LIQUID NITROGEN SUBCOOLER COIL SIZING

FOR

D-ZERO UPGRADE

D-ZERO ENGINEERING NOTE #3823.115-EN-434

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Summary

The raw calculations are attached as Appendix A. The calculations provide the analysis of the heat transferred while the LN_2 subcooler is in use. In order to achieve an acceptable conclusion, the assumption of a fully developed thermal boundary layer was made. The hot fluid or the fluid condensing on the inside surface will determine the rate of heat transfer because $A_o = A_i$ and $h_o A_o \gg h_i A_i$. The conclusion drawn is to use a 1/2" OD copper tube wound approximately 8 times about an 8" diameter circle.

There are also calculations concerning the size of the nitrogen supply and subcooler vent. The maximum mass flow rate was determined as 52.5 g/s and the sizing of ~~these~~ the nitrogen supply and subcooler vent should be chosen accordingly.

SUBJECT

LN₂ SUBCOOLER COIL SIZING CALC'S

NAME
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5/11/95

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CHECKED BY: STEVE SAKLA 6-28-95

DETERMINE PROCESS STATES:

FIGURE 1: LN₂ SUBCOOLER SYSTEM.

STATE ①

$$\begin{aligned} P_1 &= 35 \text{ PSIG} \approx 3.5 \text{ ATM} \\ X_1 &= 0.0 \\ T_1 &= 89.834 \text{ K} \\ h_1 &= -95.175 \text{ J/g} \end{aligned}$$

STATE ②

$$\begin{aligned} P_2 &= 30.5 \text{ PSIG} \approx 3.0 \text{ ATM} \quad (\text{SEE E.N. \# 422}) \\ X_2 &= .032 \\ T_2 &= 88.077 \text{ K} \\ h_{2L} &= -98.938 \text{ J/g} \\ h_{2g} &= 84.167 \text{ J/g} \\ h_2 &= -93.053 \text{ J/g} \\ \mu_L &= 1,050 \mu \text{ g/cm}^3 \\ \mu_g &= 61.3 \mu \text{ g/cm}^3 \end{aligned}$$

$$h_2 = (1-x)h_{2L} + xh_{2g}$$

STATE ③ (SUBCOOLED)

$$\begin{aligned} P_3 &= 30 \text{ PSIG} \approx 3.0 \text{ ATM} \\ T_3 &= 78 \text{ K APPROX.} \\ h_3 &= -119.946 \text{ J/g} \\ v_3 &= 1.241 \text{ cc/g} \\ \dot{m}_3 &= 25.42 \text{ g/s} = 30 \text{ gph} \\ \mu_3 &= 1,485 \mu \text{ g/cm}^3 \end{aligned}$$

STATE ④ (SAT. VAPOR)

$$\begin{aligned} P_4 &= 1.0 \text{ ATM} \\ X_4 &= 1.0 \\ T_4 &\approx 77.364 \text{ K} \\ h_4 &= 77.232 \text{ J/g} \end{aligned}$$

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► DETERMINE AMOUNT OF COOLING FOR STATE ② → ③.

FROM 1st LAW:
& STEADY-STATE

$$Q = \dot{m} \Delta h = \dot{m}_3 (h_3 - h_2)$$

$$\dot{m}_3 = \frac{\dot{V}_3}{v_3} = \frac{(30 \text{ gal/hr})}{(1.241 \text{ cc/g})} \times \left(\frac{1 \text{ hr}}{3600 \text{ s}} \right) \times (3785 \text{ cc/gal}) = 25.42 \text{ g/s}$$

$$Q = (25.42 \text{ g/s}) (-119.946 \text{ J/g} + 93.053 \text{ J/g}) = \underline{-684 \text{ W}}$$

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ON P. 145 OF BARRON :

$$d\dot{Q} = -C_h dT_h$$

$$d\dot{Q} = -C_c dT_c$$

$$d\dot{Q} = U dA (T_h - T_c)$$

 $C = \dot{m} C_p$, capacity rate

► NEED TO DETERMINE LENGTH OF TUBE (ASSUME 3/4" OD) TO ACHIEVE 684 W OF COOLING.

ASSUME : 1) POOL BOILING ON OUTSIDE SURFACE (COLD FLUID)
2) CONDENSING ON INSIDE SURFACE (HOT FLUID)

$$T_{h1} = 88.1 \text{ K} \quad T_c = T_{\text{BATH}} = 77 \text{ K}$$

$$T_{h2} = 78 \text{ K}$$

TEMP. DISTRIBUTION :

FIGURE 2: TEMP. DISTRIBUTION IN LN₂ SUBCOOLER.

