

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

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

$$Q := 240 \text{W} \quad L1 := 4 \text{m} \quad \text{tube length, round trip}$$

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

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

**C3F8 Fluid Properties at -25C**

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

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

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

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

**Tube Fluid Parameters, based on inlet and exit flow quality**

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

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

$$G_t := \frac{\dot{m}}{A_t} \quad R_{\text{liq}} := \frac{G_t \cdot D_h}{\mu_{\text{liq}}} \quad R_{\text{liq}} = 2.519 \times 10^3$$

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

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

$$\Phi_2^2 = E + \frac{3.24 \cdot F_2 \cdot H_f}{(\text{Fr})^{0.045} \cdot (\text{We})^{0.035}} \quad \text{basic equation for two phase flow correction to single phase flow pressure drop}$$

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

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

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

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

$$dpdz_{1o} := \frac{2 \cdot C_{flo} \cdot G_t^2}{D_h \cdot \rho_{liq}} \quad \text{frictional pressure drop based on fluid being solely single phase}$$

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

$$\Delta P_f = 7.279 \times 10^3 \cdot \text{Pa} \quad \Delta P_f = 72.787 \cdot \text{mbar}$$

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

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

$$\Delta P_{lo} := 2 \cdot \frac{C_{flo} \cdot G_t^2}{D_h \cdot \left( \frac{x}{\rho_v} + \frac{1-x}{\rho_{liq}} \right)^{-1}} \cdot L1 \quad \Delta P_{lo} = 10.107 \cdot \text{mbar}$$

$$\Delta P := \Delta P_{lo} + \Delta P_f \quad \Delta P = 82.894 \cdot \text{mbar}$$

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

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

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

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

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

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

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

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

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

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

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

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

$$j_{liq0} := 1 - j_{vo} \quad j_{liq0} = 1.845 \times 10^{-3} \text{ volume fraction of liquid at inlet}$$

$$\Phi_m := \frac{(1 - x_o)^2}{j_{liq0}} - \frac{(1 - x_{in})^2}{j_{liqin}} + \left( \frac{x_o^2}{j_{vo}} - \frac{x_{in}^2}{j_{vin}} \right) \frac{\rho_{liq}}{\rho_v} \quad \Phi_m = 75.588$$

Pressure difference to momentum change  $\Delta P_m$

$$\Delta P_m := \Phi_m \cdot \frac{\dot{m}^2}{A_t^2 \cdot \rho_{liq}} \quad \Delta P_m = 7.888 \cdot \text{mbar}$$

**Total Pressure Drop**  $\Delta P_T := \Delta P + \Delta P_m \quad \Delta P_T = 90.782 \cdot \text{mbar}$

**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  $f_{f0}$  and since  $dpdz_{l0} =$  their same term

$$\Delta P_{fnew} := dpdz_{l0} \cdot \frac{L1}{(0.85 - 0.05)} \cdot \int_{0.05}^{0.85} \left( 1 + \frac{1}{x^{0.5}} \right)^4 \cdot (1 - x)^{1.75} dx$$

$$\Delta P_{fnew} = 1.022 \times 10^4 \text{ Pa} \quad \Delta P_{Tnew} := \Delta P_{fnew} + \Delta P_m$$

$$\Delta P_{Tnew} = 1.101 \times 10^4 \text{ Pa} \quad \Delta P_{Tnew} = 110.101 \cdot \text{mbar} \quad \text{with acceleration pressure drop}$$

**Change in Temperature**

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

use higher of two methods and use the change in  $\Delta T/\Delta P$

at -25C the  $\Delta T/\Delta P = K/6800\text{Pa}$

$$\Delta T_{sat} := \Delta P_{Tnew} \frac{K}{6800\text{Pa}} \quad \text{use 110mbar for Table 4}$$

$$\Delta T_{sat} = 1.619\text{K} \quad \text{use 1.6C for Table 4}$$