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Cryogenics for Noble Liquid Detectors

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Introduction

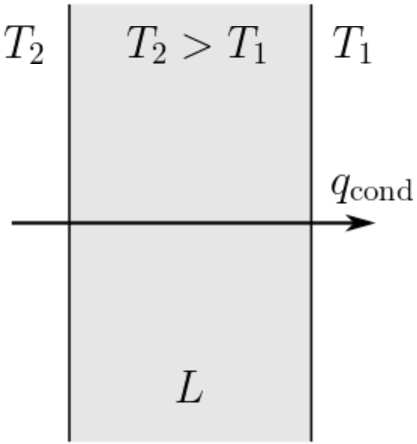
- Goal is to give an overview of some of the relevant physical effects and of the many technologies and techniques employed in the design, installation, and operation of liquefied noble gas detectors
- Knowledge in many fields is required
  - Vacuum technology,
  - Mechanical engineering,
  - Process engineering,
  - High purity gas delivery, and others...
- We will cover
  - Heat transfer mechanisms, rates
  - Some of the equipment commonly used
  - Instrumentation
  - Typical operations with cryogenic noble liquid detectors
  - Purification techniques
  - Special topics for dual-phase TPCs

Cryogenic fluids as detection media

- Cryogenic fluids most often consist of two phases in equilibrium (pure substance)
- Unless specific precautions are taken, cryogenic liquids are always close to boiling
- Very different behavior than our everyday experience of liquids (water in a mostly nitrogen atmosphere)
- Flash evaporation of the liquid if the pressure is reduced suddenly, temperature decreases to the saturation temperature at the lower pressure
- Possible to suppress the boiling tendency by subcooling the liquid or superheating the vapor
- Small changes are better to change the overall thermodynamic state
- Stability, stability...

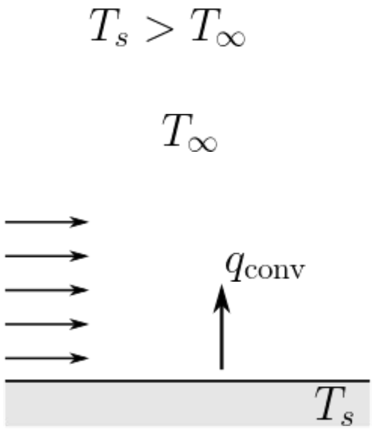
Heat transfer mechanisms

Conduction



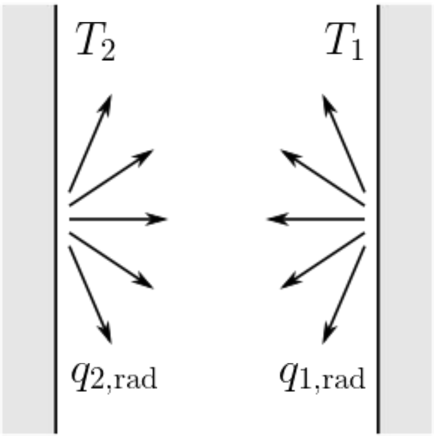
$$q_{\text{cond}} = \frac{kA}{L}\left(T_2 - T_1\right)$$

Convection



$$q_{\text{conv}} = hA\left(T_s - T_\infty\right)$$

Radiation



$$q_{\text{rad}} = \sigma F_E F_A A\left(T_2^4 - T_1^4\right)$$

Conduction

$$q_{\mathrm{cond}} = \frac{kA}{L}(T_2 - T_1)$$

- How to reduce heat transfer through conduction?
  - Evacuate gases
  - Material with low thermal conductivity
  - Increase the length
  - Reduce the cross section

Flynn, “Cryogenic Engineering”

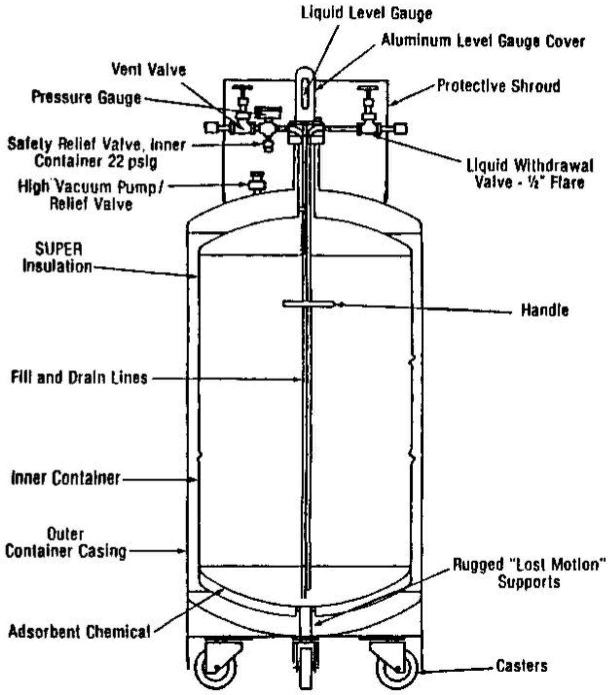


Figure 9.43 Commercial cryogenic storage system.

Convection

$$q_{\text{conv}} = hA\left(T_s - T_\infty\right)$$

Transfer of energy from/to a surface due to the movement of a fluid

- Can be classified as free convection and forced convection
  - Free convection, buoyancy-driven flow
  - Forced convection, pressure-driven flow
- Heat transfer rate characterized by a "heat transfer coefficient" *h*
- Heat transfer coefficient correlations valid for large classes of fluids make it possible to obtain rates in geometrically similar problems

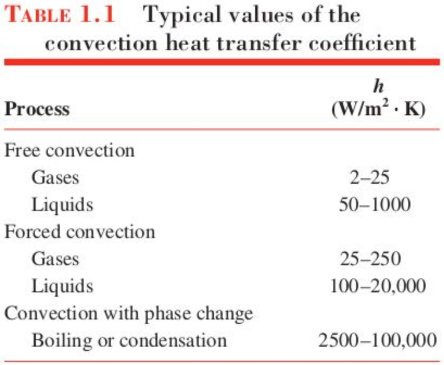
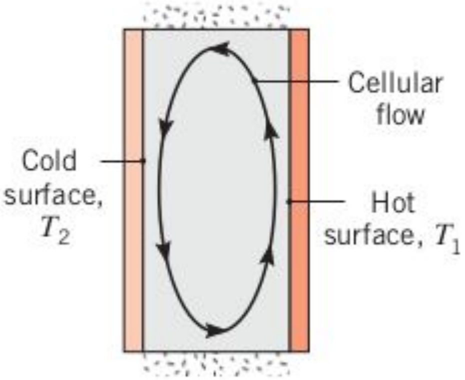
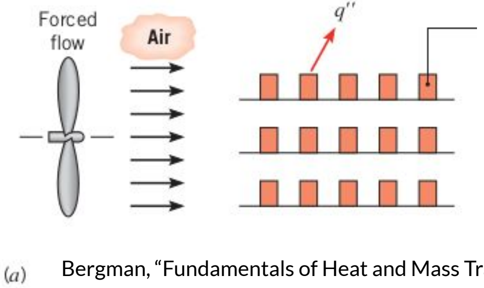


TABLE 1.1 Typical values of the convection heat transfer coefficient

Process	h $(\mathrm{W/m^2 \cdot K})$
Free convection	
Gases	2–25
Liquids	50–1000
Forced convection	
Gases	25–250
Liquids	100–20,000
Convection with phase change	
Boiling or condensation	2500–100,000



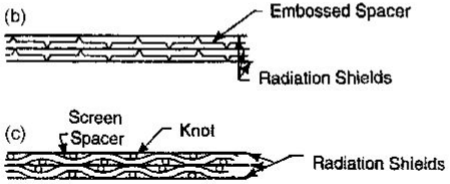


Bergman, "Fundamentals of Heat and Mass Transfer"

Radiation

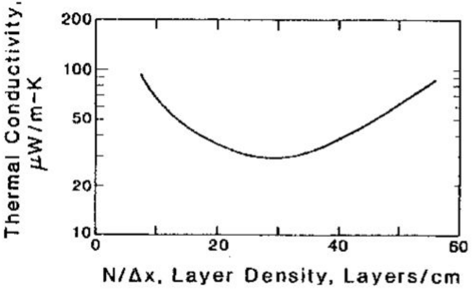
$$q_{\mathrm{rad}} = \sigma F_E F_A A \left(T_2^4 - T_1^4\right)$$

