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Helium two-phase flow in a thermosiphon open loop

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Outline

□ Cooling large superconducting magnet

□ Thermosiphon open loops

□ Experimental facility and ranges of the study

□ COMSOL Multiphysics Modeling
□ Results with COMSOL Multiphysics

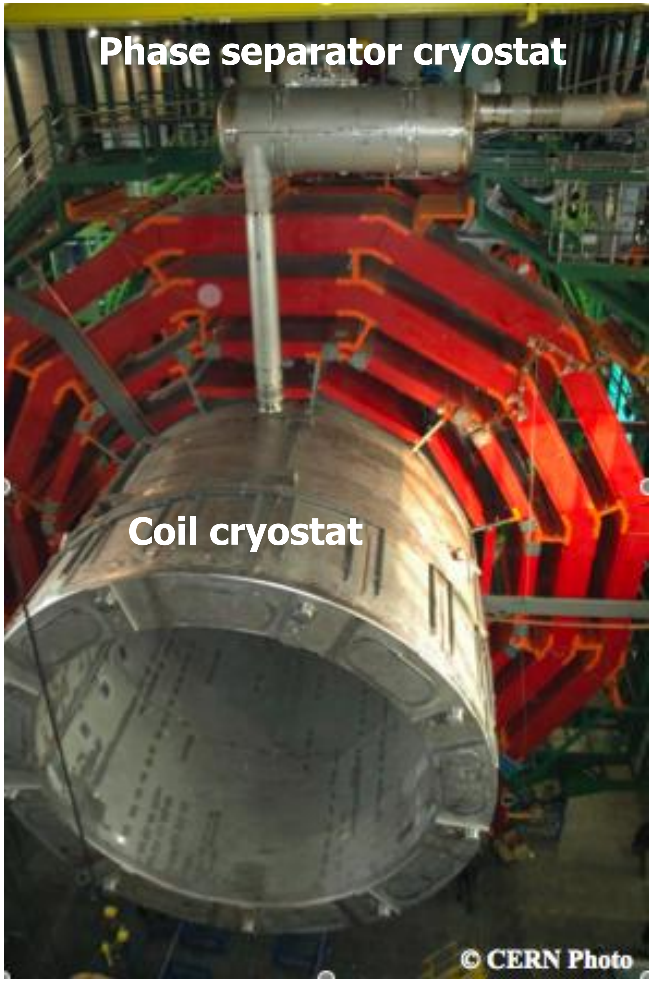
□ Comparison with experimental results

Cooling large superconducting magnet

- Compact Muon Solenoid magnet
  - 7 m diameter and 12.5 m long
  - 4 T at the center
  - Liquid helium temperature cooling (4.2 K)
- Unique magnet of large scale
  - Reduction of the quantity of cryogen
    - Lower the cost of operation
  - Protection in case of quench
    - Lv $\approx 2\ 10^4$ J/Kg
    - Phase change $\rho_l/\rho_v \approx 7$
- External cooling
- Two-phase thermosiphon cooling method

Thermosiphon open loops (1/2)

- Open reservoir/phase separator
  - No re-cooling of the warm liquid or re-condensation of the vapor



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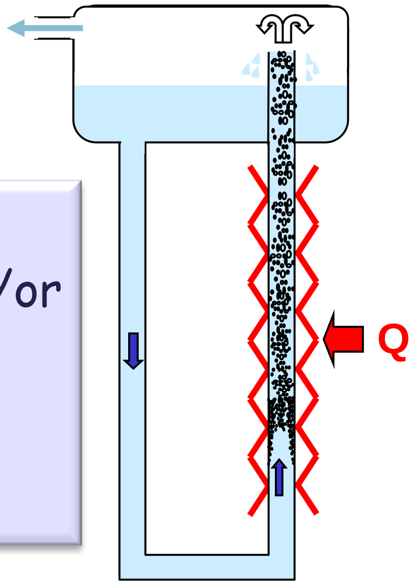
- Power to be extracted
- Decrease in liquid density and/or vaporization
- Branch weight unbalance
- Flow induced



