Recent Advances in Cryogenic Pulsating Heat Pipes

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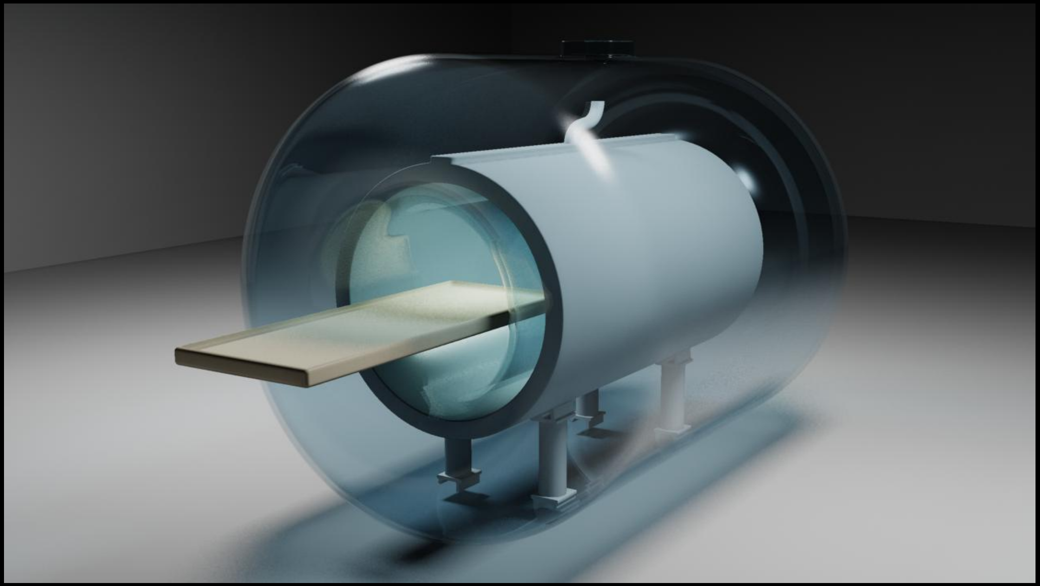
Where are we going?

- Introduction to the topic
- What have we learned from room temperature phps?
- What have we learned from cryogenic phps?
  - significance of the fill ratio
  - oscillations are long range
  - non-uniform heating produces system adjustments

INTRODUCTION

Technology Challenge

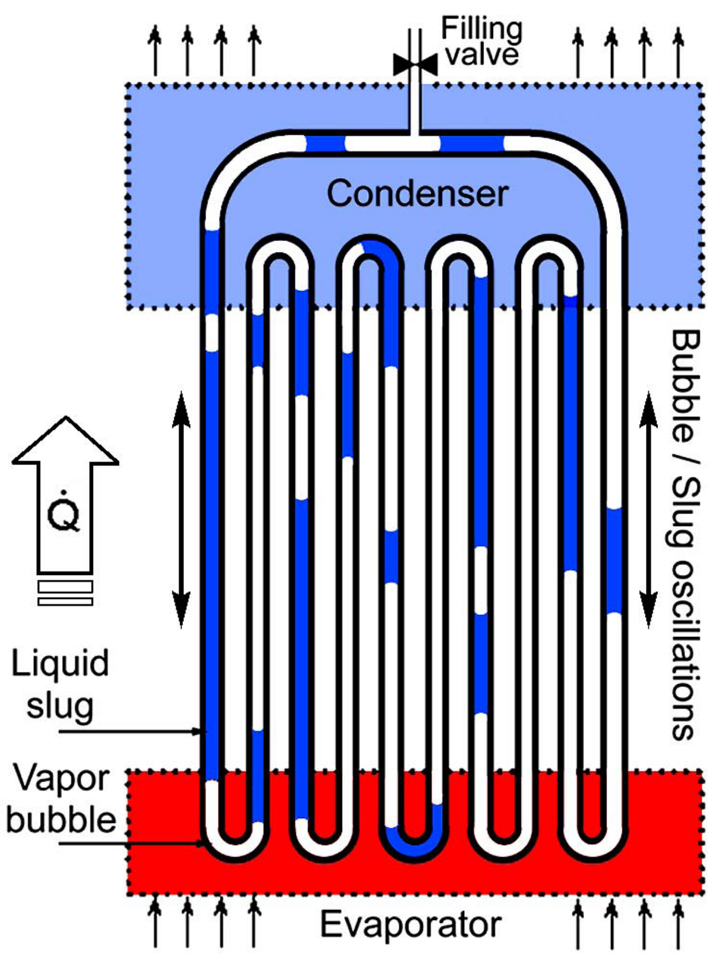
- Regenerative cryocoolers provide localized cooling
  - Stirling, GM, Pulse-tube coolers eliminate (or reduce) the need to handle liquid cryogens, but cooling is produced only at the tip of the cold-finger
- Cryogenic applications require distributed cooling
  - superconducting magnet examples: accelerators, MRI, NMR
  - Length scales are typically ~ 1 meter



Technology Challenge

- Options for distributing the cooling power
  - High conductivity metals
    - Large cross sectional area required to maintain low ΔT
      - Cu (RRR 100): A ~ 10 cm² for $\nabla T < 1.5 \frac{K}{m}$ with Q ~ 1 watt
  - Hybrid regenerative / recuperative coolers (GM/Brayton, Stirling/JT, etc.)
    - multiple compressors
    - cryogenic check valves
  - Thermo-siphon and re-condenser
  - Heat pipes
    - Conventional
    - Capillary loop pipes
    - Pulsating heat pipes

What is a Pulsating Heat Pipe (PHP)?

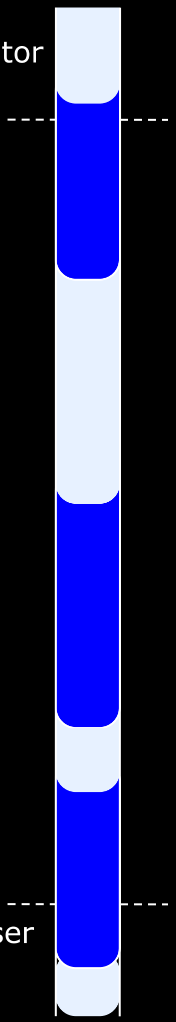


Khandekar, S., 2004, Thermo-hydrodynamics of Closed Loop Pulsating Heat Pipes,”

Institut fur Kernenergetik und Energiesysteme der Universitat Stuttgart

- First developed in 1990: Akachi, *5th Intl. Heat Pipe Symposium*
- Multiple loops of capillary tubing (no wicking structure)
- Partially filled with heat transfer fluid – alternating liquid slugs and vapor plugs
- Oscillatory and circulatory motions effectively transfer heat from evaporator (hot) end to condenser (cold) end
- World wide interest for room temperature applications

Factors influencing behavior



- Fluid properties:
  - Surface tension σ , liquid & vapor densities ρ_l, ρ_v

    Critical Bond number: $Bo = d\sqrt{\frac{g(\rho_l - \rho_v)}{\sigma}} < 2$

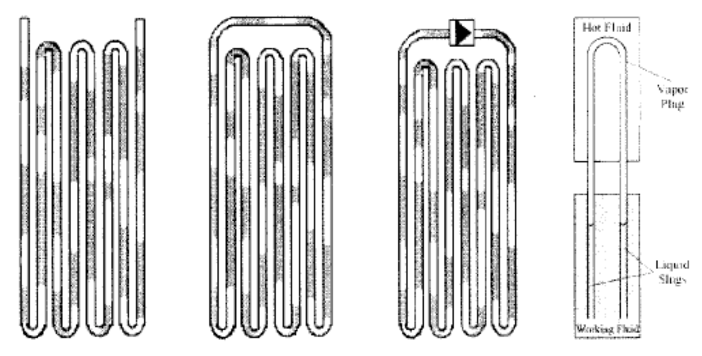
    Capillary forces define separate liquid slugs, vapor plugs
  - Saturation line $\left.\frac{dP}{dT}\right|_{sat}$, and latent heat h_{lv}

    evaporation at hot end increases local pressure

    condensation at cold end decreases local pressure
  - Sensible heat carried by slugs & plugs: C_p
  - Pressure drop along the walls: μ_l, μ_v
  - Velocity induced heat transfer with walls: $h_l, h_v, \alpha_l, \alpha_v$
  - Inertial forces of liquid slugs: Pr_l, Pr_v

Factors influencing behavior

- Geometry
  - Diameter, d, loop length, L
  - Tube shape (cross section)
  - Number of loops, N
  - Configuration: closed loop, open loop, open end



- Operation
  - Fill ratio (20% - 80%)
  - Orientation with respect to gravity (Critical number of turns, N > 16)
  - Heat input

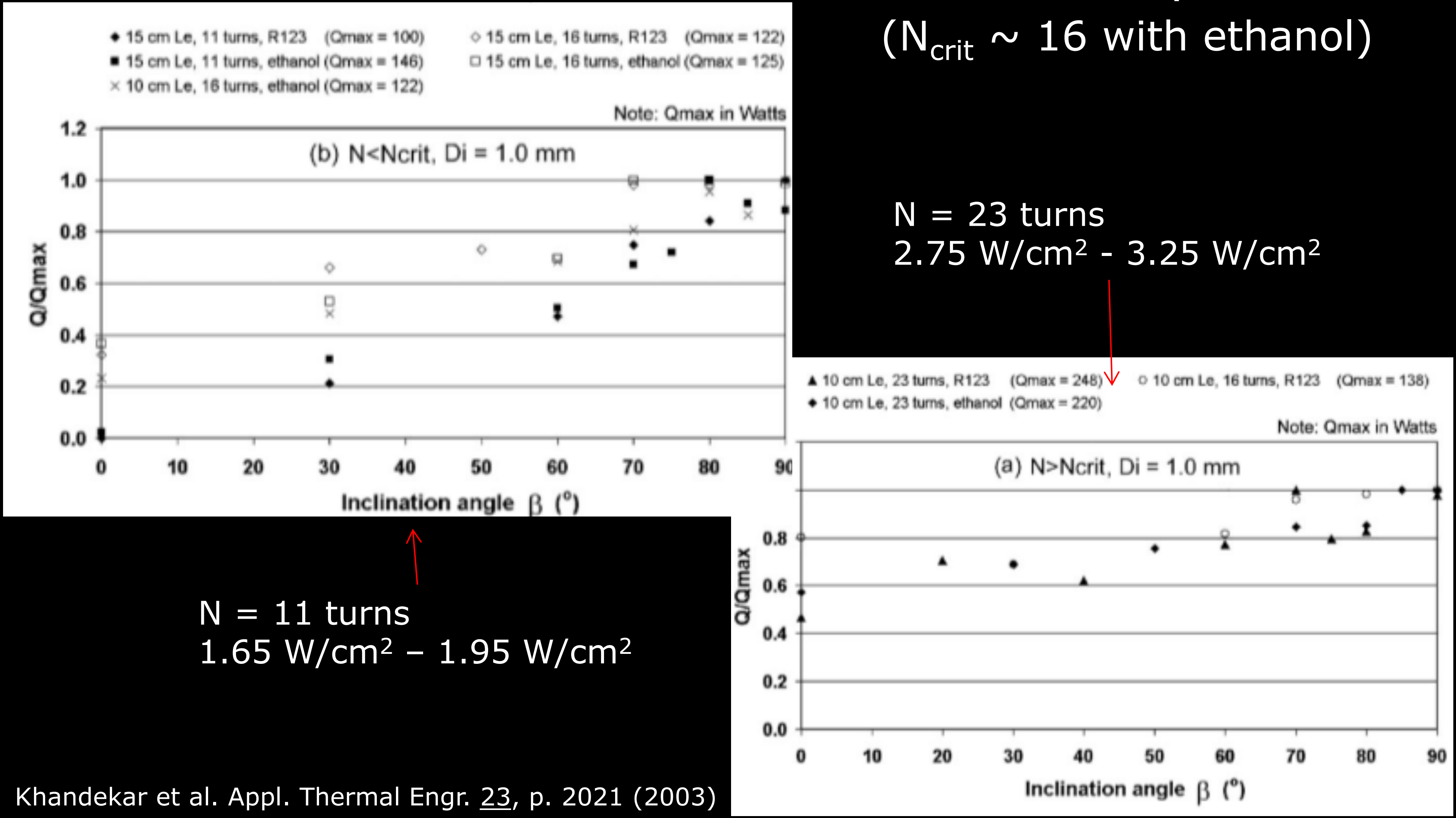
RESULTS FROM
ROOM TEMPERATURE PHPS

What do we know so far?

- Onset conditions: heat flux or $\Delta T = T_e - T_c$
- Various operational regimes:
  - Low heat flux: oscillatory slug/plug motion
    - 90%-95% of heat transfer is via sensible, rather than latent, heat
  - Medium heat flux: circulatory slug/plug flow
  - High heat flux: circulatory annular flow
    - Primary heat transfer via evaporation/condensation of film layer
- Effective conductivity comparable with conventional heat pipe (orders of magnitude larger than pure metals)
- Optimum charge ratios exist
- As charge ratio increases (20-80%), oscillation amplitude decreases, frequency increases
- Zero gravity improves performance: $We < 4; \quad D_{crit} = \frac{4\sigma}{\rho_l v^2}$
- Nano-particles improve performance (2-3x)

What do we know so far?

