Design and Operation of a Cryogenic Nitrogen Pulsating Heat Pipe

Luis Diego Fonseca Flores

Advisor: Franklin Miller
Co-Advisor: John Pfotenhauer

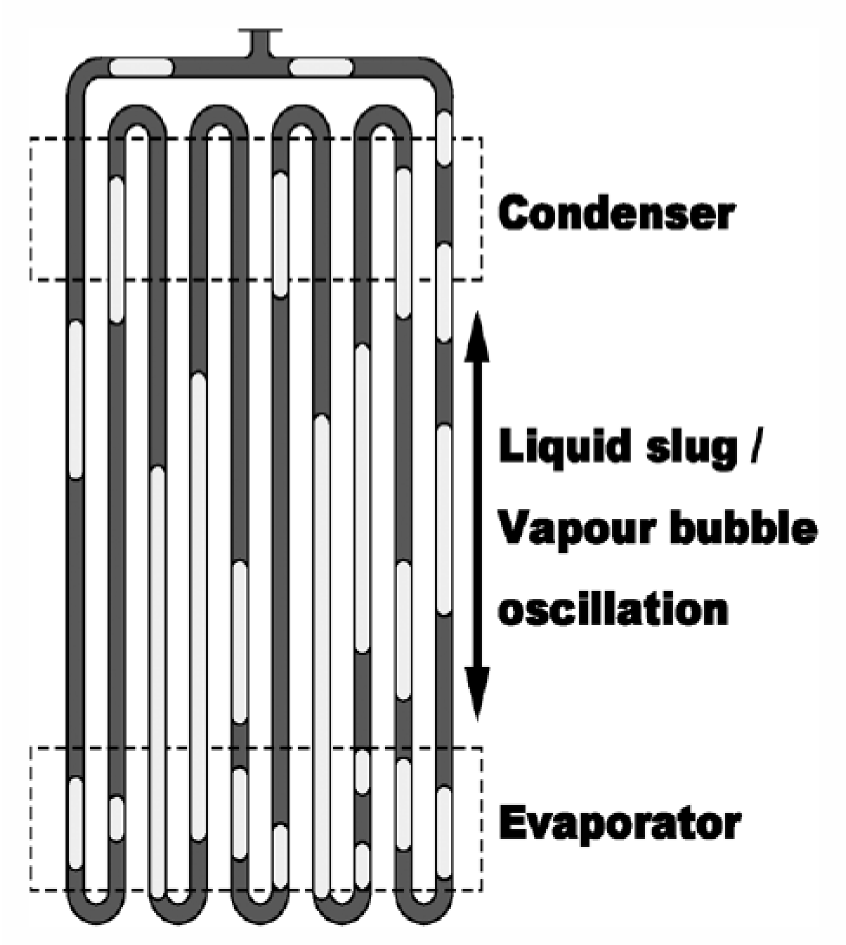
Department of Mechanical Engineering
University of Wisconsin-Madison

Overview

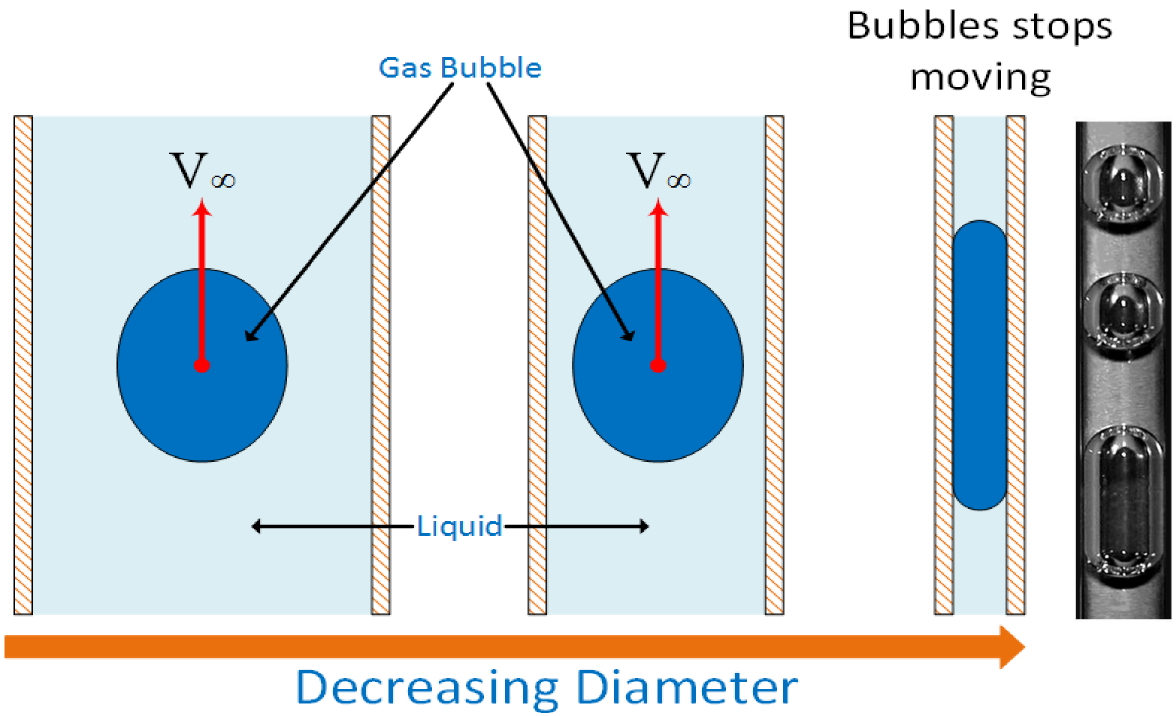
- Concept
- Main Design Parameter
- Experimental Setup
- Results
- Future Improvements
- Questions

PHP Concept

- Pulsating Heat Pipes: oscillations/pulsations are cause by the change in volumetric expansion and contraction in evaporator and condenser.
- Liquid plugs and vapor bubbles are formed.



