Calculation By: M. Adamowski
Checked By:
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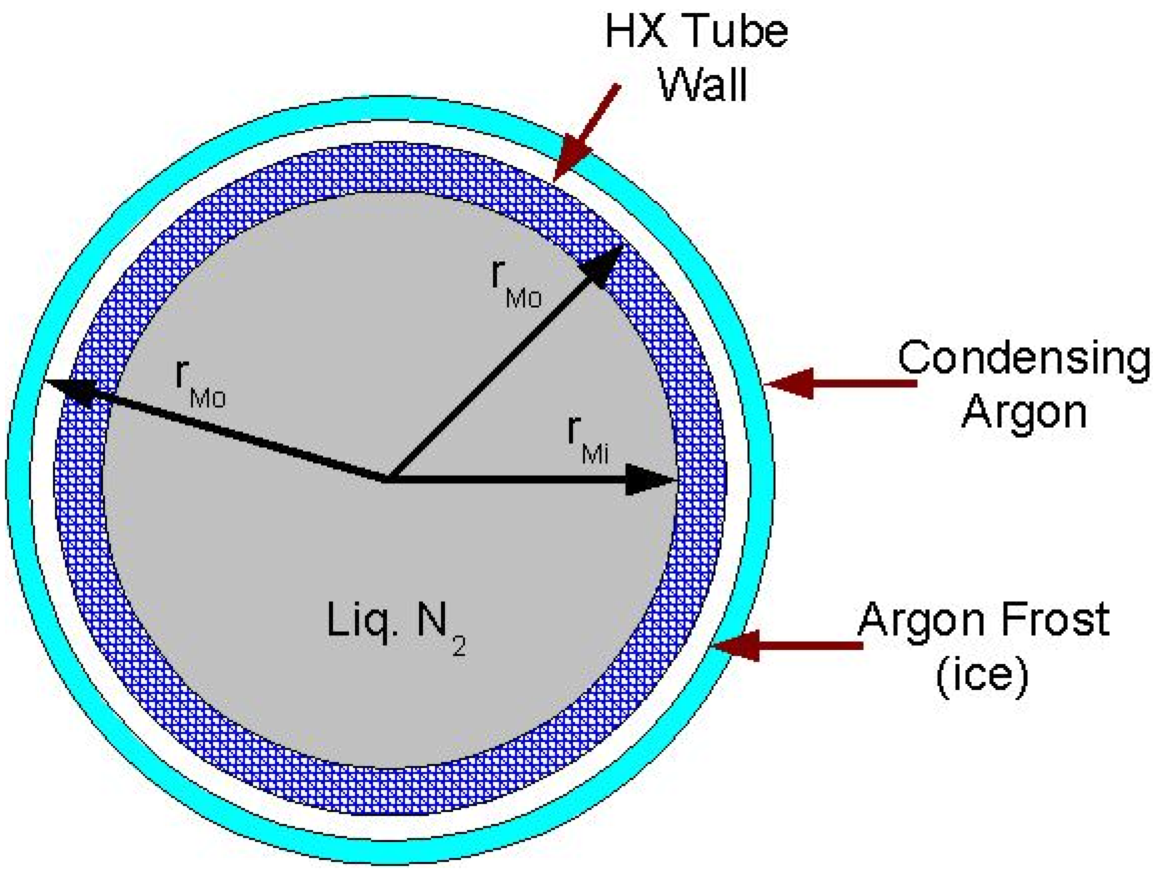
Revision: D

Tube Heat Transfer - Boiling Liquid N2 and Condensing Argon

The HX heat transfer area is estimated by calculating the heat transfer for condensing Argon on horizontal tubes with boiling liquid Nitrogen inside the tube.



