Lecture 18
Helium II

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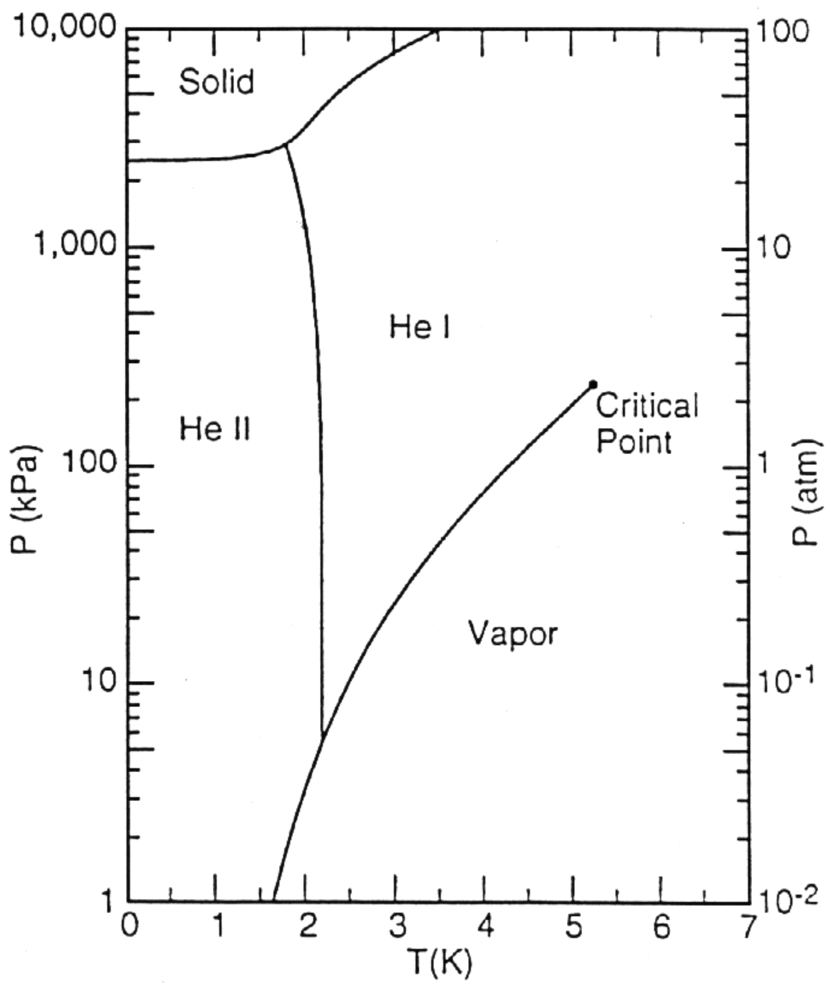
Goals

- Describe the properties of He II including:
  - Nature of He II
  - Two fluid model
  - Quantized vortices
  - Heat transfer
    - » Internal convection
    - » Mutual friction
    - » Heat Transfer limits
    - » Kapitza conductance
  - Fluid mechanics
  - Fountain Pumps and porous plugs
  - He II refrigerators
  - He II Heat Exchangers

He II
Superfluid Helium

- 2nd liquid phase of helium (hence He II)
- Phase transition is 2nd order (no latent heat) but there is a discontinuity in the specific heat (λ transition)
- $T_{\lambda max}$ = 2.2 K
- Has unique thermal and fluid properties
  - High effective thermal conductivity
  - Zero viscosity under certain conditions

