Reference: Boiling and Condensation and Gas-Liquid Flow, Whalley

Frictional Pressure Drop Analysis-Stave Barrel C3F8, Quality of 5% after injection using Friedel correlation

$t := .012in \qquad mbar := 10^{-3} bar \qquad \mu Pa := 10^{-6} Pa \qquad kJ := 1000J$

$Q := 240W \qquad L1 := 2m$ tube length, round trip

$c_h := 4.9mm - 2 \cdot t \qquad c_r := \frac{4.9}{2} mm - t \qquad w_c := 2mm \qquad A_c := w_c \cdot c_h + \pi \cdot c_r^2$

$P_c := 2 \cdot w_c + 2 \cdot \pi \cdot c_r \qquad D_h := 4 \cdot \frac{A_c}{P_c} \qquad D_h = 5.272 \cdot mm \qquad A_t := A_c$

C3F8 Fluid Properties at -25C

$T_i := (273.15 - 25)K \qquad T_i = 248.15K \qquad \mu_v := 10.28 \mu Pa \cdot s \qquad \mu_{liq} := 267.5 \mu Pa \cdot s$

$c_{liq} := 1019 \frac{J}{kg \cdot K} \qquad \rho_{liq} := 1565 \cdot \frac{kg}{m^3} \qquad \rho_v := 16.39 \frac{kg}{m^3}$

$k_v := 0.009 \frac{W}{m \cdot K} \qquad k_{liq} := 0.053 \frac{W}{m \cdot K} \qquad \sigma := .015 \frac{N}{m}$ perfluoropropane surface tension at 253.15K

$h_{liq} := 173.7 \frac{kJ}{kg} \qquad h_v := 275.6 \frac{kJ}{kg} \qquad \Delta h := h_v - h_{liq} \qquad \Delta h = 101.9 \cdot \frac{kJ}{kg} \qquad \lambda := \Delta h$

Tube Fluid Parameters, based on inlet and exit flow quality

$x := .05 \qquad x_o := .85 \qquad mdot := \frac{Q}{(x_o - x) \cdot \Delta h} \qquad mdot = 2.944 \times 10^{-3} \frac{kg}{s} \qquad \nu_{liq} := \frac{\mu_{liq}}{\rho_{liq}}$

$G_{liq} := mdot \cdot (1 - x) \qquad G_{liq} = 2.797 \times 10^{-3} \frac{kg}{s} \qquad G_v := mdot - G_{liq} \qquad G_v = 1.472 \times 10^{-4} \frac{kg}{s}$

$G_t := \frac{mdot}{A_t} \qquad R_{liq} := \frac{G_t \cdot D_h}{\mu_{liq}} \qquad R_{liq} = 2.519 \times 10^3$

$R_{fgo} := \frac{G_t \cdot D_h}{\mu_v} \qquad R_{fgo} = 6.554 \times 10^4 \qquad C_{fgo} := 0.079 \cdot R_{fgo}^{-0.25} \qquad C_{fgo} = 4.937 \times 10^{-3}$

$R_{flo} := \frac{G_t \cdot D_h}{\mu_{liq}} \qquad R_{flo} = 2.519 \times 10^3 \qquad C_{flo} := 0.079 \cdot R_{flo}^{-0.25} \qquad C_{flo} = 0.011$

$\Phi 2^2 = E + \frac{3.24 \cdot F2 \cdot Hf}{(Fr)^{0.045} \cdot (We)^{0.035}}$ basic equation for two phase flow correction to single phase flow pressure drop

$$a1 := \frac{\rho_{liq} \cdot C_{fgo}}{\rho_v \cdot C_{flo}} \qquad a1 = 42.277 \qquad b1 := \frac{{G_t}^2 \cdot D_h}{\sigma} \qquad d1 := \frac{{G_t}^2}{g \cdot D_h}$$

