Spallation Neutron Source Project, Los Alamos National Laboratory

Magnet Water Cooling Calculation For The Quadrupole Magnet in the Diagnostic Plate (D Plate) Beam Line.

Purpose of Calculation:

The purpose of this calculation is to determine if the maximum pressure drop of 30 psi across the magnet cooling lines is sufficient to cool the magnet and to determine if the coolant water flow will keep the magnet coil temperature to about 90 degrees F
.

Assumptions:

- The magnet, which was originally designed for 200 amps of current, will only need 171 amps. This new current was determined by Mike Plum, who is the project leader for the Diagnostic Plate.
- The water cooling circuits for the coils will be in parallel. There will be a manifold attached to the magnet that will distribute cooling water to each coil.
- The maximum water pressure drop across each coil cooling circuit can only be 30 psi. This maximum pressure drop was determined by John Bernardin who is the project leader for the linac cooling system.
- The coil has to operate at a temperature less the 120 Fahrenheit or 322 Kelvin . This figure was determined by David Barlow who designed the original magnet and knows the epoxies and insulation materials used in manufacturing the coils.

Results:

The new lower current of 171 amps gives a power dissipation per coil of 585 watts. The maximum pressure drop is about 29 psi with a total flow rate of 0.72 gallons per minute. The temperature increase across the coil is about 23 degrees Fahrenheit. The input water can be chilled to 68 degrees Fahrenheit so the final average temperature the coil will be about 93 degrees Fahrenheit. Well beneath the upper limit of 120 degrees Fahrenheit. The difference between the temperature of the water and the temperature of the copper coil is less then 1 degree.

Robert Gillis
TechSource
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Quadrupole Magnet used in the SNS Diagnostic Plate

The purpose of this calculations is to determine if the magnet can be water cooled to a temperature less than 120 F with a water cooling system that can only supply a maximum pressure drop across the magnet of 30 psi. Dave Barlow designed the quadrupole magnet that is being used in the D Plate beam line. His original calculations where 200 amps, 800 watts/coil, 3/16 inch square copper conductor, 1/8 in diameter cooling hole. In this application the magnet will operate with less current.

INPUTS:

$water_temp_{in} := 293 \cdot K$

$amps := 171amp$

$conductor_in := 0.1875 \cdot in$

$\rho := 999.552 \frac{kg}{m^3}$ Density of water

$pole_turn_length := 15.5956m$

$\delta := 90$ Degrees, (Bend angle in the coil)

$coolant_hole_{diam} := 0.0032m$

$\mu := 695 \cdot 10^{-6} \frac{N \cdot sec}{m^2}$ Viscosity

$flex_tube_{ID_magnet} := 0.5in$

$flow_rate_{per_coil} := 0.00001142 \frac{m^3}{sec}$ Water flow rate per coil

$\Delta P_{max} := 206843Pa$

$Manifold_{flow} := 13 \frac{gal}{min}$

$Magnet_{flow} := 10 \frac{gal}{min}$

The calculate resistance of one coil, based on the original design is:

$power_per_pole := 800W$

$Resist_{coil} := \frac{power_per_pole}{(200amp)^2}$ $\qquad Resist_{coil} = 0.02\,\Omega$

Quadrupole Magnet used in the SNS Diagnostic Plate

The magnet will not be operated at 200 amps, but at a reduced rate of 171 amps. Calculate the power dissipated from the coil at the lower current.

$$power_coil := amps^2 \cdot Resist_{coil}$$

$$power_coil = 584.82\,W$$

The maximum allowable temperature of the operating coil has to be less than 120 degrees F or 322 degrees K. At the flow rate given, determine the maximum temperature of the magnet

To do this, calculate the velocity of the water in the coolant channel.