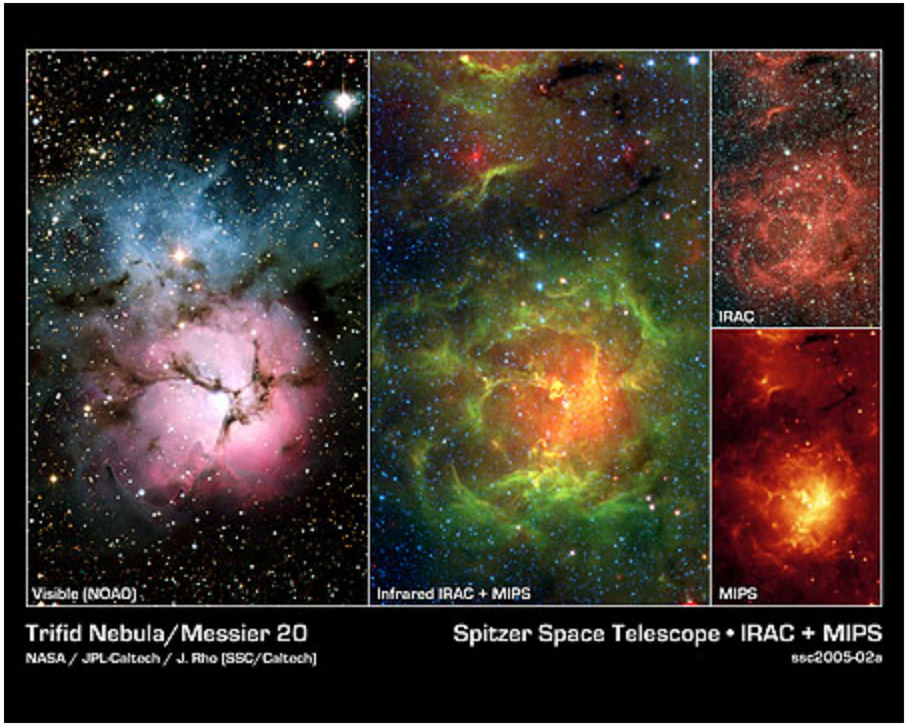
Recall the Helium Phase Diagram



Applications of He II

- Lower temperature results in:
  - Higher field s/c magnets (Tore Supra, LHC, high field labs in USA, Japan and Europe)
  - Lower BCS losses in SCRF (CEBAF, SNS, ILC, FRIB)
  - Lower background temperatures for IR astronomy (COBE, IRAS, Spitzer)
- Fundamental studies of turbulence
- Superfluid "wind tunnels" (very large Re#)

Applications of He II

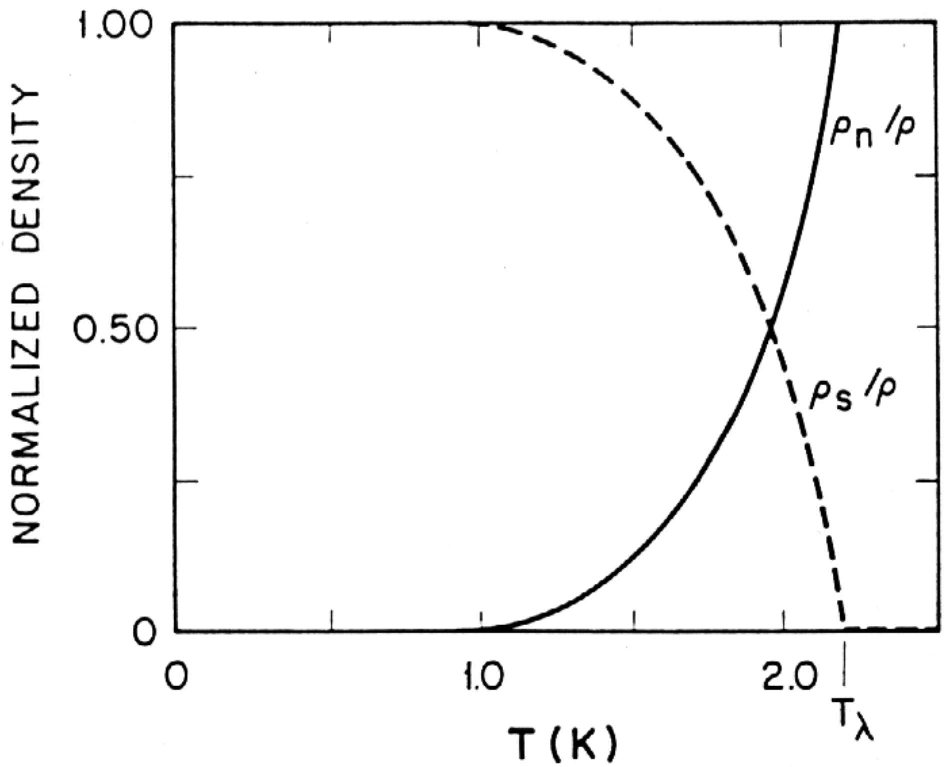


What is He II ?

- A Bose – Einstein Condensate
  - A fraction of atoms in He II have condensed to the quantum ground state
  - He II was the first BE condensate discovered
  - The only one that has significant industrial applications
- The properties of He II can be understood via the two fluid model

Two Fluid Model

- He II can be thought of a fluid with two interpenetrating components:
  - Normal fluid component
    - » Finite viscosity
    - » Finite entropy
  - Superfluid component
    - » Zero viscosity
    - » Zero entropy
- The interaction of these components can explain He II behavior



Relative Densities of Superfluid and Normal fluid components
(From Helium Cryogenics – Van Sciver)

Quantized Vortices (or does He II at 1 K rotate in a bucket)

- At 1 K He II is almost entirely the superfluid component and thus has almost 0 viscosity. This would imply that He at 1 K in a spinning bucket wouldn't rotate but it does. What's the answer?
  - The vortices are quantized:

$$C = \int V_s \cdot dl = n\frac{h}{m}$$

- Solves rotating bucket problem
  - In the body of the fluid: $\nabla^2 V_s = 0$
  - At the wall: $\nabla^2 V_s \neq 0$
- This has been experimentally observed
- The quantized vortices in the superfluid component are an important part of heat transfer mechanism in He II

