

I. PRESSURE DROP IN D0 RUN2B STAVE

Giobatta Lanfranco

*Fermi National Accelerator Laboratory
Particle Physics Division / Silicon Engineering Group - Mechanical Dep.
e-mail: giobatta@fnal.gov*

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1. Abstract

The D0 Run2b stave structure has been tested to determine the pressure drop along the cooling line and suggest a possible cooling pipe size. The measured pressure drop, charted versus the flow rate, shows good agreement with what is theoretically predicted, the latter underestimating the experimental data in the worst case with a 5.5% error.

At a fixed flow rate of 175-ml/min and bulk temperature of -15°C, a cooling pipe formed from a 0.158” (4.0mm) ID tube would meet the 3.0 psi target pressure drop. With the same piping and a bulk temperature of -10°C the pressure drop is around 2.3 psi.

2. Instrumentation

The flowmeter (Gilmont model GF 6540 1230, steel ball 230 type) used for the flow measurements is provided with software for converting the scale division reading into the volumetric flow rate for any given fluid viscosity and density. We have determined the accuracy of this software by calibrating the device using a graduated beaker and measuring the elapsed time with a chronometer. A comparison between the flow rate directly measured and the values provided by Gilmont is charted in Figure I-1. The measured flows are typically 10% below those calculated from the Gilmont software.

The temperature in the fluid has been measured at the inlet and the outlet of the flowmeter using two platinum RTDs of 1000 Ω impedance produced by Sensor Scientific¹.

¹ Permissible deviation in °C = $\pm [0.3 + 0.005 \times T]$

The differential pressure between the inlet and the outlet has been measured using a gage with a resolution of 0.05 psi and a full scale of 5 psi.

