Solve for convective film coefficient using: Principles of Heat Transfer by Kreith

$T_c := (273.15 - 35)K$ $T_c = 238.15K$ $kJ := 1000J$ $mbar := 10^{-3}bar$ $\mu Pa := 10^{-6}Pa$

$Q := 240W$ $L1 := 2m$ $\sigma := 0.012\frac{N}{m}$ $c_{liq} := 2039\frac{J}{kg \cdot K}$

$\rho_{liq} := 1096 \cdot \frac{kg}{m^3}$ $\rho_v := 31\frac{kg}{m^3}$ $\mu_{liq} := 178\mu Pa \cdot s$ $\mu_v := 12.\mu Pa \cdot s$

$k_l := 0.153\frac{W}{m \cdot K}$ $k_v := 0.013\frac{W}{m \cdot K}$

$h_{liq} := 123.05\frac{kJ}{kg}$ $h_v := 436.23\frac{kJ}{kg}$ $\Delta h := h_v - h_{liq}$ $\Delta h = 313.18 \cdot \frac{kJ}{kg}$ $\lambda := \Delta h$

$x_i := 0.05$ $x_o := 0.85$ $mdot := \frac{Q}{(x_o - x_i) \cdot \Delta h}$ $mdot = 9.579 \times 10^{-4}\frac{kg}{s}$

Tube dimensions $t := .012in$ wall thickness

$d_o := 2.8mm$ $d_i := d_o - 2 \cdot t$ $A_c := \frac{\pi}{4} \cdot d_i^2$ round tube

$D_h := d_i$ $D_h = 2.19 \cdot mm$ $A_t := A_c$ $P_c := \pi \cdot D_h$ $L1 = 2m$

$G1 := \frac{mdot}{A_t}$ $G1 = 254.209\frac{kg}{m^2 \cdot s}$

$h_{flux} := \frac{240W}{P_c \cdot L1}$ $h_{flux} = 1.744 \times 10^4 \cdot \frac{W}{m^2}$ $T_{sat} := T_c$ $T_{sat} = 238.15K$ fluid saturation temperature

$k_w := 200\frac{W}{m \cdot K}$ aluminum tube wall for T_{sat} = 238K the saturation pressure is 12.024bar

$P := 12.024bar$ $P = 1.202 \times 10^6 Pa$ $Pr_{liq} := \frac{\mu_{liq} \cdot c_{liq}}{k_l}$ $Pr_{liq} = 2.372$

$\alpha_{liq} := \frac{k_l}{\rho_{liq} \cdot c_{liq}}$ $\alpha_{liq} = 6.846 \times 10^{-8}\frac{m^2}{s}$ thermal diffusivity

Reference: Kreith

$i := 0..5$ $x := \begin{pmatrix} .05 \\ .1 \\ .5 \\ .6 \\ .7 \\ .85 \end{pmatrix}$ this a linear change flow quality along the ube length

$$X_{ttinverse_i} := \left(\frac{x_i}{1-x_i}\right)^{0.9} \cdot \left(\frac{\rho_{liq}}{\rho_v}\right)^{0.5} \cdot \left(\frac{\mu_v}{\mu_{liq}}\right)^{0.1} \qquad X_{ttinverse} = \begin{pmatrix} 0.321 \\ 0.628 \\ 4.54 \\ 6.54 \\ 9.734 \\ 21.632 \end{pmatrix}$$

$$Ftt_i := 2.35 \cdot \left(X_{ttinverse_i} + 0.213\right)^{0.736} \qquad Ftt = \begin{pmatrix} 1.481 \\ 2.07 \\ 7.402 \\ 9.585 \\ 12.746 \\ 22.742 \end{pmatrix}$$

convective cooling

$$h_{c_i} := 0.023 \cdot \left[\frac{G1 \cdot (1-x_i) \cdot D_h}{\mu_{liq}}\right]^{0.8} \cdot Pr_{liq}^{0.4} \cdot \frac{k_l}{D_h} \cdot Ftt_i \qquad h_c = \begin{pmatrix} 2.017 \times 10^3 \\ 2.701 \times 10^3 \\ 6.035 \times 10^3 \\ 6.538 \times 10^3 \\ 6.906 \times 10^3 \\ 7.078 \times 10^3 \end{pmatrix} \cdot \frac{W}{m^2 \cdot K}$$

h_c is the cooling from forced convection. The next step is to calculate the cooling from evaporation.