- Suppression of any pressurization system

- Liquid level needs to be controlled to avoid dryout
- Minimum heat flux to start the flow
- Flow oscillations at low heat flux

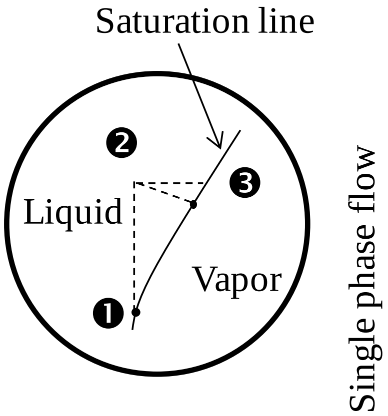
Thermosiphon open loops (2/2)

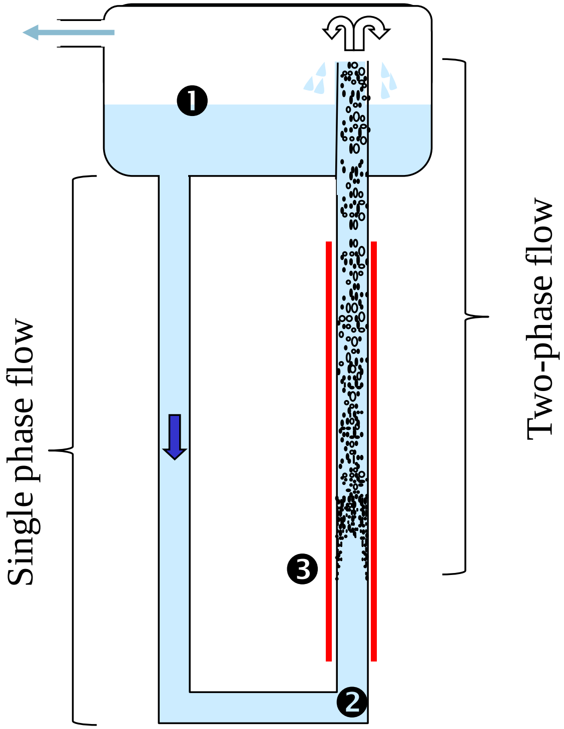
- In the downward branch, the flow is single phase
    - Adiabatic branch and the liquid is sub-cooled
    - Pressure and the temperature increase from ❶ to ❷

- The upward branch is heated partially and above it is adiabatic (the riser)
    - Flow is first in single phase from ❷ to ❸
    - Fluid reaches the saturation temperature at point ❸
    - Fluid temperature also increases up to the saturation line

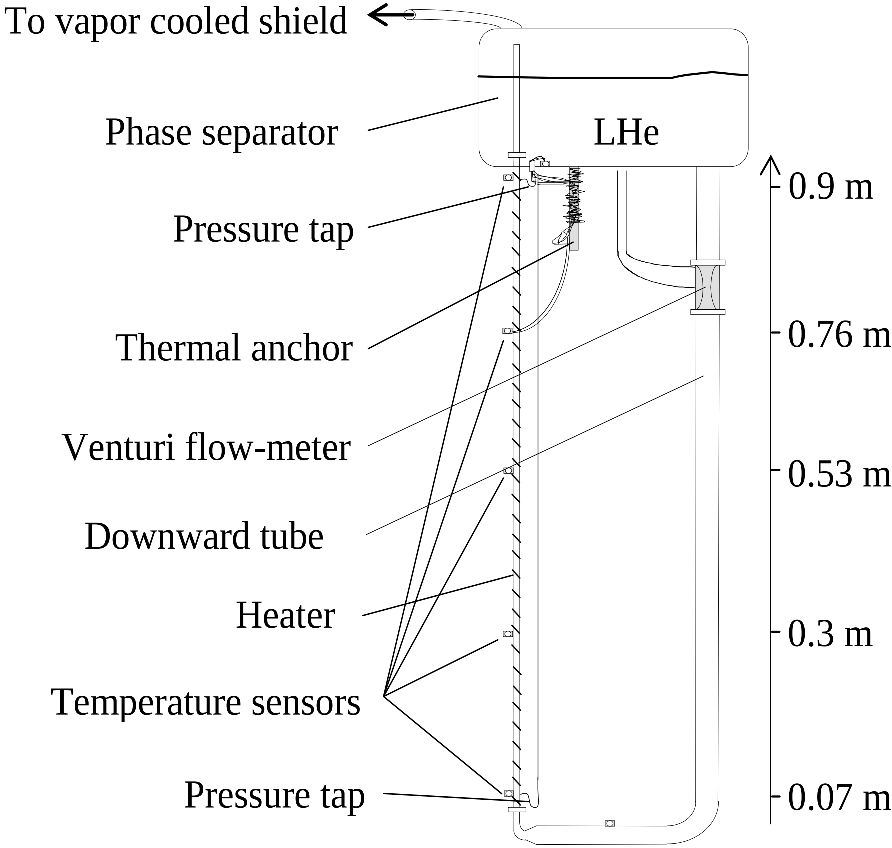
- Point ❸ is the onset of nucleate boiling
    - Then the flow above ❸ is two-phase
    - Fluid temperature decreases following the saturation line