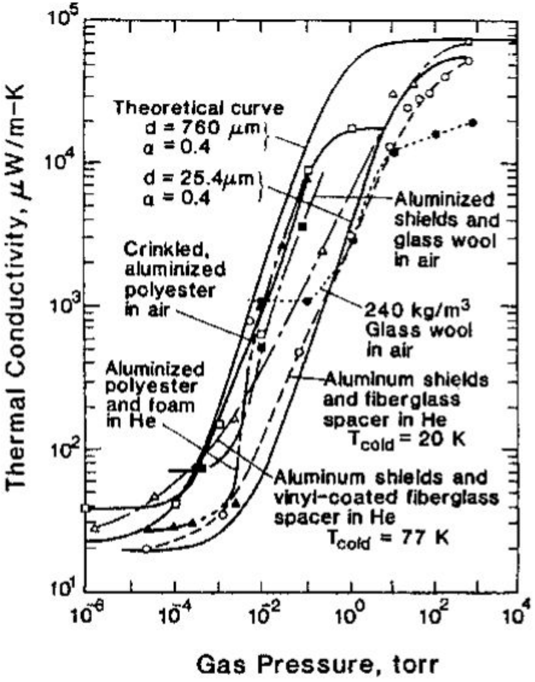
- Factor F_A that depends on viewing area
- Factor F_E that depends on emissivity of surfaces
- How to reduce radiative heat transfer?
  - Low emissivity surfaces
  - Surface at intermediate temperature? MLI
- Multi-layer insulation



- Effect of residual gas
- Layer density effect

Flynn, “Cryogenic Engineering”





Dimensionless groups

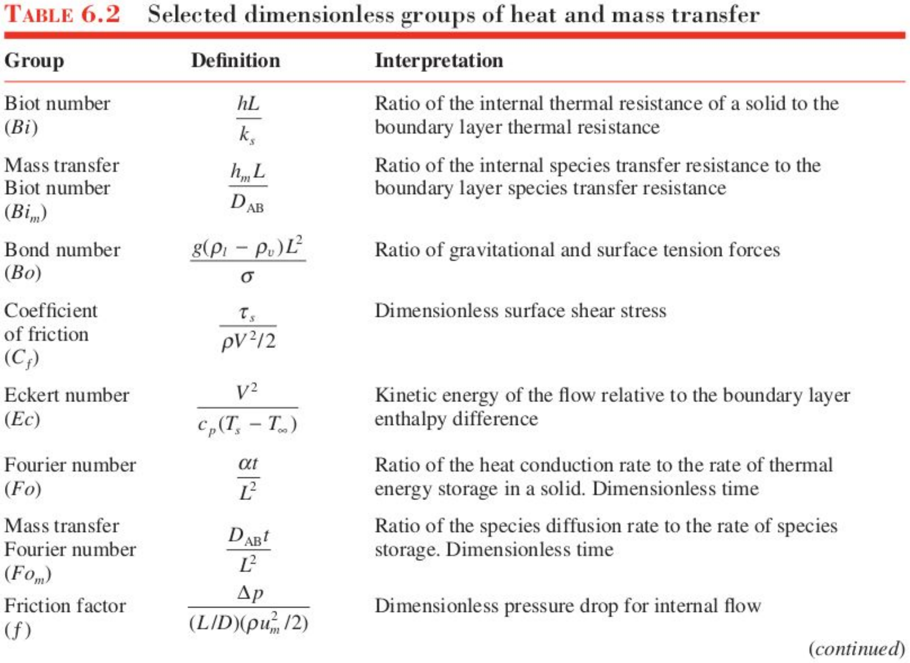


TABLE 6.2 Selected dimensionless groups of heat and mass transfer

Group	Definition	Interpretation
Biot number (Bi)	$\frac{hL}{k_s}$	Ratio of the internal thermal resistance of a solid to the boundary layer thermal resistance
Mass transfer Biot number (Bi_m)	$\frac{h_m L}{D_{AB}}$	Ratio of the internal species transfer resistance to the boundary layer species transfer resistance
Bond number (Bo)	$\frac{g(\rho_l - \rho_v)L^2}{\sigma}$	Ratio of gravitational and surface tension forces
Coefficient of friction (C_f)	$\frac{\tau_s}{\rho V^2/2}$	Dimensionless surface shear stress
Eckert number (Ec)	$\frac{V^2}{c_p(T_s - T_\infty)}$	Kinetic energy of the flow relative to the boundary layer enthalpy difference
Fourier number (Fo)	$\frac{\alpha t}{L^2}$	Ratio of the heat conduction rate to the rate of thermal energy storage in a solid. Dimensionless time
Mass transfer Fourier number (Fo_m)	$\frac{D_{AB}t}{L^2}$	Ratio of the species diffusion rate to the rate of species storage. Dimensionless time
Friction factor (f)	$\frac{\Delta p}{(L/D)(\rho u_m^2/2)}$	Dimensionless pressure drop for internal flow

(continued)

Bergman, “Fundamentals of Heat and Mass Transfer”

TABLE 6.2 *Continued*

Group	Definition	Interpretation
Grashof number (Gr_L)	$\frac{g\beta(T_s - T_\infty)L^3}{\nu^2}$	Measure of the ratio of buoyancy forces to viscous forces
Colburn j factor (j_H)	$St\,Pr^{2/3}$	Dimensionless heat transfer coefficient
Colburn j factor (j_m)	$St_m\,Sc^{2/3}$	Dimensionless mass transfer coefficient
Jakob number (Ja)	$\frac{c_p(T_s - T_{\text{sat}})}{h_{fg}}$	Ratio of sensible to latent energy absorbed during liquid–vapor phase change
Lewis number (Le)	$\frac{\alpha}{D_{AB}}$	Ratio of the thermal and mass diffusivities
Mach number (Ma)	$\frac{V}{a}$	Ratio of velocity to speed of sound
Nusselt number (Nu_L)	$\frac{hL}{k_f}$	Ratio of convection to pure conduction heat transfer
Peclet number (Pe_L)	$\frac{VL}{\alpha} = Re_L\,Pr$	Ratio of advection to conduction heat transfer rates
Prandtl number (Pr)	$\frac{c_p\mu}{k} = \frac{\nu}{\alpha}$	Ratio of the momentum and thermal diffusivities
Reynolds number (Re_L)	$\frac{VL}{\nu}$	Ratio of the inertia and viscous forces
Schmidt number (Sc)	$\frac{\nu}{D_{AB}}$	Ratio of the momentum and mass diffusivities
Sherwood number (Sh_L)	$\frac{h_m L}{D_{AB}}$	Ratio of convection to pure diffusion mass transfer
Stanton number (St)	$\frac{h}{\rho V c_p} = \frac{Nu_L}{Re_L\,Pr}$	Modified Nusselt number
Mass transfer Stanton number (St_m)	$\frac{h_m}{V} = \frac{Sh_L}{Re_L\,Sc}$	Modified Sherwood number
Weber number (We)	$\frac{\rho V^2 L}{\sigma}$	Ratio of inertia to surface tension forces