Direct Observation of Quantized Vortices via Electron Trapping

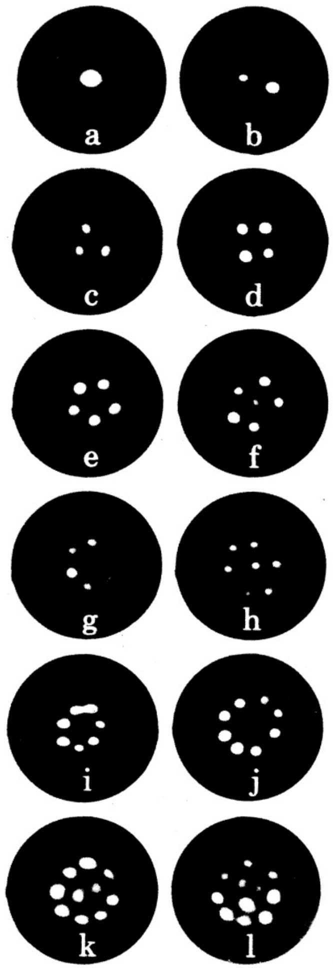
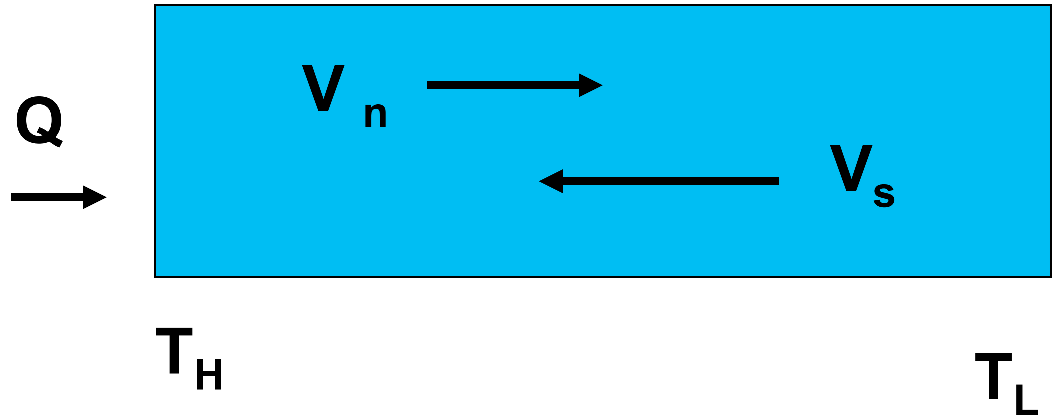


Fig. 4.26. Photographic reproduction of vortex line array in rotating He II (from Yarmchuk and Packard[12]): (a) through (l) indicate increasing angular frequency.

Heat Transfer in He II

- The basic mechanism is internal convection:



- No net mass flow
- Note that this is not conduction or classical convection but an entirely different heat transfer mechanism
- This can be extremely efficient (more than 1000x better than conduction through copper)

Heat Transfer in He II

- There are 2 heat transfer regimes:
  - $V_s < V_{sc}$

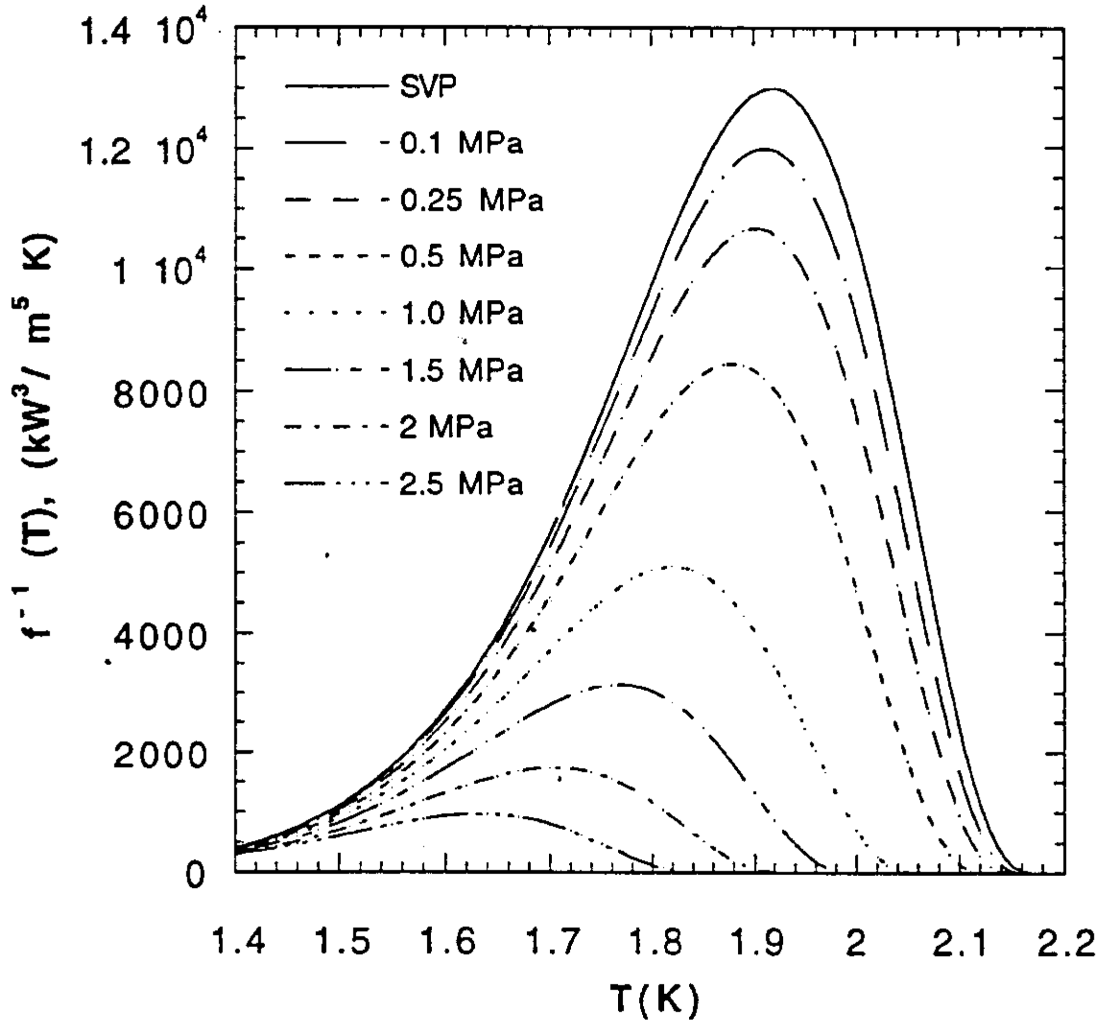
$$q = \frac{(\rho s d^2)T}{\beta \eta_n}\frac{dT}{dx}$$

