How to Select the Right Control Valve

A Modeling Approach to Evaluate the Installed Characteristic and Process Gain

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Thank you!

Presenters

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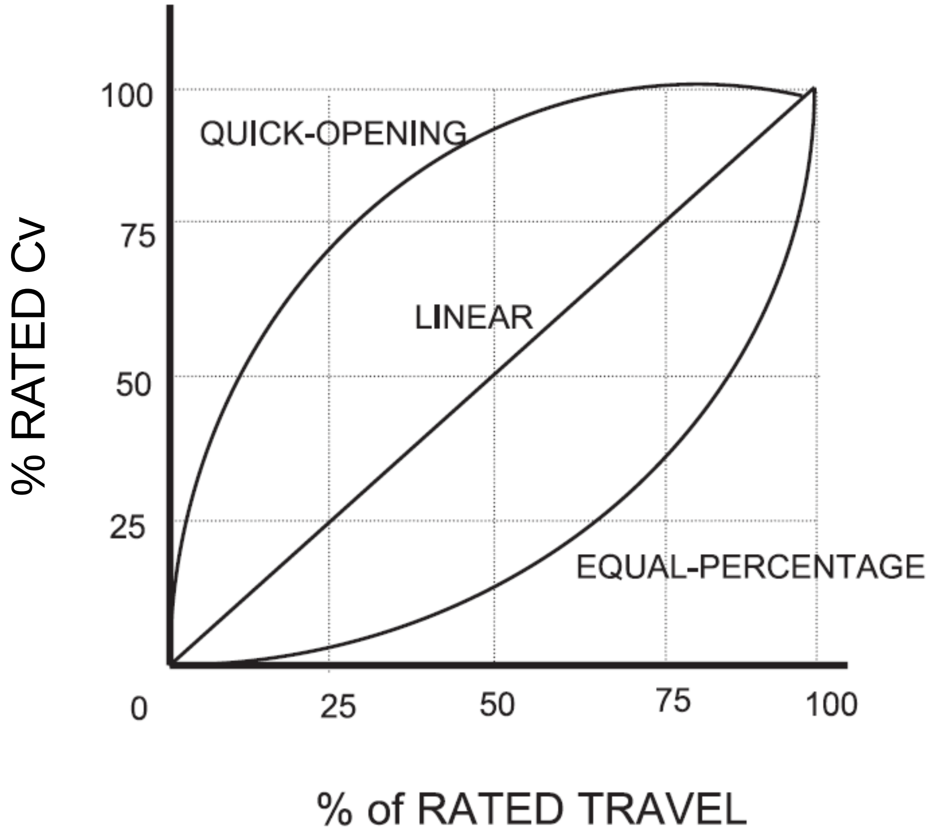
Introduction

- One important requirement in selecting the right control valve is ensuring that the valve has the proper installed characteristic and process gain
- Process gain has been identified as an important characteristic; see work by Greg McMillan or Emerson’s Mark Coughran or EnTech paper
- We’ll see how to develop a model to evaluate control valve performance
- We’ll look at some examples of modeling techniques to help us analyze control valves

Inherent vs. Installed Valve Characteristics

- Quick review of control valve basics
- Three basic inherent valve characteristics – linear, equal percentage, quick opening



Inherent vs. Installed Valve Characteristics

- The installed characteristic usually differs from the inherent due to changes in pressure drop – as flow increases, there is less pressure drop available across the valve
- It's usually desirable to have a relatively linear installed characteristic
- A valve's Cv has engineering units, because d/p is proportional to the square of the flow rate, the units are:

$$gpm/\sqrt{psi}$$

Process Gain

- Process gain is the percent change in the process variable divided by the percent change in controller output
- Based on extensive experience, process control experts have determined the recommended range for process gain, 0.5 to 2.0, for self-regulating processes
- During the design phase of a project, it sometimes becomes desirable to model a control valve’s installed process gain performance

“I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind.”

- Lord Kelvin

Modeling Methods

- Modeling software – General purpose math programs vs. specialized packages
- Mathcad, Mathematica, Matlab, Maple, or even Excel can be used to develop mathematical models of the piping and equipment
- Examples presented use Mathcad
  - Ease of use; Powerful solver and graphing capabilities
  - Displays all equations in conventional math notation
  - No hidden cells or formulas
  - Readily handles automatic conversions between U.S. Customary and SI engineering units

Basis of Modeling Approach

- General purpose software such as Mathcad configured to implement the governing equations for piping, equipment, and valves
- Crane Technical Paper No. 410 provides the background information and equations for mathematical model of piping, valves, orifice plates, etc.
- Bernoulli's Theorem and the Darcy formula for liquid flow and compressible fluid flow

Darcy formula, liquid flow… $Q_{KL}(P_1, P_2, Ka, d, sg) := 236 \cdot \frac{d^2}{in^2} \cdot \sqrt{\frac{P_1 - P_2}{62.34 \cdot sg \cdot Ka}} \cdot \frac{gpm}{\sqrt{psi}}$

Main Formulae

- Key Formulae

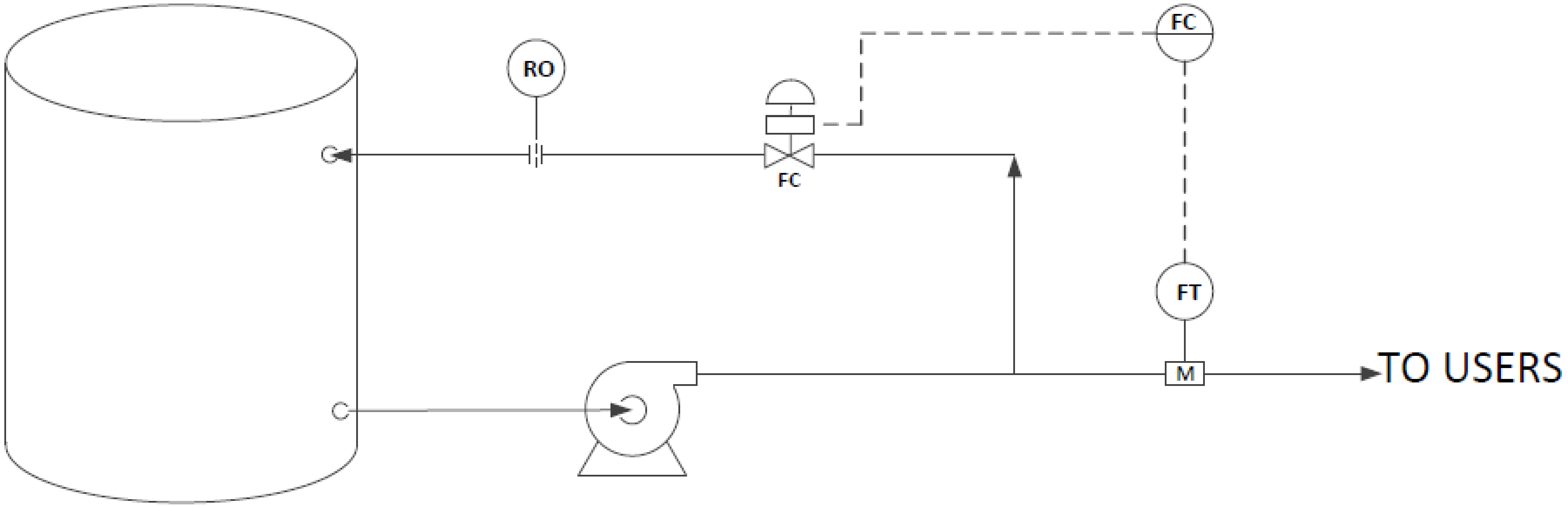
$$f_t(d) := \frac{0.25}{\log\left(\frac{3.7 \cdot d}{\varepsilon}\right)^2}$$

$$K_{pipe}(d, L) := f_t(d) \cdot \frac{L}{d}$$

K of valve from Cv…

$$K_{Cv}(Cv, d) := 891 \cdot \frac{d^4}{Cv^2} \cdot \frac{gpm^2}{psi \cdot in^4}$$

Example 1: Liquid Flow – Pump Recycle Loop



- Pump Minimum Flow Bypass Control Valve Problems
  - Existing valve was subject to cavitation, which the field attempted to reduce by installing a restriction orifice
  - Valve characteristic questionable
  - Loop was not controlling properly
  - Ideally, protect two parallel pumps (A/B), each requiring 50 gpm min flow
- Is the valve okay? What size orifice is needed?

