Cryogenic fluid behavior (with emphasis on normal helium)

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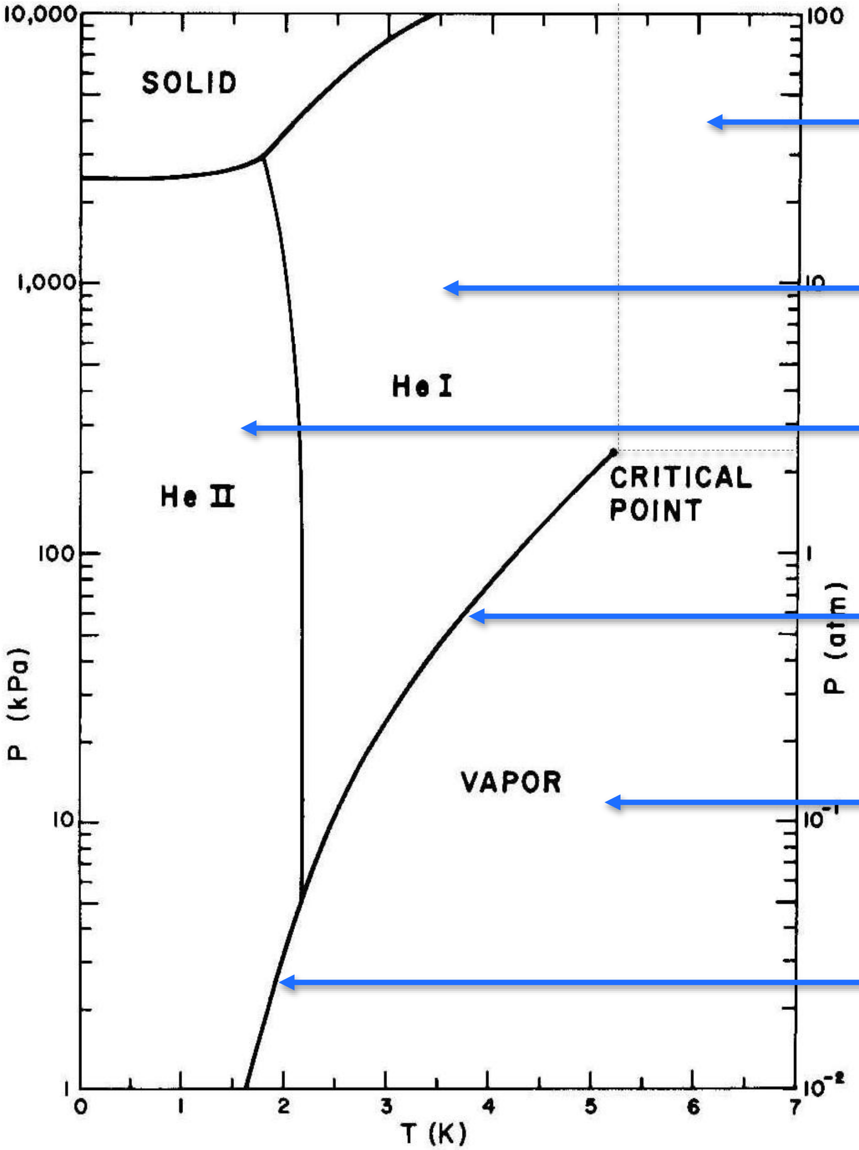
Goals of this lecture

- Familiarize with different types of flow and heat transfer systems in large scale helium cryogenics
- Learn engineering design parameters of cryogenic helium systems
  - Here we will focus only on normal helium
  - Superfluid helium and its properties will be covered in another lecture.
- Briefly look at other common cryogens – nitrogen, argon

Phase diagram of helium



Supercritical He

Pressurized He I (liquid)

Pressurized He II (liquid)

Saturated He I

He vapor

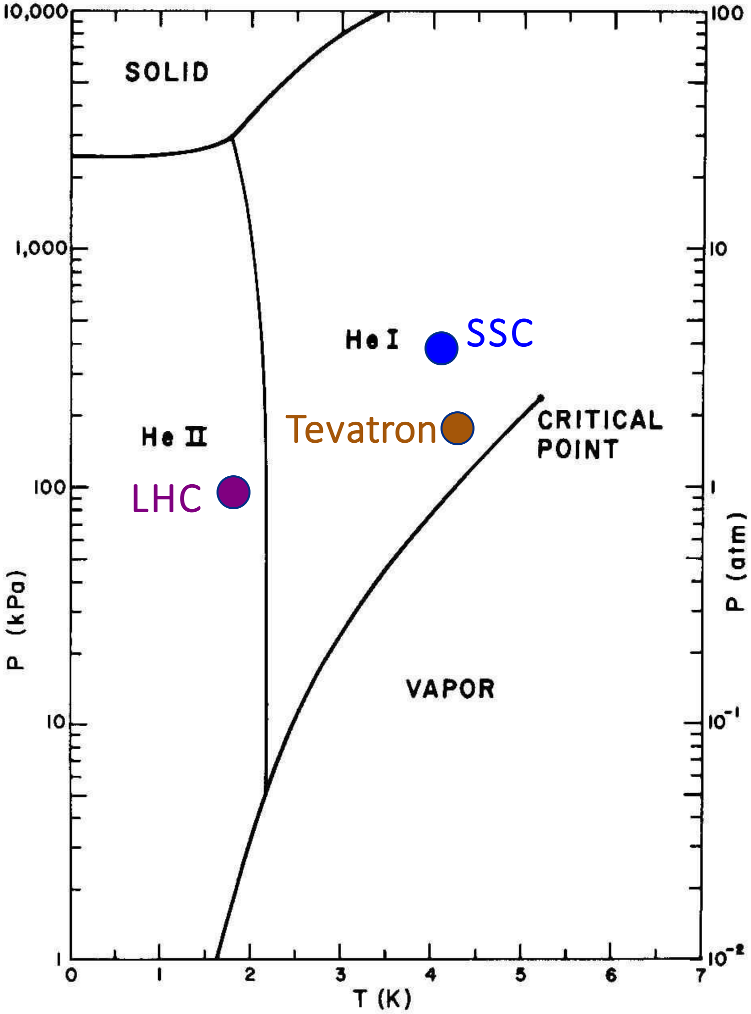
Saturated He II

S. W. Van Sciver, Helium Cryogenics (2012), pg. 60

Cooling modes in large helium cryogenic systems

Accelerator magnets are often cooled with pressurized liquid or forced flow of supercritical helium

