## Process Modelling, Simulation and Control for Chemical Engineers. Solved problems. Chapter 7: Conventional control systems and hardware: Part II.

This document contains my own solutions to the problems proposed at the end of each chapter of the book "Process Modelling, Simulation and Control for Chemical Engineers" Second Edition, by William L. Luyben. As such, I can't guarantee that the proposed solutions are free from errors. Think about them as a starting point for developing or as a means of checking your own solutions. Any comments or corrections will be appreciated. Contact me at francisco.angel.rod@gmail.com
The computer programs developed for this chapter (Python) are available at:
https://www.dropbox.com/sh/q0y3s1cirukjqgy/AABceRnO9LrAO-R9Cv84zBBXa?dl=0

## Problem 15

Liquid (sp gr = 1) is pumped from a tank at atmospheric pressure through a heat exchanger and a control valve into a process vessel held at 100 psig pressure. The system is designed for a maximum flow rate of 400 gpm. At this maximum flow rate the pressure drop across the heat exchanger is 50 psi.
A centrifugal pump is used with a performance curve that can be approximated by the relationship:

$$\Delta P_p = 198.33 - 1.458 * 10^{-4} F^2$$

where $\Delta P_p$: pump head in psi, $F$: flow rate in gpm. The control valve has linear trim.

(a) Calculate the fraction that the control valve is open when the throughput is reduced to 200 gpm by pinching down on the control valve.

(b) An orifice-plate/differential pressure transmitter is used for flow measurement. If the maximum full-scale flow reading is 400 gpm, what will the output signal from the electronic flow transmitter be when the flow rate is reduced to 150 gpm?

## Solution

(a) P: Pump, CV: Control valve:

$$\begin{aligned}
\Delta P_P(400[gpm]) &= 175[psi] \\
\Delta P_{CV}(400[gpm]) &= 175 - 50 - 100 = 25[psi] \\
C_v &= 400/\sqrt{25} = 80 \\
\Delta P_P(200[gpm]) &= 192[psi] \\
\Delta P_{CV}(200[gpm]) &= 192 - 50(200/400)^2 - 100 = 79.5[psi] \\
x(200[gpm]) &= 200/(80\sqrt{79.5}) = 0.28
\end{aligned}$$

(b)

$$FT = 4 + 16 * 150/400 = 10[mA]$$

## Problem 16

Design liquid level control systems for the base of a distillation column and for the vaporizer shown in Figure 1. Steam flow to the vaporizer is held constant and cannot be used to control level. Liquid feed to the vaporizer can come from the column and/or from the surge tank. Liquid from the column can go to the vaporizer and/or to the surge tank.
Since the liquid must be cooled if it is send to the surge tank and then reheated in the vaporizer, there is an energy cost penalty associated with sending more material to the surge tank than is absolutely necessary. Your level control system should therefore hold both levels and also minimize the amount of material sent to the surge tank. (**Hint**: One way to accomplish this is to make sure that the valves in the lines to and from the surge tank cannot be opened simultaneously.)

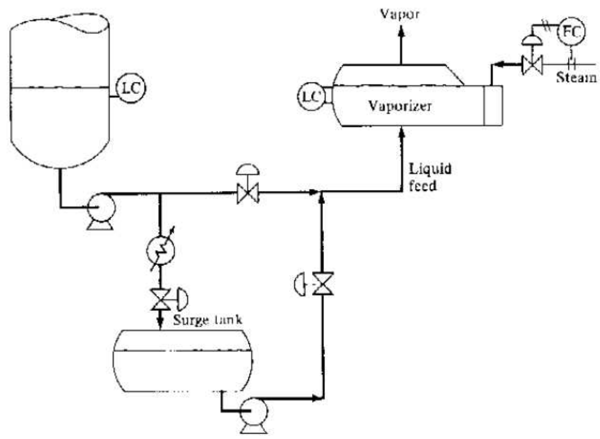


Figure 1: Distillation column base level control.

## Solution

The proposed control scheme consists of controlling vaporizer level using control valves V1 and V2 (Figure 2), V1 opens only when the level on the vaporizer is above set point, whereas valve V2 opens when the level on the vaporizer is below set point. The level of the base of the column is controled using V3. Using this scheme, liquid will be bypassed to the surge tank only when the vaporizer level is above the set point.