Tube Data

Tube Wall Thickness

$wall_{th} := 0.028in$

Tube Outer Diameter

$Tube_{outer\_dia} := 0.25in$

$$r_{Mo} := \frac{Tube_{outer\_dia}}{2}$$

Tube Length

$L := 36 \cdot in$

Tube Inner Diameter

$Tube_{inner\_dia} := Tube_{outer\_dia} - 2 \cdot wall_{th}$

$Tube_{inner\_dia} = 0.194 \cdot in$

$$r_{Mi} := \frac{Tube_{inner\_dia}}{2}$$

metal thermal conductivity (316 SS)

$$k_M := 8.11 \cdot \frac{W}{m \cdot K}$$

Argon Data

Argon physical properties from NIST REPROP

argon liquid density

$\rho_{Ar\_l} := 1396 \cdot \frac{kg}{m^3}$

argon vapor density

$\rho_{Ar\_v} := 0.4 \cdot \frac{lb}{ft^3}$

argon liquid visc

$\mu_{Ar\_l} := .261 \cdot cP$

argon liq thermal conductivity

$k_{Ar.liq} := 128.5 \cdot \frac{mW}{m \cdot K}$

argon ice thermal conductivity

$k_{ice} := 133 \cdot \frac{mW}{m \cdot K}$

argon condensing temperature

$T_{Ar} := 87.8 \cdot K$

argon heat of vaporization

$h_{Ar\_fg} := 161 \cdot \frac{kJ}{kg}$ $\quad h_{Ar\_fg} = 69.21754 \cdot \frac{BTU}{lbm}$

argon freezing temperature

$T_{Ar\_freeze} := 83.8 \cdot K$ $\quad T_{ice} := T_{Ar\_freeze}$

Nitrogen Data

Nitrogen physical properties from NIST REPROP

Nitrogen boiling temperature

$$T_{N2} := 77.3 \cdot K$$

Nitrogen liquid thermal cond.

$$k_{N2\_liq} := 144 \cdot \frac{mW}{m \cdot K}$$

Nitrogen liquid density

$$\rho_{N2\_liq} := 807 \cdot \frac{kg}{m^3}$$

Nitrogen Heat of Vaporization

$$Hvap_{N2} := 199 \cdot \frac{kJ}{kg}$$

Nitrogen Vapor Density

$$\rho_{N2\_gas} := 4.5 \cdot \frac{kg}{m^3}$$

Nitrogen Liquid Viscosity

$$\mu_{N2\_l} := .162 \cdot cP$$

Nitrogen Liquid specific heat

$$Cp_{N2\_l} := 0.77 \cdot \frac{kJ}{kg \cdot K}$$

Mass flow of N2 based on 70% outlet vapor quality

$$Massflow_{N2} := 240 \cdot \frac{lb}{hr}$$

Heat Load

The heat load on the HX is taken as twice the heat absorbed by the LAPD tank from the environment. Using twice the tank heat provides a design margin.

$Tank_{heat} := 2106 \cdot W$ $Q_{req} := 2 \cdot Tank_{heat}$ $Q_{req} = 4212 \cdot W$

Boiling Nitrogen Heat Transfer Coefficient

Excess Nitrogen is used to keep the tube side wetted. Under these conditions the Nitrogen boiling heat transfer coefficient will be uniform for the whole tube length.

$$h_{N2\_boil} := 1500 \cdot \frac{kW}{m^2 \cdot K}$$

this N2 boiling heat transfer coefficient is at a a minimum N2 mass flux.

$$N2_{massflux\_for\_h} := 70 \cdot \frac{kg}{m^2 \cdot s}$$

ref: "Flow boiling heat transfer characteristics of nitrogen in plain and wire coil inserted tubes", International Journal of Heat and Mass Transfer 50 (2007)

Tube heat transfer

The tube heat transfer is calculated as concentric rings of heat transfer. The rings are inner tube metal surface, tube metal wall, Argon ice layer and outer ice surface. The calculations are arranged starting inside the tube at liquid N2 temperature and then proceeds through the concentric rings to the tube outside at condensing Argon temperature.

