Fluids and Thermal Laboratory
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Experiment No. 03

HEAD LOSS IN A PIPE SYSTEM

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Abstract

Although introduced in most basic physics or fluid mechanics class, and generally presents a decent description of flow through a pipe for incompressible fluids, the Bernoulli equation is not the complete story, and would not be appropriate to use when modeling or designing actual pipe systems. This is because it completely ignores losses in pipes. In the same vein, it also is unable to take into account any inputs, such as pressure generated from pumps. We must use what is known as the Extended Bernoulli Equation, also known as the mechanical energy equation. This, as the name suggests, is the Bernoulli equation, but has extra terms that allow it to take into account losses throughout pipes, as well as pressure generated from pumps within a system. These pipe losses act against the flow, and decrease the pressure driving the fluid as it flows throughout the pipes. These losses depend on many factors, and are generally classified as Major Losses, which are from straight section of pipe, and Minor Losses, which come from pipe fittings, bends, and other components. In this lab, the losses for straight pipes, bends, and globe and gate valves were found.

Nomenclature

D	pipe diameter	L	section length
D_{sm}	standard pipe diameter	L_A	length of section A
D_{lg}	large pipe diameter	L_L	length of section L
f	Friction factor	P	pressure
g	gravity	Q	flow rate
h_L	head loss	r	bend radius
$h_{\#}$	height of manometer #	r_X	bend radius of labeled bend
K_b	Average loss coefficient of bend	v	velocity
K_c	loss coefficient of contraction	$z_{\#}$	height of # from ground
K_e	loss coefficient of expansion	ρ	density of fluid
K_{gl}	loss coefficient of globe valve	μ	dynamic viscosity of fluid
K_{ga}	loss coefficient of gate valve	$\Re$	Reynolds number

Introduction

Pressure and head losses are important considerations when designing a pipe system. However, because of how difficult it is to model flow, and because these losses depend on a myriad of factors, such as surface roughness, material, diameter, and so forth, it would be impractical to analytically find the losses various components would cause in a pipe system. This is why the experiment was designed to find the loss coefficients from typical components and sections in a typical piping system. We found coefficients, and not the actual losses, because flow rate is too specific to a system and how it is set up. On the other hand, using dimensionless analysis, we could find the coefficient of loss that each component provided, which was more general, and could be used to extrapolate use when designing piping systems. In addition, our results were useful in finding which factors correlated most to head loss for each component. For example, it was found that the Reynolds number correlated to loss coefficients through straight sections of pipe, but not through the bends. These correlations are useful for gaining an intuition about how changing certain factors would affect the losses incurred throughout a piping system, which is useful in engineering.

The presented equations must be complete and thorough with no mistakes. Variables should be clearly defined within the text, *i.e.*, the cross-sectional area of the pipe A is given by

$$A = \pi r^2 \qquad)$$

where r is the radius of the pipe.

Experimental Details

The experimental setup consisted of two piping systems - A Light-blue line and a Dark-blue line. Each line had differently sized bends, different contractions and expansions, and a different valve towards the end of their flows. Both piping systems primarily used D_{sm} = 13.7mm for most of its flow. A water pump supplied the water flow to both pipe systems, and its maximum volumetric flow-rate is Q = 6 gal/min (378.54 cm3/s). They also both had gate valves near the beginning of their flows, however, these were more used to adjust flow rate. The flow rate through each pipe was controlled by adjusting their respective valves. At the end of the two circuits was a tank of 10 L to collect the water, which was then fed back into the pump. Before and after each component of interest were a pair of manometers, which measured the pressure before and after the flow passed through a component. The manometers were filled with water, and each gave out a different height reading that corresponded to the pressure it was measuring. Each manometer was labeled with a different number, so that referencing them would be easier.