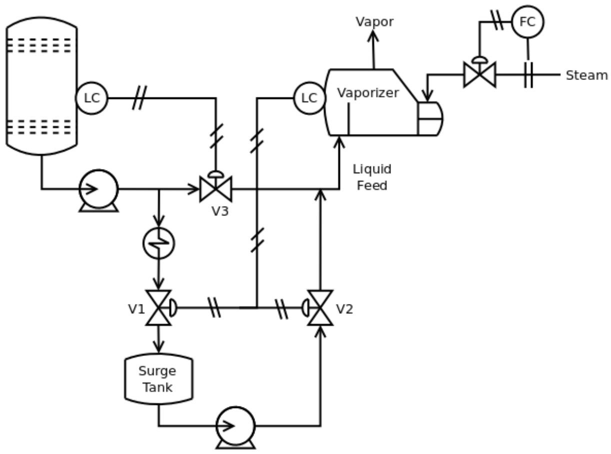


Figure 2: Proposed control scheme.

## Problem 17

A chemical reactor is cooled by a circulating oil system as sketched in Figure 3. Oil is circulated through a water cooled heat exchanger and through control valve $V_1$. A portion of the oil stream can be bypassed around the heat exchanger through control valve $V_2$. The system is to be designed so that at design conditions:

- The oil flow rate through the heat exchanger is 50 gpm (sp gr = 1) with a 10 psi pressure drop across the heat exchanger and with $V_1$ control valve 25 percent open.
- The oil flow rate through the bypass is 100 gpm with the $V_2$ control valve 50 percent open.

Both control valves have linear trim. The circulating pump has a flat pump curve. A maximum oil flow rate through the heat exchanger of 100 gpm is required.

(a) Specify the action of the two control valves and the two temperature controllers.

(b) Calculate the size of the two control valves and the design pressure drops over the two valves.

(c) How much oil will circulate through the bypass valve if it is wide open and the valve in the heat exchanger loop is shut?

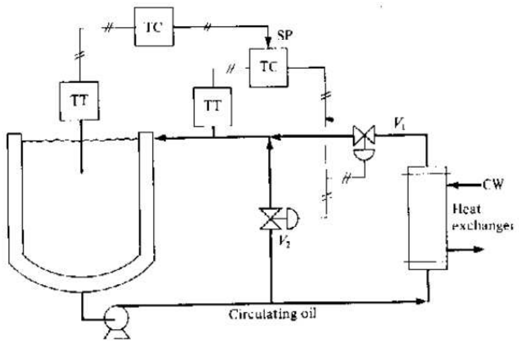


Figure 3: Circulating oil cooling system.

## Solution

(a) In case of failure, we want maximum cooling capacity, so $V_2$ is air to open, and $V_1$ is air to close. When reactor temperature increase, cooling control system set point must decrease, so $TC_R$ is reverse acting. When cooling water temperature increase, the control signal must decrease (to close $V_2$ and open $V_1$), so $TC_{CW}$ is reverse acting.

(b) The design equations for $V_1$ and $V_2$ are:

$$\begin{aligned} 50 &= 0.25C_{v,1}\sqrt{\Delta P_T - 10} \\ 100 &= C_{v,1}\sqrt{\Delta P_T - 10 * 2^2} \\ 100 &= 0.50C_{v,2}\sqrt{\Delta P_T} \end{aligned}$$

The results are: $C_{v,1} = 31.6$, $\Delta P = 50[psi]$ and $C_{v,2} = 28.3$.

(c) The flow is calculated from:

$$F = 28.3\sqrt{50} = 200[gpm]$$

## Problem 18

The formula for the flow of saturated steam through a control valve is:

$$W = 2.1C_v f_x \sqrt{(P_1 + P_2)(P_1 - P_2)}$$

where W: $lb_m/h$ steam, $P_1$: upstream pressure (psia), $P_2$: downstream pressure (psia).
The temperature of the steam cooled reactor shown in Figure 4 is 285 °F. The heat that must be transferred from the reactor into the steam generation system is $25 * 10^6$ BTU/h. The overall heat transfer coefficient for the cooling coils is 300 $BTU/hft^2\,°F$. The steam discharges into a 25 psia steam header. The enthalpy difference between saturated steam and liquid condensate is 1000 $BTU/lb_m$. The vapor pressure of water can be approximated over this range of pressure by a straight line.

$$T(°F) = 195 + 1.8P(psia)$$

Design two systems, one where the steam drum pressure is 40 psia at design and another where it is 30 psia.