To start the calculation, initial guesses are made for the tube inside metal temperature and the heat flux, q.

Initial Guesses

$h_{Mi} := h_{N2\_boil}$ $\quad q := -200 \cdot W$

The heat transfer calculations are define with a Mathcad GIVEN block to allow use of Mathcad's equation solving ability.

Given

$$T_{Mi} := T_{N2} - \frac{q}{2 \cdot \pi \cdot r_{Mi} \cdot L \cdot h_{Mi}}$$

inner surface formula arranged to solve for inside tube metal temperature

$$T_{Mo} := T_{Mi} - q \cdot \frac{\ln\left(\frac{r_{Mo}}{r_{Mi}}\right)}{(2 \cdot \pi \cdot k_M \cdot L)}$$

metal tube wall formula arranged to solve for outside tube metal temperature

$$r_{ice} := r_{Mo} \cdot \exp\left(\frac{T_{Mo} - T_{ice}}{q} \cdot 2 \cdot \pi \cdot k_{ice} \cdot L\right)$$

Argon ice layer formula arranged to solve for the radius of the outside ice surface.

$$wall_{ice} := r_{ice} - r_{Mo}$$

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The ice outside heat transfer coefficent is for condensing Argon. This coefficient is estimated as condenstion on a horizontal tube.

$$h_{Ar\_condi} := 0.728\left[\frac{g\cdot\rho_{Ar\_l}\cdot\left(\rho_{Ar\_l}-\rho_{Ar\_v}\right)\cdot k_{Ar.liq}^{\ 3}\cdot h_{Ar\_fg}}{Tube_{outer\_dia}\cdot\mu_{Ar\_l}\cdot\left(T_{ice}-T_{Ar}\right)}\right]^{\frac{1}{4}}$$

$$h_{Ar\_cond} := \mathrm{Re}\left(h_{Ar\_condi}\right)$$ use the real portion of the 4th root solution

ref: Heat, Mass and Momentum Transfer, by Rohsenow, 1961, pg 248, Condensation on horizontal tube formula.

$$q := 2\cdot\pi\cdot r_{ice}\cdot L\cdot h_{Ar\_cond}\cdot\left(T_{ice}-T_{Ar}\right)$$ outer ice layer heat transfer formula arranged to solve for heat transferred.