  - $V_s > V_{sc}$
    - » Mutual Friction Regime (quantized vortices interact with the viscosity of the normal component

$$q = \left[f^{-1}(P,T)\frac{dT}{dx} \right]^{1/3}$$

- As $V_{sc} \sim d^{1/4}$ (cgs units) the mutual friction regime is most applicable in engineering applications of He II

Heat Conductivity Function



He II Heat Transfer Limits

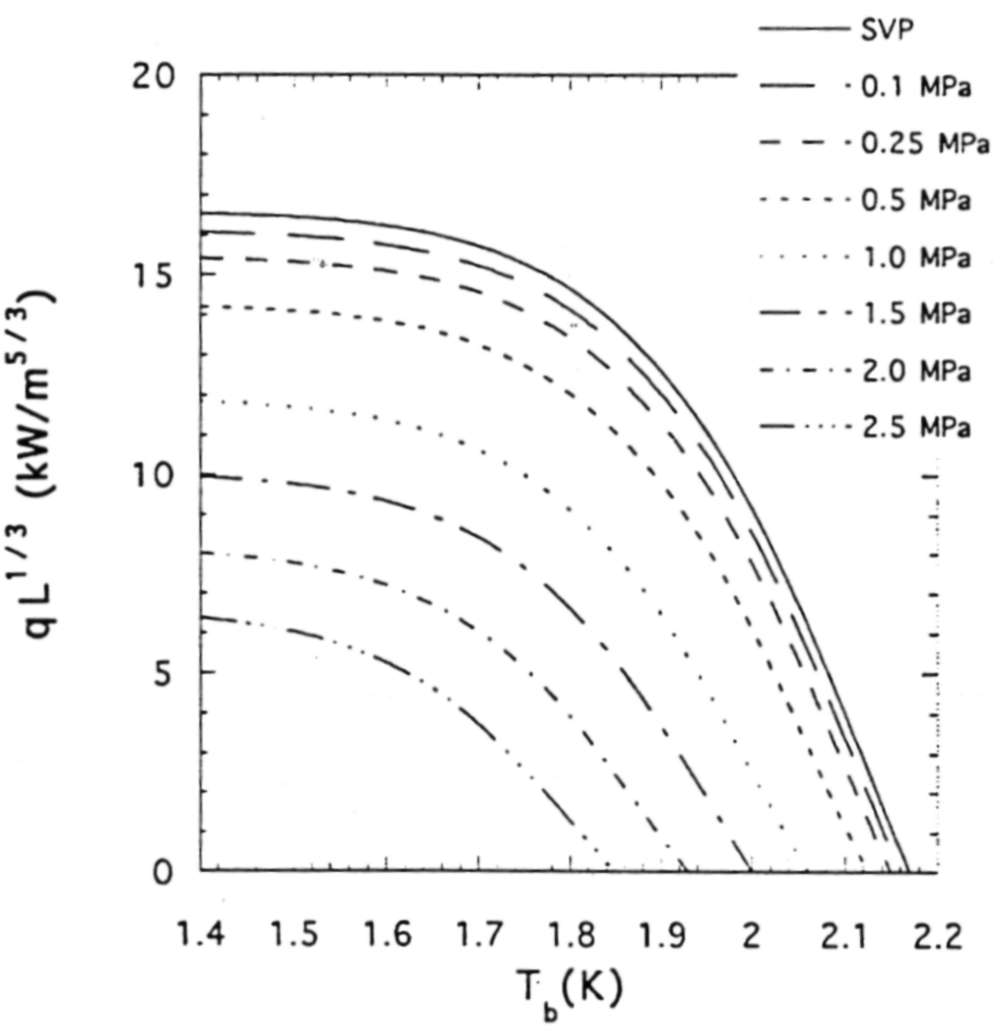
- In pressurized He II: T_h must be less than T_λ
- Thus the peak heat flux q* is:

$$q^* L^{1/3} = \left(\int_{T_b}^{T_\lambda} f^{-1}(T)\, dt \right)^{1/3}$$

- At 1.9 K and 1 bar :