The light blue circuit had bends G, H, and J. The bend radii of each respectively was r_G = 50.8mm, r_H = 101.6mm, and r_J = 152.5mm. Before and after each bend respectively, were manometers 15 & 16, 11 & 12, and 13 & 17. Near the beginning of its flow, the piping system has a sudden expansion. This expansion is D_{lg} = 26.4mm in diameter, and spans the length of section L, which is L_L = 901.7 mm long. After this length, the flow would experience a sudden contraction, and return to D_{sm} = 13.7mm. At the end of its flow rate, it had a globe valve, which we measured the loss coefficient. The pressures before and after it were measured directly with pressure transducers, connected to taps 17 & 18.

The dark blue circuit had bends B, and C. The bend radii of each respectively was r_B = 0mm, and r_C = 20.55mm. Before and after each bend respectively, were manometers 5 & 6, and 1 & 2. Near the beginning of its flow, the piping system was a straight section of D_{sm} = 13.7mm and length of section A, which is L_A = 914.4 mm long. At the end of its flow rate, it had a gate valve, which we measured the loss coefficient. The pressures before and after it were measured with pressure transducers, connected to taps 19 & 20.

Before starting the experiment, we had to ensure that the equipment would give us proper readings, and that all readings would start with reference to 0 flow rate and pressure. We first had to ensure that the common inlet was connected to the supply side of the pump and the outlet was connected to the holding tank. Then, we placed both the water intake hose and the return hose into the tank. We then turned on the pump, but only admitted water into the dark-blue circuit by closing the globe valve (which was at the end of the light blue circuit), and opening the gate valve (which was at the end of the dark blue circuit). Fully opening the gate valve while water was only allowed to flow in the dark blue circuit ensured that there was nearly no pressure drop across the globe valve, and this allowed the piezometers to accurately have a zero reference to measure from.We had to allow water to flow through it for two to three minutes, and had to bleed out trapped air from the piezometers. After ensuring the dark blue circuit was prepared, we then shut off the gate valve, and admitted water into the light-blue circuit by opening the globe valve. Again, fully opening the globe valve while water was only allowed to flow in the light blue circuit ensured that there was nearly no pressure drop across the globe valve, and this allowed the piezometers to accurately have a zero reference to measure from.We had to allow water to flow through it for two to three minutes, and had to bleed out trapped air from the piezometers. We were now ready to start the experiment.

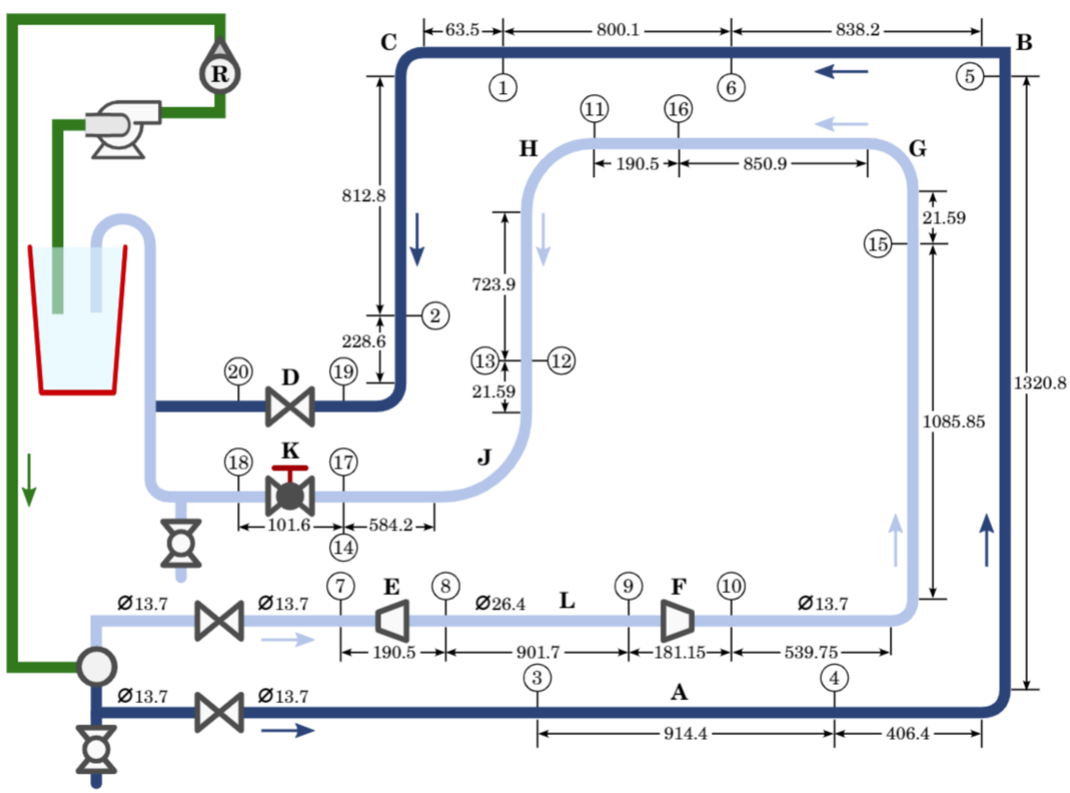
We started on the dark blue circuit. We closed the globe valve (at the end of the light blue circuit), and opened the gate valve (at the end of the dark blue circuit) so that water was only allowed to flow into the dark-blue circuit. To get different flow rates with the same pump, we adjusted the volumetric flow-rate by adjusting the gate valve D (the one at the end of the dark blue flow rate) so that the meter R indicated 10% of the maximum volumetric flow-rate. We then recorded the height of

