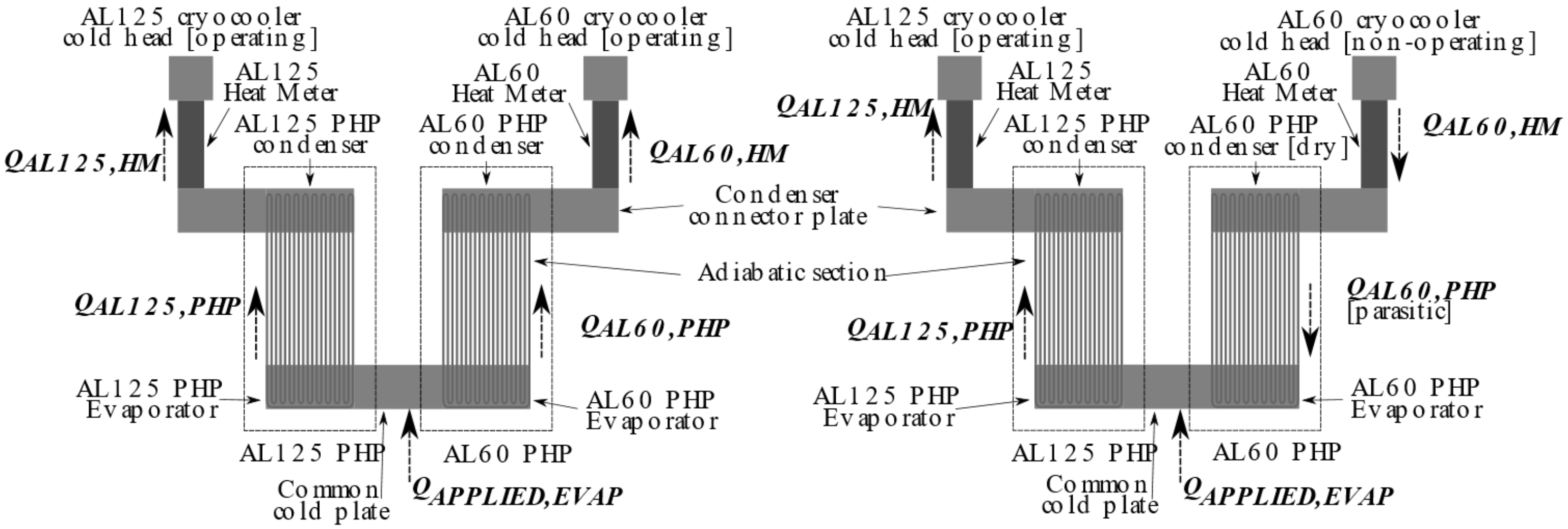

Figure 3. Schematic of a two-condenser, two-cryocooler PHP system showing heat flows and PHP working fluid states for both AL125 and AL60 cryocoolers operating (left) and for the AL125 cryocooler operating and the AL60 cryocooler non-operating (right). AL60 and AL125 are cryocooler models used in the experiment for this work. See paper for details

Experiment design and setup

Dual cryocooler / dual PHP assembly

- (1) Cryomech AL125 (120W @ 80K)
- (1) Cryomech AL60 (60W @ 80K)
- Cryocooler cold head temperature control with resistance heater
- calibrated conduction heat meter with platinum resistance temperature sensors (PRTs) for measuring heat load into each cryocooler cold head
- (2) nitrogen PHPs, each condenser connected to a single cryocooler
- PHP evaporator plates are thermally linked with copper plates
- resistance heaters provide evaporator heat load
- heat shield attached to AL125 cold head (not shown) encapsulates entire assembly
- Vertical bottom-heated orientation for both PHPs