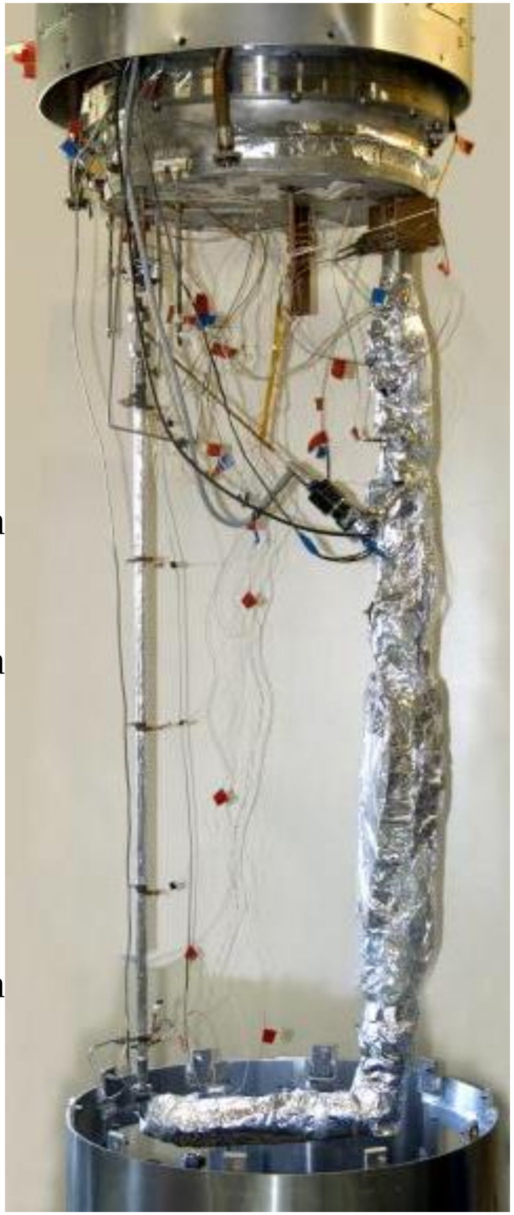
Saturation line
❷
❸
Liquid
Vapor
❶





Experimental facility and ranges





- ☐ Test section
  - ○ 10 mm inner diameter
  - ○ ~1 m heated length
  - ○ Tsensor ± 2 mK
- ☐ Ranges
  - ○ P: 1.004 ± 0.006 10^5 Pa
  - ○ q: 0-25 kW/m^2
  - ○ m: 0-12 g/s
  - ○ x: 0 – 25%

COMSOL Multiphysics Modeling (1/2)

- Homogeneous model implemented in Comsol Multiphysics

  - Mass $$\frac{d}{dz}\left(\rho_i \cdot \frac{du}{dz}\right)=0 \qquad \text{with } \rho_i=\rho_l \text{ or } \rho_i=\rho_m \text{ with } \frac{1}{\rho_m}=\frac{x}{\rho_v}+\frac{1-x}{\rho_l}$$