Heat transfer coefficients correlations

Correlations for external flow

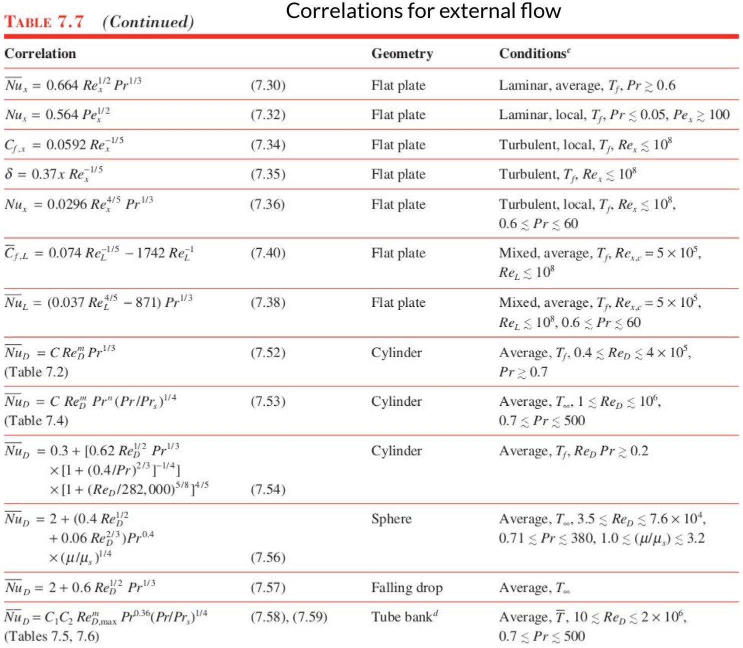


TABLE 7.7 *(Continued)*

Correlation		Geometry	Conditions[c]
$\overline{Nu}_x = 0.664\, Re_x^{1/2}\, Pr^{1/3}$	(7.30)	Flat plate	Laminar, average, T_f, $Pr \gtrsim 0.6$
$Nu_x = 0.564\, Pe_x^{1/2}$	(7.32)	Flat plate	Laminar, local, T_f, $Pr \lesssim 0.05$, $Pe_x \gtrsim 100$
$C_{f,x} = 0.0592\, Re_x^{-1/5}$	(7.34)	Flat plate	Turbulent, local, T_f, $Re_x \lesssim 10^8$
$\delta = 0.37x\, Re_x^{-1/5}$	(7.35)	Flat plate	Turbulent, T_f, $Re_x \lesssim 10^8$
$Nu_x = 0.0296\, Re_x^{4/5}\, Pr^{1/3}$	(7.36)	Flat plate	Turbulent, local, T_f, $Re_x \lesssim 10^8$, $0.6 \lesssim Pr \lesssim 60$
$\overline{C}_{f,L} = 0.074\, Re_L^{-1/5} - 1742\, Re_L^{-1}$	(7.40)	Flat plate	Mixed, average, T_f, $Re_{x,c} = 5 \times 10^5$, $Re_L \lesssim 10^8$
$\overline{Nu}_L = (0.037\, Re_L^{4/5} - 871)\, Pr^{1/3}$	(7.38)	Flat plate	Mixed, average, T_f, $Re_{x,c} = 5 \times 10^5$, $Re_L \lesssim 10^8$, $0.6 \lesssim Pr \lesssim 60$
$\overline{Nu}_D = C\, Re_D^m\, Pr^{1/3}$ (Table 7.2)	(7.52)	Cylinder	Average, T_f, $0.4 \lesssim Re_D \lesssim 4 \times 10^5$, $Pr \gtrsim 0.7$
$\overline{Nu}_D = C\, Re_D^m\, Pr^n\, (Pr/Pr_s)^{1/4}$ (Table 7.4)	(7.53)	Cylinder	Average, T_∞, $1 \lesssim Re_D \lesssim 10^6$, $0.7 \lesssim Pr \lesssim 500$
$\overline{Nu}_D = 0.3 + [0.62\, Re_D^{1/2}\, Pr^{1/3} \times [1 + (0.4/Pr)^{2/3}]^{-1/4}] \times [1 + (Re_D/282{,}000)^{5/8}]^{4/5}$	(7.54)	Cylinder	Average, T_f, $Re_D\, Pr \gtrsim 0.2$
$\overline{Nu}_D = 2 + (0.4\, Re_D^{1/2} + 0.06\, Re_D^{2/3})Pr^{0.4} \times (\mu/\mu_s)^{1/4}$	(7.56)	Sphere	Average, T_∞, $3.5 \lesssim Re_D \lesssim 7.6 \times 10^4$, $0.71 \lesssim Pr \lesssim 380$, $1.0 \lesssim (\mu/\mu_s) \lesssim 3.2$
$\overline{Nu}_D = 2 + 0.6\, Re_D^{1/2}\, Pr^{1/3}$	(7.57)	Falling drop	Average, T_∞
$\overline{Nu}_D = C_1 C_2\, Re_{D,\max}^m\, Pr^{0.36}(Pr/Pr_s)^{1/4}$ (Tables 7.5, 7.6)	(7.58), (7.59)	Tube bank[d]	Average, $\overline{T}$, $10 \lesssim Re_D \lesssim 2 \times 10^6$, $0.7 \lesssim Pr \lesssim 500$

Bergman, “Fundamentals of Heat and Mass Transfer”

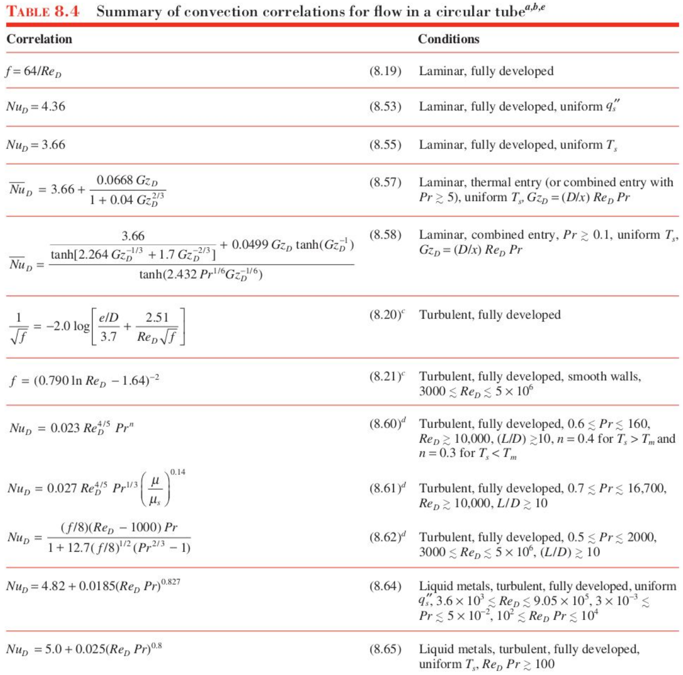


TABLE 8.4 Summary of convection correlations for flow in a circular tube[a,b,e]

Correlation		Conditions
$f = 64/Re_D$	(8.19)	Laminar, fully developed
$Nu_D = 4.36$	(8.53)	Laminar, fully developed, uniform q_s''
$Nu_D = 3.66$	(8.55)	Laminar, fully developed, uniform T_s
$\overline{Nu}_D = 3.66 + \dfrac{0.0668\, Gz_D}{1 + 0.04\, Gz_D^{2/3}}$	(8.57)	Laminar, thermal entry (or combined entry with $Pr \gtrsim 5$), uniform T_s, $Gz_D = (D/x)\, Re_D\, Pr$
$\overline{Nu}_D = \dfrac{\dfrac{3.66}{\tanh[2.264\, Gz_D^{-1/3} + 1.7\, Gz_D^{-2/3}]} + 0.0499\, Gz_D \tanh(Gz_D^{-1})}{\tanh(2.432\, Pr^{1/6} Gz_D^{-1/6})}$	(8.58)	Laminar, combined entry, $Pr \gtrsim 0.1$, uniform T_s, $Gz_D = (D/x)\, Re_D\, Pr$
$\dfrac{1}{\sqrt{f}} = -2.0 \log\left[\dfrac{e/D}{3.7} + \dfrac{2.51}{Re_D \sqrt{f}}\right]$	(8.20)[c]	Turbulent, fully developed
$f = (0.790 \ln Re_D - 1.64)^{-2}$	(8.21)[c]	Turbulent, fully developed, smooth walls, $3000 \lesssim Re_D \lesssim 5 \times 10^6$
$Nu_D = 0.023\, Re_D^{4/5}\, Pr^n$	(8.60)[d]	Turbulent, fully developed, $0.6 \lesssim Pr \lesssim 160$, $Re_D \gtrsim 10{,}000$, $(L/D) \gtrsim 10$, $n = 0.4$ for $T_s > T_m$ and $n = 0.3$ for $T_s < T_m$
$Nu_D = 0.027\, Re_D^{4/5}\, Pr^{1/3} \left(\dfrac{\mu}{\mu_s}\right)^{0.14}$	(8.61)[d]	Turbulent, fully developed, $0.7 \lesssim Pr \lesssim 16{,}700$, $Re_D \gtrsim 10{,}000$, $L/D \gtrsim 10$
$Nu_D = \dfrac{(f/8)(Re_D - 1000)\, Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)}$	(8.62)[d]	Turbulent, fully developed, $0.5 \lesssim Pr \lesssim 2000$, $3000 \lesssim Re_D \lesssim 5 \times 10^6$, $(L/D) \gtrsim 10$
$Nu_D = 4.82 + 0.0185(Re_D\, Pr)^{0.827}$	(8.64)	Liquid metals, turbulent, fully developed, uniform q_s'', $3.6 \times 10^3 \lesssim Re_D \lesssim 9.05 \times 10^5$, $3 \times 10^{-3} \lesssim Pr \lesssim 5 \times 10^{-2}$, $10^2 \lesssim Re_D\, Pr \lesssim 10^4$
$Nu_D = 5.0 + 0.025(Re_D\, Pr)^{0.8}$	(8.65)	Liquid metals, turbulent, fully developed, uniform T_s, $Re_D\, Pr \gtrsim 100$

