Using CHEMCAD for Piping Network Design and Analysis
Part 1 – Unbranched Pipes

By

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Abstract

CHEMCAD is a powerful tool for designing and analyzing complex piping networks. It enables the engineer to integrate the piping network simulation into the overall process simulation, calculating a momentum balance in addition to a heat and material balance. This makes it possible to quickly evaluate the effects of changes in the process concept, or of its chemicals, on the piping network.

Part 1 of this paper presents a tutorial on how to use the piping network tool for unbranched pipe analysis. Part 2 progressively adds complexity with more complicated networks, culminating in examples that demonstrate how CHEMCAD can be used to analyze practical plant piping problems.

Introduction

The CHEMCAD software suite is a powerful tool for designing and analyzing complex piping networks (1). As shown in **Figure 1**, CHEMCAD contains a number of UnitOps that calculate flow as a function of pressure drop. These are: Pipe Simulator, Control Valve, Valve, Pump, Node, Compressor, and Expander.

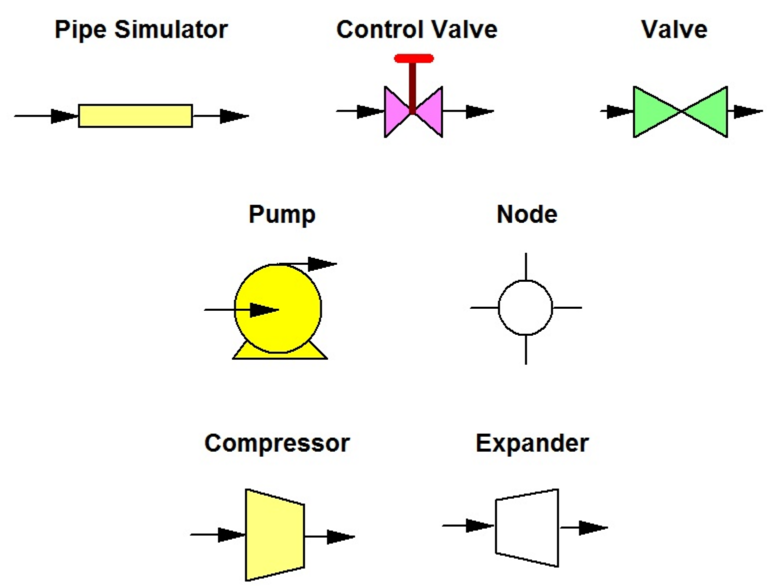


Figure 1 – CHEMCAD UnitOps that calculate flow as a function of pressure drop

Since this paper focuses on liquid piping systems, we will examine the first five of these unit operations in CHEMCAD to show how they can be combined to simulate complex piping networks.

We will begin by examining the Pipe Simulator and showing how it can be used for pipe sizing. We will explore the various calculation options available for this UnitOp, and add a pump to construct a simple single-line example. We will review the features of the Pump UnitOp, and see how the Sensitivity Study feature of CHEMCAD can be used to obtain pump head vs. flow rate for the system. Then we will add a pump curve to characterize the pump, and calculate the actual flow rate through the system.

To achieve a desired flow rate, we will add a control valve to the system, and show how the control valve sizing option in CHEMCAD can be used as a starting point for actual valve selection.

We will also add a flow restriction orifice to the system using CHEMCAD, and determine the effect on the valve position to accommodate this new flow resistance.

In Part 2, we will examine a more complicated two-branch flow problem. The significantly more complex calculation method necessary to solve this problem will be evaluated in some detail. We will then introduce a nodal approach to solving this problem, and demonstrate the improved calculation efficiency achieved. Two other basic branched problems will be solved to demonstrate the utility and power of the nodal approach.

We will follow up with practical plant piping examples, which can be analyzed in CHEMCAD to understand and correct the plant issue.

It is recommended that the reader download, open, and refer to referenced CHEMCAD files while reading about the approaches to solving the various problems discussed in this paper.

Pipe Simulator UnitOp

Figure 2 shows the CHEMCAD flowsheet for a simple pipe. The filename is **#1SizePipe**. The fluid is water and the flow rate is 20 gpm. The pipe has a 200’ horizontal run 2-90° elbows, and a 200’ vertical run with one ball valve and 3-90° elbows. What pipe size should we use?

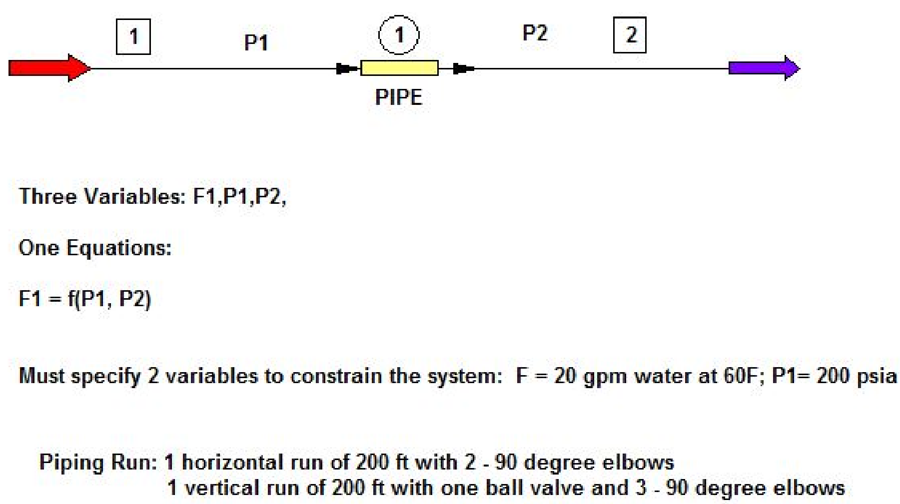


Figure 2 – Simple piping case – pipe sizing

CHEMCAD provides a pipe sizing tool, found under **Sizing** on the main menu. To use it, you must first specify the stream (stream 1) that will flow through the pipe. To do this, double-click the stream line to open the Edit Streams dialog, shown in **Figure 3**.

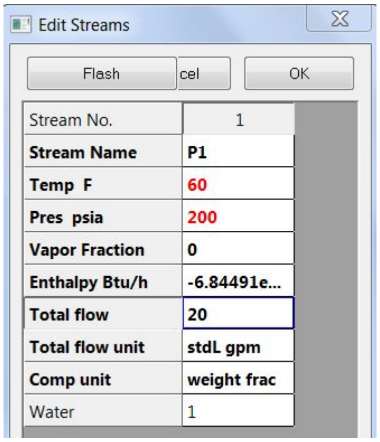


Figure 3 – The Edit Streams dialog box for stream 1

As you can see, the stream temperature, pressure, and flow rate in gpm are specified as inputs. The vapor volume fraction is calculated. Only two of these three parameters can be specified; the third is calculated by CHEMCAD. To specify the total flow in gpm, it is necessary to specify the component unit in compositional units. If mass units are specified, the total flow cannot be specified in volume units.

Now right-click stream 1 and select **Sizing** > **Line Sizing**, (see **Figure 4**) then click **OK** in the Select Streams dialog box. This brings up the Pipe Sizing dialog box, shown in **Figure 5**. Note that you can also navigate to this dialog by selecting **Sizing** > **Piping** from the main menu.

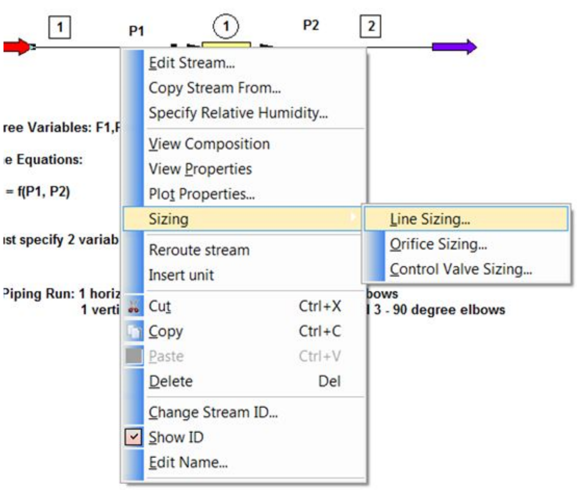


Figure 4 –Selecting Line Sizing from the right-click menu

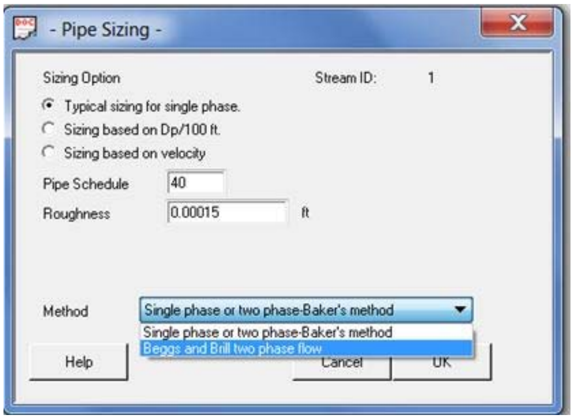


Figure 5 –The Pipe Sizing dialog box

Three sizing options are offered: *Typical sizing for single phase*, *Sizing based on frictional Dp/100 ft*, and *Sizing based on velocity*. Note that the pipe schedule must be specified, but that the default for pipe roughness is for steel pipe. Either of these entries can be changed if desired. There are two choices of flow method, with single phase and Baker's two-phase method being the first and Beggs and Brill's two-phase method being the second. Since this is a single-phase flow problem, choose the first method.

For this example, use *Typical sizing for single phase*. When you click **OK**, the results shown in **Figure 6** appear in a new tab.

```
Line Sizing for Stream 1    P1

  Stream Properties:
- - Overall - -
Mass flow  lb/h        10014.4717
Actual dens lb/ft3        62.3436
- - Liquid only - -
Mass flow  lb/h        10014.4717
Actual dens lb/ft3        62.3436
Visc cP                    1.1500

  Pipe Parameters:
                          Calculated   Next larger   Next smaller
Schedule                          40            40             40
Flow Regime             Single phase  Single phase   Single phase
Pipe ID in                    1.6100        2.0650         1.0490
Nominal Dia. in               1.5000        2.0000         1.0000
- - Overall - -
Press Drop psi/100ft          1.2916        0.3791        11.0342
Velocity ft/sec               3.1543        1.9174         7.4302
- - Liquid only - -
Reynolds Number              34163.1       26635.7        52433.4
Friction Factor               0.0258        0.0263         0.0259
Press Drop psi/100ft          1.2916        0.3791        11.0342
```

Figure 6 – Typical sizing for single-phase flow

CHEMCAD suggests a pipe size of 1.5 in., and shows the result for one pipe size larger, 2.0 in. and one pipe size smaller, 1.0 in. How accurate are the calculated pressure drops in psi/100 ft for each pipe size? **Table 2-7, Flow of Water Through Schedule 40 Steel Pipe** (2), provided at the end of this paper, gives the answer. Comparison results are given in **Figure 7**. The CHEMCAD and Crane frictional pressure drops match up very well. So, we can have confidence in the CHEMCAD results.

Example 1. Simple Piping Case - Pipe Sizing						
Comparing CHEMCAD Results To Technical Paper No. 410, Crane Co., Engineering Div., Chicago (1957)						
- - Liquid only - -						
Mass flow lb/h	10014.4717					
Actual dens lb/ft3	62.3436					
Visc cP	1.15					
Pipe Parameters:	CHEMCAD	Crane	CHEMCAD	Crane	CHEMCAD	Crane
	Calculated	Tech Paper 410	Next larger	Tech Paper 410	Next smaller	Tech Paper 410
Schedule	40		40		40	
Flow Regime	Single phase		Single phase		Single phase	
Pipe ID in	1.61		2.065		1.049	
Nominal Dia. in	1.5		2		1	
Press Drop psi/100ft	1.2916	1.28	0.3791	0.375	11.0342	10.9
Velocity ft/sec	3.1543	3.16	1.9174	1.91	7.4302	7.43

Figure 7 – CHEMCAD results compared to Crane

How should you choose what pipe diameter to use? Let's look at the fluid velocity for each pipe size.

Velocities for various fluids are given in **Table 2-2, Suggested Fluid Velocities in Pipe and Tubing**, (Ludwig, 1977). The table suggests water velocities in the range 3 - 8 ft/sec, with the caveat that "The velocities are suggestive only and are to be used to approximate line size as a starting point for pressure drop calculations. The final line size should be such as to give an economical balance between pressure drop and reasonable velocity."

The velocities for the pipe sizes CHEMCAD offers in **Figure 6** are in the suggested range for the 1.0 in. and 1.5 in. diameter pipe. Based on **Table 2-2**, the 2.0 in. pipe diameter would be rejected. The choice between the 1.0 and 1.5 in. pipe diameters would be based on the cost of piping, fittings, valves, and the pump, with the smaller pipe size likely being more economical.

The third option for pipe sizing given in **Figure 5** is *Sizing based on velocity*. If you choose this option, the dialog box provides an input for velocity (see **Figure 8**); if you use 6 ft/sec as the desired velocity, you get the results shown in **Figure 9**.

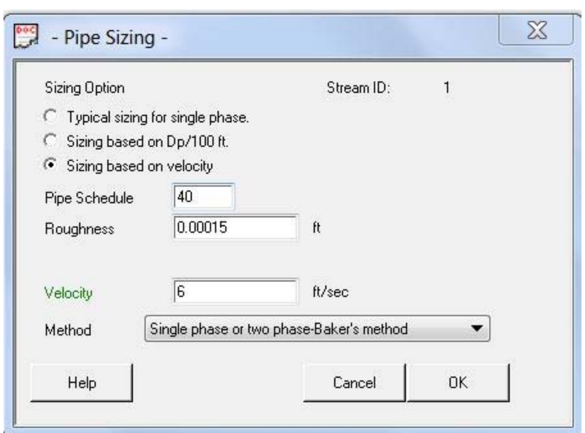


Figure 8 – Pipe Sizing dialog with Velocity field enabled

```
Line Sizing for Stream 1    P1

  Stream Properties:
- - Overall - -
Mass flow  lb/h        10014.4717
Actual dens lb/ft3        62.3436
- - Liquid only - -
Mass flow  lb/h        10014.4717
Actual dens lb/ft3        62.3436
Visc cP                    1.1500

  Pipe Parameters:
                        Calculated   Next larger   Next smaller
Schedule                        40            40             40
Flow Regime           Single phase  Single phase  Single phase
Pipe ID in                  1.6100        2.0650         1.0490
Nominal Dia. in             1.5000        2.0000         1.0000
- - Overall - -
Press Drop psi/100ft        1.2916        0.3791        11.0342
Velocity ft/sec             3.1543        1.9174         7.4302
- - Liquid only - -
Reynolds Number            34163.1       26635.7        52433.4
Friction Factor             0.0258        0.0263         0.0259
Press Drop psi/100ft        1.2916        0.3791        11.0342
```

Figure 9 – Sizing based on velocity

These results are identical to those obtained by letting CHEMCAD determine typical sizing. This is not surprising, because pipes are available only in discrete sizes. The flow conditions have to conform to what is commercially available. CHEMCAD gives the minimum pipe diameter that does not exceed the velocity specification.

The second option for pipe sizing is *Sizing based on Dp/100 ft*. I typically think of this as a result of sizing a pipe, rather than an input. The first and third sizing options are sufficient for most situations.

Let's use 1.5 in Schedule 40 pipe and enter the required information in the Pipe UnitOp. Double-click the Pipe UnitOp to open the Pipe Sizing and Rating dialog box. As shown in **Figure 10**, a variety of flow options are offered in the Method drop-down box**. Figure 11** shows the various Sizing options.

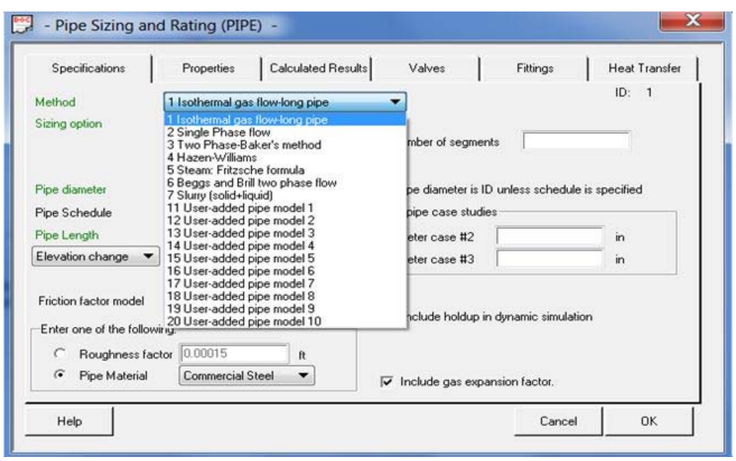


Figure 10 – Pipe UnitOp Method options

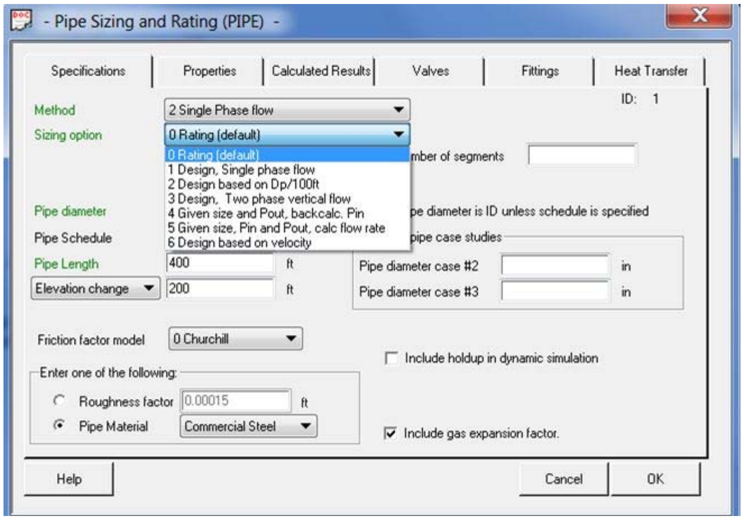


Figure 11 – Pipe UnitOp Sizing options

For now, choose **Single Phase flow** as the method and **Design, single phase flow** as the sizing option, and leave the input for pipe diameter blank, as shown in **Figure 12**.

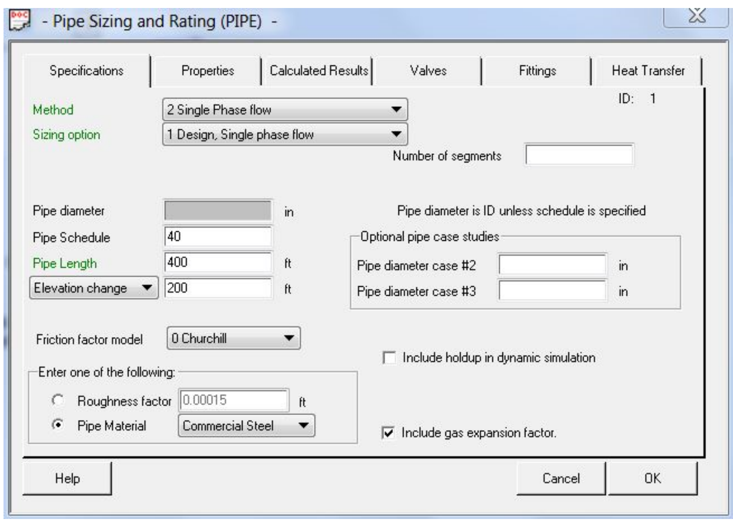


Figure 12 – Typical pipe sizing

Although the pipe length and elevation changes are specified here, you can obtain a pipe diameter with only the feed stream flow information, the pipe schedule, and the pipe roughness.

Click **OK**, and then right-click UnitOp 1 and select **Run This UnitOp**. After the unit runs, you can reopen the pipe dialog and see that the pipe diameter chosen is 1.5-inch Schedule 40. The flow calculation is also made through the pipe as configured in the dialog box.

Before we look at the calculated results, let’s again check the inputs for the pipe configuration. The pipe diameter, pipe schedule, pipe MOC and roughness, friction factor calculation method, total pipe length, and pipe vertical elevation are all specified. Two other pipe diameter cases can be specified, as I will discuss later. The use of pipe segments and fluid holdup in the pipe are explained in the help topic for the Pipe UnitOp.

Clicking on the Valves and Fittings tabs shows the available choices and the selections made for this example. These are shown in **Figures 13 and 14**, respectively. Clicking on the Properties tab shows the physical properties of the fluid used for the pipe calculations, which is water in this case.

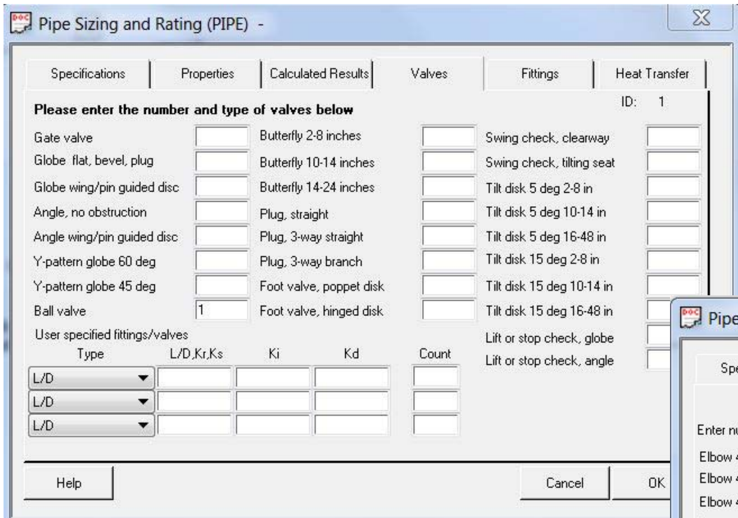


Figure 14 – The Pipe UnitOp's Valves tab

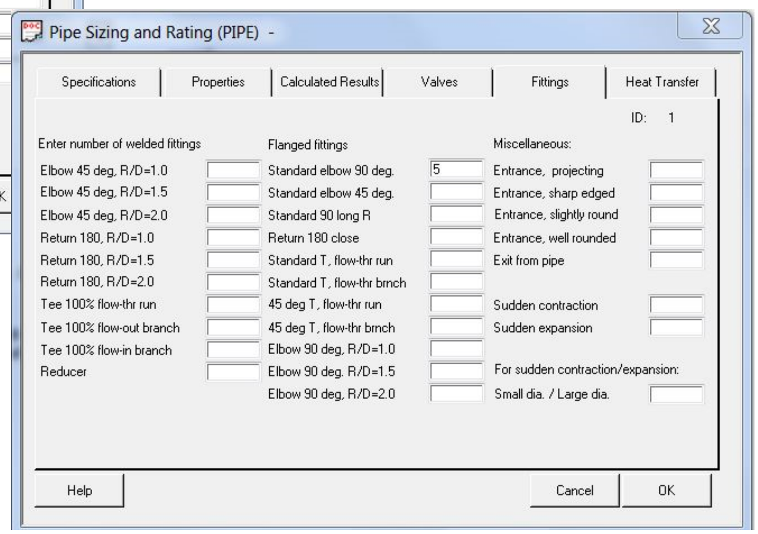


Figure 13 - The Pipe UnitOp's Fittings tab

Let's see what CHEMCAD calculates, as shown by clicking on the Calculated Results tab and given in **Figure 15**.