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► FIND h_i OF HOT FLUID :

ASSUME $\frac{3}{4}$ " OD CU TUBE , SMOOTH PIPE

$$Re_D = \frac{\rho u_m D}{\mu} \quad u_m = \frac{\dot{m}}{\rho A_c} = \frac{\dot{m}}{\rho \frac{\pi}{4} D^2} \quad \text{so } Re_D = \frac{4 \dot{m}}{\pi \mu D}$$

USE PROPERTIES @ $\bar{T}_m = 82.5 \text{ K}$: $\mu = 1,265 \mu\text{g/cm}\cdot\text{s}$, $k = .126 \text{ W/m}\cdot\text{K}$

$$Re_D = \frac{4 (25.42 \text{ g/s})}{\pi (1,265 \mu\text{g/cm}\cdot\text{s}) (.75 \text{ in}) (2.54 \text{ cm/in})} = \underline{13,431} \quad \text{TURBULENT}$$

$$Pr = 2.084$$

APPLY DITTUS - BOELTER EQN , : $Nu_D = .023 Re_D^{4/5} Pr^n$
EQN 8.60 , INCROPERA & DEWITT
 $n = 0.3 \quad \text{FOR } T_s < T_m$

ASSUME: 1) FULLY DEVELOPED FLOW (VELOCITY & THERMAL)

$$Nu_D = (.023)(13,431)^{4/5} (2.084)^{0.3} = \underline{57.5}$$

$$Nu_D = \frac{h_i D}{k}$$

$$h_i = (57.5)(.126 \text{ W/m}\cdot\text{K}) / (.75 \text{ in}) (.0254 \text{ m/in}) = \underline{380.3 \text{ W/m}^2\cdot\text{K}}$$

I WILL ASSUME A FULLY DEVELOPED THERMAL
BOUNDARY LAYER SO THAT $h_i = h_o$.

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△ NOW FIND h_o BY ASSUMING POOL BOILING OF LN₂ BATH ON OUTSIDE OF 3/4" CU TUBE. $T_{s1} = 82.5 \text{ K}$, $T_{s2} = 77.5 \text{ K}$

$$q_s/A = h_o \Delta T_E \quad \Delta T_E = T_s - T_{SAT} = T_w - T_{SAT}$$

$$\Delta T_{E1} = -310.9^\circ\text{F} + 320.8^\circ\text{F} = 9.9^\circ\text{F} \quad \text{or } 5.5 \text{ K}$$

$$\Delta T_{E2} = -319.9^\circ\text{F} + 320.8^\circ\text{F} = 0.9^\circ\text{F} \quad \text{or } 0.5 \text{ K}$$

USING ΔT_{E1} AND POOL BOILING CHART :

$$h_o = \frac{q_s''}{\Delta T_{E1}} = \frac{(9,000 \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2})}{(5.5 \text{ K})} \times \left(3.15423 \frac{\frac{\text{W}}{\text{m}^2}}{\frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2}} \right) = 5,160 \frac{\text{W}}{\text{m}^2 \cdot \text{K}}$$

* IT APPEARS THAT THE INSIDE (HOT) FLUID WILL DETERMINE RATE OF HEAT TRANSFER BECAUSE $A_o \approx A_i$ AND $h_o A_o \gg h_i A_i$. WILL DETERMINE REQUIRED LENGTH USING h_i AS CONTROLLING CRITERIA.

$$q = h_i A_i (T_{h_o} - T_{h_i}) \quad A_i = \pi D L$$

$$L = q / (h_i \pi D (T_{h_o} - T_{h_i}))$$

$$L = (-684 \text{ W}) / (380.3 \frac{\text{W}}{\text{m}^2 \cdot \text{K}} \pi (1.75 \text{ in}) (0.0254 \frac{\text{m}}{\text{in}}) (78 \text{ K} - 88 \text{ K}))$$

$$L = 3.0 \text{ m}$$

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NOW LET'S TRY TO REFINER THE CALC'S. I WILL USE 1/2" INSTEAD OF 3/4" OD CU TUBE TO INCREASE TURBULENCE AND h_i . ALSO, WILL TRY A MORE ACCURATE CORRELATION BECAUSE DITTUS-BOELTER EQN. IS KNOWN TO PRODUCE 25% ERROR.