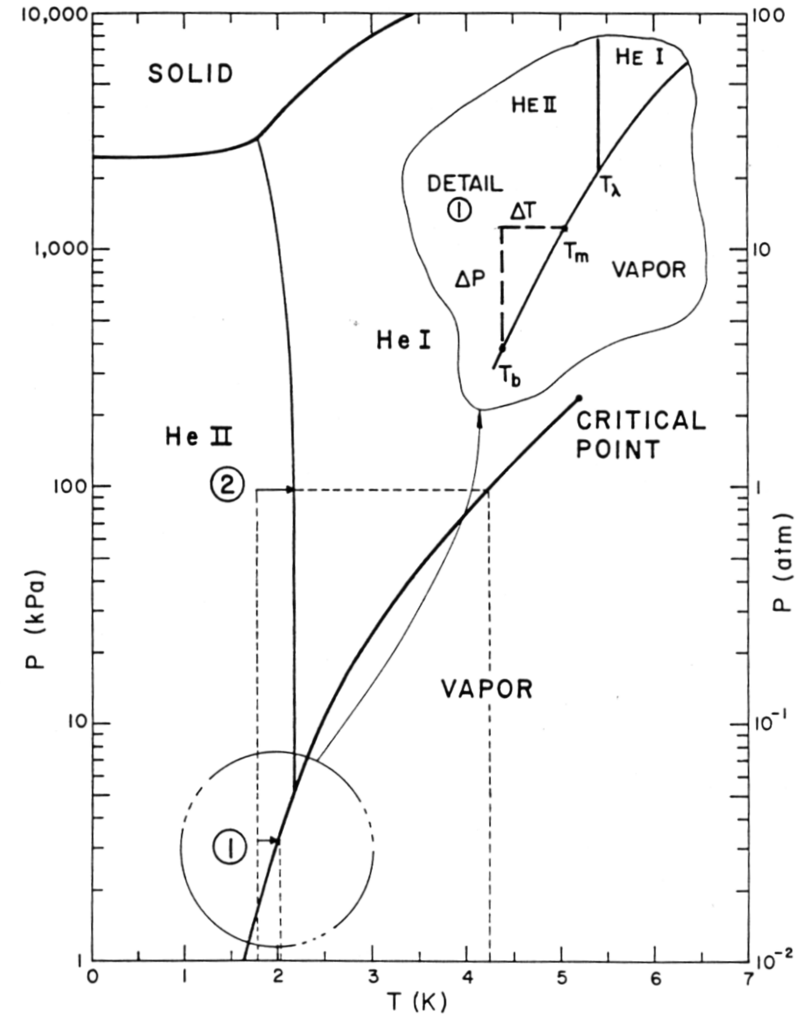
$q^* L^{1/3} \sim 15\ \mathrm{kW/m^{5/3}}$

Peak Heat Flux (q*) in Pressurized He II



Limits on He II Heat Transfer

- In saturated He II, the limit is given by the local saturation temperature & the degree of local subcooling
- In the ILC cavity He vessel this works out to about 1 W/cm^2 or ~ 30 W total through the connection tube
  - More heat than that would require a redesign
- Exceeding the heat transfer limits in either the saturated or pressurized case results in conversion to He I and boiling at the heated surface