the water in each manometer from taps Tap 1 to Tap 6 and the absolute pressure difference between Tap 19 and Tap 20, which were directly measured with pressure transducers. We then repeated the procedure above for different flow rates. We tested flow-rates from 15% to 50% of the maximum volumetric flow-rate in increments of 5%.

After this, we were finished with running measurements on the dark blue line. We were ready to start experiments on the light blue line. We closed the gate valve D (at the end of the dark blue line), and opened the globe valve K (at the end of the light blue line), and connected the pressure transducers to taps 17 & 18. Again, we collected measurements with different flow rates. We started with 10% of the maximum volumetric flow-rate, and then in increments of 5%, went up to 50% of the maximum flow rate. For each flow rate, we again recorded the height of the water in each manometer, this time, from taps Tap 7 to Tap 16 and the absolute pressure difference between Tap 17 and Tap 18, which were directly measured with pressure transducers.

After both experiments, we assumed a stable environment, and using a digital thermometer, we recorded the water temperature. We assumed this temperature remained constant for both experiments and all runs. We then used this to find the corresponding water density and viscosity.

Below are the diagrams and pictures of the setup.



RESULTS AND DISCUSSION

All measurements are in SI units, unless otherwise specified.

Table 1. Friction Factors For Both Pipes

Reynolds Number	Friction Factor of Section A (Dark Blue Pipe)	Reynolds Number	Friction Factor of Section L (Light Blue Pipe)
3.7041×10^3	0.0319	1.9222×10^3	0.2152
6.3278×10^3	0.0383	3.2037×10^3	0.0387
9.4147×10^3	0.0328	4.9657×10^3	0.0161
1.2656×10^4	0.0301	6.5676×10^3	0.0369
1.5743×10^4	0.0287	8.0092×10^3	0.0372
1.8984×10^4	0.0274	9.6912×10^3	0.0339
2.2225×10^4	0.0264	1.1373×10^4	0.0307
2.5312×10^4	0.0258	1.3135×10^4	0.0207
2.8553×10^4	0.0254	1.4817×10^4	0.0272