Solving for evaporation requires assuming a temperature difference between the tube wall and the saturation temperature of the fluid. After calculating this contribution we can solve for this temperature difference through the combination of both cooling mechanisms. If the end result agrees with the assumption, the process stops otherwise the process is repeated with a new assumed ΔT_{sat}

$$Re_{TP_i} := \frac{G1 \cdot (1-x_i) \cdot D_h}{\mu_{liq}} \cdot (Ftt_i)^{1.25} \cdot 10^{-4}$$

needed to calculate S_{tt}

$$Re_{TP} = \begin{pmatrix} 0.485 \\ 0.699 \\ 1.91 \\ 2.11 \\ 2.26 \\ 2.33 \end{pmatrix} \qquad Stt_i := \left[1 + 0.12 \cdot \left(Re_{TP_i}\right)^{1.14}\right]^{-0.1} \qquad Stt = \begin{pmatrix} 0.995 \\ 0.992 \\ 0.978 \\ 0.976 \\ 0.974 \\ 0.973 \end{pmatrix}$$

essentially constant over the tube length

For the assumed ΔT_{sat} (wall temp-fluid saturation temp) we calculate the value of ΔP_{sat} for C_3F_8. This value is the change in saturation pressure corresponding to the change in fluid temperature. At -35C the change in saturation pressure per degree C is 42330Pa, or for 2C ΔT_{sat}, the change is 84660Pa

$\Delta T_{sat} := 2K$ temperature difference between wall and fluid, assumed to start the process.

$\Delta p_{sat} := 84660Pa$ $\Delta p_{sat} = 846.6 \cdot mbar$ pressure difference for temperature difference of 2C

$$h_{b_i} := .00122 \cdot \left(\frac{k_l^{0.79} \cdot c_{liq}^{0.45} \cdot \rho_{liq}^{0.49}}{\sigma^{0.5} \cdot \mu_{liq}^{0.29} \cdot \lambda^{0.24} \cdot \rho_v^{0.24}} \right) \cdot \Delta T_{sat}^{0.24} \cdot \Delta p_{sat}^{0.75} \cdot Stt_i$$

$$h_b = \begin{pmatrix} 3.611 \times 10^3 \\ 3.602 \times 10^3 \\ 3.549 \times 10^3 \\ 3.541 \times 10^3 \\ 3.535 \times 10^3 \\ 3.532 \times 10^3 \end{pmatrix} \cdot \frac{W}{m^2 \cdot K} \qquad h_i := h_{c_i} + h_{b_i} \qquad h = \begin{pmatrix} 5.629 \times 10^3 \\ 6.303 \times 10^3 \\ 9.585 \times 10^3 \\ 1.008 \times 10^4 \\ 1.044 \times 10^4 \\ 1.061 \times 10^4 \end{pmatrix} \cdot \frac{W}{m^2 \cdot K}$$

overall film coefficient combining both heat transfer contributions

$$\Delta t_{b_i} := \frac{h_{flux}}{h_i} \qquad \Delta t_b = \begin{pmatrix} 3.098 \\ 2.767 \\ 1.819 \\ 1.73 \\ 1.67 \\ 1.644 \end{pmatrix} K$$

ΔT varies with position from 3 to 1.6C. We assumed 2C as an average, which occurs over most of the tube length.

We have not corrected for the falling saturation temperature due to pressure drop. We know pressure drop is insignificant, thus a correction for this effect is not needed.