Thermal Analysis of Recondensing Systems

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(work performed by student Dan Schick)

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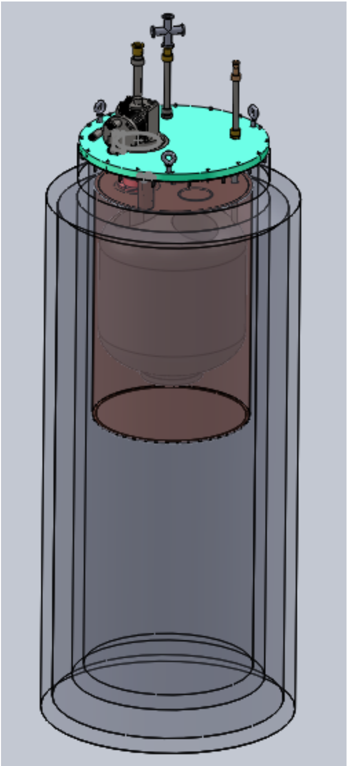


Overview

- Goals
- Background
- Modeling
- Experimental Work
- Future Work

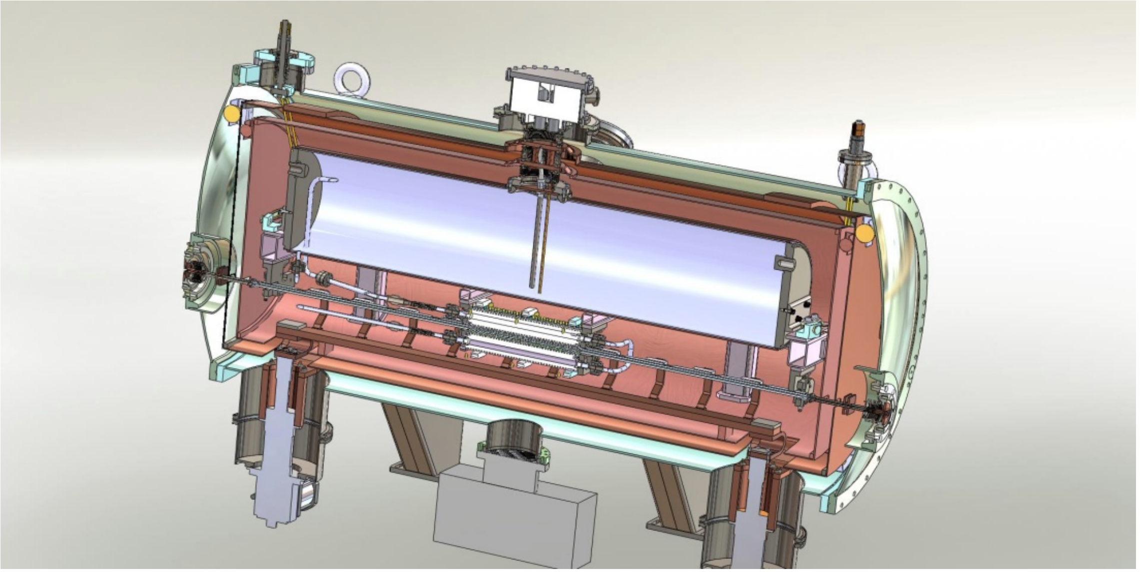


Image: Ivanyushenkov, Y. *SCU0 Conceptual Design Review*. 5 Feb 2010.

Goals

- Provide recommendations regarding liquid helium re-condensation
  - Develop models to estimate the thermal behavior of the re-condensing system
    - Film condensation
    - Vapor convection
    - Vessel conduction
  - Build and test different geometries
    - Baseline test
    - Surface enhancements

Length = 146 cm
Diameter = 30 cm

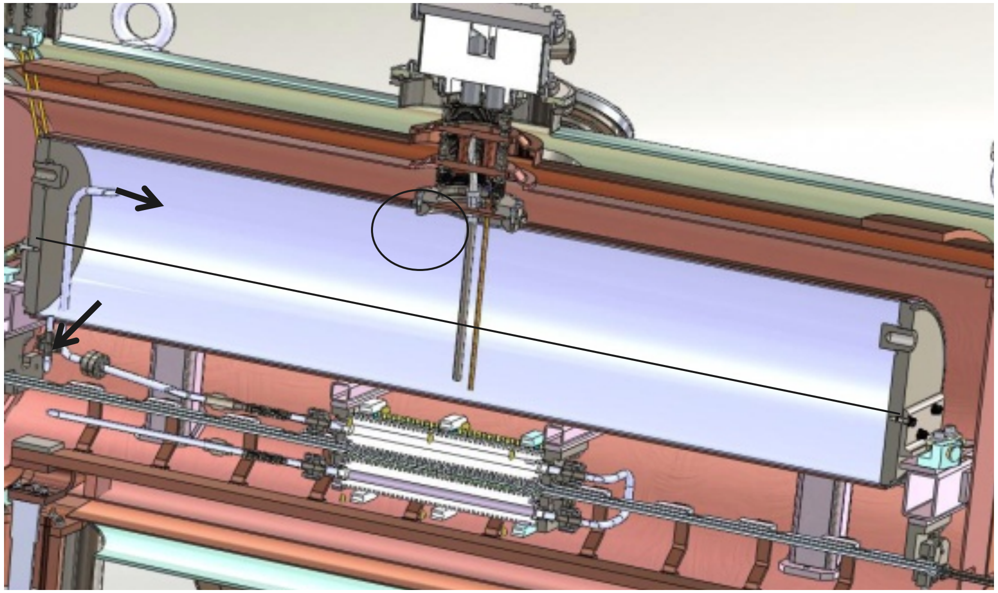
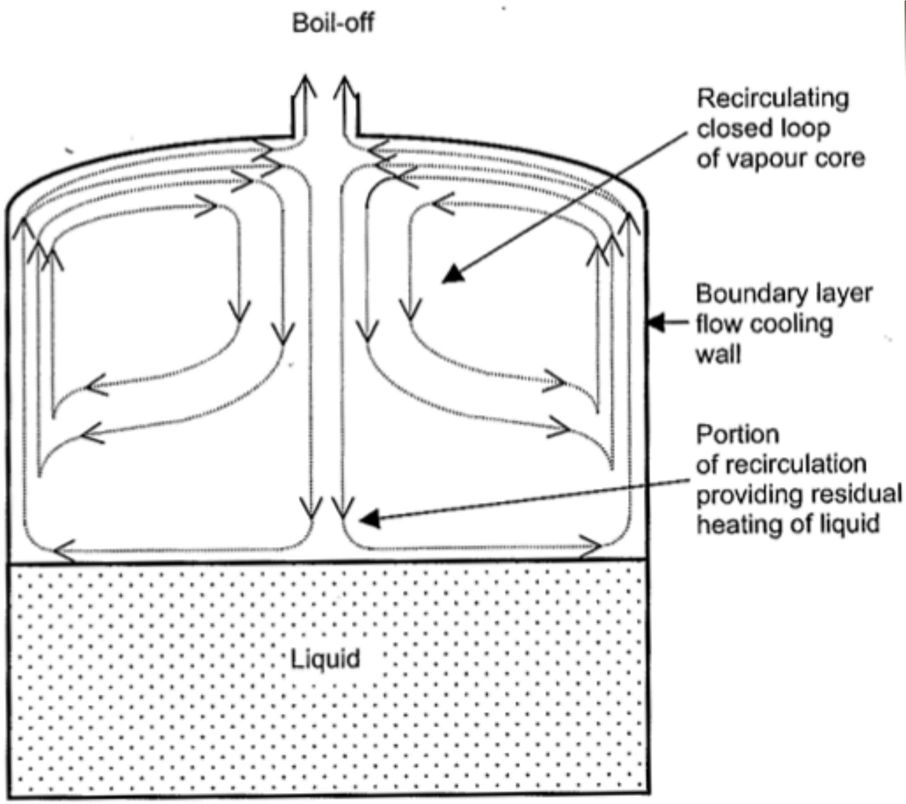


Image: Ivanyushenkov, Y. *SCU0 Conceptual Design Review*. 5 Feb 2010.

Background

- University of Southampton (Scurlock, … 1978 - 2008)
    - Convective flows in stratified cryogen vapors
        - Upward convection along side walls, downward flow in the core
        - Conductive heat leak down dewar neck is reduced



Background

- Cryomech (Wang '05-'08): Re-condensers & Liquefiers
  - LHe storage dewar at South Pole
    - 14 L/day ZBO
    - 2.7 L/day liquefaction
  - Improvements to liquefaction efficiency (w/ Scurlock)
    - Remove G10 sleeve, MLI, precooling heat exchanger
    - Add horizontal fins to OD of 2nd stage regenerator / pulse tube, and radiation shield to OD of 1st stage
    - Improve liquefaction from 12.8 L/day to 21.4 L/day

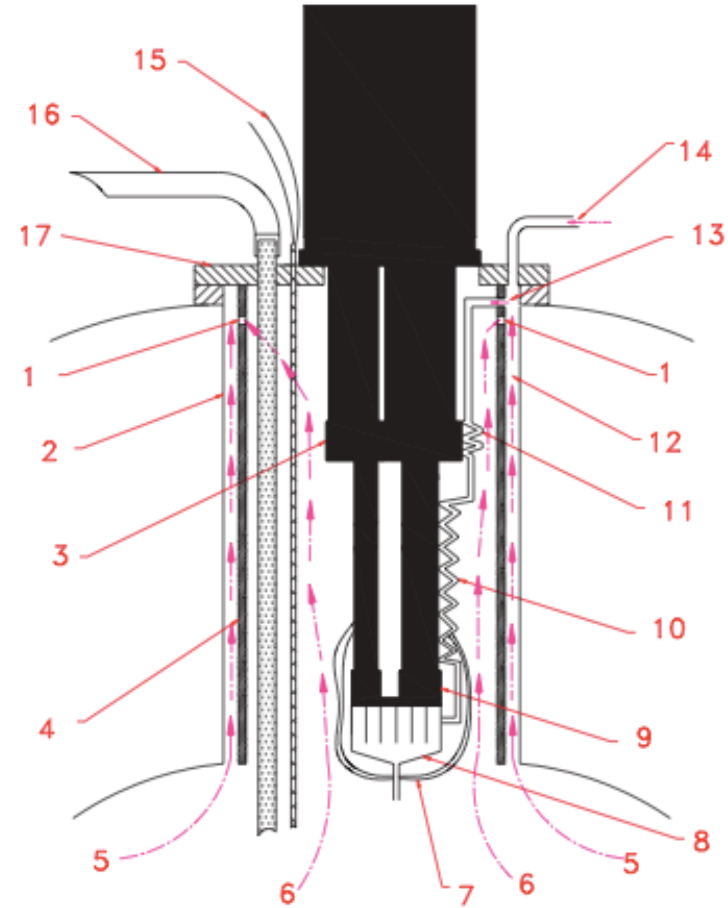


Fig. 2. Details of the pulse tube recondenser in the dewar: 1. holes for vapor flow of inside of G-10 sleeve; 2. dewar neck; 3. 1st stage heat exchanger of the cold head; 4. G-10 sleeve; 5. vapor in the circular gap; 6. vapor inside of G-10 sleeve; 7. superinsulation; 8. condenser; 9. 2nd stage heat exchanger of the cold head; 10. precooling heat exchanger on the 2nd stage regenerator; 11. precooling heat exchanger on the 1st stage; 12. annular flow channel; 13. gas inlet for liquefaction; 14. helium gas from outside of the dewar; 15. liquid level sensor; 16. liquid helium withdrawal line; 17. top flange.