$$coolant_length_area := coolant_hole_{diam} \cdot pole_turn_length$$

$$coolant_length_area = 0.05\,m^2$$

$$coolant_hole_{diam} = 3.2 \times 10^{-3}\,m$$

$$coolant_hole_area := \frac{\pi \cdot coolant_hole_{diam}^2}{4}$$

$$coolant_hole_area = 8.042 \times 10^{-6}\,m^2$$

$$V_{water} := \frac{flow_rate_{per_coil}}{coolant_hole_area}$$

$$V_{water} = 1.42\,\frac{m}{sec}$$ Velocity of the water

Calculate the Reynolds number

$$Re_D := \frac{\rho \cdot V_{water} \cdot coolant_hole_{diam}}{\mu}$$ **Reynolds number**

$$Re_D = 6.535 \times 10^3$$

Quadrupole Magnet used in the SNS Diagnostic Plate

Calculate the friction factor

$$friction_f := 0.184 \cdot Re_D^{-\left(\frac{1}{5}\right)}$$ Page 372, Eq 8.21,for a smooth surface, Incropera and Dewitt

$$friction_f = 0.032$$ Friction factor for smooth surfaces

Calculate the mass flow rate

$$mass_{flow} := flow_rate_{per_coil} \cdot \rho$$ Mass flow rate

$$mass_{flow} = 0.011 \frac{kg}{s}$$

$$c_p := 4.178 \cdot \frac{J \cdot 1000}{kg \cdot K}$$ Specific heat of water

$$c_p = 4.178 \times 10^3 \frac{J}{kg \cdot K}$$

$$water_temp_{gain} := \frac{power_coil}{mass_{flow} \cdot c_p}$$ Page 381, Eq 8.41,Incropera and Dewitt

$$water_temp_{gain} = 12.263\,K$$

$$water_temp_{max} := water_temp_{in} + water_temp_{gain}$$

$$\boxed{water_temp_{max} = 305.263\,K}$$ Maximum water temperature in the magnet

$$water_temp_mean := water_temp_{in} + \frac{water_temp_{gain}}{2}$$

$$water_temp_mean = 299.131\,K$$

$$Prandtl_number := 0.86$$ Page 774,Incropera and Dewitt

$$k_{cond_water} := 618 \cdot \frac{W}{m \cdot K}$$

Quadrupole Magnet used in the SNS Diagnostic Plate

We need to determine the temperature of the copper coil at the coil / water interface. Find the average Nusselt number (Nu) and then find the film coefficient (Hc).

$$Nu_{dh} := 0.023 \cdot Re_D^{0.8} \cdot Prandtl_number^{0.33}$$

$$Nu_{dh} = 24.678$$

The film coefficient is:

$$h_c := \frac{Nu_{dh} \cdot k_{cond_water}}{coolant_hole_{diam}}$$

$$h_c = 4.766 \times 10^6 \frac{W}{m^2 \cdot K}$$

The temperature rise across the water / copper boundary layer is:

$$area_{coolant_hole} := \left(\pi \cdot coolant_hole_{diam}\right) \cdot pole_turn_length$$

$$delta_temp_K := \frac{power_per_pole}{h_c \cdot area_{coolant_hole}}$$

$$delta_temp_K = 1.071 \times 10^{-3} K$$

Therefore there is hardly any temperature rise across the water/copper interface. Thus the copper and the water are virtually the same temperature. This assumes that the temperature across the copper cross section is constant and considering the size of the conductor and the coolant hole size, I think it is a safe assumption.

Thus the copper temperature is:

$$temp_{copper_coils} := delta_temp_K + water_temp_{max}$$

$$temp_{copper_coils} = 305.264\ K$$

Quadrupole Magnet used in the SNS Diagnostic Plate

Calculate the pressure drops due to the bends in the magnet coil. There are 11 conductors in the first layer, 11 conductors in the second layer, 10 conductors in the third layer, and 8 conductors in the last layer. The bend radius for the first layer is 0.25 inch

The equivalent pressure drop of the bends in the first layer is:

$R_1 := 0.25 \cdot in$ Bend radius

$D := 0.125in$ Inside diameter of coolant hole in coil

$$\frac{R_1}{D} = 2$$

Evaluate the following expression

$$Re_D \cdot \sqrt{\frac{D}{2 \cdot R_1}} = 3.268 \times 10^3$$

Page 359 Handbook of Hydraulic Resistance, 3rd Edition, I.E. Idelchik

From page 359, and using the above evaluation, the equation that should be used to evaluate λ is the bottom equation on that page for circular cross sections

$$\lambda_{el} := \frac{5}{Re_D^{0.45}} \left(\frac{D}{2R_1}\right)^{0.275}$$

$\lambda_{el} = 0.066$

$\delta = 90$ degrees

$$\zeta := 0.0175 \lambda_{el} \cdot \delta \cdot \frac{R_1}{coolant_hole_{diam}}$$

Page 359 Handbook of Hydraulic Resistance, 3rd Edition, I.E. Idelchik

$\zeta = 0.205$ Pressure loss coefficient

$$Head_loss_{bend} := \zeta \cdot \frac{V_{water}^2}{2}$$

Page 282, Eq:8.28 Mechanics of Fluids, Irving H. Shames. Second Ed.