  - Momentum $$-\frac{dp}{dz}-\rho_i u\frac{du}{dz}+\rho_i g\cos\theta-\left(\frac{dp}{dz}\right)_{f,j}=0$$

$$\left(\frac{dp}{dz}\right)_{f,d}=\left(\frac{f}{D_d}+\frac{\zeta_d}{l_d}\right)\rho_l\frac{u^2}{2} \qquad \left(\frac{dp}{dz}\right)_{f,u}=\left(\frac{f}{D_u}+\frac{\zeta_u}{l_u}\right)\phi_{lo}\rho_m\frac{u^2}{2}$$

$$f=\frac{0.079}{Re_j^{\,0.25}} \qquad \phi_{lo}=\left[1+x\left(\frac{\rho_l}{\rho_v}-1\right)\right]\left[1+x\left(\frac{\mu_l}{\mu_v}-1\right)\right]^{-1/4}$$

  - Energy $$4\frac{q}{D_j}=\rho_i u\frac{d}{dz}\left(h_i+\frac{u^2}{2}+gz\cos\theta\right) \qquad \text{with } h=C_pT \text{ or } h=C_pT+L_v$$

COMSOL Multiphysics Modeling (2/2)

- 1 D model with downward, horizontal and upward branches

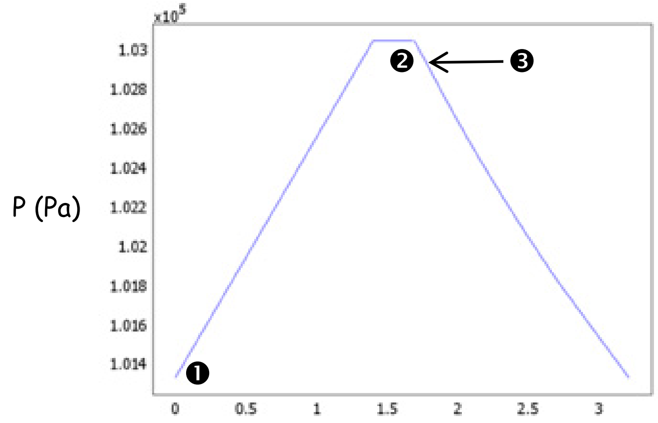
- PDE general form module was used

- Segregated mode with three groups
  - First group : conservation of mass and momentum with u and p as variables
    - Pressure fixed at the loop entrance and Neumann condition for other boundaries
    - For velocity, only Neumann conditions are used

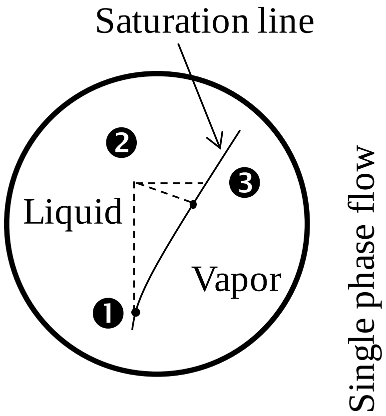
  - Second group : Energy conservation equation and consider only one variable, T
    - Temperature fixed at the loop entrance and Neumann conditions for other boundaries