Background

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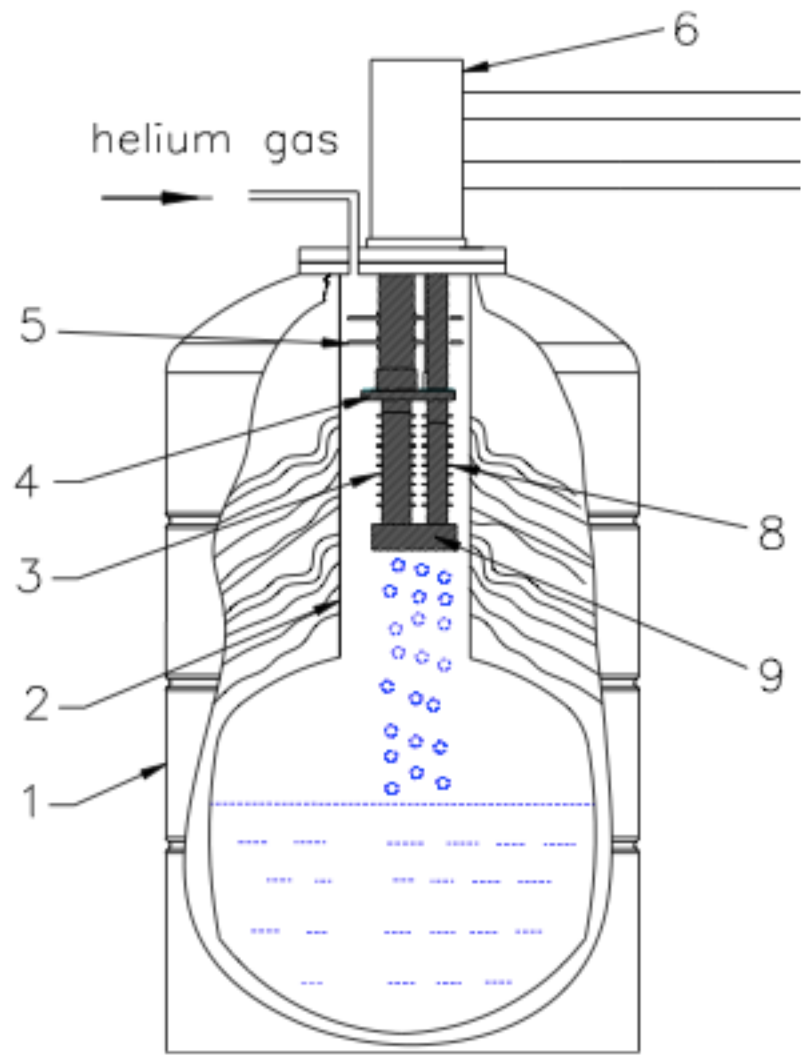

1. LHe dewar, 2. dewar neck, 3. fins on 2nd stage regenerator, 4. 1st stage, 5. radiation shields on 1st stage regenerator, 6. cryocooler valve head, 8. fins on 2nd stage pulse tube, 9. 2nd stage.

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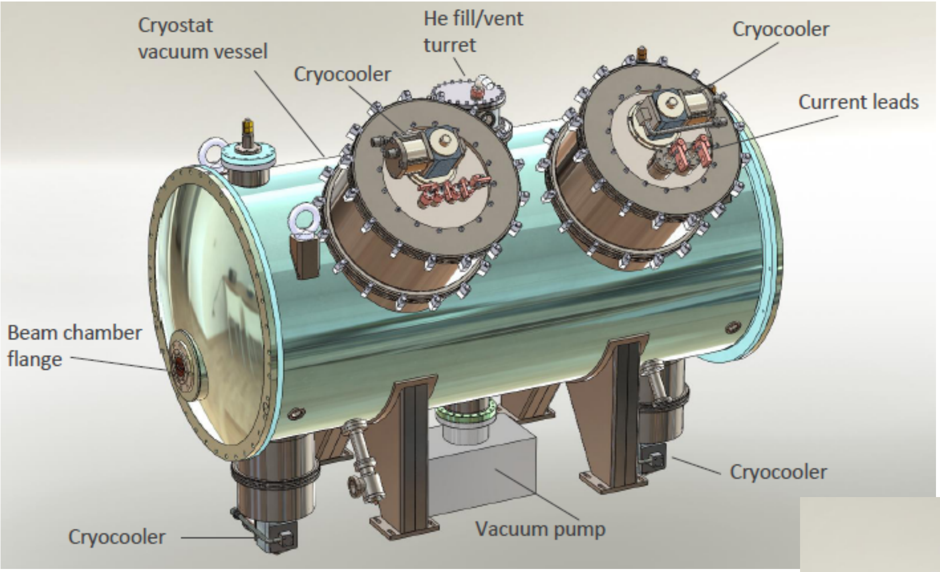
Superconducting Undulator Aparatus



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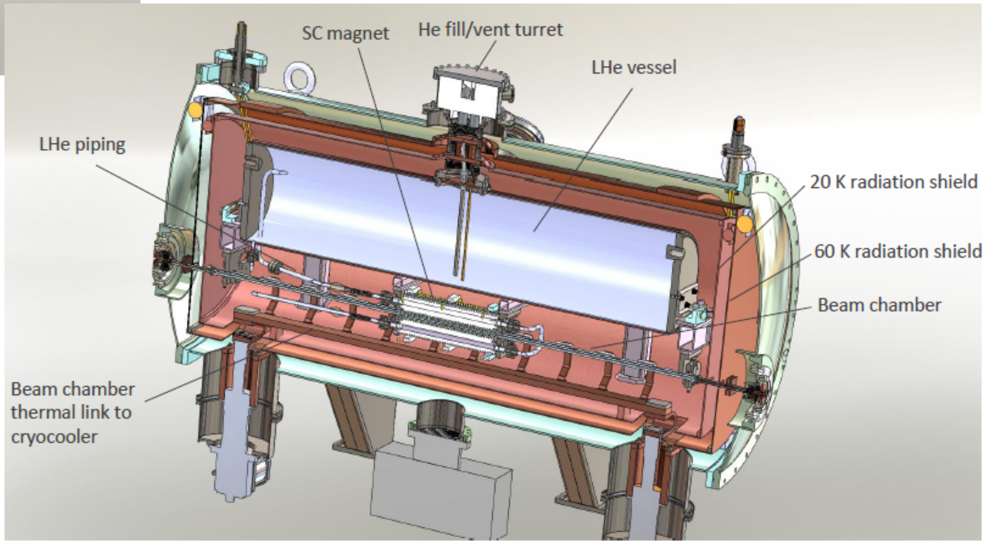
1. GM cryocoolers mounted at angle (not vertical)
2. Only the bottom side of the 2nd stage is exposed to the helium vapor
3. Entire helium vapor region is maintained near 4 K



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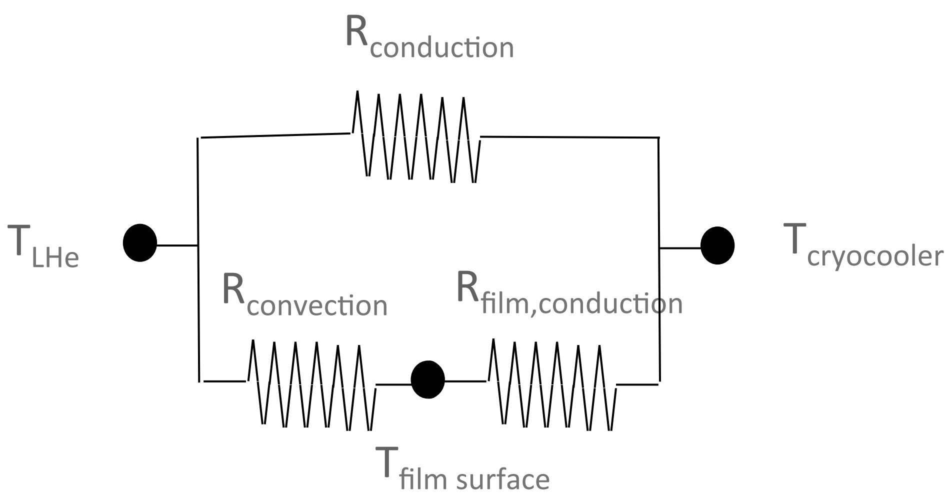
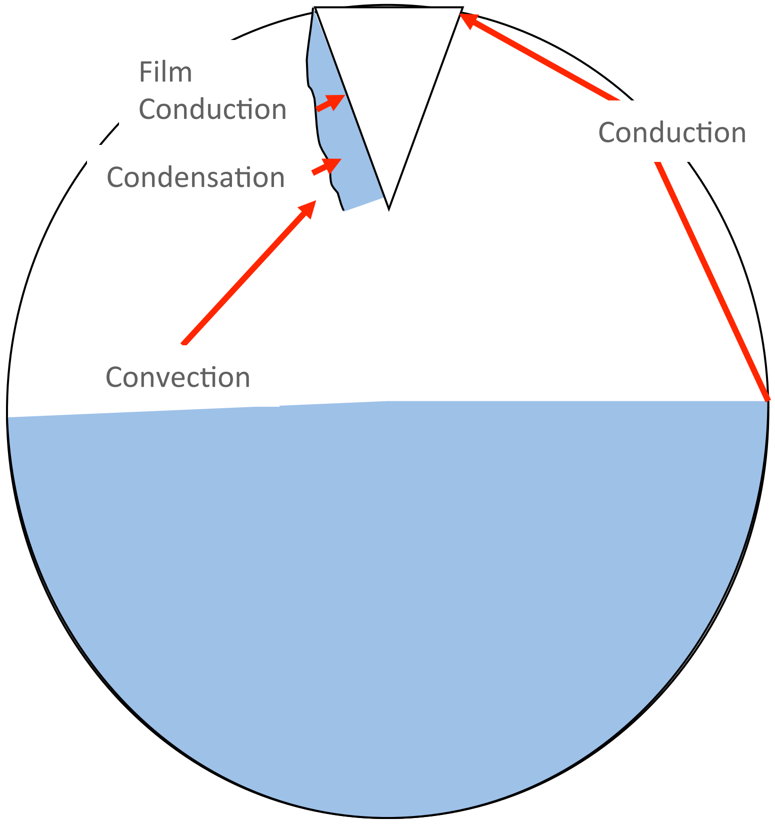
Thermal Modeling