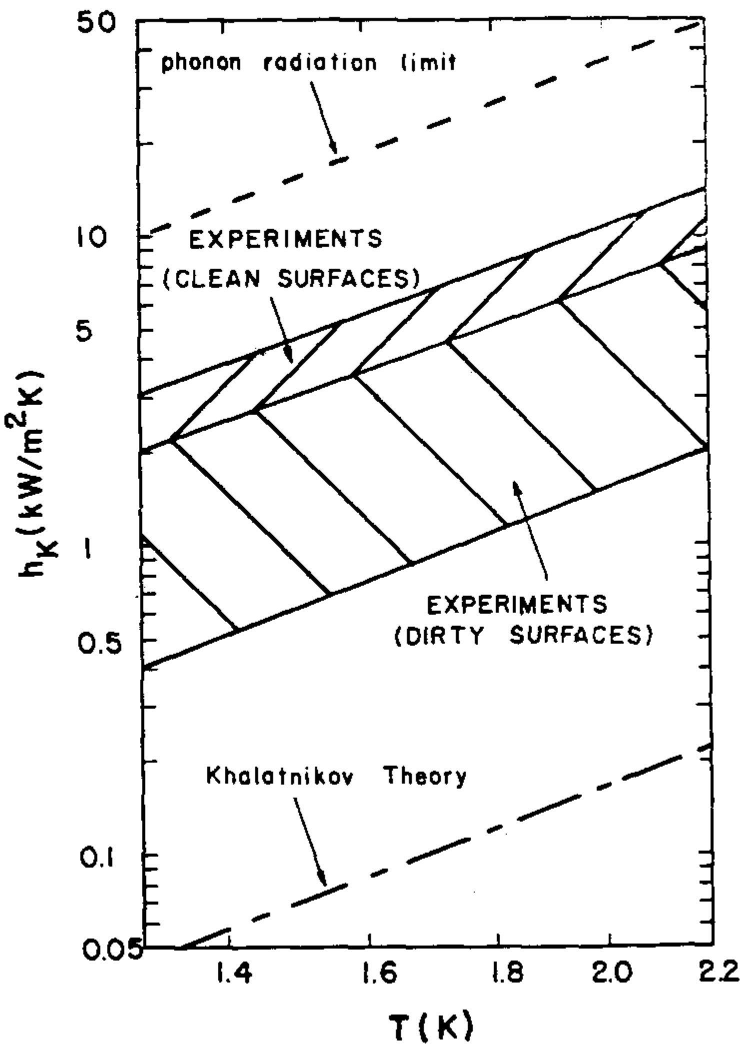


Surface Heat Transfer

- Heat transfer from a surface into He II is completely dominated by a fundamental inefficiency in moving energy from the surface to the fluid
- This effect exists but is not important in standard convection problems
  - Normally we assume $T_w = T_{fw}$ but this is not true in the case of He II
- This surface heat transfer effect is described by Kapitza Conductance
  - For q < 1 kW/m^2 $$q = h_K \Delta T_S$$
  - For q > 1 kW/m^2 $$q = a(T_s^m - T_b^m)$$
- $h_{k,}$ a and m are empirical and dependent on material, temperature and surface condition

Surface Heat Transfer

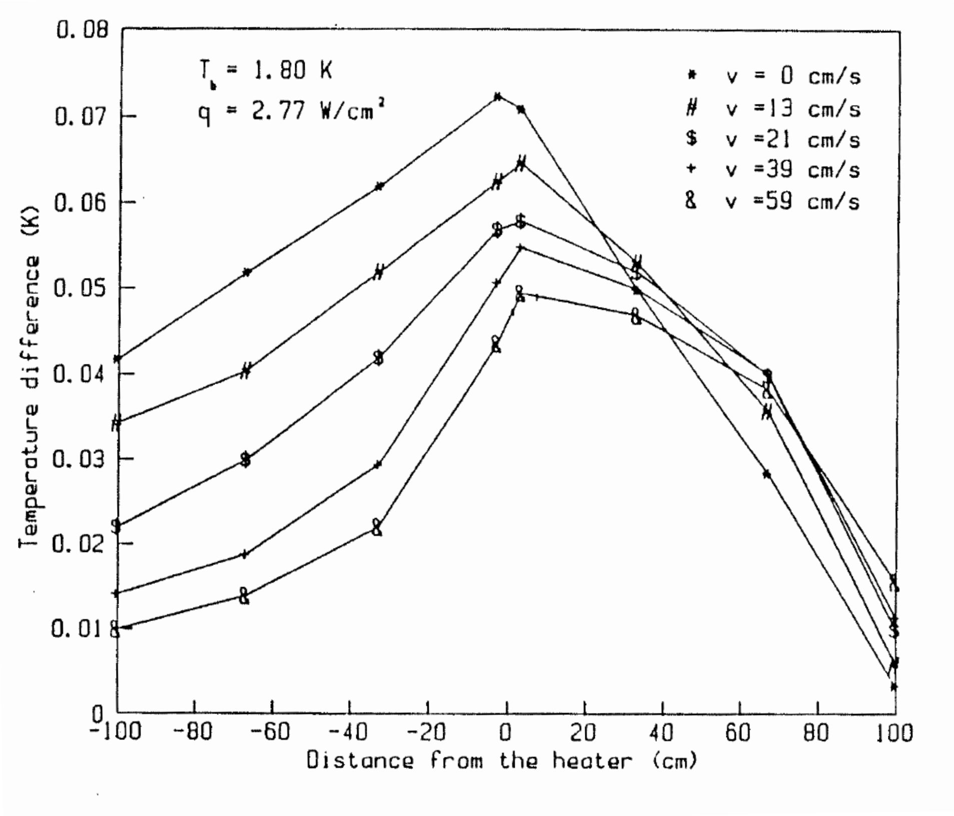
- m ~ 3
- Kapitza conductance is not dependent on helium flow rate



Kapitza Conductance for Copper
(Helium Cryogenics,Van Sciver)

Forced Convection and He II

- If Kapitza Conductance is independent of flow rate does forced convection in He II make any sense?
  - Yes! Forced convection has the effect of reducing the maximum temperature in the He II and thus allowing more heat to be transferred before reaching the peak heat flux