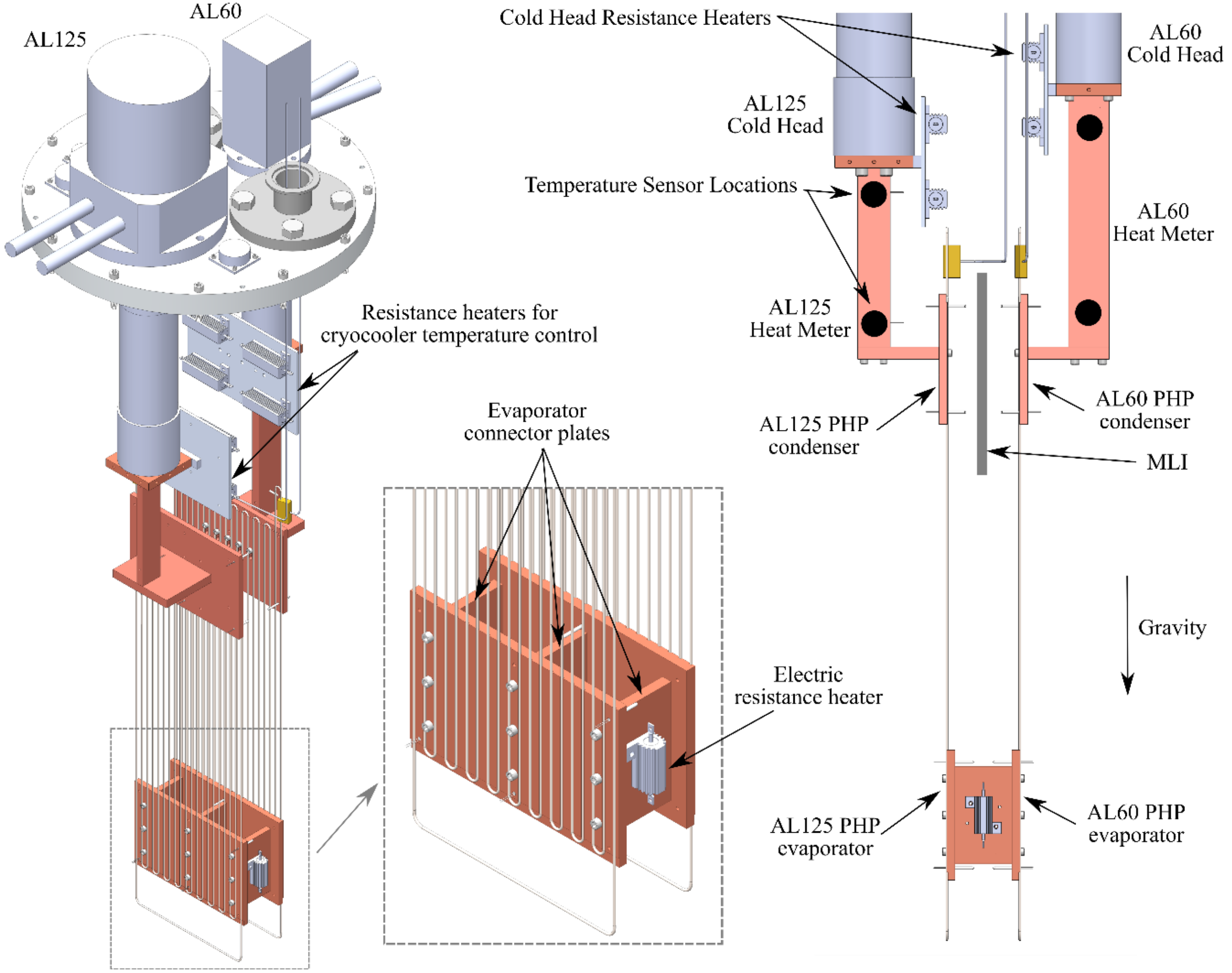

Figure 4. Experiment facility assembly

Experiment design and setup

PHP details

- AL125 and AL60 PHPs are identical except for filling tube location
- stainless steel PHP tubes with ID=1.08mm, OD=1.47mm. Critical diameter for nitrogen is approximately 2mm[5,6].
- 20 turns for each PHP
- copper evaporator and condenser plates with 6.5mm thickness and dimensions shown in **Figure 5**.
- tube sections connected with copper sleeves and silver braze
- PHP tubes are soft soldered to copper plates
- PRT sensors installed in plates at locations in **Figure 5**.