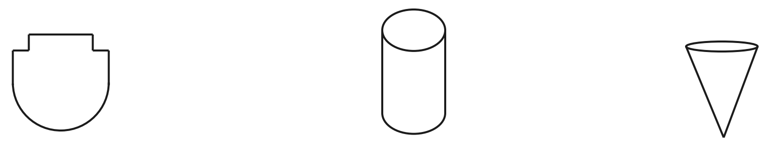
Thermal Resistance Description

- Heat transfer in system represented by the resistance network shown (most basic terms)
  - Condensation & film conduction (EES)
  - Convection (ANSYS)
  - Conduction (FEHT)



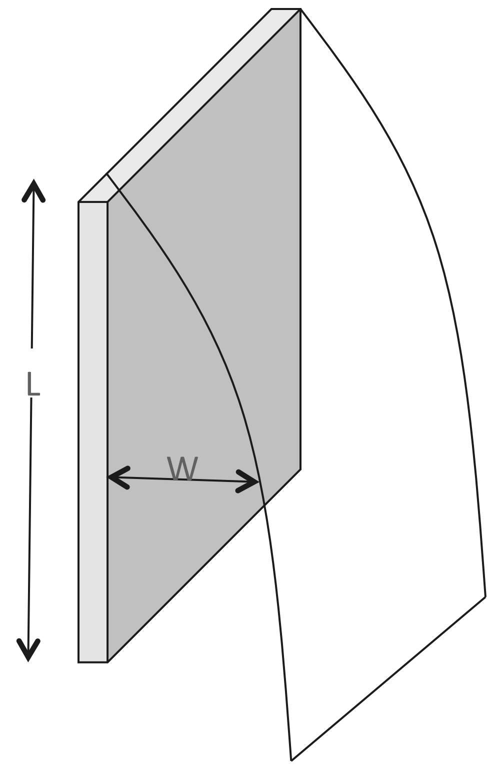


Condensation Considerations

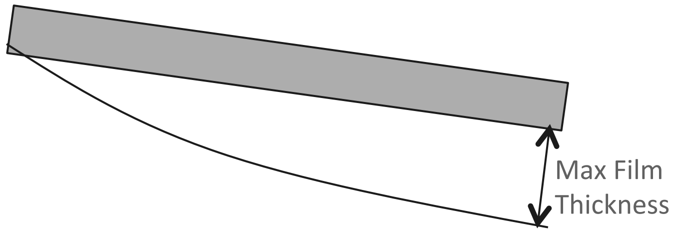


- Film development on various geometries
- Maximum film thickness of helium
  - δ_{max} = 0.3215 [mm]
    - 1 [atm], 4.2 [K], 0° from horizontal
  - δ_{max} = 0.3317 [mm]
    - 1 [atm], 4.2 [K], 20° from horizontal

$$\delta_{max} = \sqrt{\frac{\sigma_l}{g\cos(\theta)\,(\rho_l - \rho_v)}}$$

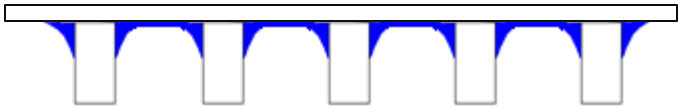


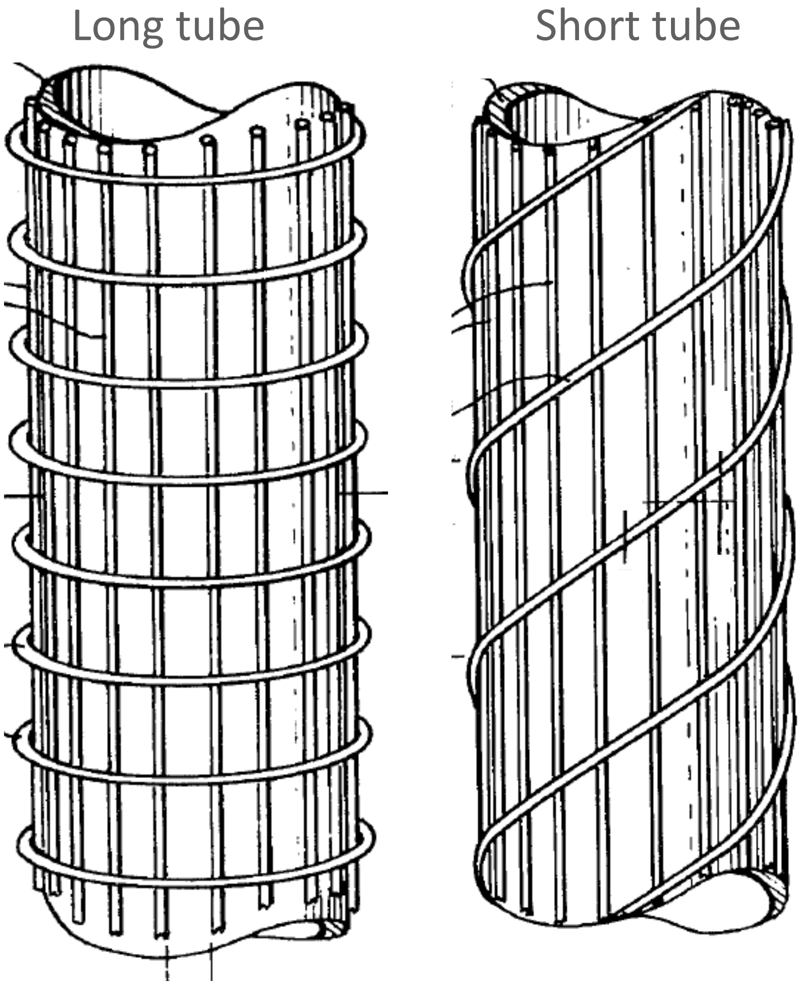
- Thin film = better heat transfer



Condensation Surface Enhancements[1]

- Collect condensate into rivulets (streams)
- Thin film regions promote good heat transfer
- Surface tension used to concentrate the condensate into drainage rivulets
- Gravity also used to collect flow





1 Enhancement for Film Condensation Apparatus. Leslie C. Kun & Elias G. Ragi. United States Patent 4,253,519. March 3rd, 1981.

Thermal Resistance - Film Conduction/Condensation

- Heat of conduction

$$Q = \frac{k\,A}{\Delta L}\Delta T = \frac{1}{\mathrm{R}}\,\Delta T$$

- Thermal resistance of conduction in parallel

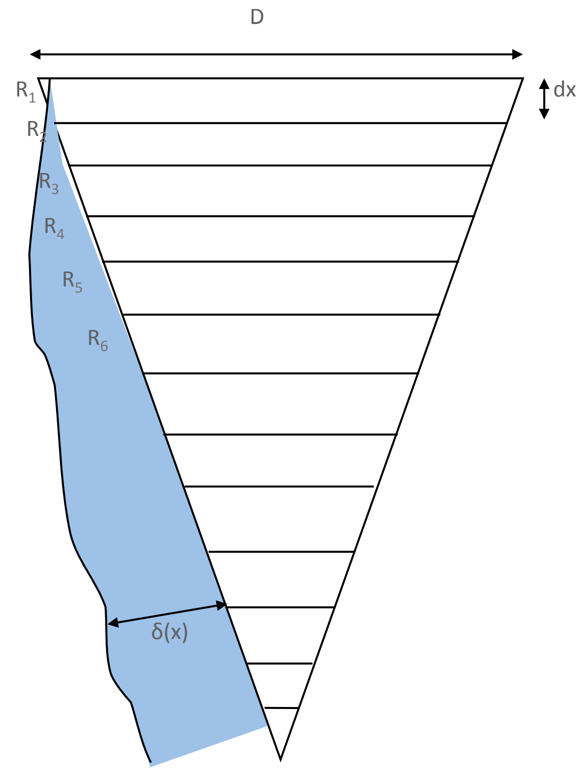
$$\dot{C}_{net} = \frac{1}{R_{net}} = \frac{k\,A(x_1)}{\Delta\delta(x_1)} + \frac{k\,A(x_2)}{\Delta\delta(x_2)} + \frac{k\,A(x_3)}{\Delta\delta(x_3)} + \cdots$$

- Integrated thermal resistance as a function of height with changing geometry areas & film thicknesses

$$\dot{C}_{net} = \int \left(\frac{1}{R_{net}}\right) = \int_{x=0}^{x=L} \left(\frac{k\,P(x)}{\Delta\delta(x)}\right) \mathrm{dx}$$

- Film condensation thickness

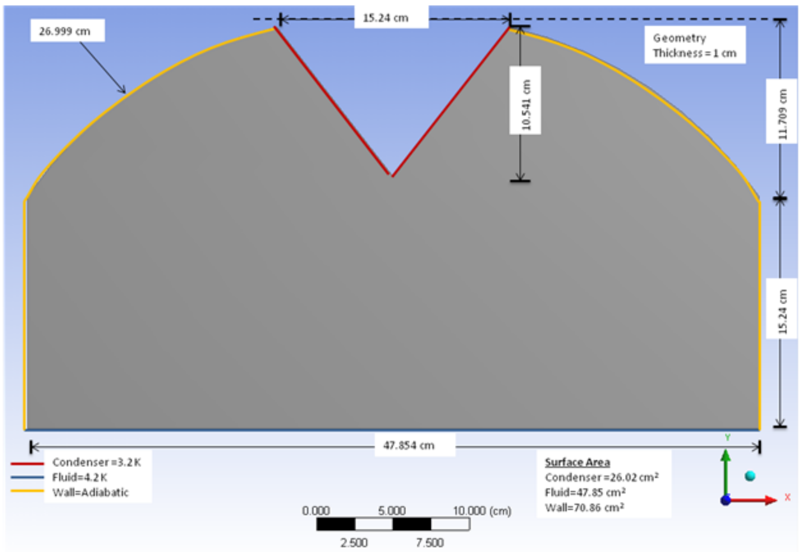
$$\delta = \left\{ \frac{4\,x\,k_{l,sat}\,\mu_{l,sat}\,(T_{sat} - T_s)}{\rho_{l,sat}\,g\cos\theta\,\left(\rho_{l,sat} - \rho_{v,sat}\right)\left[\Delta i_{vap} + \frac{3\,c_{l,sat}\,(T_{sat} - T_s)}{8}\right]} \right\}^{1/4}$$