$Head_loss_{bend} = 0.207\,Sv$

$press_{loss_per_bend} := \rho \cdot Head_loss_{bend}$

$press_{loss_per_bend} = 206.431\ Pa$

$bends_{layer1} := 11$

$pressure_{loss_layer1} := bends_{layer1} \cdot press_{loss_per_bend}$

$pressure_{loss_layer1} = 2.271 \times 10^{3}\ Pa$

The equivalent pressure drop of the bends in the second layer is:

$R_2 := R_1 + conductor_in$

$\frac{R_2}{coolant_hole_{diam}} = 3.473$ Ratio of bend radius to hole diameter

Evaluate the following expression

$Re_D \cdot \sqrt{\frac{D}{2 \cdot R_2}} = 2.47 \times 10^{3}$ Page 359 Handbook of Hydraulic Resistance, 3rd Edition, I.E. Idelchik

From page 359, and using the above evaluation, the equation that should be used to evaluate λ is the bottom equation on that page for circular cross sections

$\lambda_{el} := \frac{5}{Re_D^{0.45}} \left(\frac{D}{2R_2} \right)^{0.275}$

$\lambda_{el} = 0.056$

$\delta = 90$ degrees

$\zeta := 0.0175 \lambda_{el} \cdot \delta \cdot \frac{R_2}{coolant_hole_{diam}}$ Page 359 Handbook of Hydraulic Resistance, 3rd Edition, I.E. Idelchik

$\zeta = 0.307$ Pressure loss coefficient

$Head_loss_{bend} := \zeta \cdot \frac{V_{water}^{2}}{2}$ Page 282, Eq:8.28 Mechanics of Fluids, Irving H. Shames. Second Ed.

$Head_loss_{bend} = 0.31\ Sv$

$press_{loss_per_bend} := \rho \cdot Head_loss_{bend}$

Quadrupole Magnet used in the SNS Diagnostic Plate

$press_{loss_per_bend} = 309.726\ Pa$

$bends_{layer2} := 11$

$pressure_{loss_layer2} := bends_{layer2} \cdot press_{loss_per_bend}$

$pressure_{loss_layer2} = 3.407 \times 10^{3}\ Pa$

The equivalent pressure drop of the bends in the third layer is

$R_3 := R_2 + conductor_in$

$\frac{R_3}{coolant_hole_{diam}} = 4.961$ Ratio of bend radius to hole diameter

Evaluate the following expression

$Re_D \cdot \sqrt{\frac{D}{2 \cdot R_3}} = 2.067 \times 10^{3}$ Page 359 Handbook of Hydraulic Resistance, 3rd Edition, I.E. Idelchik

From page 359, and using the above evaluation, the equation that should be used to evaluate λ is the bottom equation on that page for circular cross sections

$\lambda_{el} := \frac{5}{Re_D^{0.45}} \left(\frac{D}{2R_3} \right)^{0.275}$

$\lambda_{el} = 0.051$

$\delta = 90$ degrees

$\zeta := 0.0175 \lambda_{el} \cdot \delta \cdot \frac{R_3}{coolant_hole_{diam}}$ Page 359 Handbook of Hydraulic Resistance, 3rd Edition, I.E. Idelchik

$\zeta = 0.398$ Pressure loss coefficient

$Head_loss_{bend} := \zeta \cdot \frac{V_{water}^{2}}{2}$ Page 282, Eq:8.28 Mechanics of Fluids, Irving H. Shames. Second Ed.