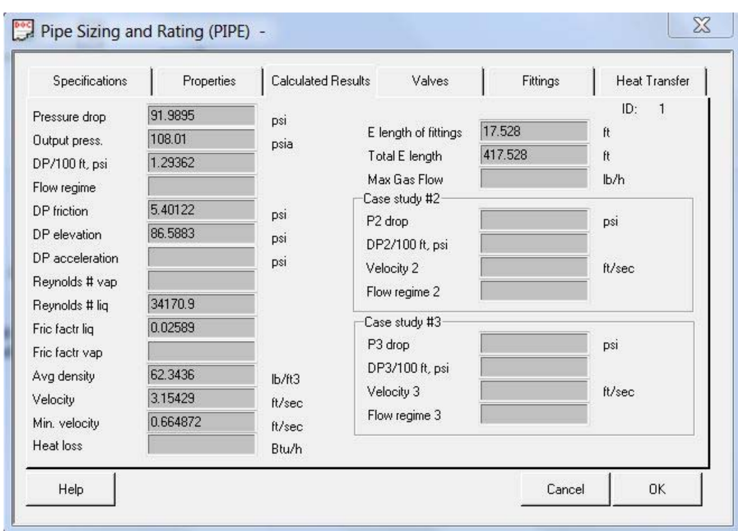


Figure 15 – The Pipe UnitOp's Calculated Results tab

The Delta P for elevation and the frictional Delta P are given as separate items. The pressure drop at the top of the list is simply the sum of the two, 91.99 psi. The pressure drop/100 ft is calculated from the frictional pressure drop and the total equivalent length of pipe, which includes the effect of fittings and valves. The velocity, Reynolds Number, and friction factor are also given. If you select **Report** > **UnitOps** > **Select UnitOps** from the main menu, you can obtain the same information and a bit more, in a form that you can print if desired.

Before moving on, let's take a look at the sizing options under the Specifications tab, as shown in **Figure 11:**

- If the 0 option, Rating, is chosen, the pipe outlet pressure is calculated when the pipe diameter, the flow rate, and the inlet pressure are specified. Running with these options produces identical results to those given in **Figure 14**, where Delta P = 91.99 psi.
- Options 1, 2, and 6 are the design options, discussed above. Option 3 is for two-phase flow and will not be discussed in this paper.
- Option 4 is the reverse of the rating option: the outlet pressure is specified and the inlet pressure is calculated. Let's choose this option and set the inlet and outlet pressures to 14.7 psia. Since the flow rate is unchanged, the delta P should also be unchanged at 91.99 psi. If you run this case, the inlet pressure is 106.69 psia and the delta P is indeed 91.99 psia, as expected.
- Option 5 calculates the flow rate with the pipe diameter and the inlet and outlet pressures as inputs. Try using this option and increasing the inlet pressure from the current 106.69 psia to 164.7 psia. Keep the outlet pressure at 14.7 psia so that Delta P = 150 psia. The flow rate increases to 73.6 gpm. Option 5 is important for more complicated branched networks, as will be discussed in Part 2 of this paper.

Now reset the flow rate and pressure of stream 1 to 20 gpm and 200 psia, respectively. Select option 0 and specify the diameter as 1.5 inches. In addition, let's do a case study and specify two other pipe diameters in the dialog box—1.0 inch and 2.0 inch—as shown in **Figure 16**.

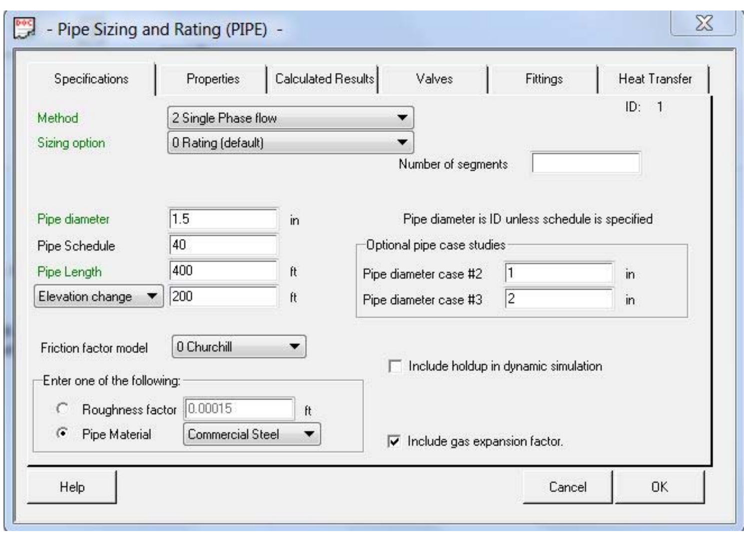


Figure 16 – The Pipe UnitOp's Calculated Results tab

If you run the pipe simulation and then look at the Calculated Results tab, you'll see that the results are identical to what you saw in **Figure 6**, as expected.

Add a Pump

Now let's add a pump to the problem, as shown in **Figure 17.** The filename is **#2SimpleCaseWithPump**.

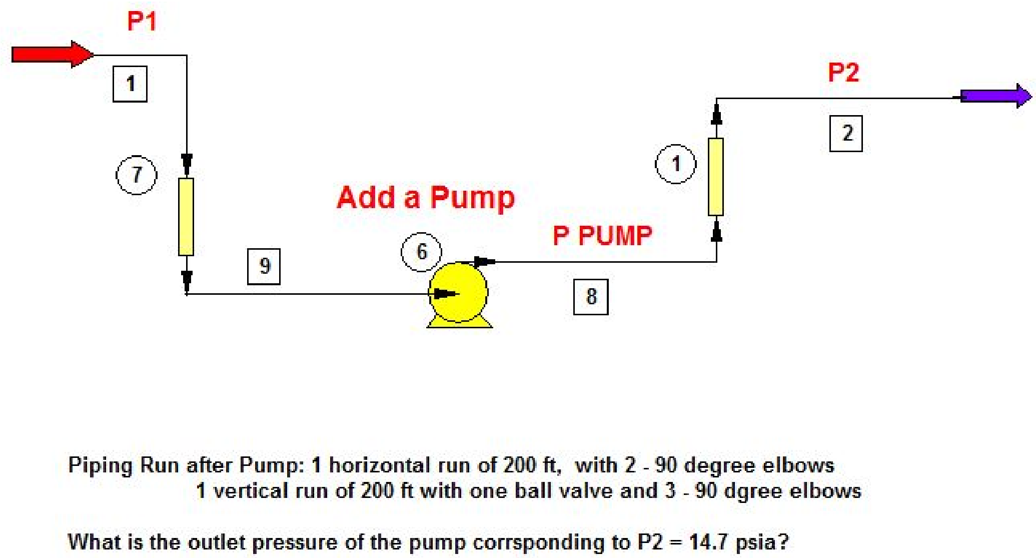
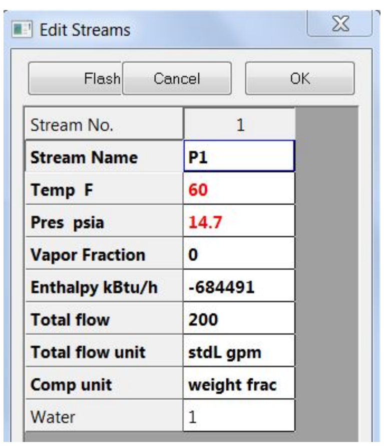


Figure 17 – Single pipe with pump

In this example the water flow rate is 200 gpm. The stream information for stream 1 is given in **Figure 18**.



Edit Streams

Flash | Cancel | OK

Stream No.	1
Stream Name	P1
Temp F	60
Pres psia	14.7
Vapor Fraction	0
Enthalpy kBtu/h	-684491
Total flow	200
Total flow unit	stdL gpm
Comp unit	weight frac
Water	1

Figure 18 – Specifications for stream 1

If we use the typical pipe sizing option for stream 1, we obtain a pipe size of 4 inches with a fluid velocity of 5 ft/sec, within the suggested range of 3 – 8 ft/sec. Typical guidelines for suction side piping for centrifugal pumps often recommend the same pipe size as the outlet piping or one pipe size larger. In this example, we will use 6 inches as the suction side pipe size, and 4 inches as the downstream pipe size. We will need to provide a reducer on the suction side of the pump at the pump inlet nozzle. In addition, there should be at least 5 – 10 pipe diameters of straight pipe entering the pump to ensure optimal suction.

Figure 19 shows the suction side pipe dialog box. It is 6 in. Sch 40, 20 feet long with a drop in elevation of 8 feet. There are 2 ball valves in this line, one reducer and two 90^0 elbows. The pump outlet line is 4 in. Sch 40 and is 400 feet long with an increase in elevation of 200 feet. It has one ball valve and five 90^0 elbows.

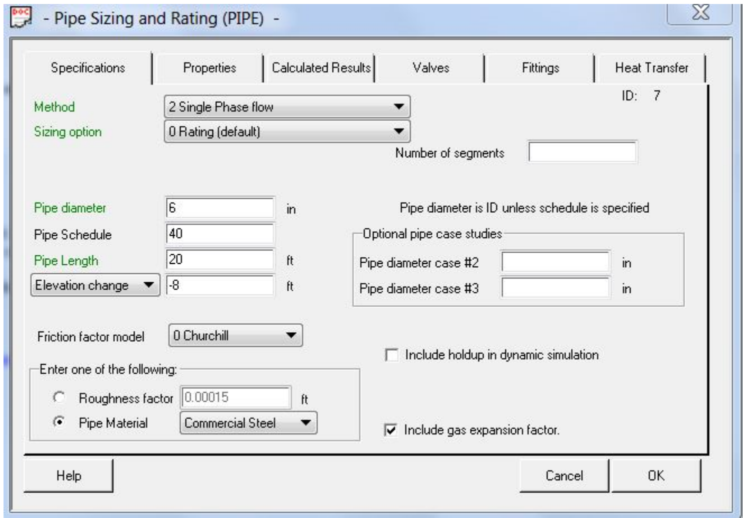


Figure 19 – Suction side pipe dialog box

What is the required pressure at the pump outlet to deliver this flow? **Figure 20** shows the pump dialog box.

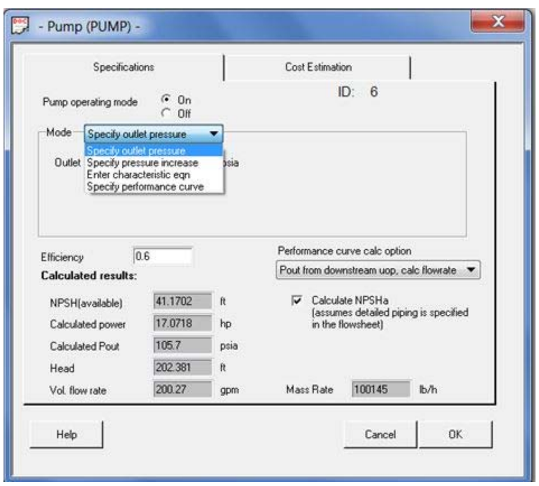


Figure 20 – Pump dialog showing mode selection

The pump can be on or off. There is a choice of modes or calculation basis. The pump outlet pressure, the pressure increase across the pump, or the pump curve can be specified. In this example, we will specify the pump outlet pressure as 150 psia. In later examples, we'll explore the more typical situation when the pump curve is known. We can also request that CHEMCAD calculate the available NPSH; we'll cover this in more detail later.

After the simulation runs, the flow rate of 200 gpm set for stream 1 is unchanged. As shown in **Figure 21**, the pump outlet pressure is 150 psia, as specified and the outlet pressure of the system is 59 psia.

FLOW SUMMARIES:

Stream No.	8	2
Stream Name	PUMP P	P2
Temp F	60.6507	60.6507
Pres psia	150.0000	58.9982
Enth kBtu/h	-6.8443E+005	-6.8443E+005
Vapor mole frac.	0.00000	0.00000
Total lbmol/h	5558.9629	5558.9629
Total lb/h	100144.7109	100144.7109
Total std L gpm	200.0000	200.0000
Total std V scfh	2109507.50	2109507.50
Flow rates in lb/h		
Water	100144.7109	100144.7109

Figure 21 – Pipe 1 inlet and outlet streams

If the desired pressure is 14.7 psia, how can that be achieved? One simple way is to recognize that the pressure drop across pipe element #1 for a flow rate of 200 gpm is fixed. This pressure drop is 150 - 59 = 91 psi. The pump pressure must be 14.7 + 91 = 105.7 psia. If we set this as the new pump pressure and run the simulation, the desired pipe outlet pressure will be achieved, as shown in **Figure 22**.

FLOW SUMMARIES:

Stream No.	8	2
Stream Name	PUMP P	P2
Temp F	60.4320	60.4320
Pres psia	105.7000	14.6954
Enth kBtu/h	-6.8445E+005	-6.8445E+005
Vapor mole frac.	0.00000	0.00000
Total lbmol/h	5558.9629	5558.9629
Total lb/h	100144.7109	100144.7109
Total std L gpm	200.0000	200.0000
Total std V scfh	2109507.50	2109507.50
Flow rates in lb/h		
Water	100144.7109	100144.7109

Figure 22 – Pipe 1 inlet and outlet streams with new pump pressure

Add a Controller

A more efficient way to determine the required pump pressure is by adding a feedback controller to the flowsheet as in **Figure 23**. The filename is **#3SimpleCaseWithPump&Controller**. In this way, any other changes in the system like flow rate or piping configuration, will be automatically accounted for without the need for a hand calculation.

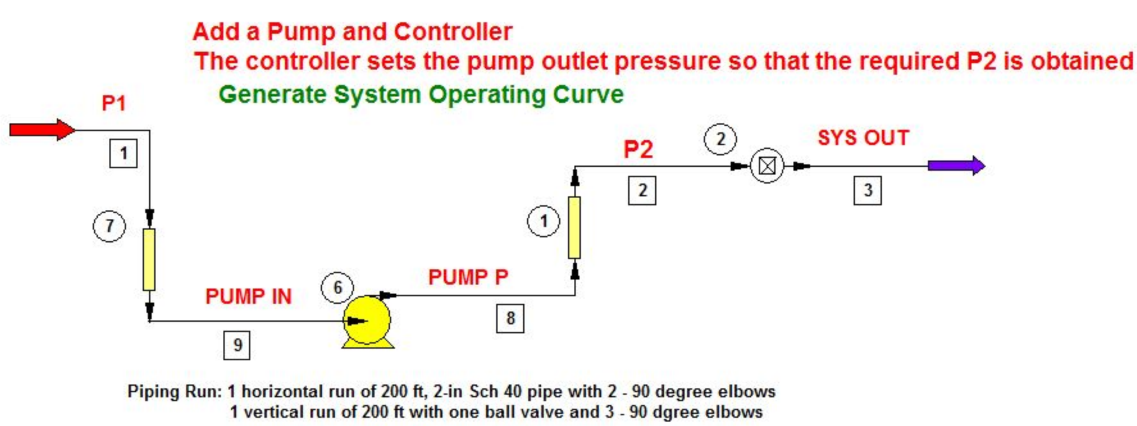


Figure 23 – Adding a feedback controller to the flowsheet

The dialog box for the controller is given in **Figure 24**. We are determining the pump outlet pressure for a desired system outlet pressure of 14.7 psia. Under the Feedback Options tab, set the tolerance to 1e-5 and let CHEMCAD decide how to vary the pump outlet pressure to best arrive at the desired outlet pressure.

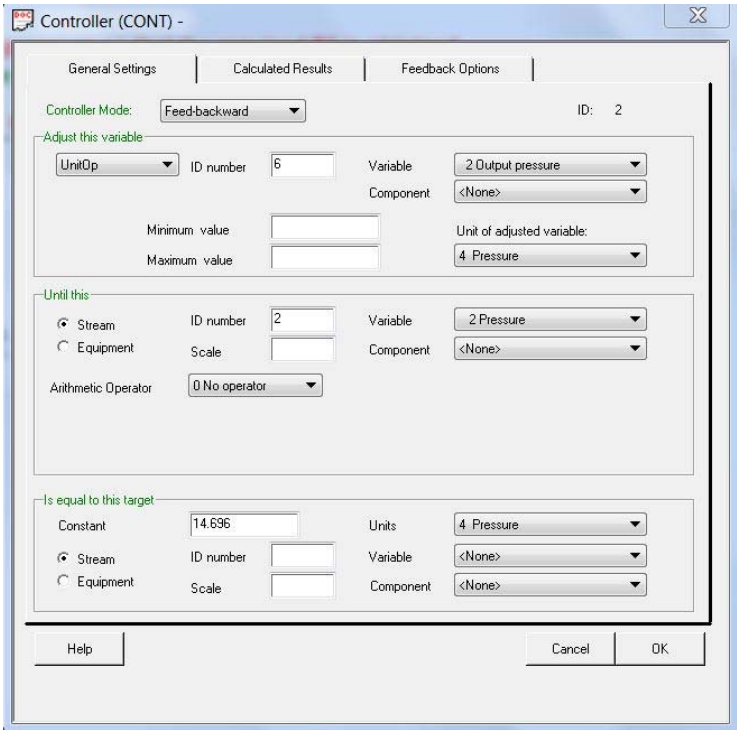


Figure 24 – Controller settings

Before running the simulation, let's arbitrarily set the pump outlet pressure at 200 psia and run the simulation with the controller turned off. Set the Controller Mode to *Controller off*. The results of the simulation are given in **Figure 25**, for all streams in the flowsheet.

Simulation: #5SimpleCaseWithPump&Controller
FLOW SUMMARIES:

Stream No.	1	2	3	8
Stream Name	P1	P2	SYS OUT	PUMP P
Temp F	60.0000*	60.5398	60.5398	60.5398
Pres psia	14.6960*	108.9965	108.9965	200.0000
Enth kBtu/h	-6.8449E+005	-6.8444E+005	-6.8444E+005	-6.8444E+005
Vapor mole frac.	0.00000	0.00000	0.00000	0.00000
Total lbmol/h	5558.9629	5558.9629	5558.9629	5558.9629
Total lb/h	100144.7109	100144.7109	100144.7109	100144.7109
Total std L gpm	200.0000	200.0000	200.0000	200.0000
Total std V scfh	2109507.50	2109507.50	2109507.50	2109507.50
Flow rates in lb/h				
Water	100144.7109	100144.7109	100144.7109	100144.7109

Stream No.	9
Stream Name	PUMP IN
Temp F	60.0007
Pres psia	18.0767
Enth kBtu/h	-6.8449E+005
Vapor mole frac.	0.00000
Total lbmol/h	5558.9629
Total lb/h	100144.7109
Total std L gpm	200.0000
Total std V scfh	2109507.50
Flow rates in lb/h	
Water	100144.7109

Figure 25 - Stream flow summaries with controller off

The Delta P across the downstream pipe is 91 psi as we previously calculated. The system outlet pressure is 109 psia. The pump outlet pressure of 200 psia is set. Note that the stream pressure at the pump inlet, 18 psia, is higher than the pressure at the upstream pipe inlet of 14.7 psia. CHEMCAD accounts for the hydrostatic pressure increase due to the 8-foot drop in elevation.

Now let's turn the feedback controller on and run the simulation to determine the pump pressure corresponding to the system outlet pressure of 14.7 psia. **Figure 26** shows the simulation results and that the pump outlet pressure is correctly determined at 105.7 psia.

FLOW SUMMARIES:

Stream No.	1	2	3	8
Stream Name	P1	P2	SYS OUT	PUMP P
Temp F	60.0000*	60.2600	60.2600	60.2600
Pres psia	14.6960*	14.6960	14.6960	105.7029
Enth kBtu/h	-6.8449E+005	-6.8447E+005	-6.8447E+005	-6.8447E+005
Vapor mole frac.	0.00000	0.00000	0.00000	0.00000
Total lbmol/h	5558.9629	5558.9629	5558.9629	5558.9629
Total lb/h	100144.7109	100144.7109	100144.7109	100144.7109
Total std L gpm	200.0000	200.0000	200.0000	200.0000
Total std V scfh	2109507.50	2109507.50	2109507.50	2109507.50
Flow rates in lb/h				
Water	100144.7109	100144.7109	100144.7109	100144.7109

Stream No.	9
Stream Name	PUMP IN
Temp F	60.0005
Pres psia	18.0767
Enth kBtu/h	-6.8449E+005
Vapor mole frac.	0.00000
Total lbmol/h	5558.9629
Total lb/h	100144.7109
Total std L gpm	200.0000
Total std V scfh	2109507.50
Flow rates in lb/h	
Water	100144.7109

Figure 26 – Stream flow summaries with controller on

This flowsheet can be used to determine the operating curve for this system. This curve shows the relationship between the pump outlet pressure, or head, and the system flow rate. In CHEMCAD, this can easily be calculated using the powerful Sensitivity Study feature. With a sensitivity analysis, we can make repetitive simulations automatically changing the flow rate incrementally and calculating the pump head at each increment. You can generate a graph of pump head vs. flow rate that can be superimposed on the pump operating curve to determine the pump's operating point and actual system flow rate.

To access an existing sensitivity analysis, select **Run** > **Sensitivity Study** > **[study name]** > **Edit**, as shown in **Figure 27**. The name of the analysis in this case is *Pump Head vs Flow Rate*.

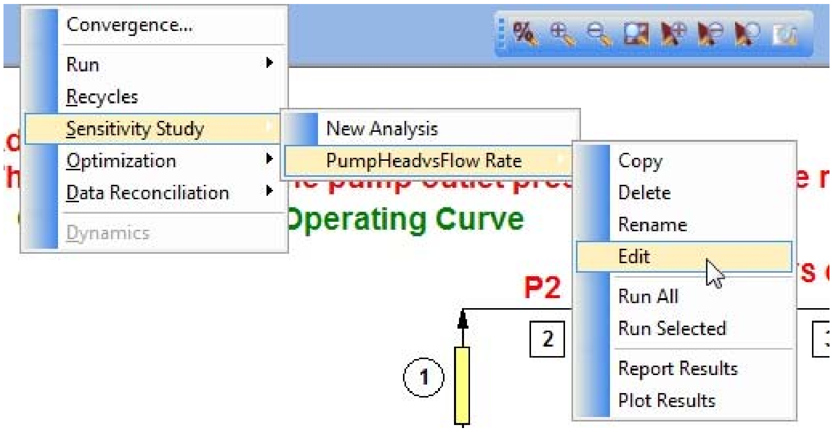


Figure 27 – Accessing the sensitivity study

The first tab in the Edit Sensitivity Study dialog box is called **Adjusting**, as shown in **Figure 28**. On this page we specify the independent variable we wish to very incrementally.