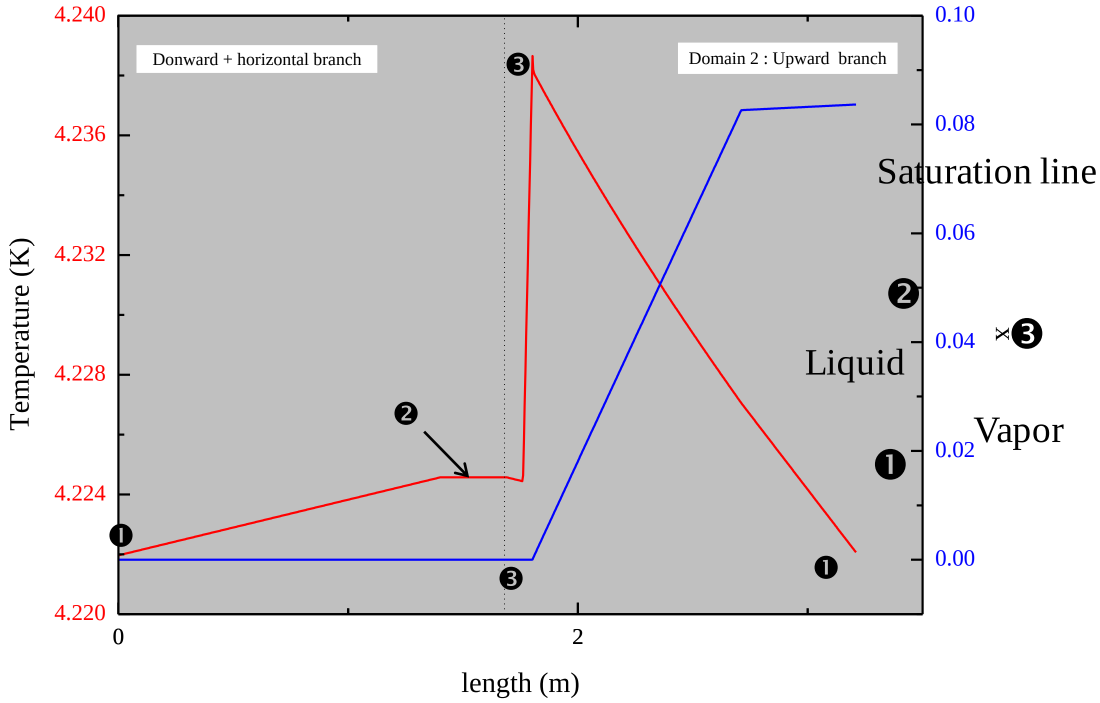
  - Third group : Energy conservation equation for the vapor quality, x
    - Quality is set to zero until the saturation temperature is reached