First Step: Plot Valve Cv vs. % Open

Valve % open...

$$zx := \begin{pmatrix} 0 \\ 10 \\ 20 \\ 30 \\ 40 \\ 50 \\ 60 \\ 70 \\ 80 \\ 90 \\ 100 \end{pmatrix} \cdot \%$$

Valve Cv...

$$Cvx := \begin{pmatrix} 0 \\ 0.32 \\ 0.52 \\ 0.97 \\ 1.56 \\ 2.08 \\ 2.99 \\ 4.03 \\ 5.85 \\ 8.71 \\ 13.0 \end{pmatrix} \cdot \frac{gpm}{\sqrt{psi}}$$

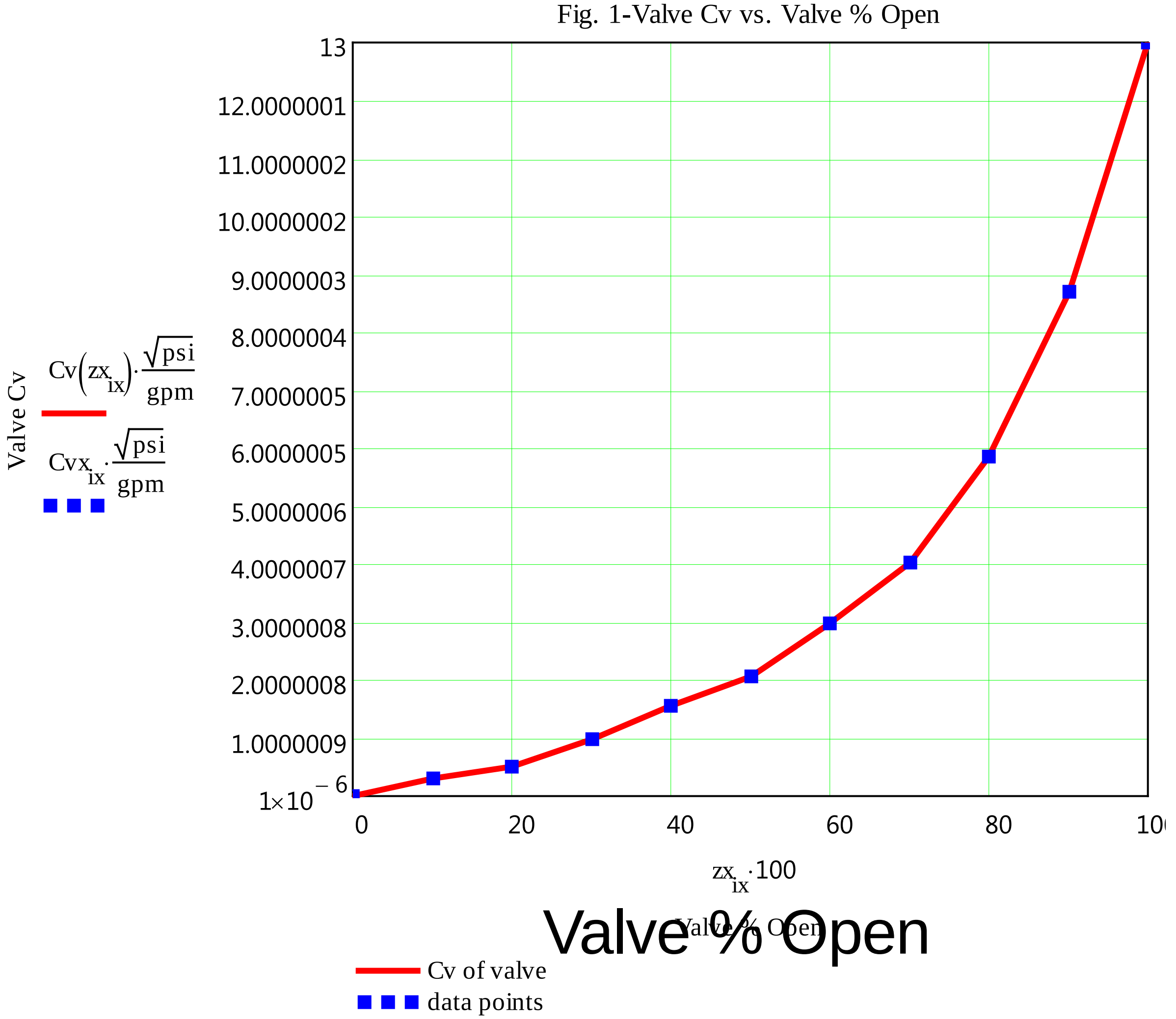
$$Cvz := lspline(zx, Cvx)$$

$$Cv(z) := interp(Cvz, zx, Cvx, z)$$

$$ix := 0 .. rows(zx) - 1$$

Graph the Cv Curve

Fig. 1-Valve Cv vs. Valve % Open



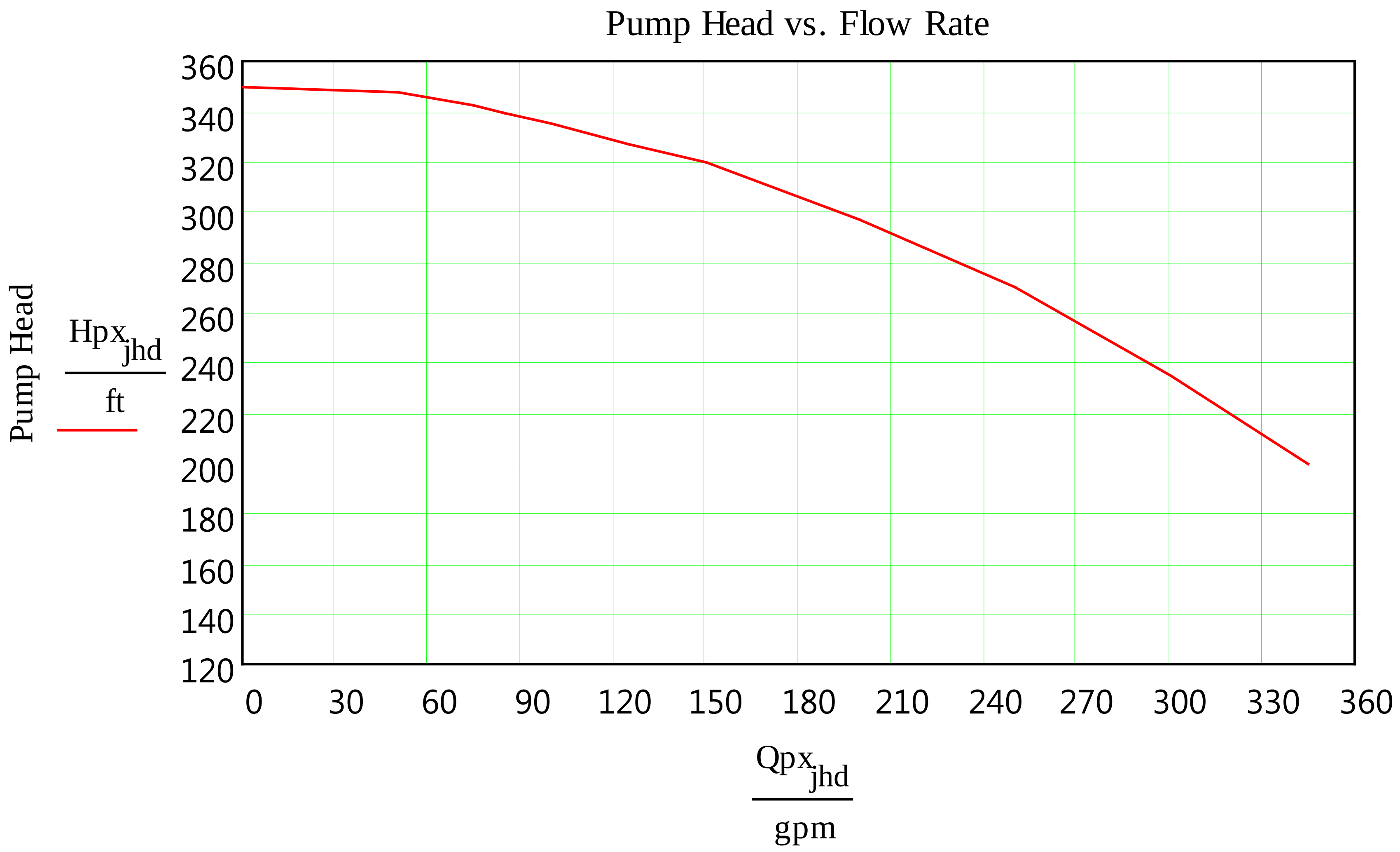
Valve CV

Valve % Open

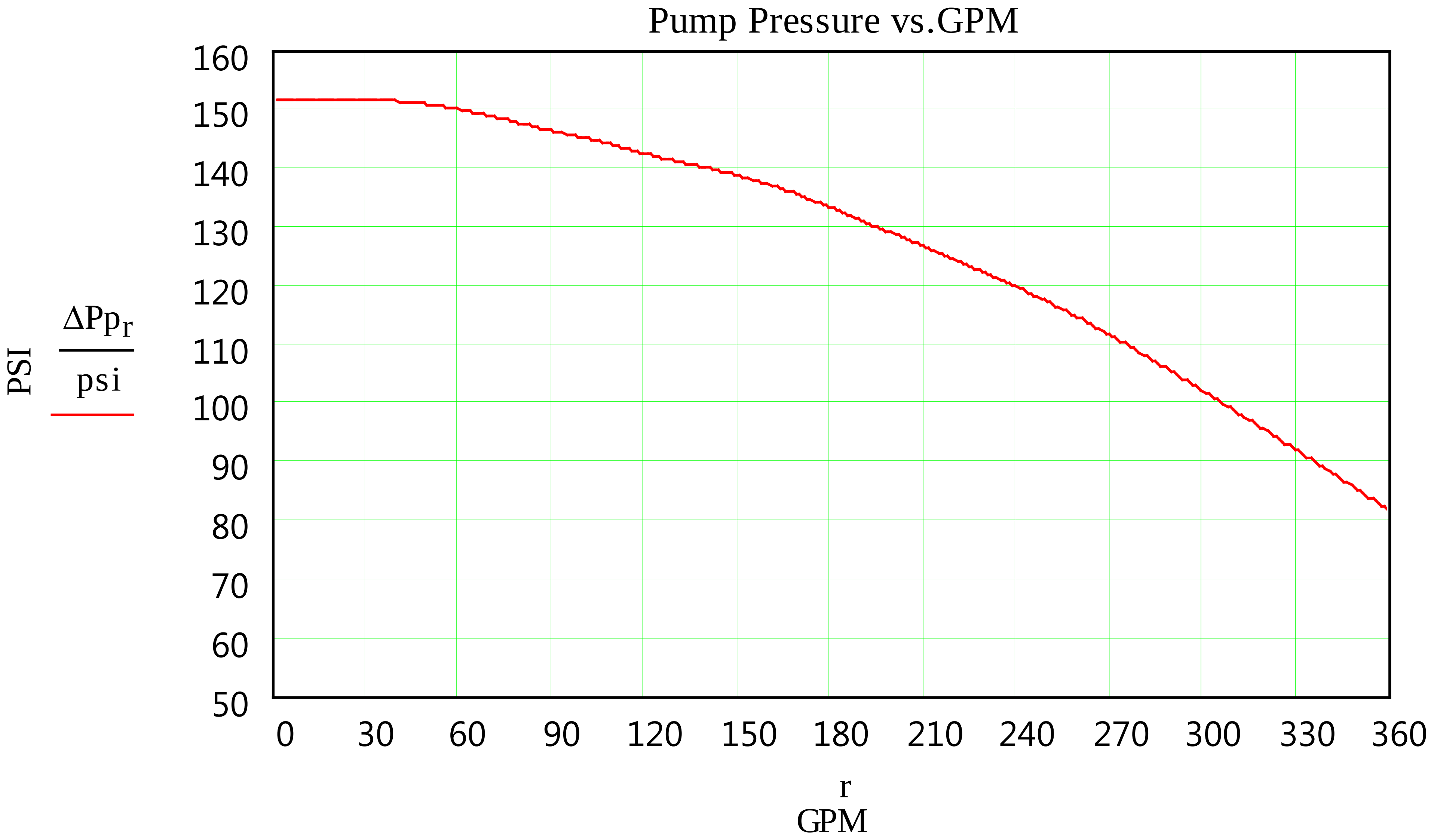
Second Step: Develop the Pump Curve

$$Qpx := \begin{pmatrix} 0 \\ 50 \\ 75 \\ 85 \\ 100 \\ 125 \\ 150 \\ 200 \\ 250 \\ 300 \\ 345 \end{pmatrix} \cdot gpm \qquad Hpx := \begin{pmatrix} 350 \\ 348 \\ 342 \\ 339 \\ 335 \\ 327 \\ 320 \\ 297 \\ 270 \\ 235 \\ 200 \end{pmatrix} \cdot ft$$