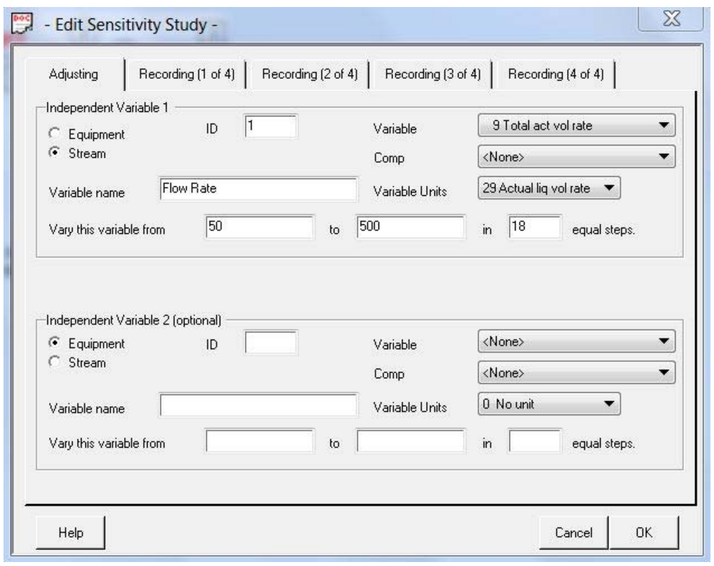


Figure 28 – The Adjusting tab

The independent variable is the flow rate of Stream 1 in gpm. Specify the flow range you want and the size of each step change in flow. The flow range is 50 – 500 gpm in 25 gpm increments. Sensitivity analysis in CHEMCAD allows us to specify a second independent variable that will provide parametric plots. This can be extremely useful in applications where we want to examine the effect of changing two system variables, for example, temperature and pressure. A second independent variable is not needed in this example.

The next three tabs of the dialog box are labelled **Recording**. As shown in **Figures 29 and 30, t**hese pages allow you to record up to twelve variables of interest for the analysis at each incremental step of CHEMCAD's calculations.

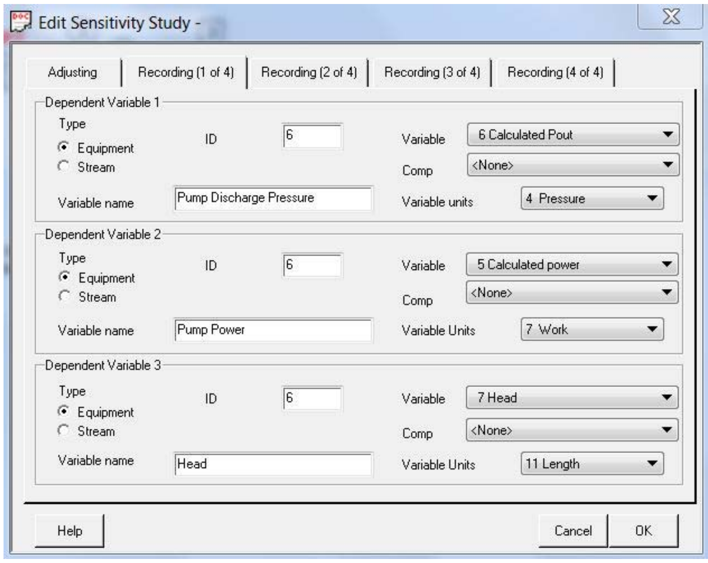


Figure 29 – Recording (dependent) variables for sensitivity study

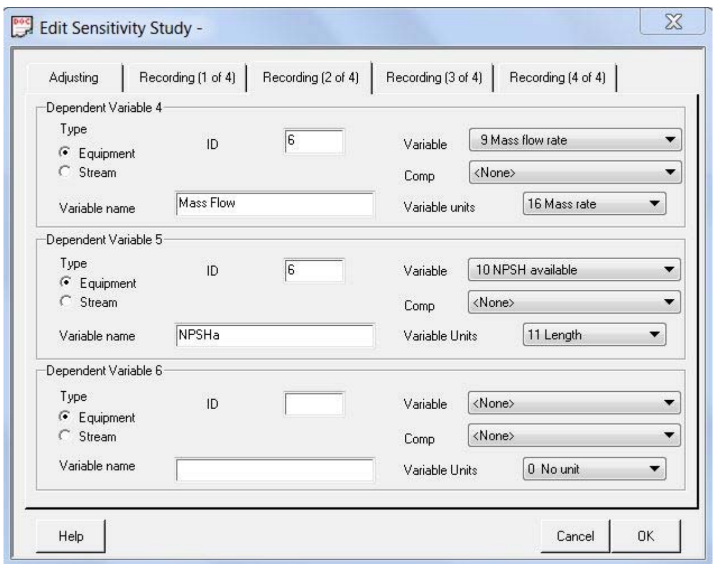


Figure 30 – Recording variables, continued

With the variables all specified, you can now execute the **Run All** command for the sensitivity study, using the menu path shown in **Figure 27**. Tabular results can be obtained by clicking on **Report Results** in the same submenu. The tabulated results are given in **Figure 31.**

Sensitivity Analysis Report						
PumpHeadvsFlow Rate						
Run	Flow Rate	Pump Discharge P	Pump Power	Head	Volumetric Flow	NPSHa
#	gpm	psia	hp	ft	gpm	ft
0	50	101.618	2.43607	192.786	50	41.338
1	75	101.988	3.67058	193.655	75	41.3221
2	100	102.483	4.92357	194.821	100	41.3007
3	125	103.103	6.2005	196.279	125	41.2739
4	150	103.844	7.50676	198.024	150	41.2417
5	175	104.708	8.84772	200.055	175	41.2042
6	200	105.692	10.2287	202.371	200	41.1615
7	225	106.796	11.6551	204.97	225	41.1134
8	250	108.02	13.1322	207.851	250	41.0602
9	275	109.365	14.6652	211.014	275	41.0017
10	300	110.828	16.2596	214.459	300	40.938
11	325	112.411	17.9205	218.184	325	40.869
12	350	114.113	19.6533	222.19	350	40.795
13	375	115.935	21.4633	226.476	375	40.7157
14	400	117.875	23.3557	231.041	400	40.6312
15	425	119.934	25.3359	235.887	425	40.5416
16	450	122.112	27.4091	241.012	450	40.4468
17	475	124.408	29.5805	246.416	475	40.3469
18	500	126.823	31.8556	252.099	500	40.2418

Figure 31 – Tabular results from the sensitivity study

To obtain graphical results, use the same menu path and click on **Plot Results**. A new dialog box opens as shown in **Figure 32**, giving the variables you might want to plot. In this case you should plot Head vs system flow rate. The graph produced is given in **Figure 33**.

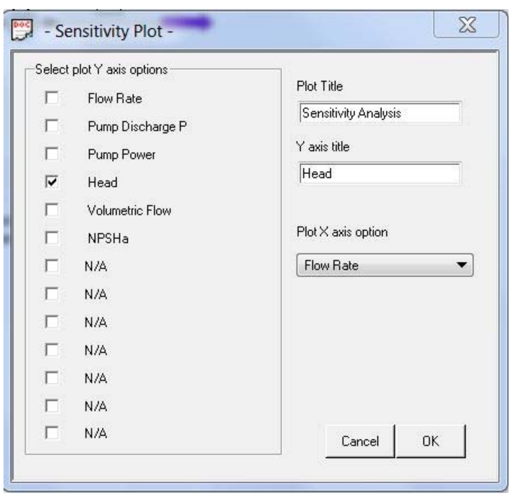


Figure 32 – Sensitivity Plot dialog box

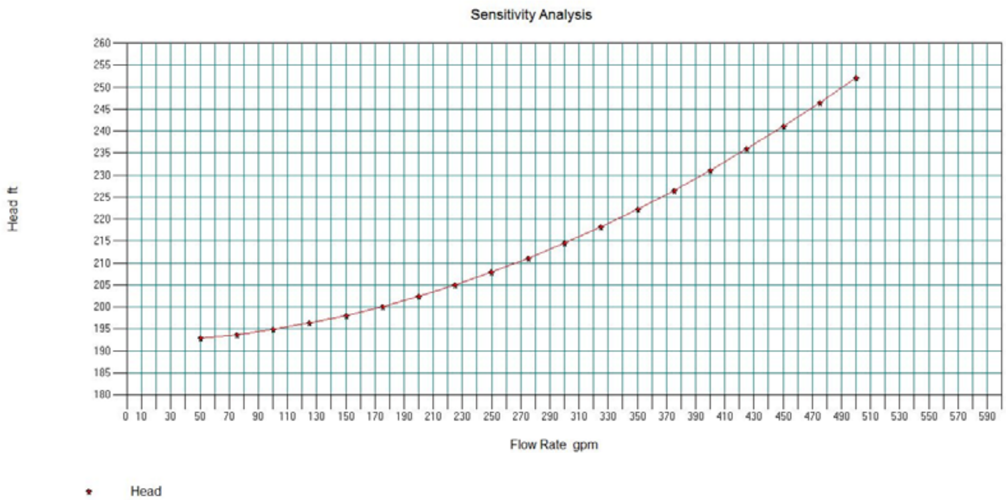


Figure 33 – Sensitivity study plot

Add the Pump Curves

Typical pump operating curves are shown in **Figure 34** (4).

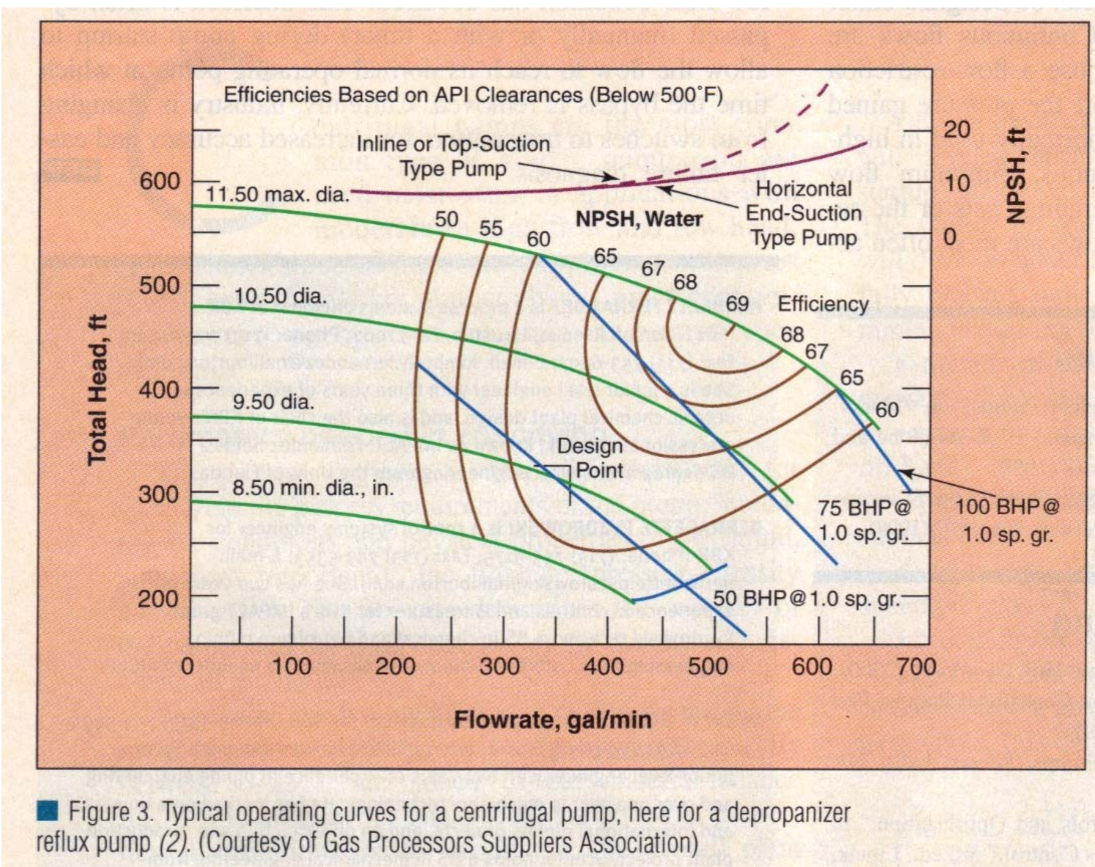


Figure 3. Typical operating curves for a centrifugal pump, here for a depropanizer reflux pump *(2)*. (Courtesy of Gas Processors Suppliers Association)

Figure 34 – Typical pump curves

This paper by Fernandez, K., et al., entitled "Understanding the Basics of Centrifugal Pump Operation," provides an excellent summary of the topic. The pump operating curves relate total head, power, NPSHR, and efficiency to flow rate for specific pump impeller diameters. Total head is defined as the difference in pressure between the outlet and inlet of the pump expressed in feet of water column.

The flowsheet for adding pump curves is shown in **Figure 35**. The filename is **#4SimpleCaseWithPumpCurve&Controller**.

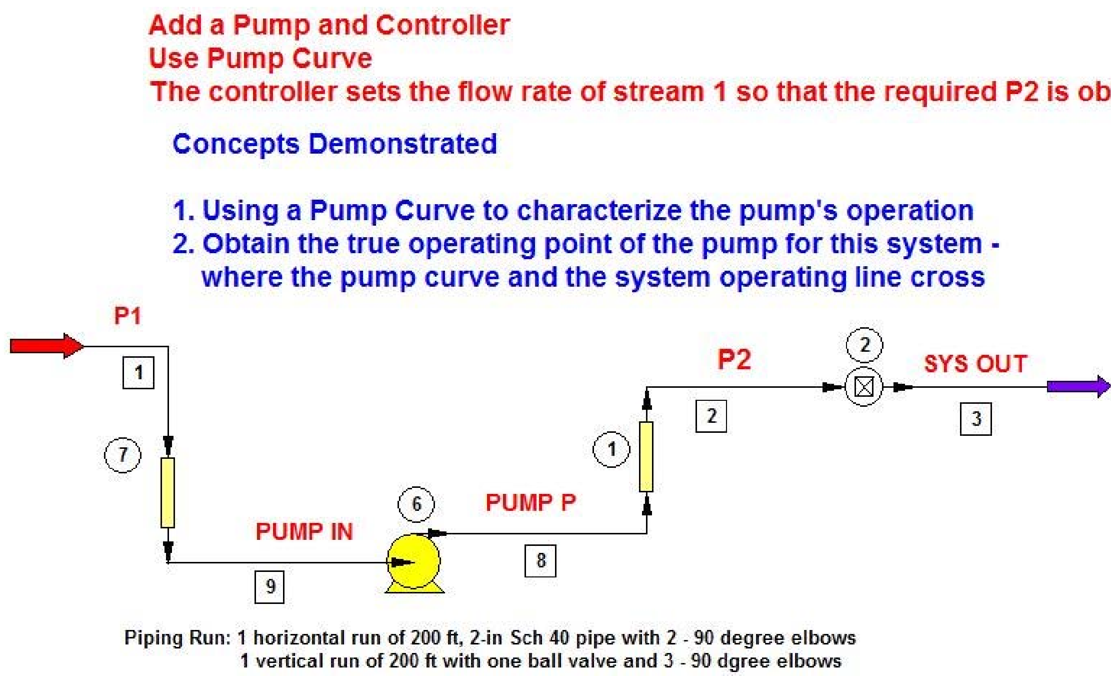


Figure 35 – Flowsheet for pump curve

If you open the pump dialog box and choose *Specify performance curve*, as shown in **Figure 36,** you can see that the pump speed is a required specification. Pump speed should be available from the pump vendor and is often provided on the pump curves. Clicking **OK** produces the filled-in input form for pump curves, as shown in **Figure 37**.

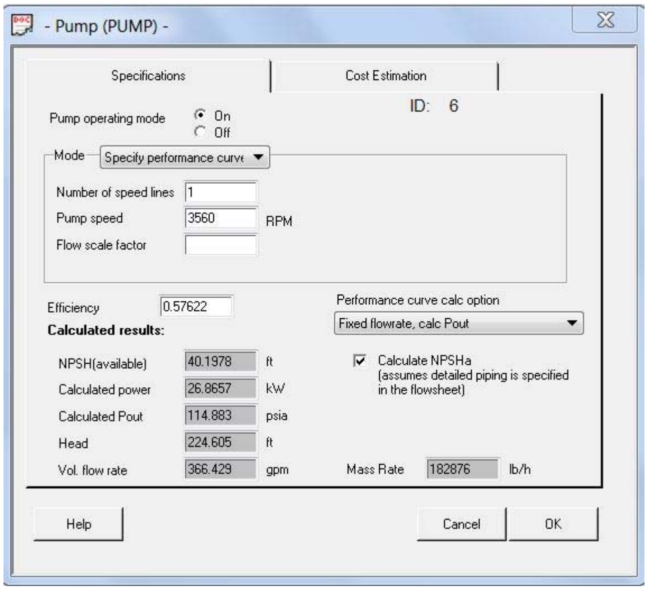
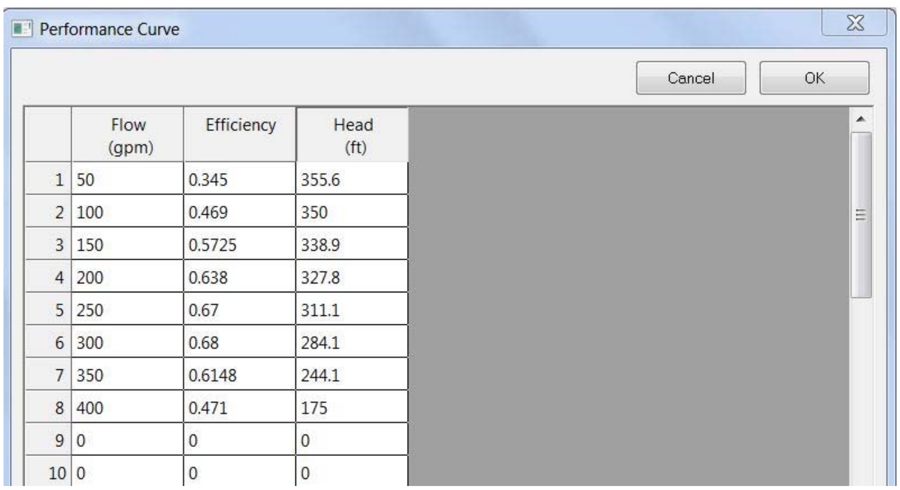


Figure 36 – Pump specifications



	Flow (gpm)	Efficiency	Head (ft)
1	50	0.345	355.6
2	100	0.469	350
3	150	0.5725	338.9
4	200	0.638	327.8
5	250	0.67	311.1
6	300	0.68	284.1
7	350	0.6148	244.1
8	400	0.471	175
9	0	0	0
10	0	0	0

Figure 37 – Pump performance curve

We can plot the total head vs flow rate curve for the pump from **Figure 37** and the head vs flow rate for the system from the table given in **Figure 31** on an Excel spreadsheet, as shown in **Figure 38**. Where they cross is the flow rate the pump should deliver. This flow rate is about 366 gpm.

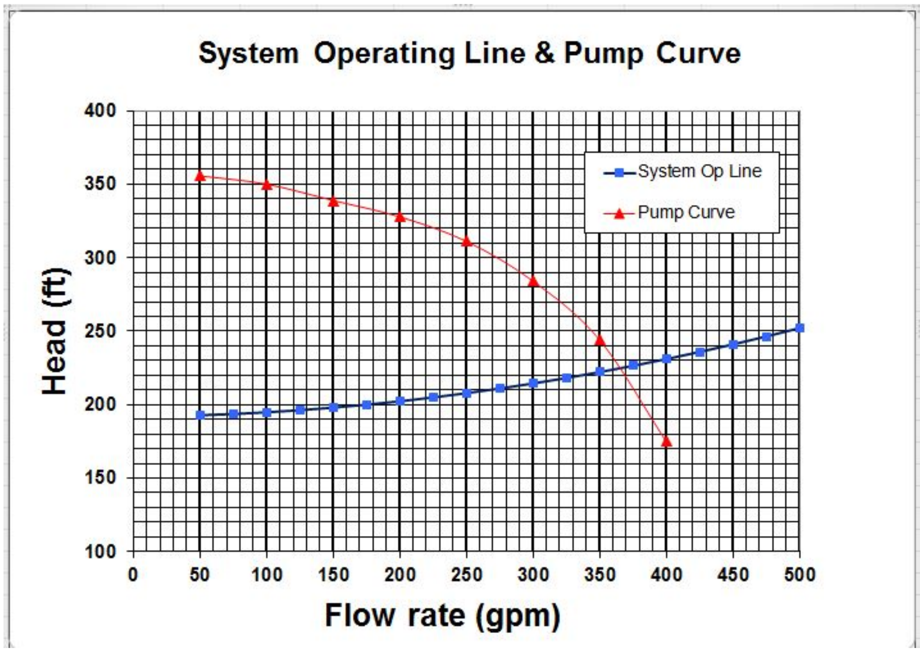


Figure 38 – System operating line and pump curve

Now let's run the CHEMCAD simulation for the flowsheet in **Figure 35** to see if this result is matched. **Figure 39**, obtained by clicking **Report** > **Stream Properties** > **All Streams** on the main CHEMCAD menu, shows that the flow rate is indeed accurately determined by CHEMCAD using the pump curve. If a lower flow rate is desired, say 200 gpm, a control valve needs to be added to the line.

STREAM PROPERTIES					
Stream No.	1	2	3	8	9
Name	P1	P2	SYS OUT	PUMP P	PUMP IN
Temp F	60	60.5002	60.5002	60.5004	59.9999
Pres psia	14.696	14.696	14.696	115.2723	17.8793
Vapor mole fraction	0	0	0	0	0
- - Liquid only - -					
Molar flow lbmol/h	10163.46	10163.46	10163.46	10163.46	10163.46
Mass flow lb/h	183094.719	183094.719	183094.719	183094.719	183094.719
Average mol wt	18.015	18.015	18.015	18.015	18.015
Actual dens lb/gal	8.3332	8.3328	8.3328	8.3328	8.3332
Actual vol gpm	**366.1547**	**366.171**	**366.171**	**366.171**	**366.1547**
Std liq gpm	365.6603	365.6603	365.6603	365.6603	365.6603
Std vap 60F scfh	3856815.75	3856815.75	3856815.75	3856815.75	3856815.75
Cp Btu/lb-F	1.0026	1.0022	1.0022	1.0022	1.0022
Z factor	0.001	0.001	0.001	0.0078	0.0012
Visc cP	1.148	1.14	1.14	1.141	1.148
Th cond Btu/hr-ft-F	0.3423	0.3425	0.3425	0.3425	0.3423
Surf. tens. dyne/cm	73.7315	73.6837	73.6837	73.6837	73.7315

Figure 39 – Stream summary using pump curve

NPSHR and NPSHA

However, before we do this, let's digress and define NPSHR, net positive suction head required, and NPSHA, net positive suction head available. The former is a characteristic of the pump and must be specified by the pump manufacturer. The latter is a characteristic of the pipe configuration and the fluid being pumped. It must be calculated as is done by CHEMCAD.