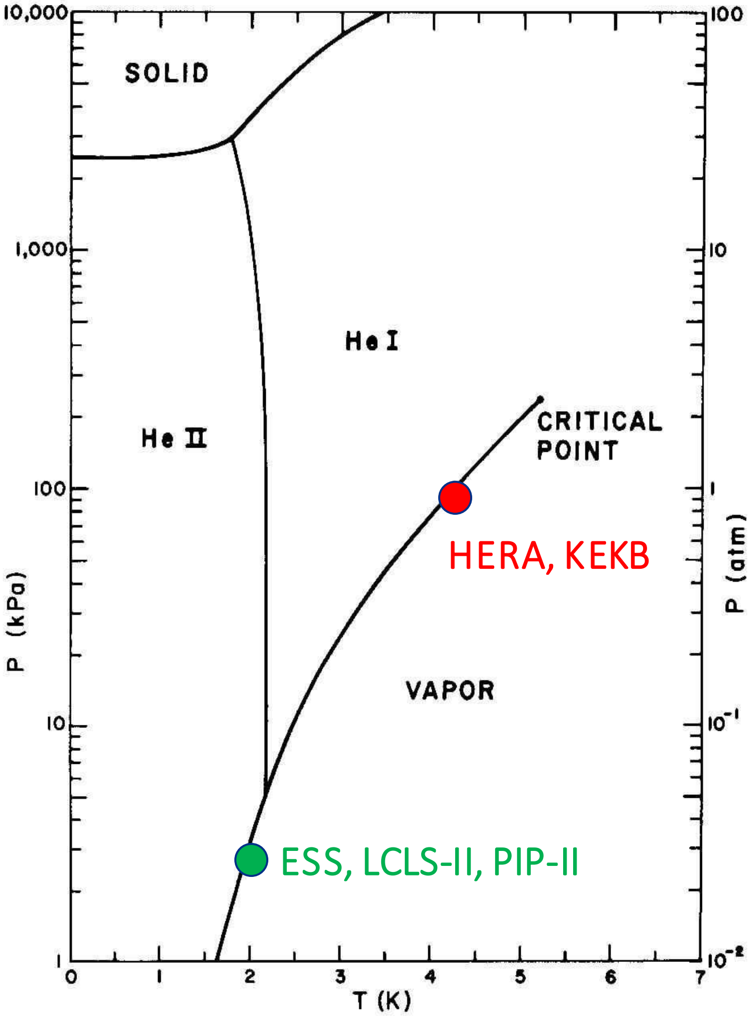
- gives maximum penetration of helium mass in magnet coils
- crucial for thermal stability since the coils operate near the superconductivity limit



Cooling modes in large helium cryogenic systems

Superconducting RF cavities are generally cooled with a saturated helium bath (normal or superfluid)

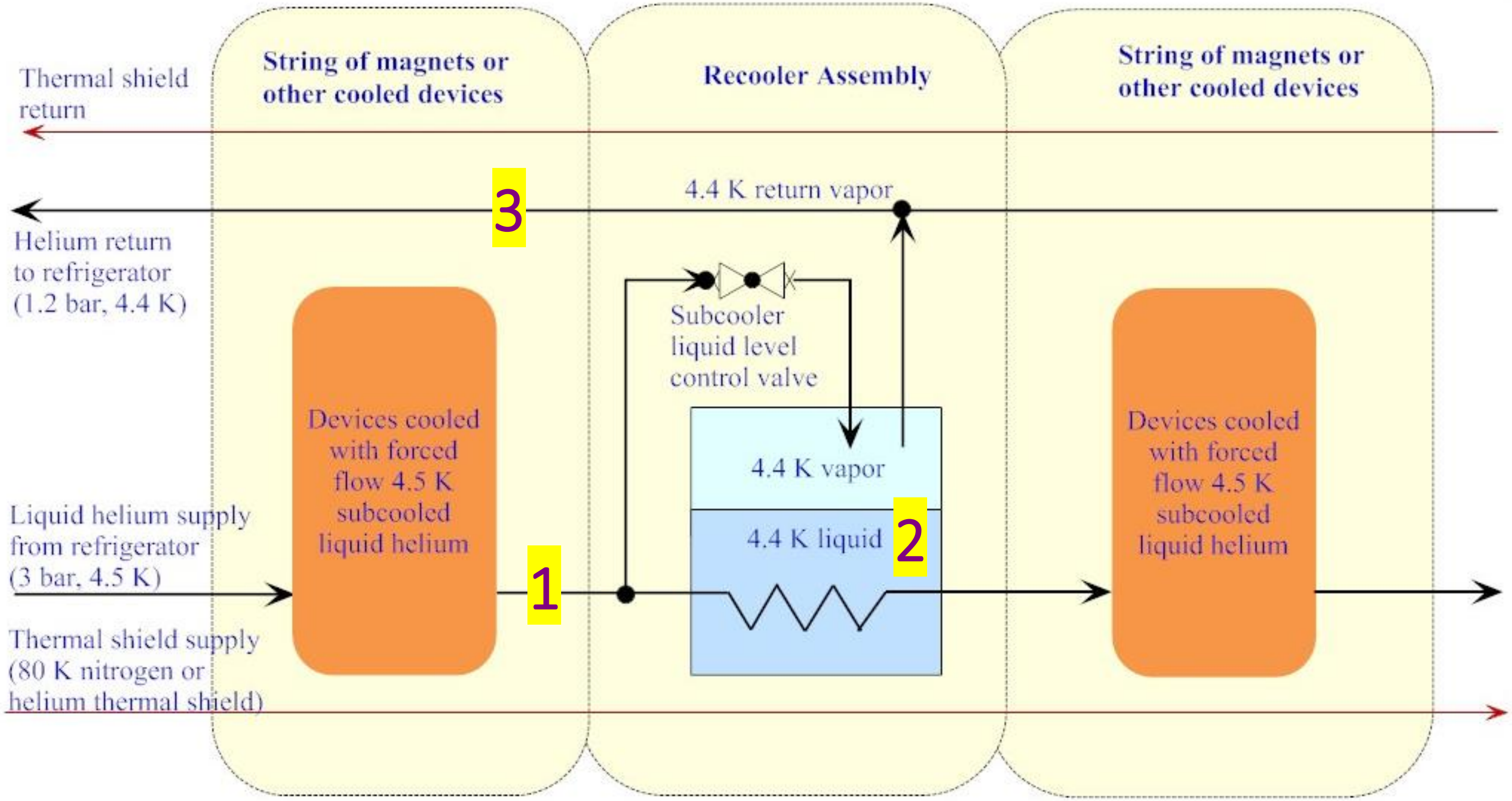
- gives pressure stability needed to minimize cavity de-tune
- offers large surface heat transfer for local hot spots
- provides nearly isothermal cooling



Helium cooling modes - examples

Re-cooler scheme for accelerator SC magnets. Modes present:

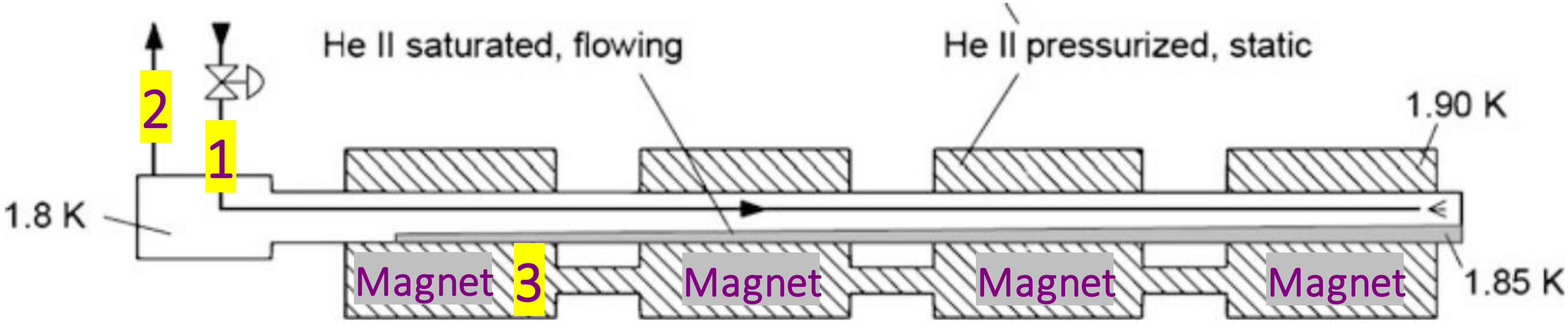
1. Subcooled liquid helium flow
2. Convection/nucleate boiling heat transfer
3. Single phase vapor flow