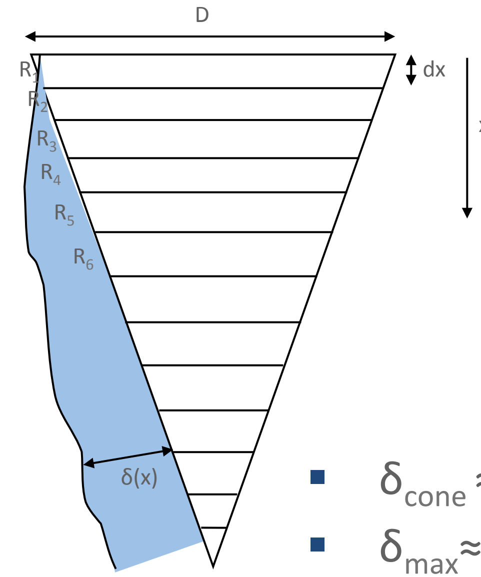


$\delta = film\,thickness$
$k_{l,sat}, \mu_{l,sat}, \rho_{l,sat}, \rho_{v,sat}, c_{l,sat}, \Delta i_{vap} =$ fluid properties
$x = length\ of\ condensation\ surface$
$T_{sat} = Saturation\ temperature$
$T_s = Surface\ temperature$
$g = gravitational\ acceleration$
$\theta = angle\ of\ surface$

Thermal Resistance - Film Conduction (Cone)

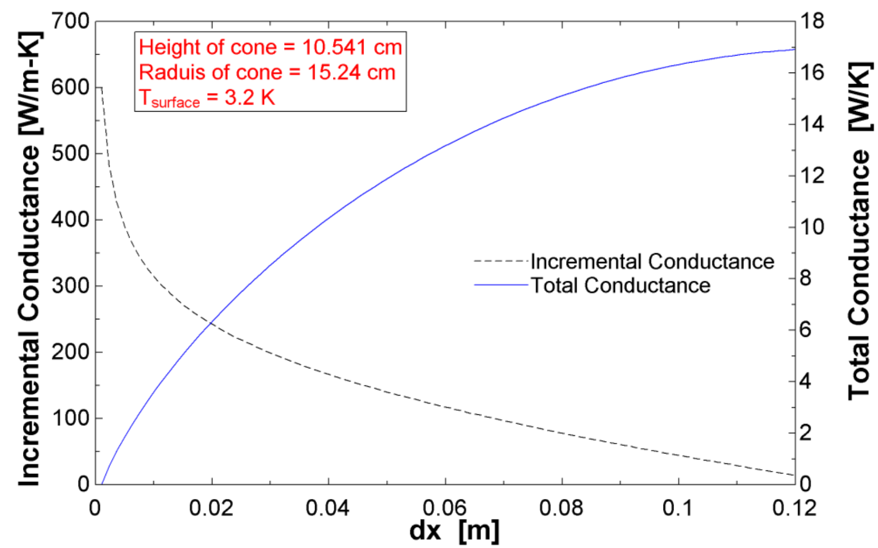
Conv #4





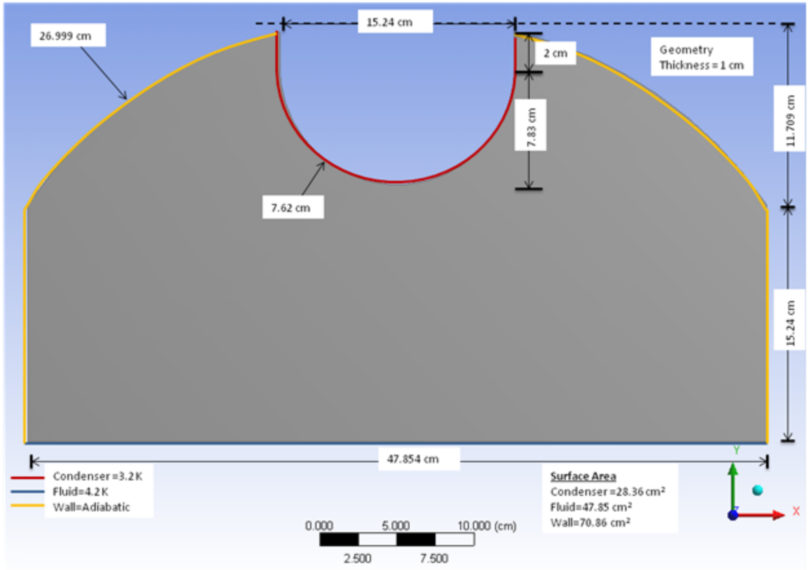
- $\delta_{cone} \approx 0.057$ mm
- $\delta_{max} \approx 0.321$ mm

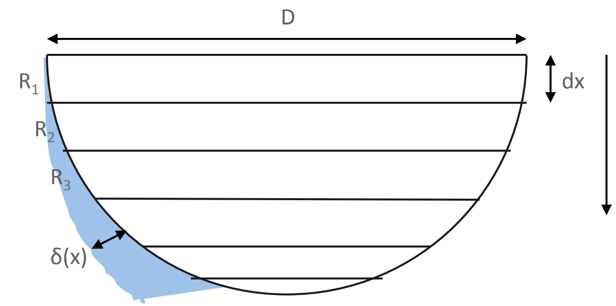
- $R_{conv} \approx 20$ K/W (Dominant)
- $R_{film,cond} \approx 0.06$ K/W



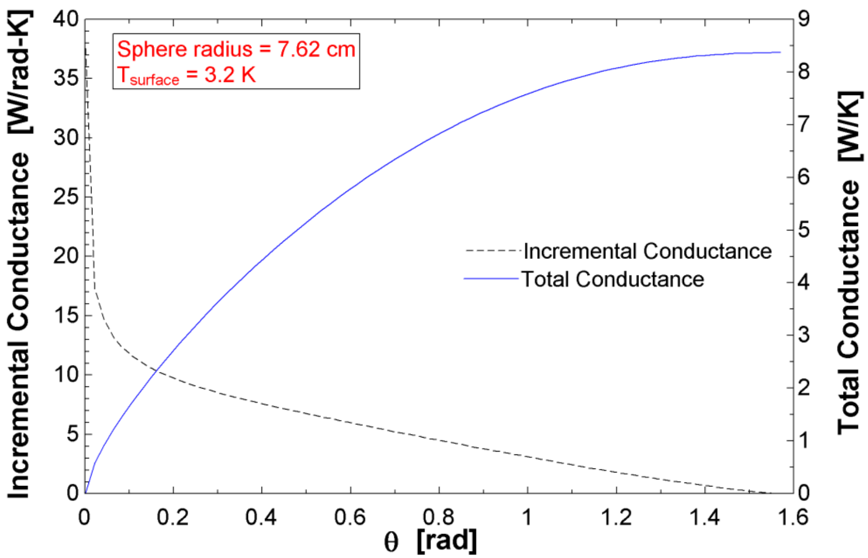
Thermal Resistance - Film Conduction (Hemisphere)