NPSHA is the absolute pressure at the suction port of the pump.

NPSHR is the minimum pressure required at the suction port of the pump to prevent the pump from cavitating.

To prevent cavitation, NPSHA must be greater than NPSHR. More suction side pressure must be available than is required by the pump. Pump cavitation occurs when the pressure at the pump inlet is below the vapor pressure of the liquid. Vapor bubbles form at the pump inlet and are moved to the discharge side of the pump where they collapse often causing pitting and damage to the pump impellers. If cavitation occurs, the pump will be noisy, will experience loss of capacity and reduced operational life. NPSHA is calculated from the following equation:

NPSHA = HA + HZ – HF + HV – HVP

where:

HA = the absolute pressure on the surface of the liquid in the supply tank.

HZ = the vertical distance between the surface of the liquid in the supply tank and the centerline of the pump. This is positive if the supply tank is above the pump and negative if it is below. As the feed tank level drops during pumping, the NPSHA will also drop.

HF = the frictional losses in the suction piping from the supply tank to the pump inlet.

HV = the velocity head at the pump suction port. This is usually small and is often ignored.

HVP = absolute vapor pressure of the liquid at the pumping temperature.

The calculations should be done in pressure units of feet of water column to match the way NPSHR is usually specified. In particular, HZ, the liquid static head must take liquid density into account for liquids other than water.

For the example of **Figure 35**, NPSHA is calculated as follows using results obtained from the CHEMCAD simulation:

NPSHA = 14.696 + 3.4682– 0.2802 + 0 – 0.2564 = 17.383 psia

This is equivalent to 40.66 feet of water column. CHEMCAD calculates 40.7 feet as shown in **Figure 40**, obtained from **Report** > **UnitOps** > **Select UnitOps** > **6** > **OK** from the main CHEMCAD menu.

Pump Summary

Equip. No.	6
Name	
Output pressure psia	400.0000
Efficiency	0.5769
Calculated power kW	26.9065
Calculated Pout psia	115.2724
Head ft	224.9566
Vol. flow rate gpm	366.1546
Mass flow rate lb/h	183094.6406
NPSH available ft	**40.7051**
Char. Eq/Perform curve	2
No. of RPM lines	1
Pump RPM	3560.0000
Request NPSH calc	1

Figure 40 – Pump summary

Add a Control Valve to Achieve a Desired Flow Rate

Now let's add a control valve downstream of the pump to control the flow to the desired 200 gpm. There are many online sources for control valve sizing (5-8). Blackmonk Engineering (7) in particular, provides an excellent step-by-step calculation guide for sizing a control valve. Guidelines for choosing a linear valve or an equal percentage valve are discussed in (9).

CHEMCAD provides a control valve sizing option. It is important to point out that this is a starting point for actual valve selection. I recommend that you use a sizing guide similar to (7) and vendor-supplied software to finalize the design.

To begin the control valve sizing for this problem, estimate the required control valve pressure drop to achieve 200 gpm flow rate. We can easily do this by going back to the simulation with filename **#3SimpleCaseWithPump&Controller**. This flowsheet corresponds to the case where we set the inlet flow to 200 gpm and used a controller to set the outlet pump pressure so that the system outlet pressure is 14.7 psia.

As shown in **Figure 41**, for simulation with filename **#5SimpleCaseEstimateControlValveDeltaP**, we add a control valve and show the pressure at various points in the pipe line corresponding to 200 gpm flow rate. Note that the calculation controller is removed because the control valve outlet pressure can be set in the control valve dialog box.

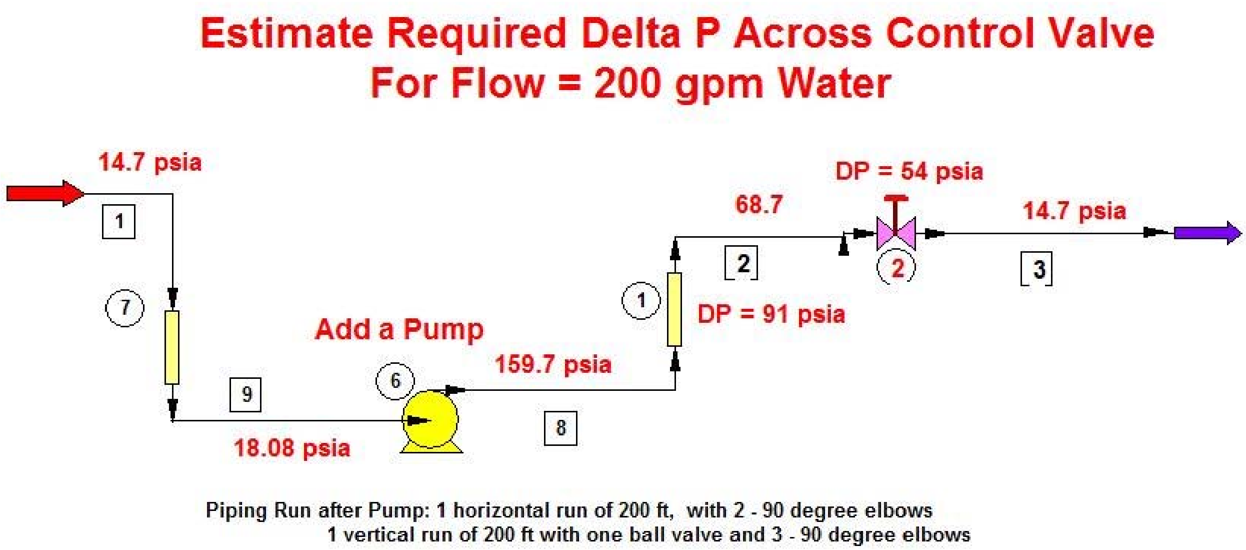


Figure 41 – Flowsheet for estimating control valve delta P

The actual pump outlet pressure is obtained from the total head vs flow rate curve for the pump. Remember that the total head is the difference between the pump outlet and inlet pressures expressed in units of feet of water column. The total head at 200 gpm is 327.8 feet of water column, as shown in **Figure 37**. This corresponds to 142.08 psia. Adding this to the pump inlet pressure of 18.08 psia gives an absolute pump outlet pressure of 160.19 psia. CHEMCAD calculates 159.97 psia, which we will use in our calculations.

The pressure drop across the downstream pipe for 200 gpm flow is 91 psia, from the simulation **#3SimpleCaseWithPump&Controller**. Thus, the pressure at the pipe outlet is 68.97 psia. We know that the system outlet pressure is 14.7 psia, so the control valve pressure drop must be approximately 54.27 psia.

Now let's size the control valve with CHEMCAD in **#5SimpleCaseEstimateControlValveDelta P**. We need to determine the valve inlet pressure, so we set the outlet pressure of the pump to 159.97 psia, as shown in the dialog box in **Figure 42**.

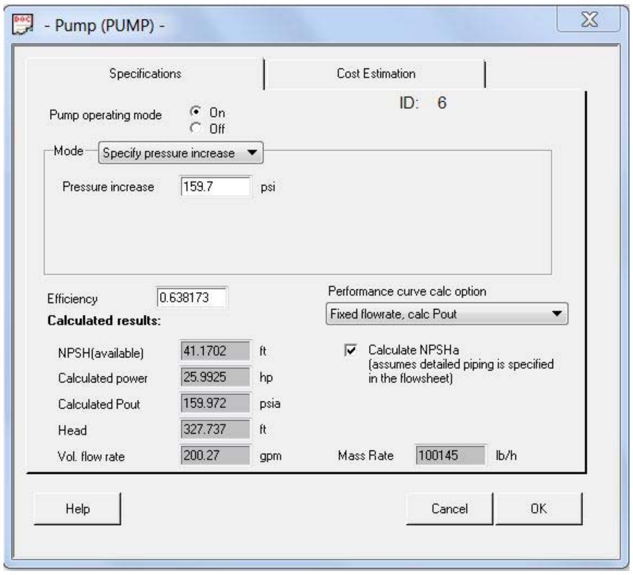


Figure 42 – Pump dialog for control valve sizing

Figure 43 shows the unspecified control valve dialog box. As you can see, the valve Cv and downstream pressure are unspecified. The defaults are linear valve and calculate valve position for a specified flow rate.

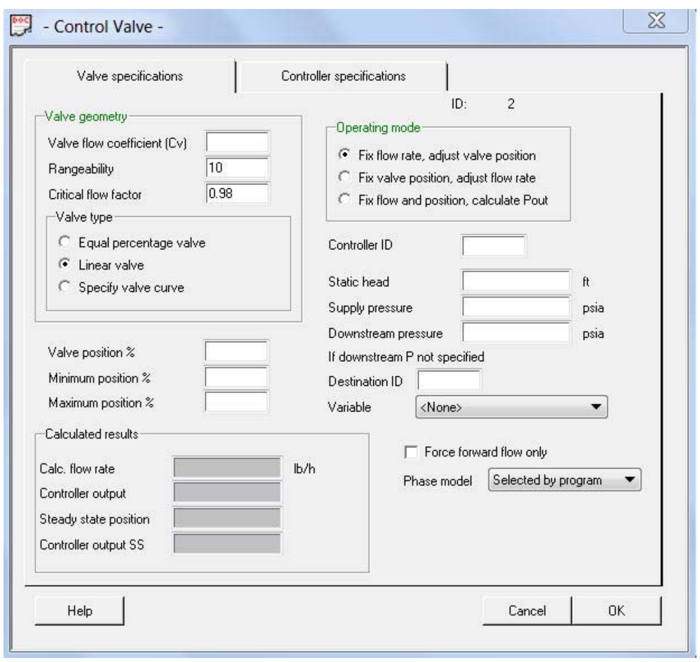


Figure 43 – Unspecified Control Valve dialog box

We now run the simulation for the units upstream of the valve, namely, the pump inlet pipe, the pump, and the outlet pipe. This establishes the inlet pressure to the control valve. The stream summary in **Figure 44** shows that this is 68.97 psia.

FLOW SUMMARIES: CONTROL VALVE SIZING - STREAMS UPSTREAM OF CONTROL VALVE

Stream No.	1	9	8	2
Stream Name	14.7 psia	18.08 psia	159.97 psia	68.97 psia
Temp F	60.0000*	60.0005	60.6594	60.6590
Pres psia	**14.7000***	**18.0807**	**159.9718**	**68.9701**
Enth kBtu/h	-6.8449E+005	-6.8449E+005	-6.8443E+005	-6.8443E+005
Vapor mole frac.	0.00000	0.00000	0.00000	0.00000
Total lbmol/h	5558.9629	5558.9629	5558.9629	5558.9629
Total lb/h	100144.7109	100144.7109	100144.7109	100144.7109
Total std L gpm	200.0000	200.0000	200.0000	200.0000
Total std V scfh	2109507.50	2109507.50	2109507.50	2109507.50
Flow rates in lb/h				
Water	100144.7109	100144.7109	100144.7109	100144.7109

Figure 44 – Control valve sizing, streams upstream of valve

If we now click on Stream 2, the control valve inlet stream, we can select control valve sizing under the sizing option. This opens the dialog box in **Figure 45**, which is filled in for this example; the outlet pressure is set at 14.7 psia.

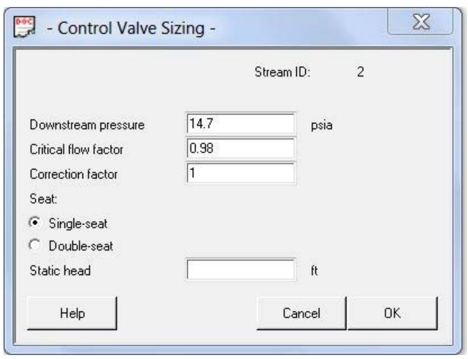


Figure 45 – Control Valve Sizing dialog box

Clicking **OK** brings up the sizing recommendation given in **Figure 46**. The stream pressure information we provided is used in the valve sizing algorithm.

```
Control Valve Sizing for Stream #   2

Loadings and Properties
                                    Vapor                 Liquid
  Flow rate                        0.0000  lb/h       100144.7109 lb/h
  Flow rate                        0.0000  ft3/hr        200.2822 gpm
  Density                          0.0000  lb/ft3          8.3327 lb/gal

  Total flow                  100144.7109  lb/h
  Upstream pressure               68.9683  psia
  Downstream pressure             14.7000  psia
  Critical flow factor             0.9800
  Corr. factor for reducers        1.0000
  Static head                      0.0000  ft
  Seat type                   Single-Seat
  Flow type                   Subcritical flow
  Calc. coefficient Cvc           27.1660
  Capacity coefficient Cv         36.0000
  Cvc / Cv ratio                   0.7546
  Valve size                       2.0000  in
```

Figure 46 – CHEMCAD recommended control valve sizing

CHEMCAD recommends a 2-inch valve with a corresponding Cv of 36. The calculated CV is what is required for the problem and CHEMCAD chooses the next higher number corresponding to a valve size, in this case 36.

Please note that Cv and valve size may vary from vendor to vendor. For example, an Emerson 2-inch ES globe valve with linear trim has a Cv of 65.3 at a valve opening of 100% (7). Returning to the valve dialog box by double-clicking the valve symbol, we see that the valve Cv and valve outlet pressure are entered automatically.

Now let's run the full flowsheet. **Figure 47** provides a stream summary showing all of the stream pressures as indicated on the flowsheet.

FLOW SUMMARIES: CONTROL VALVE SIZING

Stream No.	1	2	3	8
Stream Name	14.7 psia	68.97 psia	14.7 psia	159.97 psia
Temp F	60.0000*	60.6590	60.6592	60.6594
Pres psia	**14.7000***	**68.9701**	**14.7000**	**159.9718**
Enth kBtu/h	-6.8449E+005	-6.8443E+005	-6.8443E+005	-6.8443E+005
Vapor mole frac.	0.00000	0.00000	0.00000	0.00000
Total lbmol/h	5558.9629	5558.9629	5558.9629	5558.9629
Total lb/h	100144.7109	100144.7109	100144.7109	100144.7109
Total std L gpm	200.0000	200.0000	200.0000	200.0000
Total std V scfh	2109507.50	2109507.50	2109507.50	2109507.50
Flow rates in lb/h				
Water	100144.7109	100144.7109	100144.7109	100144.7109

Stream No.	9
Stream Name	18.08 psia
Temp F	60.0005
Pres psia	**18.0807**
Enth kBtu/h	-6.8449E+005
Vapor mole frac.	0.00000
Total lbmol/h	5558.9629
Total lb/h	100144.7109
Total std L gpm	200.0000
Total std V scfh	2109507.50
Flow rates in lb/h	
Water	100144.7109

Figure 47 – Summary showing all stream pressures in flowsheet

Opening the valve dialog box shows that the valve is 84% open. If we try a 3-inch valve with Cv of 75 as per CHEMCAD, the valve is 40.3% open. The usual guideline for valve opening at maximum expected flow rate is 20-80%. Accordingly, I would choose the 3-inch control valve. The valve can also be positioned between the pump and the pipe as shown in the file called **#6SimpleCaseControlValveAfterPump**.

Add a Restriction Orifice

CHEMCAD permits the addition of a restriction orifice plate to a piping system. This is demonstrated in the CHEMCAD file called **#7SimpleCaseWithControlValve&RO**. To size the RO, right-click stream 4, the pump outlet, and select **Sizing** > **Orifice Sizing**. This opens the filled-in orifice sizing dialog box, as shown in **Figure 48**.

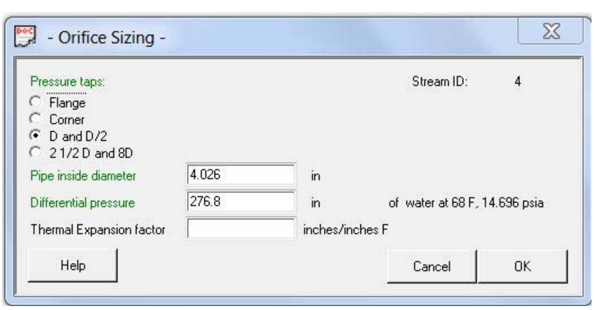


Figure 48 – The Orifice Sizing dialog box

Required inputs are pressure tap locations, pipe inside diameter, and pressure drop in inches of water column. Information about orifice configuration and pressure tap locations is available in the Chemical Engineers' Handbook (10). The pressure drop chosen for this example is 10 psi. If you click **OK**, the CHEMCAD recommended sizing is shown, as in **Figure 49**.

```
Orifice Sizing for Stream #   4

Loadings and Properties
                                    Vapor                 Liquid
  Flow rate                        0.0000  lb/h       100144.7109 lb/h
  Flow rate                        0.0000  ft3/hr        200.2822 gpm
  Density                          0.0000  lb/ft3          8.3327 lb/gal

  Pressure taps                 D and D/2
  Differential pressure          276.8000  in of water
  Reynolds No.                137887.2230
  Sm (Sizing parameter)            0.1309
  Cd (Discharge coefficient)       0.6038
  Beta ratio (d/D)                 0.4603
  Pipe inside diameter (D)         4.0260  in
  Bore size (d)                    1.8534  in
  Kr (Flow resistance factor)     45.9733
```

Figure 49 – Recommended orifice sizing

The recommended bore diameter is 1.85 inches, and the flow resistance factor, Kr, is 46. Kr is used to insert the orifice into the pipe UnitOp that follows the pump.

Returning to the flowsheet, double-click pipe UnitOp 1, then select the Valves tab as shown in **Figure 50**. The value for Kr must be inserted; it is not automatically transferred from the orifice sizing procedure. Remember to fill in the *Count* box, as shown, to provide the number of orifices.

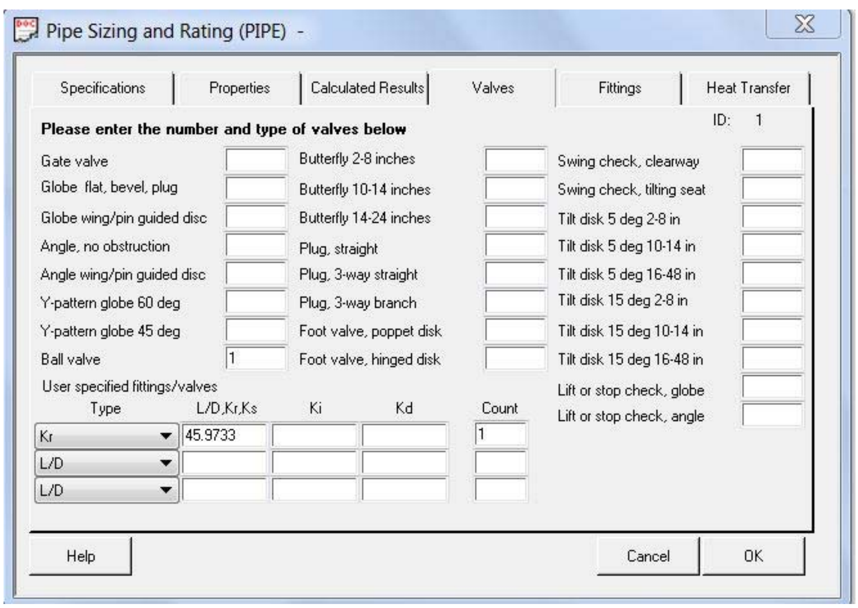


Figure 50 – Adding Kr value to the Pipe specifications

When you run the simulation, you will see that the frictional pressure drop across pipe UnitOp 1 has increased by 7.88 psi, while the Delta P across the valve has decreased by the same amount. The valve position has increased from 40.3% open to 43.6%, to adjust for the lower Delta P.

Part 2 of this paper will expand the scope of investigation to analysis of more complicated systems with branched piping.

Appendix: Referenced Tables

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Table 2-2
Suggested Fluid Velocities in Pipe and Tubing

The velocities are suggestive only and are to be used to approximate line size as a starting point for pressure drop calculations. The final line size should be such as to give an economical bala between pressure drop and reasonable velocity

Fluid	Suggested Trial Velocity	Pipe Material
Acetylene (Observe pressure limitations)	4000 fpm	Steel
Air, 0 to 30 psig	4000 fpm	Steel
Ammonia		
Liquid	6 fps	Steel
Gas	6000 fpm	Steel
Benzene	6 fps	Steel
Bromine		
Liquid	4 fps	Glass
Gas	2000 fpm	Glass
Calcium Chloride	4 fps	Steel
Carbon Tetrachloride	6 fps	Steel
Chlorine (Dry)		
Liquid	5 fps	Steel, Sch. 80
Gas	2000—5000 fpm	Steel, Sch. 80
Chloroform		
Liquid	6 fps	Copper & Steel
Gas	2000 fpm	Copper & Steel
Ethylene Gas	6000 fpm	Steel
Ethylene Dibromide	4 fps	Glass
Ethylene Dichloride	6 fps	Steel
Ethylene Glycol	6 fps	Steel
Hydrogen	4000 fpm	Steel
Hydrochloric Acid		
Liquid	5 fps	Rubber Lined
Gas	4000 fpm	R. L., Saran, Haveg
Methyl Chloride		
Liquid	6 fps	Steel
Gas	4000 fpm	Steel
Natural Gas	6000 fpm	Steel
Oils, lubricating	6 fps	Steel
Oxygen	1800 fpm Max.	Steel (300 psig Max.)
(ambient temp.)	4000 fpm	Type 304 SS
(Low temp.)		
Propylene Glycol	5 fps	Steel

Fluid	Suggested Trial Velocity	Pipe Material
Sodium Hydroxide		
0—30 Percent	6 fps	Steel
30—50 Percent	5 fps	and
50—73 Percent	4	Nickel
Sodium Chloride Sol'n.		
No Solids	5 fps	Steel
With Solids	(6 Min.— 15 Max.) 7.5 fps	Monel or nickel
Perchlorethylene	6 fps	Steel
Steam		
0–30 psi Saturated*	4000—6000 fpm	Steel
30–150 spi Saturated or superheated*	6000–10000 fpm	
150 psi up superheated	6500–15000 fpm	
*Short lines	15,000 fpm (max.)	
Sulfuric Acid		
88—93 Percent	4 fps	S. S.—316, Lead
93—100 Percent	4 fps	Cast Iron & Steel, Sch. 80
Sulfur Dioxide	4000 fpm	Steel
Styrene	6 fps	Steel
Trichlorethylene	6 fps	Steel
Vinyl Chloride	6 fps	Steel
Vinylidene Chloride	6 fps	Steel
Water		
Average service	3–8 (avg. 6) fps	Steel
Boiler feed	4–12 fps	Steel
Pump suction lines	1–5 fps	Steel
Maximum economical (usual)	7–10 fps	Steel
Sea and brackish water, lined pipe	5–8 fps } 3	R. L., concrete, asphalt-line, saran-lined, transite
Concrete	5–12 fps { (Min.)	