PHP Main Design Parameter



$$Re = \frac{F_i}{F_\mu} = \frac{\rho_L V_\infty D}{u_L}$$

$$We = \frac{F_i}{F_s} = \frac{\rho_L V_\infty^2 D}{\sigma}$$

$$Fr = \frac{F_i}{F_b} = \frac{\rho_L V_\infty^2}{(\rho_L - \rho_g) g D}$$

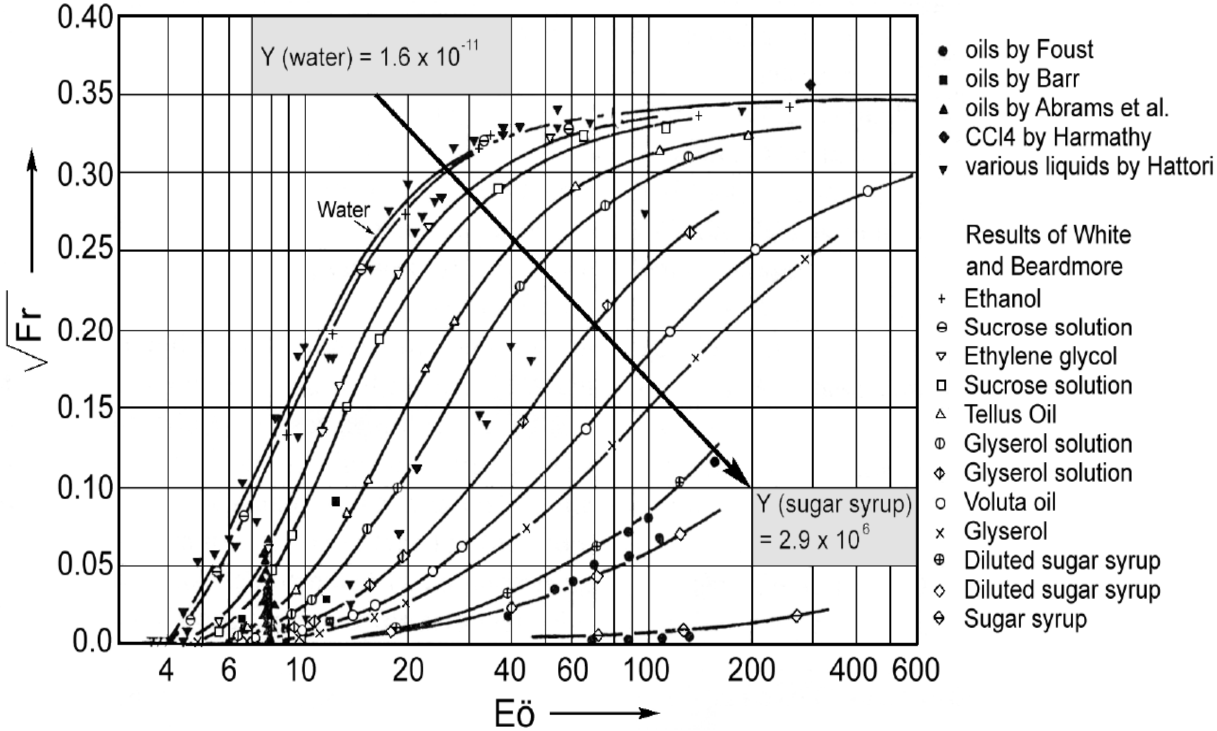
$$Ps = \frac{F_\mu}{F_b} = \frac{\mu_L V_\infty}{(\rho_L - \rho_g) g D^2}$$

$$Eo = \frac{F_b}{F_s} = \frac{(\rho_L - \rho_g) g D^2}{\sigma}$$

$$Bo = \sqrt{Eo}$$

PHP Main Design Parameter

Air bubbles through different fluids in vertical plates White and Beardmore (1962) .



$$Fr = \frac{F_i}{F_b} = \frac{\rho_L V_\infty^2}{(\rho_L - \rho_g) g D}$$

$$Ps = \frac{F_\mu}{F_b} = \frac{\mu_L V_\infty}{(\rho_L - \rho_g) g D^2}$$

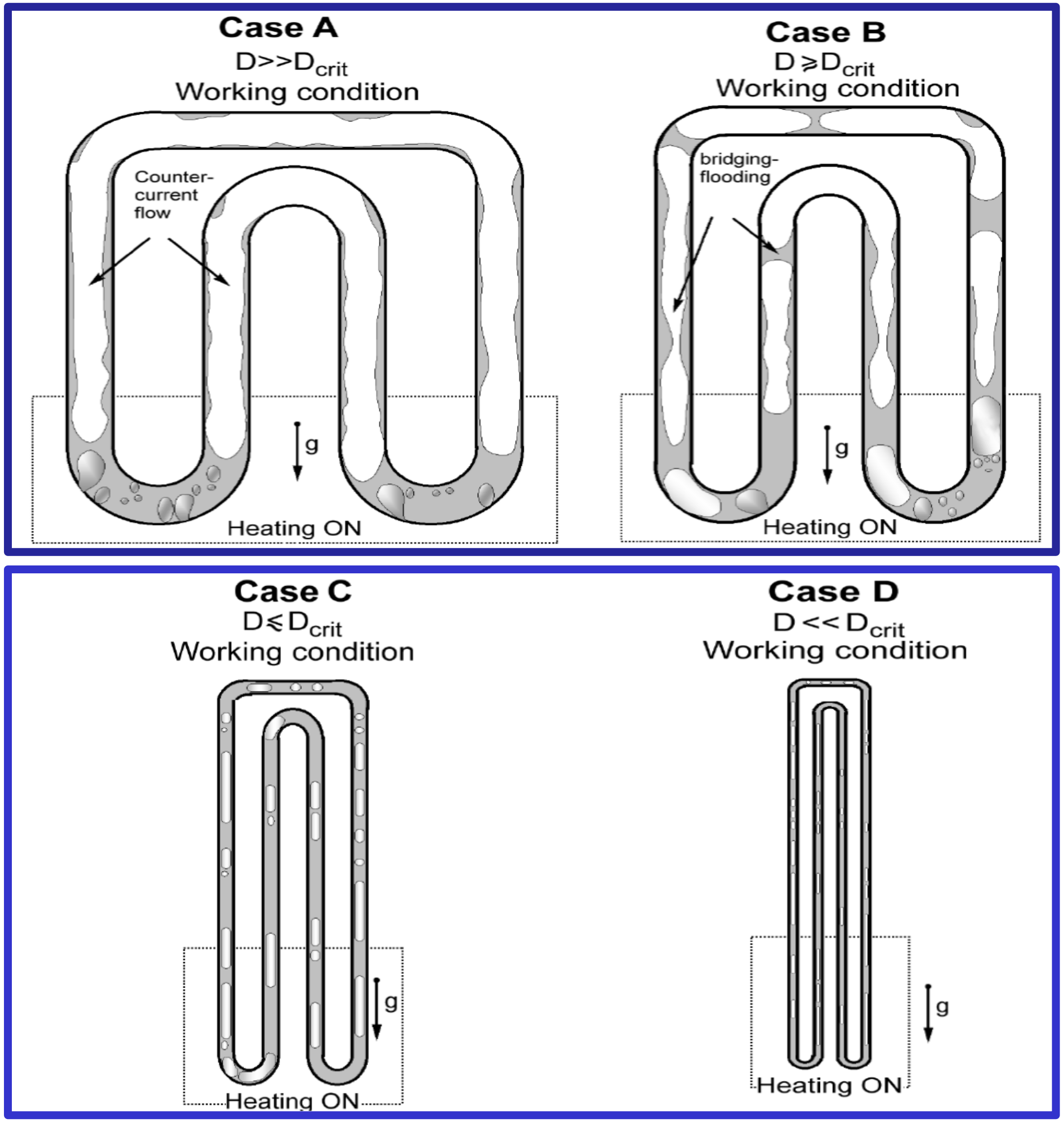
$$Eo = \frac{F_b}{F_s} = \frac{(\rho_L - \rho_g) g D^2}{\sigma}$$

$$Y = \frac{Ps^4 Eo^3}{Fr^2} = \frac{g \mu_L^4}{\rho_L \sigma^3}$$

$$Eo = Bo^2 = \frac{(\rho_L - \rho_g) g D_{crit}^2}{\sigma} \leq 4 \longrightarrow D_{crit} \leq 2\sqrt{\frac{\sigma}{(\rho_L - \rho_g) g}}$$