$$Hf := \left(\frac{\rho_{liq}}{\rho_v}\right)^{0.91} \cdot \left(\frac{\mu_v}{\mu_{liq}}\right)^{0.19} \cdot \left(1 - \frac{\mu_v}{\mu_{liq}}\right)^{0.7} \qquad Hf = 33.183$$

$$We := b1 \cdot \left(\frac{x}{\rho_v} + \frac{1-x}{\rho_{liq}}\right) \qquad Fr := d1 \cdot \left(\frac{x}{\rho_v} + \frac{1-x}{\rho_{liq}}\right)^2 \qquad F2 := x^{0.78} \cdot (1-x)^{0.224} \qquad E := (1-x)^2 + x^2 \cdot a1$$

$$z := (1-x)^2 + x^2 \cdot (a1) + \frac{3.24 \cdot \left[x^{0.78} \cdot (1-x)^{0.224}\right] \cdot Hf}{\left[d1 \cdot \left(\frac{x}{\rho_v} + \frac{1-x}{\rho_{liq}}\right)^2\right]^{0.045} \cdot \left[b1 \cdot \left(\frac{x}{\rho_v} + \frac{1-x}{\rho_{liq}}\right)\right]^{0.035}}$$

to be integrated over tube length

$$dpdz_{lo} := \frac{2 \cdot C_{flo} \cdot {G_t}^2}{D_h \cdot \rho_{liq}}$$

frictional pressure drop based on fluid being solely single phase

$$\Delta P_f := dpdz_{lo} \cdot \frac{L1}{0.85 - 0.05} \cdot \int_{0.05}^{0.85} (1-x)^2 + x^2 \cdot (a1) + \frac{3.24 \cdot \left[x^{0.78} \cdot (1-x)^{0.224}\right] \cdot Hf}{\left[d1 \cdot \left(\frac{x}{\rho_v} + \frac{1-x}{\rho_{liq}}\right)^2\right]^{0.045} \cdot \left[b1 \cdot \left(\frac{x}{\rho_v} + \frac{1-x}{\rho_{liq}}\right)\right]^{0.035}} \, dx$$

$$\Delta P_f = 3.639 \times 10^3 \cdot Pa \qquad \Delta P_f = 36.394 \cdot mbar$$

$$\int_{0.05}^{0.85} (1-x)^2 + x^2 \cdot (a1) + \frac{3.24 \cdot \left[x^{0.78} \cdot (1-x)^{0.224}\right] \cdot Hf}{\left[d1 \cdot \left(\frac{x}{\rho_v} + \frac{1-x}{\rho_{liq}}\right)^2\right]^{0.045} \cdot \left[b1 \cdot \left(\frac{x}{\rho_v} + \frac{1-x}{\rho_{liq}}\right)\right]^{0.035}} \, dx = 32.978$$

this is the correction for the two phase flow, as a multiplier

$$\Delta P_{lo} := 2 \cdot \frac{C_{flo} \cdot G_t^2}{D_h \cdot \left(\frac{x}{\rho_v} + \frac{1-x}{\rho_{liq}}\right)^{-1}} \cdot L1 \qquad \Delta P_{lo} = 5.054 \cdot mbar$$

$$\Delta P := \Delta P_{lo} + \Delta P_f \qquad \Delta P = 41.447 \cdot mbar$$

Reference: Evaporative Cooling-Conceptual Design for ATLAS SCT, T.O. Niinikoski

Pressure drop due to momentum transfer , inlet to outlet, $\Delta P_m = \Phi_m mdot^2 / (At^2 \rho_{liq})$

$$x_{in} := 0.05 \qquad x_{out} := 0.85$$

$$\rho_{hi} := \left(\frac{x_{in}}{\rho_v} + \frac{1-x_{in}}{\rho_{liq}}\right)^{-1}$$ homogeneous flow density $\rho_{hi} = 273.398 \frac{kg}{m^3}$ at inlet

$$\frac{\rho_{liq}}{\rho_{hi}} = 5.724 \qquad \frac{\rho_v}{\rho_{hi}} = 0.06$$ volume fraction of constituents at the inlet

$$\rho_{ho} := \left(\frac{x_{out}}{\rho_v} + \frac{1-x_{out}}{\rho_{liq}}\right)^{-1}$$ homogeneous flow density $\rho_{ho} = 19.247 \frac{kg}{m^3}$ at outlet