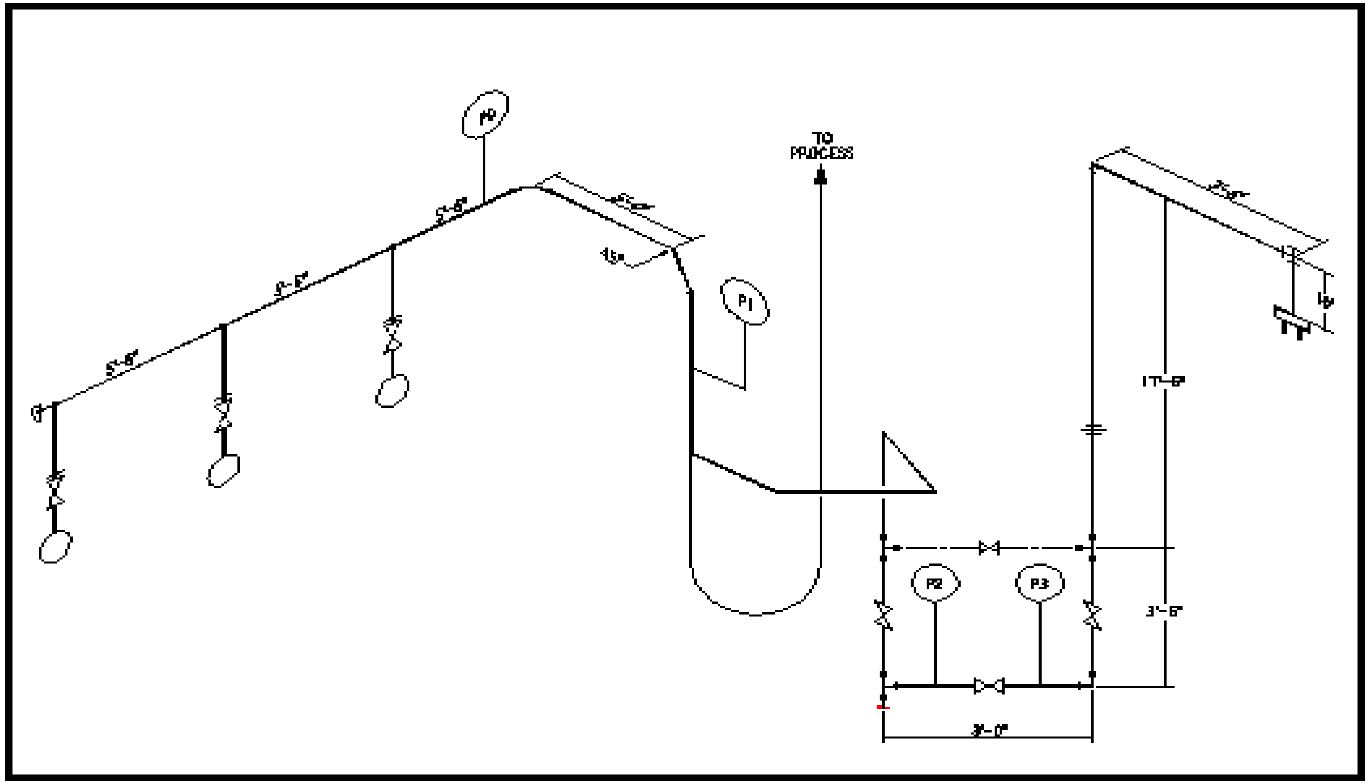
Plot the Pump Curve in Feet of Head



Plot Pump Curve in PSI



Third Step: Develop Expressions for Piping Resistance (Using Isometrics if Possible)



Resistance K for Piping and Valve

Pipe segment 1...

$$K_1 := K_{pipe}(d6, 14\cdot ft) + 2\cdot K_{el}(d6, 1.5) + K_{bend}(d6, 1.5, 45\cdot deg) \qquad K_1 = 0.98$$

Pipe segment 2...

$$K_2 := K_{pipe}(d2, 10\cdot ft) + 3\cdot K_{el}(d2, 1.5) + K_{t\_run}(d2) + K_{t\_brn}(d2) + K2_{red}\left(\frac{d1}{d2}, 180\cdot deg\right)$$

$$K_2 = 3.95$$

Pipe segment 3 (K is a function of valve opening, z)...

$$K_3(z) := K_{pipe}(d1, 3.0\cdot ft) + K_{Cv}(Cv(z), d1)$$

Last of the Piping Segments

For segment 4, define K as a function of β, the beta ratio of the orifice plate.