Helium cooling modes - examples

Bayonet heat exchangers for LHC superconducting magnets. Modes present:

1. Two phase He II flow
2. Single phase vapor flow
3. Surface heat transfer to He II (Kapitza mode)

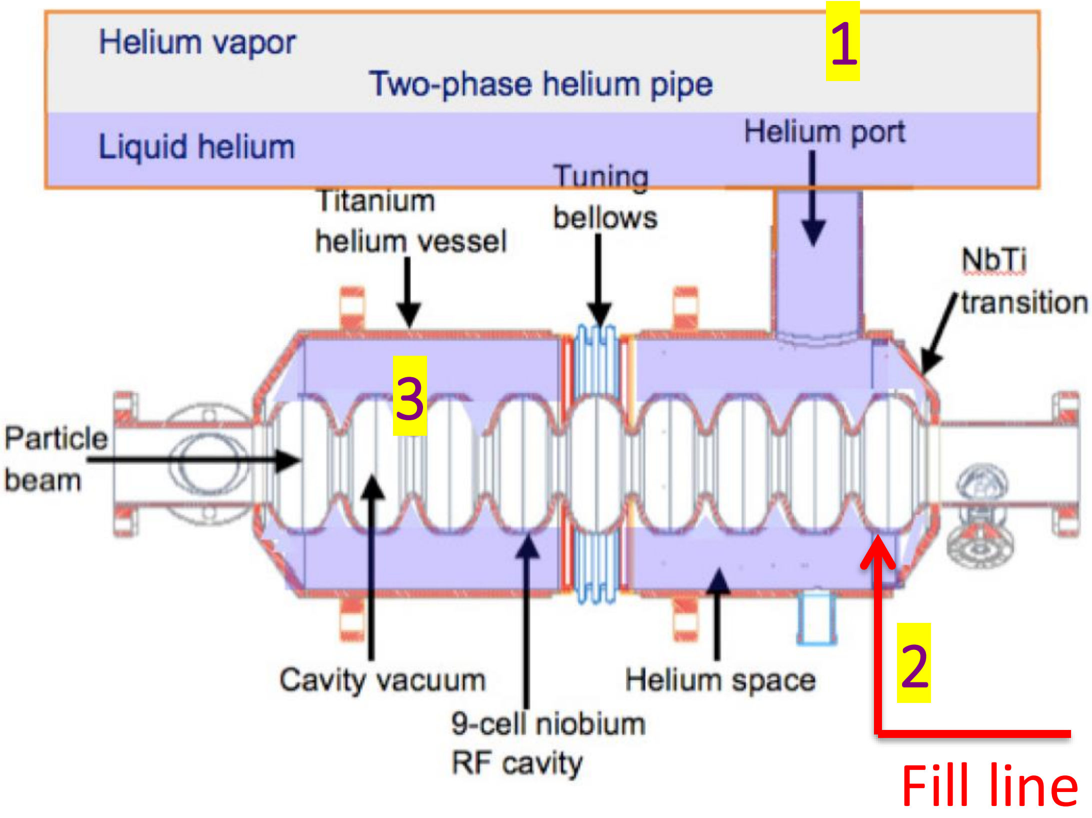


Helium cooling modes - examples

Saturated helium bath cooling of superconducting radiofrequency accelerator cavities

Modes present:

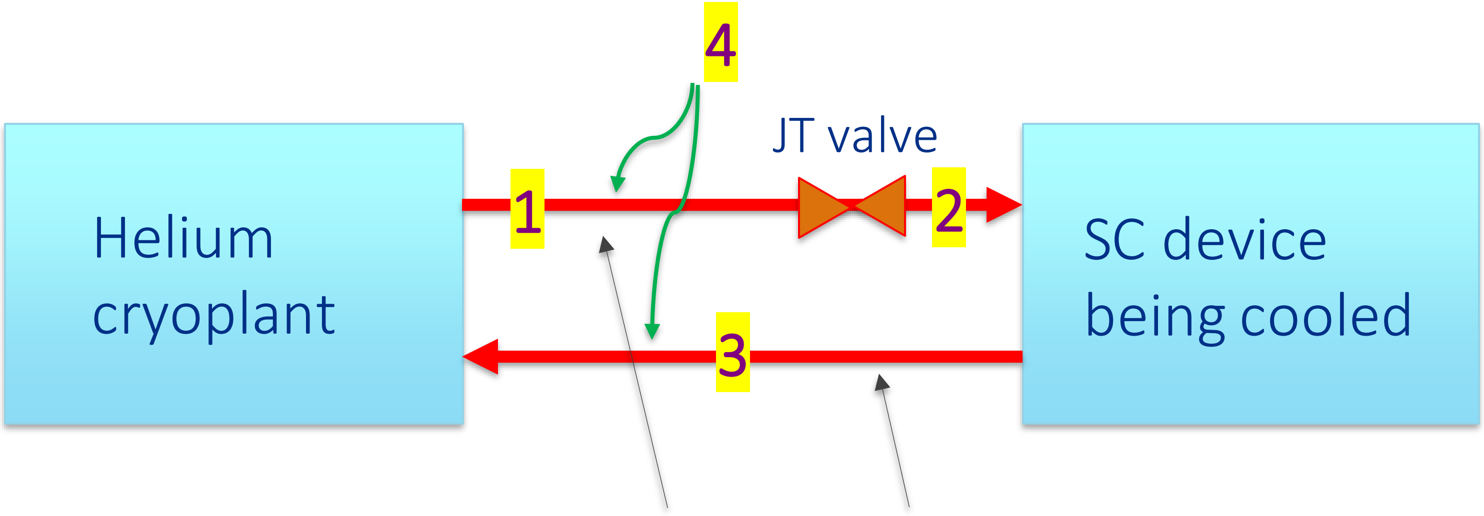
1. Single phase vapor flow
2. Two-phase flow (during bath fill)
3. Surface heat transfer (Kapitza or nucleate boiling)



Helium cooling modes - examples

Distribution of cryogenic helium. Modes present:

1. Supercritical helium flow
2. Two phase flow
3. Single phase vapor flow
4. Heat transfer (heat leak)



Supply and return pipelines
(can be very long, several 100 m)

Helium cooling modes - summary

- As seen in the prior examples, a large-scale helium cryogenic system will typically involve several flow and heat transfer modes operating in parallel
- What are the engineering parameters one should know to be able to design such helium cryosystems?

