

Reference: Boiling and Condensation and Gas-Liquid Flow, Whalley**Frictional Pressure Drop Analysis-Stave Barrel C3F8, Quality of 5% after injection using Friedel correlation**

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

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

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

$$D_h := d_i \quad D_h = 4.29\text{ mm} \quad A_t := A_c$$

C3F8 Fluid Properties at -25C

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

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

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

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

Tube Fluid Parameters, based on inlet and exit flow quality

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

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

$$G_t := \frac{m\dot{v} \cdot 2}{A_t} \quad R_{liq} := \frac{G_t \cdot D_h}{\mu_{liq}} \quad R_{liq} = 6.532 \times 10^3$$

$$R_{fg0} := \frac{G_t \cdot D_h}{\mu_v} \quad R_{fg0} = 1.7 \times 10^5 \quad C_{fg0} := 0.079 \cdot R_{fg0}^{-0.25} \quad C_{fg0} = 3.891 \times 10^{-3}$$

$$R_{flo} := \frac{G_t \cdot D_h}{\mu_{liq}} \quad R_{flo} = 6.532 \times 10^3 \quad C_{flo} := 0.079 \cdot R_{flo}^{-0.25} \quad C_{flo} = 8.787 \times 10^{-3}$$

$$\Phi_2^2 = E + \frac{3.24 \cdot F_2 \cdot H_f}{(Fr)^{0.045} \cdot (We)^{0.035}}$$

basic equation for two phase flow correction to single phase flow pressure drop

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

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

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

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

to be integrated over tube length

$$\frac{2 \cdot C_{flo} \cdot G_t^2}{D_h \cdot \rho_{liq}} \quad \text{frictional pressure drop based on fluid being solely single phase}$$

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

$$\Delta P_f = 3.133 \times 10^4 \text{ Pa} \quad \Delta P_f = 313.339 \text{ mbar}$$

$$\int_{0.05}^{0.85} (1-x)^2 + x^2 \cdot (a1) + \frac{3.24 \cdot [x^{0.78} \cdot (1-x)^{0.224}] \cdot H_f}{\left[d1 \cdot \left(\frac{x}{\rho_v} + \frac{1-x}{\rho_{liq}} \right)^2 \right]^{0.045} \cdot \left[b1 \cdot \left(\frac{x}{\rho_v} + \frac{1-x}{\rho_{liq}} \right) \right]^{0.035}} dx = 28.868$$

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

Reference: Evaporative Cooling-Conceptual Design for ATLAS SCT, T.O. NiinikoskiPressure drop due to momentum transfer , inlet to outlet, $\Delta P_m = \Phi_m m\dot{v}^2 / (A t^2 \rho_{liq})$

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

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

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

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

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

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

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

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

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

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

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

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

Pressure difference to momentum change ΔP_m

$$\Delta P_m := \Phi_m \cdot \frac{\dot{m}^2}{A_t^2 \cdot \rho_{liq}} \quad \Delta P_m = 20.029 \text{ mbar}$$

Total Pressure Drop $\Delta P := \Delta P_f + \Delta P_m$ $\Delta P = 333.368 \text{ mbar}$