Find the solution to the given equations

$\mathrm{Find}(q)$

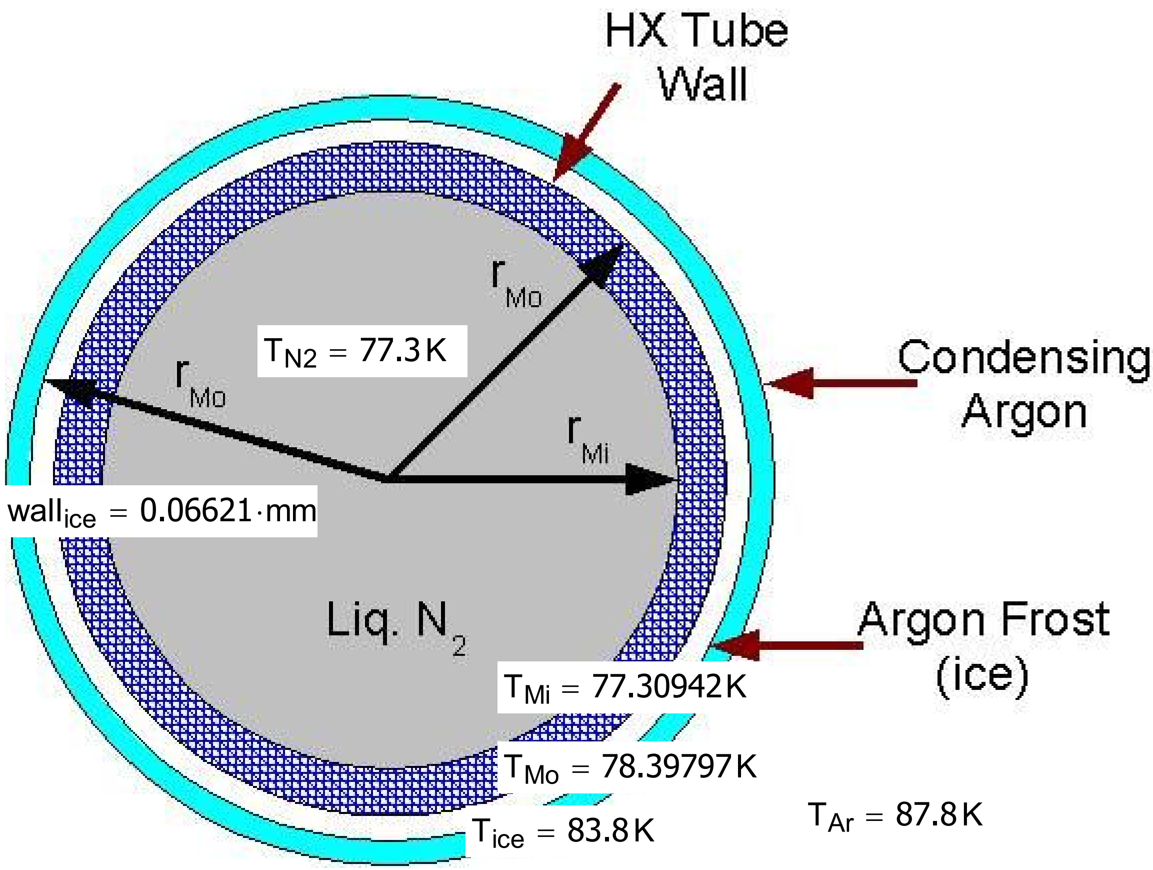
$q = -214.57319\cdot W$ $\qquad wall_{ice} = 0.06621\cdot mm$

$$heatflux_{Mi} := \frac{q}{\left(2\cdot\pi\cdot r_{Mo}\cdot L\right)} \qquad heatflux_{Mi} = -11.76293\cdot\frac{kW}{m^2}$$

$$h_{Ar\_cond} = 2880.66079\cdot\frac{W}{m^2\cdot K}$$

Summary of results for require Q of:

$Q_{req} = 4212 \cdot W$



$T_{Ar} = 87.8 K$

Estimate the Total HX area based on outside tube diameter:

$$HX_{area\_o} := 2 \cdot \pi \cdot r_{Mo} \cdot L \cdot \frac{Q_{req}}{|q|}$$

$$HX_{area\_o} = 3.85428 \cdot ft^2$$

$$HX_{tube\_count} := \frac{HX_{area\_o}}{2 \cdot \pi \cdot r_{Mo} \cdot L}$$

$$HX_{tube\_count} = 19.62967$$

N2 Mass flux

$$Massflux_{N2} := \frac{Massflow_{N2}}{HX_{tube\_count} \cdot \pi \cdot r_{Mi}^2}$$

The N2 massflux for the number of tubes needed should be equal or higher than the N2 massflux for the N2 boiling heat transfer coefficient.

$$Ans := if\left(Massflux_{N2} > N2_{massflux\_for\_h}, \text{"solution is good"}, \text{"massflux low for N2 h data"}\right)$$