Engineering design parameters

Compressor/pump power required for circulating helium depends on the pressure drop in the circuit:

$$\frac{dp}{dx} = -\frac{2G^2 f_F}{\rho D} + \frac{4qG\beta}{\rho D C_p}$$

Expression assumes helium behaves as ideal gas and has small flow velocity.
(See Helium Cryogenics chapter 4 for details)

Friction factor, f_F determines the frictional pressure drop:

- Type of flow – single phase, two-phase
- Flow regime – laminar, turbulent, mixed

Heat leak, q determines the acceleration pressure drop:

- Relevant to compressible (gas/supercritical) and two-phase flows

Engineering design parameters

Superconducting device stability/performance depends on the effectiveness of heat transfer to the helium coolant:

$$Q_{load} = h_c A(T_{load} - T_{fluid})$$

Heat transfer coefficient, h_c determines the effectiveness of heat transfer from the load to the fluid

- Mode of heat transfer – forced, natural convection, pool boiling
- Flow regime/type – laminar, turbulent, single/two-phase
- Boiling regime – nucleate, film

Relevant dimensionless parameters

Reynolds number:

- Ratio of inertia to viscosity: $\mathrm{Re}_D = (\rho v D) / \mu$
  where ρ is density, v is velocity, D is a characteristic dimension, and μ is dynamic viscosity

Prandtl number:

- Viscous/thermal diffusion: $\mathrm{Pr} = (\mu c_p) / k_f$
  where k_f and c_p are is fluid thermal conductivity and heat capacity

Grashof number:

- Buoyancy/viscous force: $Gr = g\beta(T_s - T_f)(L^3 / v^2)$
  where β is thermal expansivity, T_s and T_f are surface and fluid temperatures, L is a characteristic dimension, and *v* is kinematic viscosity

Relevant dimensionless parameters

Friction factor: $f_F = func(\mathrm{Re}_D)$

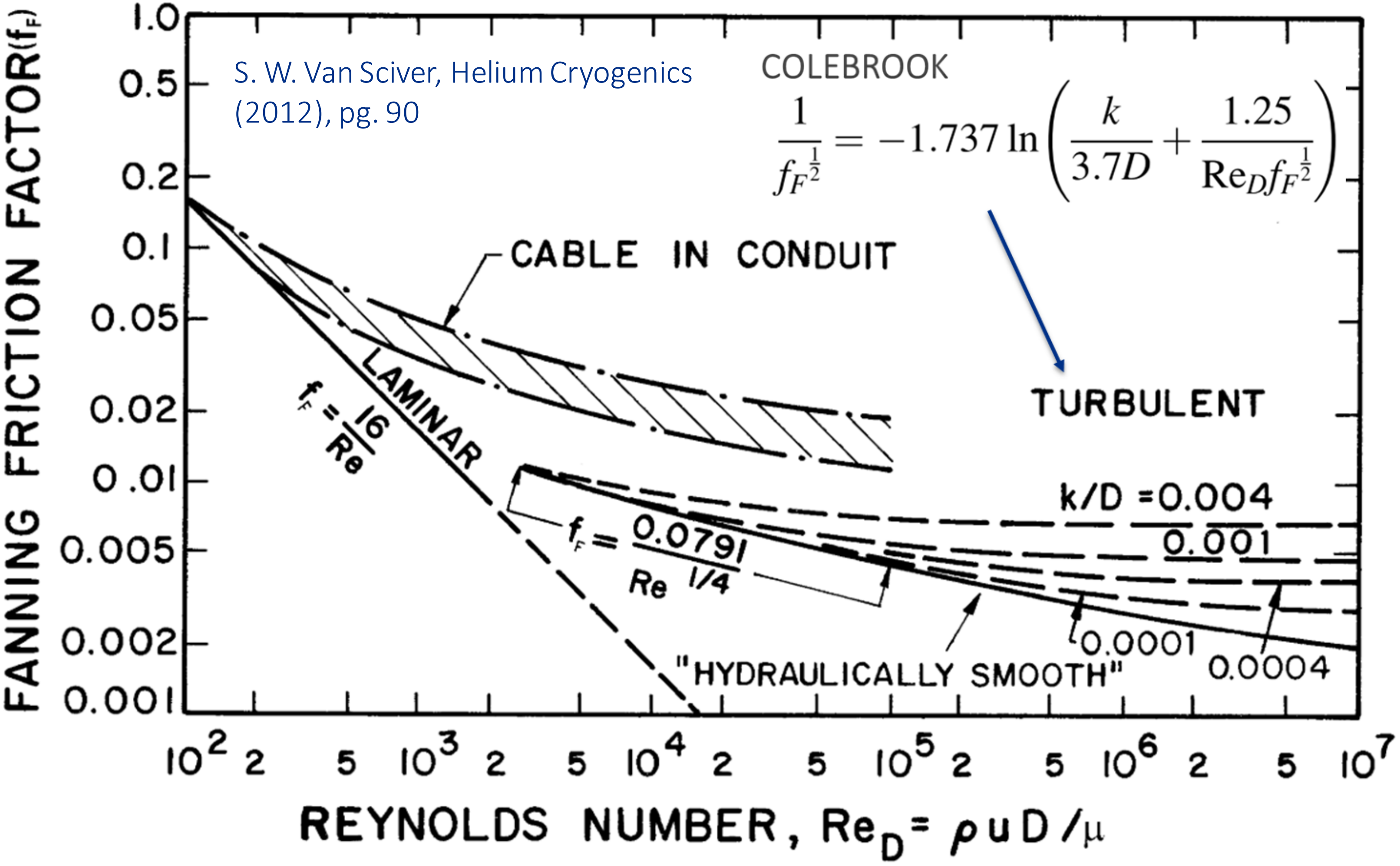
- Required for calculating pressure drop in a channel with forced flow

Nusselt number:

- For forced convection: $Nu_D = func(\mathrm{Re}_D, \mathrm{Pr}) = (hD)/k_f$
- For natural convection: $Nu_L = func(Gr, \mathrm{Pr}) = (hL)/k_f$
- Required for calculating convective heat transfer coefficient, h

Pressure drop in forced flow (single phase)

Friction factors: correlations and Moody chart



S. W. Van Sciver, Helium Cryogenics (2012), pg. 90

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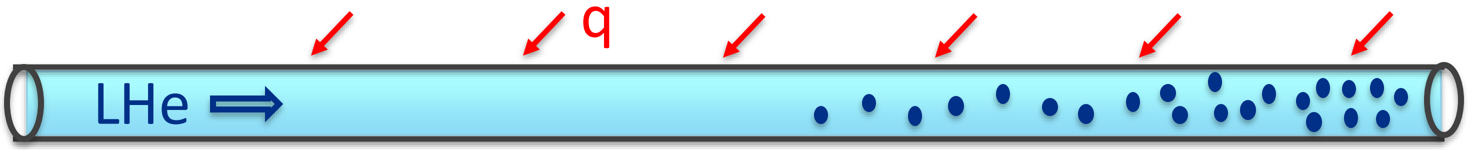
$$\frac{1}{f_F^{\frac{1}{2}}} = -1.737 \ln\left(\frac{k}{3.7D} + \frac{1.25}{\mathrm{Re}_D f_F^{\frac{1}{2}}}\right)$$

Pressure drop in forced flow (two phase)

Because of low heat of vaporization, single phase LHe flow in a long pipe can quickly become two phase from a heat in-flow to the pipe.