Note: R. L. = Rubber-lined steel.

Table 2-2, Suggested Fluid Velocities in Pipe and Tubing (Ludwig, 1977)

Table 2-7
Flow of Water Through Schedule 40 Steel Pipe*

Discharge		Pressure Drop per 100 feet and Velocity in Schedule 40 Pipe for Water at 60 F.															
		Velocity	Press. Drop	Velocity	Press. Drop	Velocity	Press. Drop	Velocity	Press. Drop	Velocity	Press. Drop	Velocity	Press. Drop	Velocity	Press. Drop	Velocity	Press. Drop
Gallons per Minute	Cubic Ft. per Second	Feet per Second	Lbs. per Sq. In.	Feet per Second	Lbs. per Sq. In.	Feet per Second	Lbs. per Sq. In.	Feet per Second	Lbs. per Sq. In.	Feet per Second	Lbs. per Sq. In.	Feet per Second	Lbs. per Sq. In.	Feet per Second	Lbs. per Sq. In.	Feet per Second	Lbs. per Sq. In.
		1/8″		1/4″		3/8″		1/2″		3/4″							
.2	0.000446	1.13	1.86	0.616	0.359												
.3	0.000668	1.69	4.22	0.924	0.903	0.504	0.159	0.317	0.061								
.4	0.000891	2.26	6.98	1.23	1.61	0.672	0.345	0.422	0.086								
.5	0.00111	2.82	10.5	1.54	2.39	0.840	0.539	0.528	0.167	0.301	0.033						
.6	0.00134	3.39	14.7	1.85	3.29	1.01	0.751	0.633	0.240	0.361	0.041						
.8	0.00178	4.52	25.0	2.46	5.44	1.34	1.25	0.844	0.408	0.481	0.102						
												1″		1 1/4″		1 1/2″	
1	0.00223	5.65	37.2	3.08	8.28	1.68	1.85	1.06	0.600	0.602	0.155	0.371	0.048				
2	0.00446	11.29	134.4	6.16	30.1	3.36	6.58	2.11	2.10	1.20	0.526	0.743	0.164	0.429	0.044		
3	0.00668			9.25	64.1	5.04	13.9	3.17	4.33	1.81	1.09	1.114	0.336	0.644	0.090	0.473	0.043
4	0.00891			12.33	111.2	6.72	23.9	4.22	7.42	2.41	1.83	1.49	0.565	0.858	0.150	0.630	0.071
5	0.01114					8.40	36.7	5.28	11.2	3.01	2.75	1.86	0.835	1.073	0.223	0.788	0.104
		2″		2 1/2″													
6	0.01337	0.574	0.044			10.08	51.9	6.33	15.8	3.61	3.84	2.23	1.17	1.29	0.309	0.946	0.145
8	0.01782	0.765	0.073			13.44	91.1	8.45	27.7	4.81	6.60	2.97	1.99	1.72	0.518	1.26	0.241
10	0.02228	0.956	0.108	0.670	0.046			10.56	42.4	6.02	9.99	3.71	2.99	2.15	0.774	1.58	0.361
						3″											
15	0.03342	1.43	0.224	1.01	0.094					9.03	21.6	5.57	6.36	3.22	1.63	2.37	0.755
20	0.04456	1.91	0.375	1.34	0.158	0.868	0.056			12.03	37.8	7.43	10.9	4.29	2.78	3.16	1.28
								3 1/2″		4″							
25	0.05570	2.39	0.561	1.68	0.234	1.09	0.083	0.812	0.041			9.28	16.7	5.37	4.22	3.94	1.93
30	0.06684	2.87	0.786	2.01	0.327	1.30	0.114	0.974	0.056			11.14	23.8	6.44	5.92	4.73	2.72
35	0.07798	3.35	1.05	2.35	0.436	1.52	0.151	1.14	0.704	0.882	0.041	12.99	32.2	7.51	7.90	5.52	3.64
40	0.08912	3.83	1.35	2.68	0.556	1.74	0.192	1.30	0.095	1.01	0.052	14.85	41.5	8.59	10.24	6.30	4.65
45	0.1003	4.30	1.67	3.02	0.668	1.95	0.239	1.46	0.117	1.13	0.064			9.67	12.80	7.09	5.85
												5″					
50	0.1114	4.78	2.03	3.35	0.839	2.17	0.288	1.62	0.142	1.26	0.076			10.74	15.66	7.88	7.15
60	0.1337	5.74	2.87	4.02	1.18	2.60	0.406	1.95	0.204	1.51	0.107			12.89	22.2	9.47	10.21
70	0.1560	6.70	3.84	4.69	1.59	3.04	0.540	2.27	0.261	1.76	0.143	1.12	0.047			11.05	13.71
80	0.1782	7.65	4.97	5.36	2.03	3.47	0.687	2.60	0.334	2.02	0.180	1.28	0.060			12.62	17.59
90	0.2005	8.60	6.20	6.03	2.53	3.91	0.861	2.92	0.416	2.27	0.224	1.44	0.074			14.20	22.0
														6″			
100	0.2228	9.56	7.59	6.70	3.09	4.34	1.05	3.25	0.509	2.52	0.272	1.60	0.090	1.11	0.036	15.78	26.9
125	0.2785	11.97	11.76	8.38	4.71	5.43	1.61	4.06	0.769	3.15	0.415	2.01	0.135	1.39	0.055	19.72	41.4
150	0.3342	14.36	16.70	10.05	6.69	6.51	2.24	4.87	1.08	3.78	0.580	2.41	0.190	1.67	0.077		
175	0.3899	16.75	22.3	11.73	8.97	7.60	3.00	5.68	1.44	4.41	0.774	2.81	0.253	1.94	0.102		
200	0.4456	19.14	28.8	13.42	11.68	8.68	3.87	6.49	1.85	5.04	0.985	3.21	0.323	2.22	0.130		
																8″	
225	0.5013	...	...	15.09	14.63	9.77	4.83	7.30	2.32	5.67	1.23	3.61	0.401	2.50	0.162	1.44	0.043
250	0.557	...	...	...	...	10.85	5.93	8.12	2.84	6.30	1.46	4.01	0.495	2.78	0.195	1.60	0.051
275	0.6127	...	...	...	...	11.94	7.14	8.93	3.40	6.93	1.79	4.41	0.583	3.05	0.234	1.76	0.061
300	0.6684	...	...	...	...	13.00	8.36	9.74	4.02	7.56	2.11	4.81	0.683	3.33	0.275	1.92	0.072
325	0.7241	...	...	...	...	14.12	9.89	10.53	4.09	8.19	2.47	5.21	0.797	3.61	0.320	2.08	0.083
350	0.7798			...	...	...	...	11.36	5.41	8.82	2.84	5.62	0.919	3.89	0.367	2.24	0.095
375	0.8355			...	...	...	...	12.17	6.18	9.45	3.25	6.02	1.05	4.16	0.416	2.40	0.108
400	0.8912			...	...	...	...	12.98	7.03	10.08	3.68	6.42	1.19	4.44	0.471	2.56	0.121
425	0.9469			...	...	...	...	13.80	7.89	10.71	4.12	6.82	1.33	4.72	0.529	2.73	0.136
450	1.003			...	...	...	...	14.61	8.80	11.34	4.60	7.22	1.48	5.00	0.590	2.89	0.151
		10″															
475	1.059	1.93	0.054			...	...	...	...	11.97	5.12	7.62	1.64	5.27	0.653	3.04	0.166
500	1.114	2.03	0.059			...	...	...	...	12.60	5.65	8.02	1.81	5.55	0.720	3.21	0.182
550	1.225	2.24	0.071			...	...	...	...	13.85	6.79	8.82	2.17	6.11	0.861	3.53	0.219
600	1.337	2.44	0.083			...	...	...	...	15.12	8.04	9.63	2.55	6.66	1.02	3.85	0.258
650	1.448	2.64	0.097			...	...	...	...	...	...	10.43	2.98	7.22	1.18	4.17	0.301
				12″		14″											
700	1.560	2.85	0.112	2.01	0.047			...	...	...	...	11.23	3.43	7.78	1.35	4.49	0.343
750	1.671	3.05	0.127	2.15	0.054			...	...	...	...	12.03	3.92	8.33	1.55	4.81	0.392
800	1.782	3.25	0.143	2.29	0.061			...	...	...	...	12.83	4.43	8.88	1.75	5.13	0.443
850	1.894	3.46	0.160	2.44	0.068	2.02	0.042	...	...	...	...	13.64	5.00	9.44	1.96	5.45	0.497
900	2.005	3.66	0.179	2.58	0.075	2.13	0.047	...	...	...	...	14.44	5.58	9.99	2.18	5.77	0.554
								16″									
950	2.117	3.86	0.198	2.72	0.083	2.25	0.052			...	...	15.24	6.21	10.55	2.42	6.09	0.613
1 000	2.228	4.07	0.218	2.87	0.091	2.37	0.057			...	...	16.04	6.84	11.10	2.68	6.41	0.675
1 100	2.451	4.48	0.260	3.15	0.110	2.61	0.068			...	...	17.65	8.23	12.22	3.22	7.05	0.807
1 200	2.674	4.88	0.306	3.44	0.128	2.85	0.080	2.18	0.042	...	...	...	...	13.33	3.81	7.70	0.948
1 300	2.896	5.29	0.355	3.73	0.150	3.08	0.093	2.36	0.048	...	...	...	...	14.43	4.45	8.33	1.11
										18″							
1 400	3.119	5.70	0.409	4.01	0.171	3.32	0.107	2.54	0.055					15.55	5.13	8.98	1.28
1 500	3.342	6.10	0.466	4.30	0.195	3.56	0.122	2.72	0.063					16.66	5.85	9.62	1.46
1 600	3.565	6.51	0.527	4.59	0.219	3.79	0.138	2.90	0.071					17.77	6.61	10.26	1.65
1 800	4.010	7.32	0.663	5.16	0.276	4.27	0.172	3.27	0.088	2.58	0.050			19.99	8.37	11.54	2.08
2 000	4.456	8.14	0.808	5.73	0.339	4.74	0.209	3.63	0.107	2.87	0.060			22.21	10.3	12.82	2.55
												20″		24″			
2 500	5.570	10.17	1.24	7.17	0.515	5.93	0.321	4.54	0.163	3.59	0.091					16.03	3.94
3 000	6.684	12.20	1.76	8.60	0.731	7.11	0.451	5.45	0.232	4.30	0.129	3.46	0.075			19.24	5.59
3 500	7.798	14.24	2.38	10.03	0.982	8.30	0.607	6.35	0.312	5.02	0.173	4.04	0.101			22.44	7.56
4 000	8.912	16.27	3.08	11.47	1.27	9.48	0.787	7.26	0.401	5.74	0.222	4.62	0.129	3.19	0.052	25.65	9.80
4 500	10.03	18.31	3.87	12.90	1.60	10.67	0.990	8.17	0.503	6.46	0.280	5.20	0.162	3.59	0.065	28.87	12.2
5 000	11.14	20.35	4.71	14.33	1.95	11.85	1.21	9.08	0.617	7.17	0.340	5.77	0.199	3.99	0.079	...	...
6 000	13.37	24.41	6.74	17.20	2.77	14.23	1.71	10.89	0.877	8.61	0.483	6.93	0.280	4.79	0.111	...	...
7 000	15.60	28.49	9.11	20.07	3.74	16.60	2.31	12.71	1.18	10.04	0.652	8.08	0.376	5.59	0.150	...	...
8 000	17.82	...	...	22.93	4.84	18.96	2.99	14.52	1.51	11.47	0.839	9.23	0.488	6.38	0.192	...	...
9 000	20.05	...	...	25.79	6.09	21.34	3.76	16.34	1.90	12.91	1.05	10.39	0.608	7.18	0.242	...	...
10 000	22.28	...	...	28.66	7.46	23.71	4.61	18.15	2.34	14.34	1.28	11.54	0.739	7.98	0.294	...	...
12 000	26.74	...	...	34.40	10.7	28.45	6.59	21.79	3.33	17.21	1.83	13.85	1.06	9.58	0.416	...	...
14 000	31.19	...	...	...	...	33.19	8.89	25.42	4.49	20.08	2.45	16.16	1.43	11.17	0.562	...	...
16 000	35.65	...	...	...	...	...	...	29.05	5.83	22.95	3.18	18.47	1.85	12.77	0.723	...	...
18 000	40.10	...	...	...	...	...	...	32.68	7.31	25.82	4.03	20.77	2.32	14.36	0.907	...	...
20 000	44.56	...	...	...	...	...	...	36.31	9.03	28.69	4.93	23.08	2.86	15.96	1.12	...	...

For pipe lengths other than 100 feet, the pressure drop is proportional to the length. Thus, for 50 feet of pipe, the pressure drop is approximately one-half the value given in the table . . . for 300 feet, three times the given value, etc.

Velocity is a function of the cross sectional flow area; thus, it is constant for a given flow rate and is independent of pipe length.

For pipe other than Schedule 40: $v = v_{40} (d_{40}/d)^2$ and $\Delta P = \Delta P_{40} (d_{40}/d)^5$ where subscript 40 refers to the conditions for schedule 40 pipe.

*By permission, "Technical Paper No. 410," Crane Co., Engineering Div., Chicago (1957)

Table 2-7, Flow of Water Through Schedule 40 Steel Pipe (Crane, 1957)

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Using CHEMCAD for Piping Network Design and Analysis

Part 2 – Branched Piping Networks

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Abstract

CHEMCAD is a powerful tool for designing and analyzing complex piping networks. It enables the engineer to integrate the piping network simulation into the overall process simulation, calculating a momentum balance in addition to a heat and material balance. This makes it possible to quickly evaluate the effects of changes in the process concept, or of its chemicals, on the piping network.

Part 1 of this paper presented a tutorial on how to use the piping network tool for unbranched pipe analysis. In Part 2 we will add complexity with more complicated networks, culminating in examples that demonstrate how CHEMCAD can be used to analyze practical plant piping problems.

Introduction

The CHEMCAD software suite is a powerful tool for designing and analyzing complex piping networks (1). In Part 1 of this paper, you saw how to use CHEMCAD to analyze unbranched flow problems. In this paper, Part 2, we will explore more complicated piping networks in which flow in a single pipe is divided between two or more downstream pipes, such as the distribution of cooling tower water to various plant heat exchangers and process vessels. We will also examine the combining of the flows from several pipelines into a single pipe, as might be seen in the return to a cooling tower. Indeed, complex piping systems are nothing more than compilations of sections of pipelines that involve dividing and combining flows.

We will begin by examining basic dividing and combining configurations, and see how these can be solved using CHEMCAD controllers. The two basic configurations will then be combined into a simple network. Again the solution will be demonstrated using CHEMCAD controllers.

Next we will explore the solution of piping network problems using a nodal method, and discuss simple rules for using nodes in CHEMCAD. Although CHEMCAD controllers can be used to solve piping networks, as the complexity increases it becomes more difficult to determine the position and settings for the controllers. In particular, specifying limits on flow rates that prevent flowsheet non-convergence from occurring can be challenging. Simulation of the piping network one section at a time to establish flow rate ranges for inclusion in the controllers of the flowsheet can be frustrating and time-consuming.

The simple rules for using nodes mitigate these issues, and provide for straightforward simulation of the entire flowsheet. However, with very complex networks, it is still advisable to build the network by converging it section by section.

Finally, we will look at practical plant piping examples, and see how CHEMCAD can be used to analyze these examples to understand and correct the plant issue.

Simple Divided Flow Problem Using Controllers

Let's start with the simple divided flow problem with the filename **#1 Simple Divided Flow - Controller Solution**. The flowsheet is given in **Figure 1**.

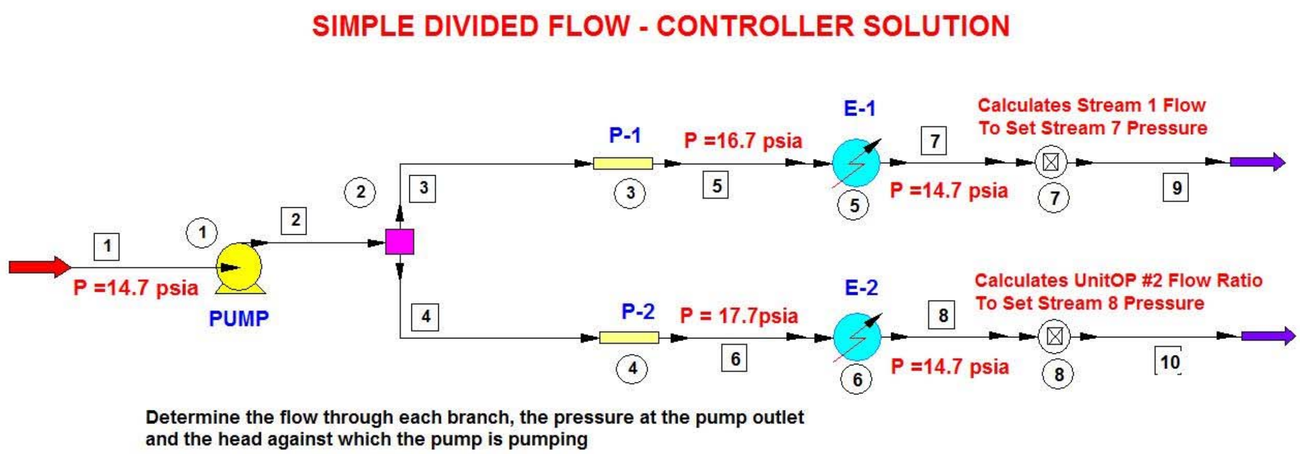
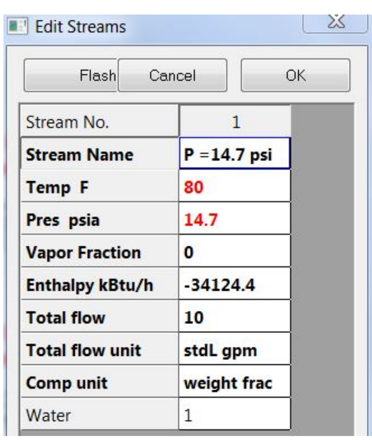


Figure 1 – Simple divided flow problem flowsheet

For details about the pump, heat exchanger, and piping specifications, see the simulation file. The temperature and pressure (80 °F and 14.7 psia, respectively) of the feed stream, stream 1, are fixed. The pressures of the exit streams are each fixed at 14.7 psia and the pressure drops of the heat exchangers are 3 and 2 psi, respectively, as noted in **Figure 1**. The outlet temperature of each exchanger is 100 °F.

The controllers are used to fix the pressure for each of the exit streams at 14.7 psia. Controller 7 adjusts the flow of stream 1 to accomplish this for stream 7. Controller 8 accomplishes this for Stream 8, by adjusting the flow ratio specification in the divider. A specified range of permissible divider settings is provided in the controller dialog box, namely, 0.10 – 0.90. The initial divider setting splits the flow equally to each branch.

Let's set the flow for Stream 1 at 10 gpm, as shown in **Figure 2**.


Edit Streams

Flash Cancel OK

Stream No.	1
Stream Name	P =14.7 psi
Temp F	80
Pres psia	14.7
Vapor Fraction	0
Enthalpy kBtu/h	-34124.4
Total flow	10
Total flow unit	stdL gpm
Comp unit	weight frac
Water	1

Figure 2 – Specifications for stream 1

Running the simulation now results in the stream information given in **Figure 3**. The total flow is about 66 gpm, with 39 gpm going to the upper pipe and 27 gpm to the lower. This makes sense since the upper pipe is 100 feet shorter than the lower one and its elevation change is 5 feet lower.

FLOW SUMMARIES:	#1 SIMPLE DIVIDED FLOW - CONTROLLER SOLUTION									
Stream No.	1	2	3	4	5	6	7	8	9	10
Stream Name					P =16.7 psia	P = 17.7psia	P =14.7 psia	P =14.7 psia		
Temp F	80	80.3765	80.3765	80.3765	80.3757	80.3764	100	100	100	100
Pres psia	14.7	77.8389	77.8389	77.8389	16.7001	17.7	14.7001	14.7	14.7001	14.7
Enth kBtu/h	-2.26E+05	-2.26E+05	-1.35E+05	-91259	-1.35E+05	-91259	-1.34E+05	-90996	-1.34E+05	-90996
Vapor mole frac.	0	0	0	0	0	0	0	0	0	0
Total lbmol/h	1839.2551	1839.2551	1095.8983	743.3568	1095.8983	743.3568	1095.8983	743.3568	1095.8983	743.3568
Total lb/h	33134.1797	33134.1797	19742.6074	13391.5723	19742.6074	13391.5723	19742.6074	13391.5723	19742.6074	13391.5723
Total std L gpm	66.1726	66.1726	39.4282	26.7444	39.4282	26.7444	39.4282	26.7444	39.4282	26.7444
Total std V scfh	697958	697958	415870	282088.03	415870	282088.03	415870	282088.03	415870	282088.03
Component mass fractions										
Water	1	1	1	1	1	1	1	1	1	1

Figure 3 – Flow summary, simple divided flow controller solution

Simple Combining Flow Problem Using Controllers

The filename for the simple combining flow problem is **#2 Simple Combining Flow - Controller Solution**. The flowsheet is given in **Figure 4**. For details about the piping and other UnitOps, see the simulation file.