Ans = "solution is good"

$$Massflux_{N2} = 80.77943 \cdot \frac{kg}{m^2 \cdot s}$$

Calc heat flux for tube inside surface

$$Heatflux_i := \frac{Q_{req}}{2 \cdot \pi \cdot r_{Mi} \cdot L \cdot \frac{Q_{req}}{|q|}}$$

$$Heatflux_i = 15158.41968 \cdot \frac{W}{m^2}$$

Calc of overall U

$$U_{all} := \frac{Q_{req}}{\left(\left|T_{N2} - T_{Ar}\right|\right) \cdot HX_{area\_o}}$$

$$U_{all} = 1120.2794 \cdot \frac{W}{m^2 \cdot K}$$

$$U_{all} = 197.29261 \cdot \frac{BTU}{hr \cdot ft^2 \cdot R}$$

Calc of tube inlet velocity

$$V_{tube\_inlet} := \frac{Massflux_{N2}}{\rho_{N2\_liq}}$$

$$V_{tube\_inlet} = 0.32841 \cdot \frac{ft}{s}$$

N2 Horizontal Tube boiling heat transfer estimate

Shah Correlation with adjustment for horizontal plain tubes
ref: Engineering Databook III by Wolverine Tube, Inc.

Vapor quality to use in calc

$x := 0.1$

Liquid Froude number

$$Fr_L := \frac{Massflux_{N2}^{2}}{\rho_{N2\_liq}^{2} \cdot g \cdot Tube_{inner\_dia}} \qquad Fr_L = 0.20728$$

IF Fr.L is greater than 0.04 then the following calc applies

calc Shah's C.o factor

$$C_o := \left(\frac{1-x}{x}\right)^{0.8} \cdot \left(\frac{\rho_{N2\_gas}}{\rho_{N2\_liq}}\right)^{0.5} \qquad C_o = 0.43308$$

set Shah's N parameter equal to C.o for this method

$N := C_o$

calc liquid Reynolds number

$$Re_L := \frac{Massflux_{N2} \cdot (1 - x) \cdot Tube_{inner\_dia}}{\mu_{N2\_l}} \qquad Re_L = 2211.3819$$

calc liquid Prandtl number

$$Pr_L := \frac{Cp_{N2\_l} \cdot \mu_{N2\_l}}{k_{N2\_liq}} \qquad Pr_L = 0.86625$$

calc liquid phase convective heat transfer coefficient by Dittus-Boelter correlation

$$\alpha_L := 0.023 \cdot Re_L^{0.8} \cdot Pr_L^{0.4} \cdot \frac{k_{N2\_liq}}{Tube_{inner\_dia}} \qquad \alpha_L = 300.776 \cdot \frac{W}{m^2 \cdot K}$$

calc convective boiling heat transfer coefficient from the liquid phase convective heat transfer coefficient

$$\alpha_{cb} := \frac{1.8 \cdot \alpha_L}{N^{-0.8}} \qquad \alpha_{cb} = 277.18293 \cdot \frac{W}{m^2 \cdot K}$$

calc the boiling number which characterizes nucleate boiling

$$B_o := \frac{Heatflux_i}{Massflux_{N2} \cdot Hvap_{N2}}$$

$$B_o = 0.00094$$

set appropriate value for Shah's F.s constant

$F_s := 15.43$

F.s equals 14.7 when B.o is greater than 0.0011
F.s equals 15.43 when B.o is less than 0.0011

calc the nucleate boiling heat transfer coefficient

$$\alpha_{nb} := \alpha_L \cdot F_s \cdot B_o^{0.5} \cdot \exp(2.74 \cdot N - 0.15)$$

$$\alpha_{nb} = 401.84662 \cdot \frac{W}{m^2 \cdot K}$$

the two phase flow boiling heat transfer coefficient is taken as the larger valve of conventive boiling or nucleate boiling

$$\alpha_{tp} := \max(\alpha_{cb}, \alpha_{nb})$$

$$\alpha_{tp} = 401.84662 \cdot \frac{W}{m^2 \cdot K}$$

The Steiner and Taborek (1992) database has the nucleate boiling heat transfer coefficient for Nitrogen as 4380 W/m2-K.

The literature value used, 1500 W/m2-K for Nitrogen boiling falls within between the conservative estimate and the database value of Steiner and Taborek. The values uses is not too conservative and not too aggressive.

ref: Engineering Data Book III, Wolverine Tube, Inc.