How to estimate the pressure drop in two-phase helium flow?

- Baker plots are used for two phase calculations of oil + gas, air + water flows.
- Work of Theilacker and Rode (1988) showed that <u>Baker plot is not suitable</u> for representing helium two-phase flows.
- Use Lockhart-Martinelli type approach (next slide).

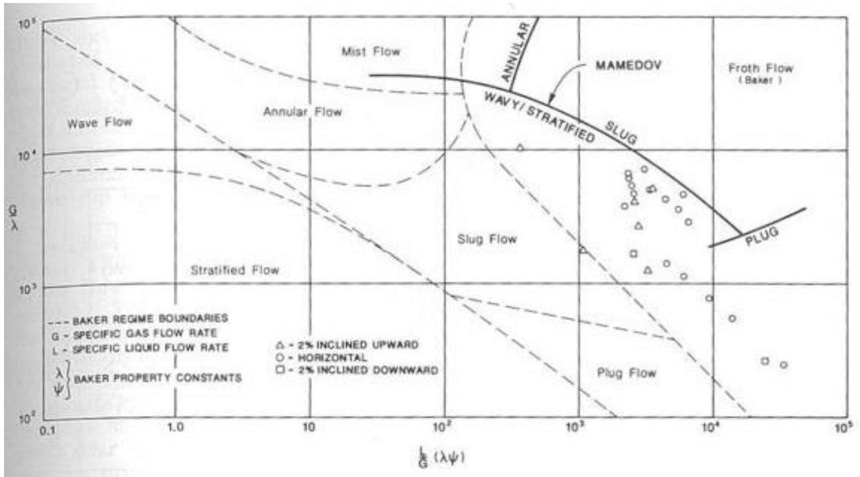


Fig. 2. Baker diagram for horizontal channels.

J. C. Theilacker and C. H. Rode, An Investigation into Flow Regimes for Two-phase Helium Flow, Adv. Cryo. Eng. 33, 391, 1988.

Pressure drop in forced flow (two phase)

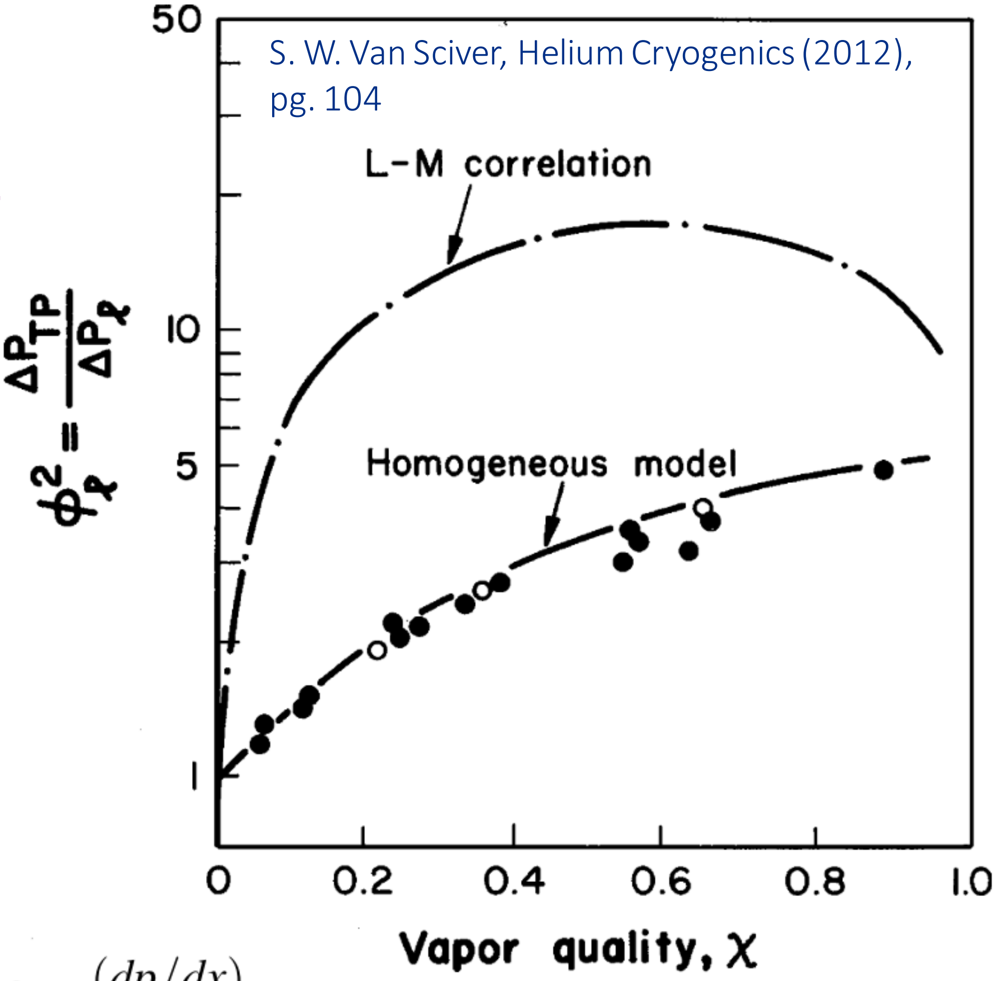
A few experiments have found that the Lockhart-Martinelli type approach with homogenous flow model shows reasonable agreement with data.

1) Calculate liquid-phase pressure drop $(dp/dx)_l$ using appropriate single phase correlation

2) Calculate homogenous model two-phase multiplier

$$\phi_l^2 = \left[1 + \chi\left(\frac{\rho_l}{\rho_v} - 1\right)\right]\left[1 + \chi\left(\frac{\mu_l}{\mu_v} - 1\right)\right]^{-n}$$