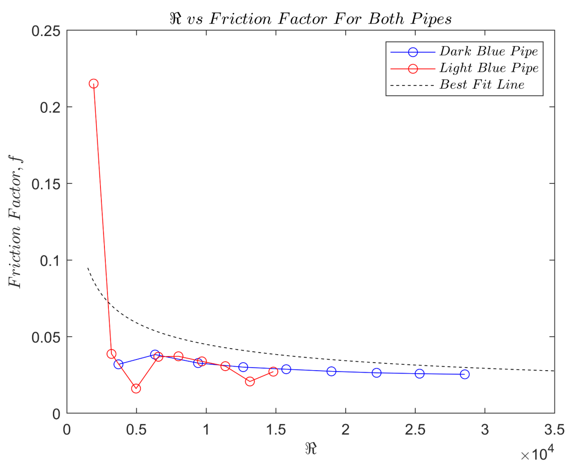


Figure 1. Friction Factor Through Straight Sections

For laminar flows, which all flows in this lab were, the equation for friction factor is $f = \frac{64}{\Re}$. So in laminar flows, as Reynolds number increases, the friction factor goes down in magnitude, which is clearly seen on the table and the plot. Something else to note is that section L had a larger pipe diameter. This affects the velocity, which affects the Reynolds number. Note, these are major losses, since they are through straight sections of pipe.

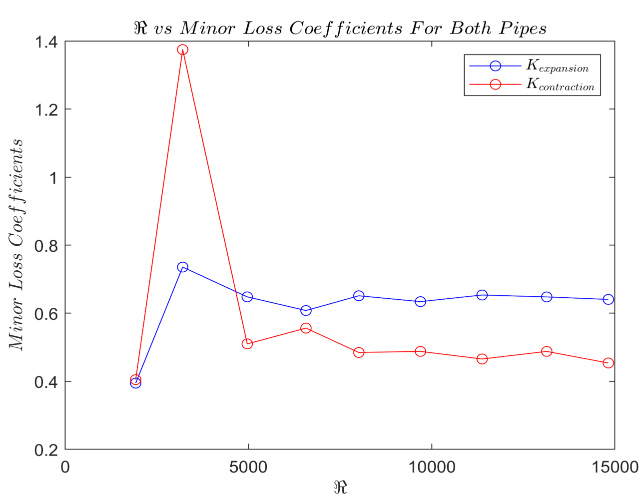


Figure 2. Minor Loss Coeffs. Of Sudden Contractions and Expansions

Table 2. Loss Coefficients Sudden Expansion/Contraction

Reynolds Number	Loss Coefficient of Sudden Exp.	Reynolds Number	Loss Coefficient of Sudden Cont.
1.9222×10^3	0.3945	1.9222×10^3	0.4048
3.2037×10^3	0.7356	3.2037×10^3	1.3748
4.9657×10^3	0.6480	4.9657×10^3	0.5099
6.5676×10^3	0.6079	6.5676×10^3	0.5562
8.0092×10^3	0.6512	8.0092×10^3	0.4846
9.6912×10^3	0.6339	9.6912×10^3	0.4877
1.1373×10^4	0.6535	1.1373×10^4	0.4655
1.3135×10^4	0.6479	1.3135×10^4	0.4878
1.4817×10^4	0.6405	1.4817×10^4	0.4538