Now that we've defined C as a function of β, K3 can be computed with β as the only independent variable ...

$$K_4(\beta) := \left(K2_{exp}\left(\frac{d1}{d2}, 180\cdot deg\right) + 2\cdot K_{el}(d2, 1.5) + K_{t\_run}(d2) \ldots \atop + K_{orf}(Cbeta(\beta), \beta) + K_{pipe}(d2, 30\cdot ft) + K_{t\_brn}(d2) + K_{exit} \right)$$

$K_{orif}(\beta) := K_{orf}(Cbeta(\beta), \beta)$

Check it out...

$K_4(0.28) = 425.6$

$K_{orif}(0.28) = 418.8$

Next: Use the Solver and the Darcy Formula

Now compute the recycle flow rate as a function of valve opening and beta ratio of orifice. Note that the baseline/datum for K calculations is the 2" line. Thus all K values are corrected to the velocity head associated with the 2" pipe. Per equation 2-5 [ref. 1], Ka=Kb(da/db)^4.

$$P_{disch} = 20.8\,psi$$

Guess...

$$q_{recyc} := 140 \cdot gpm \qquad \delta Pp\left(q_{recyc}\right) = 139.8\,psi$$

Given

$$q_{recyc} = Q_{KL}\left[\delta Pp\left(q_{recyc}\right) + Pbar, P_{disch}, K_1 \cdot \left(\frac{d2}{d6}\right)^4 + K_2 + K_3(z) \cdot \left(\frac{d2}{d1}\right)^4 + K_4(\beta), d2, G\right]$$

$$q_{re}(z, \beta) := Find\left(q_{recyc}\right)$$

Check it Out!

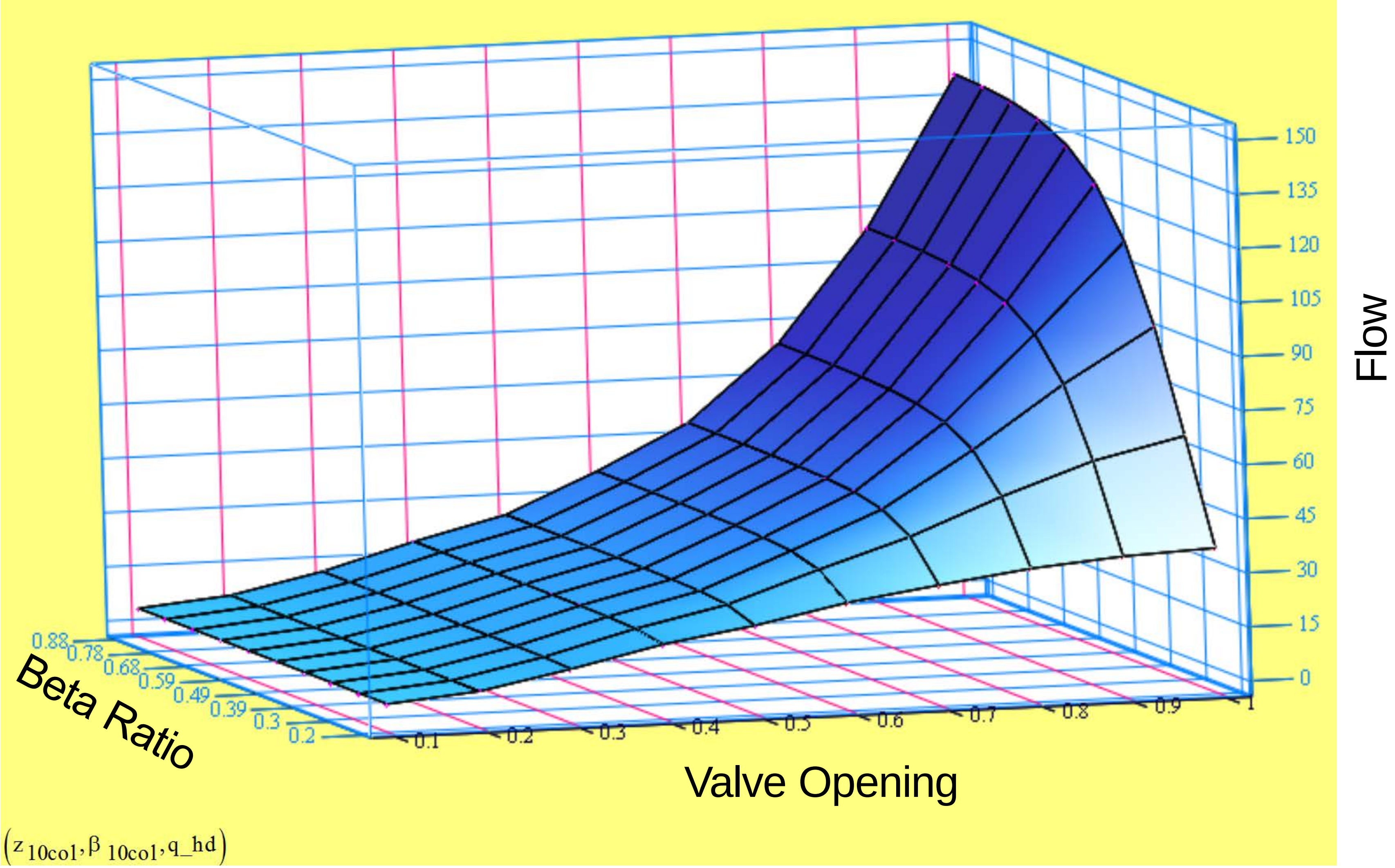
Check it out..

$$q_{re}(99.0 \cdot \%, 0.875) = 137 \text{ gpm}$$

This looks reasonable: If the valve is fully open, and the orifice has a large bore, we get a higher-than-required flow rate. Our model looks good so far!

Surface Plot: Flow vs Valve % Open, Beta ratio

Recycle Flow (gpm) as function of Beta Ratio, Valve Opening (0-1)



What's the d/p across the valve?