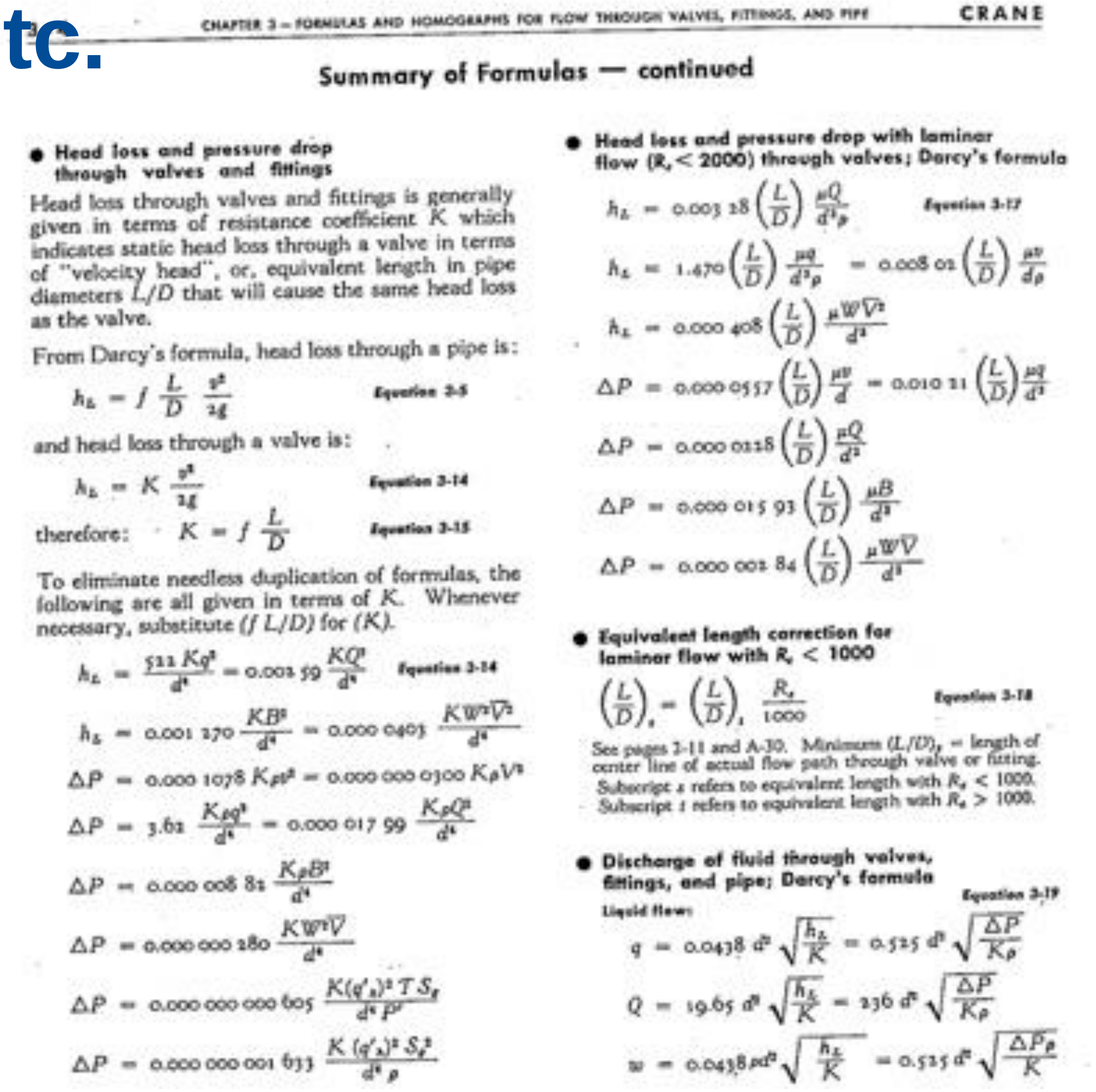
3) Calculate two-phase pressure drop $\phi_l^2 = \dfrac{(dp/dx)_{TP}}{(dp/dx)_l}$



S. W. Van Sciver, Helium Cryogenics (2012), pg. 104

Pressure drop in channels with valves, bends, fittings, etc.

Working expressions are available in literature such as Crane Technical paper #410



3-4 CHAPTER 3 – FORMULAS AND NOMOGRAPHS FOR FLOW THROUGH VALVES, FITTINGS, AND PIPE CRANE

Summary of Formulas — continued

- **Head loss and pressure drop through valves and fittings**

Head loss through valves and fittings is generally given in terms of resistance coefficient K which indicates static head loss through a valve in terms of "velocity head", or, equivalent length in pipe diameters L/D that will cause the same head loss as the valve.

From Darcy's formula, head loss through a pipe is:

$$h_L = f \frac{L}{D} \frac{v^2}{2g} \qquad \text{Equation 3-5}$$

and head loss through a valve is:

$$h_L = K \frac{v^2}{2g} \qquad \text{Equation 3-14}$$

therefore: $K = f \frac{L}{D}$ Equation 3-15

To eliminate needless duplication of formulas, the following are all given in terms of K. Whenever necessary, substitute $(f\,L/D)$ for (K).

$$h_L = \frac{0.002\,59\,Kq^2}{d^4} = 0.002\,59\,\frac{KQ^2}{d^4} \qquad \text{Equation 3-14}$$

$$h_L = 0.001\,270\,\frac{KB^2}{d^4} = 0.000\,0403\,\frac{KW^2\bar{V}^2}{d^4}$$

$$\Delta P = 0.000\,1078\,K\rho v^2 = 0.000\,000\,0300\,K\rho V^2$$

$$\Delta P = 3.62\,\frac{K\rho q^2}{d^4} = 0.000\,017\,99\,\frac{K\rho Q^2}{d^4}$$

$$\Delta P = 0.000\,008\,82\,\frac{K\rho B^2}{d^4}$$

$$\Delta P = 0.000\,000\,280\,\frac{KW^2\bar{V}}{d^4}$$

$$\Delta P = 0.000\,000\,000\,605\,\frac{K(q'_h)^2\,T\,S_g}{d^4\,P'}$$

$$\Delta P = 0.000\,000\,001\,633\,\frac{K\,(q'_h)^2\,S_g^2}{d^4\,\rho}$$

- **Head loss and pressure drop with laminar flow ($R_e < 2000$) through valves; Darcy's formula**

$$h_L = 0.003\,28\left(\frac{L}{D}\right)\frac{\mu Q}{d^2\rho} \qquad \text{Equation 3-17}$$

$$h_L = 1.470\left(\frac{L}{D}\right)\frac{\mu q}{d^2\rho} = 0.008\,02\left(\frac{L}{D}\right)\frac{\mu v}{d\rho}$$

$$h_L = 0.000\,408\left(\frac{L}{D}\right)\frac{\mu W\bar{V}^2}{d^2}$$

$$\Delta P = 0.000\,0557\left(\frac{L}{D}\right)\frac{\mu v}{d} = 0.010\,21\left(\frac{L}{D}\right)\frac{\mu q}{d^2}$$

$$\Delta P = 0.000\,0228\left(\frac{L}{D}\right)\frac{\mu Q}{d^2}$$

$$\Delta P = 0.000\,015\,93\left(\frac{L}{D}\right)\frac{\mu B}{d^2}$$

$$\Delta P = 0.000\,002\,84\left(\frac{L}{D}\right)\frac{\mu W\bar{V}}{d^2}$$

- **Equivalent length correction for laminar flow with $R_e < 1000$**

$$\left(\frac{L}{D}\right)_e = \left(\frac{L}{D}\right)_t \frac{R_e}{1000} \qquad \text{Equation 3-18}$$

See pages 2-11 and A-30. Minimum $(L/D)_t$ = length of center line of actual flow path through valve or fitting. Subscript e refers to equivalent length with $R_e < 1000$. Subscript t refers to equivalent length with $R_e > 1000$.