Conv #6



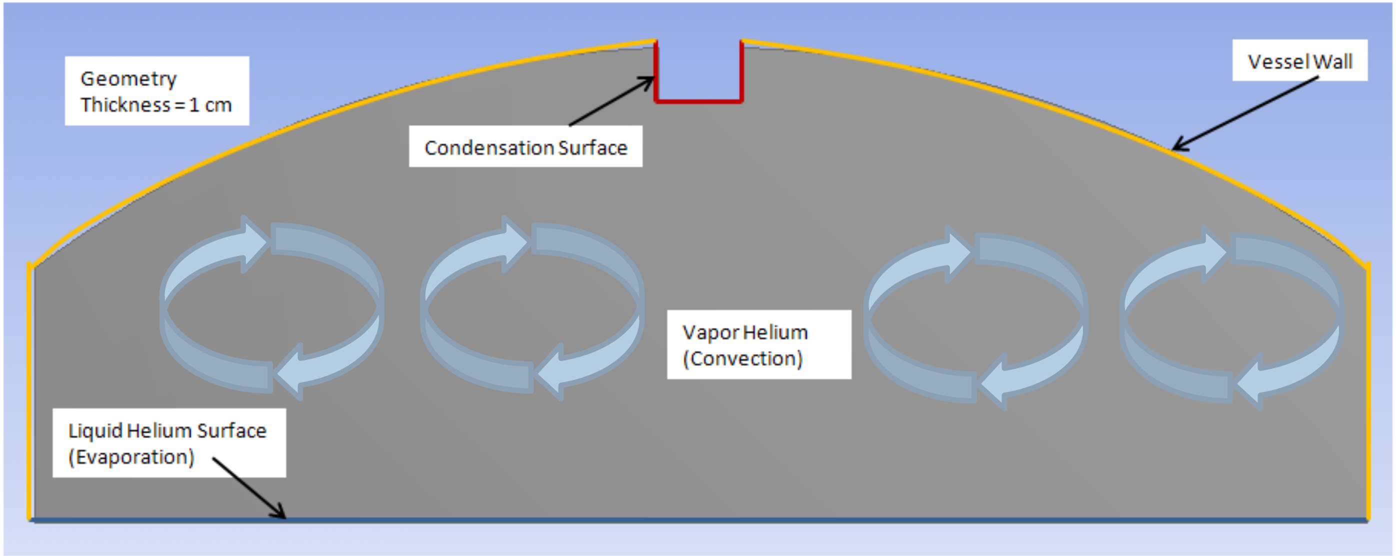


- $R_{conv} \approx 17$ K/W (Dominant)
- $R_{film,cond} \approx 0.12$ K/W



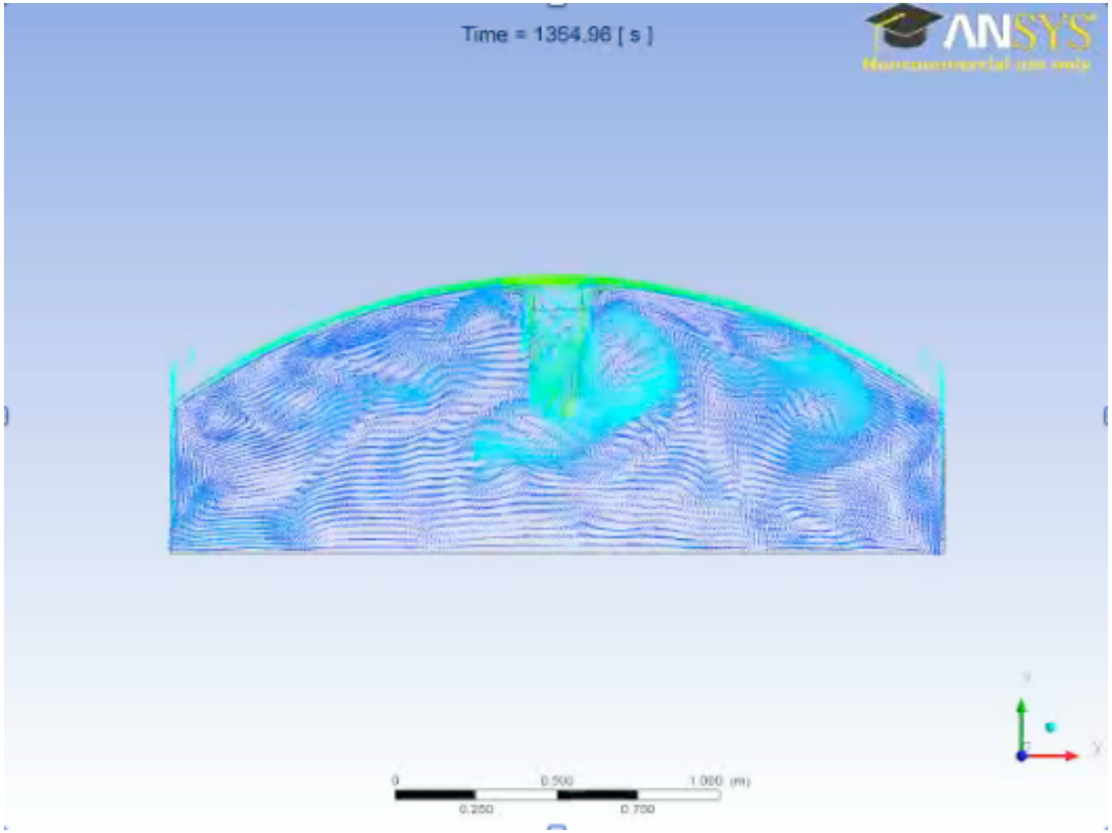
ANSYS Modeling - Convection

- Convection Modeling Constraints
  - Condenser Temp = 3.2 K
  - Fluid Temp = 4.2 K
  - Helium Vessel = Adiabatic or 4.3 K
  - Helium Gas (No condensation)
  - Total Time
  - Vessel Geometry
  - Condenser Geometry



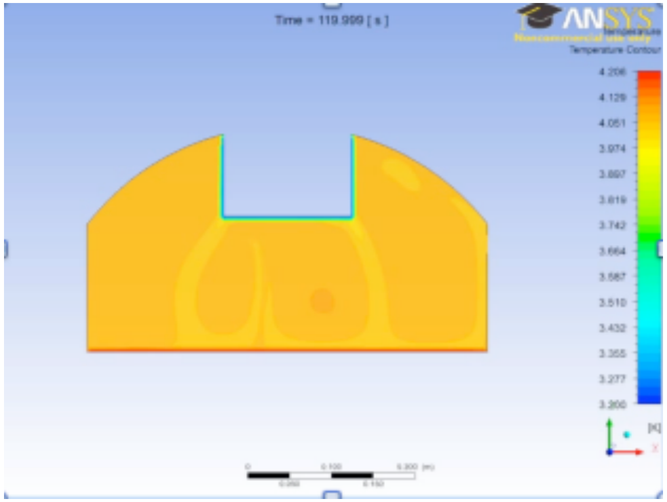
ANSYS Modeling - Convection

- Convection never reaches a steady state (long time runs)

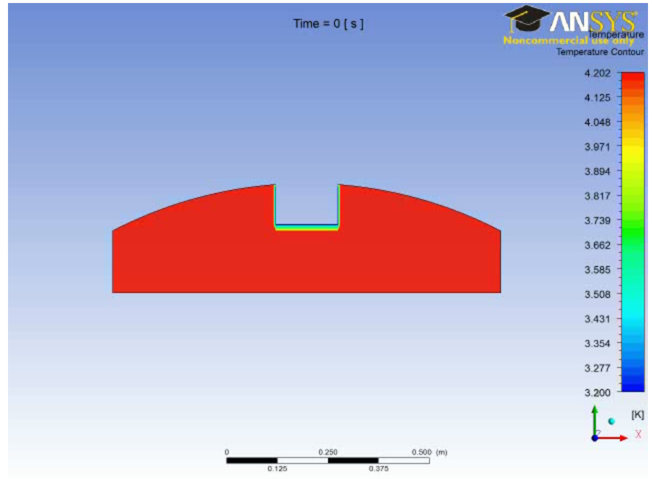


ANSYS Modeling - Convection (Increase Width)

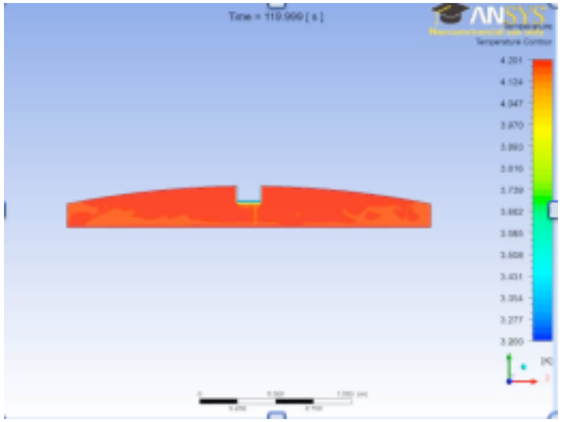
<u>Conv22:</u> H=1x, W=1x



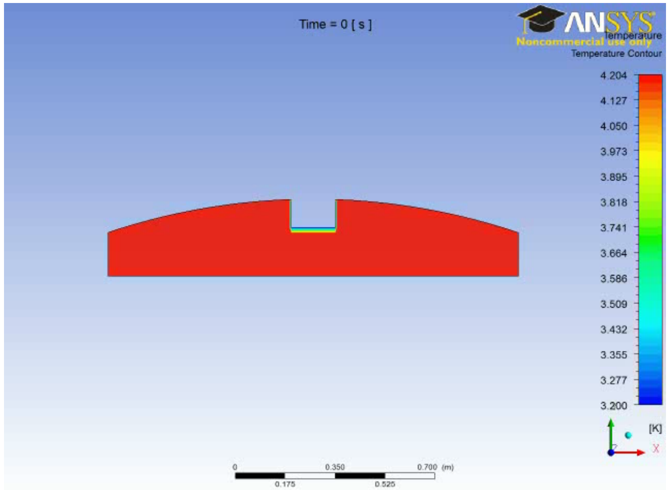
<u>Conv20:</u> H=1x, W=2x



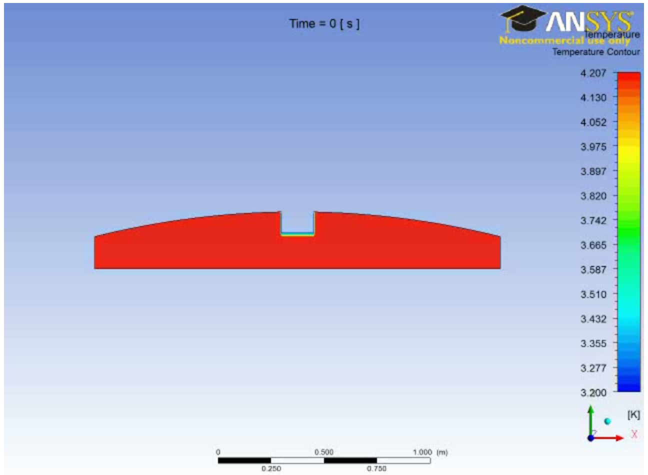
<u>Conv23:</u> H=1x, W=5x



<u>Conv21:</u> H=1x, W=3x

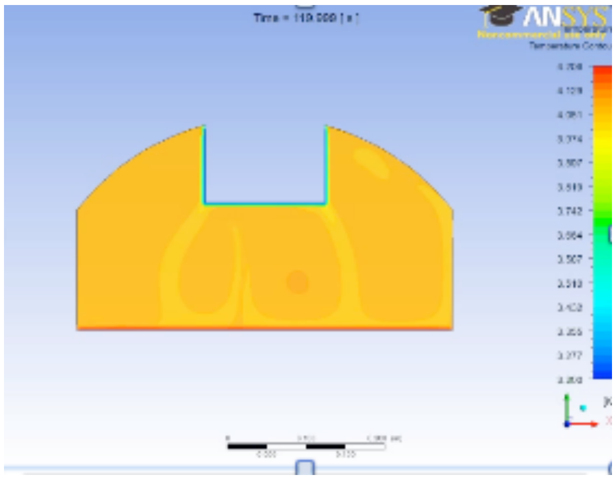


<u>Conv29:</u> H=1x, W=4x

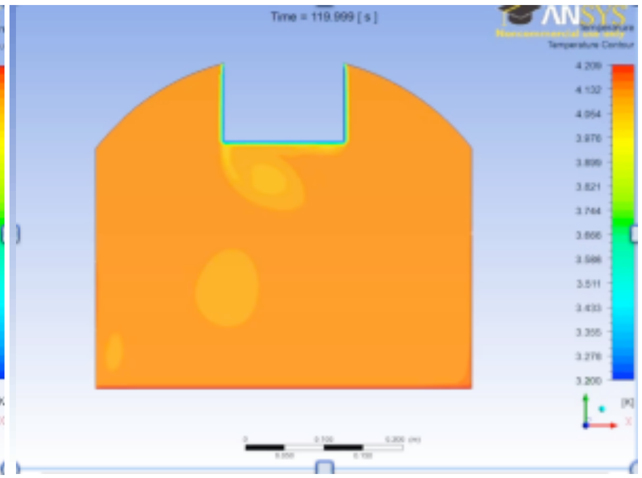


ANSYS Modeling - Convection (Increase height)