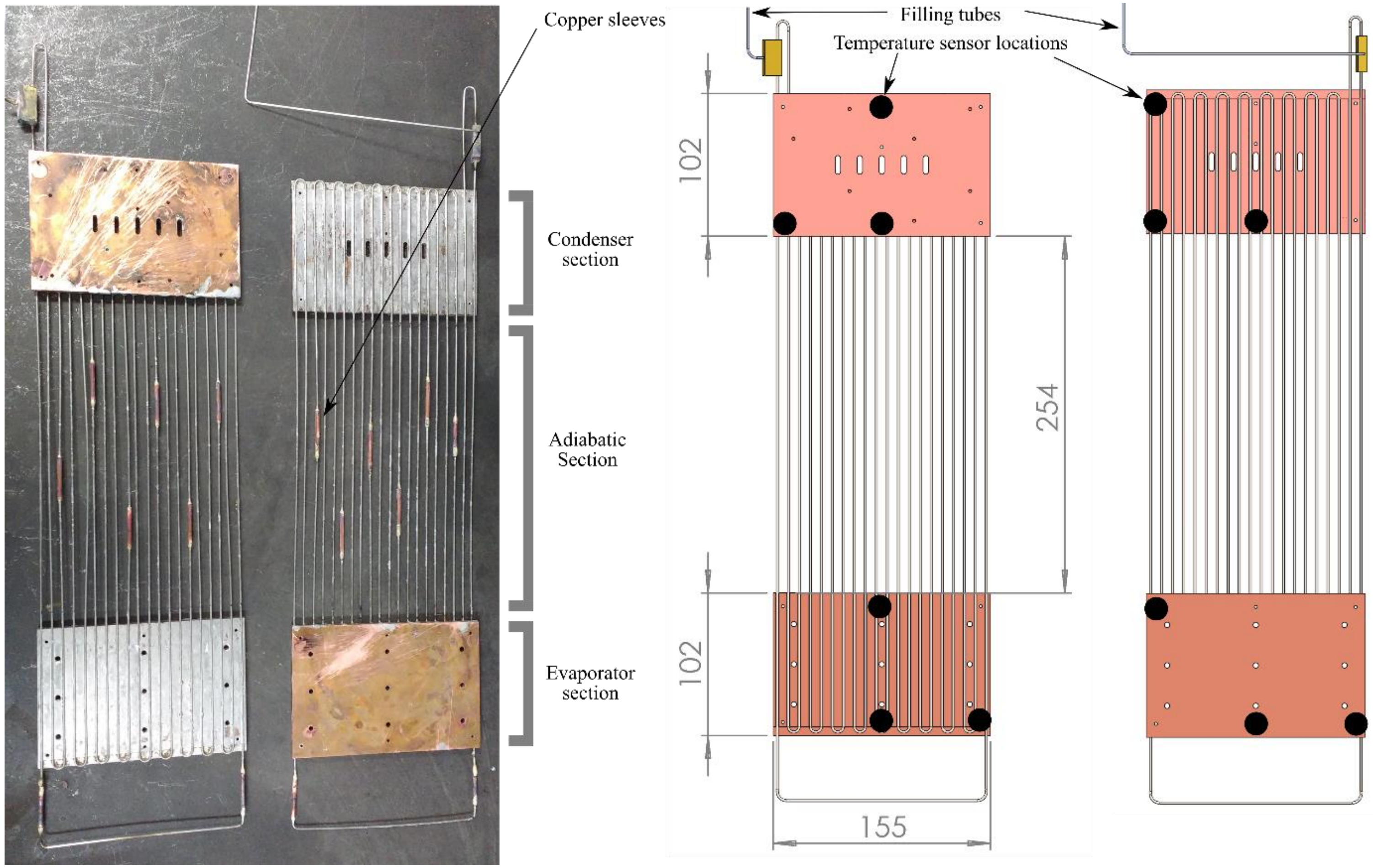

Figure 5. Image (left) and CAD assembly (right) of PHPs designed and fabricated for this work. Dimensions are in mm. See paper for details.