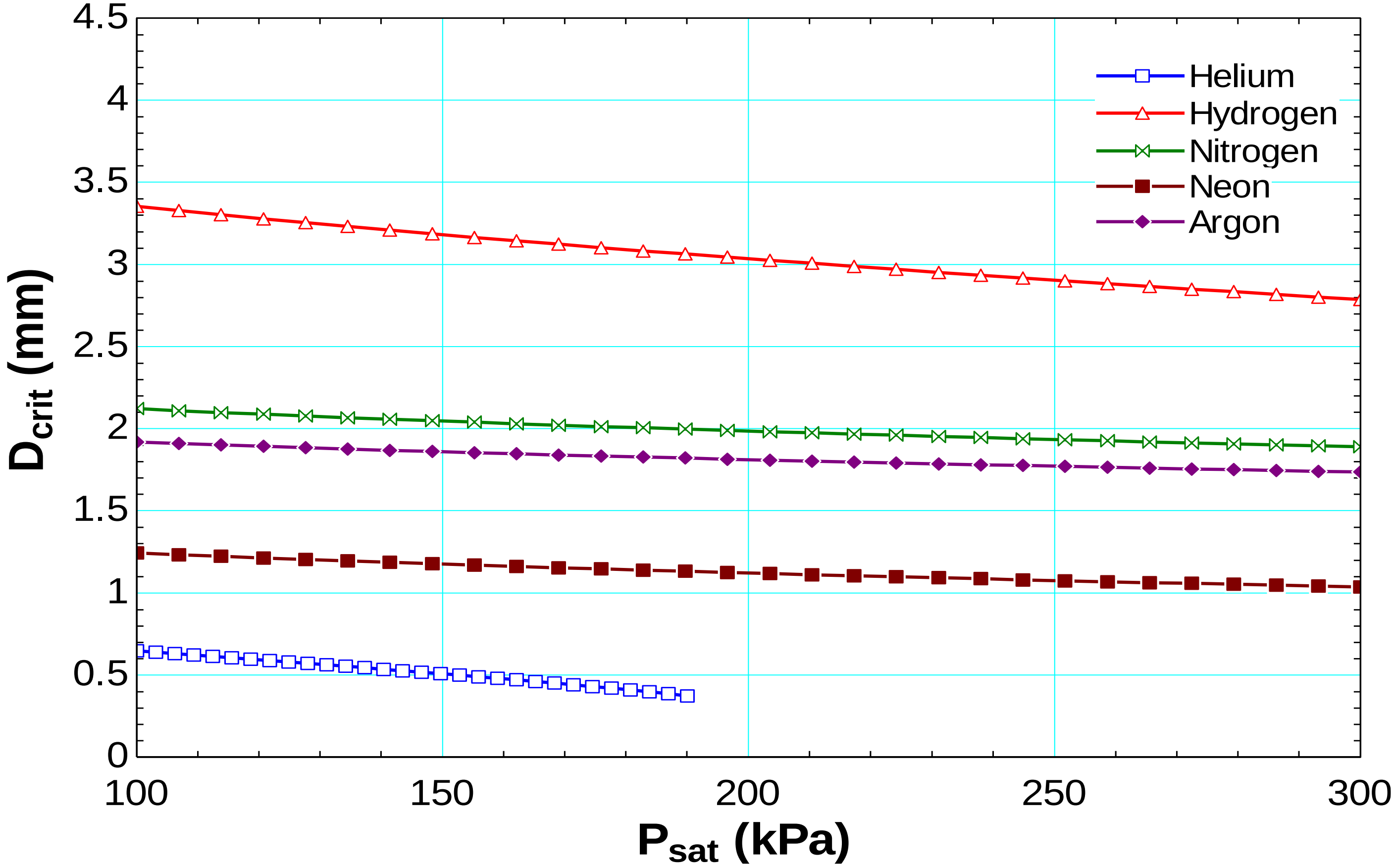
PHP Main Design Parameter

$$D_{crit} \leq 2\sqrt{\frac{\sigma}{(\rho_L - \rho_g)g}}$$



PHP Main Design Parameter

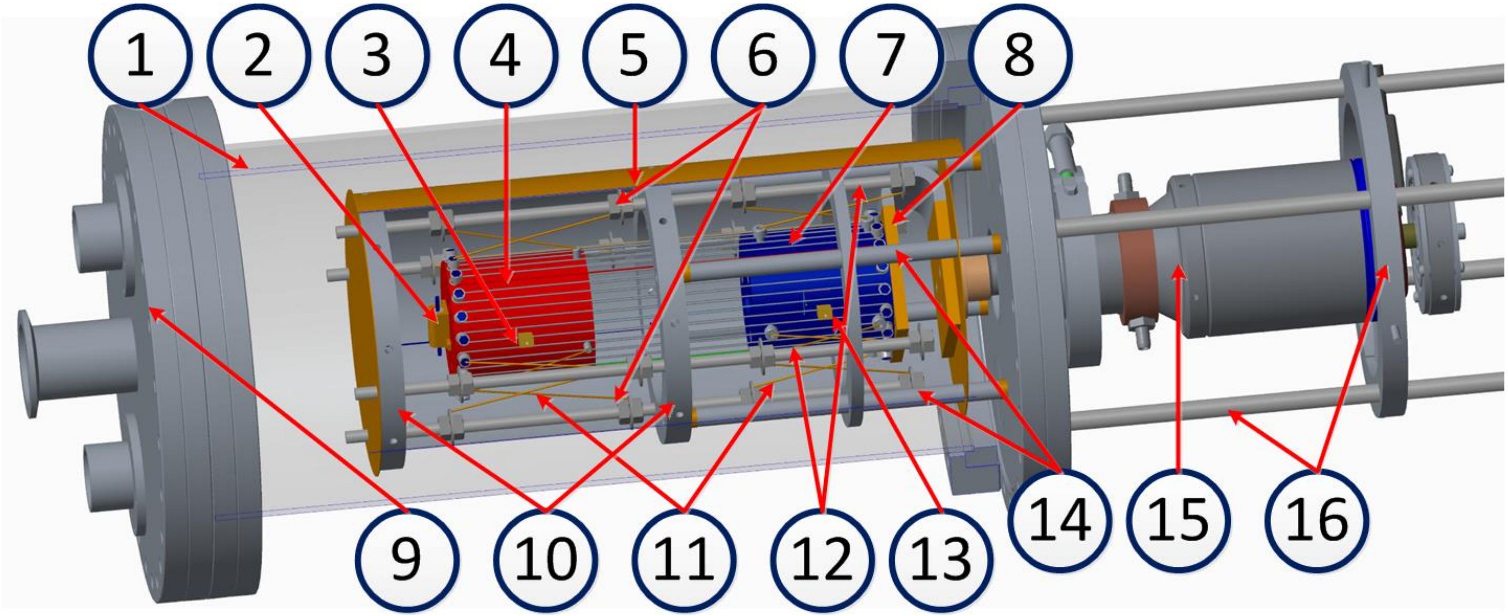
$$D_{crit} \leq 2\sqrt{\frac{\sigma}{(\rho_L - \rho_g)g}}$$