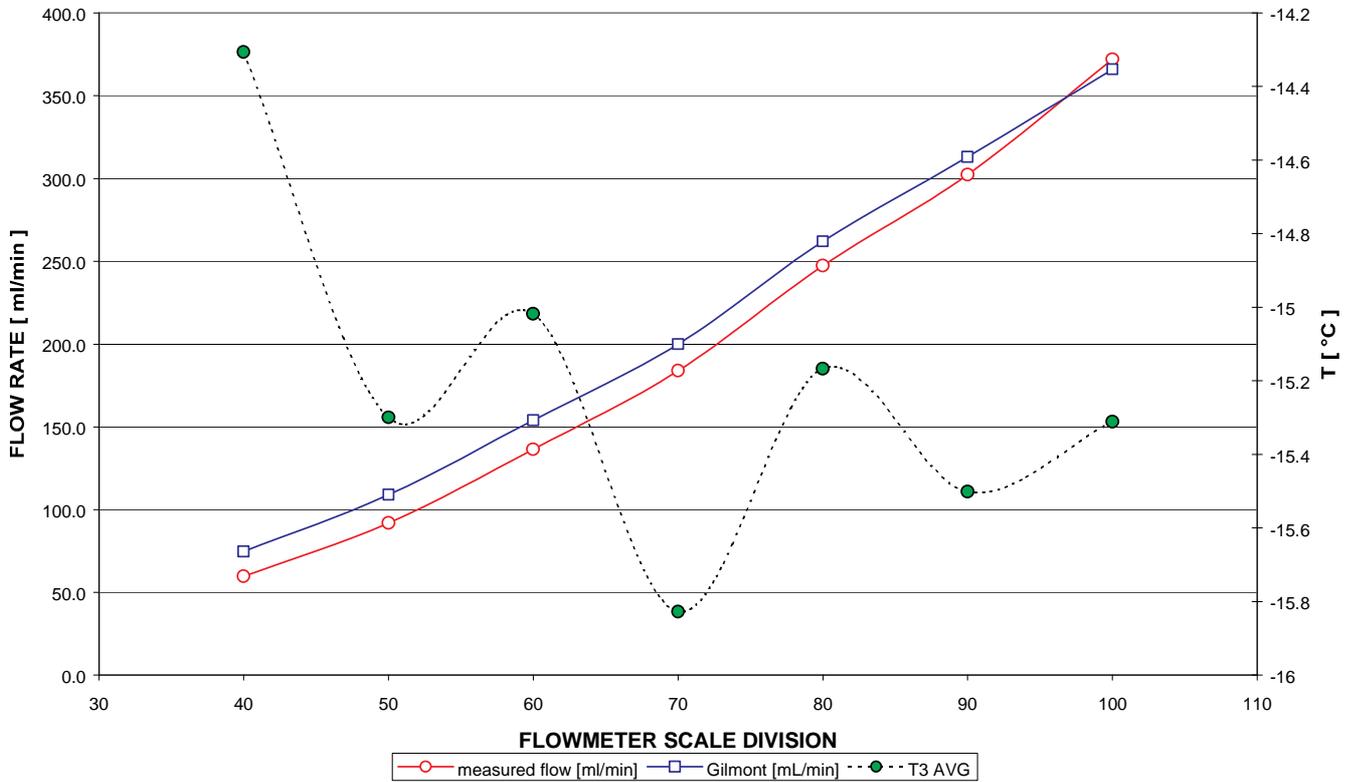


Figure I-1 - Comparison between measured flow rate and values provided by Gilmont, the flowmeter manufacturer. The chart also shows the temperature of the fluid at each measurement. Coolant: ethylene glycol 42% by mass.

3. The stave geometry

The stave used for the test is a full-scale mockup. Starting from a round PEEK tube, whose inner diameter is 0.156” with a wall thickness of 4 mils, the cooling channel is formed by squeezing the pipe between two carbon fiber skins into a stadium shape cross section approximately 5.5 mm wide and 2.0 mm high. The total length of the cooling tube is about 1400 mm, including the U shape elbow and the two aluminum fittings. This prototype has the U-shaped elbow formed from round aluminum tubing of 3/16” ID. The points where the differential pressure measurement is taken are 18 inches away from the stave. The cooling lines outside the stave have an inner diameter of 3/16”.