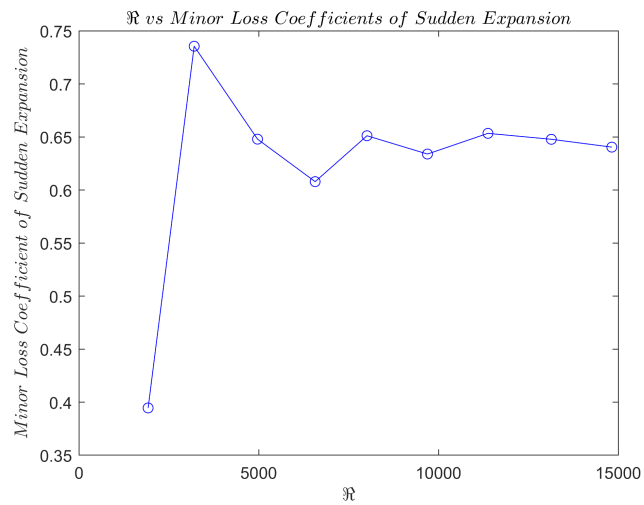


Figure 3. Minor Loss Coefficients of Sudden Expansion

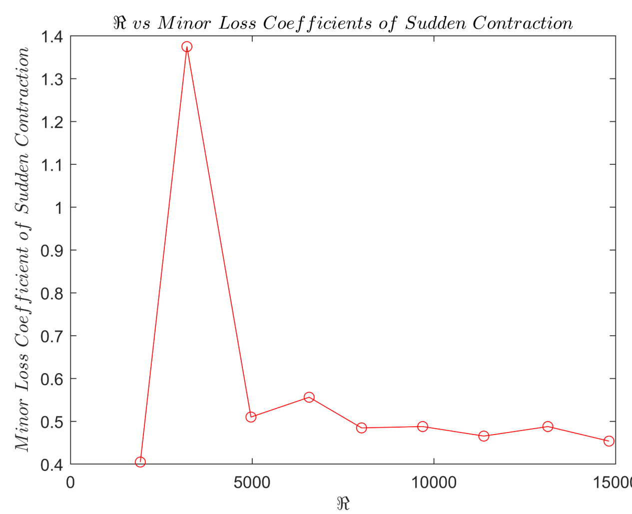


Figure 4. Minor Loss Coefficients of Sudden Contraction

It can be clearly seen that the Reynolds number, and minor losses in both the expansion and contraction do not correlate. The Reynolds number has no effect on these values. After a high enough Reynolds number, it can be clearly seen that the minor losses stay relatively constant, regardless of it.

This is because the minor loss coefficients for sudden expansions and contractions are functions of the ratios of the areas of the two ends, rather than of Reynolds number. And because the cross sectional areas of the ends of the sudden expansion and contraction never change, the minor loss coefficients of these should never change, regardless of the flow rate or Reynolds number. Below are the graphs of the minor losses of sudden expansions and sudden contractions as functions of the ratio of the areas of the two ends.