Find the ΔP across the valve…

Guess…

$$\delta Pvalve := 0.1 \cdot psi$$

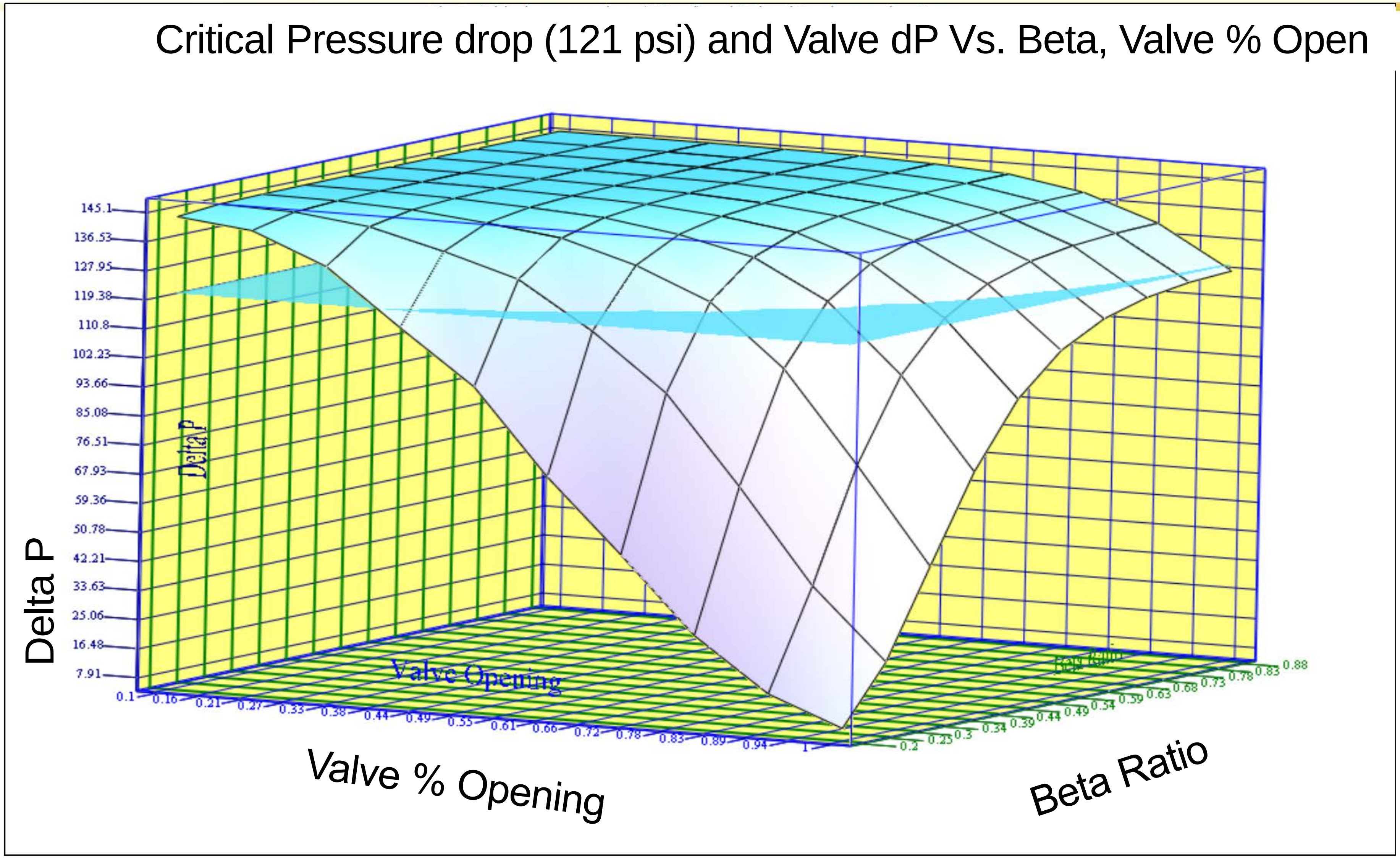
Given

$$Q_{KL}\left[P_{in}, P_{in} - \delta Pvalve, K_3(z) \cdot \left(\frac{d2}{d1}\right)^4, d2, G\right] = FLOW$$

$$dPvalve(P_{in}, z, FLOW) := Find(\delta Pvalve)$$

$$dPvalv_{i,j} := dPvalve\left[\delta Pp\left[\left(q\_hd_{i,j}\right) \cdot gpm\right], z_i, \left(q\_hd_{i,j}\right) \cdot gpm\right]$$

Plot Predicted d/p vs. Critical d/p



$$\left(z_{10col}, \beta_{10col}, \frac{dPvalv}{psi}\right), \left(z_{10col}, \beta_{10col}, dp\_crit\right)$$

Interpret the 3D Plot

- Any d/p above the “Critical” plane will result in cavitation
- By inspection, we can select an orifice size that will work
- For a given orifice size, we then can determine the minimum opening position for the valve to move out of the cavitation region
- For the selected orifice, we can compute the process gain for the valve
- In this case, visual inspection of the 3D surface plots helped with the somewhat arbitrary selection of the orifice plate beta ratio: 0.40

Set up to Plot the Process Gain

- With a beta ratio (0.40) selected, the flow can now be a function of a single variable, the valve opening (0 to 1) which is also the controller output

$$q_{re2}(z) := q_{re}(z, 0.40)$$

Check it out...

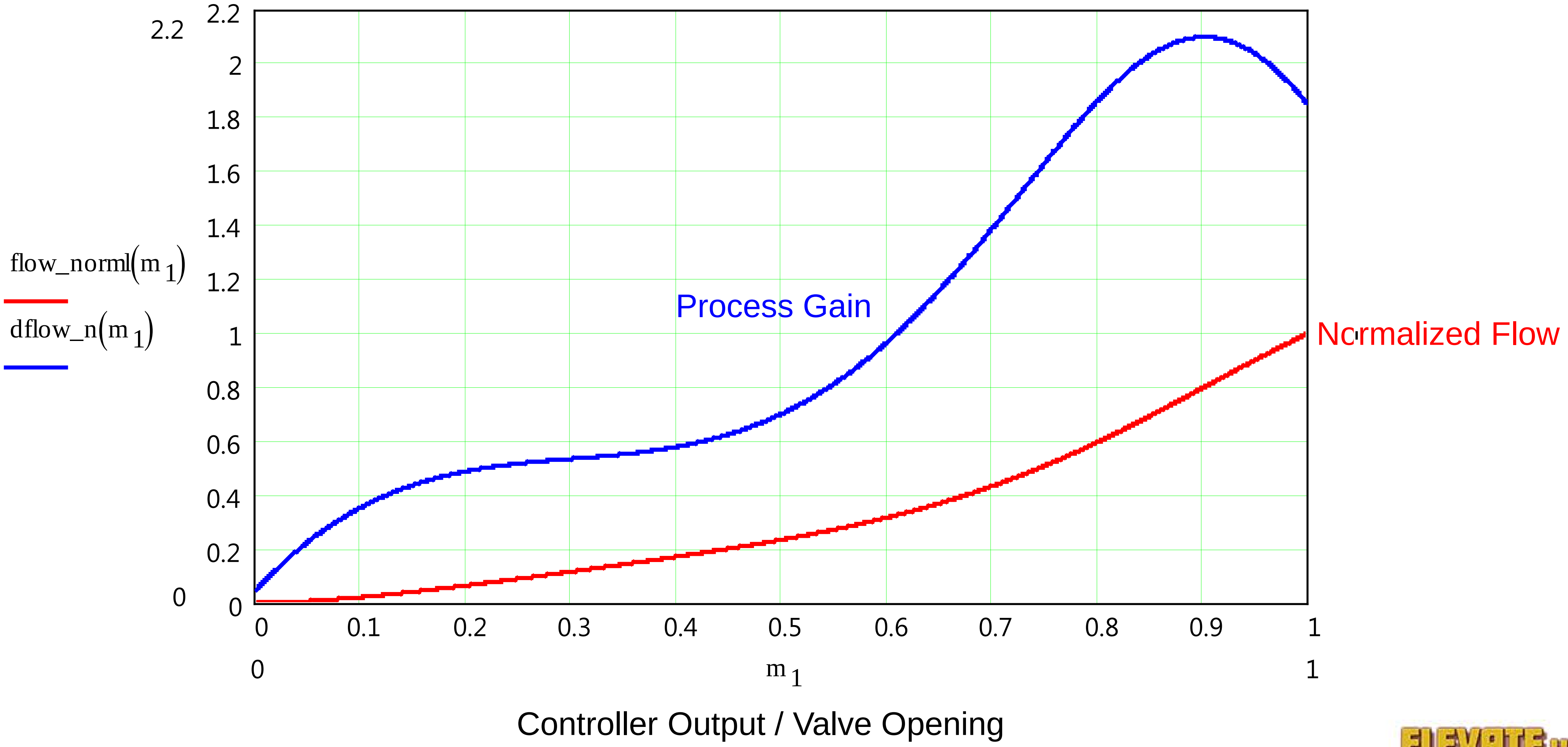
$$q_{re2}(1) = 106.6\,\text{gpm}$$

Compute “Normalized” Flow vs Valve Opening

- Now we "normalize" the flow rate (so max = 1), which allows us to calculate the Process Gain, i.e., D%PV/%output [in this case % output is the % of valve stroke]
- We also compute the derivative, i.e., the rate of change, of the normalized flow curve so we can plot the process gain on the same plot

$$\text{flow\_norml}(y) := \frac{q_{re2}(y)}{q_{re2}(1)} \qquad \text{dflow\_n}(z) := \frac{d}{dz}\text{flow\_norml}(z)$$