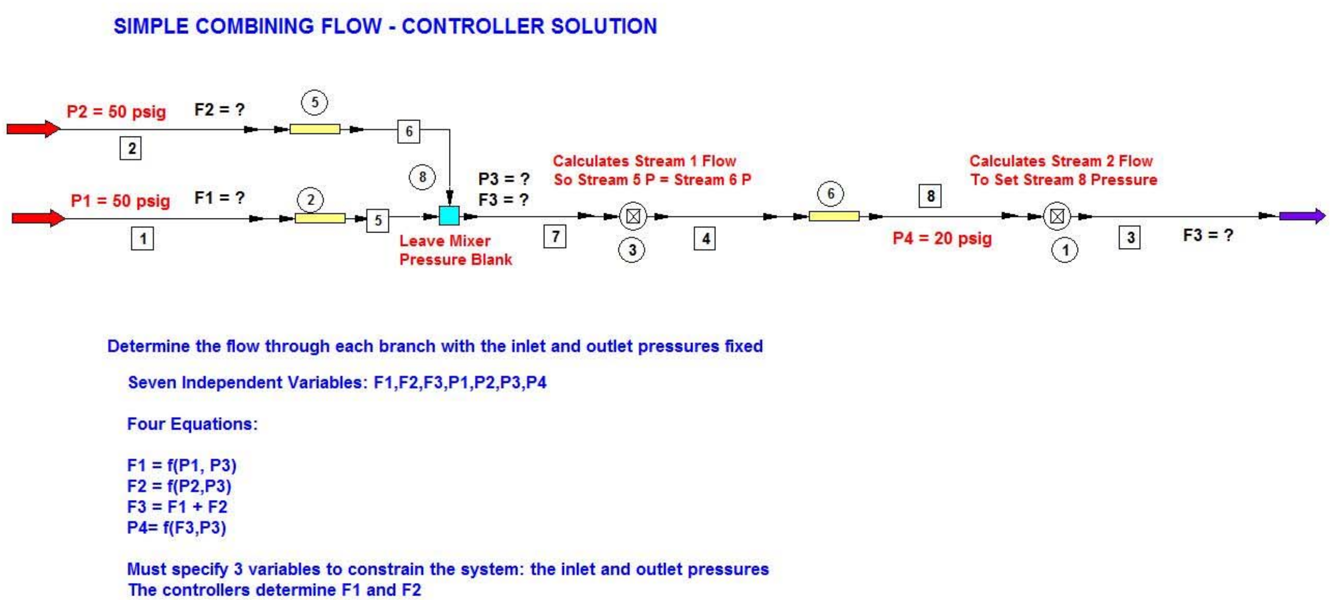


Figure 4 – Flowsheet for simple combining flow using controllers

As noted on the flowsheet, there are seven independent variables and four independent equations that define the flow problem. Three independent variables must be specified to permit solution. These are the pressures of the feed streams and the exit stream.

Controller 1 adjusts the flow of stream 2 to fix the outlet pressure at 20 psig. Controller 3 adjusts the flow of Stream 1 so that the pressures of streams 5 and 6 are equal as they enter the mixer, UnitOp 8. The initial setting for the pressure outlet of the mixer is left **blank** in the mixer dialog box.

Set the flow for streams 1 and 2 at 10 gpm, as shown in **Figure 5**.

Edit Streams

Flash | Cancel | OK

Stream No.	1	2
Stream Name	F1?	F2?
Temp F	100	100
Pres psig	50	50
Vapor Fraction	0	0
Enthalpy kBtu/h	-34024.4	-34024.4
Total flow	10	10
Total flow unit	stdL gpm	stdL gpm
Comp unit	weight frac	weight frac
Water	1	1

Figure 5 – Feed stream specifications

Running the simulation now results in the stream information given in **Figure 6**. The total flow is about 13.3 gpm, with 7.7 gpm flowing through the upper pipe and 5.7 gpm through the lower. This makes sense, since the lower pipe has a larger equivalent length.

Stream No.	**1**	**2**	**3**	**4**
Stream Name	F1?	F2?		
Temp C	25.0024*	25.0024*	25.0025	25.0025
Pres psig	**50.0000***	**50.0000***	**20.0000**	**24.6056**
Enth kBtu/h	-19056.	-25795.	-44851.	-44851.
Vapor mole frac.	0.00000	0.00000	0.00000	0.00000
Total lbmol/h	155.1468	210.0087	365.1555	365.1555
Total lb/h	2794.9690	3783.3074	6578.2764	6578.2764
Total std L gpm	**5.5819**	**7.5557**	**13.1375**	**13.1375**
Total std V scfh	55702.68	75399.90	131102.58	131102.58
Flow rates in lb/h				
Water	2794.9690	3783.3074	6578.2764	6578.2764

Stream No.	**5**	**6**	**7**	**8**
Stream Name		P2 = ?	P3 = ?	
Temp C	25.0022	25.0025	25.0025	25.0025
Pres psig	**24.6056**	**24.6056**	**24.6056**	**20.0000**
Enth kBtu/h	-19056.	-25795.	-44851.	-44851.
Vapor mole frac.	0.00000	0.00000	0.00000	0.00000
Total lbmol/h	155.1468	210.0087	365.1555	365.1555
Total lb/h	2794.9690	3783.3074	6578.2764	6578.2764
Total std L gpm	**5.5819**	**7.5557**	**13.1375**	**13.1375**
Total std V scfh	55702.68	75399.90	131102.58	131102.58
Flow rates in lb/h				
Water	2794.9690	3783.3074	6578.2764	6578.2764

Figure 6 – Flow summary for simple combining flow controller solution

Simple Network Using Controllers

We now combine the simple divided flow flowsheet with the simple combining flow flowsheet to construct a simple network, as shown in **Figure 7**. The filename is **#3 Simple Network – Controller Solution.** For details about the piping and other UnitOps, see the simulation file.

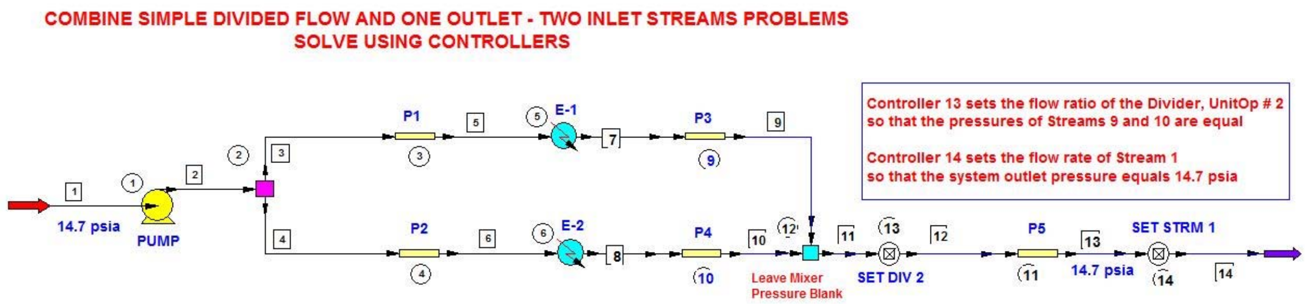


Figure 7 – Flowsheet for simple network using controllers

This flowsheet combines the two previous ones, to construct a simple network similar to a cooling system network in a plant. A cold water stream at 80 °F from the cooling tower is split to provide cooling for two heat exchangers. The streams are recombined and returned to the cooling tower.

We need to know the flow rate provided by the pump, the pump outlet pressure, the flow rates of the two streams, and the pressure after they recombine. There are only two independent variables: one at the system inlet and one at the system outlet. When these are specified, all of the flow-related variables between them, the "interior variables," can be calculated.

In this example, the independent variables are the system inlet and outlet pressures. Controller 13 iteratively calculates the stream split until the respective pressures of the streams are equal when they recombine. Controller 14 iteratively calculates the flow rate into the pump until the system outlet pressure equals 14.7 psia, the value fixed initially as one of the independent variables.

If either of the independent variables is changed, all of the "interior variables" will also change. It is not surprising, however, that if the system inlet and outlet pressures are equal, the calculated flow results are independent of the actual value of these pressures. This is shown in **Figure 8**, for inlet and outlet pressures of 14.7 psia and 64.7 psia, respectively.

	SIMPLE NETWORK PROBLEM WITH EQUAL SYSTEM INLET AND OUTLET PRESSURES													
FLOW SUMMARIES:	**Simple Network With System Inlet and Outlet Pressures = 14.7 psia**													
Stream No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Stream Name	14.7 psia												14.7 psia	
Temp F	80	80.4009	80.4009	80.4009	80.4015	80.4007	100	100	100.0002	100.0005	100.0003	100.0003	100.0005	100.0005
Pres psia	**14.7**	**82.0197**	**82.0197**	**82.0197**	**57.494**	**54.2292**	**55.494**	**51.2292**	**41.5054**	**41.5054**	**41.5054**	**41.5054**	**14.7001**	**14.7001**
Enth kBtu/h	-1.19E+05	-1.19E+05	-68871	-50022	-68871	-50022	-68674	-49879	-68674	-49879	-1.19E+05	-1.19E+05	-1.19E+05	-1.19E+05
Vapor mole frac.	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total lbmol/h	968.4645	968.4645	561.0011	407.4635	561.0011	407.4635	561.0011	407.4635	561.0011	407.4635	968.4646	968.4646	968.4646	968.4646
Total lb/h	17446.8887	17446.8887	10106.4346	7340.4546	10106.4346	7340.4546	10106.4346	7340.4546	10106.4346	7340.4546	17446.8887	17446.8887	17446.8887	17446.8887
Total std L gpm	**34.8434**	**34.8434**	**20.1837**	**14.6597**	**20.1837**	**14.6597**	**20.1837**	**14.6597**	**20.1837**	**14.6597**	**34.8434**	**34.8434**	**34.8434**	**34.8434**
Total std V scfh	367511.59	367511.59	212887.92	154623.69	212887.92	154623.69	212887.92	154623.69	212887.92	154623.69	367511.63	367511.63	367511.63	367511.63
FLOW SUMMARIES:	**Simple Network With System Inlet and Outlet Pressures = 64.7 psia**													
Stream No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Stream Name	64.7 psia												64.7 psia	
Temp F	80	80.4013	80.4013	80.4013	80.4012	80.4012	100	100	99.9998	100.0002	99.9996	99.9996	99.9996	99.9996
Pres psia	**64.7**	**132.0197**	**132.0197**	**132.0197**	**107.4938**	**104.229**	**105.4938**	**101.229**	**91.5051**	**91.5051**	**91.5051**	**91.5051**	**64.7**	**64.7**
Enth kBtu/h	-1.19E+05	-1.19E+05	-68871	-50021	-68871	-50021	-68673	-49878	-68673	-49878	-1.19E+05	-1.19E+05	-1.19E+05	-1.19E+05
Vapor mole frac.	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total lbmol/h	968.4511	968.4511	560.9944	407.4567	560.9944	407.4567	560.9944	407.4567	560.9944	407.4567	968.4512	968.4512	968.4512	968.4512
Total lb/h	17446.6465	17446.6465	10106.3145	7340.3325	10106.3145	7340.3325	10106.3145	7340.3325	10106.3145	7340.3325	17446.6465	17446.6465	17446.6465	17446.6465
Total std L gpm	**34.8429**	**34.8429**	**20.1834**	**14.6595**	**20.1834**	**14.6595**	**20.1834**	**14.6595**	**20.1834**	**14.6595**	**34.8429**	**34.8429**	**34.8429**	**34.8429**
Total std V scfh	367506.5	367506.5	212885.41	154621.13	212885.41	154621.13	212885.41	154621.13	212885.41	154621.13	367506.53	367506.53	367506.53	367506.53

Figure 8 – Flow summaries for simple network using a controller

Figure 9 provides the pump characteristics for each case. Because both pressures were increased by the same amount, the resistance to flow that the pump experiences does not change and it operates at the same point on the pump curve. The NPSHA, however does change, because the upstream pressure has increased.

Pump Summary			Pump Summary	
Pin = Pout = 64.7 psia			**Pin = Pout = 14.7 psia**	
Equip. No.	1		Equip. No.	1
Name	PUMP		Name	PUMP
Output pressure psia	100		Output pressure psia	100
Efficiency	0.5		Efficiency	0.5
Calculated power hp	2.7487		Calculated power hp	2.7487
Calculated Pout psia	**132.0197**		**Calculated Pout psia**	**82.0197**
Head ft	155.8638		Head ft	155.8636
Vol. flow rate gpm	34.973		Vol. flow rate gpm	34.9735
Mass flow rate lb/h	17446.65		Mass flow rate lb/h	17446.89
NPSH available ft	**148.6235**		**NPSH available ft**	**32.8597**
Char. Eq/Perform curve	2		Char. Eq/Perform curve	2
Request NPSH calc	1		Request NPSH calc	1

Figure 9 – Comparison of pump characteristics for the two cases

Solving Piping Problems with Controllers - Summary

We have demonstrated with three simple examples that controllers can be used to solve increasingly complicated piping problems. Furthermore, we have shown that the number of independent variables that must be specified to solve such problems is equal to the total number of independent system inlet and outlet streams.

For the simple divided flow problem and the simple combining flow problem, there are three independent variables, as shown in **Figure 1** and **Figure 4**, respectively. In each case we specified the system inlet and outlet pressures. The simple network problem of **Figure 7** has only one inlet and one outlet stream, and only two independent variables.

Using CHEMCAD, it is possible to add any number of simple network piping configurations together to develop and simulate complex piping systems used in plant-wide cooling tower networks, raw material distribution networks, solvent collection systems, liquid waste collection, and vapor emissions to flare or scrubber systems.

In each case, the number of degrees of freedom is determined by the number of independent inlet and outlet streams. As the systems become more and more complex, however, the difficulty in simulation lies in determining the location and settings of the controllers internal to the system that are required to complete the calculation. This can be quite frustrating and time-consuming.

Using Nodes for Piping Network Simulation

CHEMCAD offers a simple and robust alternative to using controllers that does not require the details of feedback controller calculations to be consciously considered. This approach uses nodes. It is only necessary to determine and set the values of the system independent variables at each of the independent inlet and outlet streams of the system. As will be shown, although nodes are required to be placed at “interior” positions in the piping network flowsheet, their settings are all identical and invariant.

The use of nodes for piping networks originated with Hardy Cross, a structural engineering professor at the University of Illinois at Urbana–Champaign. The Hardy Cross Method, first published in 1936, is an iterative method for determining the flow in pipe network systems where the inputs and outputs are known, but the flow inside the network is unknown (2). Other investigators (3 - 6), have sought to improve on the original method over the years.

Let's begin with a single pipe element, as shown in **Figure 10**. The corresponding filename is **#4 Single Pipe With Nodes**.

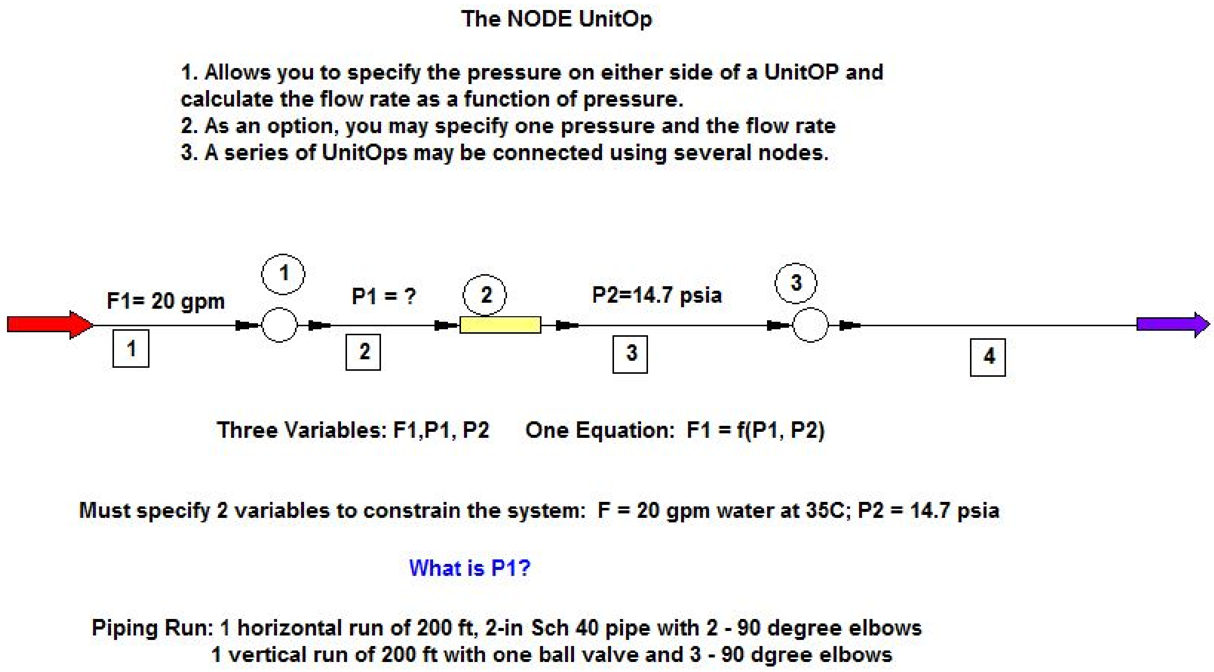


Figure 10 – Single pipe with nodes flowsheet

This is a simple example of nodes to demonstrate their use. There are three variables that define the flow problem: the flow rate and the inlet and outlet pressures. There are two degrees of freedom for this problem. We must fix these degrees of freedom by specifying any two of the three variables. The third variable can then be calculated.

The dialog box for the node in the feed stream is shown in **Figure 11**.

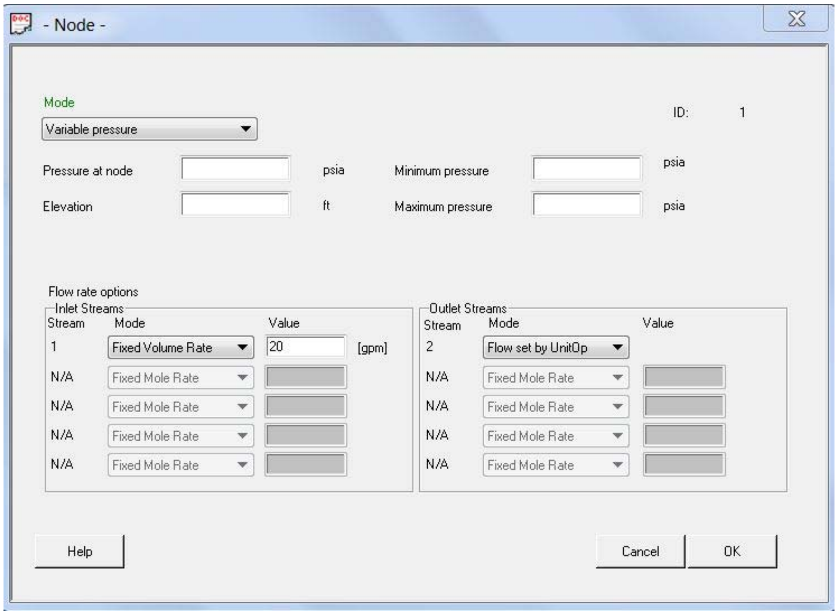


Figure 11 – Node dialog box for inlet with fixed flow rate

There are two input choices for this inlet node. You can specify either the system inlet pressure or the inlet flow rate. For this example, fix the inlet flow rate at 20 gpm. Mass and molar flow units can also be specified, if desired. The pressure specification is *Variable pressure* because this value will be calculated.

Alternatively, you can fix the pressure and fill in a value for it, and let the flow rate be the calculated variable by designating the stream into the node as a *Free inlet stream*. This is shown in **Figure 12**.

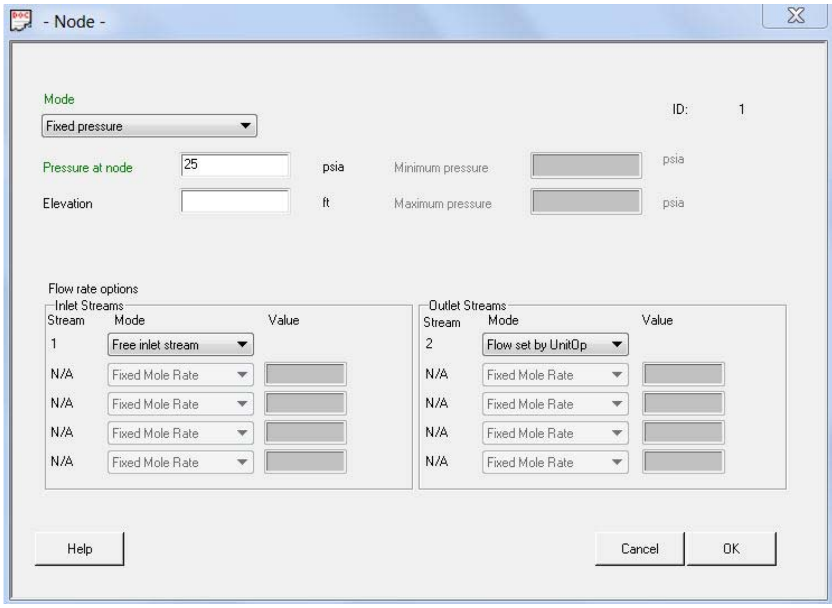


Figure 12 – Node dialog box for inlet with fixed pressure

In both cases, indeed for every inlet node, the outlet stream flow—the downstream pipe in this case—is set to *Flow set by UnitOP*.

Now let's look at the settings for the outlet node, shown in **Figure 13**.

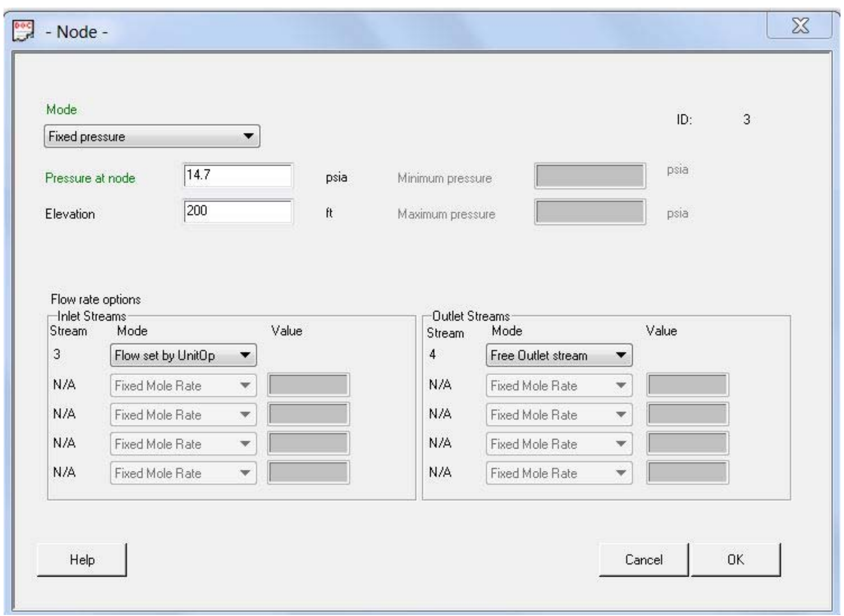


Figure 13 – Node dialog box for outlet with fixed pressure

There are two input choices for this outlet node. You can specify either the system outlet pressure or the outlet flow rate. For this example, fix the outlet pressure at 14.7 psia. The outlet flow specification is set to *Free outlet stream*, as the flow rate has already been specified in the inlet node. For every outlet node, the inlet stream flow specification is *Flow set by UnitOP*, the upstream pipe in this case.

It is important to note that the piping elevation at the physical location of each node in a flowsheet needs to be specified in the Node dialog box, as it is in **Figure 13**, for the outlet node. The pipe dialog box shows an elevation of 200 feet that must be indicated for the node following the pipe. For a series of pipes with changing elevations, the elevation at a given node is the sum of the elevations of the pipes upstream of it.