Results (preliminary)

- Operating conditions
  - State 1
    - AL125 operating with $T_{condenser}$ ~70K
    - AL60 operating with $T_{condenser}$ ~70K
    - 'ON state'
  - State 2
    - AL125 operating with $T_{condenser}$ ~70K
    - AL60 non-operating with $T_{condenser}$ ~290K
    - 'OFF state'
- Sum of heat meter measurements agrees with electric heat applied at evaporator
- ~9.0W through each PHP demonstrated (not maximum as dryout did not yet occur) in ON state
- ~1.3W parasitic load through AL60 PHP in 'OFF state'

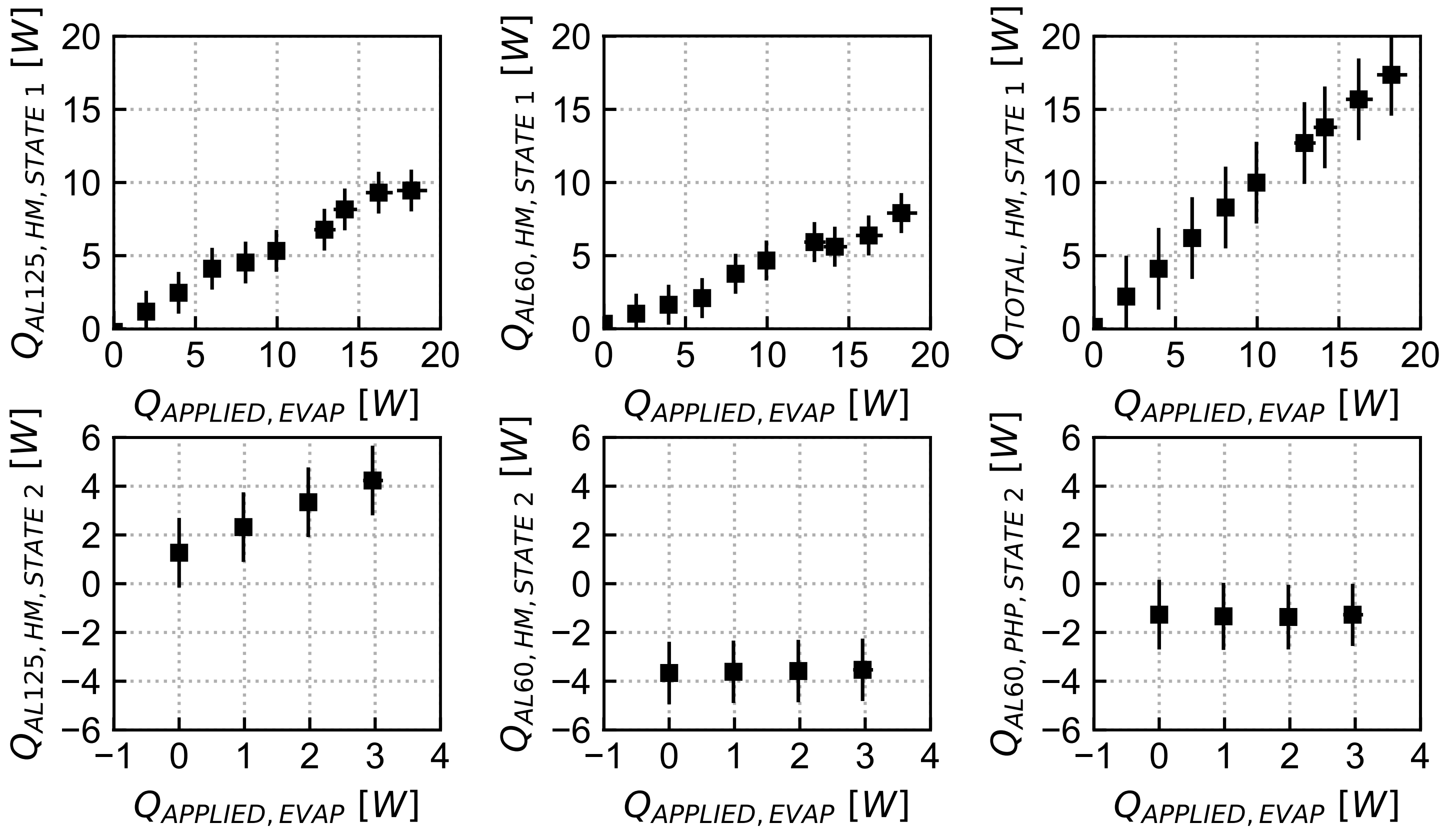

Figure 6. Heat measurements through AL125 and AL60 heat meters in state 1 and state 2 as functions of applied evaporator heat load. AL60 PHP parasitic load on evaporator in state 2 as a function of applied evaporator heat load (bottom right panel). See paper for details.

Results (preliminary)

PHP effective thermal conductivity

- up to ~40000 [W/m-K] PHPs in 'ON state'
- ~50 [W/m-K] for AL60 PHP in 'OFF state'
- conductivity of AL60 PHP in 'OFF state' does not vary significantly with applied evaporator load

Ratio of 'ON state' to 'OFF state' thermal conductivity

- depends on 'ON state' applied evaporator heat load
- up to ~850

Performance is similar to other nitrogen PHPs[7,8,9]