- Critical number of turns for orientation independence



(N_{crit} ~ 16 with ethanol)

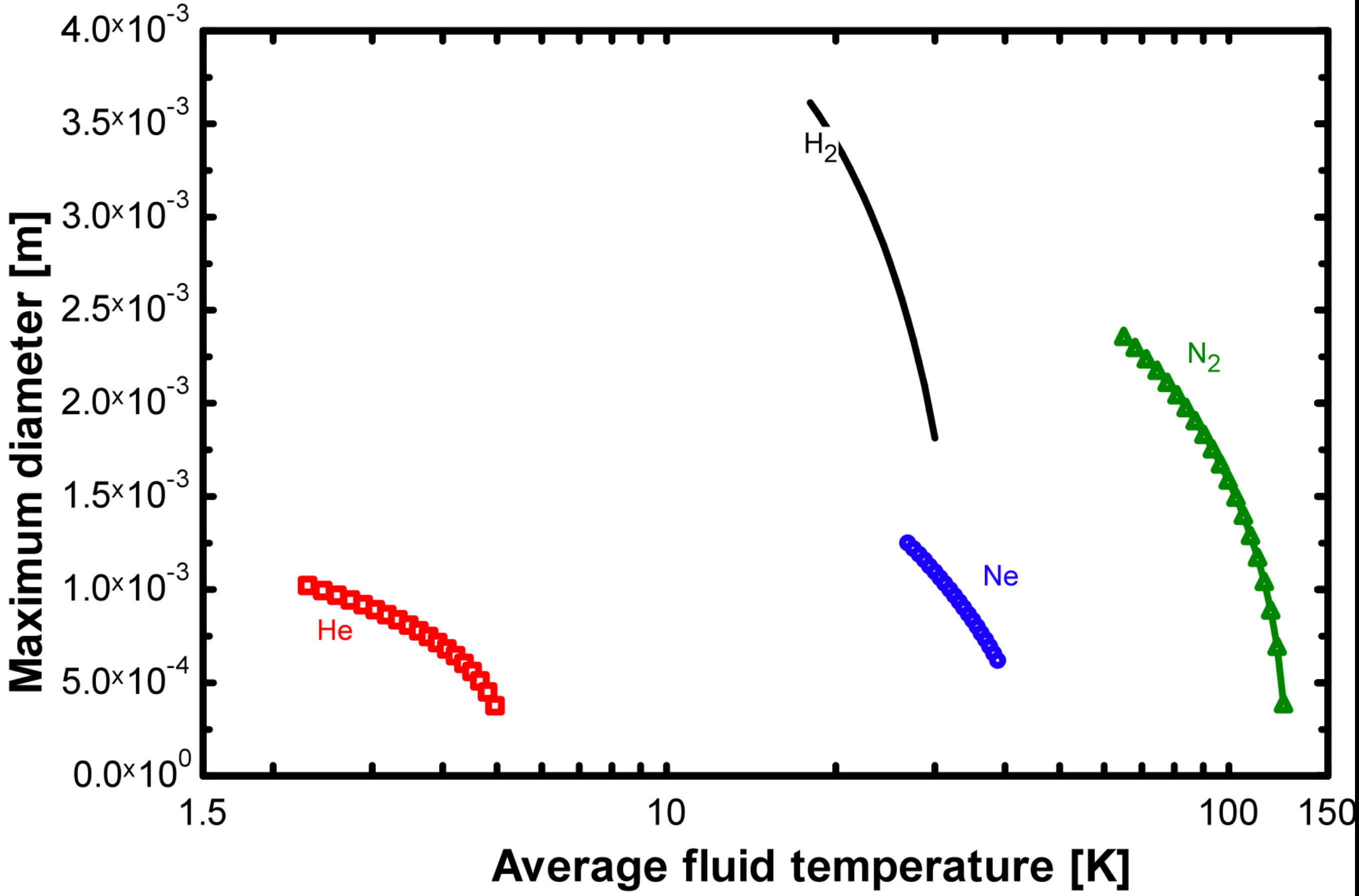
N = 23 turns
2.75 W/cm² - 3.25 W/cm²

N = 11 turns
1.65 W/cm² – 1.95 W/cm²

Khandekar et al. Appl. Thermal Engr. <u>23</u>, p. 2021 (2003)

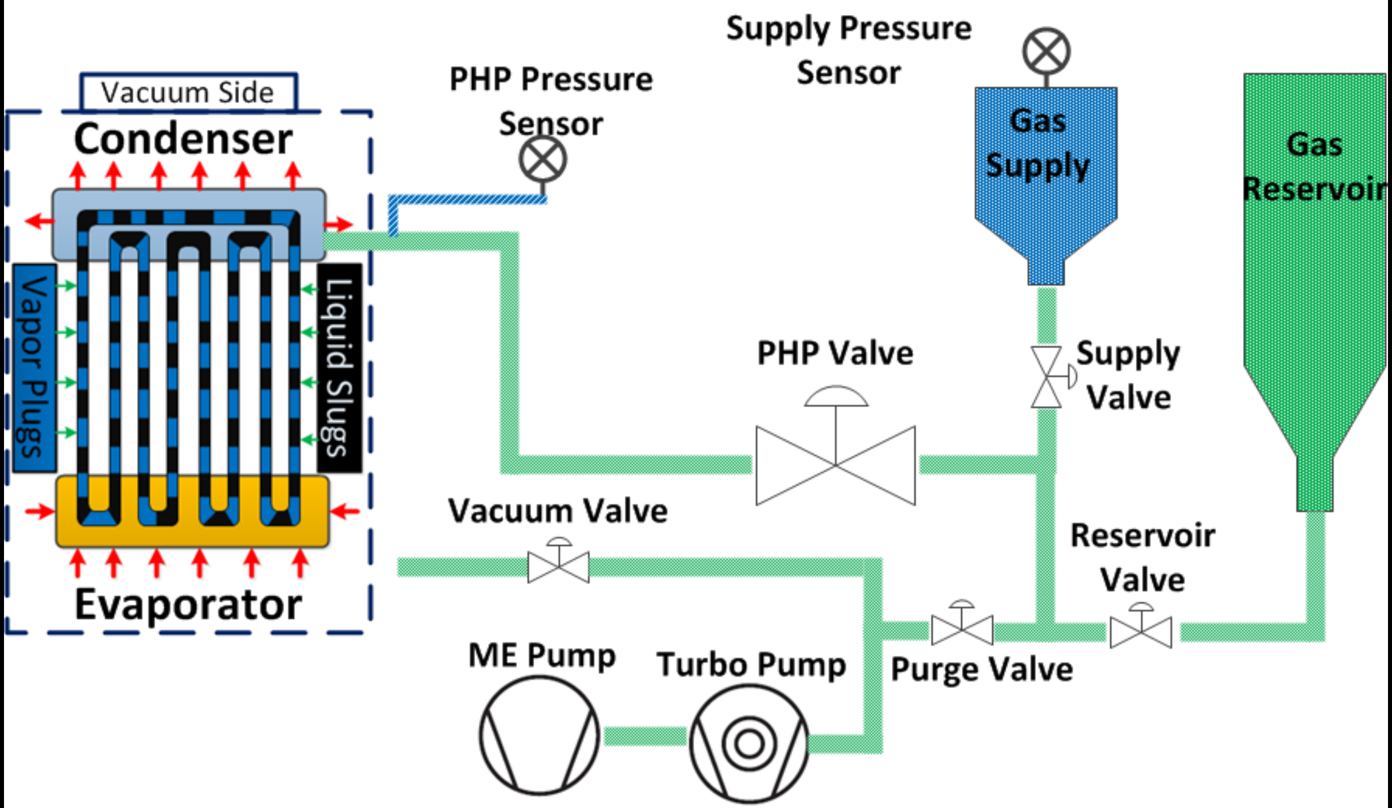
CRYOGENIC PULSATING HEAT PIPES

Critical Bond Number for Cryogenic fluids

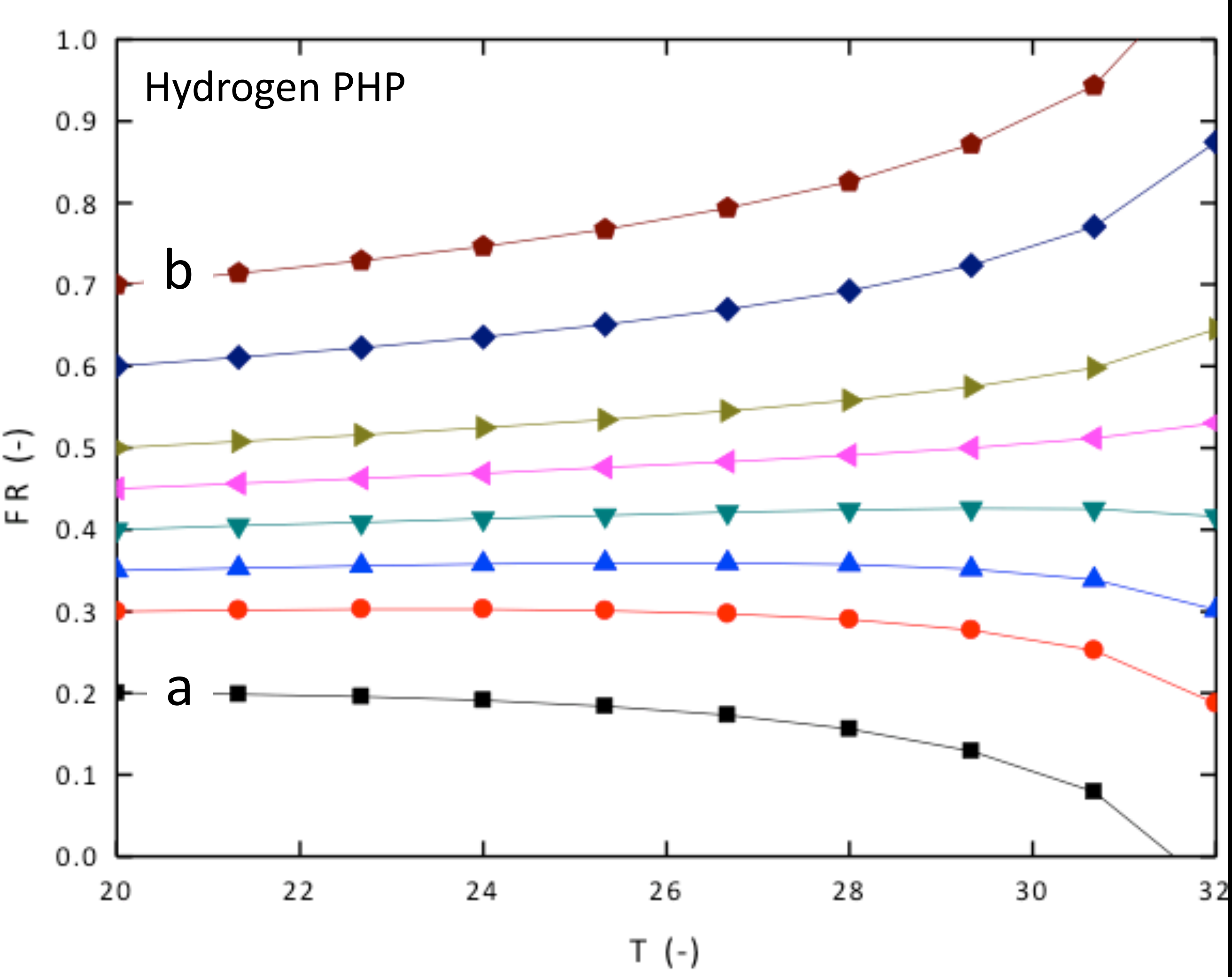


What are we learning about cryogenic PHPs?

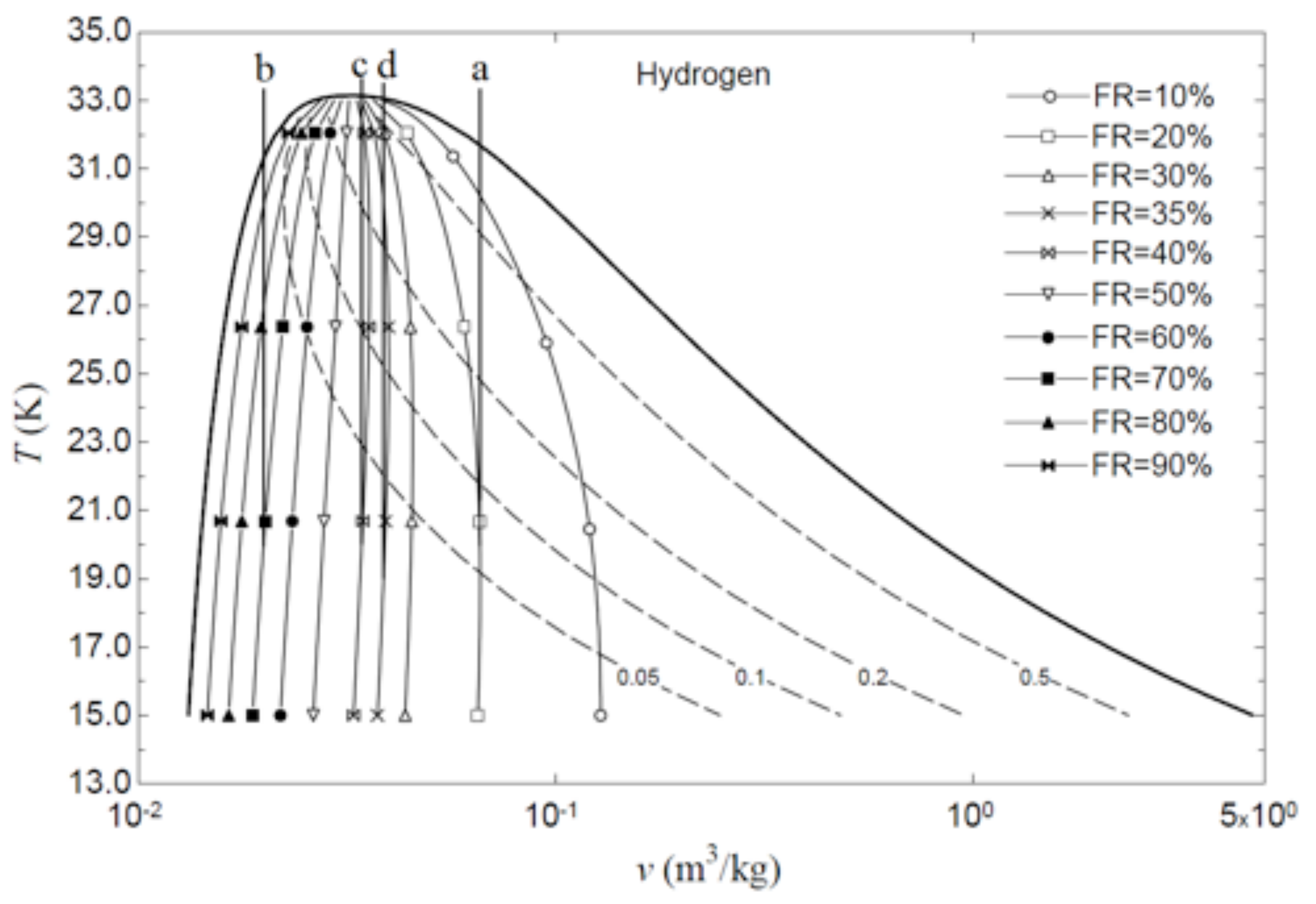
- Fill ratio: $FR = \frac{V_l}{V_{PHP}}$ $V_l = \frac{m_o - \sum m_i - \rho_{v,sat} V_{PHP}}{\rho_{l,sat} - \rho_{v,sat}}$ $m_o = \frac{P_o V_{tank}}{RT_o}$