$Head_loss_{bend} = 0.401\ Sv$

Quadrupole Magnet used in the SNS Diagnostic Plate

$press_{loss_per_bend} := \rho \cdot Head_loss_{bend}$

$press_{loss_per_bend} = 401.126\ Pa$

$bends_{laye3} := 10$

$pressure_{loss_layer3} := bends_{layer2} \cdot press_{loss_per_bend}$

$pressure_{loss_layer3} = 4.412 \times 10^{3}\ Pa$

The equivalent pressure drop of the bends in the fourth layer is

$R_4 := R_3 + conductor_in$

$\frac{R_4}{coolant_hole_{diam}} = 6.449$ Ratio of bend radius to hole diameter

Evaluate the following expression

$Re_D \cdot \sqrt{\frac{D}{2 \cdot R_4}} = 1.812 \times 10^{3}$ Page 359 Handbook of Hydraulic Resistance, 3rd Edition, I.E. Idelchik

From page 359, and using the above evaluation, the equation that should be used to evaluate λ is the bottom equation on that page for circular cross sections

$\lambda_{el} := \frac{5}{Re_D^{0.45}} \left(\frac{D}{2R_4} \right)^{0.275}$

$\lambda_{el} = 0.047$

$\delta = 90$ degrees

$\zeta := 0.0175 \lambda_{el} \cdot \delta \cdot \frac{R_4}{coolant_hole_{diam}}$ Page 359 Handbook of Hydraulic Resistance, 3rd Edition, I.E. Idelchik

$\zeta = 0.481$ Pressure loss coefficient

$Head_loss_{bend} := \zeta \cdot \frac{V_{water}^{2}}{2}$ Page 282, Eq:8.28 Mechanics of Fluids, Irving H. Shames. Second Ed.

Quadrupole Magnet used in the SNS Diagnostic Plate

$Head_loss_{bend} = 0.485\,Sv$

$press_{loss_per_bend} := \rho \cdot Head_loss_{bend}$

$press_{loss_per_bend} = 485.166\,Pa$

$bends_{laye4} := 8$

$pressure_{loss_layer4} := bends_{laye4} \cdot press_{loss_per_bend}$

$pressure_{loss_layer3} = 4.412 \times 10^{3}\,Pa$

Total equivalent pressure drops due to all of the magnet coil bends is:

$$press_loss_{all_bends} := pressure_{loss_layer1} + pressure_{loss_layer2} \cdots + pressure_{loss_layer3} + pressure_{loss_layer4}$$

$press_loss_{all_bends} = 1.397 \times 10^{4}\,Pa$

$press_loss_{all_bends} = 2.026\,psi$

The pressure drop across the coil (length plus bends) is:

$$head_loss := friction_f \cdot \frac{(pole_turn_length) \cdot V_{water}^{2}}{coolant_hole_{diam} \cdot 2}$$

Eq 8.20, page 276, Mechanics of Fluids, Irving H. Shames, 2nd Ed.

$head_loss = 156.007\,\frac{m^3}{kg}\,Pa$

$pole_turn_length = 15.596\,m$

$coolant_hole_{diam} = 3.2 \times 10^{-3}\,m$

$coil_delta_pressure := \rho \cdot head_loss + press_loss_{all_bends}$

$V_{water}^{2} = 2.016\,Sv$

$coil_delta_pressure = 1.699 \times 10^{5}\,Pa$

$V_{water} = 1.42\,\frac{m}{s}$

$\boxed{coil_delta_pressure = 24.643\,psi}$

$friction_f = 0.032$

Quadrupole Magnet used in the SNS Diagnostic Plate

The next step is to calculate the pressure drops from the manifold to and from the magnet. In this line there is a globe valve, flow meter, and some expansion and contraction areas. Each pressure drop is denoted by a K# in the following sketch. The expansion and take-off pressure drop coefficients are a function of the Reynolds number