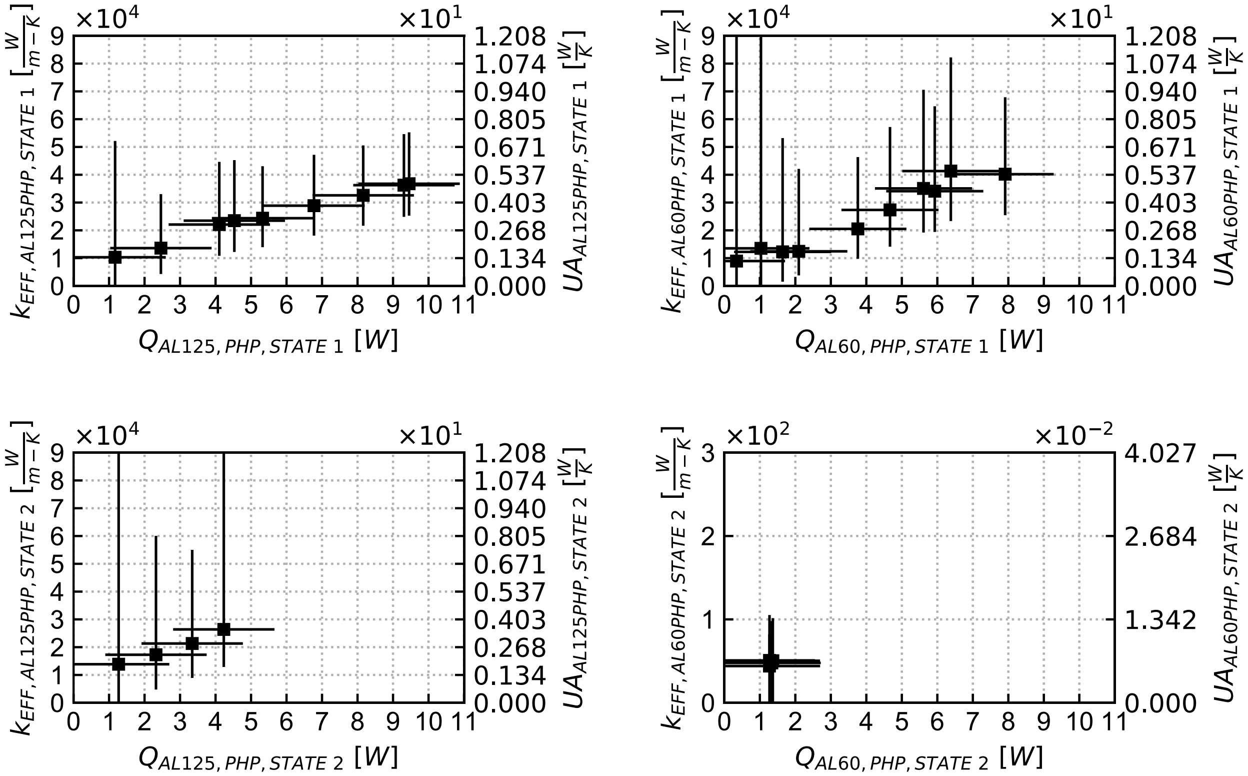

Figure 7a. Effective thermal conductivities and associated conductance for each PHP as functions of PHP heat loads for state 1 and state 2. See paper for details.

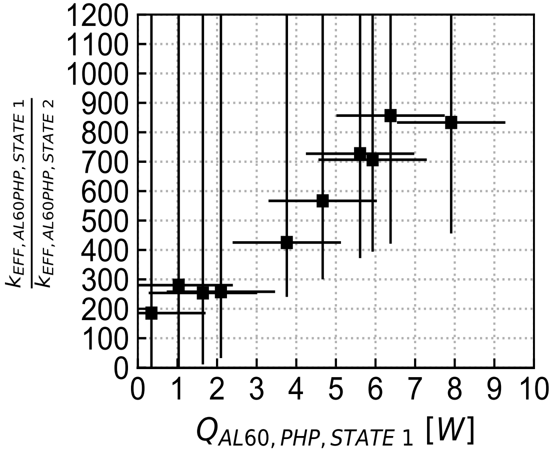

Figure 7b. Ratio of 'ON state' to 'OFF state' thermal conductivity for the AL60 PHP. See paper for details.

Conclusions and future work

- Preliminary on-state PHP performance comparable to existing nitrogen PHPs
  - 9W total heat transfer achieved through each PHP
  - 40000 W/m-K effective thermal conductivity
- Preliminary off-state PHP performance
  - ~1.3W parasitic load on ~70K evaporator via the dry PHP due to the non-operating cryocooler (with cold head at ~290K)
  - on/off effective thermal conductivity ratios of up to 850
- Comments on improving off-state performance
  - lower parasitic loads and higher on/off effective thermal conductivity possible by extending PHP length
  - PHP length for this work limited by external factors (existing dewar and space for heat meters)
  - $\frac{parasitic\ load}{operating\ PHP\ \mathrm{maximum}\ capacity} \approx 0.14$ for this experiment. With proper design considerations (extended PHP length), this could be substantially lowered