Fill ratio does not remain constant

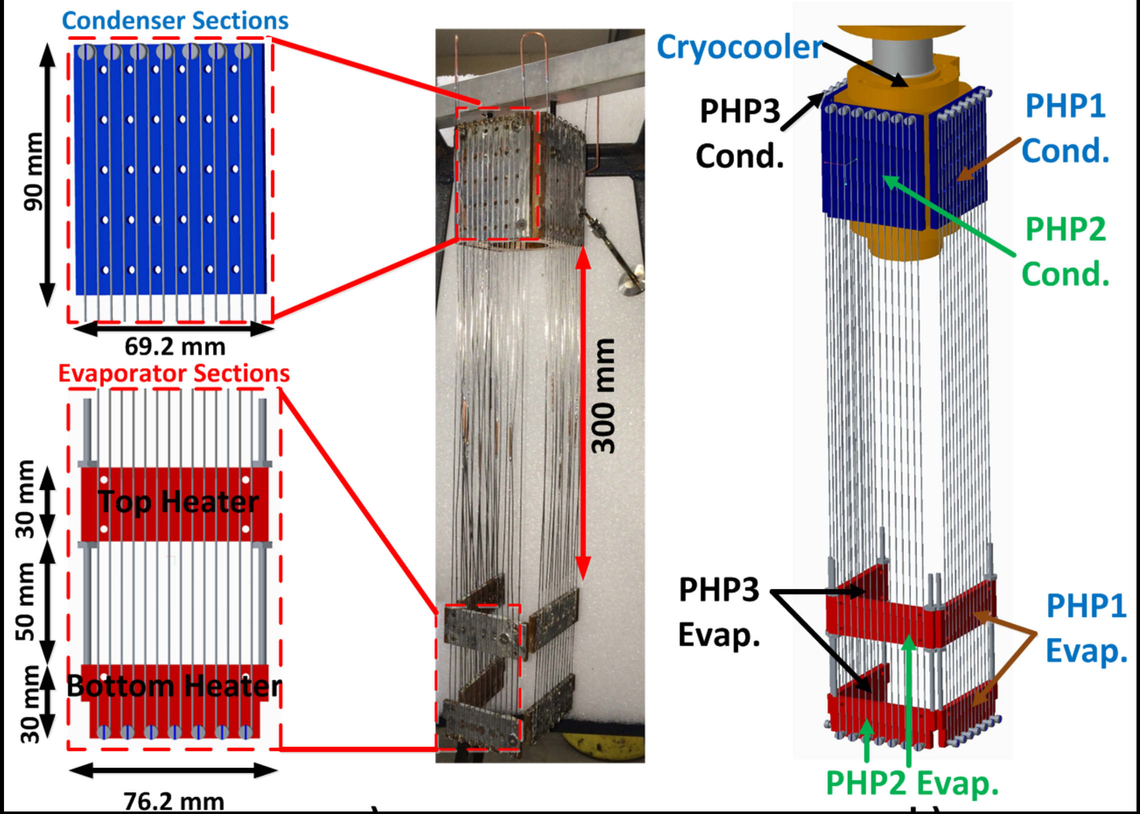


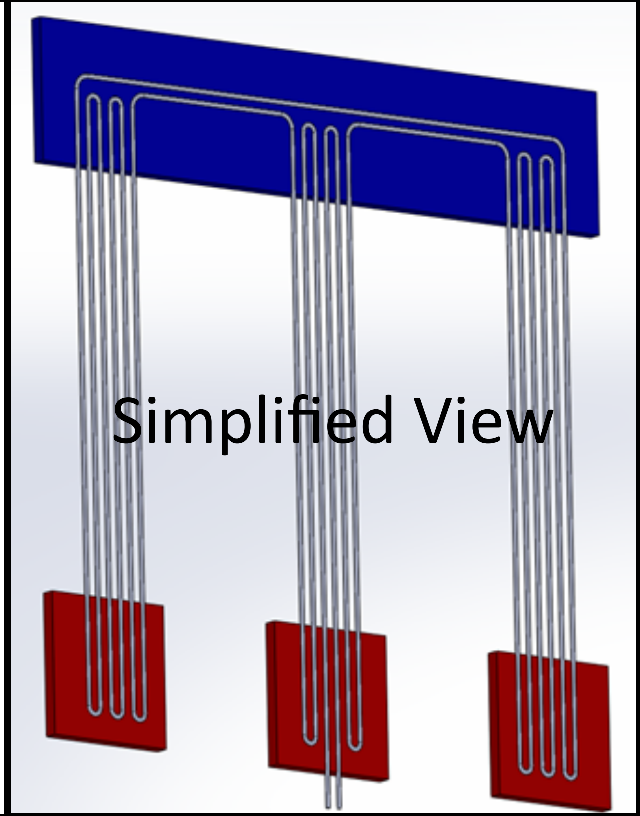
Two-phase region for hydrogen



Optimum fill ratio is configuration dependent

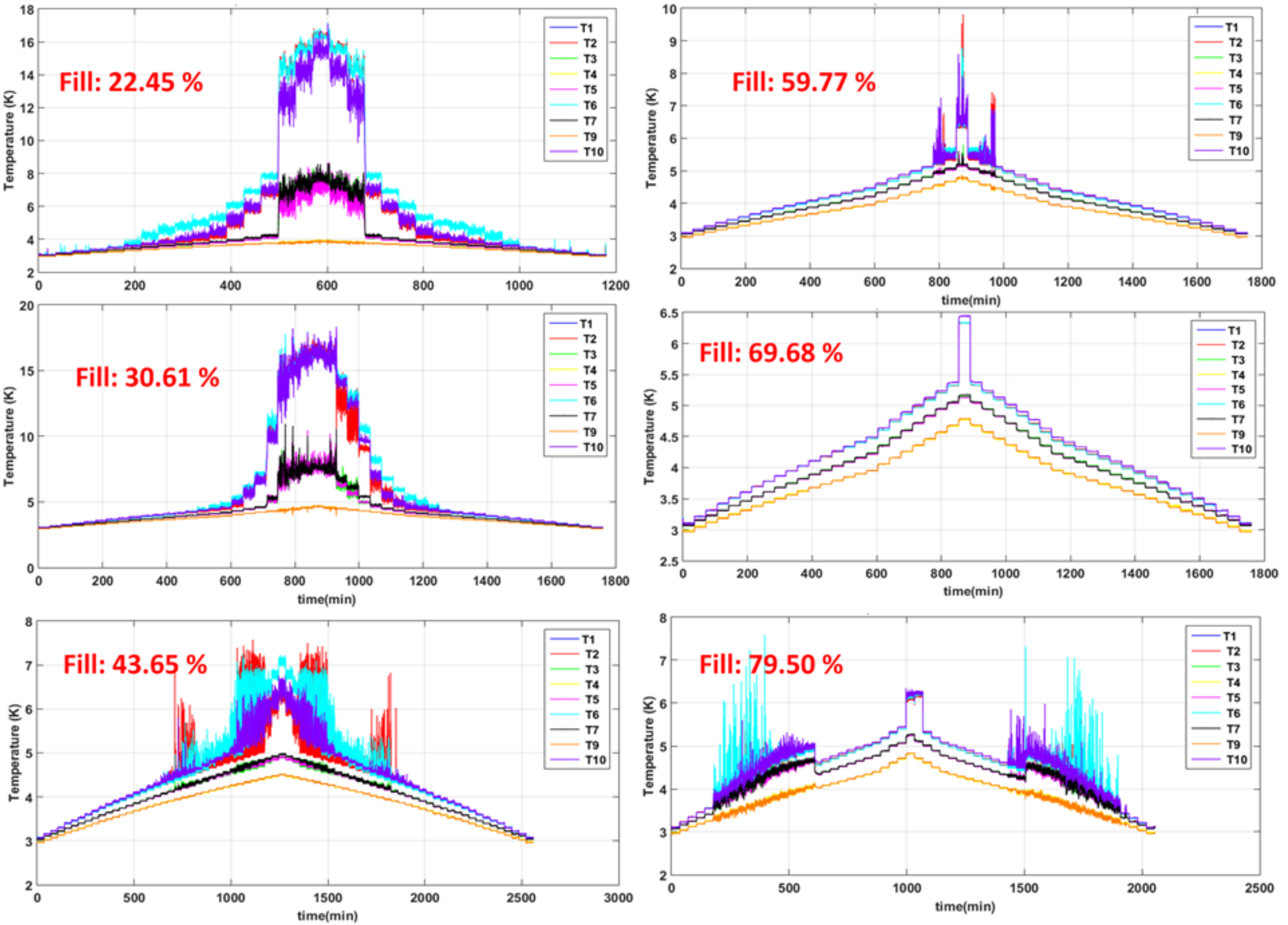
Helium php test rig at UW-Madison



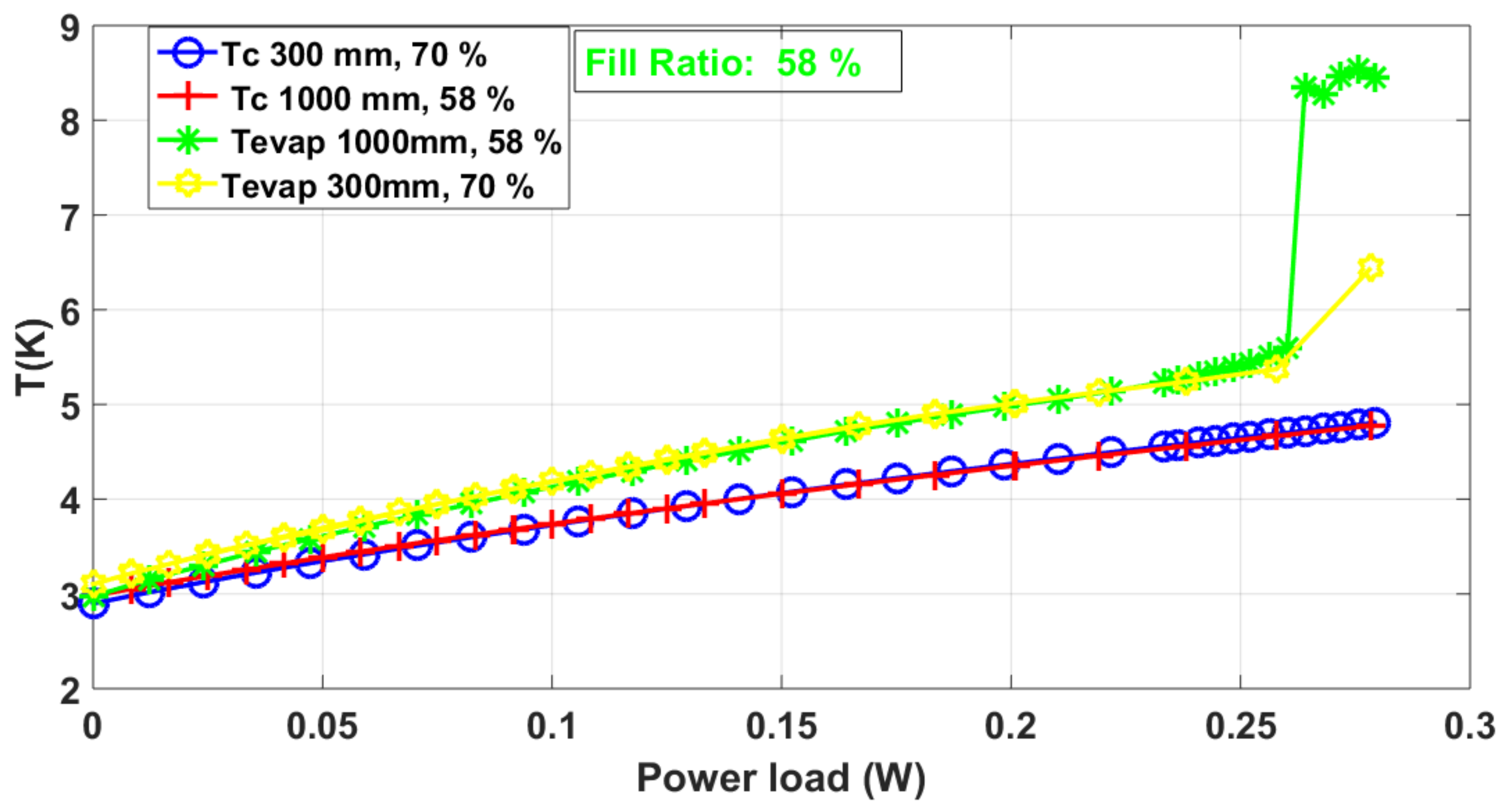


- Vertical orientation, condenser on top
- 3 connected sections, 7 loops/section, independent heated zones