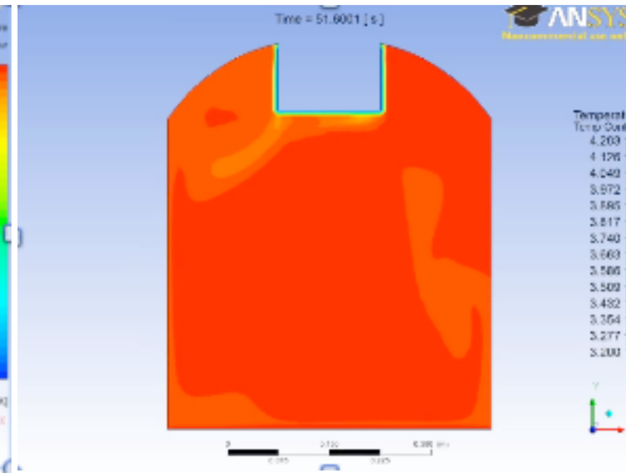
<u>Conv22:</u> H=1x, W=1x



<u>Conv24:</u> H=2x, W=1x

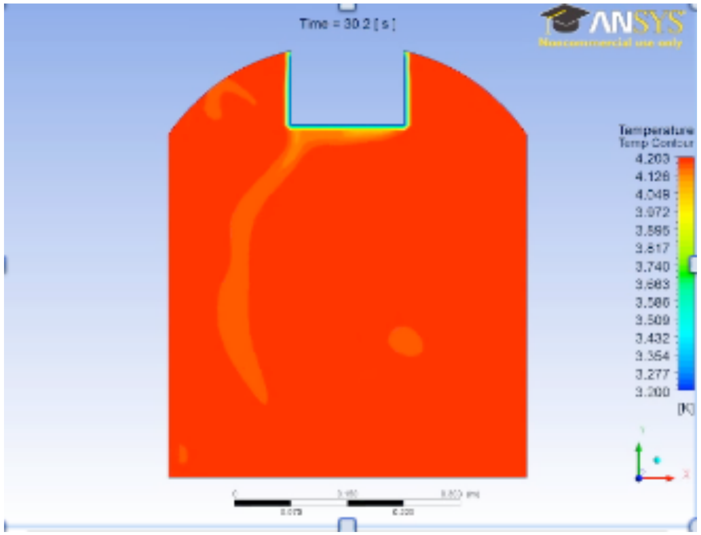


<u>Conv7:</u> H=3x, W=1x

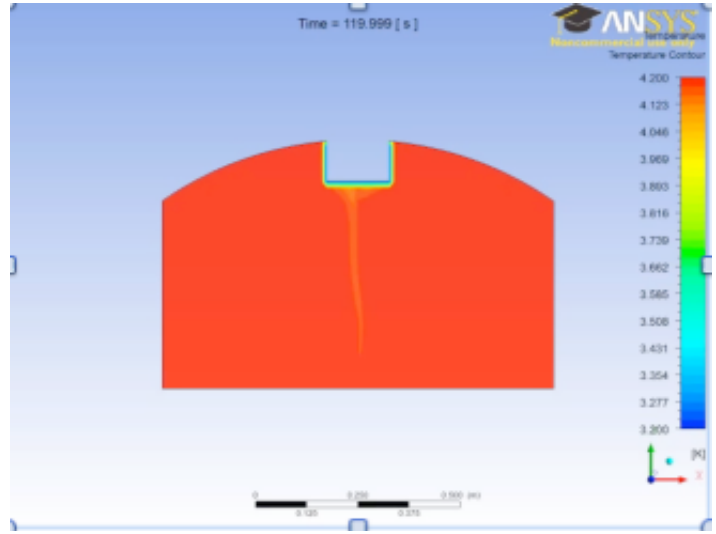


ANSYS Modeling - Convection (Very large vessels)

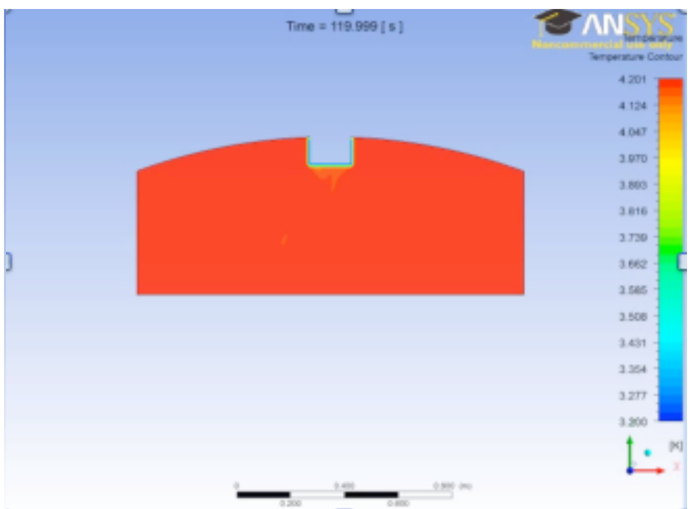
Conv7: H=3x, W=1x



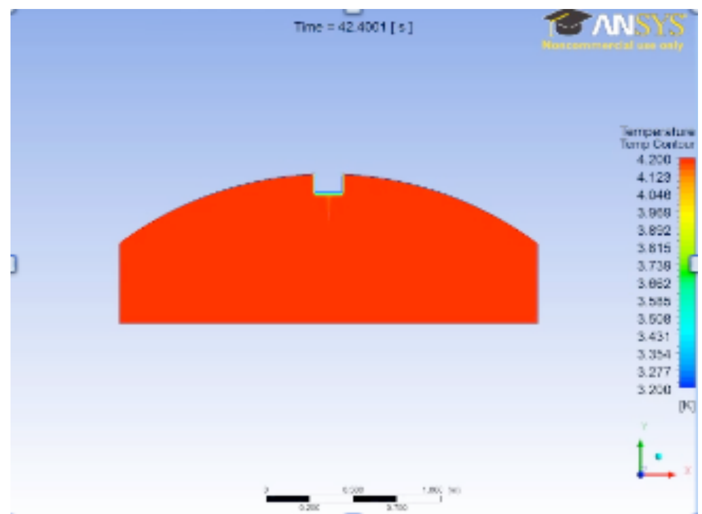
Conv17: H=3x, W=2x



Conv18: H=3x, W=3x

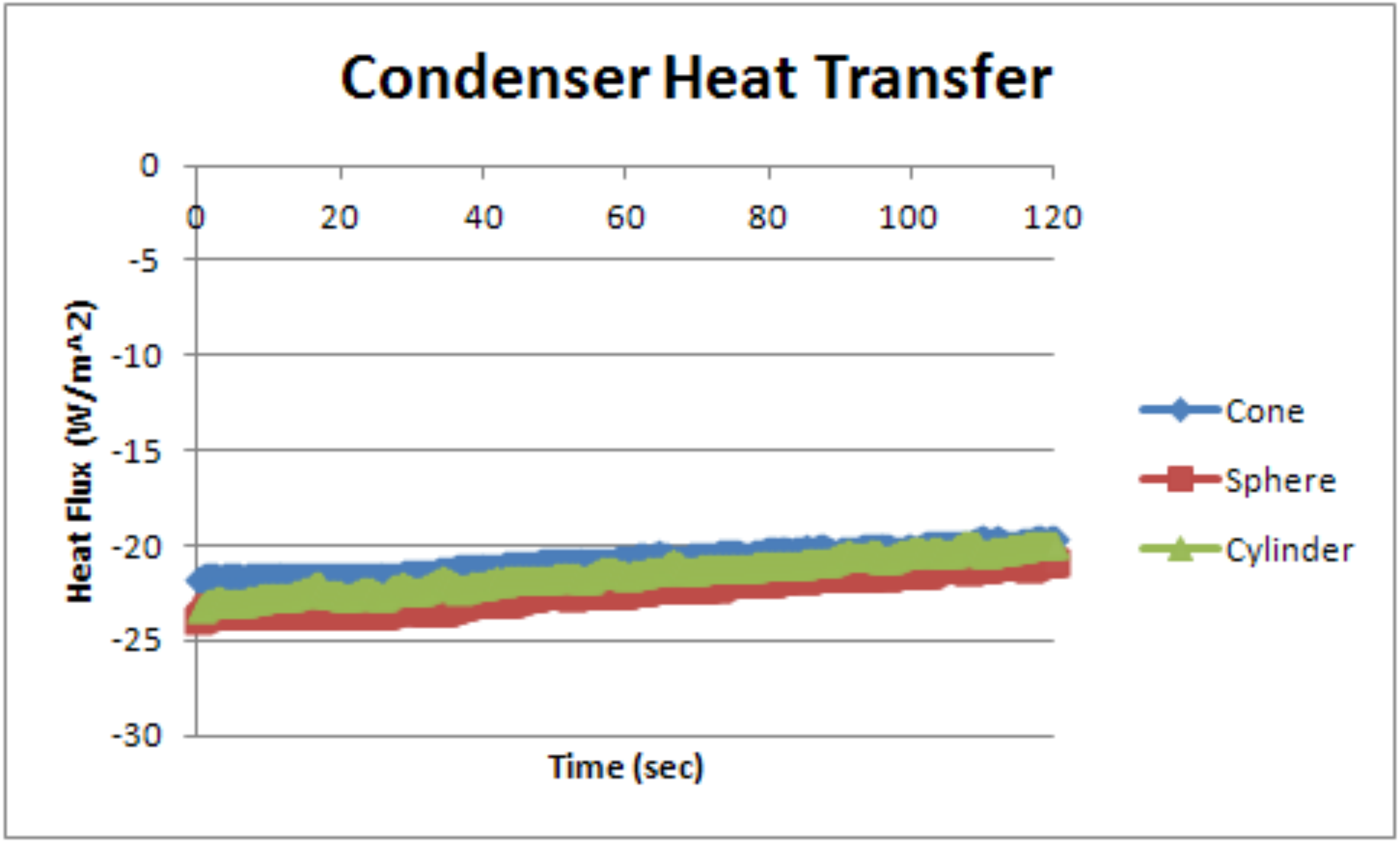


Conv8: H=3x, W=5x



ANSYS Modeling - Convection

- Condensation tip geometry comparisons
- Little difference between condenser geometries