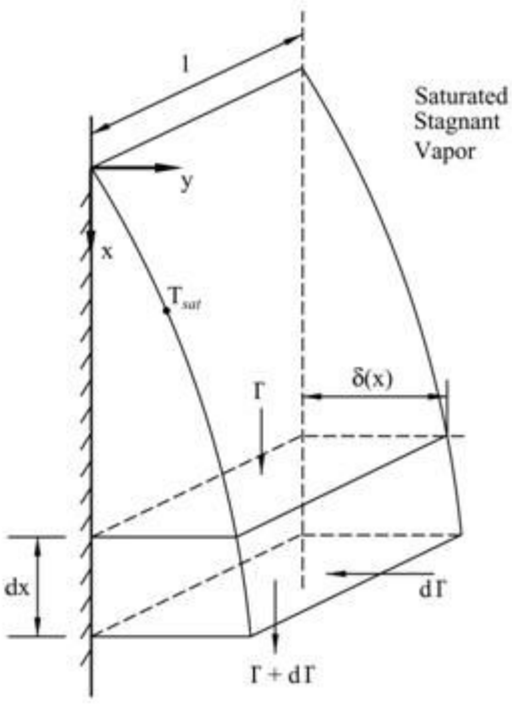
Condensation heat transfer

- Nusselt analysis of laminar film condensation on a vertical plate
- Closed form expression for the heat transfer coefficient

$$\delta = \left[\frac{4k_l\mu_l x\Delta T}{\rho_l(\rho_l-\rho_v)gh_{lv}}\right]^{1/4}$$

$$Nu_x = \frac{h_x x}{k_l} = \left[\frac{\rho_l(\rho_l-\rho_v)gh_{lv}x^3}{4\mu_l x\Delta T}\right]^{1/4}$$

- Can be used to design condensers, cold fingers



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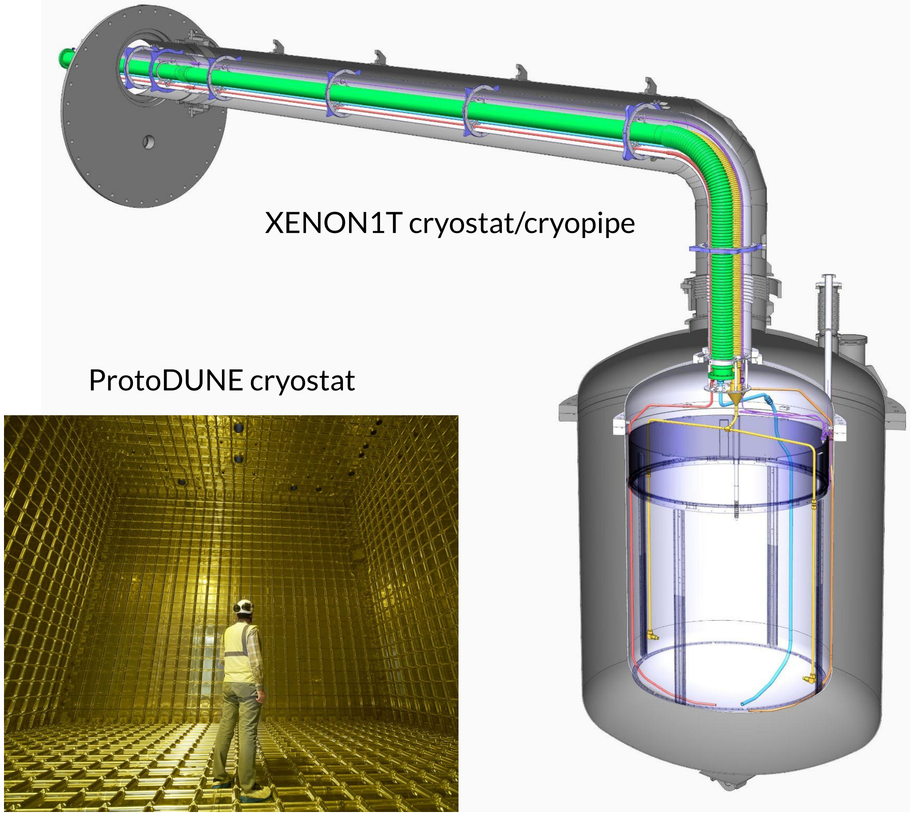
Equipment

- A very brief look at some of the equipment commonly used in cryogenic liquefied noble gas detectors
    - Cryostats
    - Cooling apparatus
    - Transfer lines
    - Valves
    - Pumps

Cryostats

- Where the cryogenic liquid is kept cold
- Commonalities
    - Minimize heat influx to the cryogenic liquid
    - Insulation (vacuum, MLI, passive insulation)
    - Minimize conduction through supports
    - Manage thermal contractions
- In the case of low-background experiments
    - Minimize the mass (pressure resistance diminished)
- With very large detectors, bigger challenges
    - Large thermal contractions
    - Vacuum insulation impractical



XENON1T cryostat/cryopipe

ProtoDUNE cryostat

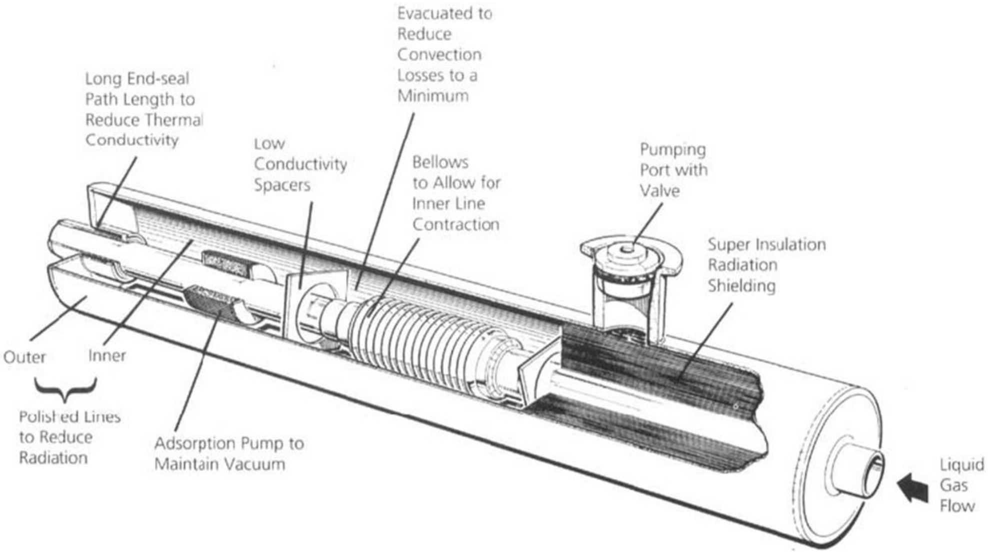
Cooling apparatus

- Many different strategies are employed to extract heat from the cryostat
- Among the more common ones
  - Cryocoolers
    - Pulse-tube refrigerators (MEG, XMASS, XENON, PANDA-X)
    - Stirling-type (ICARUS, LN_2 secondary cooling loop)
    - GM-refrigerators (XENON cryogenic distillation column)
  - LN_2 cooling
    - LUX/LZ (LN_2 thermosyphon GXe condenser)
    - Darkside-50 (LN_2/GAr condenser)
    - XENON1T/nT LXe/SXe storage,
    - XENONnT cryogenic purification LXe/LN_2 heat exchanger
    - Darkside-20k (LN_2/GAr condensers for AAr and UAr)

Iwatani PC-150

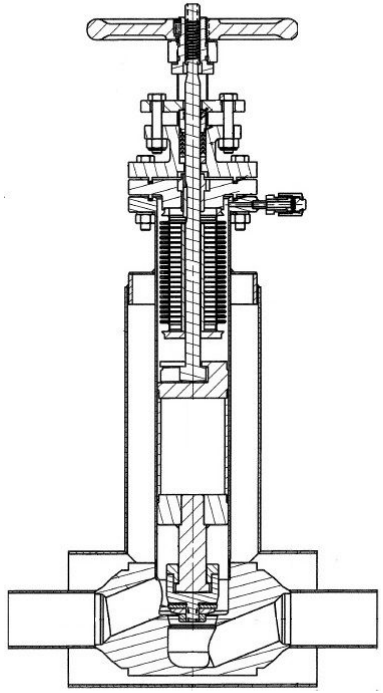
Transfer lines

- Vacuum-jacketed piping to reduce heat flow to cryogenic fluid
- Low conductive heat flow
  - G10 supports keep inner tube centered
  - Point contact to outer tube
- Low convective heat flow
  - Vacuum insulation
  - Getter pumps
- Low radiative heat flow
  - Multi-layer insulation
  - Low emissivity tubing
- Sizing is important and should be determined from flow requirement



Valves

- Typical requirements for cryogenic noble liquid detectors
    - High-purity fluid compatibility
        - Electropolished surfaces
        - No lubricant
    - Low heat influx
    - Low external leak rate (bellows-sealed)
    - Reliable low-temperature operation
    - High flow coefficient
- Also desired
    - Low heat capacity (faster cool down)
    - Serviceability in vacuum jacketed lines
- Multiple valve manufacturers to choose from