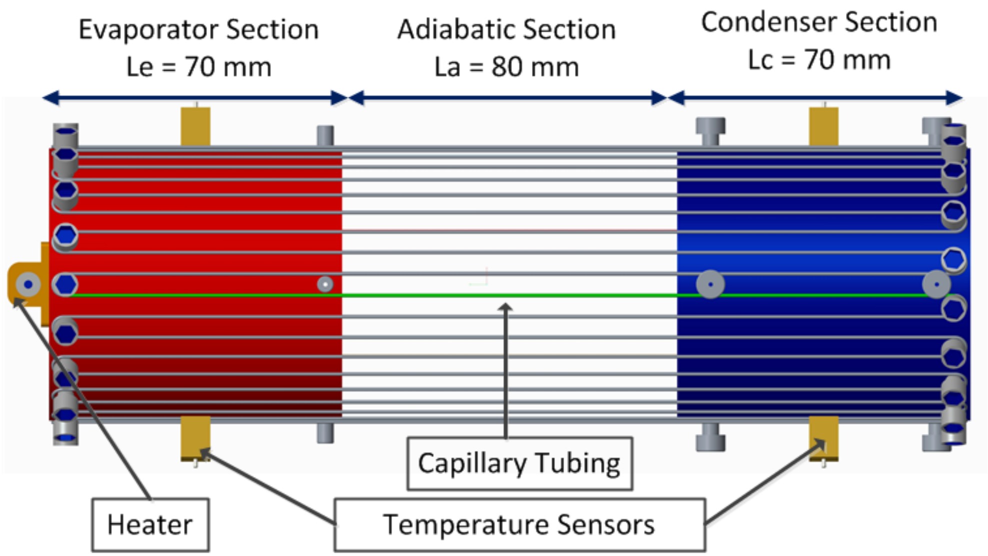
Experimental Setup

Main Components:

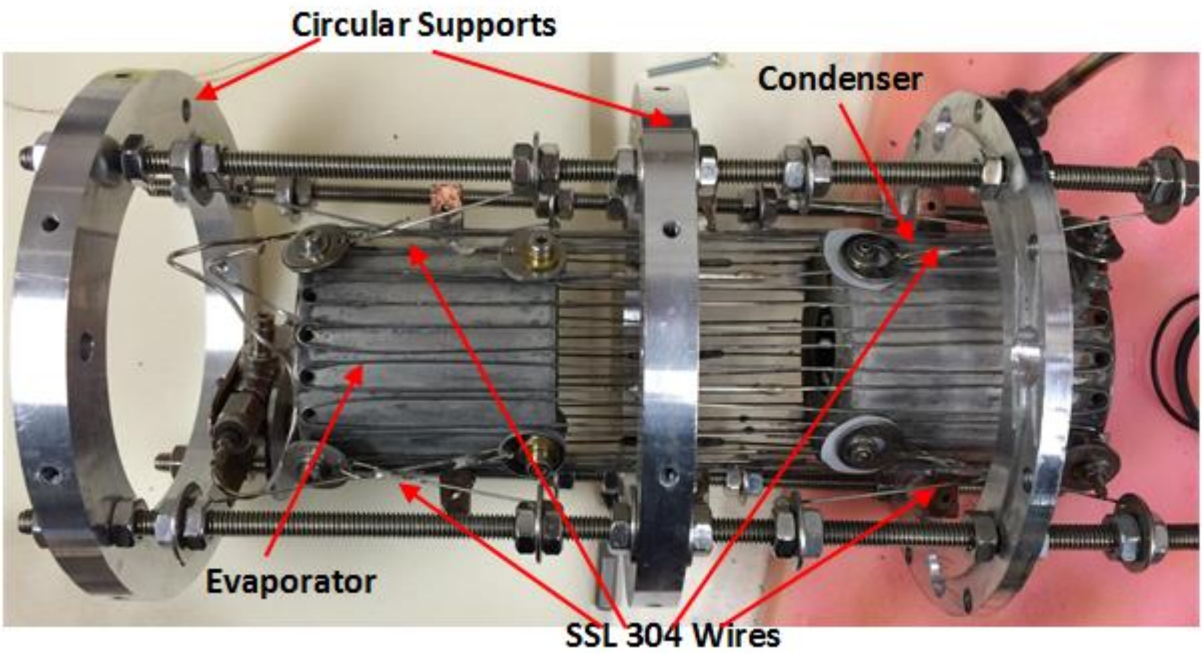
1) 20 cm OD Vacuum Nipple.
2) PHP heat at Evaporator.
3) PT-103 temperature casing at evaporator.
4) Evaporator Section.
5) Thermal Jacket: Cu 110 Grade.
6) Wire Support Tensors.
7) Condenser Section.
8) Thermal Bus: from cryocooler to condenser.
9) Vacuum and temperature feedthrough flange.
10) AL 6061 Circular Supporting Plates.
11) Supporting Wires for condenser and evaporator sections.
12) Threaded rod to fix circular supports (10).
13) PT-103 temperature casing at condenser.
14) SSL support tubes for circular support. Bolted from bottom flange to circular support.
15) Sunpower CT cryocooler. Nominal operation: 10 W at 77 K.
16) Support Structure for cryocooler.