Find out what the Reynolds number is for the flow in the main manifold

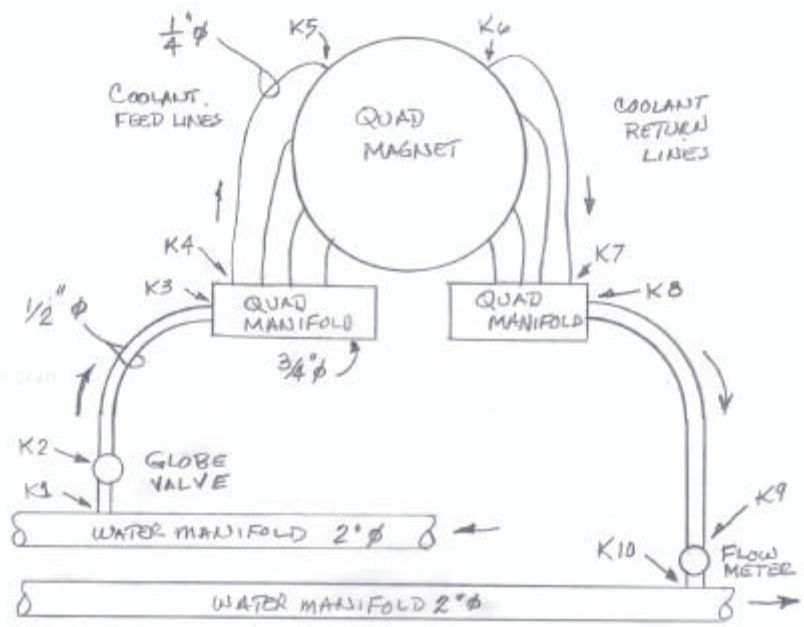
$$flow_{manifold} := 15.3 \frac{gal}{min} \qquad manifold_{id} := 2.157in$$

$$area_{man} := \frac{\pi \cdot manifold_{id}^2}{4}$$

$$vel_{man} := \frac{flow_{manifold}}{area_{man}} \qquad vel_{man} = 0.409 \frac{m}{s}$$

$$Re_D := \frac{\rho \cdot vel_{man} \cdot manifold_{id}}{\mu}$$

$$Re_D = 3.226 \times 10^4$$



Quadrupole Magnet used in the SNS Diagnostic Plate

$$flow_rate_{per_coil} = 0.181 \frac{gal}{min}$$

Calculate the various Reynolds numbers for the flow channels. This information is needed to determine the "k" values in Handbook of Hydraulic Resistance, 3rd edition, by I.E. Idelchik

1/2 inch line from the main manifold to the quad manifold

$$vel_{0.5_diam} := \frac{\left(flow_rate_{per_coil} \cdot 4\right)}{\left[\frac{\pi \cdot (0.5in)^2}{4}\right]} \qquad vel_{0.5_diam} = 0.361 \frac{m}{s}$$

$$Re_{0.5_diam} := \frac{\rho \cdot vel_{0.5_diam} \cdot 0.0254m}{\mu} \qquad Re_{0.5_diam} = 1.317 \times 10^4$$

Reynolds number is calculated for the upstream flow per Handbook of Hydraulic Resistance, 3rd edition, by I.E. Idelchik, page 189 item #1.

0.25 inch line from the quad manifold to the coils

$$vel_{0.25_dam} := \frac{flow_rate_{per_coil}}{\left[\frac{\pi \cdot (0.25 \cdot in)^2}{4}\right]} \qquad vel_{0.25_dam} = 0.361 \frac{m}{s} \qquad flow_rate_{per_coil} = 1.142 \times 10^{-5} \frac{m^3}{s}$$

$$Re_{0.25_diam} := \frac{\rho \cdot vel_{0.25_dam} \cdot 0.0064m}{\mu} \qquad Re_{0.25_diam} = 3.319 \times 10^3$$

0.125 inch diameter cooling channel in the magnet coils

$$vel_{0.125_diam} := \frac{flow_rate_{per_coil}}{\left[\frac{\pi \cdot (0.125 \cdot in)^2}{4}\right]} \qquad vel_{0.125_diam} = 1.442 \frac{m}{s}$$

$$Re_{0.125_diam} := \frac{\rho \cdot vel_{0.125_diam} \cdot 0.0064m}{\mu} \qquad Re_{0.125_diam} = 1.328 \times 10^4$$

Quadrupole Magnet used in the SNS Diagnostic Plate

The ratios for junction 1 are:

$$Aratio_1 := \frac{0.5^2}{2^2} \qquad Aratio_1 = 0.063$$

$$Qratio_1 := \frac{flow_rate_{per_coil} \cdot 4}{Manifold_{flow} - Magnet_{flow}} \qquad Qratio_1 = 0.241$$