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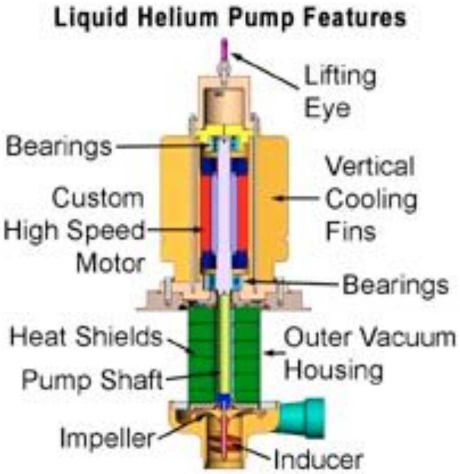
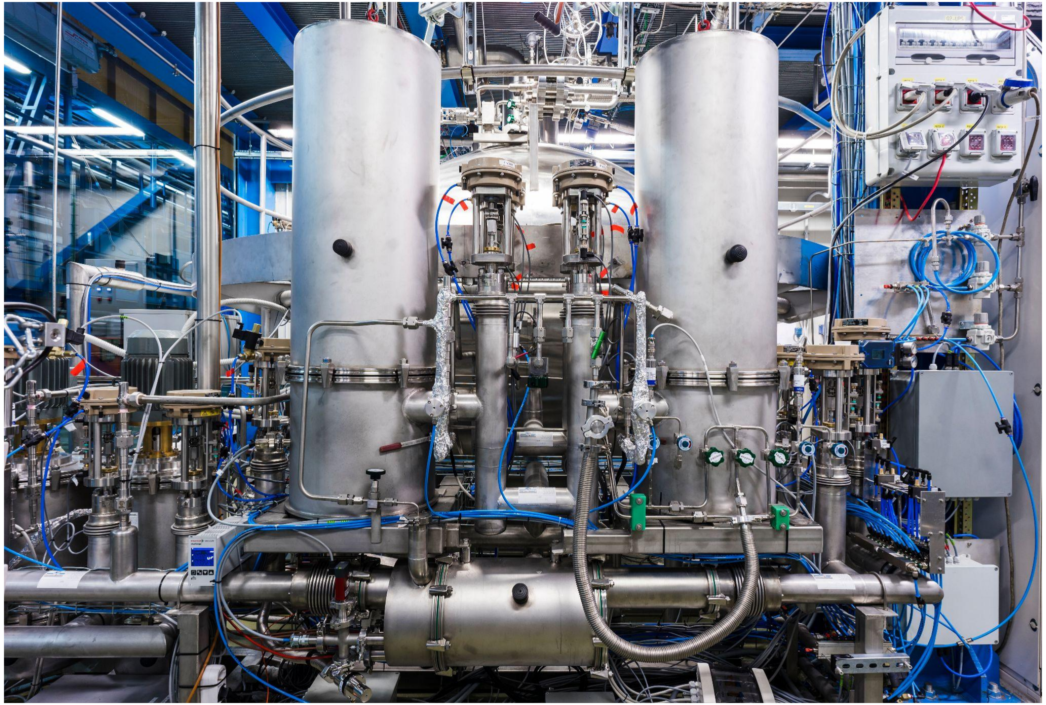
Cryogenic liquid pumps

- Used in a number of liquid noble gas experiments for circulation/purification system
    - ICARUS, MEG, ProtoDUNE, XENONnT
- Barber-Nichols BNCP-32C-000
    - High-purity fluid compatibility
        - Hermetically sealed pump with magnetic shaft coupling
        - Stainless steel construction (except impeller, bearings)
    - Low heat influx
        - Thin-walled shaft/housing
        - Anti-convection baffles
    - Vacuum housing / removable rotating assembly
    - High-speed motor with VFD
        - Wide performance range



Assembled system with cryogenic equipment

- XENONnT cryogenic purification system
  - Cryogenic liquid pumps
  - Vacuum insulated valves
  - Vacuum jacketed piping
  - Vacuum insulated filter enclosures
  - Instrumentation (next section)



Instrumentation

- The accurate measurement of properties such as temperature, pressure, flow, quality, and liquid level are very important for the proper operation of liquified noble gas detectors
- Measurement of properties at cryogenic temperatures can pose unique and subtle challenges
- When possible, use conventional instrumentation
- For sensors that need to be inside the cryostat
  - Install redundant sensors for critical parameters
  - Consider robustness of the sensor and the mounting technique
- If possible, try to avoid cryogenic instrumentation feedthroughs

Temperature

- In cryogenic liquid noble detectors one usually needs to measure the temperature of gases, liquids, and surfaces
- In general, three critical aspects for an optimal performance of cryogenic temperature sensors
    - Mounting of the sensor
        - Sensor must be able to dissipate the Joule heating
        - Minimize thermal contact resistance
        - Match thermal expansion coefficients (sensor/adhesive/surface)
    - Joining of sensor leads and electrical cables
        - 4-lead measurement (RTDs)
        - Voltage difference across dissimilar metals (thermocouple sensors)
    - Thermal anchoring of wires
        - Heat flowing to the sensor from the cables can induce a temperature offset
        - Wind wires to a thermal mass so heat does not flow to the sensor itself

Temperature

- Many different types of sensors to choose from:

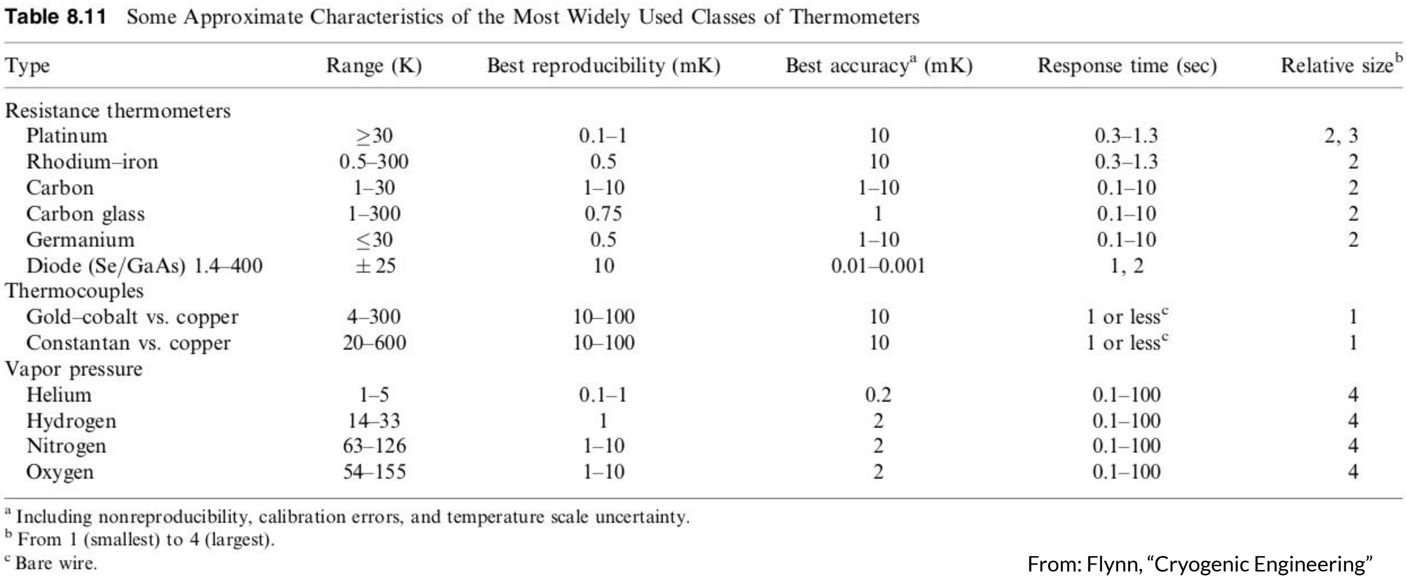


Table 8.11 Some Approximate Characteristics of the Most Widely Used Classes of Thermometers

Type	Range (K)	Best reproducibility (mK)	Best accuracy[a] (mK)	Response time (sec)	Relative size[b]
Resistance thermometers					
Platinum	≥30	0.1–1	10	0.3–1.3	2, 3
Rhodium–iron	0.5–300	0.5	10	0.3–1.3	2
Carbon	1–30	1–10	1–10	0.1–10	2
Carbon glass	1–300	0.75	1	0.1–10	2
Germanium	≤30	0.5	1–10	0.1–10	2
Diode (Se/GaAs) 1.4–400	± 25	10	0.01–0.001	1, 2	
Thermocouples					
Gold–cobalt vs. copper	4–300	10–100	10	1 or less[c]	1
Constantan vs. copper	20–600	10–100	10	1 or less[c]	1
Vapor pressure					
Helium	1–5	0.1–1	0.2	0.1–100	4
Hydrogen	14–33	1	2	0.1–100	4
Nitrogen	63–126	1–10	2	0.1–100	4
Oxygen	54–155	1–10	2	0.1–100	4

[a] Including nonreproducibility, calibration errors, and temperature scale uncertainty.