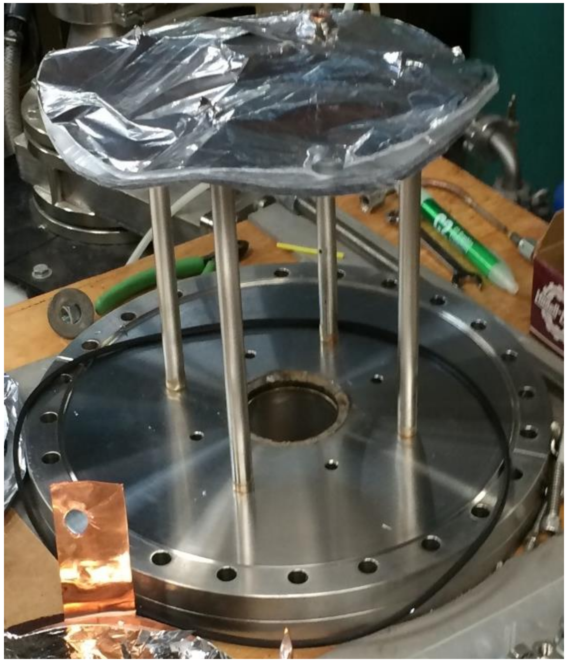
Experimental Setup: PHP Core

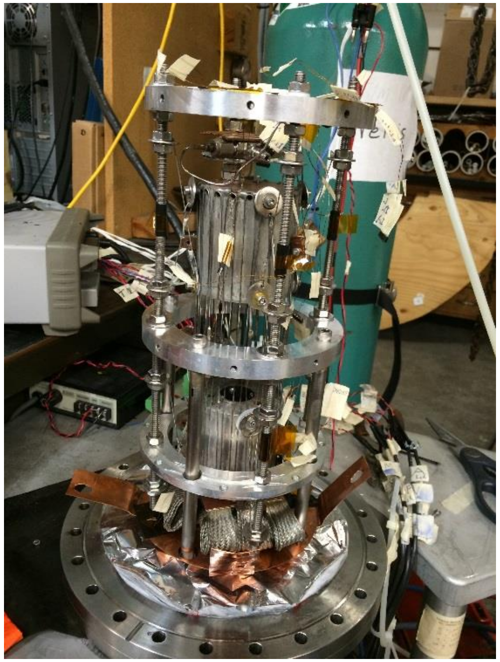


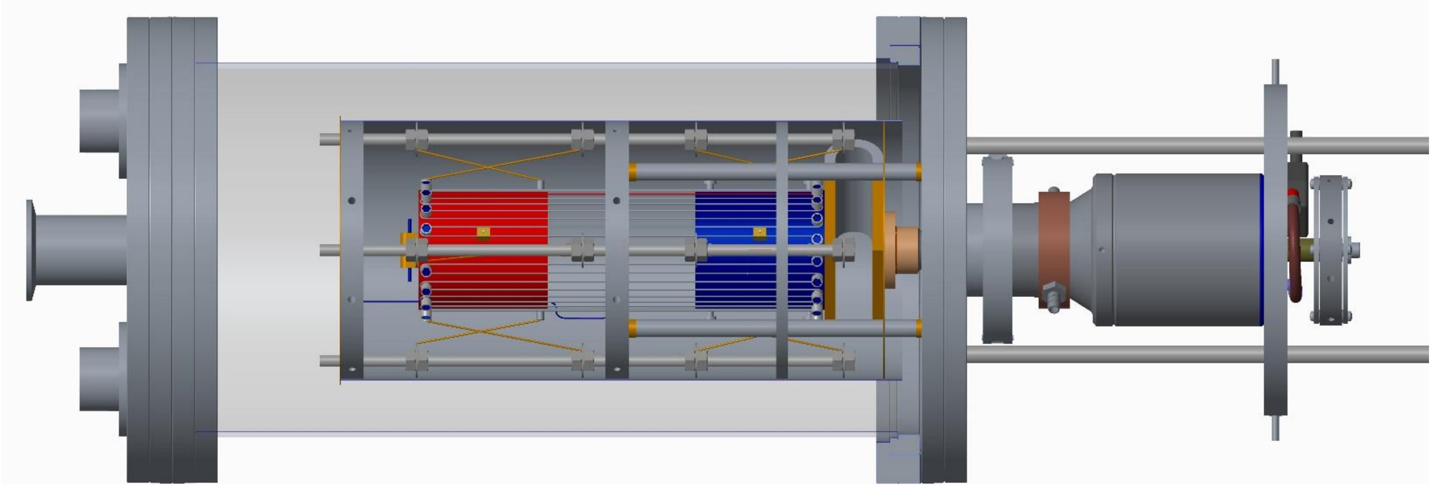
- Condenser section have an OD of 65 mm.
- Capillary tubing are soldered to both sections.
- PHP core are supported by SSL 304 Wires.