Relative volume fraction of liquid and vapor phases at the inlet and exit

$$j_{in} := \frac{x_{in} \cdot mdot}{\rho_v \cdot A_t} + \frac{(1-x_{in}) \cdot mdot}{\rho_{liq} \cdot A_t} \qquad j_{in} = 0.467 \frac{m}{s}$$ total volume flux at inlet

$$j_o := \frac{x_o \cdot mdot}{\rho_v \cdot A_t} + \frac{(1-x_o) \cdot mdot}{\rho_{liq} \cdot A_t} \qquad j_o = 6.64 \frac{m}{s}$$ total volume flux at exit

$$j_{vin} := \frac{x_{in}}{x_{in} + (1-x_{in}) \cdot \frac{\rho_v}{\rho_{liq}}} \qquad j_{vin} = 0.834$$ volume fraction of vapor at inlet

$$j_{liqin} := 1 - j_{vin} \qquad j_{liqin} = 0.166$$ volume fraction of liquid at inlet

$$j_{vo} := \frac{x_o}{x_o + (1-x_o) \cdot \frac{\rho_v}{\rho_{liq}}} \qquad j_{vo} = 0.998$$ volume fraction of vapor at inlet

$j_{liqo} := 1 - j_{vo}$ $\qquad j_{liqo} = 1.845 \times 10^{-3}$ volume fraction of liquid at inlet

$$\Phi_m := \frac{(1 - x_o)^2}{j_{liqo}} - \frac{(1 - x_{in})^2}{j_{liqin}} + \left(\frac{x_o^{\ 2}}{j_{vo}} - \frac{x_{in}^{\ 2}}{j_{vin}}\right)\frac{\rho_{liq}}{\rho_v} \qquad \Phi_m = 75.588$$

Pressure difference to momentum change ΔP_m

$$\Delta P_m := \Phi_m \cdot \frac{mdot^2}{A_t^{\ 2} \cdot \rho_{liq}} \qquad \Delta P_m = 7.888 \cdot mbar$$

Total Pressure Drop $\qquad \Delta P_T := \Delta P + \Delta P_m \qquad \Delta P_T = 49.335 \cdot mbar$

<u>A new source for predicting pressure drop</u>

R. Reinhard, Y. Hwang Vapor Compression Heat Pumps with Refrigerant Mixtures.

Martinelli and Nelson Correlation

C_{fgo} agrees with their f_{fo} and since $dpdz_{lo}$ = their same term

$$\Delta P_{fnew} := dpdz_{lo} \cdot \frac{L1}{(0.85 - 0.05)} \cdot \int_{0.05}^{0.85} \left(1 + \frac{1}{x^{0.5}}\right)^4 \cdot (1 - x)^{1.75}\, dx$$

$\Delta P_{fnew} = 5.111 \times 10^3 Pa \qquad \Delta PTnew := \Delta P_{fnew} + \Delta P_m$

$\Delta PTnew = 5.899 \times 10^3 Pa \qquad \Delta PTnew = 58.994 \cdot mbar$ $\qquad$ with acceleration pressure drop

Change in Temparture

The change in saturation temperature corresponding to the pressure drop is as follows:

use higher of <u>two methods and use the change in ΔT/ΔP</u>

at -25C the ΔT/ΔP= K/6800Pa

$$\Delta Tsat := \Delta PTnew \frac{K}{6800Pa}$$

use 59mbar for Table 4

$\Delta Tsat = 0.868\,K$

use 1.0C for Table 4