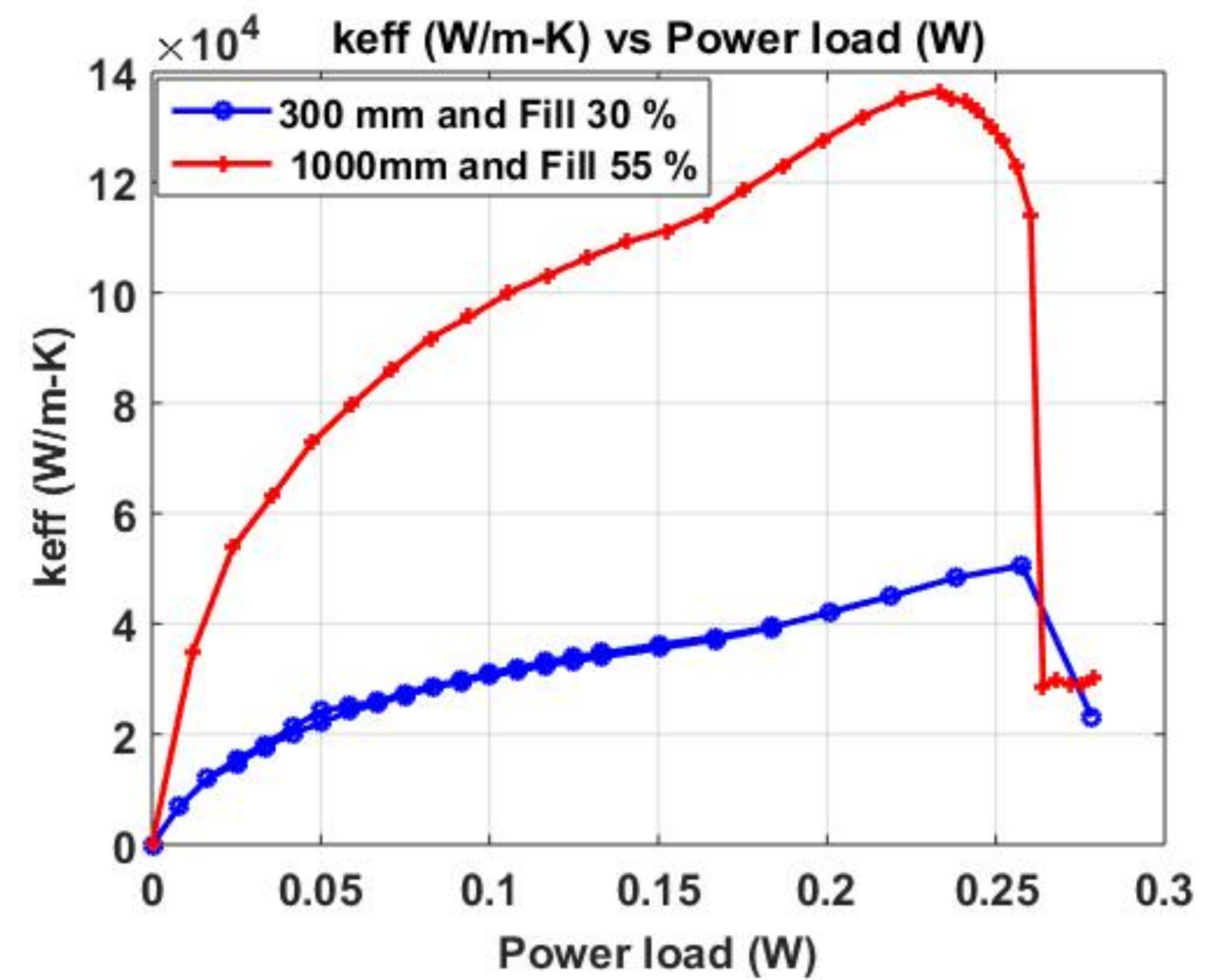
T(Q) data with $L_{adiabatic}$ = 300 mm



Performance data: dependence on $L_{adiabatic}$

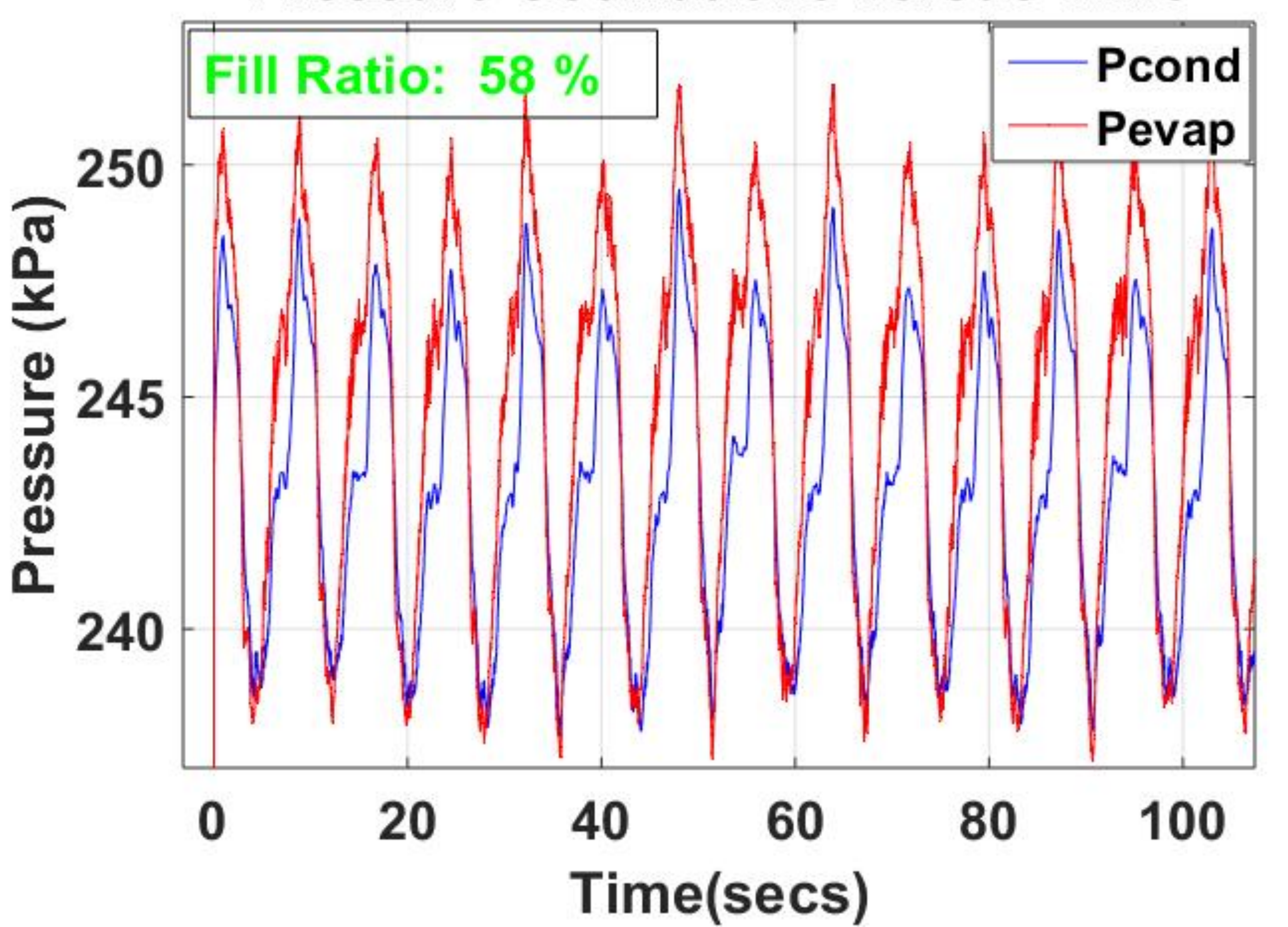


Pseudo performance parameter: k_{eff}



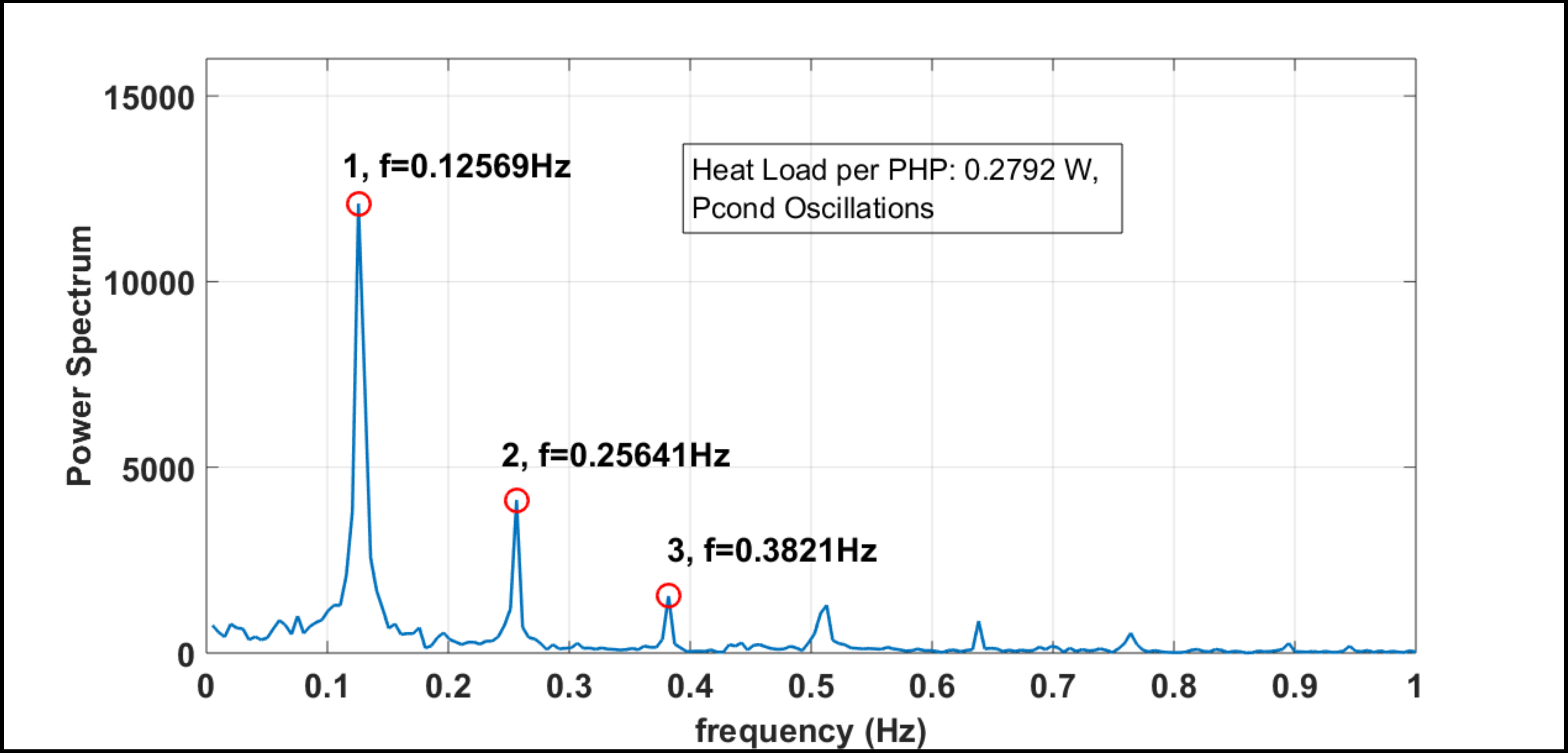
Operation includes long-range oscillations

UW-Madison Helium PHP



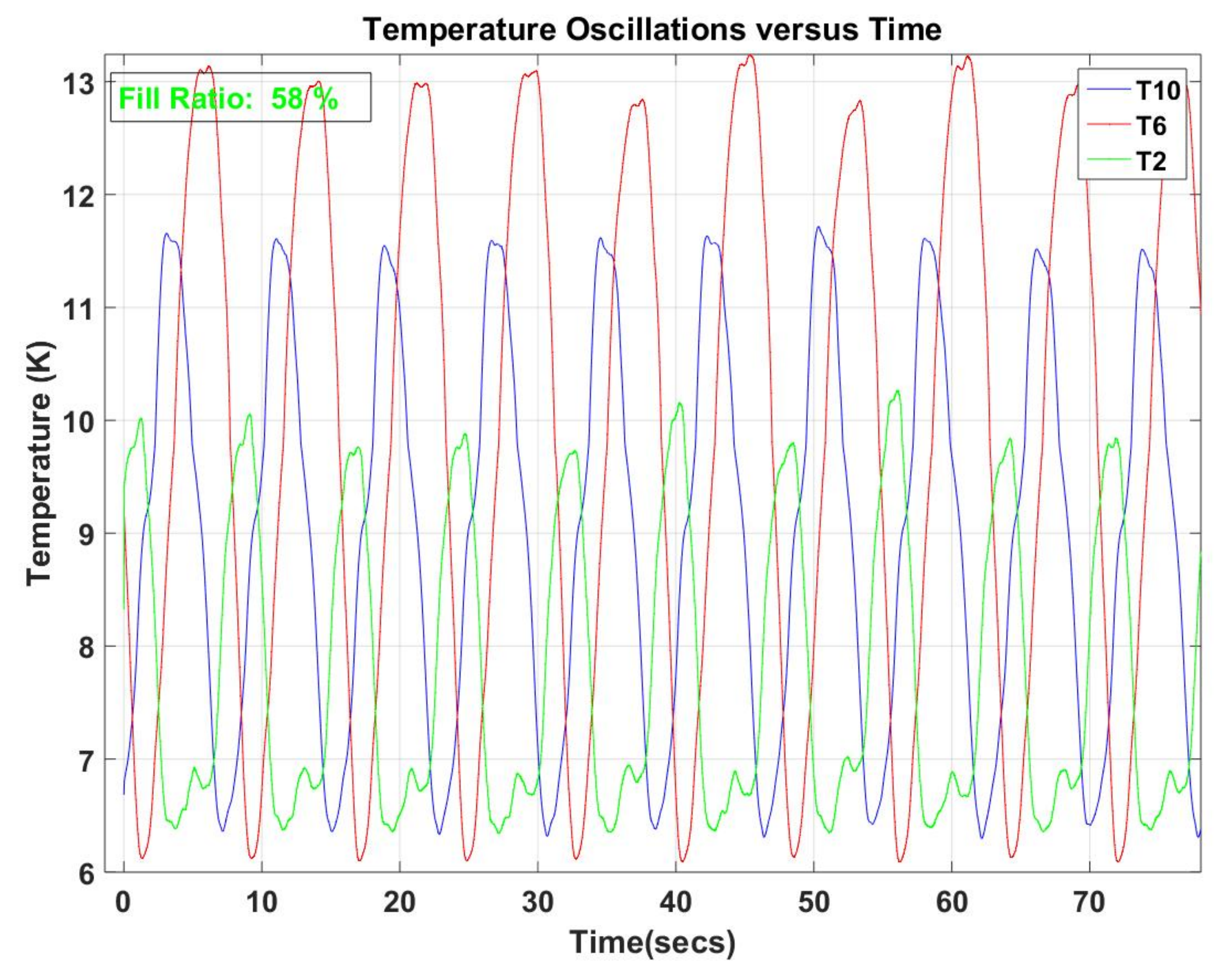
Power spectral information from pressure data

UW-Madison Helium PHP



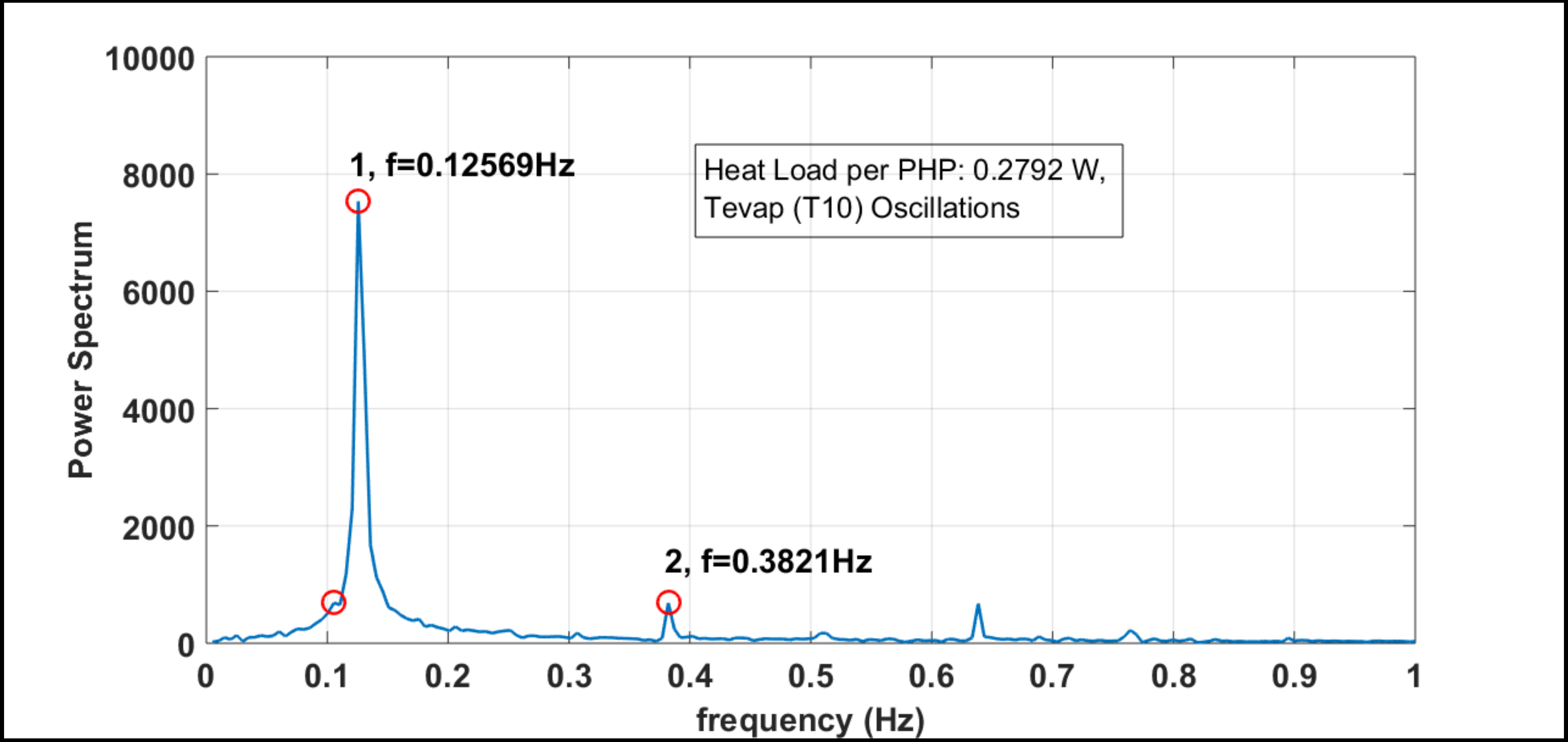
Oscillations between 3 evaporators

UW-Madison Helium PHP



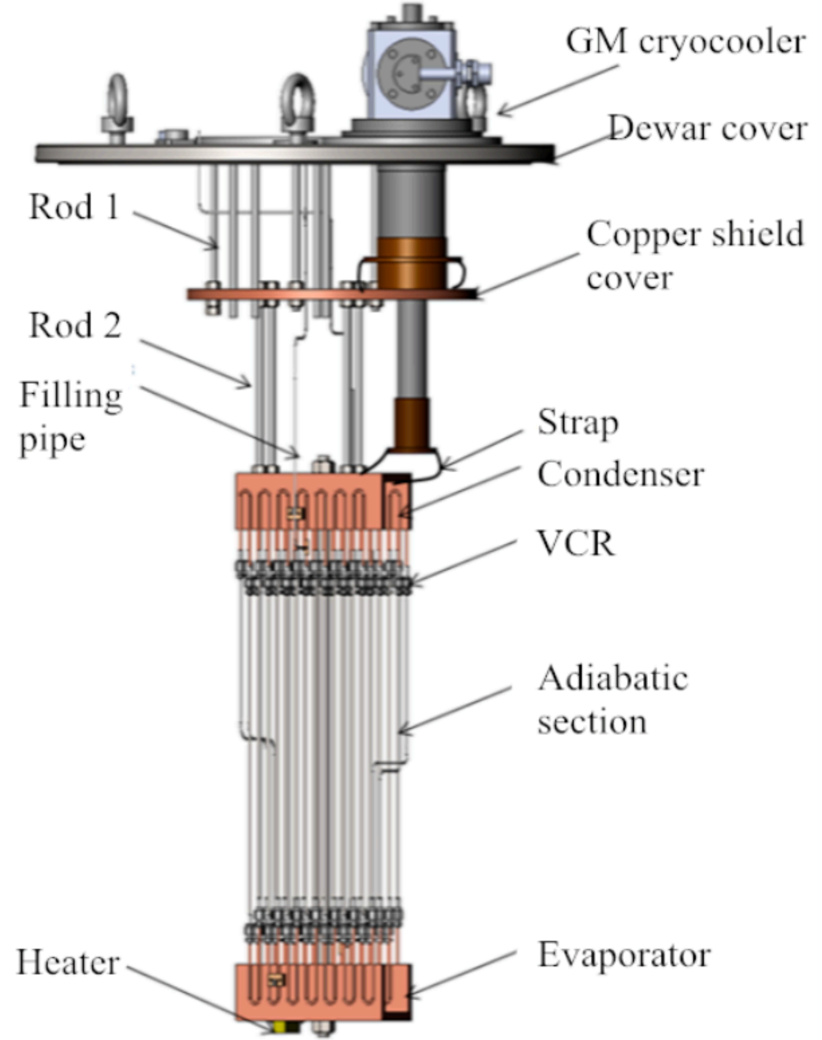
Power spectral information from T_{evap} data

