LIQUID NITROGEN SUBCOOLER FOR CALORIMETERS LN2 SUPPLY

ENGINEERING NOTE

3823.115-EN-568

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Author: Mike Sarychev

Approved: _____

Scope

This note provides calculations of heat load and coil sizing for a LN2 subcooler which will be installed in the liquid nitrogen line going from Dewar 42 to the Liquid argon calorimeters. This subcooler must improve LN2 quality and facilitate LAr pressure regulation.

System description

The system is described in Engineering note 3740.510-EN-382. This note contains the calculations of heat loads/pressure drops of the liquid Nitrogen supply line going from the Dewar 42 to the liquid Argon calorimeters, and also the sizing of existing LN2 subcooler located in the U-tube. The note is used as a reference.

Heat load and sizing calculations

The state of Nitrogen @ point 6 - ECS entrance (according to 3740.510-EN-382) is used in the calculations. The quality of liquid $x = 0.0066$ with the use of existing 75 W LN2 subcooler. It has been determined that we need 29.3 W of additional subcooling in order to obtain 100% liquid at this point with the mass flow of 25 g/s. Keeping in mind the possible error in heat transfer calculations, a 300W subcooler will be installed to replace the old 75 W subcooler.

In order to achieve an acceptable conclusion, an assumption of a fully developed 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" copper tube wound approximately 8 times about a 9" diameter circle. The pressure drop in this coil will be 0.05 psi (0.0034 atm) and can be neglected.

References

3740.510-EN-382 by David Bell/Russ Rucinski
3823.115-EN-434 by Andy Kuwazaki/Todd Leicht

Attachment: Heat load and coil sizing calculations

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According to engineering note 3740.510-EN-3A2, the state of Nitrogen in point 6 (ECS entrance) is :

$$P = 3.75 \text{ atm}$$

$$h = -92.3 \text{ J/g}$$

$$T = 90.6^\circ \text{K}$$

$$h_f = -93.475 \text{ J/g}$$

$$x = 0.0066$$

$$h_g = -85.380 \text{ J/g}$$

Additional cooling needed to have 100% liquid ($x=0$)

$$\Delta h = h_f - h_{\text{existing}} = 93.475 - 92.3 = 1.173 \text{ J/g}$$

with the flow rate of 31 gal/hr
(25 g/s)

$$Q = m \Delta h = 1.173 \cdot 25 = 29.3 \text{ W}$$

Existing subcooler is 75 W

in ideal case, we need $75 + 29.3 = 104.3 \text{ W}$

in real life, we will design a subcooler with 300 W heat load.

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State @ (1)

(per 3740.510-EN-382)

$$P = 3.37 \text{ atm.}$$

$$T = \text{XXXX} 89.5 \text{ K}$$

$$V = 1.47 \text{ cm}^3/\text{g}$$

$$x = 0.002$$

$$h = -95.8 \text{ J/g}$$

Flow calculations

$$\dot{m}_{\text{TOTAL}} = \dot{m}_{\text{boiloff}} + \dot{m}_{\text{sys.}} + \dot{m}_{\text{subcool.}}$$

$\Downarrow$
 25 g/s

As 3823.115-EN-434 for a similar Dewar, the boiloff from heat leaks to the power is 1 in per hour

$$V_c = (1") \frac{\pi}{4} (0.625 \text{ in})^2 =$$

$$= 28.6 \text{ in}^3/\text{hour} = 0.403 \text{ cm}^3/\text{s}$$

$$@ 77 \text{ K } \rho_{\text{sat. liquid}} = 0.808 \text{ g/cm}^3$$

$$\dot{m}_{\text{subcool}} = \frac{300 \text{ W}}{199} = 1.5 \text{ g/s}$$

$$\dot{m}_{\text{boiloff}} = \rho V_c = 0.808 \times 0.403 = 0.325 \text{ g/s}$$

$$\Delta h_{\text{vap}} = 47.5 \text{ cal/g} = 199 \text{ J/g}$$

Additional heat load

$$Q = \dot{m}_{\text{boiloff}} \times \Delta h_{\text{vap}} = 0.325 \times 199 = 64.7 \approx 65 \text{ W but we'll use it}$$