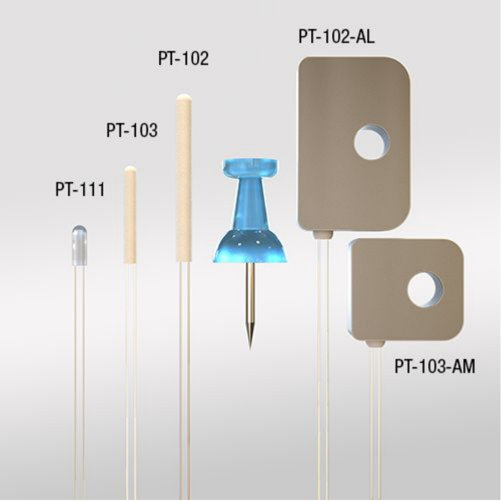
[b] From 1 (smallest) to 4 (largest).

[c] Bare wire.

From: Flynn, "Cryogenic Engineering"

Temperature

- For liquid noble gas detectors, a very common choice is wire-wound Pt100 RTDs
    - For example, LakeShore Cryotronics PT-102/3 (ceramic) or PT-111 (glass)
    - Available in a bolted surface mount package (-AL)
    - Large temperature range (14 K - 873 K) (673 K for PT-111)
    - Very high reproducibility (±5 mK @ 77K)
    - Fast response time (≈2 s @ 77 K)
- Sensor compatibility with high vacuum environment



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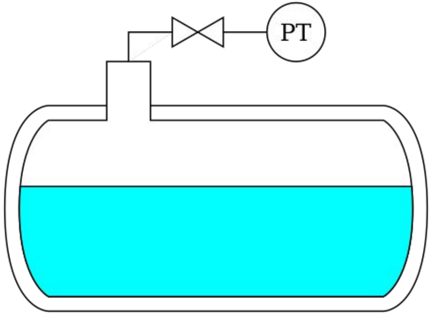
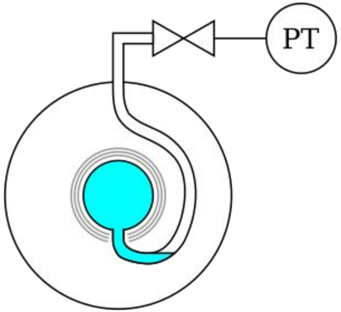
Pressure

- Possible to use room temperature transducers with increased distance for thermal decoupling from the cryogenic fluid
- Many types of commercial transducers for high-purity gases that are adequate:
  - Capacitance or strain gauge type, ≈0.25% FS accuracy
  - Small cavity volume, low Ra stainless steel 316L wetted surface, VCR fitting
- In the case of cryogenic liquids, use a sensing tube (also called “impulse line”) to the measurement point
- The sensing tube geometry should
  - Ensure the transducer is exposed to gas only (do not insulate)
  - Look for a stable equilibrium liquid position with acceptable heat leak
  - Try to minimize any hydrostatic pressure error



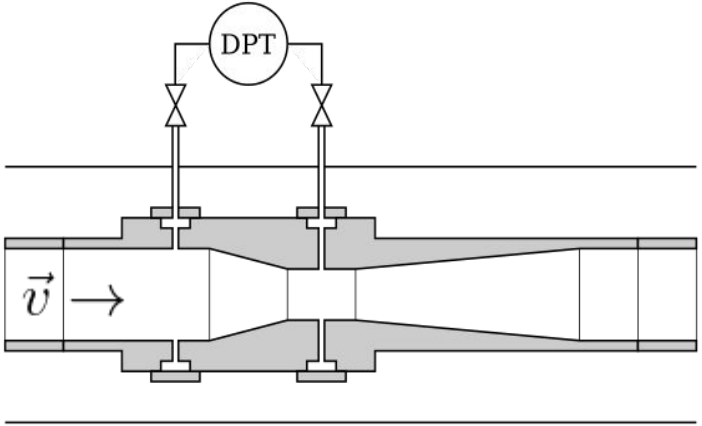


Flow

- Cryogenic liquid flows can be measured with different techniques
    - Venturi flow meter (volumetric flow rate)
    - Coriolis flow meter (mass flow rate, density)
    - Others (turbine, orifice plate, ultrasonic, etc)
- Sometimes it is simpler to use a gas mass flow meter / heat exchanger (e.g. gas-phase purification)
- Cryogenic liquid flow meters are very sensitive to two-phase flow conditions
    - Coriolis flow meters less so
- Room temperature differential pressure transducers and sensing tubes can be used for pressure drop flow meters (venturi, orifice plate, V-cone, etc)

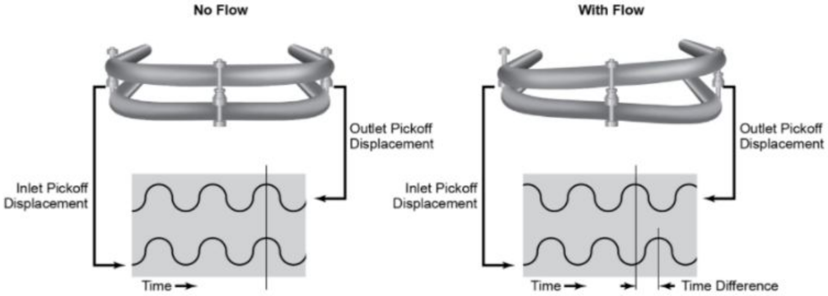
Flow

- Venturi flow meter
  - Restriction leads to velocity dependent pressure drop



$$\dot{V} = f(\Delta p)$$

- Coriolis flow meter
  - Vibrating (accelerating) tube twists with flow inside (recall that the coriolis force goes as $-\vec{\omega} \times \vec{v}$)
  - Phase shift proportional to mass flow



credit: visaya.solutions

$$\dot{m} \propto \Delta t, \quad \rho \propto f^{-2}$$

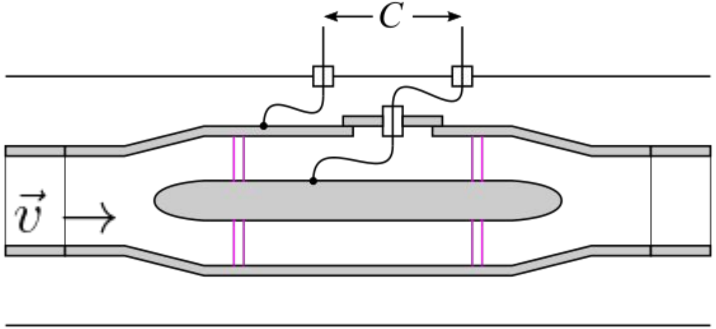
Vapor fraction

- Cryogenic liquids are often near saturated conditions, two-phase flow conditions possible
- Useful to be able to measure the vapor fraction in the fluid
- Capacitance measurement is a common technique
    - Dielectric constant (ϵ) varies with vapor fraction (φ)
    - Vapor fraction can be obtained from capacitance (C)
    - Be careful as ϵ depends on pressure and temperature

$$\epsilon = \varphi\epsilon_g + (1-\varphi)\epsilon_l$$

- Can also be used to measure two-mixture density

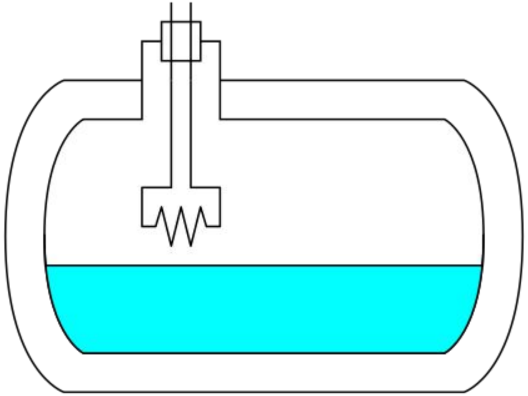
$$\rho = \varphi\rho_g + (1-\varphi)\rho_l$$