- **Discharge of fluid through valves, fittings, and pipe; Darcy's formula**

Equation 3-19

Liquid flow:

$$q = 0.0438\,d^2\sqrt{\frac{h_L}{K}} = 0.525\,d^2\sqrt{\frac{\Delta P}{K\rho}}$$

$$Q = 19.65\,d^2\sqrt{\frac{h_L}{K}} = 236\,d^2\sqrt{\frac{\Delta P}{K\rho}}$$

$$w = 0.0438\,\rho d^2\sqrt{\frac{h_L}{K}} = 0.525\,d^2\sqrt{\frac{\Delta P\rho}{K}}$$

Convective heat transfer

Internal forced flow of normal helium (single phase)

For single phase forced flow of helium (liquid, supercritical), traditional engineering correlations are best at describing the experimental data.

$$Nu_D = \text{constant}$$

for fully developed laminar flow (rarely seen in practice)

$$\overline{\text{Nu}} = 0.023\text{Re}_D^{4/5}\text{Pr}^{2/5}$$

Dittus-Boelter average Nusselt number for fully developed turbulent flow

$$\text{Nu} = 0.0259\ \text{Re}_D^{4/5}\text{Pr}^{2/5}\left(\frac{T_s}{T_m}\right)^{-0.716}$$

local Nusselt number for fully developed turbulent flow, accounting for variation in wall and fluid temperatures

Convective heat transfer

Internal forced flow of normal helium (two-phase)

For two phase forced flow of helium, Lockhart Martinelli type correlations are shown to work. But experimental data is limited and so, the correlations cannot be generalized over systems.

Calculate Nusselt number in liquid phase

$$\mathrm{Nu}_l = 0.023(\mathrm{Re}_l)^{0.8}(\mathrm{Pr}_l)^{0.4}(1-\chi)^{0.8}$$

Calculate pressure drops in the two phases, the ratio gives the LM parameter

$$\chi_{tt}^2 = \frac{(dp/dx)_v}{(dp/dx)_l}$$

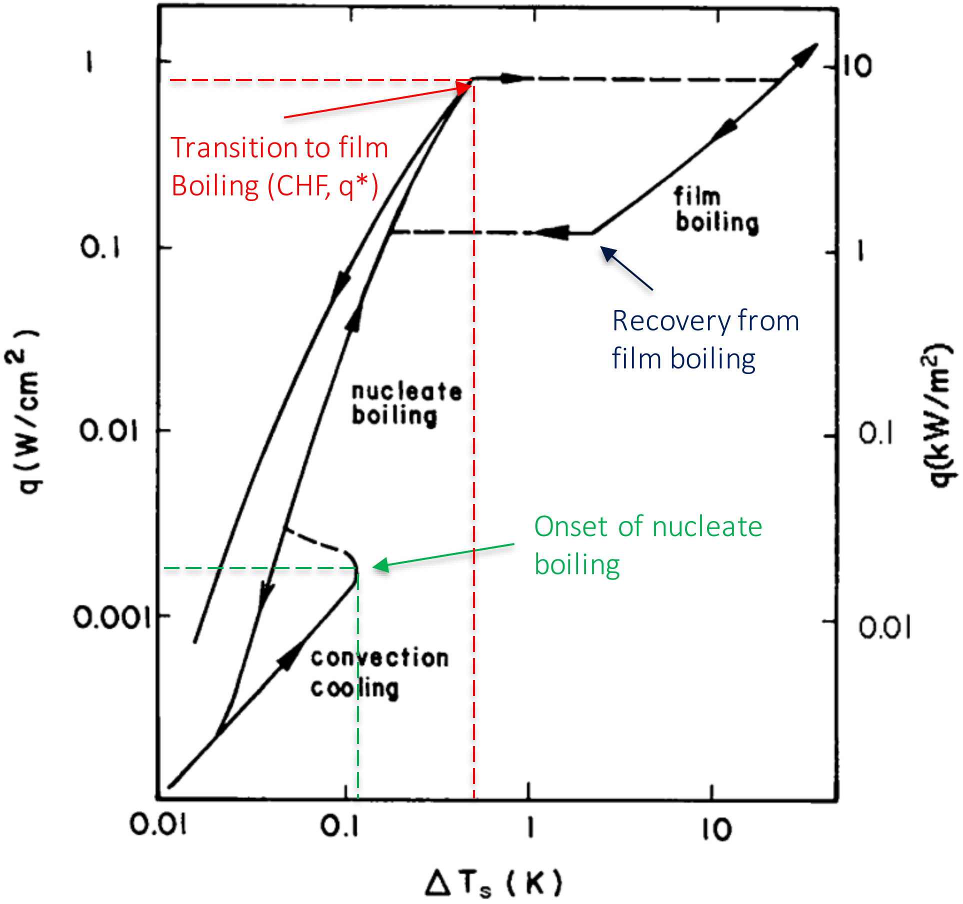
Two-phase Nusselt number correlation (general form)

$$\frac{Nu_{\exp}}{Nu_l} = A\chi_{tt}^{-n}$$

<u>Note</u>: Vapor quality must be known for estimating two-phase Nu

Convective heat transfer

Pool boiling in normal liquid helium



Transition to film Boiling (CHF, q*)

Recovery from film boiling

Onset of nucleate boiling

S. W. Van Sciver, Helium Cryogenics (2012), pg. 118

The normal He pool boiling curve is like that for conventional liquids

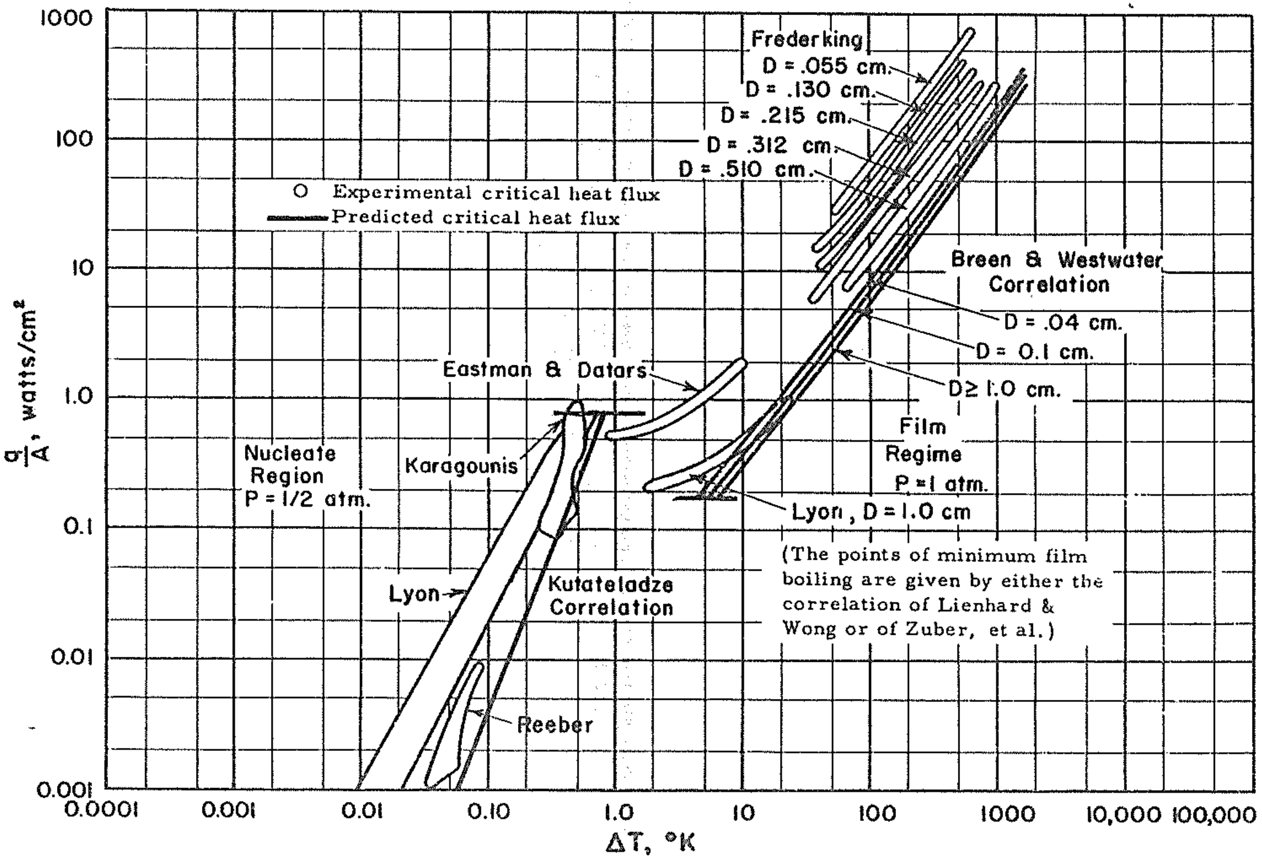
- Convection
- Nucleate boiling
- Film boiling
- Recovery with hysteresis