ANSYS Modeling – Convection

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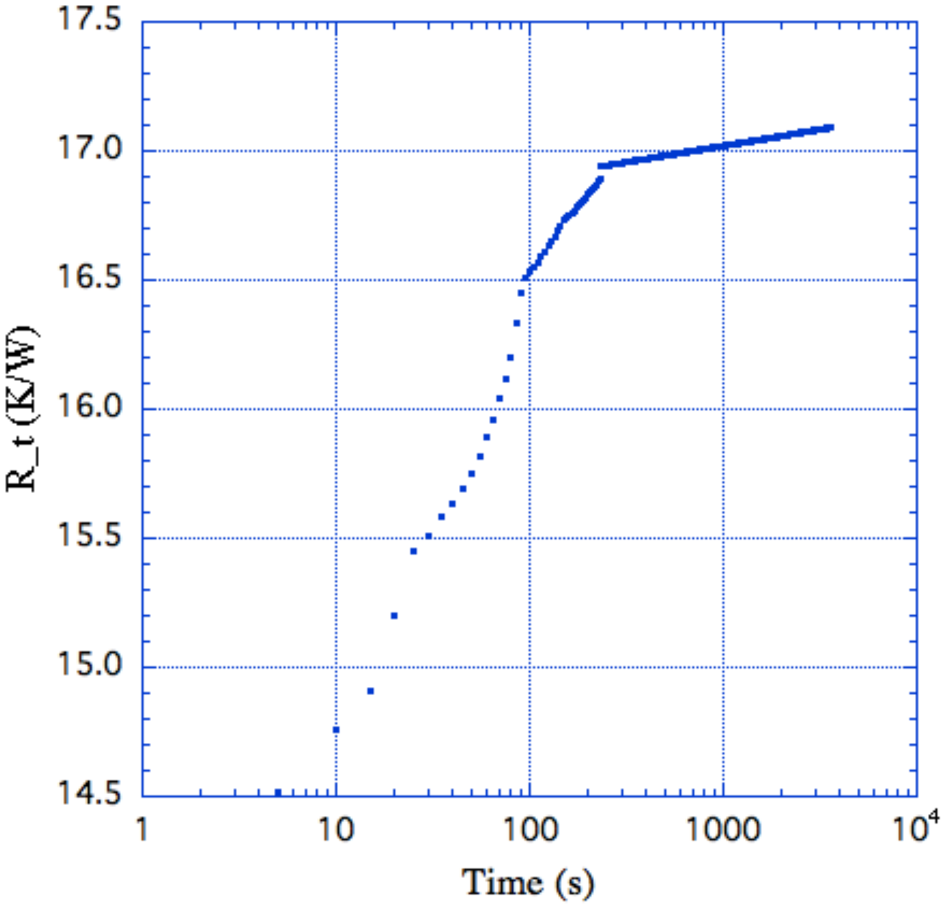
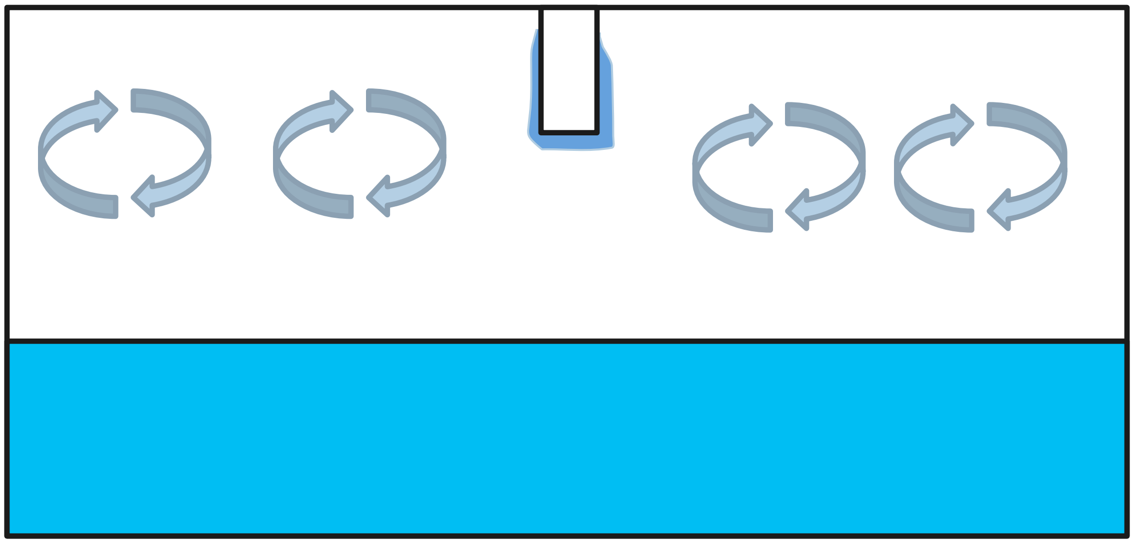


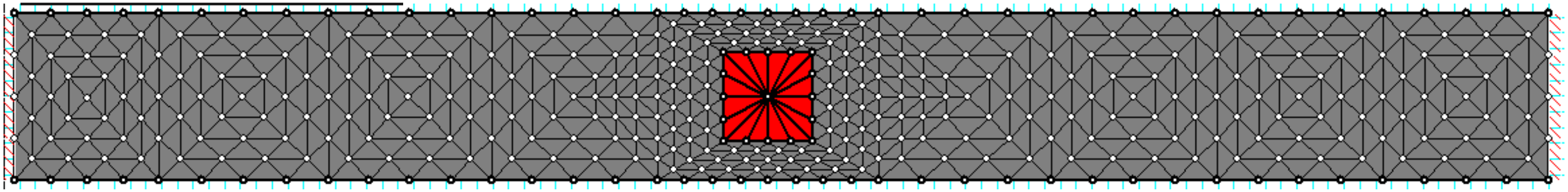
ANSYS Modeling (Convection) - Conclusions

- Size of the vessel impacts convection
- Geometry of condensation tip does not dramatically effect convection
- Order of magnitude for UW test quasi ‘steady state’ is 3-4 minutes
- Order of magnitude thermal resistance is 20 K/W

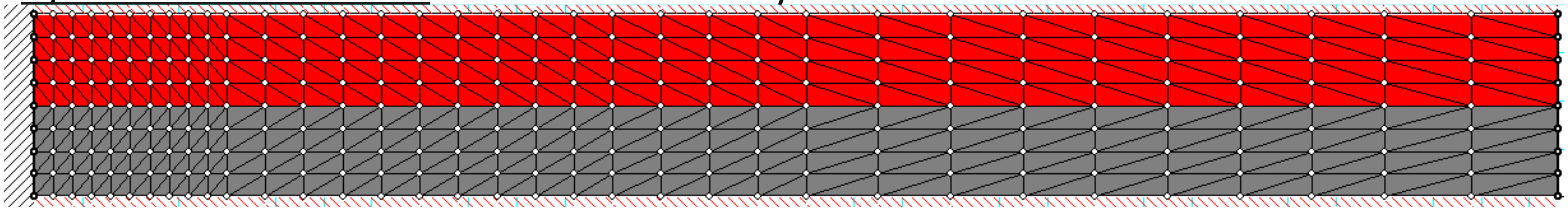


Thermal Resistance - Vessel Conduction (FEHT)

Cartesian Coordinates – Flatten vessel



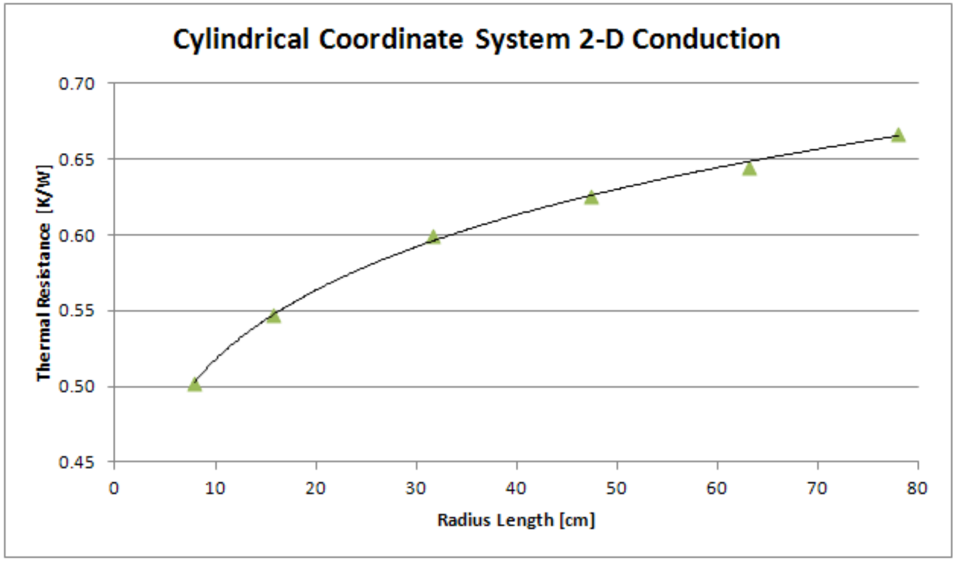
Cylindrical Coordinates – Rotate around cryocooler



- 3D to 2D approximation
- Weighted by cross-sectional area

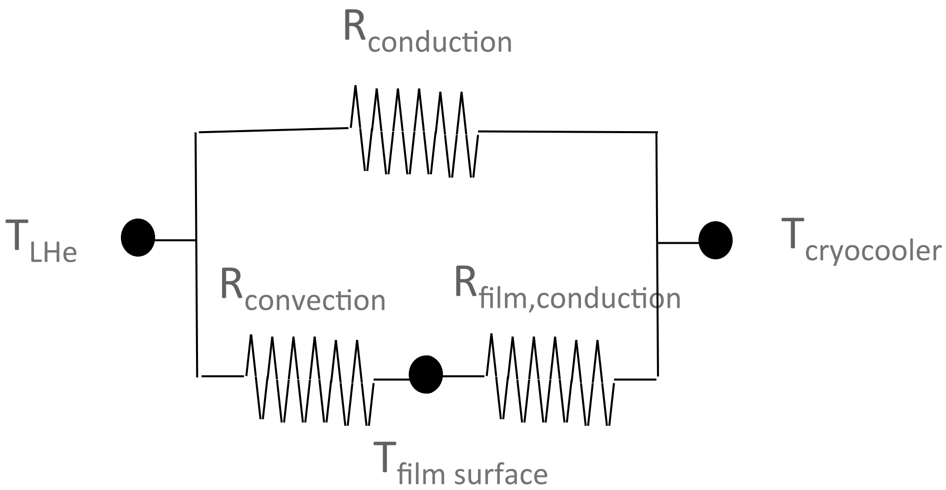
$$k_{eff}(4[K]) = \frac{A_{c,304SS}}{A_{c,tot}} k_{304SS}(4[K]) + \frac{A_{c,Cu}}{A_{c,tot}} k_{Cu}(4[K])$$

- Without copper
  - 3x higher thermal resistance



Modeling Conclusions

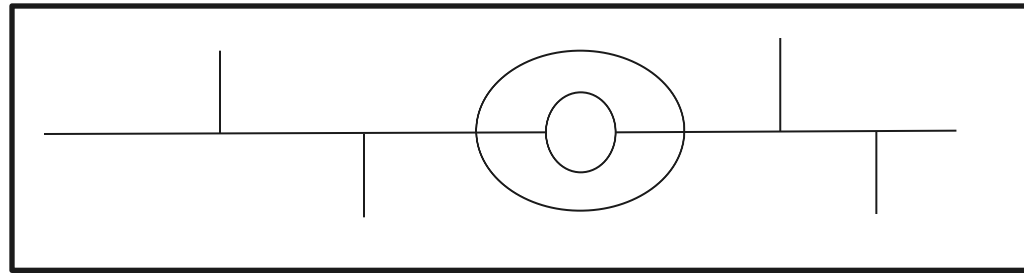
- Vessel conduction
  - $R_{film,cond} \approx 0.5$ K/W
- Vapor convection
  - $R_{conv} \approx 20$ K/W (Dominant)
- Film condensation
  - $R_{film,cond} \approx 0.1$ K/W