Graph the Valve’s Performance

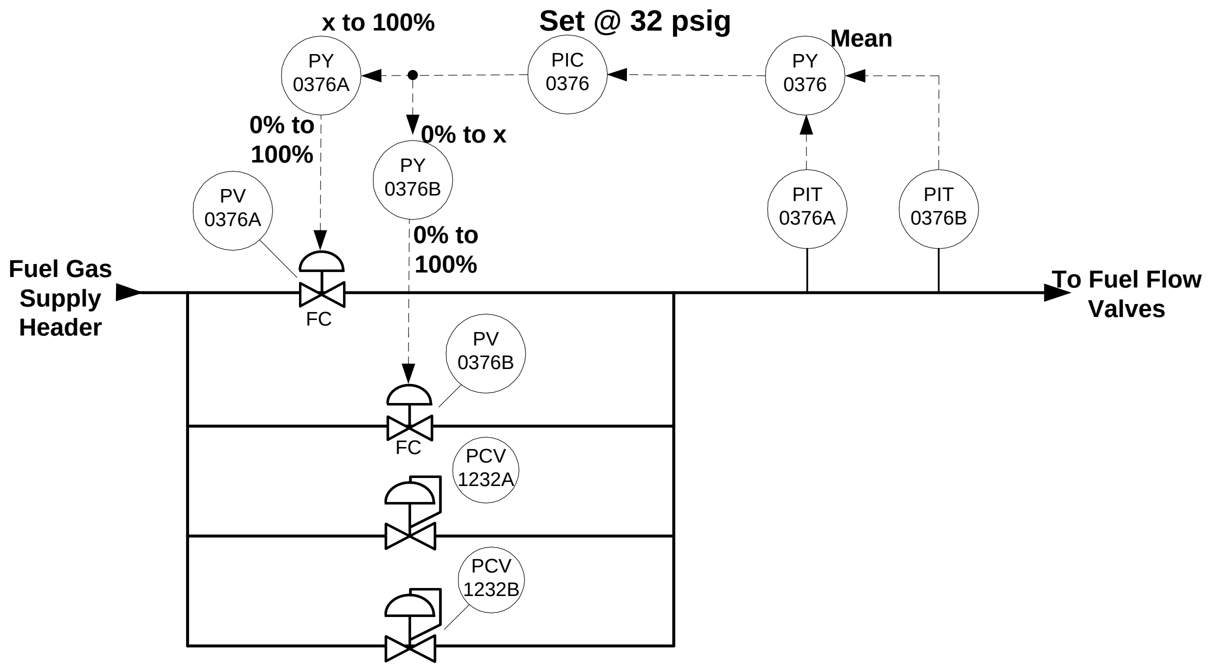


Conclusions

- From the graph, we can see that the process gain exceeds the desired limits (0.5 to 2.0)
- This fits our intuitive grasp that this was the wrong choice for this valve, an equal percentage valve characteristic where the pressure drop is relatively constant across the valve
- The recommended solution?
  - Install orifice with 0.40 beta ratio
  - Use a look-up table in the DCS to compute the valve position as a function of the measured flow
  - The look-up table incorporates a “step change” to ensure relatively large minimum opening to avoid high d/p across the valve and cavitation

Example 2: Fuel Gas to Platformer

- **Fuel Gas Pressure Control**



- **Objective**
  - The purpose of the controller is to maintain the fuel gas supply pressure at 32 psig to the downstream flow control valves for the 4 heater cells, with a design flow of 6.2 x 10^5 scfh, max of 7.5 x 10^5 scfh

Darcy Formula for Gas

Darcy formula for compressible fluid flow, including critical pressure drop limitations:

$$Qx_{Kg}(P_1, P_2, Ka, d, sg, temp, Z, k) := 678 \cdot Yx\left(\frac{P_1 - P_2}{P_1}, Ka, k\right) \cdot \frac{P_1}{psi} \cdot \left(\frac{d}{in}\right)^2 \cdot \sqrt{\frac{rx\left(\frac{P_1 - P_2}{P_1}, Ka, k\right)}{Ka \cdot Z \cdot \frac{temp}{R} \cdot sg}} \cdot scfm$$

Model the Proposed Valves

Fuel Gas Split Range Valve Flow Calculations

To start, let's plot curves of valve Cv vs. valve position

The Cv data for valves is selected from Fisher catalog 12

The large valve has a 6x4 inch EWT body, the smaller valve is a 4-inch ET with Whisper III trim.

Set Up Cv Data for Curve Fitting

Valve % Open

$$zx := \begin{pmatrix} 0 \\ 10 \\ 20 \\ 30 \\ 40 \\ 50 \\ 60 \\ 70 \\ 80 \\ 90 \\ 100 \end{pmatrix} \cdot \%$$

Big Valve

$$CvA := \begin{pmatrix} 10^{-5} \\ 30.9 \\ 69.9 \\ 110 \\ 149 \\ 187 \\ 223 \\ 253 \\ 281 \\ 307 \\ 325 \end{pmatrix} \cdot \frac{gpm}{\sqrt{psi}}$$

Smaller Valve (Cg)

$$CvBx := \begin{pmatrix} 10^{-5} \\ 100 \\ 400 \\ 900 \\ 1390 \\ 1800 \\ 2250 \\ 2720 \\ 3200 \\ 3600 \\ 3730 \end{pmatrix} \cdot \frac{gpm}{30.081\sqrt{psi}}$$

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Develop Polynomial Equation for Cv Curve

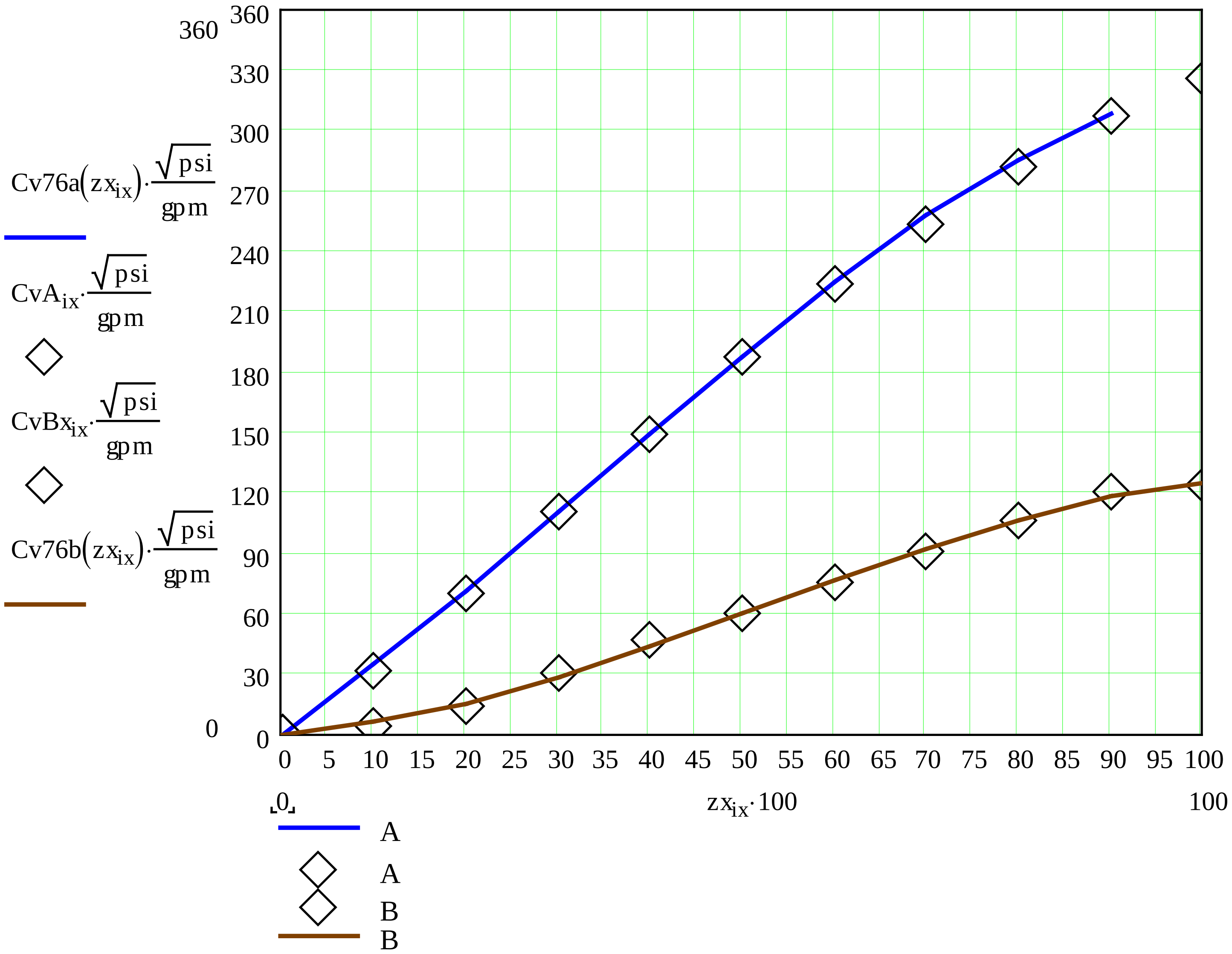
- The cubic spline interpolation function in Mathcad yields piecewise cubic equations that connect all data points but result in non-continuous overall curves
- For quick curve fitting, Mathematica will compute the coefficients, exponents, etc., for any user-defined equation for a data set
- Best approach is to then plot the curves and the data points to verify a satisfactory solution