(a) Calculate the area of the cooling coils for each case.

(b) Calculate the $C_v$ value of the steam valve in each case, assuming that the valve is half open at design conditions: $f_x = 0.5$.

(c) What is the maximum heat removal capacity of the system for each case?

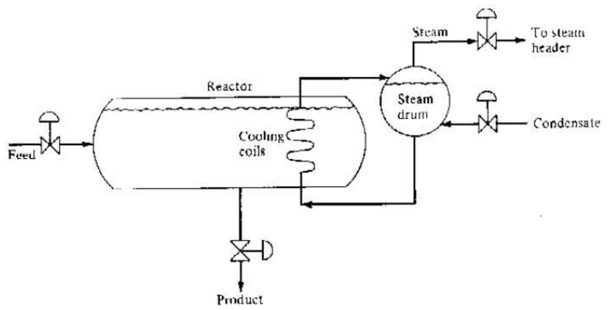


Figure 4: Circulating oil cooling system.

## Solution

(a) The steam drum temperature in each case are:

$$T(P = 40[psia]) = 195 + 1.8 * 40 = 267\,^{\circ}F$$
$$T(P = 30[psia]) = 195 + 1.8 * 30 = 249\,^{\circ}F$$

The required area of cooling coils are:

$$A(P = 40[psia]) = 25 * 10^6/(300(285 - 267)) = 4630[ft^2]$$
$$A(P = 30[psia]) = 25 * 10^6/(300(285 - 249)) = 2315[ft^2]$$

(b) The steam flow is:

$$W = \frac{Q}{\lambda} = \frac{25 * 10^6[BTU/h]}{1000[BTU/lb_m]} = 25 * 10^3[lb_m/h]$$

The valve coefficients are:

$$C_v(P = 40[psia]) = \frac{25 * 10^3}{2.1 * 0.5\sqrt{(40 + 25)(40 - 25)}} = 762.5$$
$$C_v(P = 30[psia]) = \frac{25 * 10^3}{2.1 * 0.5\sqrt{(30 + 25)(30 - 25)}} = 1435.8$$

(c) The maximum value of steam flow occurs when the valve is completely open, at this condition, the steam drum pressure value must satisfy:

$$2.1C_v\sqrt{(P - 25)(P + 25)} = \frac{Q}{\lambda} = \frac{Ah(T_R - (195 + 1.8P))}{\lambda}$$

The results are: for a steam drum design pressure of 40 psia: maximum heat removal rate: $3.84 * 10^7$ BTU/h, steam drum pressure: 34.6 psia, and steam drum temperature: 257 °F. For a steam drum design pressure of 30 psia: maximum heat removal rate: $2.90 * 10^7$ BTU/h, steam drum pressure: 26.8 psia, and steam drum temperature: 243 °F.

Code(s) used: P18HeatRemoval.py

## Problem 19

Cooling water is pumped through the jacket of a reactor. The pump and the control valve must be designed so that:

(a) The normal cooling water flow rate is 250 gpm.

(b) The maximum emergency rate is 500 gpm.

(c) The valve cannot be less than 10 percent open when the flow rate is 100 gpm.

Pressure drop through the jacket is 10 psi at design. The pump curve has a linear slope of -0.1 psi/gpm.
Calculate the $C_v$ value of the control valve, the pump head at design rate, the size of the motor required to drive the pump, the fraction that the valve is open at design, and the pressure drop over the valve at design rate.

## Solution

(a) The following conditions must be satisfied ($\Delta P_{T,D}$: Total pressure drop at design conditions):

$$500 = C_v \sqrt{\Delta P_{T,D} - 0.1(500 - 250) - 10(500/250)^2} \tag{1}$$

$$0.1 \leq 100/\left(C_v \sqrt{\Delta P_{T,D} - 0.1(100 - 250) - 10(100/250)^2}\right) \tag{2}$$

Replacing $C_v$ from the first equation into the second expression gives $\Delta P_{T,D} \geq 91.1$. A value of 92 [psi] is used, from (1) a value of $C_V = 96.2$ is calculated. The power required is:

$$\begin{aligned}
P &= q\Delta P \\
P &= 250 * 0.003785 * 92 * 6895/60 = 10004[watt] \\
P &= 10004[watt] * \frac{1}{746}\left[\frac{hp}{watt}\right] = 13.4[hp]
\end{aligned}$$

The valve pressure drop at design is $\Delta P_{v,D} = 92 - 10 = 82[psi]$, the fraction of valve open is:

$$x = 250/(96.2\sqrt{82}) = 0.287$$

## Problem 20

A $C_2$ splitter column uses vapor recompression (Figure 5). Because of the low temperature required to stay below the critical temperatures of ethylene and ethane, the auxiliary condenser must be cooled by a propane refrigeration system.