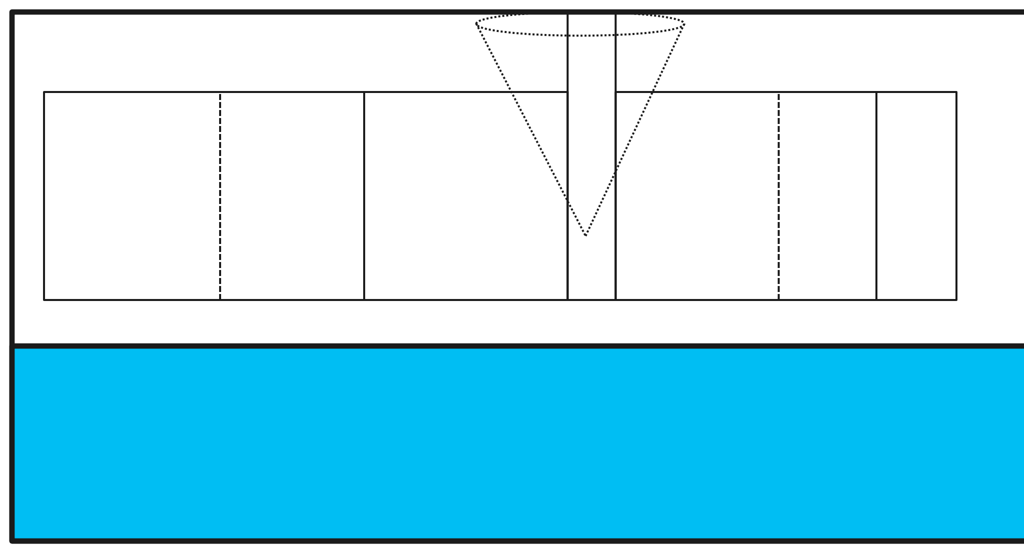
Extended Surfaces in Vapor Region

- Extended surface helps reduce convective thermal resistance
- Ideas
  - Copper sheets that fold open
  - Expandable aluminum foam

Top View

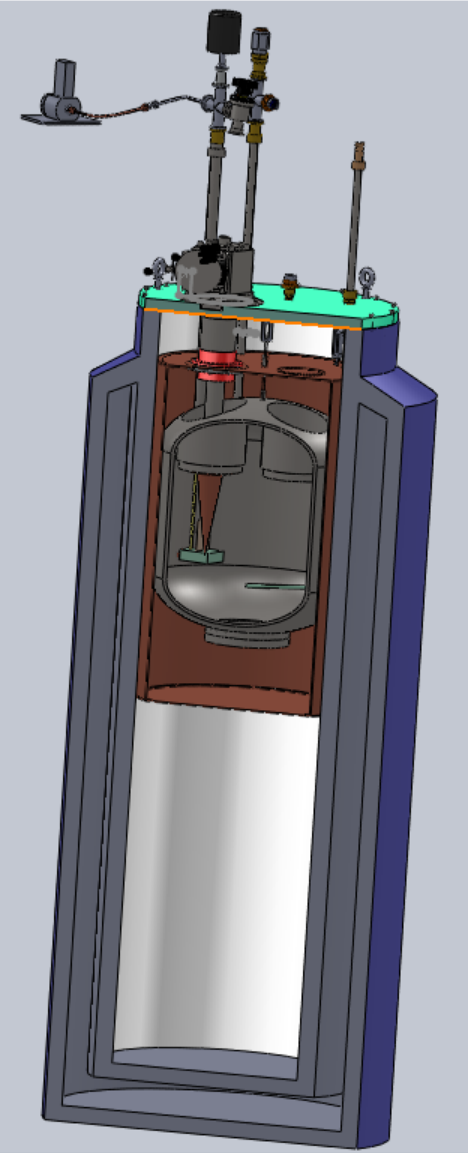


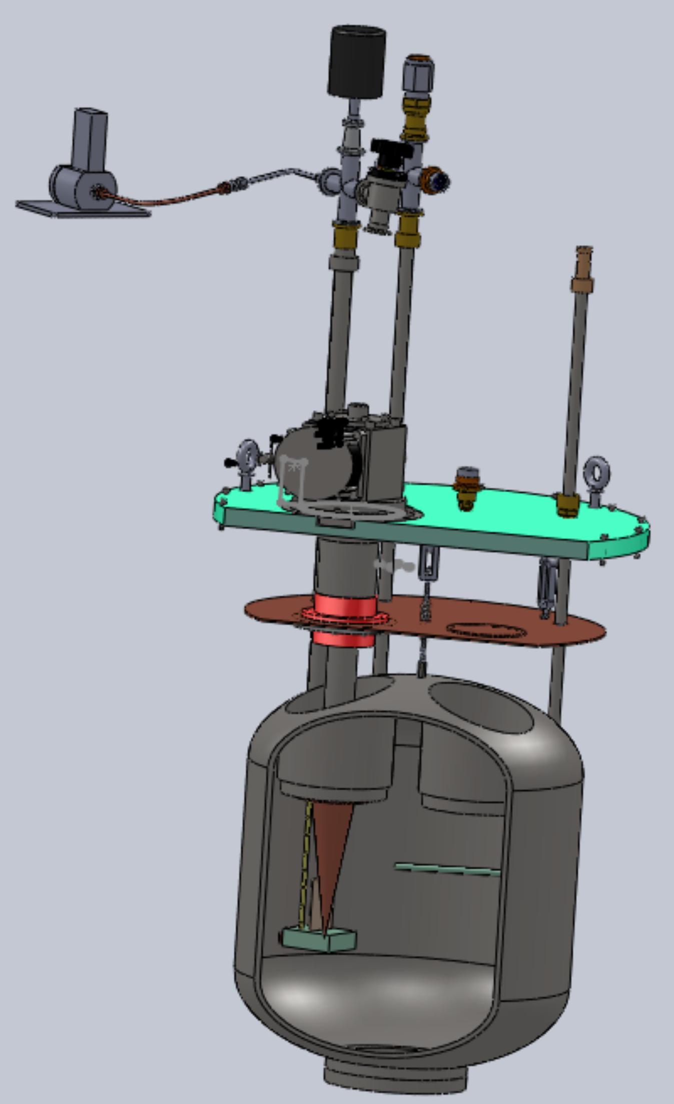
Side View



Experimental Work

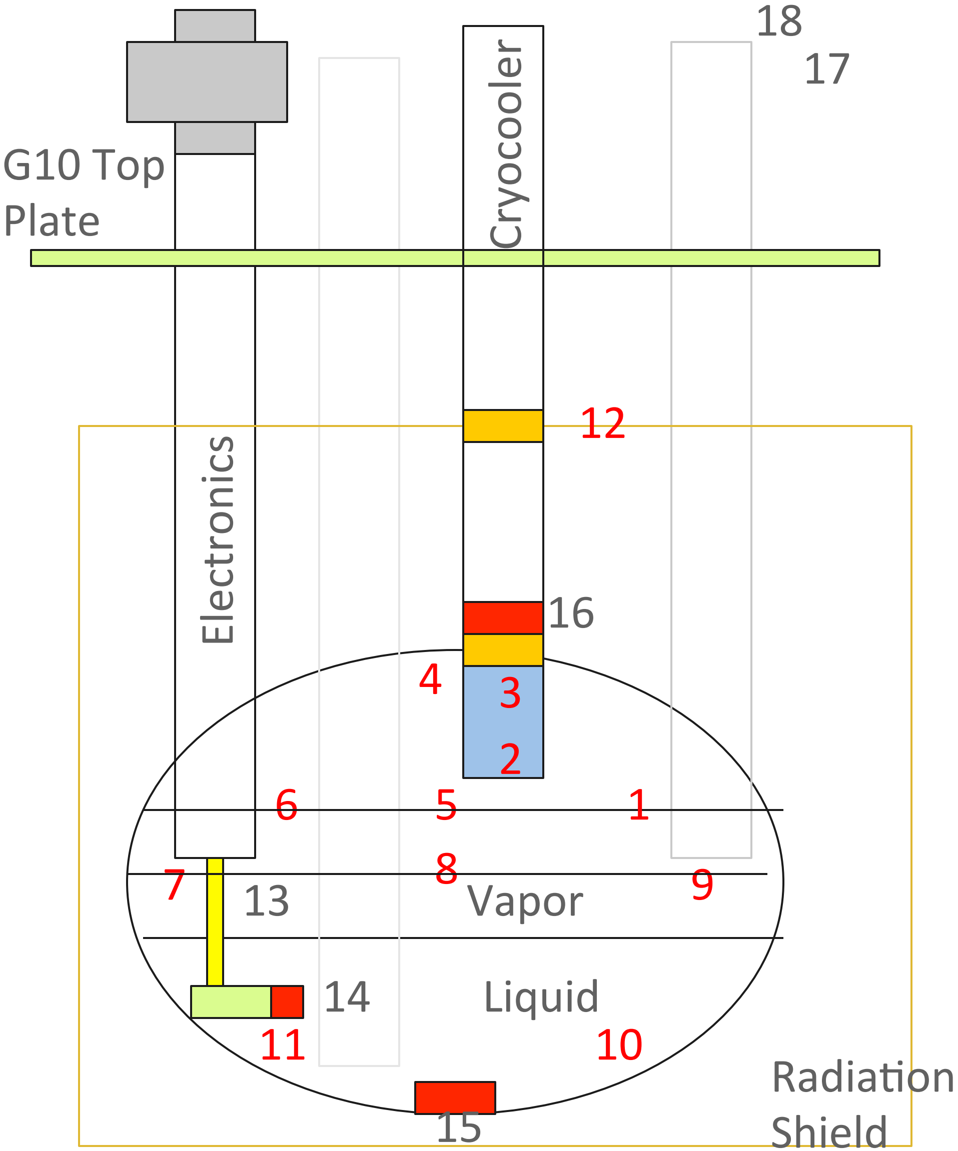
Experimental Setup – Cut Outs





Experimental Setup – Assembly & LN_2 Filling

Electronics Schematic



1-12. Thermometer (Cernox)
13. Liquid level indicator
14-16. Heater
17. Flow meter
18. Pressure transducer

- Characterize transient temperatures in the vapor region to compare to ANSYS modeling

Future Work

- Heat Transfer Flange Leak
  - Stainless Steel Backing Ring
- Run experiment
  - Baseline test (No cryocooler)
  - Bare cryocooler tip (with cryocooler)
  - Various extended surfaces
  - Surface enhancements

Acknowledgements

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  - Elizabeth R. Moog, Yuri Ivanyushenkov, Joel Fuerst, Robert L Kustom, Quentin Hasse
- Work performed by Dan Schick
  - with assistance from Dan Potratz, Diego Fonseca, and others at UW-Madison

Questions?