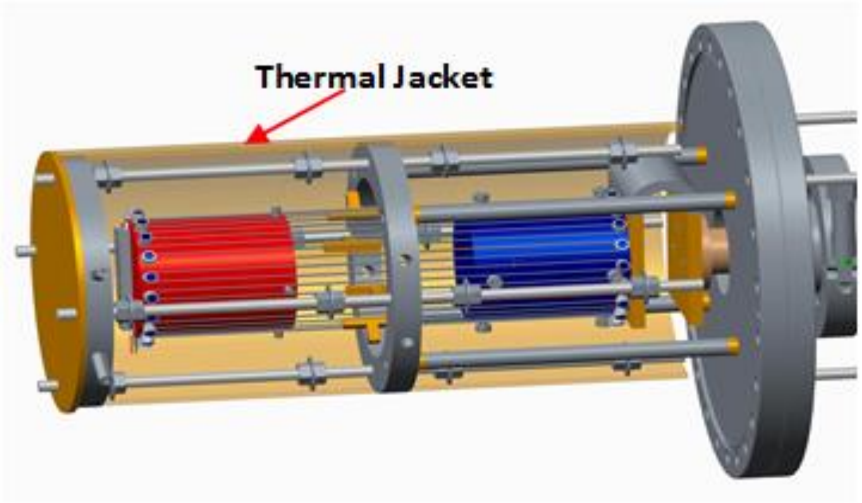
Experimental Setup: Support Structure

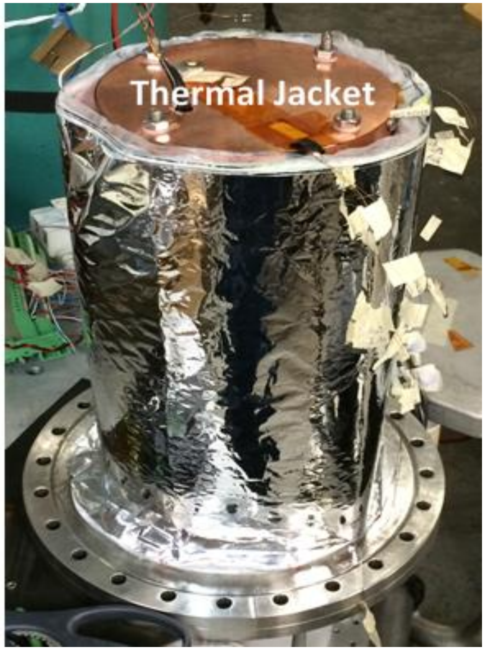




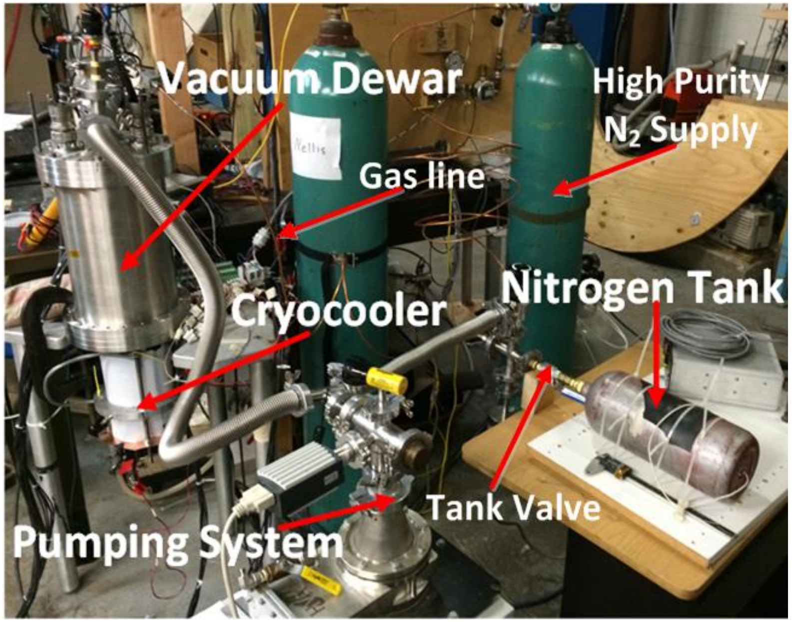


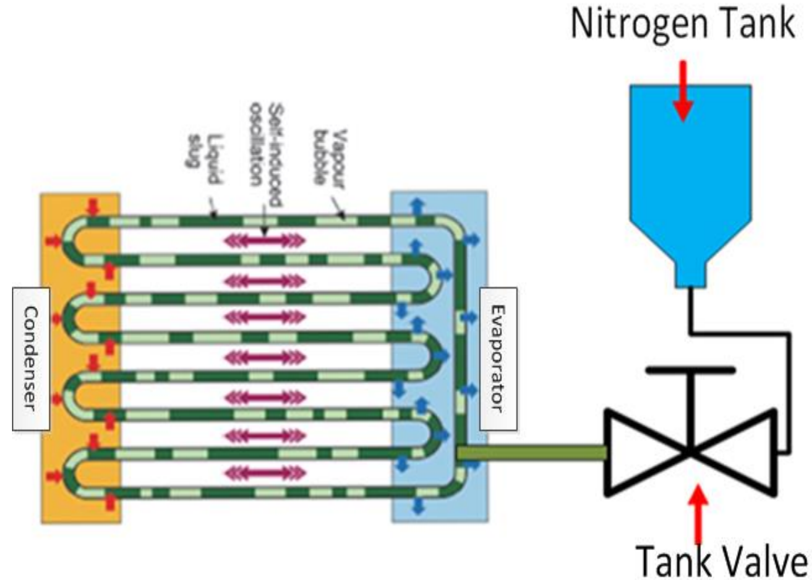
Experimental Setup: Thermal Jacket and MLI