Transition heat fluxes and the associated superheats are small

- Onset nucleate boiling: ~0.1 K, ~1e-3 W/cm^2
- Transition to film boiling: ~1 K, **q*** ~1 W/cm^2
- Recovery from film boiling: ~0.1 W/cm^2 (~ten-fold smaller than CHF)

Convective heat transfer

Normal helium pool boiling data and correlations



Boiling Heat Transfer for Oxygen, Nitrogen, Hydrogen, and Helium,
by E.G. Brentari, et al, NBS Technical Note 317, Boulder, CO, 1965.

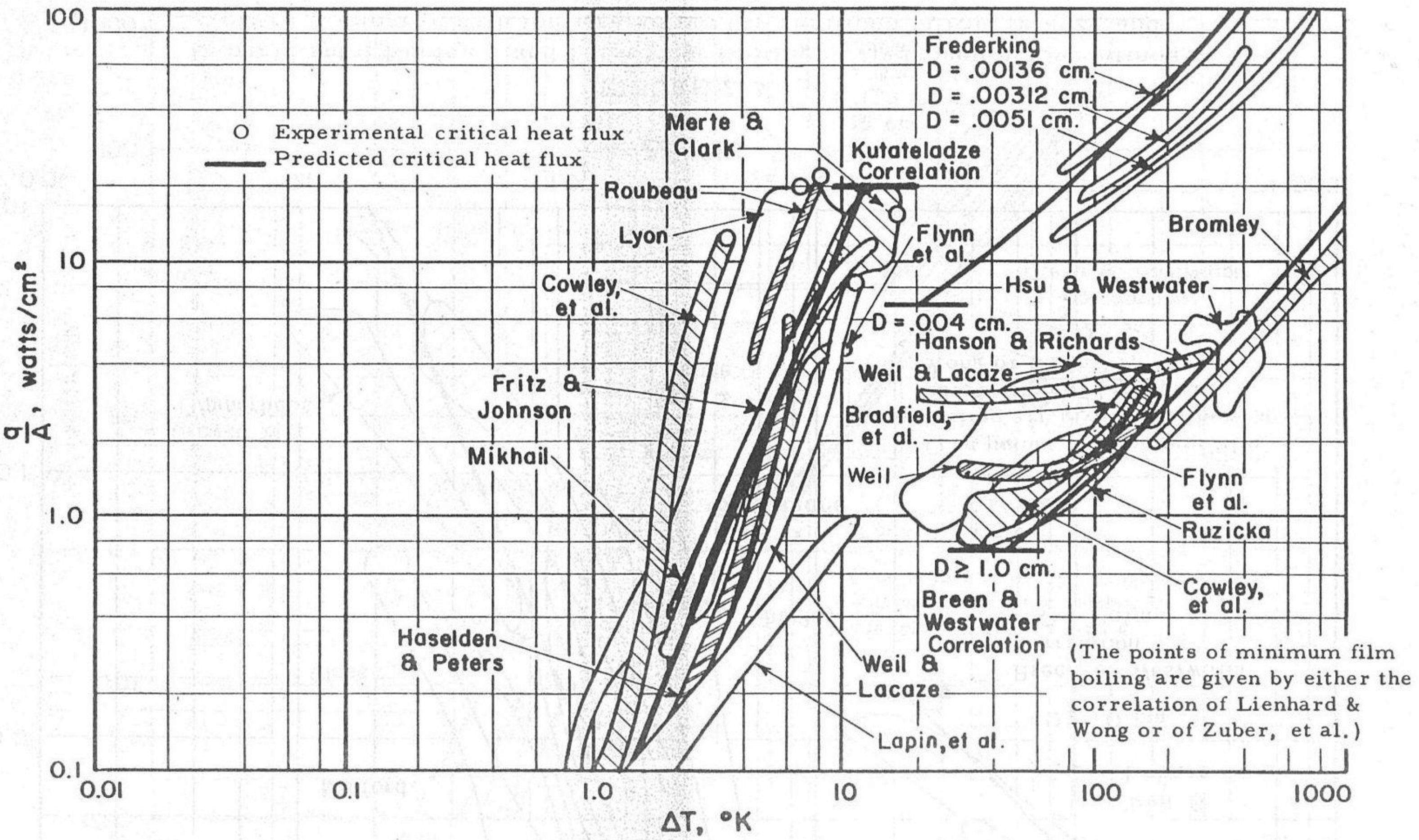
Other cryogens

Nitrogen and argon are other commonly used cryogens in large scale systems

- Liquid nitrogen is commonly used to cool 75-80 K thermal radiation shields around helium baths/pipes
- Liquid argon is used in time projection chamber (eg. neutrino detector in Fermilab DUNE)

Since both nitrogen and argon are normal fluids, most pressure drop and heat transfer correlations discussed earlier apply respectively to their flow and heat transfer modes.

Nitrogen pool boiling data and correlations



(The points of minimum film boiling are given by either the correlation of Lienhard & Wong or of Zuber, et al.)

FIGURE 2.2

Experimental Nucleate and Film Pool Boiling of Nitrogen at One Atmosphere Compared with the Predictive Correlations of Kutateladze and Breen and Westwater

References and further reading

- S. W. Van Sciver, “Helium Cryogenics,” Plenum Press, 1986.
- Ovid Baker, "Design of Pipelines for the Simultaneous Flow of Oil and Gas," Oil and Gas Journal (July 26, 1954) p. 185-195.
- J. C. Theilacker and C. H. Rode, “An Investigation into Flow Regimes for Two-phase Helium Flow,” Advances in Cryogenic Engineering, Vol. 33, pp. 391-398, 1988.
- E.G. Brentari, et al, “Boiling Heat Transfer for Oxygen, Nitrogen, Hydrogen, and Helium,” NBS Technical Note 317, Boulder, CO, 1965.
- Crane Technical Paper #410 “Flow of Fluids through Valves, Fittings, and Pipes”.