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

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

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

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

$d_o := 4.9mm$ $\quad d_i := d_o - 2 \cdot t$ $\quad A_c := \frac{\pi}{4} \cdot d_i^2$ round tube

$D_h := d_i$ $\quad D_h = 4.29 \cdot mm$ $\quad A_t := A_c$

C3F8 Fluid Properties at -25C

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

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

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

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

Tube Fluid Parameters, based on inlet and exit flow quality

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

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

$G_t := \frac{mdot}{A_t}$ $\quad R_{liq} := \frac{G_t \cdot D_h}{\mu_{liq}}$ $\quad R_{liq} = 3.266 \times 10^3$

$R_{fgo} := \frac{G_t \cdot D_h}{\mu_v}$ $\quad R_{fgo} = 8.499 \times 10^4$ $\quad C_{fgo} := 0.079 \cdot R_{fgo}^{-0.25}$ $\quad C_{fgo} = 4.627 \times 10^{-3}$

$R_{flo} := \frac{G_t \cdot D_h}{\mu_{liq}}$ $\quad R_{flo} = 3.266 \times 10^3$ $\quad C_{flo} := 0.079 \cdot R_{flo}^{-0.25}$ $\quad C_{flo} = 0.01$

$$\Phi 2^2 = E + \frac{3.24 \cdot F2 \cdot Hf}{(Fr)^{0.045} \cdot (We)^{0.035}}$$

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

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

$$\Delta P_f = 1.007 \times 10^4 \cdot Pa \qquad \Delta P_f = 100.7 \cdot mbar$$

$$\int_{0.05}^{0.85} (1-x)^2 + x^2 \cdot (a1) + \frac{3.24 \cdot \left[x^{0.78} \cdot (1-x)^{0.224}\right] \cdot Hf}{\left[d1 \cdot \left(\frac{x}{\rho_v} + \frac{1-x}{\rho_{liq}}\right)^2\right]^{0.045} \cdot \left[b1 \cdot \left(\frac{x}{\rho_v} + \frac{1-x}{\rho_{liq}}\right)\right]^{0.035}} \, dx = 31.205$$

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

$$\Delta P_{lo} := 2 \cdot \frac{C_{flo} \cdot G_t^{\,2}}{D_h \cdot \left(\frac{x}{\rho_v} + \frac{1-x}{\rho_{liq}} \right)^{-1}} \cdot L1 \qquad \Delta P_{lo} = 14.778 \cdot \text{mbar}$$

$$\Delta P := \Delta P_{lo} + \Delta P_f \qquad \Delta P = 115.477 \cdot \text{mbar}$$

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

$$j_{in} := \frac{x_{in} \cdot mdot}{\rho_v \cdot A_t} + \frac{(1-x_{in}) \cdot mdot}{\rho_{liq} \cdot A_t}$$ $j_{in} = 0.745 \frac{m}{s}$ total volume flux at inlet

$$j_o := \frac{x_o \cdot mdot}{\rho_v \cdot A_t} + \frac{(1-x_o) \cdot mdot}{\rho_{liq} \cdot A_t}$$ $j_o = 10.58 \frac{m}{s}$ total volume flux at exit

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

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

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

$j_{liqo} := 1 - j_{vo}$ $j_{liqo} = 1.845 \times 10^{-3}$ 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

$$\Delta P_m := \Phi_m \cdot \frac{mdot^2}{A_t^{\,2} \cdot \rho_{liq}} \qquad \Delta P_m = 20.029 \cdot mbar$$

Total Pressure Drop $\Delta P_T := \Delta P + \Delta P_m$ $\Delta P_T = 135.506 \cdot mbar$

A new source for predicting pressure drop

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

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

$\Delta P_{fnew} = 1.494 \times 10^4 Pa$ $\Delta PTnew := \Delta P_{fnew} + \Delta P_m$

$\Delta PTnew = 1.695 \times 10^4 Pa$ $\Delta PTnew = 169.474 \cdot mbar$

Change in TempartURE

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

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

at -25C the ΔT/ΔP= K/6800Pa

$$\Delta Tsat := \Delta PTnew \frac{K}{6800Pa}$$ **use 170mbar for Table 4**

$\Delta Tsat = 2.492 K$ **use 2.5C for Table 4**