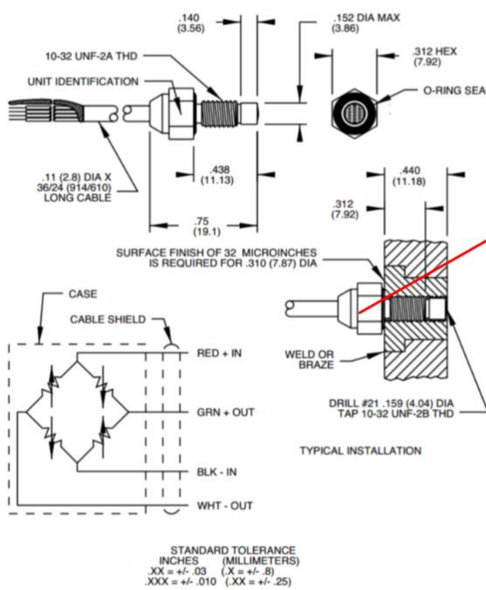




Experimental Setup: Vacuum Pumps

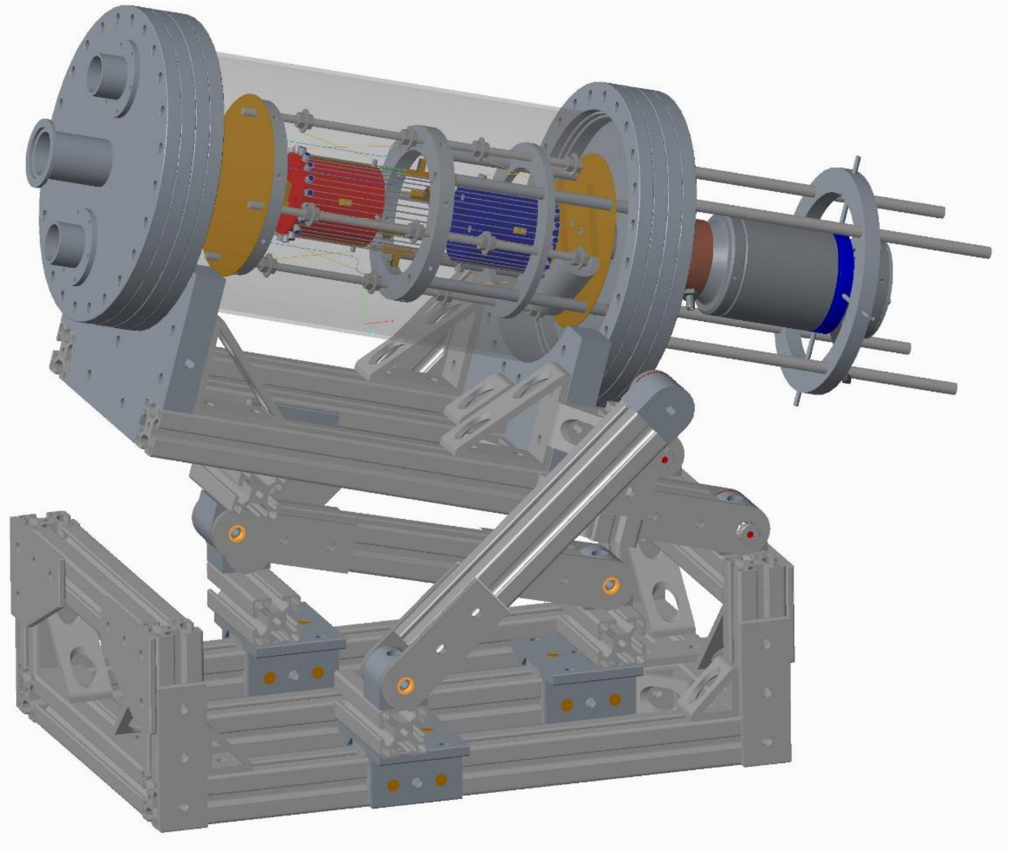






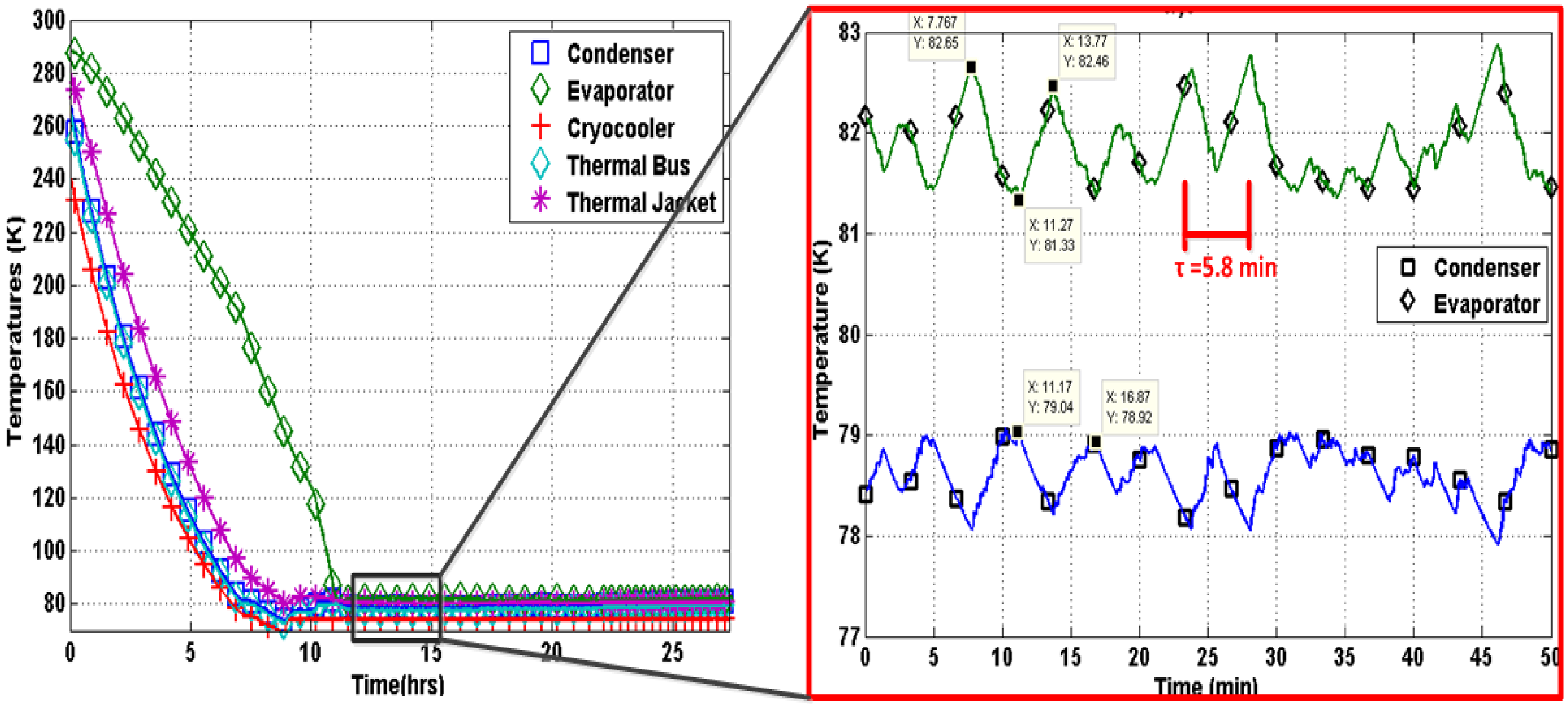
Experimental Setup: Future Test Bed

Inclination test bed to run PHP at different orientation angles.



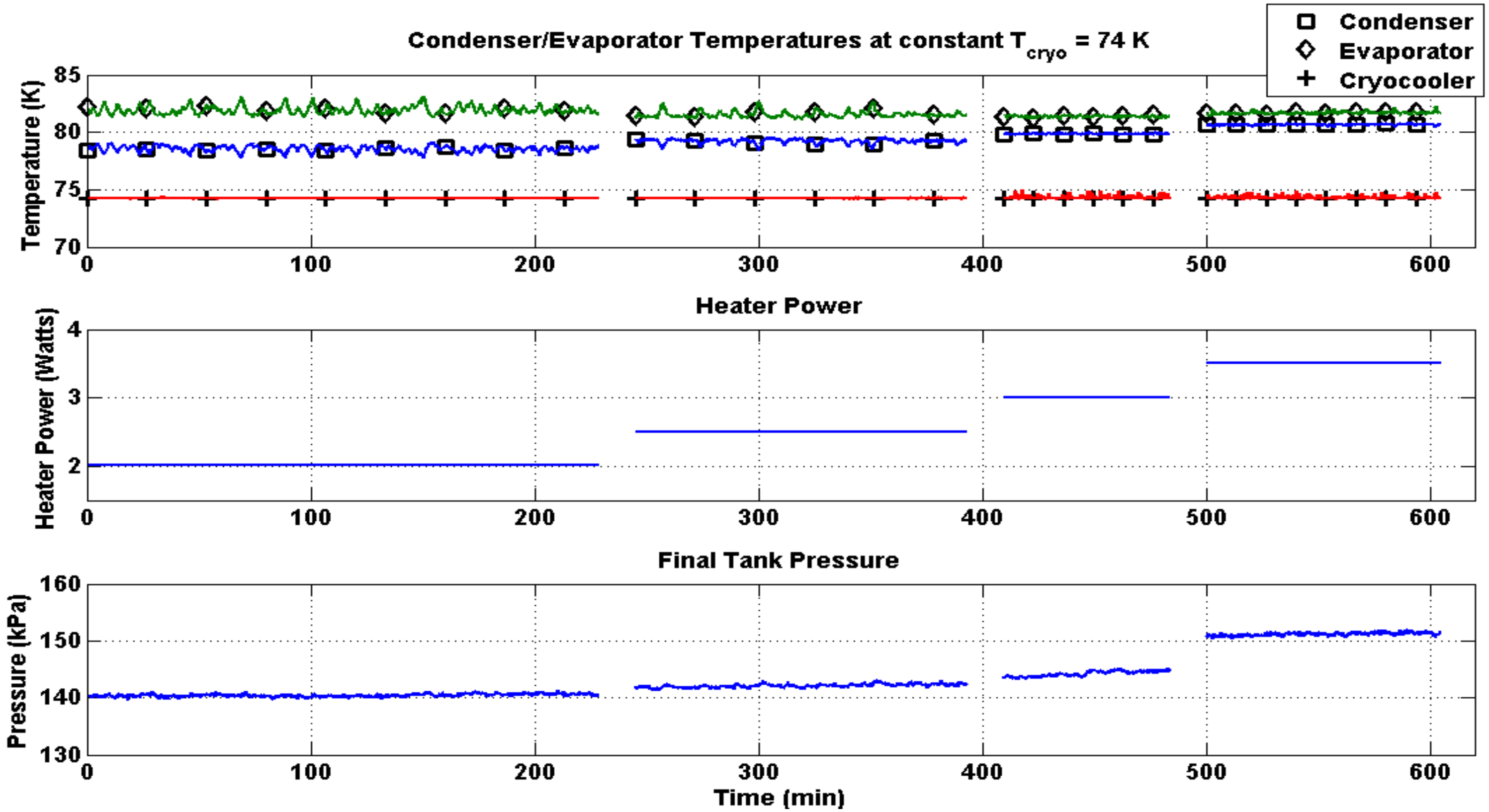
Experimental Results

- Horizontal orientation.
- Cooldown curve took 12 hours to reach saturation temperatures.
- Pressure in PHP around 140 kPa.
- At heat load below 2 W, time periods reached 5.8 min.