UW-Madison Helium PHP



LH2 Measurements - 2015

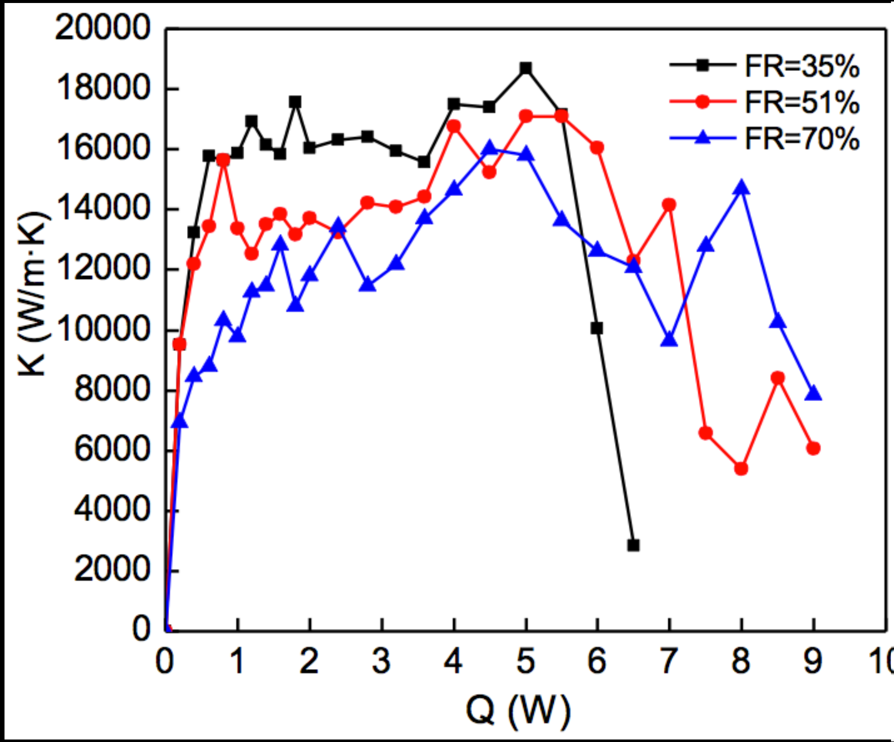
- Y.M. Liu, H.R. Deng, Z.H. Gan, *Zhejiang University*



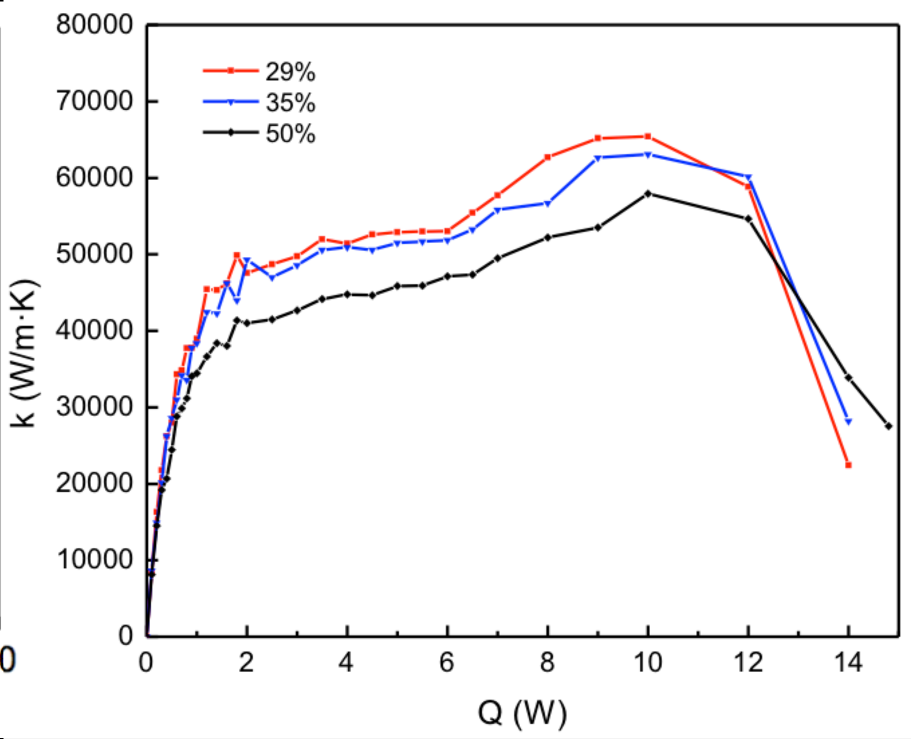
- Adjustable length adiabatic section: 100 mm – 500 mm
- Variable number of turns: 1 to 28
- 2.3 mm diameter capillary: variable characteristics of php for T > 25 K
- Spectral power information as a function of the heat load from pressure data

LH2 Measurements - 2015

Effective Conductivity: L_a = 100 mm



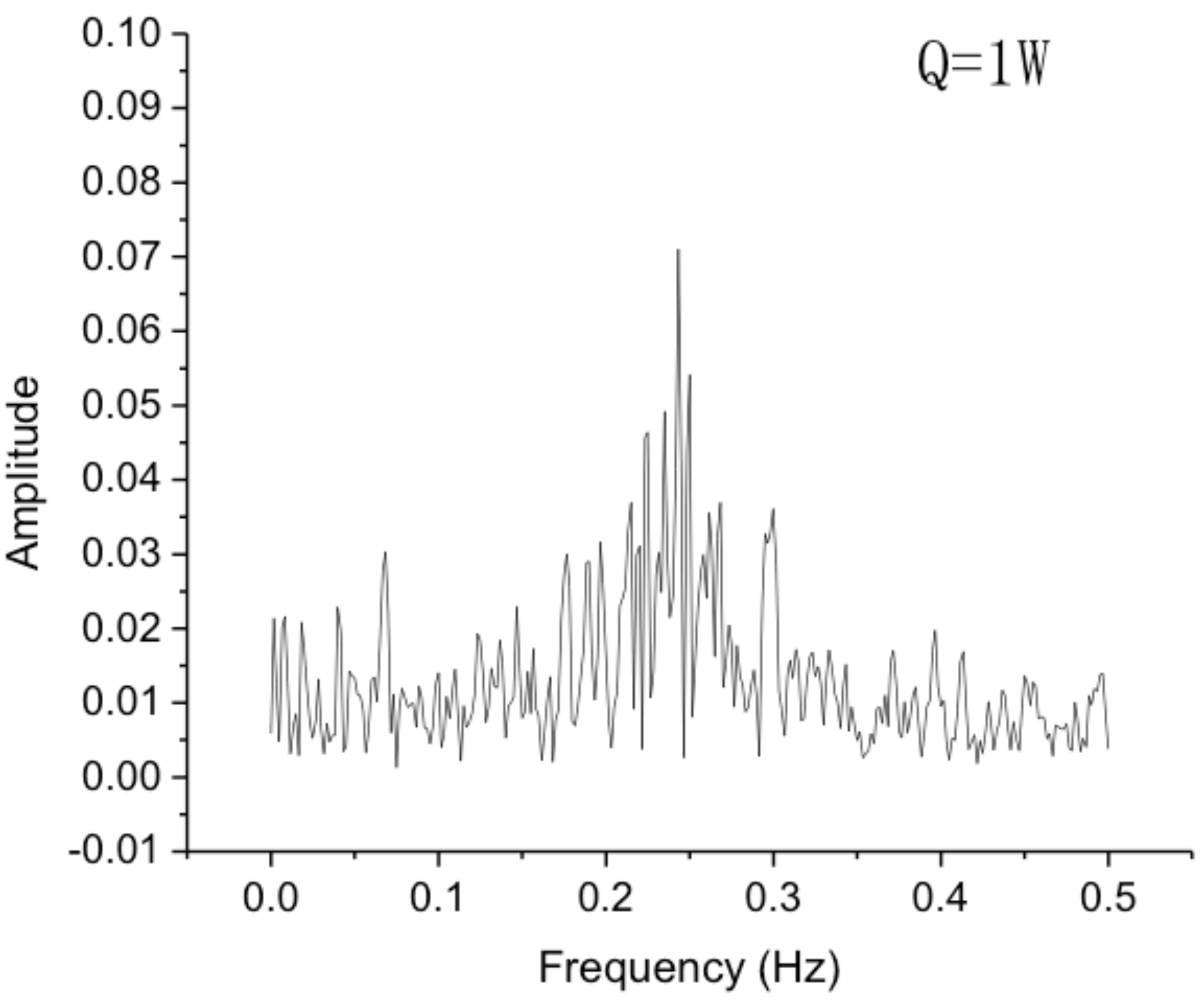
Effective Conductivity: L_a = 500 mm



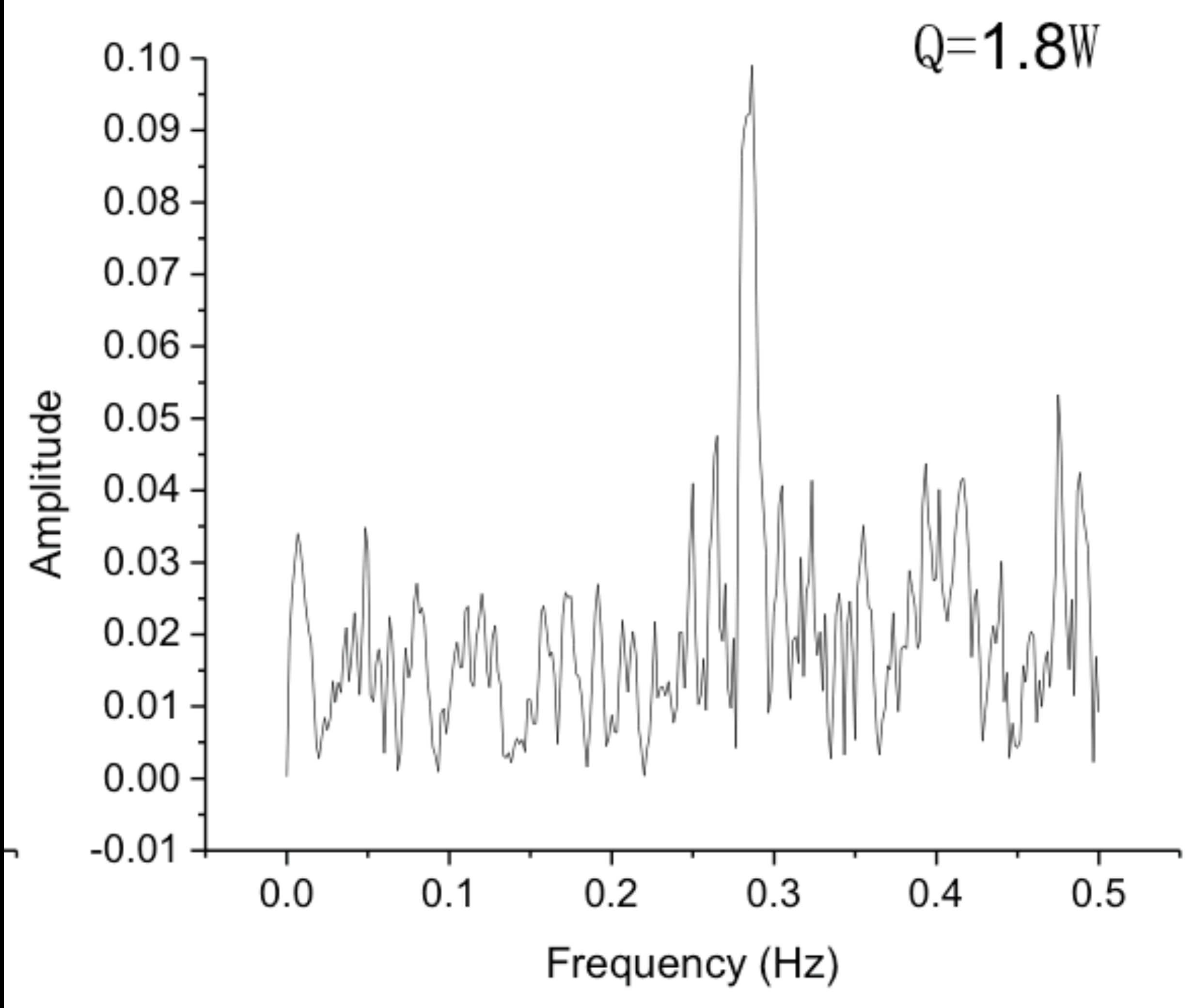
Increasing L_a from 100 mm to 500 mm, with 50% fill, and 6 W of heat:
T_E-T_c increases from 1.38 K to 1.69 K
Effective conductivity increases from 16 kW/m-K to 45 kW/m-K