He II Fluid Dynamics

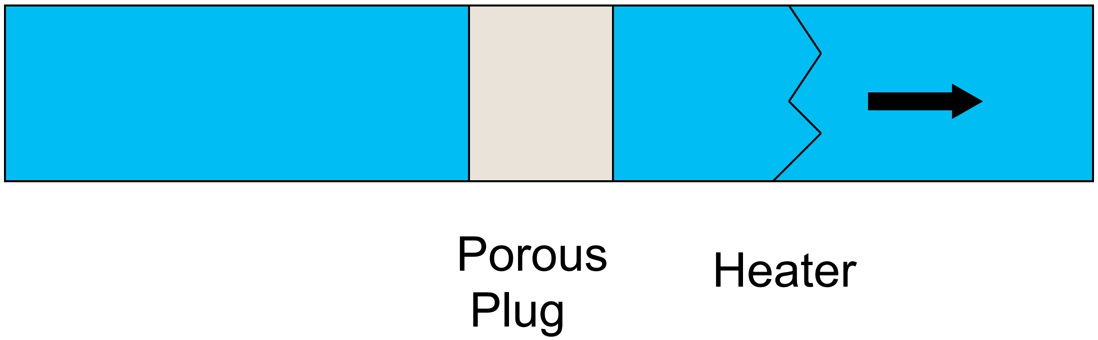
- Despite the presence of the superfluid component, in almost all engineering applications He II behaves as a classical fluid. This includes :
  - Pump performance
    - » Except cavitation in saturated He II
  - Pressure drop in tubes, valves, bellows and fittings
  - Flow metering techniques
- This is likely a result of the quantized vortices in the superfluid component being coupled via mutual friction to the normal fluid viscosity
- However, keep in mind that the unique heat transfer properties still exist as described.

He II Fluid Dynamics

- He II does behave differently in cases of:
  - Film flow
  - Porous plugs
  - Hot wire anemometers
    - » Since Kapitza conductance is independent of mass flow rate, HWA will not work in He II
  - Two – phase flow (liquid/vapor) due to the large density difference between liquid and vapor in the case of He II

Fountain Pumps

- Unique to He II
- Allows pumping with no moving parts
- Superfluid component can pass through the porous plug while normal fluid component can't
- $\Delta P = \rho S \Delta T$



Fountain Pumps

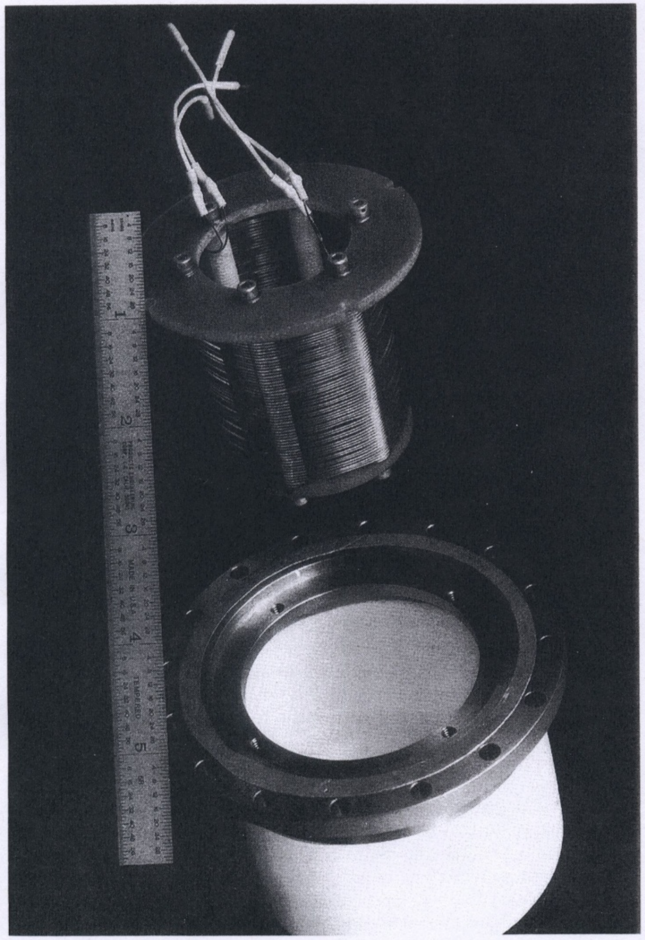


Figure 10-21 The fountain effect pump developed for the SHOOT flight demonstration. It is an alumina–silica composite ceramic with a 0.4-μm effective pore size. This pump demonstrated a flow rate of 30 g/s in flight (from Ref. [43]).