- Future work
  - measurements over a full range of fill ratios
  - reconfigure PHP plumbing into a single 40 turn loop
  - design and build of system with helium as the working fluid

Acknowledgements

- Funding for this work provided by the United States Office of Naval Research
- Grant number: N00014-18-1-2705

References

1. Holley B and Faghri A 2005 *Int. J. Heat Mass Transf.* **48** 2635–51
2. Charoensawan P, Khandekar S, Groll M and Terdtoon P 2003 *Appl. Therm. Eng.* **23** 2009–20
3. Khandekar S, Gautam A and Sharma P 2008 *Int. J. Thermal.* Sci. **48** 535–46
4. Mok M 2017 *Development of a Multiple Evaporator Nitrogen Pulsating Heat Pipe for Space Cryogenics Applications* University of Wisconsin – Madison
5. Khandekar S 2004 *Thermo-hydrodynamics of Closed Loop Pulsating Heat Pipes* Institut für Kernenergetik und Energiesysteme der Universität Stuttgart
6. Fonseca L, Miller F and Pfotenhauer J 2018 *Appl. Therm. Eng.* **130** 343–53
7. Mameli M, Marengo M and Khandekar S 2013 *Int. J. Thermal. Sci.* **75** 140–52
8. Mito T, Natsume K, Yanagi N, Tamura H, Tamada T, Shikimachi K, Hirano N and Nagaya S 2010 *IEEE Trans Appl Supercond* **20** 2023-26
9. Jiao A, Ma H and Critser J 2009 *Int. J. Heat Mass Transf.* **52** 3404–09