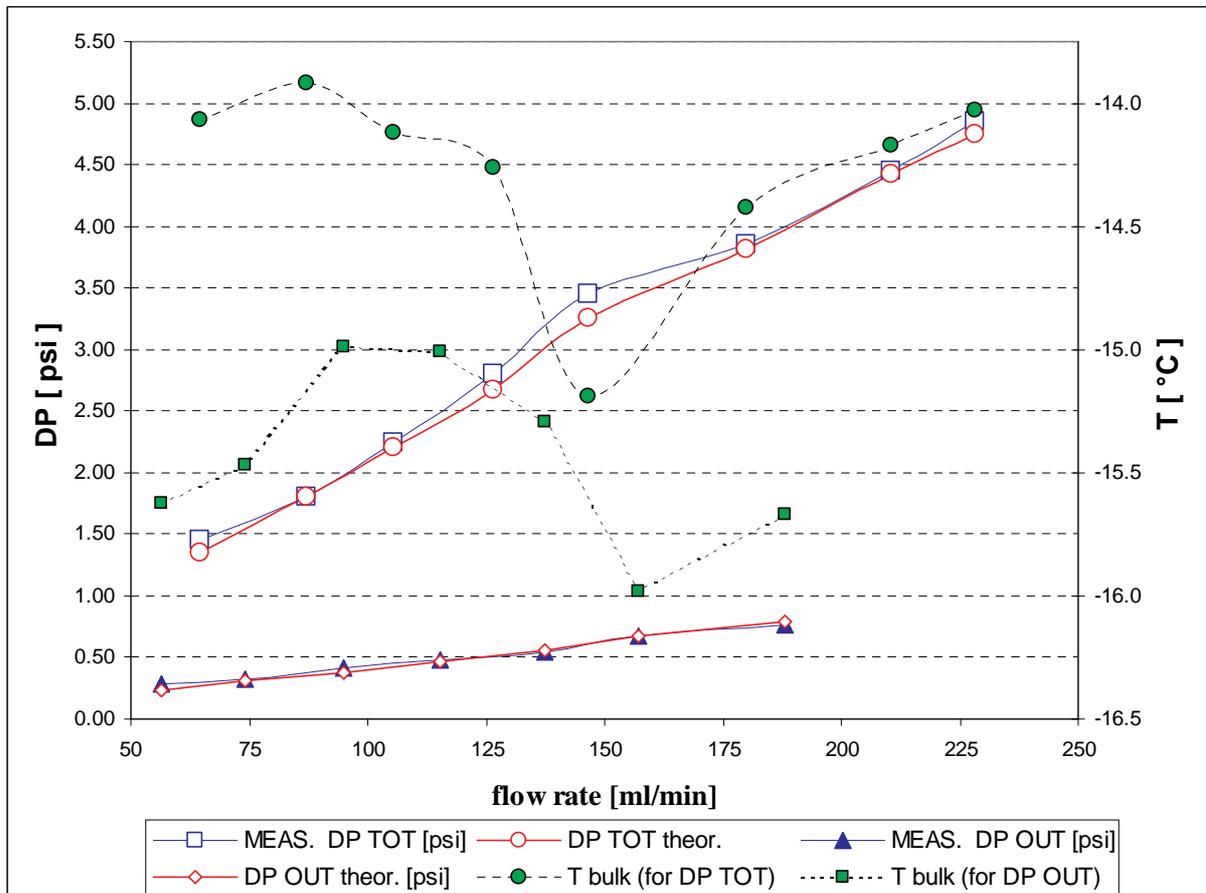


Figure I-2 - Measured and theoretically predicted pressure drop between the two control points (18" from the stave inlet) versus flow rate (upper curves). The lower curves show the measured and theoretically predicted pressure drop along the supply/return lines between the control points where the pressure is measured and the stave connections. The temperature of the fluid at each measurement is also shown. Coolant: ethylene glycol 42% by mass.

4. Results

Figure I-2 shows a comparison between the measured and the theoretically predicted pressure drop between the two control points (18" from the stave inlet/outlet), charted versus the flow rate. Operating the system with a low impedance jumper in place of the stave it has been possible to measure the pressure drop along the supply/return lines; this measurement is compared with the theoretical expectation in Figure I-2. The graph reports the value of bulk temperature at each measured point. The flow rates presented in Figure I-2 have been corrected to account for the difference between the Gilmont software calculation and our measured flow data using a linear interpolation.

The theoretical pressure drop has been calculated taking into account the dependency of the friction coefficient on the pipe cross sectional shape and assuming, given the low Reynolds number, fully

developed laminar flow. There is excellent agreement between theory and experiment. For example, the theoretical expectation accurately predicts the observed pressure increase when the fluid temperature dropped to -15.4°C .

In Figure I-3 the estimated pressure drop is charted versus the cooling pipe width, given a fixed flow rate of 175 ml/min and fluid bulk temperatures of -10°C and -15°C .