$k1 := 4.5$ Page 456, bottom table. Handbook of Hydraulic Resistance, 3rd edition, by I.E. Idelchik

To calculate K3, the ratio area's of the feed line and the quad manifold have to be detrmined.

$$area_{feedline} := \frac{\pi \cdot [0.5 \cdot (in)]^2}{4} \qquad area_{feedline} = 0.196\,in^2$$

$$area_{quad_manifold} := \frac{\pi \cdot [0.75 \cdot (in)]^2}{4} \qquad area_{quad_manifold} = 0.442\,in^2$$

$$ratio_6 := \frac{area_{feedline}}{area_{quad_manifold}} \qquad ratio_6 = 0.444$$

$$Re_{0.5_diam} = 1.317 \times 10^4$$

$k3 := 0.80$ Page 208, bottom table. Handbook of Hydraulic Resistance, 3rd edition, by I.E. Idelchik - worst case.

$k4 := 0.5$ Page 160, bottom table. Handbook of Hydraulic Resistance, 3rd edition, by I.E. Idelchik

$k5 := 0.5$ Page 160, bottom table. Handbook of Hydraulic Resistance, 3rd edition, by I.E. Idelchik

Quadrupole Magnet used in the SNS Diagnostic Plate

Calculate the area ratio of the interface between the coolant return line and the coil at K6

$area_{coil} := \frac{\pi \cdot 0.125 \cdot in^2}{4}$ $\quad area_{coil} = 6.334 \times 10^{-5} m^2$

$area_{return_line} := \frac{\pi \cdot 0.25 \cdot in^2}{4}$ $\quad area_{return_line} = 1.267 \times 10^{-4} m^2$

$ratio_6 := \frac{area_{coil}}{area_{return_line}}$ $\quad ratio_6 = 0.5$

$Re_{0.125_diam} = 1.328 \times 10^4$

$k6 := 0.57$ Page 208, bottom table. Handbook of Hydraulic Resistance, 3rd edition, by I.E. Idelchik

$Re_{0.25_diam} = 3.319 \times 10^3$

$k7 := 0.87$ Page 208, bottom table. Handbook of Hydraulic Resistance, 3rd edition, by I.E. Idelchik

$k8 := 0.5$ Page 160, bottom table. Handbook of Hydraulic Resistance, 3rd edition, by I.E. Idelchik

$k9 := 2.78$ Taken from Final Design, Water Cooling Resonance Control System for the CCL, page 71

Area ratios for junction 10 are:

$Aratio_{10} := \frac{0.5^2}{2^2}$ $\quad Aratio_{10} = 0.063$

$Qratio_{10} := \frac{flow_rate_{per_coil} \cdot 4}{Manifold_{flow} - Magnet_{flow}}$ $\quad Qratio_{10} = 0.241$

$k10 := 2.97$ Page 438, table. Handbook of Hydraulic Resistance, 3rd edition, by I.E. Idelchik

Quadrupole Magnet used in the SNS Diagnostic Plate

The following table summarizes the "K" or "Cv" factors and flow velocities in the magnet cooling line.

SYMBOL	DESCRIPTION	LINE SIZE	REYNOLDS NUMBER	"Cv" or "K" FACTOR
K1	Take off from main manifold	1/2"	1.07E4	4.5
Cv2	Globe valve	1/2"	NA	3.82
K3	Entrance to magnet manifold	1/2"	1.07E4	0.36
K4	Entrance to cooling line	¼"	NA	0.5
K5	Entrance to magnet coil	1/8"	NA	0.5
K6	Entrance to cooling line	¼"	1.1E4	0.25
K7	Entrance to magnet manifold	¼"	2.7E3	1.4
K8	Entrance to flex tube	1/2"	NA	0.5
K9	Flow meter	1/2"	NA	2.78
K10	Entrance to main manifold	1/2"	NA	2.97

$$h_{L1} := k1 \cdot \frac{vel_{0.5_diam}^{2}}{2} \qquad h_{L1} = 0.293\,Sv$$

Page 282, Eq 8.28, Mechanics of Fluids, Irving H. Shames, Second Edition.