LN₂ PROPERTIES @ T = 82.5 K :

▶ START BY FINDING h_i :

$\mu = 1,265 \mu\text{g/cm}^3$, $k = .126 \text{ W/m}\cdot\text{K}$

$$Re_D = \frac{4 \dot{m}}{\pi \mu D}$$

$$Re_D = 4(25.42 \text{ g/s}) / \pi (1,265 \mu\text{g/cm}^3) (.5") (2.54 \text{ cm/in}) = \underline{20,146}$$

$$Pr = 2.084$$

APPLY EQN 8.62a , : $Nu_D = \frac{(f/8) Re_D Pr}{1.07 + 12.7(f/8)^{1/2} (Pr^{2/3} - 1)}$
INCROPERA & DEWITT

FOR SMOOTH PIPES : $f = (1.82 \log_{10} Re_D - 1.64)^{-2}$

FROM FIG. 3 OF I & D : $f = .026$

$$Nu_D = \frac{(.026/8)(20,146)(2.084)}{1.07 + 12.7(.026/8)^{1/2} (2.084^{2/3} - 1)} = \underline{89.3}$$

$$h_i = \frac{Nu_D k}{D} = \frac{(.89.3)(.126 \text{ W/m}\cdot\text{K})}{.5" (.0254 \text{ m/in})} = \underline{886 \text{ W/m}^2\cdot\text{K}}$$

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AGAIN ASSUME FULLY DEVELOPED THERMAL BOUNDARY LAYER SO $h_i = h_o$. THEN,

$$q = h_i A_i (T_{ho} - T_{hi}) \quad A_i = \pi D L$$

$$L = q / h_i \pi D (T_{ho} - T_{hi})$$

$$L = (-684 \text{ W}) / ((886 \text{ W/m}^2 \text{ K}) \pi (.5") (.0254 \text{ m})) (78 \text{ K} - 88 \text{ K})$$

$$L = 1.93 \text{ m}$$

NEED 3.0 TURNS @ 8" Ø CIRCLE.

(ONE TURN = $\pi(8") = 25.13" = .638 \text{ m}$)

* WE ACTUALLY DIDN'T GAIN ANYTHING BECAUSE $A_i <$ THE PREVIOUS ATTEMPT. SO AS FINAL CHECK I WILL USE 2ND CORRELATION W/ 3/4" TUBE

$$Re_D = 13,431, \quad Pr = 2.084$$

$$Nu_D = \frac{(.026/8)(13,431)(2.084)}{1.07 + 12.7(.026/8)^{1/2}(2.084^{1/3} - 1)} = 59.6$$

$$h_i = \frac{Nu_D k}{D} = \frac{(59.6)(.126 \text{ W/m K})}{.75"(.0254 \text{ m})} = 394.2 \text{ W/m}^2 \text{ K}$$

$$L = (-684 \text{ W}) / (394.2 \text{ W/m}^2 \text{ K}) \pi (.75") (.0254 \text{ m}) (78 \text{ K} - 88 \text{ K}) = 2.9 \text{ m}$$

CONCLUSION: USE 1/2" OD CU TUBE WOUND ~ 8 TIMES ABOUT AN 8" Ø CIRCLE.

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- DETERMINE FLOW RATES OF ① LN₂ BATH BOIL-OFF
AND ② REQ'D SUPPLY FROM LN₂ DEWAR.

THERE ARE 2 OPERATING MODES OF THE LN₂ SUBCOOLER.

- 1) AS LN₂ SUBCOOLER
- 2) AS He COOLDOWN HEAT EXCHANGER

AS A LN₂ SUBCOOLER, $Q_{LN_2} = 684 \text{ W}$ IS REQUIRED (SEE P.2)
AND AS A He COOLDOWN HX, $Q_{He} = 10,287 \text{ W}$ IS
REQUIRED (SEE DESIGN CALC'S FOR He COOLDOWN HX & VAPORIZER).
TO FIND $\dot{m}_4|_{\text{max}}$ I WILL USE Q_{He} .

FIGURE 3: HEAT LOAD TO LN₂ SYSTEM.