Here are the Resulting Polynomials

$$Cv76b(z) := \left(31.4375 \cdot z + 258.804 \cdot z^{2} - 165.258 \cdot z^{3}\right) \cdot \frac{gpm}{\sqrt{psi}}$$

$$Cv76a(z) := \left(321.296 \cdot z + 213.76 \cdot z^{2} - 212.151 \cdot z^{3}\right) \cdot \frac{gpm}{\sqrt{psi}}$$

Plot Cv Curves and Points to Confirm Results



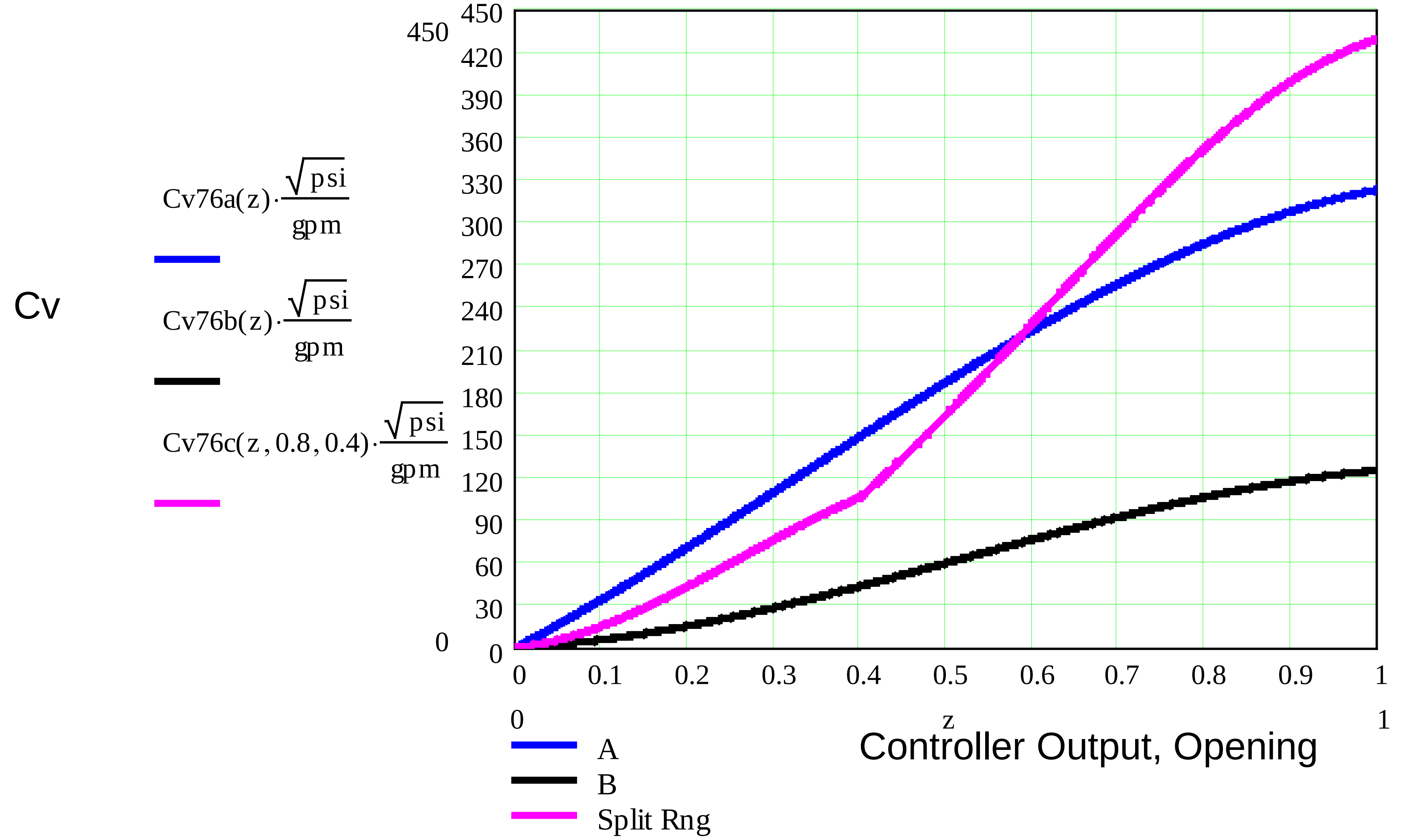
Setup to Test Split Range Configurations

Now let's allow configurable split range setup. Let "LS" represent the software limit stop on the small valve B and let "sw" be the controller output point where the small valve is fully opened (to the soft limit stop), and the big valve A begins to open. The A valve will be fully open at controller output of 1. "Cv76c" is the overall Cv for the split range operation.

$$Cv76c(z, LS, sw) := \text{if}\left[z < sw, Cv76b\left(\frac{LS}{sw}\cdot z\right), Cv76b(LS) + Cv76a\left[(z - sw)\cdot\frac{1}{1 - sw}\right]\right]$$

Plot Valve Cv and Split Range Setup

Cv plot for each valve and combined (split range)



What We Learned from the Graphs

- The goal: make the two, split-range valves act like one, large valve
  - Ensure that the combined Cv provides adequate capacity
  - Try to get the minimum discontinuity at the transition point, when we stop opening the smaller valve and begin opening the larger valve
- Using the overall Cv equation with three variables, plot some trial cases for configuration variables LS and sw, showing the process gain
- Verify we meet the capacity requirements, i.e., max flow required

Compute Flow Based on Split Range Valves

Next step: Setup the solver on the Darcy formula to find flow *qa1* as a function of controller output *z*, the soft limit stop *LS*, and the controller switch point *sw*:

$$Qx_{Kg}\left(60\cdot psi + P_{bar}, 32\cdot psi + P_{bar}, K_{Cv}(Cv76c(z, LS, sw), d12), d12, sg_{1}, 710\cdot R, 1.0, 1.208\right) = qa1\cdot scfh$$

$$q_{im}(z, LS, sw) := Find(qa1)$$

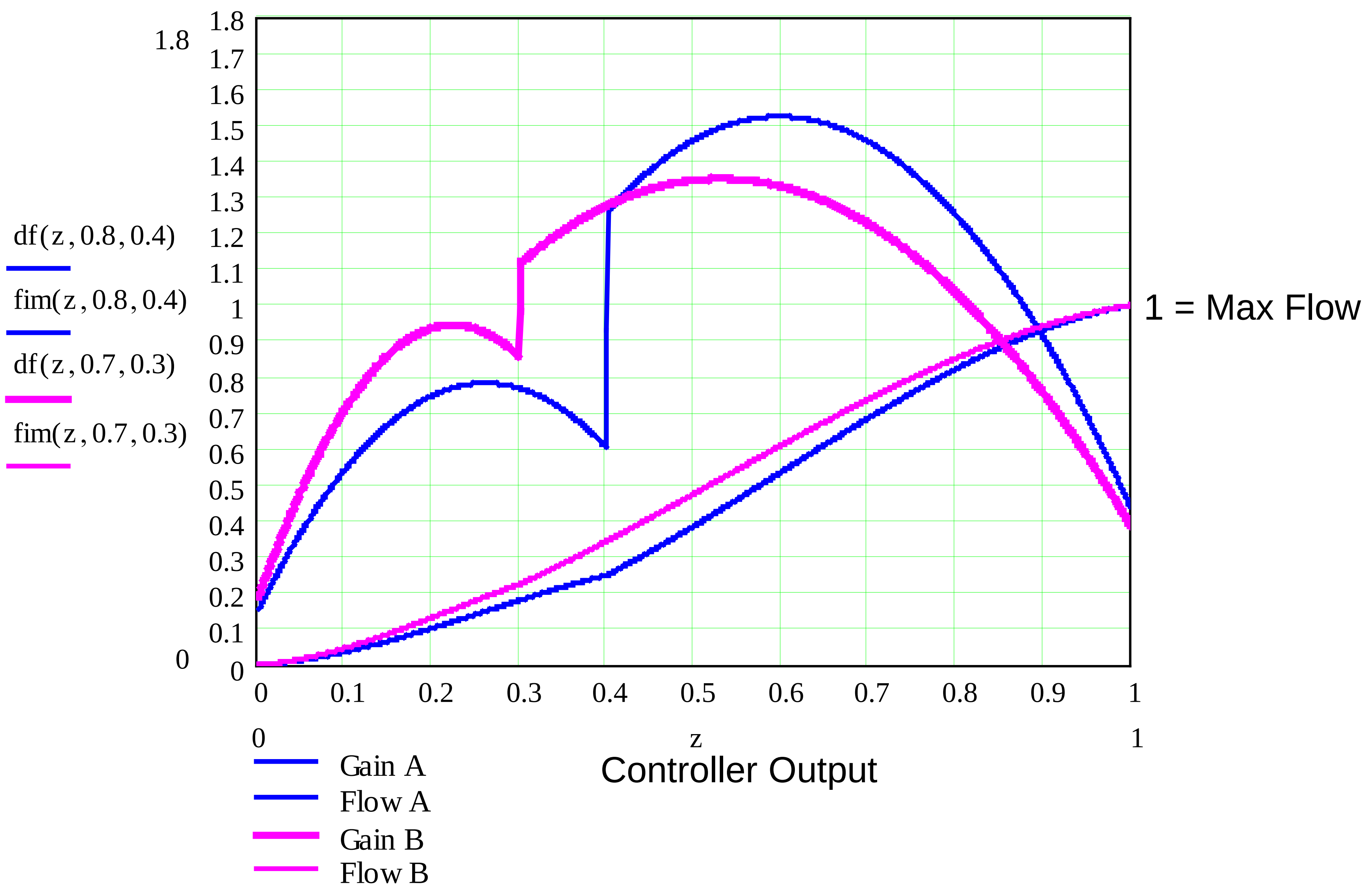
What’s the Process Gain?