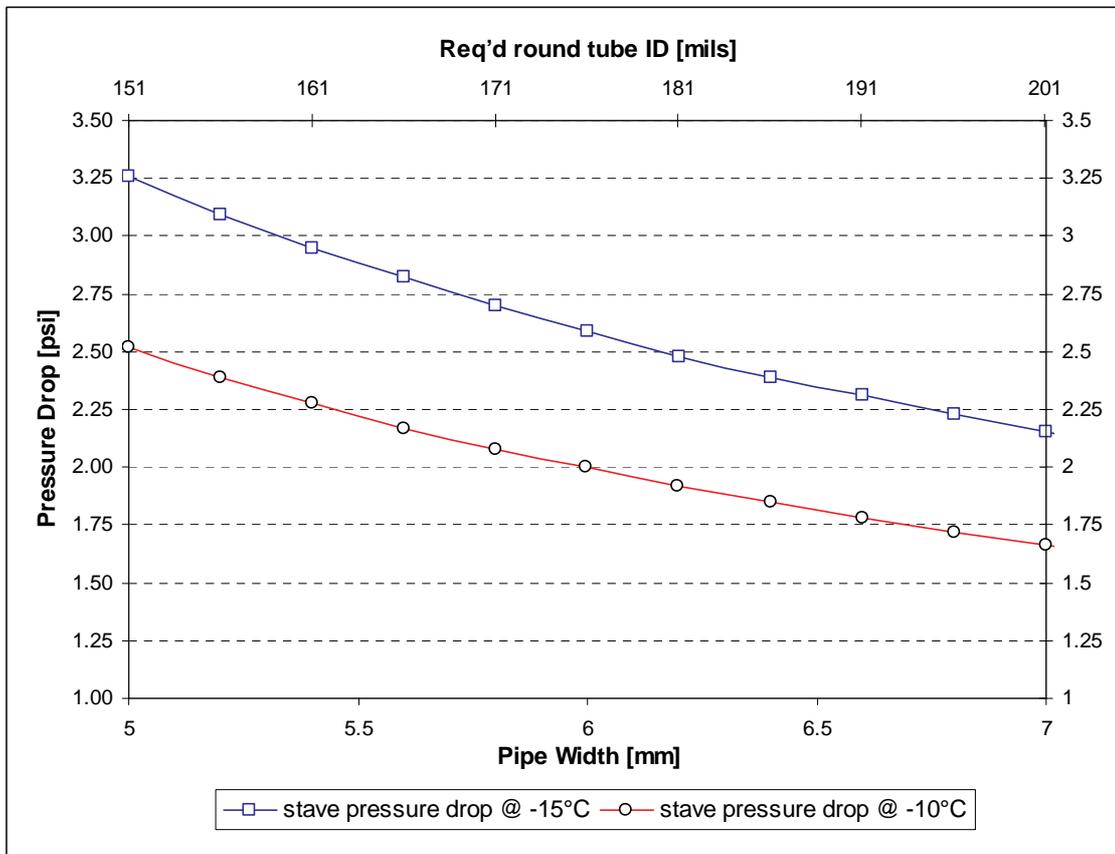


Figure I-3 – Estimated pressure drop versus cooling pipe width, given a fixed flow rate of 175 ml/min and a fluid bulk temperature of -10°C and -15°C . Coolant: ethylene glycol 42% by mass.

The cooling delivery system for D0 is limited to a flow rate of 175ml/min per stave. This is determined by the size of the existing piping on the return side between the detector region and the pump (~200ft. of vacuum jacketed stainless steel lines) and the necessity to both operate the system within the detector volume below atmospheric pressure and ensure that the fluid does not cavitate in the pump. This estimate relies on a ΔP in the stave of no more than 3psi. From Figure I-3 we can see that this pressure drop corresponds to a PEEK tube inner diameter of 0.158” for -15°C coolant. Smaller tube sizes offer the benefits of lower mass and higher flow velocities for fixed mass flow rate, and hence

higher heat transfer coefficients. Larger tube sizes offer more heat transfer area and hence lower temperature gradients through the PEEK wall and support structures. Finally, the U-shaped bend near $Z=0$ can be more easily and reliably fabricated the smaller the tube size. Further considerations, such as matching the OD to the ID of a commercially available aluminum tube we can use as a coupling out of the stave, need to be taken into account when selecting a final tube diameter. Based on these studies the recommended tube size would be 0.156-0.163" ID (0.166-0.171" OD).

5. APPENDIX - The codes

5.1. Pressure drop code

geometrical data

$$h := 1.8\text{mm}$$

$$l := \frac{\pi \cdot 0.158\text{in} - \pi \cdot 1.8\text{mm}}{2}$$

$$w := l + h$$

$$w = 5.276\text{mm}$$

$$\text{cooling tube size} \quad d := \frac{3}{16}\text{in}$$

$$\text{outer pipe ID} \quad d = 4.762\text{mm}$$

$$A_{\text{cross_stave}} := l \cdot h + \pi \cdot \left(\frac{h}{2}\right)^2$$

$$\text{wetted_perimeter} := 2 \cdot l + \pi \cdot h$$

$$D_H := 4 \frac{A_{\text{cross_stave}}}{\text{wetted_perimeter}}$$

$$A_{\text{cross_out}} := \pi \cdot \left(\frac{d}{2}\right)^2$$

$$L_{\text{in_stave}} := 2 \cdot 620\text{mm}$$

$$L_{\text{in_stave}} = 1240\text{mm}$$

$$\tau := 1 \quad \{\tau \text{ is } =0 \text{ if the stave is disconnected and the line is with jumper}\}$$

$$L_{\text{out_stave}} := 480\text{mm} + 370\text{mm} + 30\text{mm} + 30\text{mm} + (50.2\text{mm} + \pi \cdot 15\text{mm}) \cdot \tau$$

$$L_{\text{out_stave}} = 105.712\text{cm}$$

$$\rho_b := 1.070 \frac{\text{gm}}{\text{cm}^3}$$

INPUT FIELD

$$\mu_b := \begin{pmatrix} 10.971 \\ 11.090 \\ 11.210 \\ 11.713 \\ 11.150 \\ 11.030 \\ 10.912 \\ 11.030 \end{pmatrix} \frac{\text{poise}}{100}$$

$$i := 0.. \text{rows}(\mu_b) - 1$$

Correction Gilmont flowmeter curve

Gilmont

$$\text{data1} := \begin{pmatrix} 74.7 \\ 109 \\ 154 \\ 200 \\ 262 \\ 313 \\ 366 \end{pmatrix}$$

measured

$$\text{data2} := \begin{pmatrix} 59.7 \\ 91.9 \\ 136.5 \\ 183.9 \\ 247.3 \\ 302.3 \\ 372.0 \end{pmatrix}$$

$$\text{data} := \text{augment}(\text{data1}, \text{data2})$$

$$\text{data} = \begin{pmatrix} 74.7 & 59.7 \\ 109 & 91.9 \\ 154 & 136.5 \\ 200 & 183.9 \\ 262 & 247.3 \\ 313 & 302.3 \\ 366 & 372 \end{pmatrix}$$

$$\text{data} := \text{csort}(\text{data}, 0)$$

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$$X := \text{data}^{\langle 0 \rangle} \quad Y := \text{data}^{\langle 1 \rangle} \quad S := \text{cspline}(X, Y)$$

$$\text{flw}(f) := \text{interp}(S, X, Y, f) \cdot \frac{\text{mL}}{\text{min}}$$