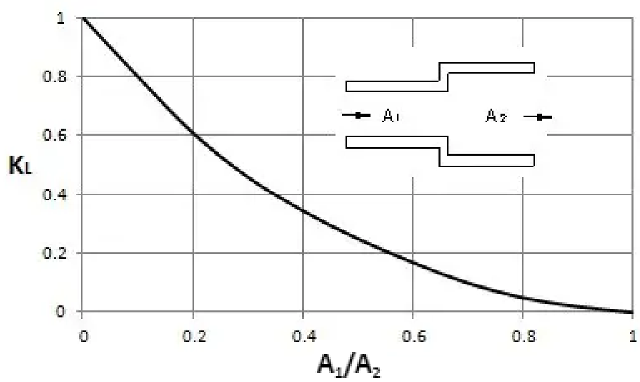


Figure 5. Actual Minor Losses of Sudden Expansion

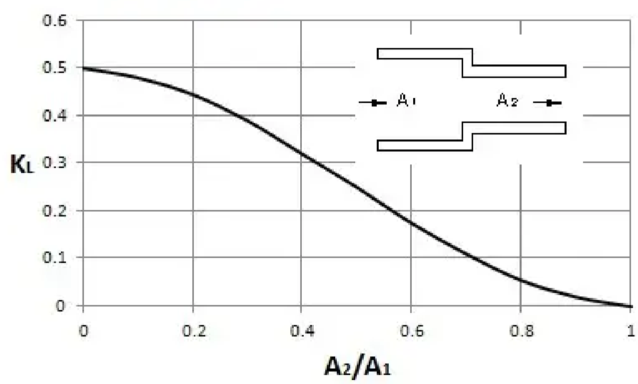


Figure 6. Actual Minor Loss Coefficients of Sudden Expansion

In the error analysis for the recorded minor loss coefficients against what the above graphs say the minor loss coefficients should be, it is useful to analyze when the recorded coefficients start to become steady as Reynolds number increases. The average of the data points after the huge spike (starting at $\Re$ = 4.9657 × 10^3 for both) will be taken, and compared to the theoretical value of each coefficient. It is chosen to use the average, rather than doing an error analysis for each point, since the loss coefficient should be a single number, rather than something that varies with Reynolds number. This means that it isn't useful to run error analysis on each point, because we would rather see what the experiment settles on for the value of loss coefficient, The sudden expansion starts from D_{sm} = 13.7mm and goes to D_{lg} = 26.4mm. And because both areas are circular, then:

$$\frac{A_{sm}}{A_{lg}} = \frac{\pi(D_{sm}/2)^2}{\pi(D_{lg}/2)^2} = \frac{D_{sm}^{\ 2}}{D_{lg}^{\ 2}} = \frac{(0.0137m)^2}{(0.0264m)^2} \approx 0.2692$$

Meaning that $K_e \approx 0.5$ according to the graph. The average of the minor loss coefficients of the sudden expansion from $\Re$ = 4.9657 × 10^3 onwards is:

$$= \frac{0.6480+0.6079+0.6512+0.6339+0.6535+0.6479+0.6405}{7} \approx 0.6404$$

This makes the percent error between the theoretical value and the actual value:

$$\%Err = \frac{|Theoretical - Actual|}{Theoretical} \times 100\% = \frac{|0.5-0.6404|}{0.5} \times 100\% = 28.08\%$$

Because the contraction started at D_{lg} and ended at D_{sm}, The ratio of areas will still remain 0.2692. According to the graph, at this value, $K_c \approx 0.4$. The average value of the minor loss coefficients of the sudden contraction from $\Re$ = 4.9657 × 10^3 onwards is:

$$= \frac{0.5099+0.5562+0.4846+0.4877+0.4655+0.4878+0.4538}{7} \approx 0.4922$$

This makes the percent error between the theoretical value and the actual value:

$$\%Err = \frac{|Theoretical - Actual|}{Theoretical} \times 100\% = \frac{|0.4-0.4922|}{0.4} \times 100\% = 23.05\%$$

What causes such a high error may be inaccurate manometer readings, since the calculation of K_e from lab data was:

$$K_e = \frac{g\pi^2 D_{sm}^4}{8Q^2}(h_7 - h_8) + 1 - \left(\frac{D_{sm}}{D_{lg}}\right)^4$$

And the calculation of K_c from lab data was:

$$K_c = \frac{g\pi^2 D_{sm}^4}{8Q^2}(h_9 - h_{10}) - 1 + \left(\frac{D_{sm}}{D_{lg}}\right)^4$$

Where $h_\#$ is the manometer reading at that tap.

It was discovered after the lab that some of the pressure transducers and manometers were either incorrectly calibrated, or had air bubbles. This means that the final value calculated for the actual minor loss coefficients might not be too accurate.

Table 3. Bend Loss Coefficients

Ratio of Bend Radius to Pipe Diameter	Average Bend Loss Coefficient
0.0000	1.6219
0.0015	1.6047
3.7080	-1.1499
7.4161	-1.1696
11.1314	-1.0999