$$\text{Total heat load } Q = 300 \text{ W} + 65 \text{ W} = 365 \text{ W}$$

State @ (2)

$$P = 3.37 \text{ (I will neglect the pressure drop)}$$

$$h = -95.8 \text{ J/g} - \frac{365}{26.825} = -109.4 \text{ J/g}$$

$$\Downarrow$$

$$T = 83^\circ \text{ K}$$

seems too high
 → use it

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Coil Sizing

$$T_{h1} = 89.5 \text{ K}$$

$$T_{h2} = 83 \text{ K}$$

$$T_w = 26.25 \text{ K}$$

LN₂ properties @ 26.25°K

$$\mu = 1,125 \cdot 10^{-6} \text{ g/cm} \cdot \text{s}$$

$$K = 0.120 \frac{\text{W}}{\text{m} \cdot \text{K}}$$

To increase turbulence (better heat transfer)
I will use 1/2" Ø copper tube

$$Re_D = \frac{\rho \bar{V} D}{\mu} \quad \bar{V} = \frac{\dot{m}}{\rho A} = \frac{\dot{m}}{\rho \frac{\pi}{4} D} \Rightarrow$$

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

$$Re_D = \frac{4 \cdot 26.825 \text{ g/s}}{\pi \cdot 1,125 \cdot 10^{-6} \text{ g/cm} \cdot \text{s} \cdot 0.5 \text{ in} \cdot 2.54 \text{ cm/in}} = 23,916$$

per 2nd ed. of Dewitt (EQN 8-62a)

$$Nu_D = \frac{(\frac{f}{8}) Re_D Pr}{1.07 + 12.7 (\frac{f}{8})^{1/4} (Pr^{2/5} - 1)}$$

$$Pr = 1.954$$

$$Nu_D = \frac{(0.026/8) \cdot 23,916 \cdot 1.954}{1.07 + 12.7 (0.026/8)^{1/4} \cdot (1.954^{2/5} - 1)} = 102.75$$

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$$h_i = \frac{Nu_D \cdot K}{D} = \frac{602.75 \cdot 0.120 \frac{W}{m \cdot K}}{0.5 in \cdot 0.025 \frac{m}{in}} = 970 \frac{W}{m^2 K}$$

Assuming $A_o \approx A_i$, and $h_o A_o \gg h_i A_i$
for pool boiling of LN₂ outside on $\frac{1}{8}$ " ϕ tube
 $h_i = h_o$

$$q = h_i A_i \Delta T \quad A = \pi D L \quad \Delta T = T_{wall} - T_{fluid}$$

$$T_{wall} = 78 K \text{ (sat)}.$$

$$T_{fluid} = 86.25 K$$

$$\left(\frac{T_{h,i} + T_{h,o}}{2} \right)$$

$$L = \frac{q}{\pi D h \Delta T}$$

$$L = \frac{-365 W}{\pi \cdot 0.5 in \cdot 0.025 m/in \cdot 970 \frac{W}{m^2 K} \cdot (78 K - 86.25 K)} = 1.16 m = 3.81 ft$$

Cooling coil diameter will be 9", so
one turn will give us $\pi \cdot 9" = 28.26" = 2.355 ft$

$$\text{we will need } \frac{3.81}{2.355} = 1.62 \text{ turns} \Rightarrow$$

$\Rightarrow$ will make 6 turns, and the total
pipe length will be 14.13 ft

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$$\Delta P = 3.36 \cdot 10^{-6} \frac{f L W^2}{D^5 \cdot \rho}$$

@ 77K

$$\rho = 768/\text{cm}^3 = 47.5 \text{ lb/ft}^3$$

$$f = 0.026$$

$$W = 26.825 \text{ g/s} = 212 \text{ lb/hr}$$

$$d = 0.5 \text{ in}$$

$$\Delta P = 3.36 \cdot 10^{-6} \times \frac{0.026 \cdot 14.13 \cdot 212^2}{0.5^5 \cdot 47.5} =$$

$$= 0.037 \text{ psi}$$

$$\text{or } 0.0025 \text{ atm.}$$

— we can neglect it
in our calculations