Let's look at the Convergence dialog box, as shown in **Figure 14,** accessed from the main CHEMCAD menu by selecting **Run** > **Convergence**. Note that the calculation sequence is *Simultaneous modular*. When a piping simulation is set up in CHEMCAD with nodes, the calculation sequence automatically defaults to this setting.

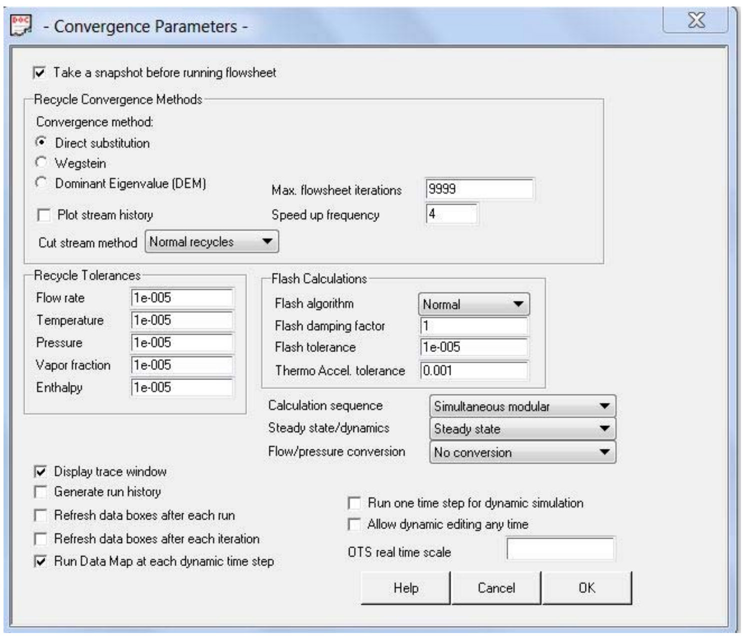


Figure 14 – The Convergence Parameters dialog box with Simultaneous modular *calculation sequence selected*

If the pipe dialog box is open, as shown in **Figure 15**, we see that the sizing option used is *Rating (default)*. CHEMCAD suggests that for piping simulations with nodes, the sizing option choice should be: *Given size, Pin and Pout, calc flow rate*. In my personal experience, I have found that both of these sizing options work. However, since Chemstations recommends the latter, I suggest that the reader follow it.

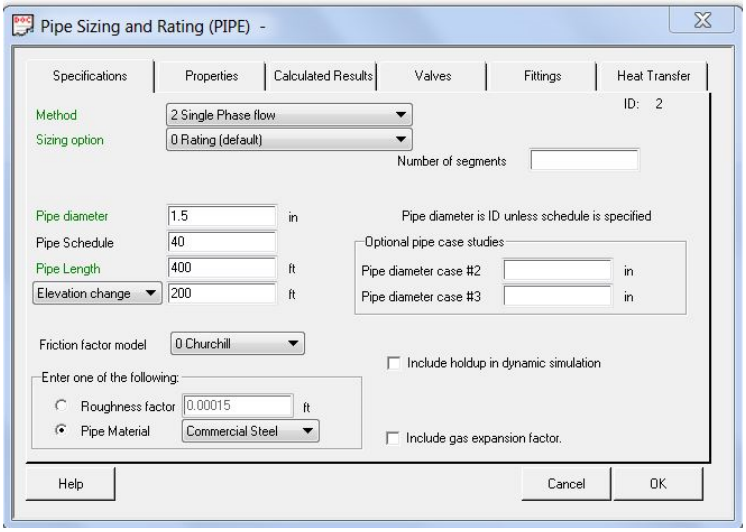


Figure 15 – Pipe dialog with Rating (default) *sizing option selected*

Let's now run the 20 gpm flow rate case. The required upstream pressure is 106.7 psia. Open the pipe dialog box to check results, as shown in **Figure 16**.

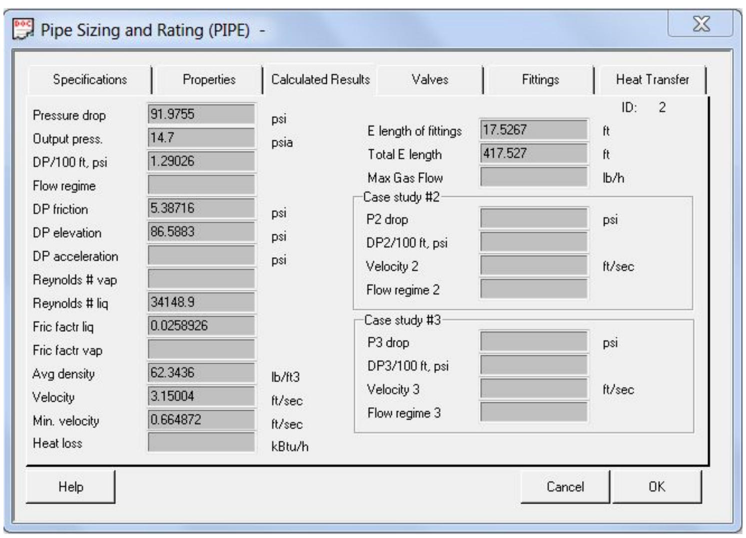


Figure 16 – Calculated results for the pipe UnitOp

To have flow through this pipe, enough upstream pressure needs to be applied to overcome the 200 feet of elevation, corresponding to 86.6 psia. What happens if the upstream pressure is 75 psia and the downstream pressure is 15 psia? The Delta P at 60 psia is not sufficient to overcome the piping elevation change, and no flow would occur. Water would enter the pipe and rise to height corresponding to the 60 psia pressure differential, roughly 138 feet. How does CHEMCAD handle this situation?

Let's set the inlet pressure at the Inlet Node to 75 psia, as shown in **Figure 17**, and change the outlet pressure at the Outlet Node to 15 psia.

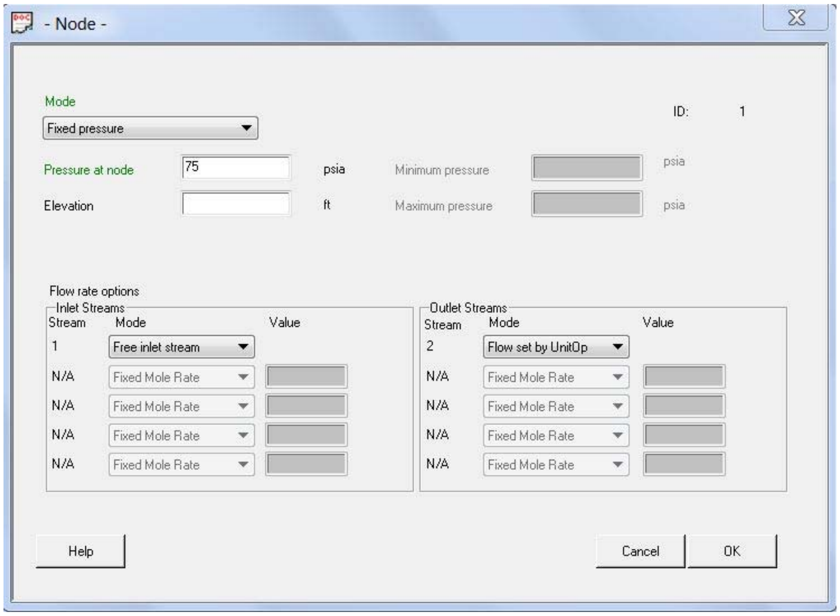


Figure 17 – Inlet node fixed pressure at 75 psia

When this simulation runs, it converges mathematically. However, CHEMCAD calculates a negative flow rate. The calculated inlet and outlet streams are given in **Figure 18**.

FLOW SUMMARIES:

Stream No.	2	3
Stream Name		
Temp F	59.9946	59.9947
Pres psia	**75.0000**	**15.0000**
Enth kBtu/h	1.6001E+005	1.6001E+005
Vapor mole frac.	0.00000	0.00000
Total lbmol/h	**-1299.4570**	**-1299.4570**
Total lb/h	**-23409.7168**	**-23409.7168**
Total std L gpm	**-46.7518**	**-46.7518**
Total std V scfh	-493116.16	-493116.16
Flow rates in lb/h		
Water	-23409.7168	-23409.7168

Figure 18 – Flow summaries for pipe inlet and outlet streams

Rules for Using Nodes

Now let's define some simple rules and strategies for using nodes in complex piping networks. There are three combinations of settings that are typical for inlet and outlet nodes, as shown in **Figure 19**. In each case two variables are fixed and one is calculated. **Figure 20** provides some guidelines for complex piping network simulations with CHEMCAD.

Some Rules For Simulating Piping Networks With Nodes

1. Option 5 should be chosen for pipe simulators: " Given size, Pin and Pout, calc flow rate"
2. Interior nodes are always specified as "Flow set by UnitOP" for the inlet and outlet streams and the pressure is always Variable.
3. The degrees of freedom for the problem are set by constraints at the process Inlet and Outlet Nodes
4. The RUN mode for the simulation must be Simultaneous Modular

Settings For Inlet And Outlet Nodes

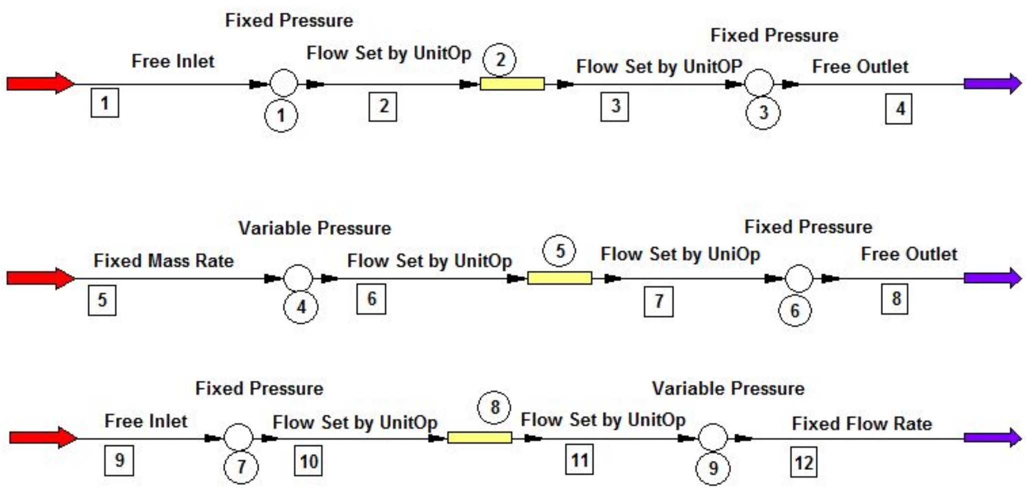


Figure 19 – Rules for using nodes to simulate piping networks

Some Guidelines for Piping Network Simulations With Chemcad

1. Develop a general diagram of the system, designating blocks or areas of the flowsheet which will be developed in Chemcad one at a time.
2. Use an easy to follow coding system to relate the actual piping elements in the plant with their representation in Chemcad.
3. For complex systems, build the Chemcad flowsheet in small segments, converging each increasingly more complicated flowsheet before adding additional piping sections. This allows easier troubleshooting for errors.
4. When possible, provide reasonable guesses for pressures at internal nodes, based on converged calculations made previously for adjacent nodes. This might help make convergence easier.
5. Be sure that the elevation for nodes are correct and are compatible with that given for elevation changes in adjacent piping.
6. If the calculation seems to be proceeding but convergence does not occur, try simply to rerun it.
7. If a singular matrix error message occurs:
   a) print the stream summary and check for anomalies, like negative flow rates. The pressure drop may be too high for units for which it is specified and not calculated, like heat exchangers.
   b) try rerunning the simulation
   c) try relaxing the convergence specification
   d) provide reasonable pressure estimates for internal modes in areas of the flowsheet which have not already converged
8. Save all converged "simpler" flowsheets as you build up to more complicated ones. They provide a converged starting point for the next more complex flowsheet which may be hopelessly unconverged. Retreat to a safe position and start again.
9. For internal nodes the input is ALWAYS: Variable Pressure, Flow Set by Unit Op, In and Out
10. Constraints on the system are ALWAYS set by the external nodes

Figure 20 – Guidelines for building piping network simulations using CHEMCAD

Simple Network Using Nodes

Now let's go back to the simple network problem and solve it with nodes. The flowsheet is given in **Figure 21**. The filename is **#5 Simple Network - Solve With Nodes**.

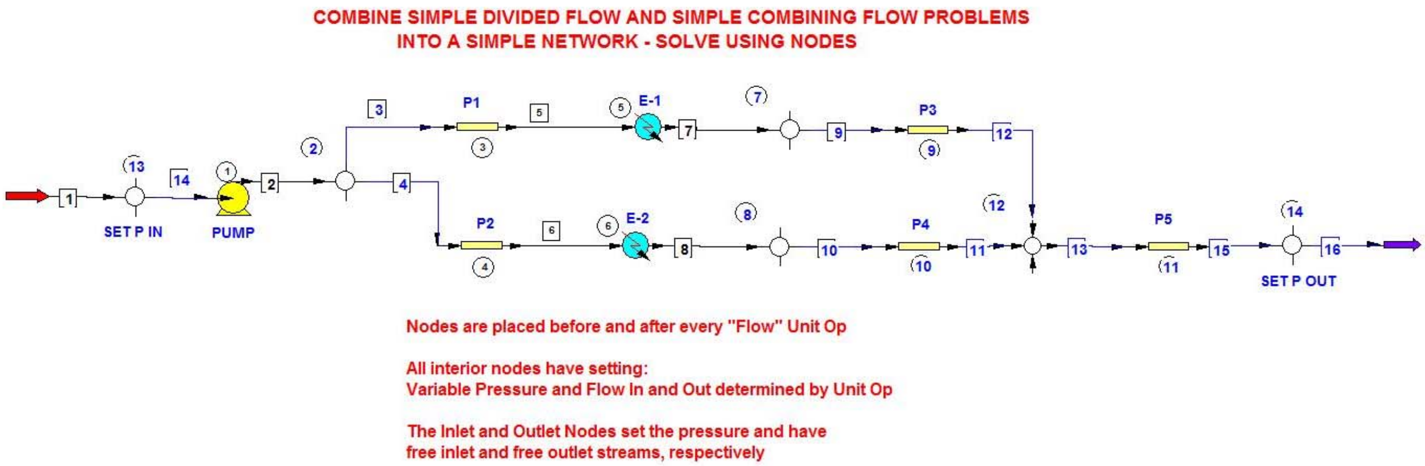


Figure 21 – Solving the simple network problem using nodes

There is one inlet stream and one outlet stream, so there are two degrees of freedom. The system inlet and outlet pressures are specified, as shown in the inlet and outlet node dialog boxes, given in **Figure 22 and Figure 23**, respectively.

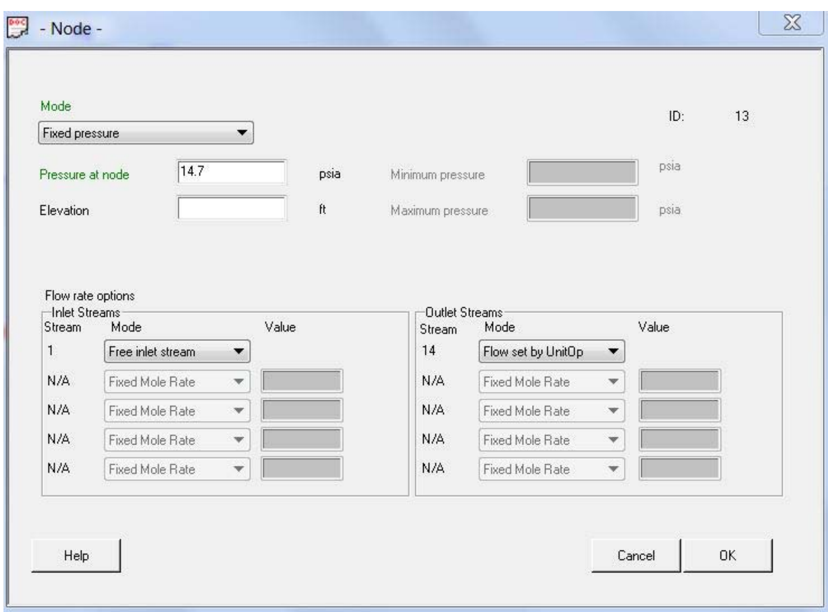


Figure 22 – Specifying system inlet pressure

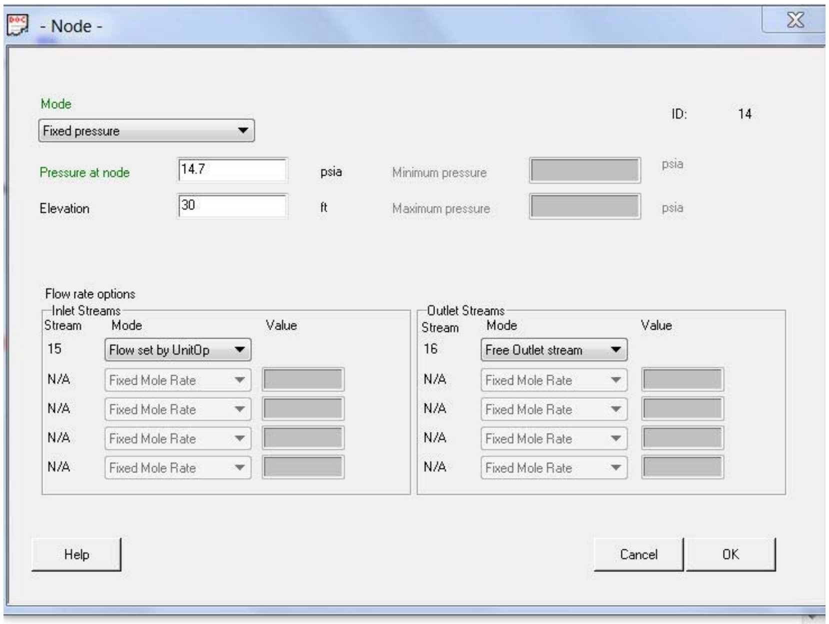


Figure 23 – Specifying system outlet pressure

The system inlet and outlet flows are designated as free streams, to be calculated by CHEMCAD. All of the internal nodes have identical settings: variable pressure and flow in and flow out set by the upstream and downstream UnitOp, respectively. In flowsheets that are difficult to converge, it is often helpful to estimate the pressure at internal nodes, as indicated in the guidelines provided in **Figure 20**. Note that the elevation values shown in the Node dialog boxes reflect the elevation changes of the pipe sections in the flowsheet.

Let's set the flow rate for stream 1 at 10 gpm, as shown in **Figure 24**, and run the simulation. **Figure 25** shows a comparison of the results for the solution using controllers and that using nodes. They are identical, as one would expect.

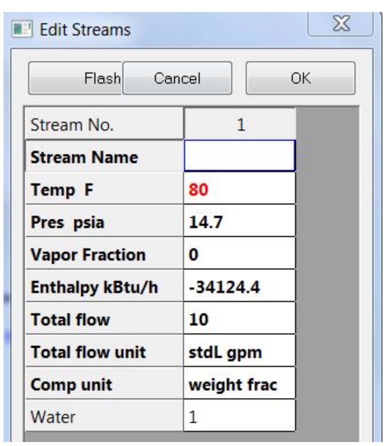


Figure 24 – Setting stream 1 flow rate to 10 gpm

SIMPLE NETWORK PROBLEM - COMPARE CONTROLLER AND NODE SOLUTIONS

FLOW SUMMARIES:	Simple Network - Solve With Controllers															
Stream No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14		
Temp F	80	80.4009	80.4009	80.4009	80.4015	80.4007	100	100	100	100.001	100.0003	100.0003	100.0005	100.0005		
Pres psia	**14.7**	**82.0197**	**82.0197**	**82.0197**	**57.494**	**54.2292**	**55.494**	**51.2292**	**41.5054**	**41.5054**	**41.5054**	**41.5054**	**14.7001**	**14.7001**		
Enth kBtu/h	-1.19E+05	-1.19E+05	-68871	-50022	-68871	-50022	-68674	-49879	-68674	-49879	-1.19E+05	-1.19E+05	-1.19E+05	-1.19E+05		
Vapor mole frac.	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
Total lbmol/h	968.4645	968.4645	561.001	407.464	561.001	407.464	561.001	407.464	561.001	407.464	968.4646	968.4646	968.4646	968.4646		
Total lb/h	17446.889	17446.889	10106.4	7340.45	10106.4	7340.45	10106.4	7340.45	10106.4	7340.45	17446.889	17446.889	17446.889	17446.889		
Total std L gpm	**34.8434**	**34.8434**	**20.1837**	**14.6597**	**20.1837**	**14.6597**	**20.1837**	**14.6597**	**20.1837**	**14.6597**	**34.8434**	**34.8434**	**34.8434**	**34.8434**		
Total std V scfh	367511.59	367511.59	212888	154624	212888	154624	212888	154624	212888	154624	367511.63	367511.63	367511.63	367511.63		

FLOW SUMMARIES:	Simple Network - Solve With Nodes															
Stream No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Temp F	80	80.4002	80.4003	80.4003	80.3998	80.4004	100	100	100	99.9999	100	100.0004	99.9998	79.9991	100.0002	100.0002
Pres psia	**14.7**	**82.0197**	**82.0197**	**82.0197**	**57.4939**	**54.2292**	**55.4939**	**51.2292**	**55.4939**	**51.2292**	**41.5054**	**41.5054**	**41.5054**	**14.7**	**14.7**	**14.7**
Enth kBtu/h	-1.19E+05	-1.19E+05	-68872	-50022	-68872	-50022	-68674	-49879	-68674	-49879	-49879	-68674	-1.19E+05	-1.19E+05	-1.19E+05	-1.19E+05
Vapor mole frac.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total lbmol/h	968.4649	968.4649	561.002	407.464	561.002	407.464	561.002	407.464	561.002	407.464	407.4642	561.002	968.4661	968.4649	968.4661	968.4661
Total lb/h	17446.895	17446.895	10106.5	7340.47	10106.5	7340.47	10106.5	7340.47	10106.5	7340.47	7340.4678	10106.451	17446.916	17446.895	17446.916	17446.916
Total std L gpm	**34.8434**	**34.8434**	**20.1837**	**14.6597**	**20.1837**	**14.6597**	**20.1837**	**14.6597**	**20.1837**	**14.6597**	**14.6597**	**20.1837**	**34.8434**	**34.8434**	**34.8434**	**34.8434**
Total std V scfh	367511.72	367511.72	212888	154624	212888	154624	212888	154624	212888	154624	154623.97	212888.27	367512.16	367511.72	367512.16	367512.16

Figure 25 – Comparison of using controllers and nodes, showing that results are identical

Now, let's end this paper with two examples that demonstrate how CHEMCAD's piping package can be used to analyze real plant problems.