Fourier's law does not properly characterize the thermal transport

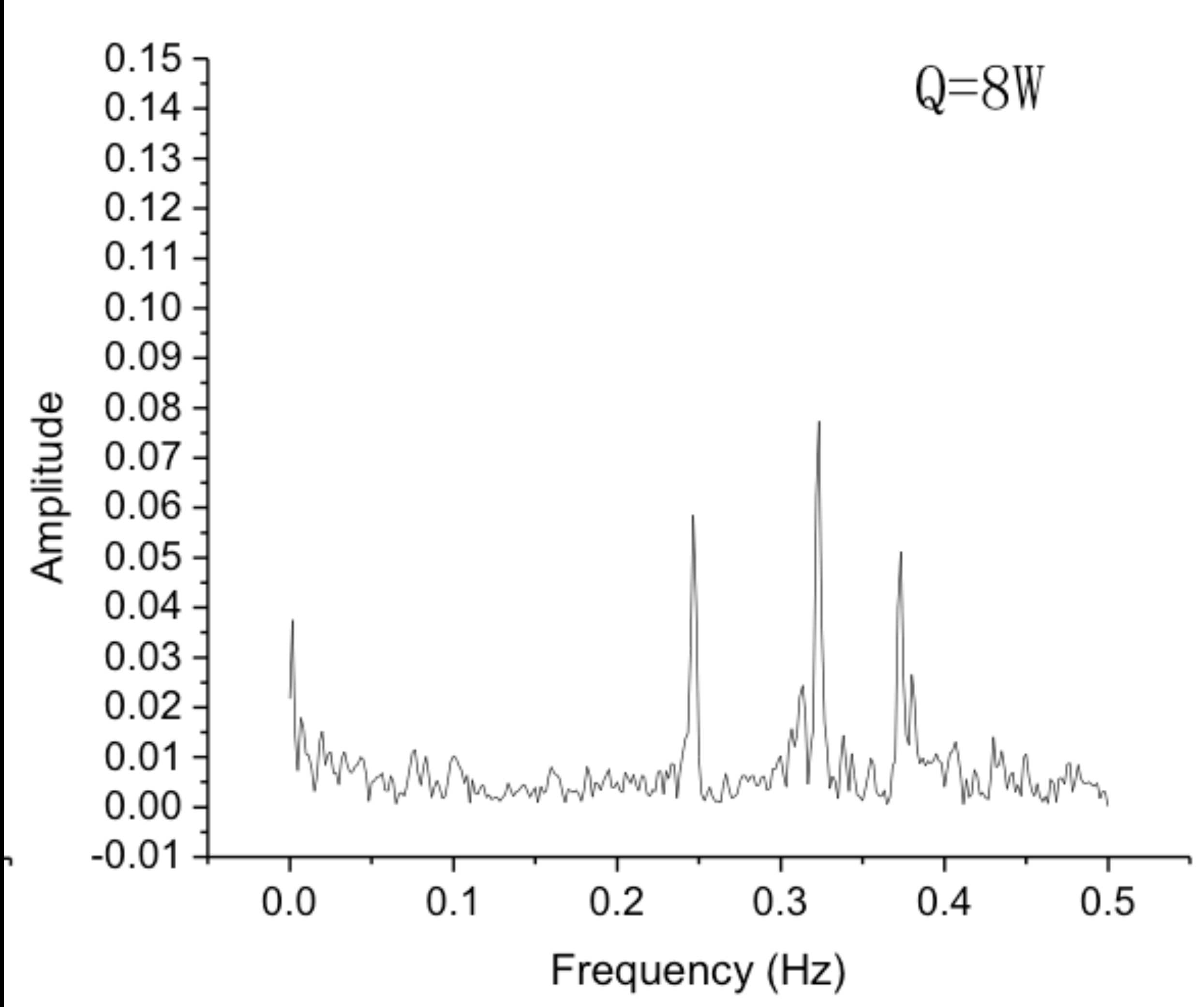
LH2 Measurements - 2015



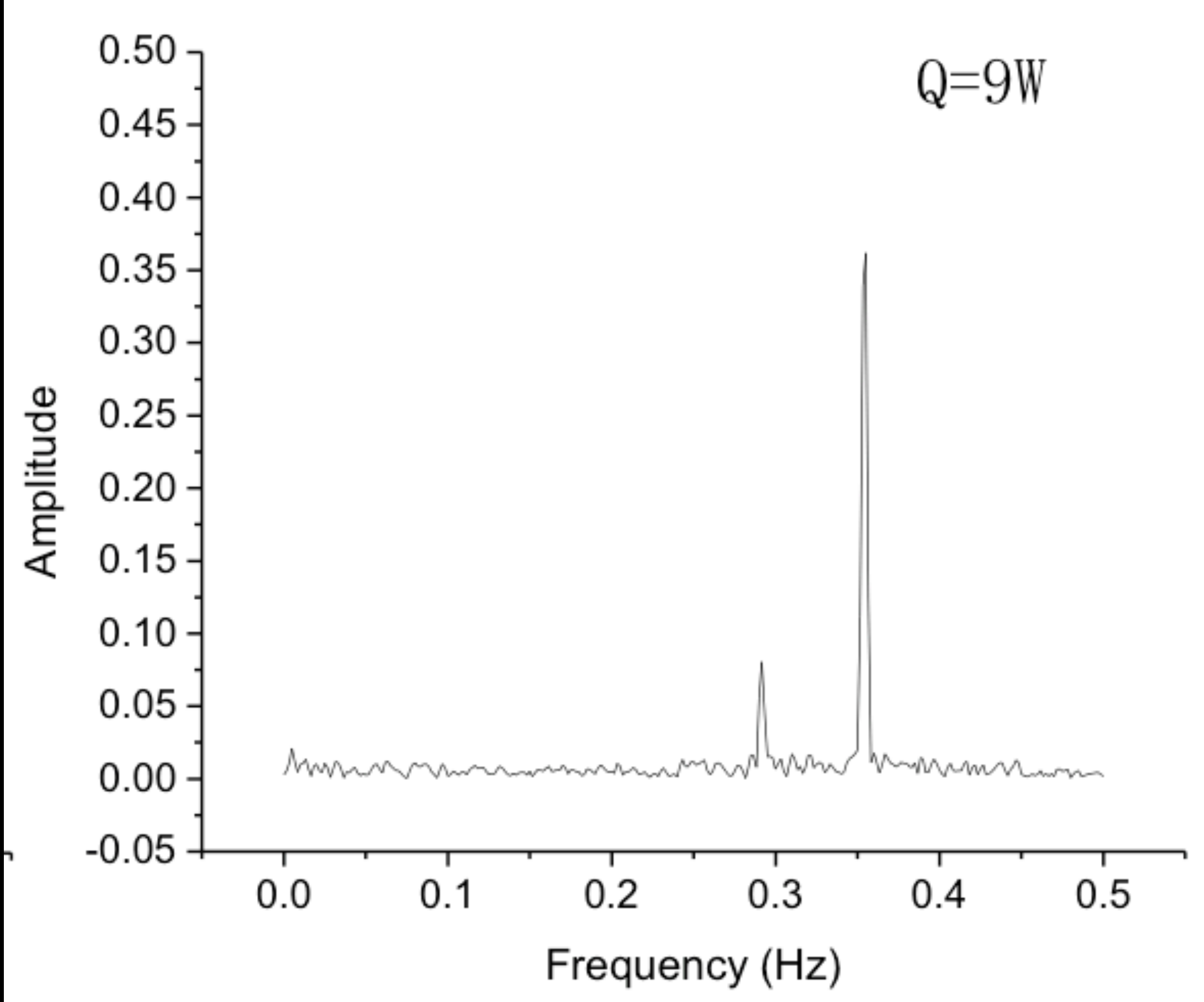
LH2 Measurements - 2015



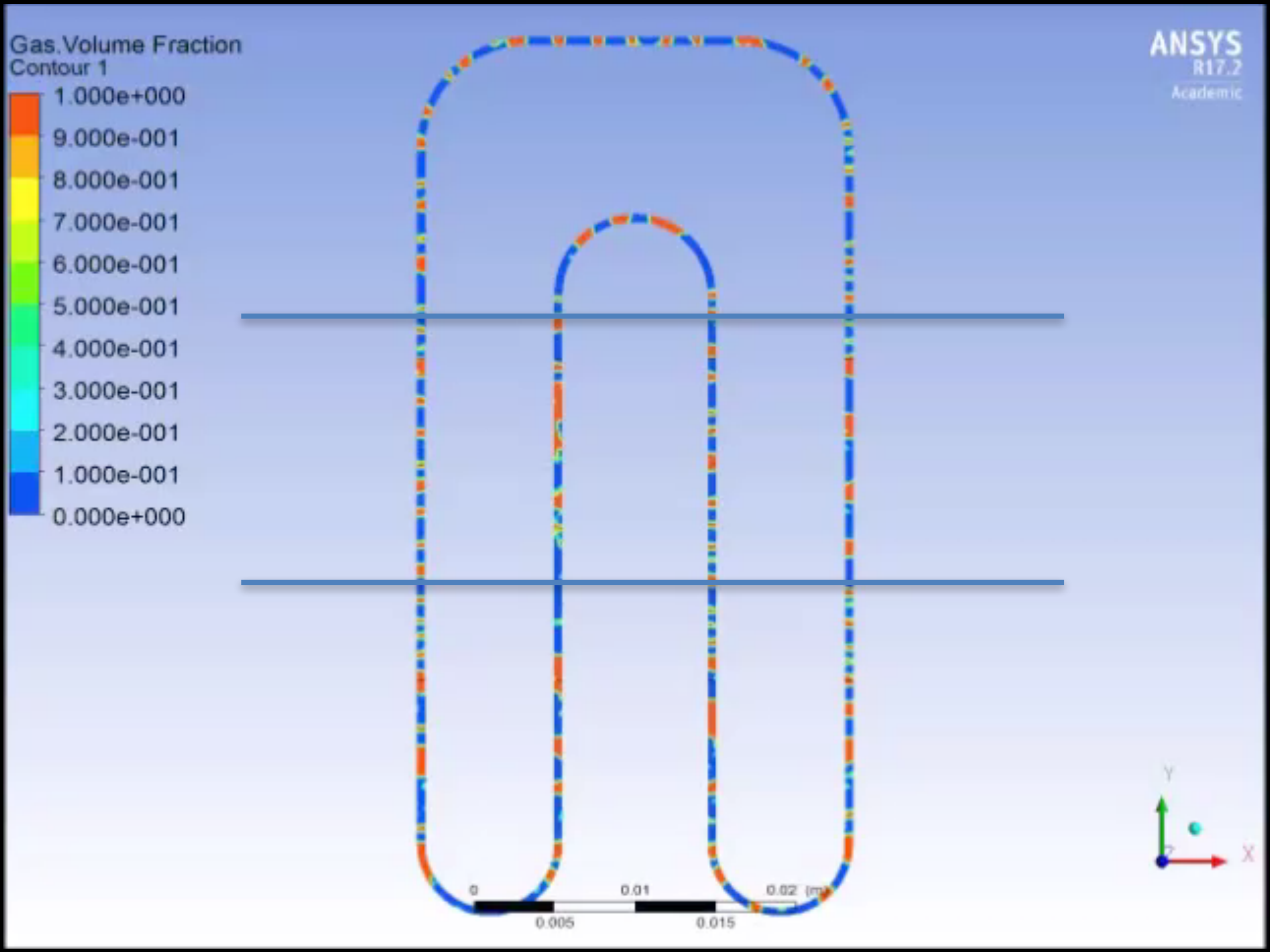
LH2 Measurements - 2015



LH2 Measurements - 2015



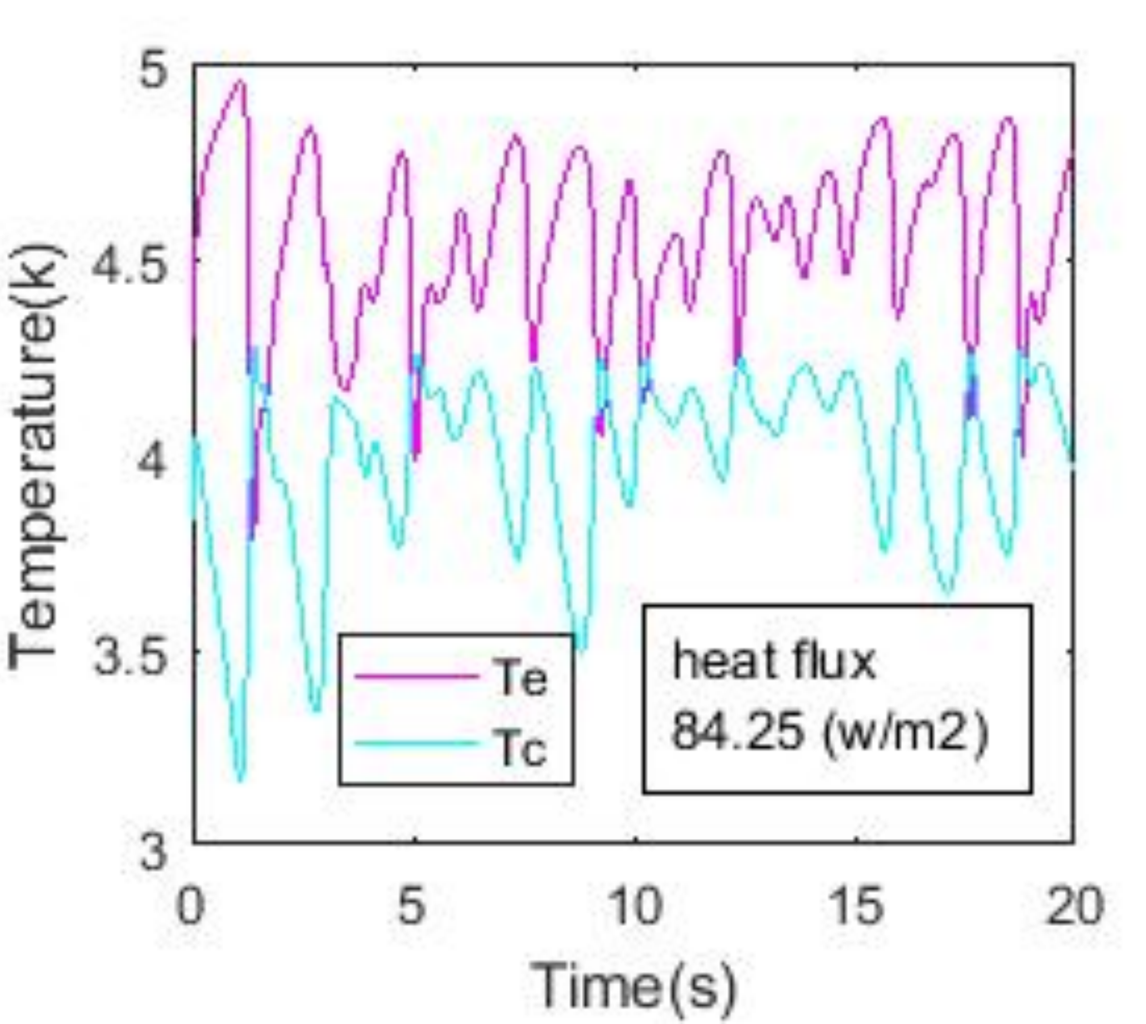
Fluent simulation: helium php



D = 0.5 mm