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1ST DETERMINE $Q_{\text{SURROUNDINGS}}$:

FROM TEST PERFORMED ON 5/10/95 BY RUSS RUCINSKI & D. MILLER, AN UNCOVERED DEWAR WAS FOUND TO LOSE 5" OF LN₂ OVER A 5 HOUR PERIOD.

$$\text{BOILOFF} \approx 1 \text{ in/hr}$$

$$V_L = (1 \text{ in}) \frac{\pi}{4} (12 \frac{3}{4} \text{ in})^2 = 127.7 \text{ in}^3$$

$$\therefore \text{BOILOFF} = 127.7 \text{ in}^3/\text{hr}$$

FIGURE 4: DEWAR FOR LN₂ SUBCOOLER & He COOLDOWN HX.

ASSUME THAT $Q_{\text{SURROUNDINGS}} = Q_{\text{BOILOFF}}$, WHERE Q_{SUR} WILL ULTIMATELY BE THE HEAT LOAD ON THE LN₂ BATH DUE TO : CONDUCTION THROUGH TOP LID PENETRATIONS AND OTHER DEWAR HEAT LEAKS.

$$\Delta h_{\text{VAP}} = 197.6 \text{ kJ/kg}$$

FROM TABLE 4.2.19 IN "MARK'S STAND. HANDBOOK FOR M.E.'S", 9TH ED.

$$@77\text{K}, 1.0 \text{ ATM}, \rho_{\text{SAT. LIQUID}} = .808 \text{ g/cc}$$

$$@77\text{K}, 1.0 \text{ ATM}, \rho_{\text{SAT. VAPOR}} = .00457 \text{ g/cc}$$

$$@300\text{K}, 1.0 \text{ ATM}, \rho_{\text{gas}} = .00114 \text{ g/cc}$$

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SOLVING FOR $Q_{SUR} = Q_{BOILOFF}$:

$$\dot{m}_{BOILOFF} = \rho_{SAT. LIQ} \cdot \dot{V}_L$$

$$\dot{m}_{BOILOFF} = (.808 \text{ g/cc}) (2.54 \text{ cm/in})^3 (127.7 \text{ in}^3/\text{hr}) \left(\frac{1 \text{ hr}}{3600 \text{ s}} \right)$$

$$\dot{m}_{BOILOFF} = 0.470 \text{ g/s}$$

$$Q_{SUR} = Q_{BOILOFF} = \dot{m}_{BOILOFF} \cdot \Delta h_{VAP}$$

$$Q_{SUR} = (.470 \text{ g/s}) (197.6 \text{ kJ/kg}) = \underline{92.9 \text{ W}}$$

A LITTLE HIGH?
WILL USE AS
CONSERVATIVE► NOW TO FIND $\dot{m}$ OF LN₂ BOILOFF FROM THE SUBCOOLER DURING He COOLDOWN :

$$Q = Q_{He} + Q_{SUR} = \dot{m}_4 \Delta h_{VAP}$$

$$\dot{m}_4 = \frac{(10,287 \text{ W}) + (92.9 \text{ W})}{(197.6 \text{ kJ/kg})} = \underline{52.5 \text{ g/s}} \quad \text{MAXIMUM.}$$

► DURING STEADY-STATE LN₂ SUBCOOLING ?

$$Q = Q_{LN_2} + Q_{SUR} = \dot{m}_4 \Delta h_{VAP}$$

$$\dot{m}_4 = \frac{(684 \text{ W}) + (92.9 \text{ W})}{(197.6 \text{ kJ/kg})} = \underline{3.9 \text{ g/s}} \quad \sim 435 \text{ scfh}$$

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► FINALLY :

DURING He COOLDOWN -

$$\dot{m}_1 = \dot{m}_2 = \dot{m}_4 = \underline{52.5 \text{ g/s}}$$

DURING LN₂ SUBCOOLING -

$$\dot{m}_1 = \dot{m}_2 = \dot{m}_3 + \dot{m}_4 = (25.42 \text{ g/s}) + (3.9 \text{ g/s}) = \underline{29.32 \text{ g/s}}$$

RECOMMENDATIONS ⇒

- 1) USE 1/2" OD. Cu TUBE WOUND ~ 8 TIMES ABOUT AN 8" DIA. CIRCLE FOR THE LN₂ COIL.
- 2) SIZE N₂ SUPPLY, AND SUBCOOLER VENT FOR MAX. $\dot{m} = 52.5 \text{ g/s}$.

$$W_{mz} = \left(\frac{\text{Btu}}{\text{hr-ft}^2} \right) \times 3.15423$$

Figure 17. Typical pool boiling characteristic curve.