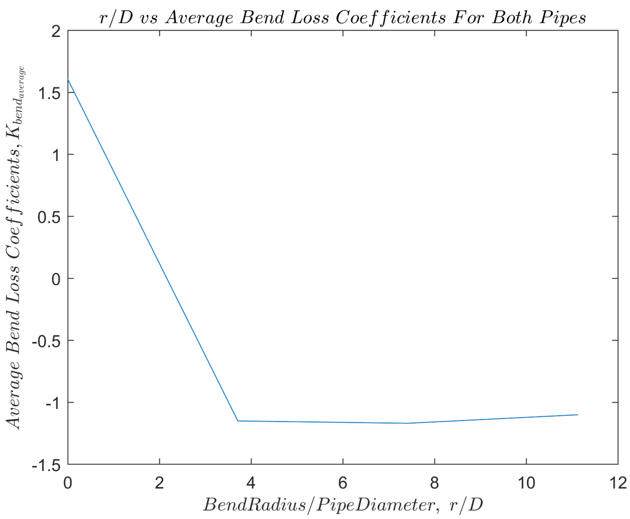


Figure 7. Bend loss Coefficients

Ignoring the negative data points (these are bad data points from the test), it can be clearly seen that as the ratio of bend radius to pipe diameter increases, the loss coefficient decreases. This makes sense, since if the ratio R/D is larger, the flow is smooth, and isn't as sharp.

Assuming no change in diameter from one end of the bend to the other, and using the small diameter,Dsmall, as the default diameter, the equation for the minor loss coefficient of a bend can be found with the equation:

$$K_{bend} = \frac{g\pi^2 D^4_{small}}{8Q^2}\left(h_{manometer-in} - h_{manometer-out} + z_1 - z_2\right) + f\frac{L}{D_{small}}$$

Where L, is the total length of the straight section between the manometers, and the friction factor coefficient can be found with the equation using the Blasius approximation:

$$f = 0.0785 * Re \ ; \ Re = \frac{4\rho Q}{\pi \mu D_{small}}$$

Table 4. Loss Coefficients of Gate and Globe Valves

Reynolds Number	Loss Coefficient of Gate Valve	Reynolds Number	Loss Coefficient of Globe Valve
3.7041×10^3	2177.3663	3.7041×10^3	2177.3663
6.3278×10^3	699.4514	6.3278×10^3	759.3565
9.4147×10^3	294.9187	9.4147×10^3	285.4819
1.2656×10^4	145.7190	1.2656×10^4	151.5478
1.5743×10^4	79.1085	1.5743×10^4	90.1430
1.8984×10^4	44.0395	1.8984×10^4	50.8612
2.2225×10^4	22.6809	2.2225×10^4	33.0428
2.5312×10^4	13.1147	2.5312×10^4	14.5719
2.8553×10^4	0.0000	2.8553×10^4	5.7257

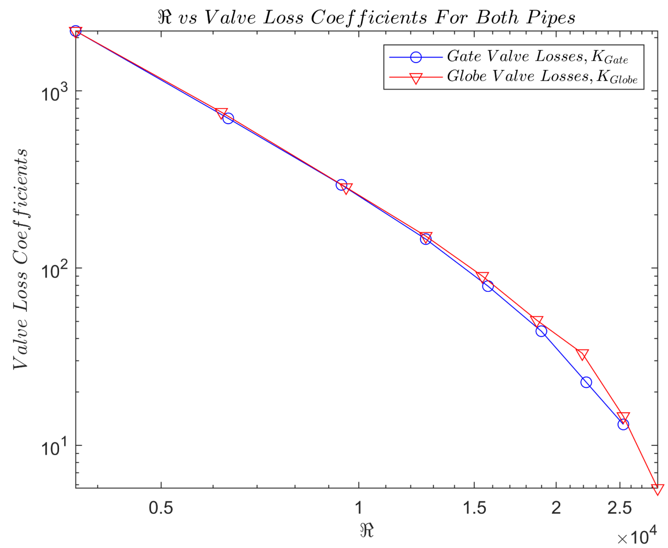


Figure 8. Valve loss Coefficients

As seen from the table and plot, the gate valve and the globe valve have similar trends for their loss coefficients as a function of Reynolds number. It can also be clearly seen that as the Reynolds number increases, the loss coefficient decreases.

References

Minor Head Loss (no date) *S.B.A. Invent*. Available at: https://sbainvent.com/fluid-mechanics/minor-head-loss/.

Author, Salvador Mayoral, 2023, *Head loss in a pipe-system Experiment No. 03*, California State University, Fullerton