Porous Plugs for Phase Separation

- How do we vent He at zero g?
  - There is no gravity driven stratification – how do we separate vapor from liquid?
- The use of He II with porous plugs provides a solution
- Build the plug with pores large enough to admit both the normal fluid and superfluid components
- Evaporation at the vent end causes cooling. The superfluid component is driven back to the dewar and only vapor escapes
- If the plugs are properly sized the helium in the dewar will stay at the correct temperature

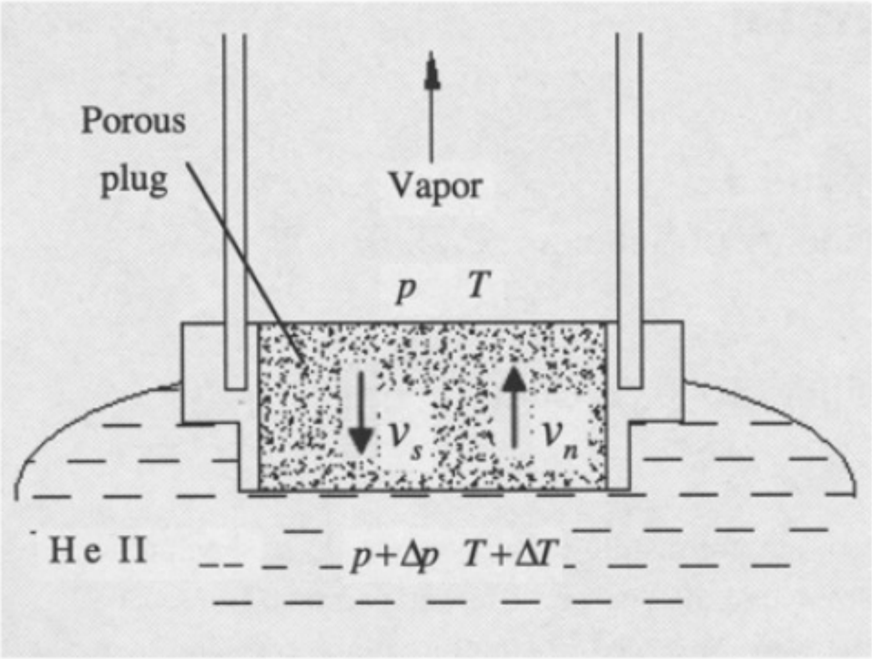
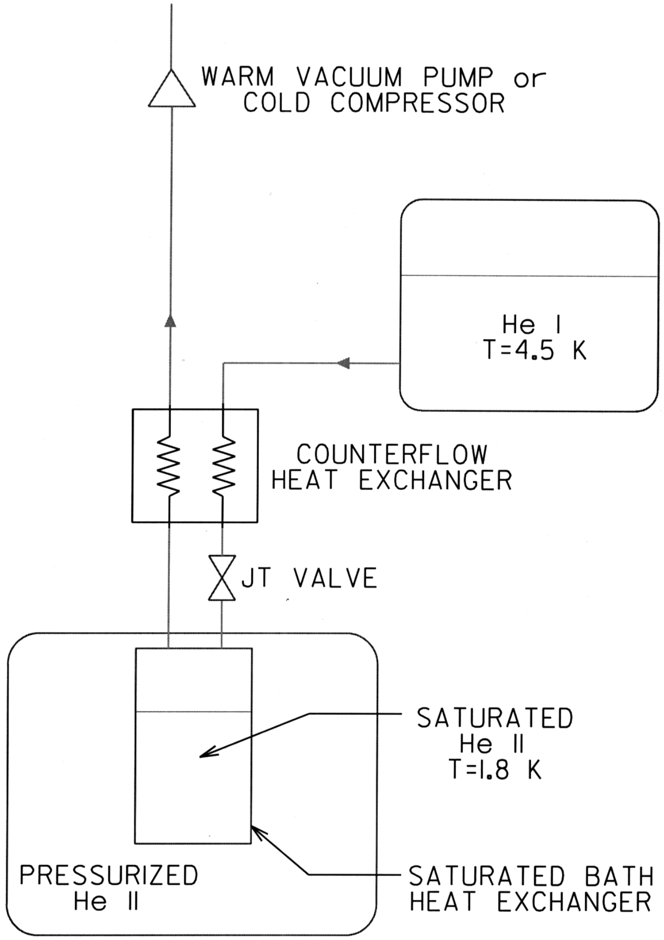


Fig.1 Schematic diagram of a He II vapor-liquid phase separator

Yu et al. J. Thermal Science Vol. 14, No. 1 (2005)

Typical He II Refrigeration System



He II (Superfluid Helium) S. W. Van Sciver, in Handbook of Cryogenic Engineering,

He II
Heat Exchangers

- Must take into account the unique He II heat transfer properties
- Must allow for rapidly changing specific heat with temperature
- Handbook methods e.g. ε - NTU are not suitable

Summary

- He II is a unique fluid that displays quantum behavior on a macroscopic scale
- He II has significant applications in large scale cryogenics for scientific research
- Despite its unique properties, the use of He II in industrial scale engineering applications is well understood and significant experience exists: Tore Supra, LHC, Jlab, NASA
- This lecture just hit the high points and many other He II topics remain including :
  - Film flow
  - Second sound
  - Detailed investigations of heat and mass transfer
- There is a large amount of information in the literature