$$\frac{C}{L} = \frac{2\pi\epsilon\epsilon_0}{\ln(r_o/r_i)}$$

Level

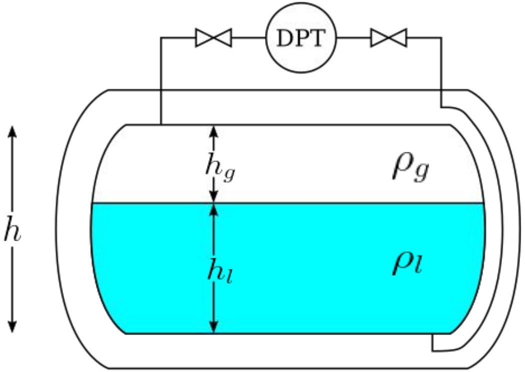
- Various techniques to measure the level of a cryogenic liquid
  - Hydrostatic pressure
  - Capacitance
  - Electrical resistance
  - Ultrasonic
- Hydrostatic and capacitance methods are the most commonly used
- Capacitance used when greater precision is required
- The electrical resistance method often used for level “switches”



$$h_{\mathrm{conv},l} \gg h_{\mathrm{conv},g}$$

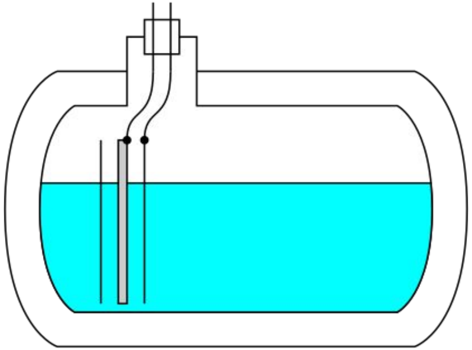
Level

- Hydrostatic pressure level measurement
  - Room temperature differential pressure transducer
  - One gas-phase and one liquid-phase sensing tube



$$\Delta p = (\rho_l - \rho_g) g h_l + \rho_g g h$$

- Capacitance level measurement
  - Cylindrical capacitor geometry
  - Sub-millimeter precision level measurement



$$C = C_l + C_g = \frac{2\pi \left[L_l(\epsilon_l - \epsilon_g) + L\epsilon_g\right]\epsilon_0}{\ln(r_i/r_o)}$$

Typical operations

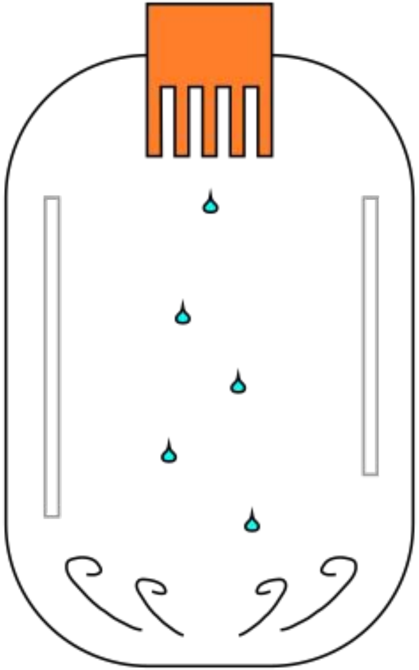
- Evacuation
    - Reduction of the quantity of impurities that will be mixed with the cryogenic liquid
- Cool-down
    - Preparation before being able to fill the detector with the cryogenic liquid
- Filling
    - Transfer from a form of storage to the detector until nominal volume reached
    - Can occur with the fluid in the liquid or gaseous phase
- Data acquisition / continuous purification
    - State in which a detector spends most of its life
- Recuperation
    - Gradual transfer of the cryogenic liquid from the detector back to storage
- Warm-up

Evacuation

- Main purpose is the reduction of the quantity of impurities mixed with the cryogenic fluid
- Often performed with turbomolecular pumps and dry backing pumps
- Not always possible (e.g. very large cryostats that cannot withstand external pressure)
    - Use dilution to reduce the quantity of impurities
- Vacuum level requirement often dictated by impurities continuously released
- Example: 1 ms electron lifetime in a 10t LXe detector (≈3500 L)
    - At equilibrium, electron lifetime ≈ $V/(\Lambda \cdot \tau)$, where Λ is impurity desorption rate, τ purification time constant
    - Assume $\tau = 1$ d, then directly $\Lambda < 3.5\ \mu s^{-1} \cdot$ L/d ≈ 0.63 mg O_2/d
    - Assume a factor 100 between cold and room temperature O_2 desorption rate
    - Estimate the minimum vacuum level requirement given vacuum pumping speed
    - For example, with a 20 L/s effective pumping speed, then p O_2 < 3.5x10^-5 mbar

Cool-down

- Reduce the thermal gradients in inner detector components that could occur during filling
- Often the cryostat is the largest thermal mass, inner detector structures contribute less but are often fragile
- Maximum cool down rate is usually constrained by the most fragile component
- With careful design it is sometimes possible to simply cool down the inner structures and fill simultaneously
- Condensation/boiling heat transfer coefficients are much larger than those from natural convection
    - Very difficult to extract extract heat from cryostat using just cold gas
    - Arrangement to have condensation/evaporation cycle
    - Limit the condensation rate to limit the rate



Cool-down

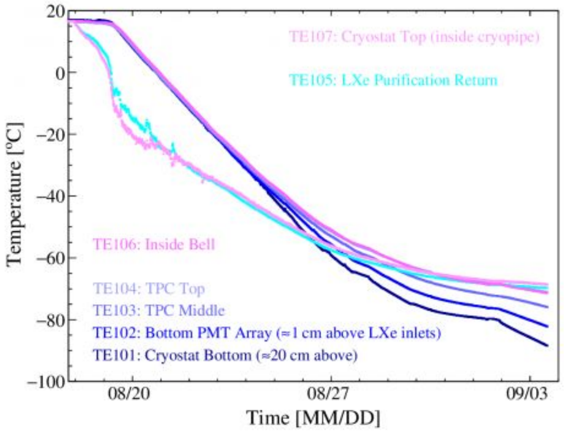
- Example
    - 1.5m OD stainless steel electrode in GXe, 150 μm OD wires, 2 cm OD circular cross section ring frame
    - Use correlation for natural convection around a cylinder (Churchill & Chu):

$$h = \frac{k}{D}\left\{0.6 + \frac{0.387\,\mathrm{Ra}_D^{1/6}}{\left[1 + (0.559/\mathrm{Pr})^{9/16}\right]^{8/27}}\right\}^2$$

    - Point mass *M* with area *A* and heat capacity *c*, cooling time constant

$$\tau = \frac{Mc}{hA}$$

    - Wire cooling time constant ≈17 s, frame cooling time constant ≈3000 s
    - Impose a maximum gas volume temperature cooling rate to satisfy maximum temperature gradient allowable

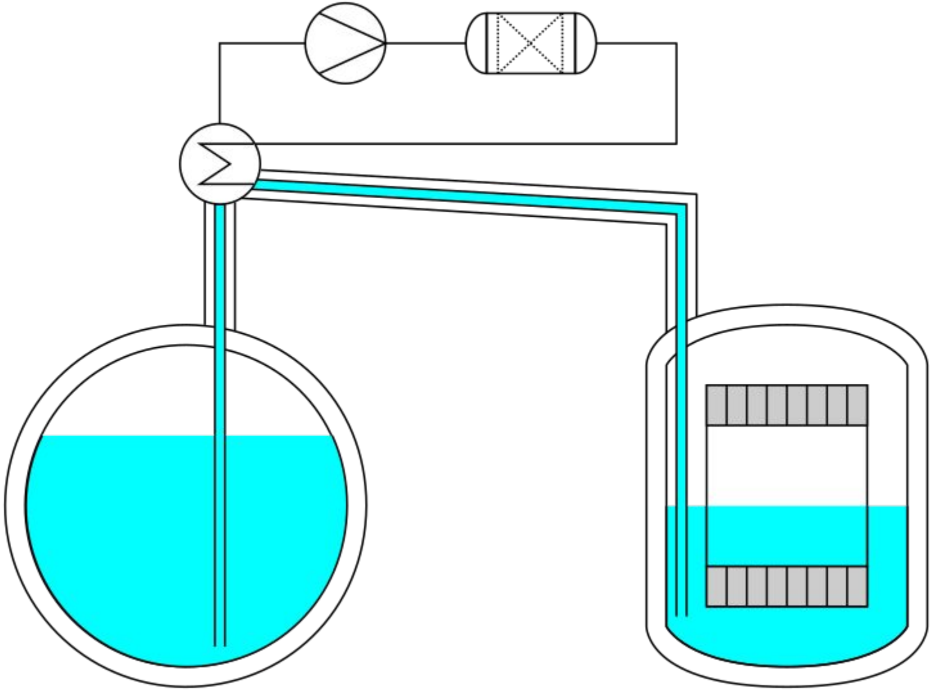


Filling

- Transfer of the cryogenic fluid from storage to the detector until nominal volume reached
- Very often performed in dynamic equilibrium at approximately constant pressure
  - With expensive cryogenic fluids, excess pressure cannot be vented
- Filling the detector in the gaseous phase
  - Filling speed might be limited by the available cooling power
  - Traditional gas-phase purification possible
- Filling the cryogenic liquid directly
  - Faster filling rates achievable even with limited cooling power
  - Cool down operation very likely a requirement
  - Use of heat exchangers make gas-phase purification also possible (XENON1T/nT)