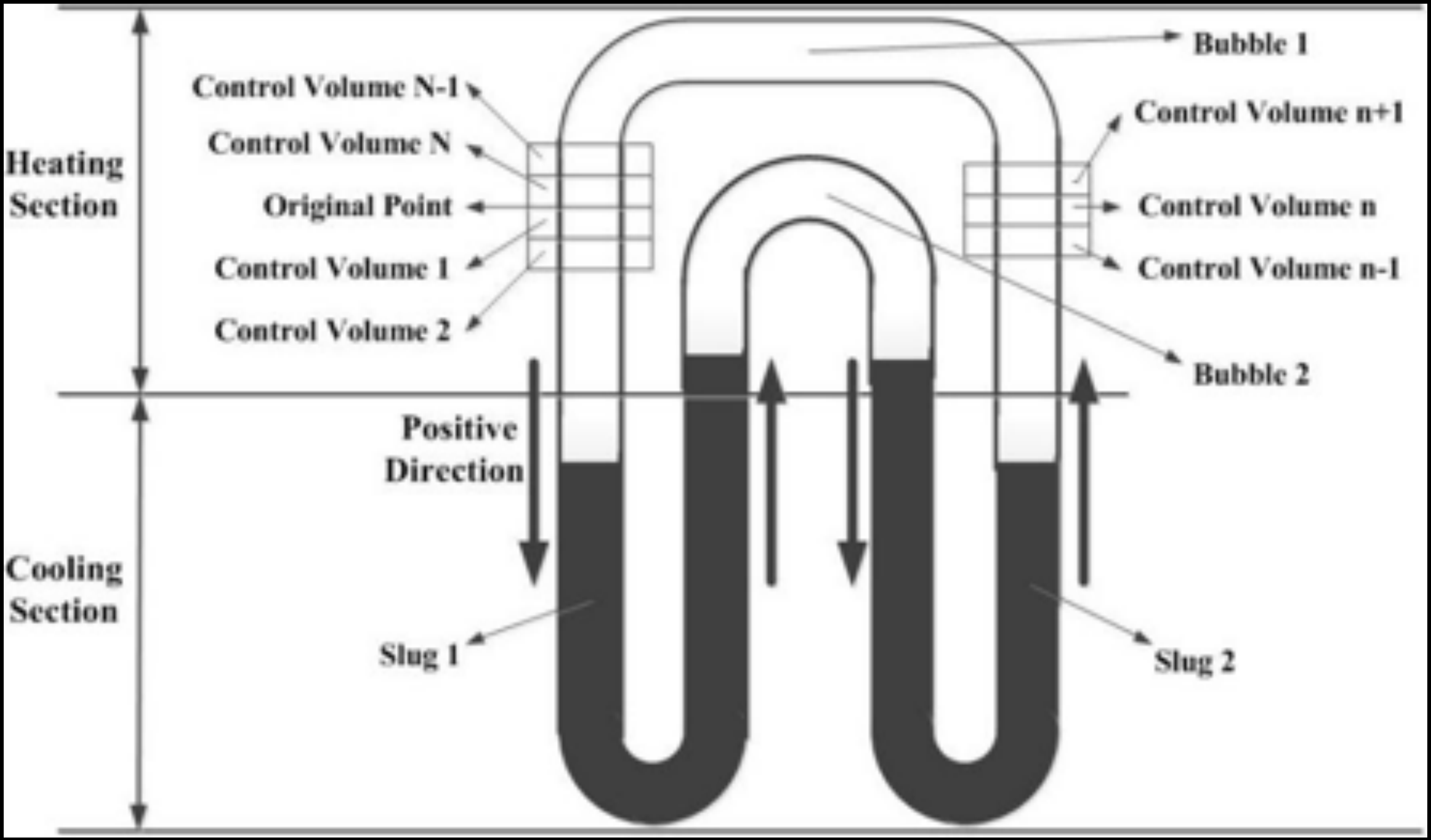
L_{evap} = 10 mm
$L_{adiabatic}$ = 20 mm
L_{cond} = 20 mm

System oscillations via fluent model

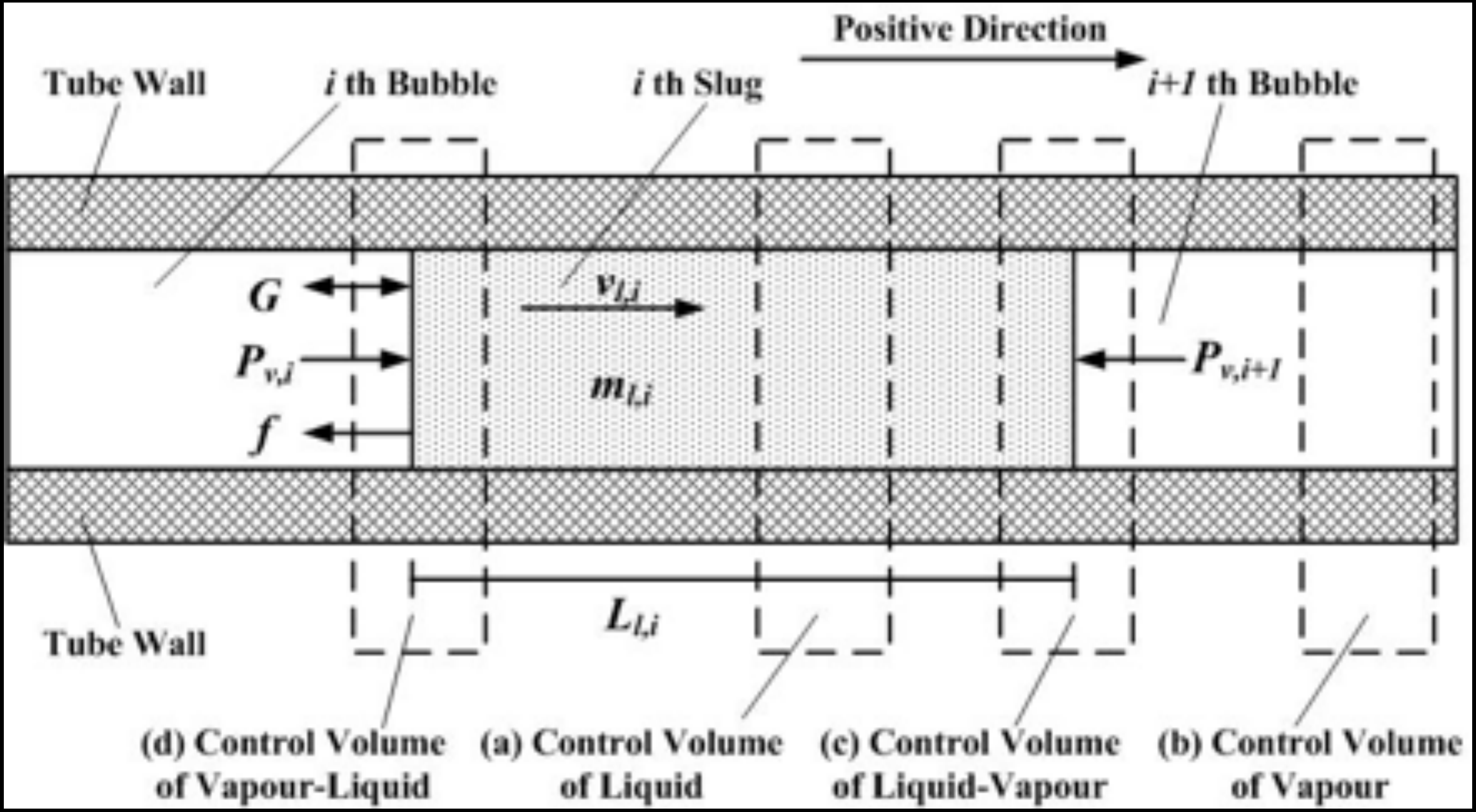


Numerical Investigation of N_2 and H_2 PHP

DY Han, X Sun, ZH Gan, JM Pfotenhauer, and B Jiao

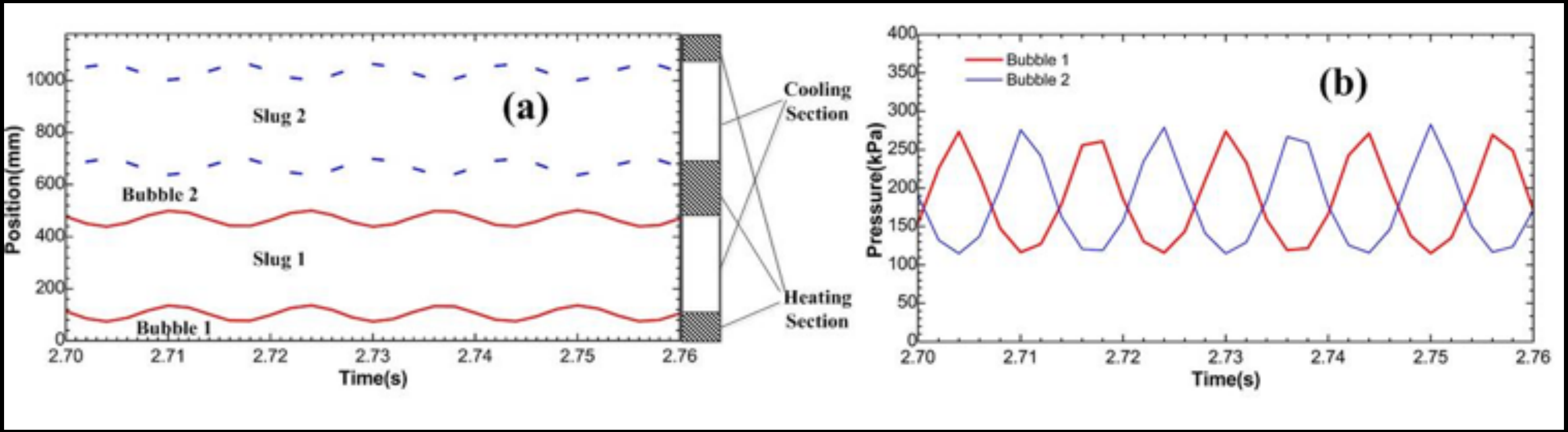


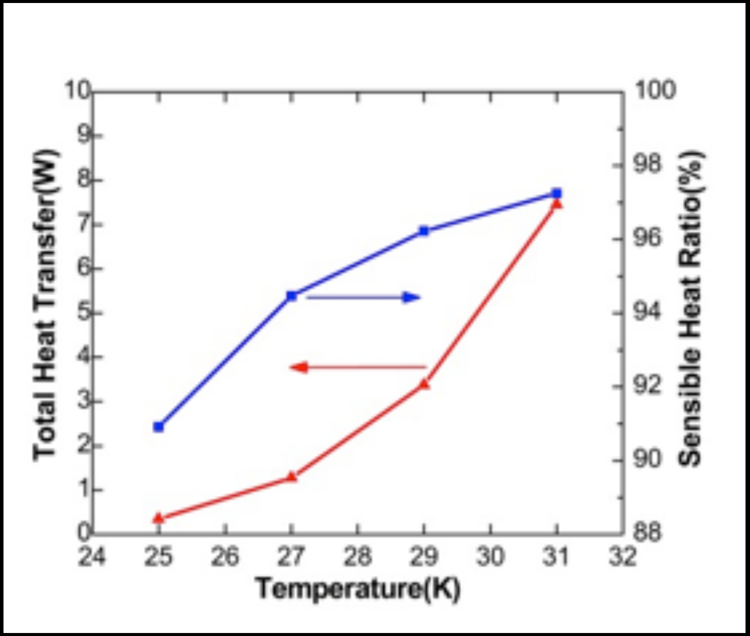
Energy, momentum, and mass balance in 4 different region-types