$$h_{L3} := k3 \cdot \frac{vel_{0.5_diam}^{2}}{2} \qquad h_{L7} := k7 \cdot \frac{vel_{0.25_dam}^{2}}{2}$$

$$h_{L4} := k4 \cdot \frac{vel_{0.25_dam}^{2}}{2} \qquad h_{L8} := k8 \cdot \frac{vel_{0.5_diam}^{2}}{2}$$

$$h_{L5} := k5 \cdot \frac{vel_{0.125_diam}^{2}}{2} \qquad h_{L9} := k9 \cdot \frac{vel_{0.5_diam}^{2}}{2}$$

$$h_{L6} := k6 \cdot \frac{vel_{0.25_dam}^{2}}{2} \qquad h_{L10} := k10 \cdot \frac{vel_{0.5_diam}^{2}}{2}$$

I called the Crane Company for a Cv coefficient for a 1/2" globe valve and they said it was Cv=3.82. The relationship between K and Cv is: K=((29.9*D^2)/Cv)^2 where D is the diameter in inches (0.5). This equation can be found on page 2-8 of the Crane Company technical paper 410. Therefore, K2 = 3.8

$$k2 := 3.8$$

$$h_{L2} := k2 \cdot \frac{vel_{0.5_diam}^{2}}{2}$$

Quadrupole Magnet used in the SNS Diagnostic Plate

The pressure drop across the flow meter is typically 4 psi. This value is taken from "SPONSLER CO., INC. Catalog. Bulletin 5007 5/97. The value of K9 in the table above will not be used, but instead, we will use 4 psi.

$$\Delta p_{flow_meter} := 27579 \cdot Pa$$

Add up all of the head losses (all of the K losses):

$$h_{L_total} := h_{L1} + h_{L2} + h_{L3} + h_{L4} + h_{L5} + h_{L6} + h_{L7} + h_{L8} + h_{L10}$$

$$\Delta p_k := \rho \cdot h_{L_total}$$

$$\Delta p_k = 1.463 \times 10^3 \, Pa$$

$$\Delta p_k = 0.212 \, psi$$

Calculate the pressure drop from the 2 inch main supply water manifold up to the magnet supply manifold and then from the magnet return manifold to the 2 inch main return manifold. There are four coils in the magnet, so the flow rate, which is given in flow per coil, has to multiplied by four.

$$flex_tube_{ID_magnet} = 0.013 \, m$$

This is the 1/2 inch diameter flex tube from the main manifold to the magnet manifold.

$$Vel_{mag_flex_hose} := \frac{flow_rate_{per_coil} \cdot 4}{\frac{\pi \cdot flex_tube_{ID_magnet}^2}{4}}$$

$$Vel_{mag_flex_hose} = 0.361 \, \frac{m}{s}$$

$$Length_{mag_flex_hose} := 32in$$

Calculate the Reynolds number

$$Re_D := \frac{\rho \cdot Vel_{mag_flex_hose} \cdot flex_tube_{ID_magnet}}{\mu}$$

Reynolds number

$$Re_D = 6.586 \times 10^3$$

Quadrupole Magnet used in the SNS Diagnostic Plate

Calculate the friction factor for the flex tubing

$friction_f := 0.184 \cdot Re_D^{-\left(\frac{1}{5}\right)}$ Page 372, Eq 8.21,for a smooth surface, Incropera and Dewitt

$friction_f = 0.032$ Friction factor for smooth surfaces

$$head_loss := friction_f \cdot \frac{(Length_{mag_flex_hose}) \cdot Vel_{mag_flex_hose}^2}{flex_tube_{ID_magnet} \cdot 2}$$

$$head_loss = 0.132 \frac{m}{s^2} m$$

$$delta_pressure_{flex_tubing} := \rho \cdot head_loss$$

$$\boxed{delta_pressure_{flex_tubing} = 131.856\ Pa}$$

$$head_loss = 0.132\ Sv$$

$$\rho = 999.552 \frac{kg}{m^3}$$

Total pressure drop from 2" feed manifold to 2" return manifold is:

$$\Delta total_pressure_drop := \Delta p_k + coil_delta_pressure + delta_pressure_{flex_tubing} + \Delta p_{flow_meter}$$

$$\Delta total_pressure_drop = 1.991 \times 10^5\ Pa$$

$$\boxed{\Delta total_pressure_drop = 28.874\ psi}$$