INPUT FIELD

$$\text{flow_rate} := \text{flw} \left(\begin{array}{c} 243.5 \\ 226.0 \\ 196.0 \\ 164.0 \\ 144.0 \\ 123.0 \\ 104.0 \\ 80.2 \end{array} \right)$$

estimate from Gilmont corrected

$$\text{flow_rate} = \left(\begin{array}{c} 228.3 \\ 210.5 \\ 179.8 \\ 146.7 \\ 126.4 \\ 105.5 \\ 87.1 \\ 64.7 \end{array} \right) \frac{\text{mL}}{\text{min}}$$

Pressure drop estimate

ϕ correction factor for laminar friction coefficient in presence of rectangular cross section

$$fi := \left(\begin{array}{cc} 0 & 1.5 \\ 0.1 & 1.34 \\ 0.3 & 1.10 \\ 0.5 & 0.97 \\ 0.8 & 0.9 \\ 1 & 0.88 \end{array} \right) \quad fi := \text{csort}(fi, 0) \quad X := fi^{\langle 0 \rangle} \quad Y := fi^{\langle 1 \rangle} \quad S := \text{cspline}(X, Y) \quad \phi(x) := \text{interp}(S, X, Y, x)$$

$$\phi := \phi \left(\frac{h}{w} \right)$$

$$\phi = 1.065$$

$$V_{\text{fluid_stave}_i} := \frac{\text{flow_rate}_i}{A_{\text{cross_stave}}}$$

$$Re_{stave_i} := \rho_b \cdot V_{fluid_stave_i} \cdot \frac{D_H}{\mu_{b_i}} \quad Re_{stave} = \begin{pmatrix} 117.761 \\ 107.394 \\ 90.737 \\ 70.877 \\ 64.127 \\ 54.119 \\ 45.163 \\ 33.213 \end{pmatrix}$$

$$f_{stave_i} := \left(\phi \cdot \frac{64}{Re_{stave_i}} \right) \quad \text{hold if } Re \leq 2320$$

$$\Delta P_{stave_i} := f_{stave_i} \cdot \frac{L_{in_stave}}{D_H} \cdot \frac{1}{2} \cdot \rho_b \cdot (V_{fluid_stave_i})^2$$

$$V_{fluid_out_i} := \frac{flow_rate_i}{A_{cross_out}}$$

$$Re_{out_i} := \rho_b \cdot V_{fluid_out_i} \cdot \frac{d}{\mu_{b_i}} \quad Re_{out} = \begin{pmatrix} 99.233 \\ 90.497 \\ 76.461 \\ 59.726 \\ 54.038 \\ 45.604 \\ 38.058 \\ 27.988 \end{pmatrix}$$

$$f_{out_i} := \left(\frac{64}{Re_{out_i}} \right) \quad \Delta P_{out_stave_i} := f_{out_i} \cdot \frac{2L_{out_stave}}{d} \cdot \frac{1}{2} \cdot \rho_b \cdot (V_{fluid_out_i})^2 \quad \Delta P_{tot_i} := \Delta P_{out_stave_i} + \Delta P_{stave_i}$$

SOLUTION

$$\Delta P_{stave} = \begin{pmatrix} 3.728 \\ 3.474 \\ 2.999 \\ 2.557 \\ 2.097 \\ 1.732 \\ 1.414 \\ 1.063 \end{pmatrix} \text{ psi} \quad \Delta P_{out_stave} = \begin{pmatrix} 1.014 \\ 0.945 \\ 0.816 \\ 0.696 \\ 0.57 \\ 0.471 \\ 0.385 \\ 0.289 \end{pmatrix} \text{ psi} \quad \Delta P_{tot} = \begin{pmatrix} 4.742 \\ 4.419 \\ 3.815 \\ 3.253 \\ 2.667 \\ 2.203 \\ 1.799 \\ 1.352 \end{pmatrix} \text{ psi}$$