Lower Than Expected Raw Material Delivery Rate

An acrylic acid (AA) off-loading piping system has been designed for a plant located in Europe. The design flow rate is 50,000 L/hr (220 gpm) so that the delivery truck could be off-loaded in no more than 30 minutes. The actual observed rate after start-up was about 35,000 L/hr, resulting in an off-load time of about 43 minutes. Why is the flow rate lower than expected, and how can it be improved without incurring a large cost?

The AA off-loading piping system, as designed, is shown in **Figure 26**.

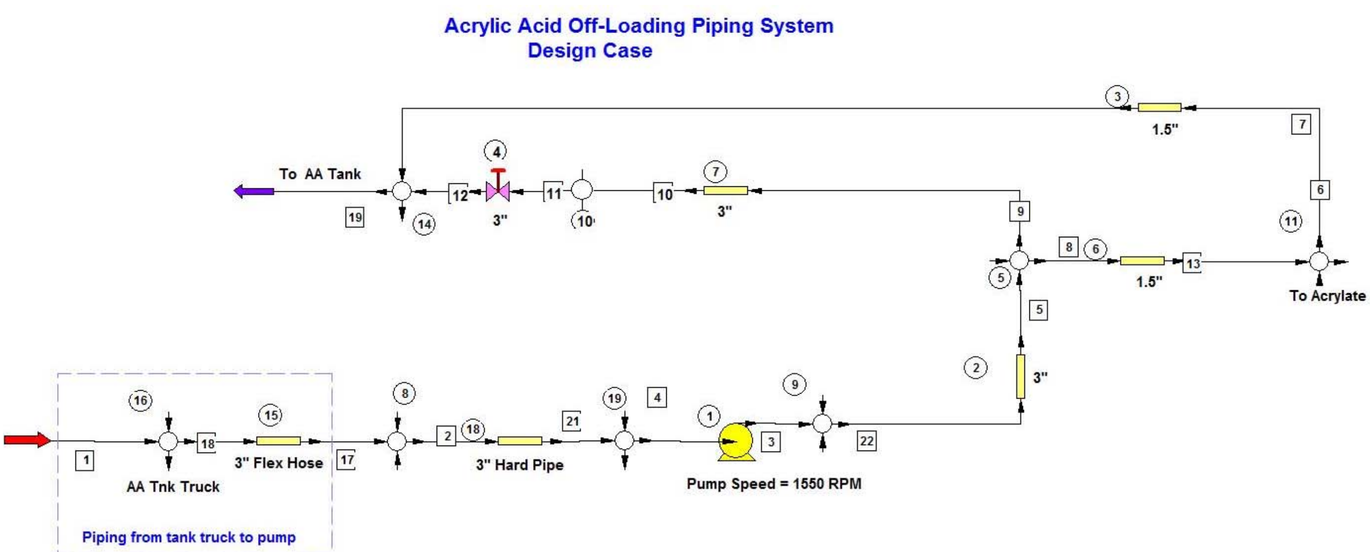


Figure 26 – Flowsheet of acrylic acid off-loading piping system

Acrylic acid is delivered to the plant by truck. The operator uses flexible hose to connect to the hard pipe at the inlet to the plant acrylic acid pump. The flow out of the pump has two branches; the first goes to the plant's acrylic acid storage tank, and the second goes to the acrylate process.

When the storage tank is being loaded, the flow to the process is blocked. The same pump is used to feed the process from the storage tank. So, when acrylic acid is delivered, it takes two paths to the storage tank. The CHEMCAD file for this design case is **#6 AA Off-load System – Design Case**. The details of the piping can be reviewed by opening the dialog boxes for each of the UnitOps.

The inlet and outlet nodes, respectively, set the inlet and outlet pressures at 14.7 psia. The 3” control valve has a Cv of 75 and is set at 100% open, as shown in **Figure 27**.

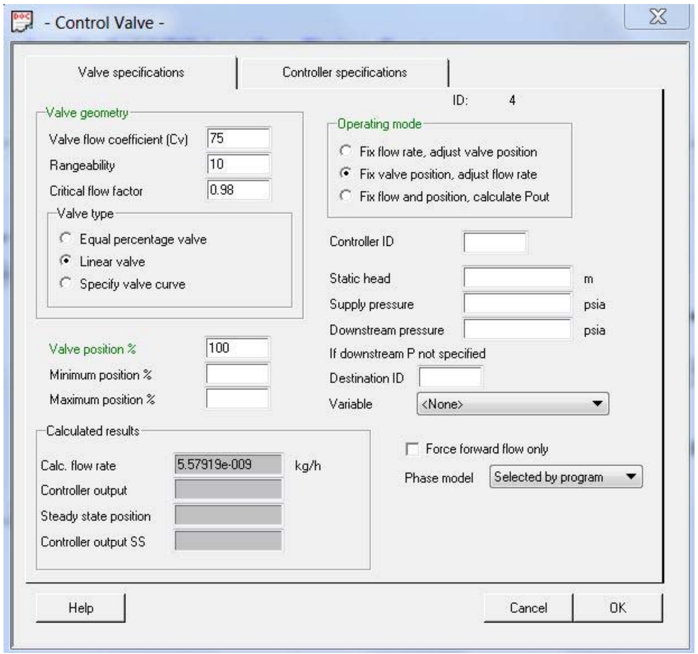


Figure 27 – Control Valve dialog box for AA off-load design case

When you run the flowsheet, you see that the maximum flow to the AA storage tank is 57,128 L/hr, which will deliver the desired quantity of AA in less than 30 minutes. The results are given in **Figure 28**.

Stream No.	19
Stream Name	**To AA Tank**
Temp F	77.1886
Pres psia	14.7000
Enth MMBtu/h	-307.16
Vapor mole frac.	0.00000
Total kmol/h	839.3104
Total kg/h	60484.0703
Total std L liter/	**57128.0313**
Total std V scfh	702173.13
Flow rates in kg/h	
Acrylic Acid	60484.0703

Figure 28 – Maximum flow to AA tank

The piping design as conceived is adequate for delivering the desired flow. What could be restricting the AA flow?

One possibility is that the installed valve trim is not right. Suppose a restricted capacity trim was supplied. Many restricted capacity trim combinations are designed to furnish about 40% of full-size trim capacity. Let’s suppose this occurred in this plant, and run another simulation with the valve position set at 40% open. The filename is **#7 AA Off-load System – Reduced Valve Trim**, and the Control Valve dialog box is shown in **Figure 29**.

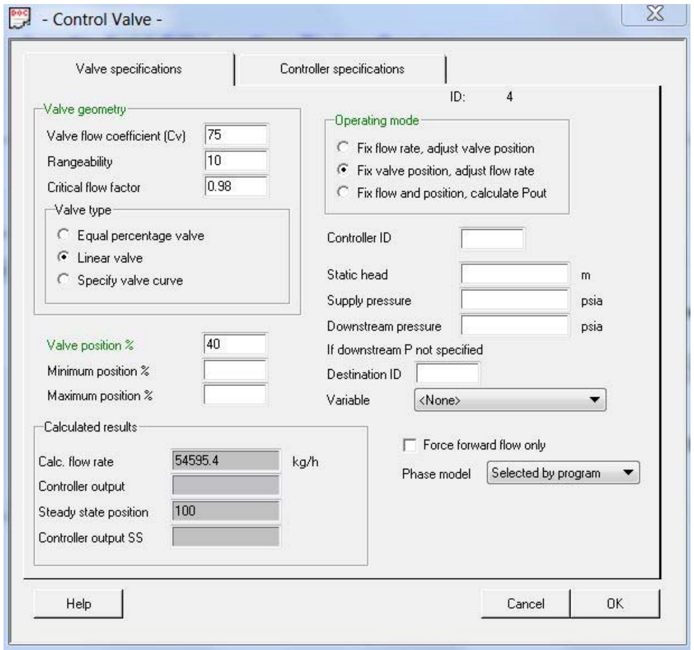


Figure 29 – Control Valve dialog box set to 40% open

When you run this flowsheet, you see that the flow to the AA storage tank is now 35,458 L/hr. The results are given in **Figure 30**.

```
FLOW SUMMARIES:
    REDUCED VALVE TRIM CASE
Stream No.                    19
Stream Name           To  AA Tank
Temp  F                  77.2488
Pres  psia               14.7000
Enth  MMBtu/h            -190.65
Vapor mole frac.         0.00000
Total kmol/h            520.9463
Total kg/h            37541.4766
Total std L liter/    35458.4375
Total std V scfh       435827.41
Flow rates in kg/h
Acrylic Acid          37541.4766
```

Figure 30 – Maximum flow to AA tank with valve 40% open

This flow is consistent with what the plant actually experienced. When the valve manufacturer was called in, it was found that, indeed, a restricted capacity trim was supplied. When the valve was replaced with one having the correct trim, the desired flow was achieved.

Can a feed line to a scrubber be tied in to an existing process feed line?

An existing line feeds molar excess methanol from the recovered methanol storage tank to a process that uses methanol as a reactant. The piping arrangement is shown in **Figure 31**. Details can be found in the CHEMCAD file called **#8 Original Recovered Methanol Line To Process**.

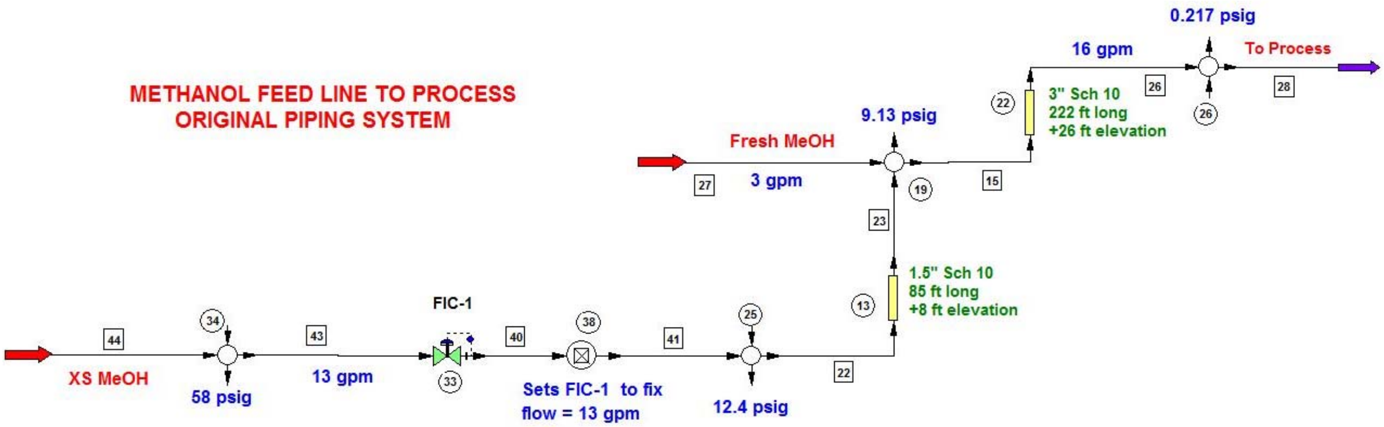


Figure 31 – Flowsheet for recovered methanol line to process problem

Heretofore, the plant has used fresh methanol as the scrubbing fluid for vapor vented to the atmosphere. It has been determined that it is economically advantageous to use recovered methanol instead of fresh as the scrubbing fluid.

The plant would like to tie in a new feed line to the scrubber from the recovered methanol line. The plant suggested tie-in is depicted in **Figure 32**. The filename is **#9 Proposed Plant Piping Tie-In**.

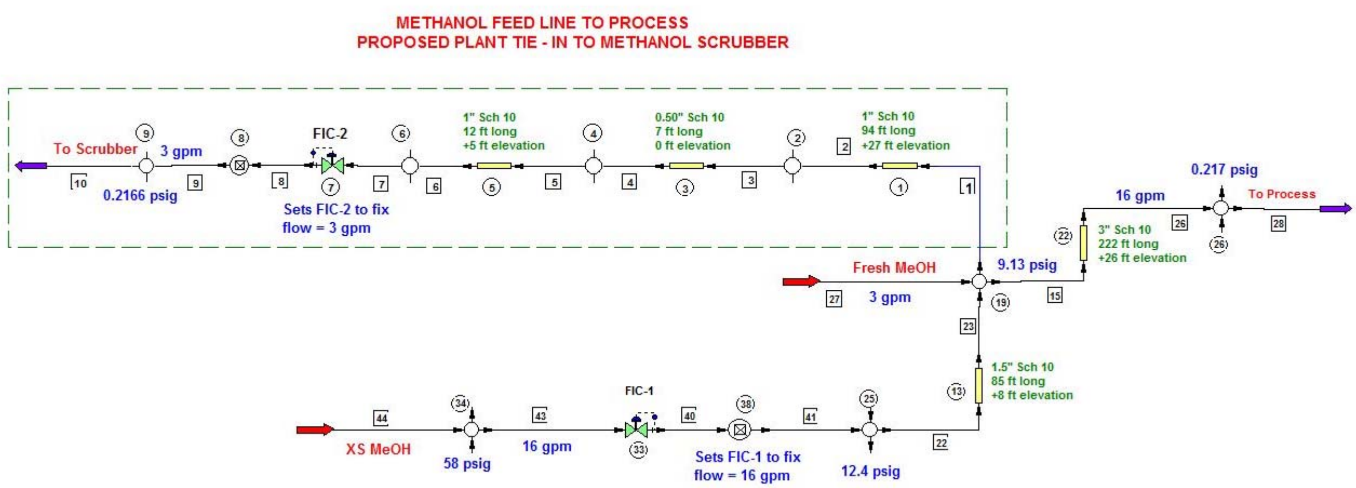


Figure 32 – Flowsheet for proposed plant piping tie-in problem

Before running this simulation, first isolate the piping tie-in and determine the supply pressure needed to feed 3 gpm of methanol to the scrubber. The piping layout is shown in **Figure 33**, and the filename is **#10 Methanol Scrubber Feed Line – Isolated**.

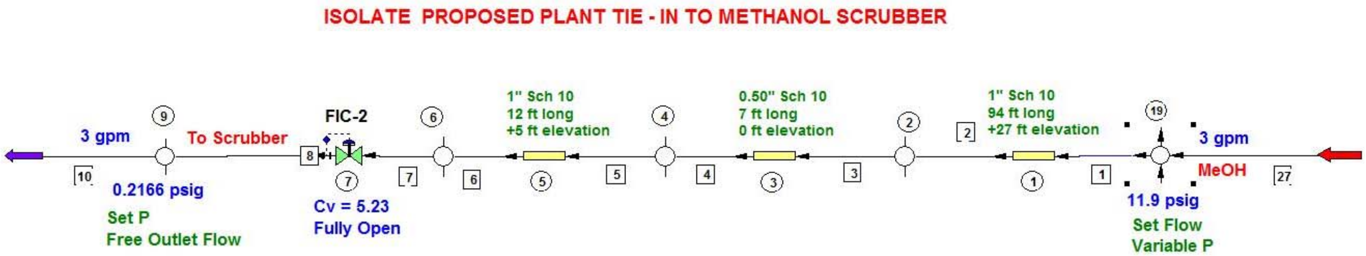


Figure 33 – Flowsheet for isolating the tie-in to the methanol scrubber

When you run this simulation with a fully open control valve, you will see that the minimum supply pressure at node 19 is 11.9 psig. Most of the pressure is required to overcome the elevation increase of the piping.

When you run the simulation callled **#8 Original Recovered Methanol Line To Process**, as you can see from **Figure 31**, the pressure at the proposed tie-in point is only 9.13 psig. Consequently, the chosen tie-in point will not work. If you now run the simulation called **#9 Proposed Plant Piping Tie-In**, you will see that the simulation does not converge; the results show negative pressure in the new line. The required pipe line outlet pressure, fixed at 0.2166 psig, cannot be achieved.

Two solutions were offered. As shown in **Figure 34**, the first relocates the new piping to the scrubber to a tie-in point upstream of control valve FIC-1. This creates a parallel flow line and requires additional piping as shown in the figure. The filename is **#11 Relocate Proposed Plant Piping Tie-In**.

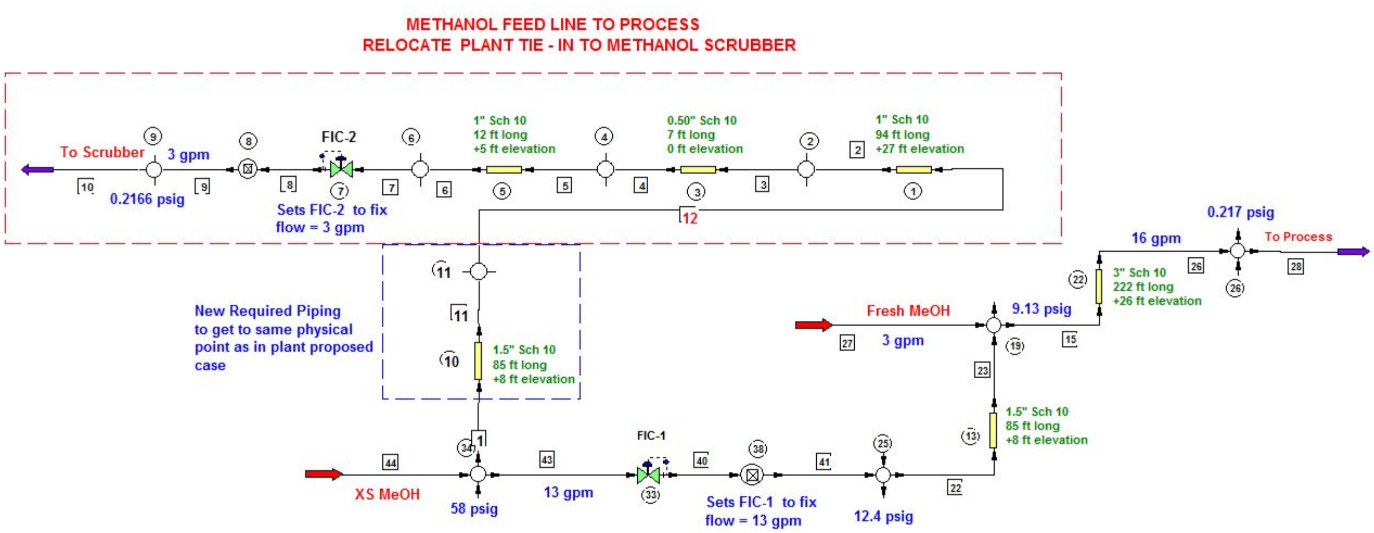


Figure 34 – Flowsheet showing relocation of new piping to a point upstream of control valve FIC-1

In this case, there is more than enough pressure at node 34 to overcome the change in piping elevation and supply 3 gpm of methanol to the scrubber. Note that most of the pressure drop in the line is taken across the control valve.

The second approach is to add a booster pump to the scrubber feed line. This is shown in **Figure 35**. The filename is **#12 Proposed Plant Piping Tie-In Add Pump**. The booster pump is added to raise the supply pressure to 20 psig. The plant chose this option, rather than the additional piping, since the cost was lower.

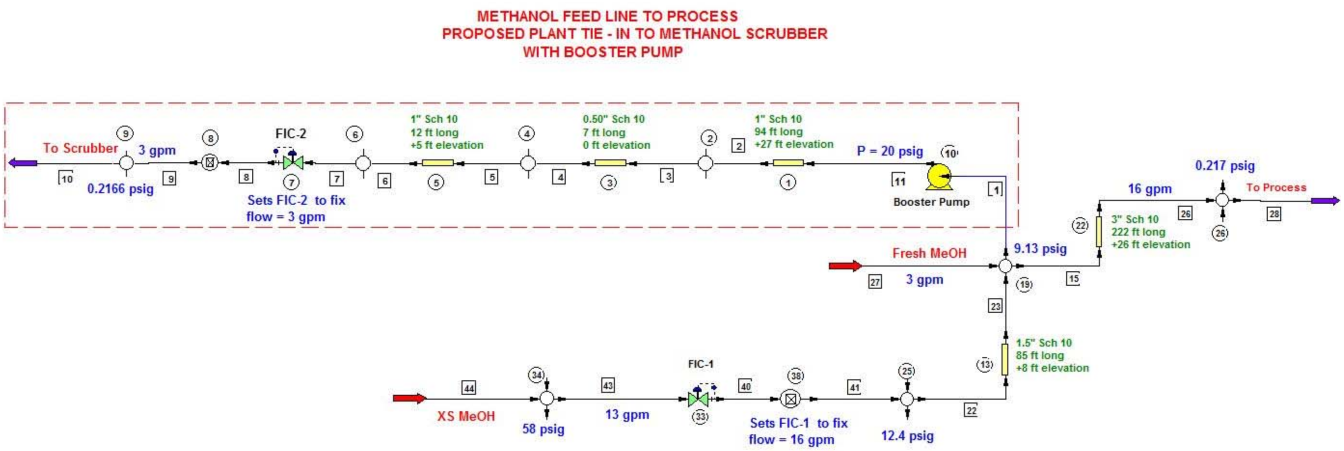


Figure 35 – Flowsheet showing addition of a booster pump to the scrubber feed line

In both this example and the previous one, CHEMCAD provided a powerful tool for analyzing the existing piping layouts and for simulating alternatives for corrective action. In each case, the analysis led to a successful modification of the piping system so that plant objectives could be met.

Summary

Part 1 of this paper explained how the various CHEMCAD UnitOps that relate to piping analysis can be configured to simulate an unbranched piping system. It started with a detailed look at the Pipe UnitOP and various methods for pipe sizing available in CHEMCAD. Results were compared to standard tabulated results for water with excellent agreement.

A pump UnitOP was added to the pipe to determine what flow would be achieved with the corresponding pump curve. The meaning of NPSHA was discussed.

A control valve UnitOP was inserted into the simulation to demonstrate how it could be used to achieve a desired flow rate. Important considerations for valve selection were discussed. It was shown how a restriction orifice can be added to the pipe line. The effect on valve position to maintain the desired flow rate was demonstrated.

Part 2 extended the discussion to branched piping systems. It began with discussions on the use of controllers for solving simple divided flow and simple combining flow problems. These piping configurations were then combined into a simple network. Again it was shown how controllers can be used to simulate this system.

As the complexity of such systems increases, as in a cooling tower piping network, it becomes increasingly difficult to properly locate the controllers and determine the correct settings for an easy solution. To overcome these difficulties, the use of a nodal solution approach was introduced. Nodal positioning and settings were discussed for a single pipe. Guidelines for the use of nodes in complex networks were provided. The simple network problem previously solved with controllers was solved using nodes. The solutions were compared and found to be identical.

Two actual plant piping problems were then presented. It was shown how CHEMCAD was used to analyze them and to determine design modifications that resulted in meeting plant objectives.

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