Filling

- Example
  - XENON1T/nT: filling LXe in liquid phase
  - Use of a two-phase heat exchanger make it possible to use a gas pump and a gas purifier



Data acquisition / continuous purification

- State in which a detector spends most of its life
  - Acquiring data probably the reason the detector was built in the first place...
- Requirements on the cooling system of the detector
  - Maintain thermodynamic conditions as stable as possible
  - Extract heat constant flowing in to keep temperature, pressure, and liquid level constant
  - Equipment redundancy for continuous operation
    - Unexpected equipment failure
    - Maintenance
  - Resilience to loss of electrical power
- Continuous purification is most often required to reach required purity
  - Electronegative impurities in particular usually make continuous purification a requirement
  - Continuous removal of radioactive impurities (e.g. ^{222}Rn) can also be an important element
  - More details on this important topic discussed in the next section (purification techniques)

Recuperation

- Gradual transfer of the cryogenic liquid from the detector back to storage
- Multiple reasons why recuperation might be performed
  - Detector maintenance/upgrade is required
  - Severely limited access to laboratory is likely
  - Decommissioning of the experiment
- Gaseous phase recuperation
  - Limited by the heat that can be delivered to the liquid phase
  - Pressure reduction can be substantial if heat input is low
- Liquid phase recuperation
  - Very small decrease in pressure during recuperation

Recuperation

- Different types of storage

high-pressure gas cylinders

liquid/gas storage

solid/gas storage

Purification techniques

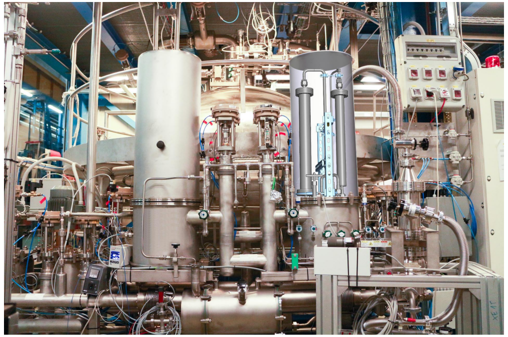
- A broad subdivision can be defined as
  - Batch purification, for the removal of impurities present in the source of noble gas used
  - Continuous purification, for the removal of impurities that are constantly released into the target
- Furthermore, we can subdivide the types of impurities to be removed
  - Electronegative impurities (O_2, H_2O)
    - Minimize the outgassing rate (material selection, preparation)
    - Measure material properties, model expected impurity load
  - Radioactive impurities (mainly ^{222}Rn but also ^{85}Kr, …)
    - ^{222}Rn
      - Minimize with mitigation techniques
      - Prevent it from reaching the target, remove it before it decays in the target
    - ^{85}Kr not produced continuously but can outgas/leak in

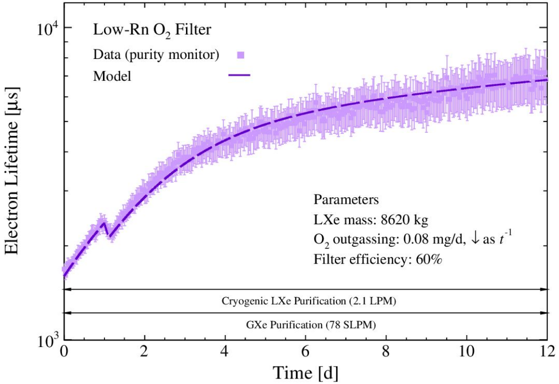
Gas-Phase Purification

- “Traditional” gas-phase purification of the cryogenic liquid via heat exchangers
- Desired system features
  - Large mass flow rates
  - Continuous operation
  - Pump maintenance while detector remains full
  - No down time from purifier replacement
  - Small contribution from radioactive impurities
- Commercial gas purifiers for large flow rates available
  - Outlet purity <0.1 ppb for O_2, H_2O, N_2, H_2, CH_4
- Clean positive displacement pumps
  - nEXO-style magnetically-coupled piston pump

Cryogenic liquid-phase purification

- Very high mass flow rates (>1 kg/s) and cleanliness achievable with specialized commercial products
- Cryogenic liquid flows through a filter vessel filled with sorbent(s)
- High performance sorbents exist but typically have high Rn emanation rate
- Low-background experiments need sorbents with high O_2 sorption speed per unit Rn emanation rate
- ≈7 ms electron lifetime with 6 kg/min in XENONnT





Cryogenic distillation

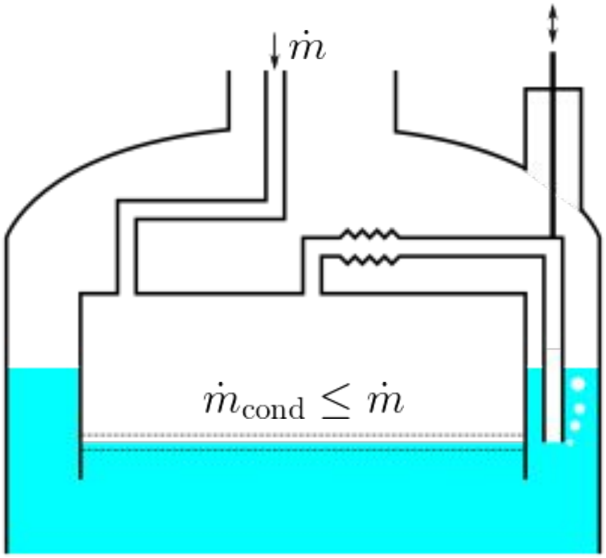
- Successfully used for ^{85}Kr removal (XMASS, XENON)
  - Can also be used for continuous removal
  - Continuous GXe-phase removal is very efficient
- Novel ^{222}Rn removal system for XENONnT
  - LXe in / LXe out @ 70 kg/h
  - Use of clean custom-developed condenser, HE, and heat pump
  - GXe volume sources are also handled by the same system
  - Additional factor of 2 reduction for LXe volume sources
- ARIA (DarkSide-20k)
  - Will be used to separate ^{39}Ar from ^{40}Ar
  - Batch purification

Special topic for dual-phase TPCs

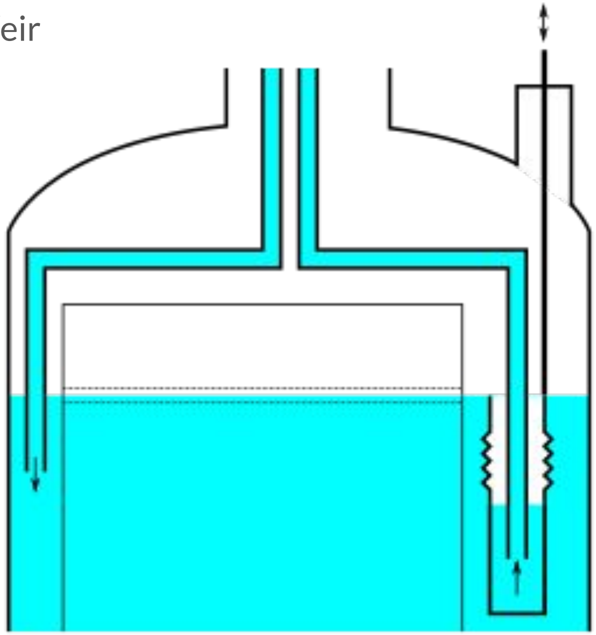
- There are a number of topics relevant to dual-phase TPCs that require an understand of cryogenics to be fully appreciated
- Examples
    - Mechanism to have an adjustable liquid level for the proportional region
    - Fluctuations in the proportional gain from pressure or level fluctuations
    - Magnitude of the velocity field in the TPC convection cell(s)

Liquid level setting

- Diving bell



- Weir



Summary

- Covered many topics related to cryogenics as applied to the design and operation of liquefied noble gas detectors
    - Heat transfer mechanisms and rates,
    - Common equipment,
    - Instrumentation,
    - Operations,
    - Purification,
    - ...
- Obviously it is difficult to go into many details in one lecture
- Hopefully this introduction and overview can serve as a guide for further exploration

Thank you for your attention!