5.2. Pressure versus pipe width

geometrical data

$$h := 1.8\text{mm}$$

$$w := 5\text{mm}, 5.2\text{mm}.. 8.2\text{mm}$$

$$\text{cooling tube size} \quad d := \frac{3}{16}\text{in}$$

$$\text{outer pipe ID} \quad d = 4.8\text{mm}$$

$$A_{\text{cross_stave}}(x) := (x - h) \cdot h + \pi \cdot \left(\frac{h}{2}\right)^2$$

$$\text{wetted_perimeter}(x) := 2 \cdot (x - h) + \pi \cdot h$$

$$D_H(x) := 4 \frac{A_{\text{cross_stave}}(x)}{\text{wetted_perimeter}(x)}$$

$$L_{\text{in_stave}} := 2 \cdot (600 - 21)\text{mm} + \pi \cdot 21\text{mm}$$

$$L_{\text{in_stave}} = 1223.973\text{mm}$$

$$L_{\text{out_stave}} := 1.5\text{in} \cdot 2$$

$$A_{\text{cross_out}} := \pi \cdot \left(\frac{d}{2}\right)^2$$

INPUT FIELDS

$$\rho_b := 1.069 \frac{\text{gm}}{\text{cm}^3}$$

$$\mu_b := 8.947 \cdot \frac{\text{poise}}{100}$$

$$\text{flow_rate} := 175 \frac{\text{mL}}{\text{min}}$$

Pressure drop estimate

ϕ correction factor for laminar friction coefficient in presence of rectangular cross section

$$fi := \begin{pmatrix} 0 & 1.5 \\ 0.1 & 1.34 \\ 0.3 & 1.10 \\ 0.5 & 0.97 \\ 0.8 & 0.9 \\ 1 & 0.88 \end{pmatrix} \quad fi := \text{csort}(fi, 0) \quad X := fi \langle 0 \rangle \quad Y := fi \langle 1 \rangle \quad S := \text{cspline}(X, Y) \quad \phi(x) := \text{interp}(S, X, Y, x) \quad \phi(x) := \phi\left(\frac{h}{x}\right)$$

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$$V_{\text{fluid_stave}}(x) := \frac{\text{flow_rate}}{A_{\text{cross_stave}}(x)}$$

$$Re_{\text{stave}}(x) := \rho_b \cdot V_{\text{fluid_stave}}(x) \cdot \frac{D_H(x)}{\mu_b}$$

$$f_{\text{stave}}(x) := \left(\phi(x) \cdot \frac{64}{Re_{\text{stave}}(x)} \right) \quad \text{hold if } Re \leq 2320$$

$$\Delta P_{\text{stave}}(x) := f_{\text{stave}}(x) \cdot \frac{L_{\text{in_stave}}}{D_H(x)} \cdot \frac{1}{2} \cdot \rho_b \cdot (V_{\text{fluid_stave}}(x))^2$$

$$V_{\text{fluid_out}} := \frac{\text{flow_rate}}{A_{\text{cross_out}}}$$

$$Re_{\text{out}} := \rho_b \cdot V_{\text{fluid_out}} \cdot \frac{d}{\mu_b} \quad Re_{\text{out}} = 93.2 \quad f_{\text{out}} := \left(\frac{64}{Re_{\text{out}}} \right)$$

$$ID(x) := \frac{\text{wetted_perimeter}(x)}{\pi}$$

$$\Delta P_{\text{out_stave}} := f_{\text{out}} \cdot \frac{2L_{\text{out_stave}}}{d} \cdot \frac{1}{2} \cdot \rho_b \cdot (V_{\text{fluid_out}})^2$$

$$\Delta P_{\text{stave_TOT}}(x) := \Delta P_{\text{out_stave}} + \Delta P_{\text{stave}}(x)$$

RESULTS

w =	mm	ID(w) =	in	1000	ΔP _{stave_TOT} (w) =	psi
5		151.1			2.52	
5.2		156.1			2.39	
5.4		161.1			2.28	
5.6		166.1			2.17	
5.8		171.1			2.08	
6		176.1			2	
6.2		181.1			1.92	
6.4		186.2			1.85	
6.6		191.2			1.78	
6.8		196.2			1.72	
7		201.2			1.66	
7.2		206.2			1.61	
7.4		211.2			1.56	
7.6		216.2			1.51	
7.8		221.2			1.47	
8		226.3			1.43	