Next...let's find the slope, i.e., the process gain. Let's define normalized flow as a function of three variables: controller output z, the soft limit stop LS, and the controller switch point sw. Then compute the derivative to find Process Gain.

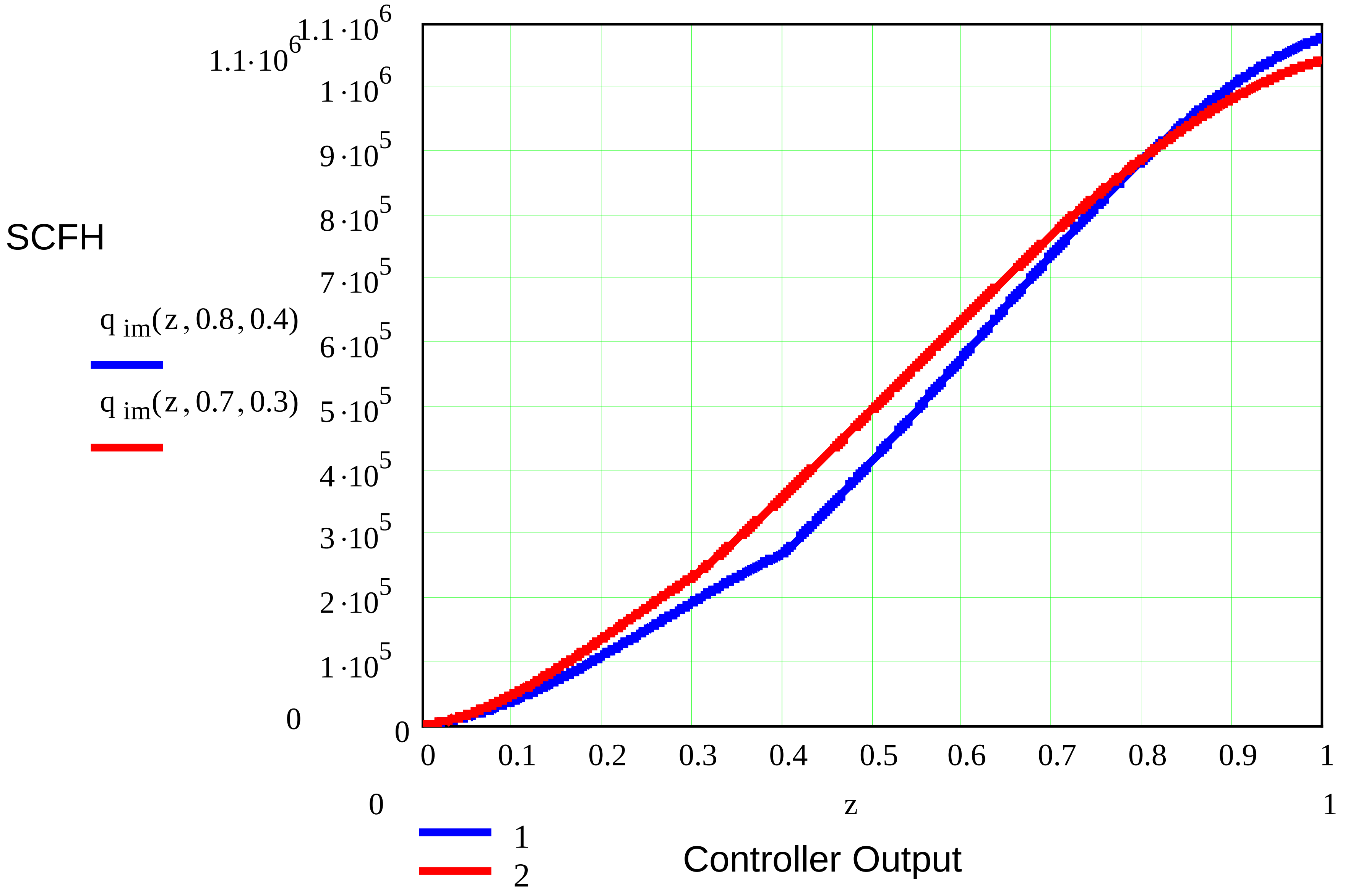
$$\mathrm{fim}(z, LS, sw) := \frac{q_{im}(z, LS, sw)}{q_{im}(1, LS, sw)}$$

$$\mathrm{df}(z, LS, sw) := \frac{d}{dz}\mathrm{fim}(z, LS, sw)$$

Plot Normalized Flow and Process Gain (Two Cases)



Verify the Fuel Gas Flow Rate



Example 2 Conclusions

- The proposed split range setup provides the required rangeability, plenty of capacity and headroom
- The process gain falls within the desired range, with the only exceptions being the extreme end ranges of the controller output (i.e., the range of valve positions that are outside the normal limits of recommended operation)

Business Results Achieved

- Example 1: Proper setup of controller and re-sizing of restriction orifice plate allowed for satisfactory operation using the existing control valve, saving thousands of dollars
- Example 2: Coordination with our LBP on proper selection of Fisher control valves ensured smooth startup of this major refinery expansion, which has been in virtually continuous operation for several years now. The proper operation of the platformer controlled by these valves is the heart of this reformer system and this major refiner has reported a very high level of satisfaction with the delivered project.

Summary

- We've briefly seen the following steps in design/modeling:
  - The Desired Range of Control Valve Process Gain
  - The Empirical and Mathematical Bases for Modeling Valve Performance
  - How the Graphical Presentation of Data Helps Analysis and Assessment
- The Foregoing Analysis can Provide Confidence in the Selection of the Right Control Valve, Knowing the Installed Performance
- Assured Valve Performance Allows Focus on Controller Tuning and Performance, with Resultant Cost Savings or Productivity Benefits
- Questions?

Where To Get More Information

- Crane Technical Paper No. 410, *Flow of Fluids*
- Sessions with Emerson's Mark Coughran, James Beall
- Greg McMillan's books, e.g., *101 Tips for a Successful Automation Career*
- Fisher Catalog 12 (http://www.documentation.emersonprocess.com/groups/public/documents/catalog/cat12_s1.pdf)
- http://www.documentation.emersonprocess.com/groups/public/documents/articles_articlesreprints/headleyrev_spr03_valvemag.pdf

Acknowledgements:

Thanks to Dave Bruchie and Mark Coughran!

Relevant Presentations

Track	Title	Presenter	Schedule
3-5121	Solving Pressure Control Loop Problems in Hydrocarbons Processing Plants	Mark Coughran	Wednesday (10-10:45am), Thursday (1:15-2pm)
3-5080	Achieving Operational Excellence on a Semi-Continuous Process: A DeltaV APC Project	James Beall	Tuesday (8-8:45am), Thursday (4-15-5pm)
6-5771	Impact of Control Valve Performance on Control Performance	James Beall	Wednesday (10-10:45am), Thursday (2:15-3pm)
MTE-6326	Process Control Optimization	James Beall	Friday (9-9:30 am and 10-11:30 am)
3-5787	Unleash the Power of DeltaV PID Control	James Beall	Tuesday (3-3:45pm), Thursday (10-10:45am)

Thank You for Attending!

Enjoy the rest of the conference.

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