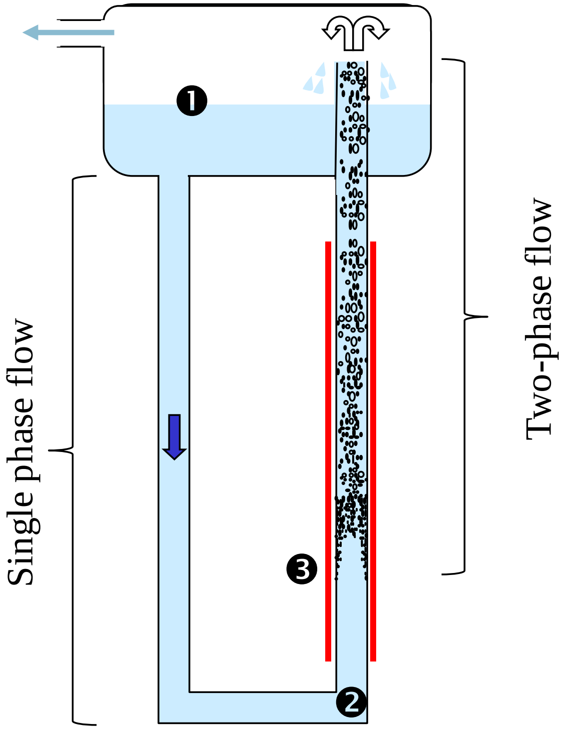
Results with COMSOL Multiphysics



- ☐ Case for 600 W/m²
- ☐ p=101325 Pa
- ☐ Convergence 10^{-7}
- ☐ 960 elements

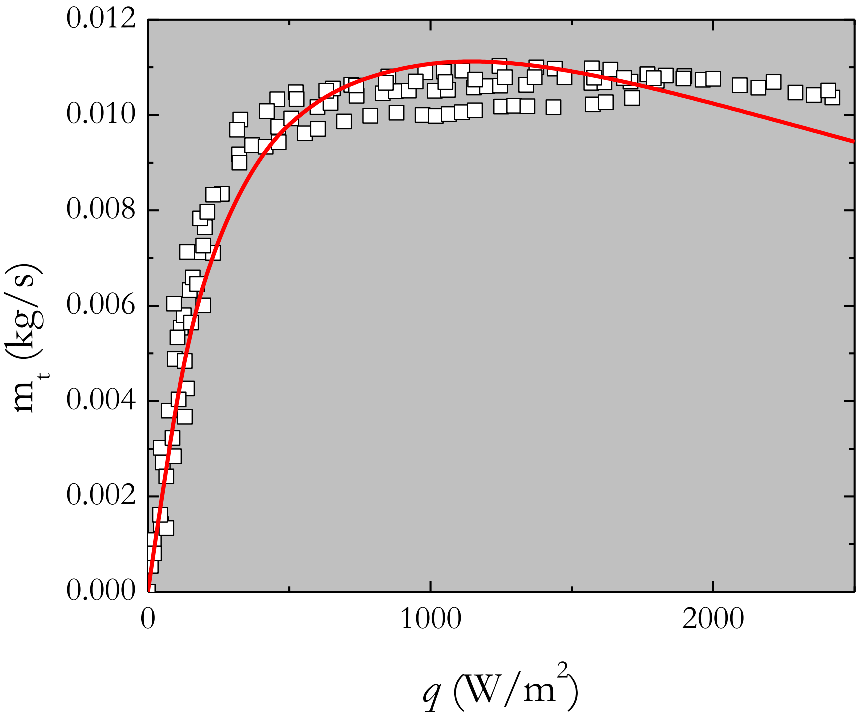






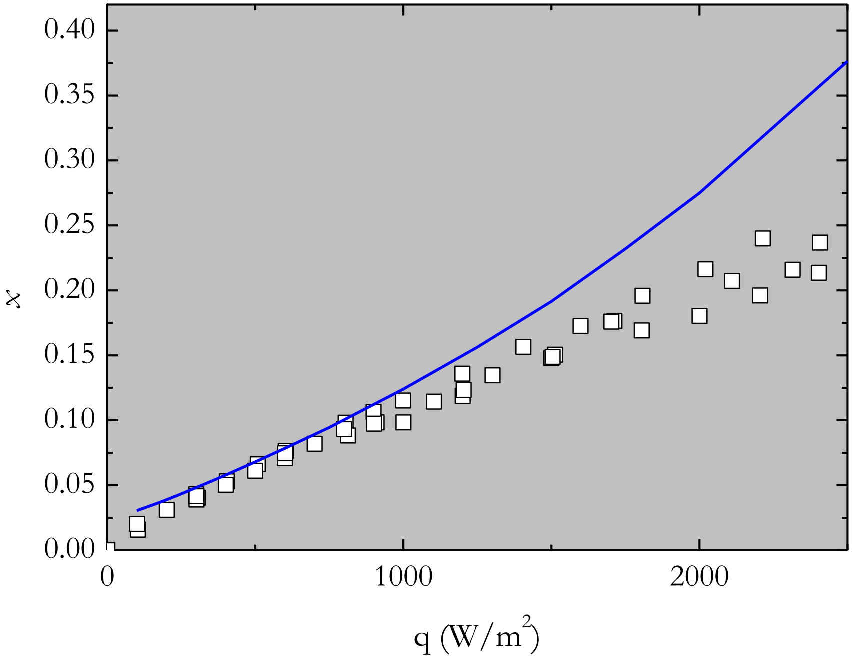
Comparison with experimental results

- ☐ At low heat flux, the flow is dominated by the gravity term
- ☐ At higher heat flux the friction term increases causing the slight decrease of the total mass flow rate



Comparison with experimental results

- ☐ Vapor quality reproduced with good accuracy up to 1500 W/m^2
  - ○ At 1500 W/m^2 —> film boiling appears
  - ○ No thermodynamic equilibrium between the two phases
  - ○ Homogeneous model no longer holds



- ☐ Model sufficiently accurate to be used for designing cooling system

Conclusions

- COMSOL Model sufficiently accurate to be used for designing cooling system with a thermosiphon loop in two-phase helium

- COMSOL easy to handle for non expert
  - Easy implementation and modification of physics models

- Next is transient
  - Pressure rise due to vaporization in liquid helium
    - Mechanical constraints on the magnet structure
    - Fluid management
  - Adding multi-physics
    - Interaction with the stability of superconductors
    - Magnetic field interaction