Experimental Results

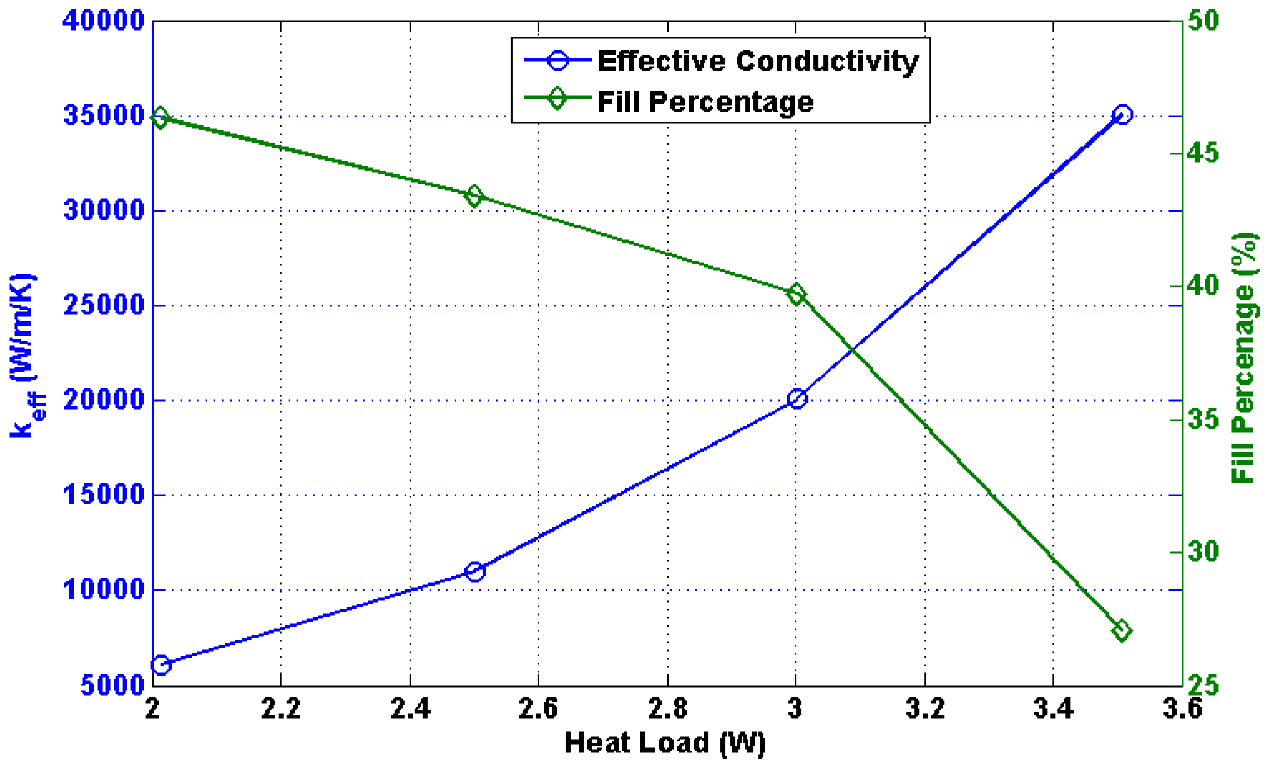
- Horizontal orientation.
- Maintained constant cryocooler temperature of 74 K.
- Increased heat load from 2 W to 3.5 W.
- ΔT between sections decreased from 3.3 K to 1 K.
- Oscillations periods decreased dramatically, most frequent were between 18 and 42 seconds.



Experimental Results

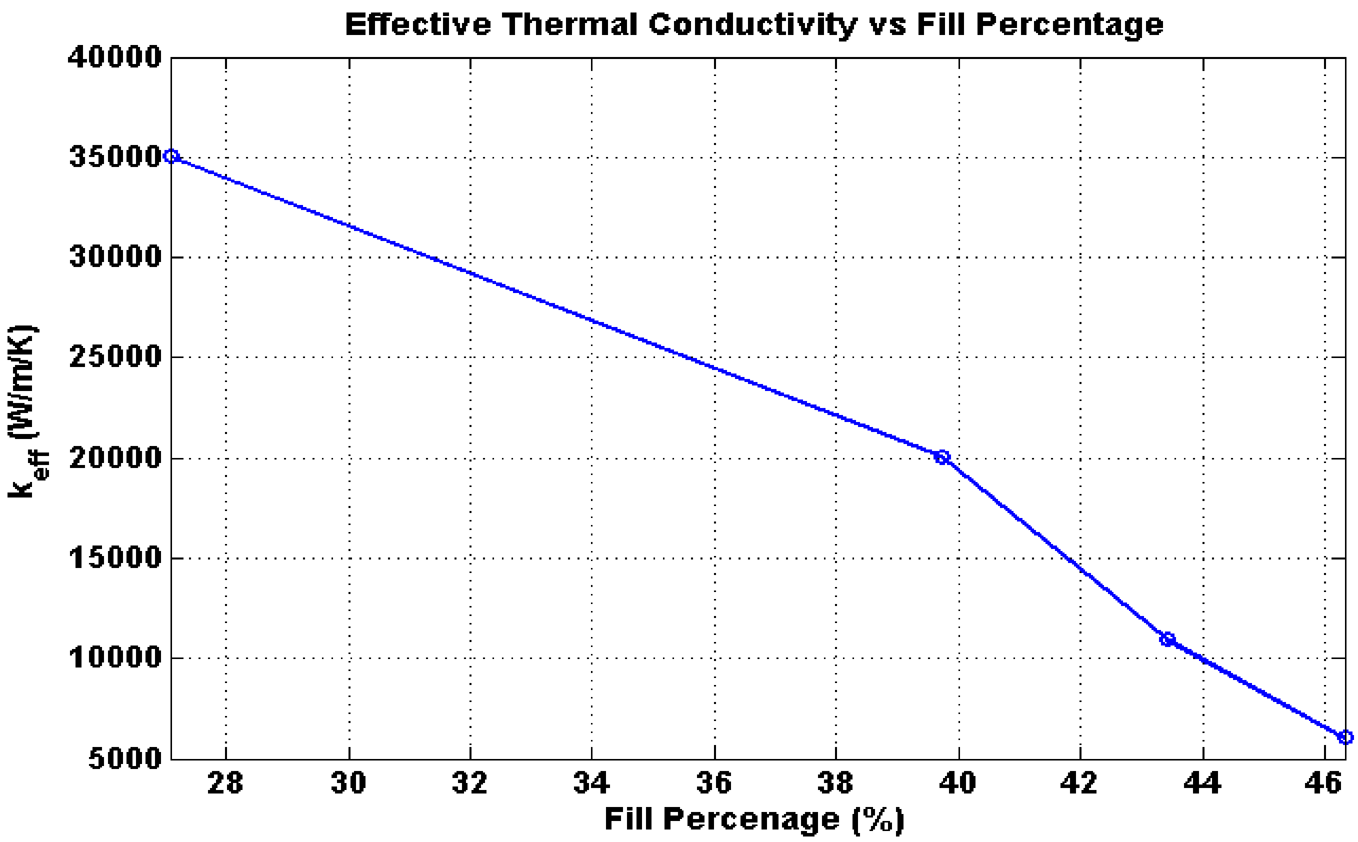
- As heat load increases effective thermal conductivity k_{eff} increases but Fill Percentage f_{liq} decreases.

$$N_{total} = \frac{P_{final} V_{\text{tank}}}{R T_{amb}} + \frac{P_{final} V_{gas-lines}}{R T_{gas-lines}} + \bar{r}_{l,sat} V_l + \bar{r}_{v,sat} \left(V_{PHP} - V_l \right) \qquad f_{liq} = \frac{V_l}{V_{php}}$$



Experimental Results

- it should be noted that the effective thermal conductivity is higher at low fill percentages at a constant cryocooler cold tip of 74 K.



Future Work

- Build inclination test bed.
- Test different adiabatic lengths.
- Divide evaporator section in 3 sections to have 3 independent heaters.
- Test experiment in a zero gravity environment (Parabolic Flight) to verify usage for space applications. NASA’s flight opportunity program.
- Currently building another PHP to test more than one cryogen: Argon, Nitrogen, Helium, Neon and Hydrogen. (Supported by Sumitomo)

Special Thanks

- Sunpower Inc. for all their help and consulting of the operation of the CT cryocooler.

Questions?