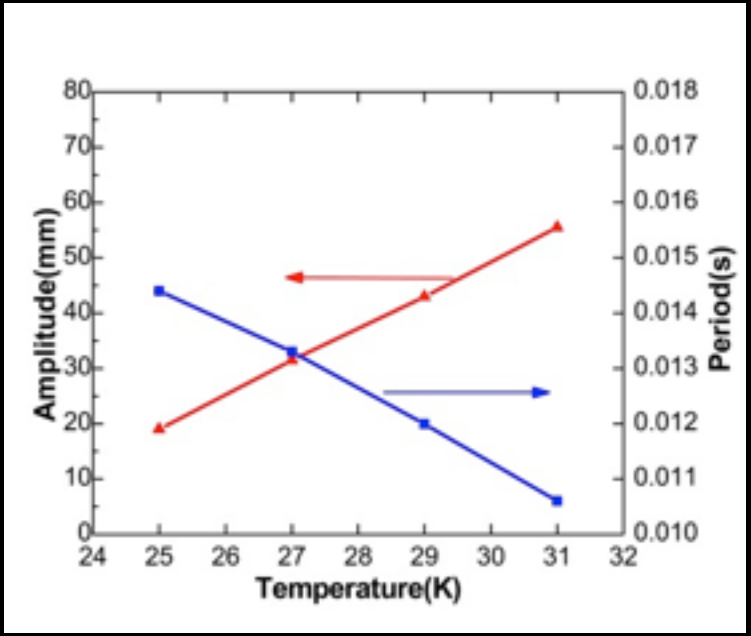
Bubble-slug oscillations

Hydrogen PHP



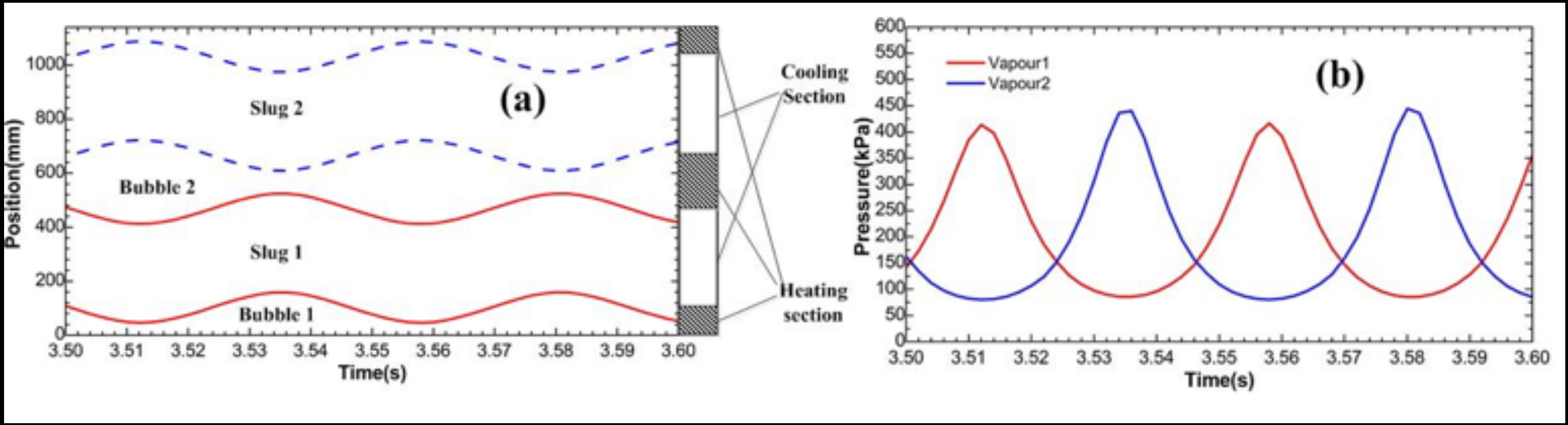


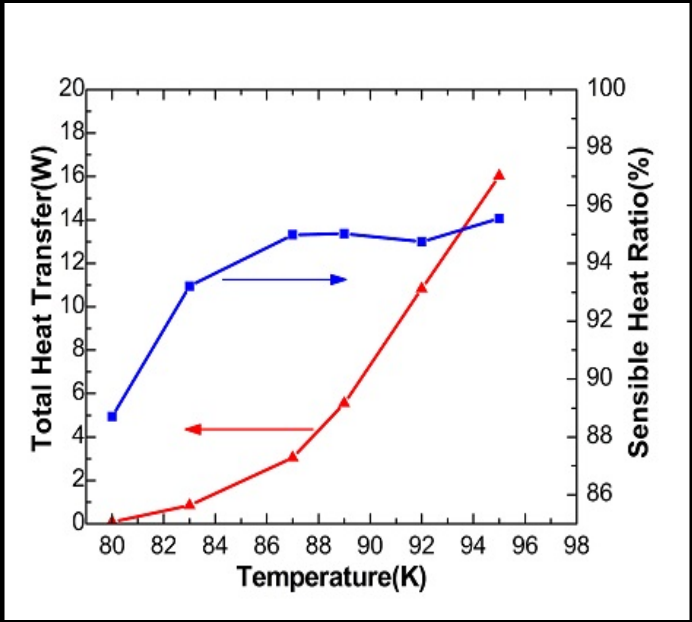
ƒ ~ 60-100 Hz



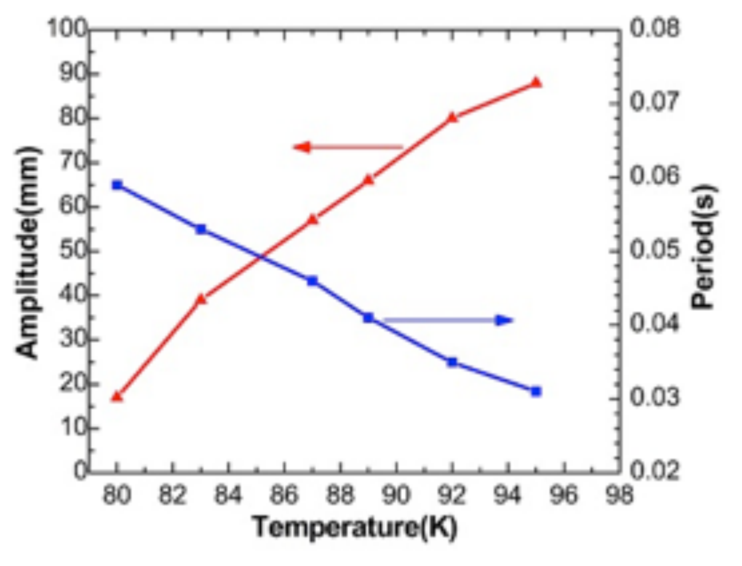
Bubble-slug oscillations

Nitrogen PHP

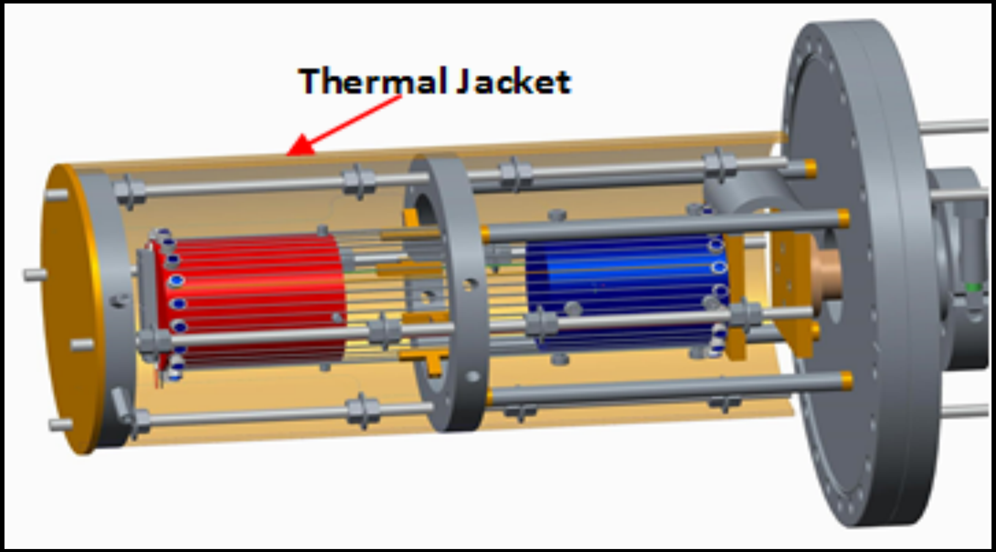


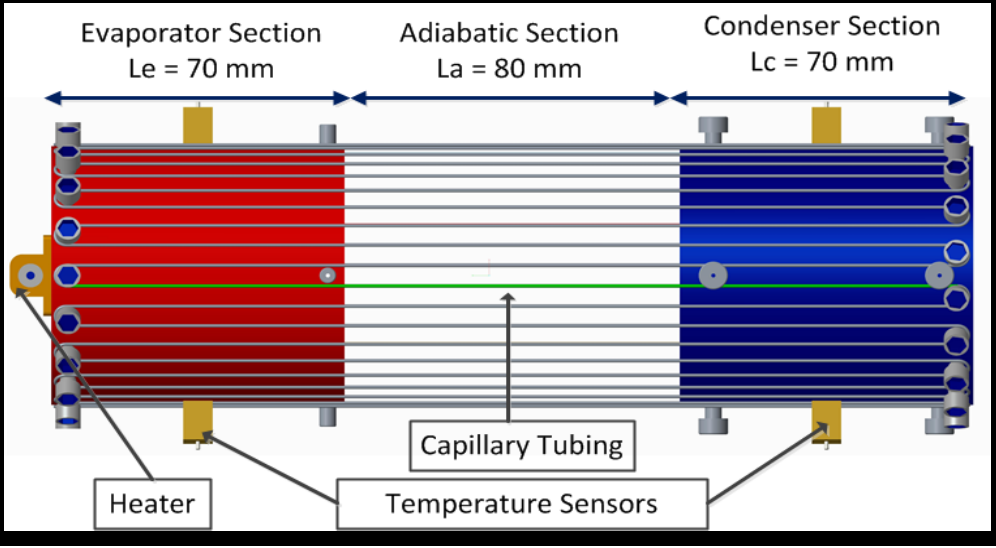


f ~ 17-33 Hz

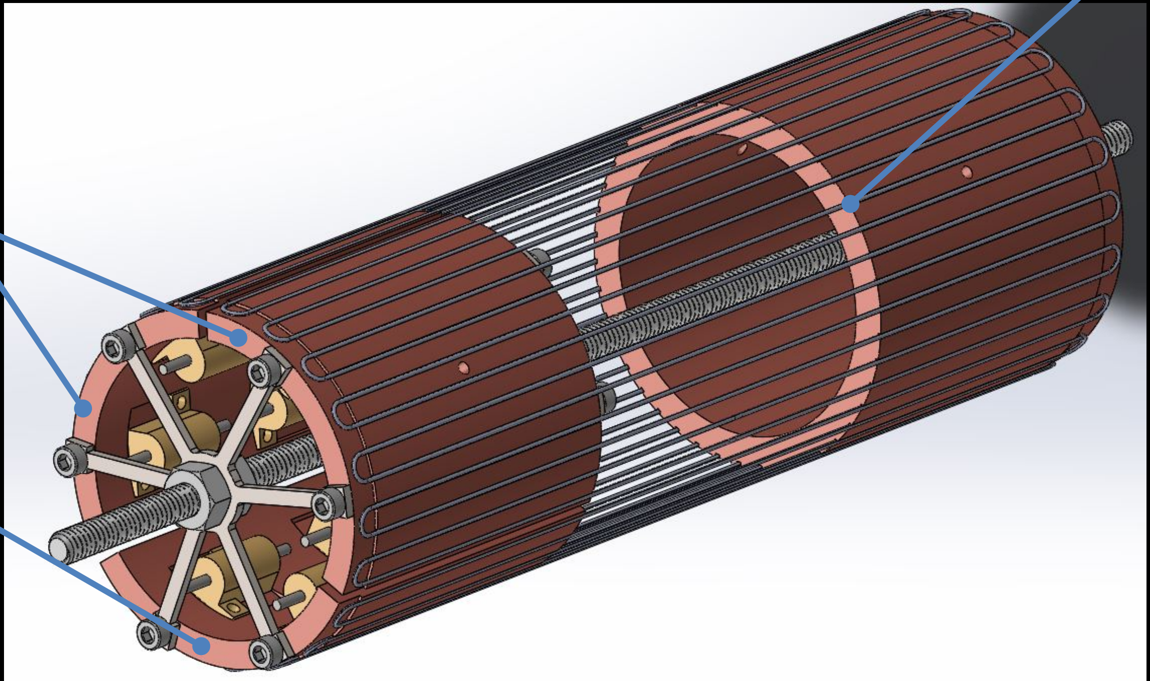


N_2 php with non-uniform heating





Results – Decreasing Load on One Section



T_{cond} = ~90 K

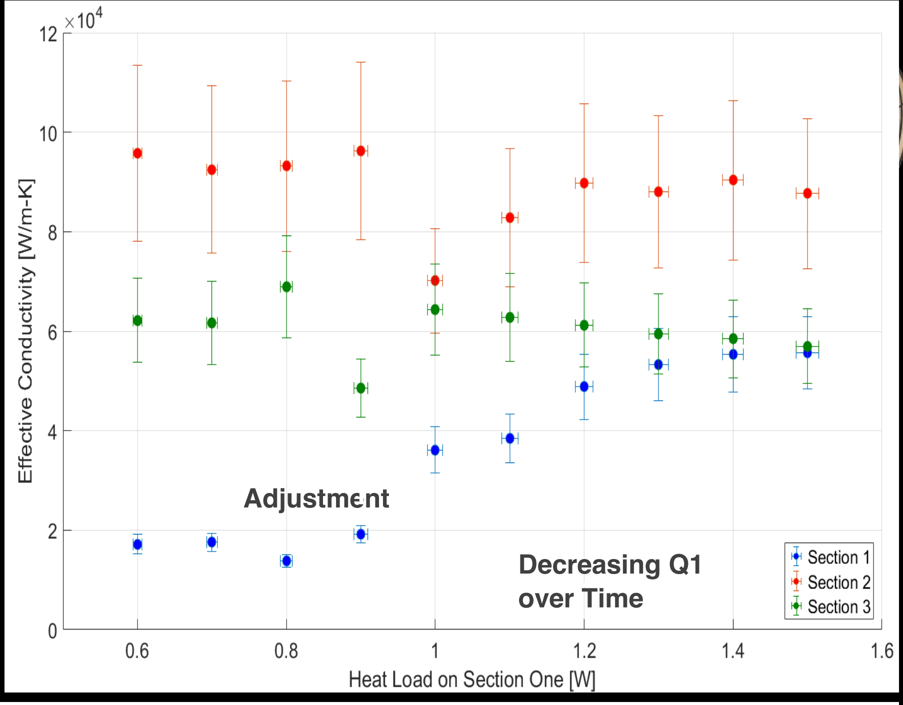
Q2 & Q3 constant at 1.5 W

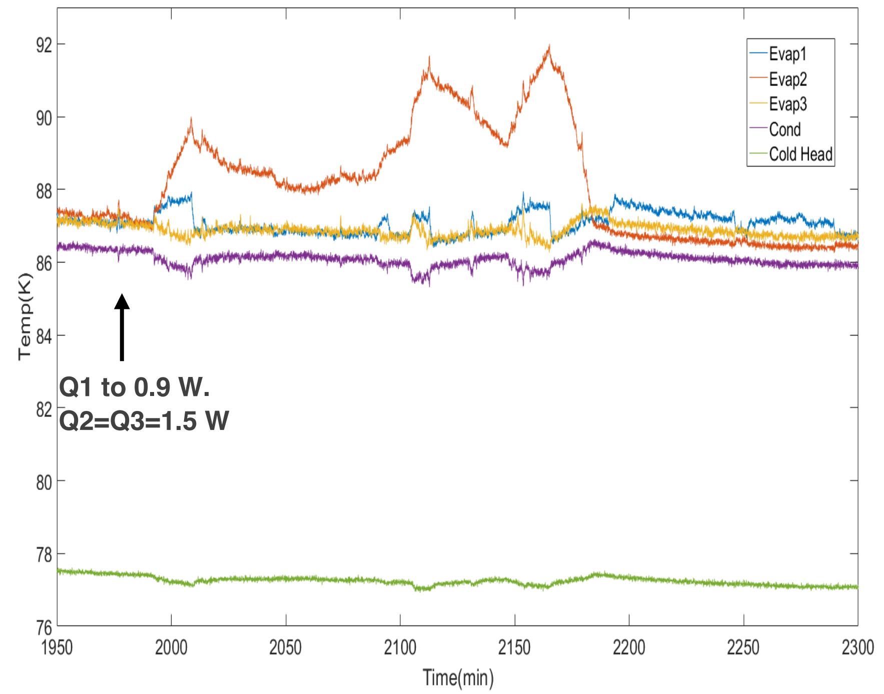
Q1 reduced in steps of 100mW

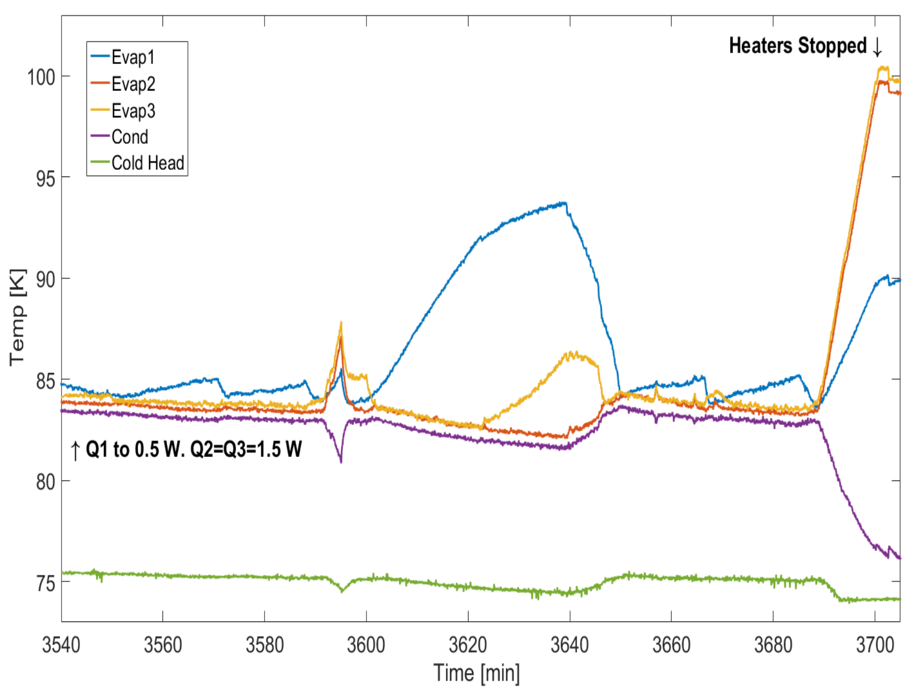
V_{fill} = 60%

Results – Decreasing Load on One Section

- First occurrence of “adjustment” at 3.9 W total
- PHP stopped working at total heat load of 3.5 W
- Example of PHP operating with non-uniform heat loads







Salient Observations

- Fill ratio for cryogenic PHP may not be constant, even though the overall specific volume is constant
- An optimum fill ratio exists
- By maintaining an optimum fill ratio, $T_E - T_C$ is fairly insensitive to the adiabatic length
- Long-range oscillations provide effective heat transfer
- Non-uniform heating produces system adjustments

Questions or Comments?