(a) Specify the action of all control valves.

(b) Sketch a control concept diagram which accomplishes the following objectives:

  (i) Level in the propane vaporizer is controlled by the liquid propane flow from the refrigeration surge drum.

  (ii) Column pressure is controlled by adjusting the speed of the column compressor through a steam flow control speed control pressure control cascade system.

  (iii) Reflux is flow controlled. Reflux drum level sets distillate flow. Base level sets bottoms flow.

  (iv) Column tray 10 temperature is controlled by adjusting the pressure in the propane vaporizer, which is controlled by refrigeration compressor speed.

  (v) High column pressure opens the valve to the flare.

(c) How effective do you think the column temperature control will be? Suggest an improved control system which still achieves minimum energy consumption in the two compressors.

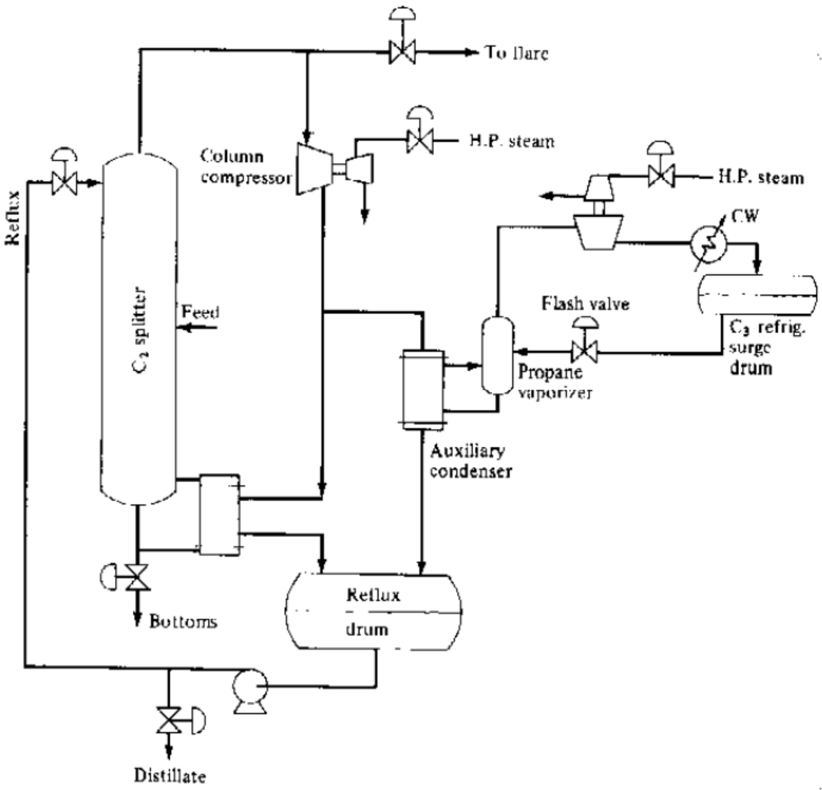


Figure 5: $C_2$ splitter column.

## Solution

(a) High pressure steam valves are air to open. Column contents are evacuated by specifying both flare and bottom valves air to close. Reflux drum contents are keep in place by using both distillate and reflux valves air to open. Refrigeration system surge drum contents are keep in place by an air to open flash valve.

(b) The proposed control diagram is shown in Figure 6.

(c) Temperature control is slow, because when a change in propane vaporizer pressure is required to adjust temperature, the entire refrigeration loop must stabilize first, from compressor to surge tank to vaporizer. A new control scheme is proposed and shown in Figure 7. Temperature is controlled by varying the proportion of flow between auxiliary condenser and splitter reboiler. Also, flow in the refrigeration loop is controlled to return to a design value, by varying propane vaporizer pressure. This way, faster temperature control is achieved, isolating the slower dynamics of the refrigeration loop.

## Problem 21

Hot oil from the base of a distillation column is used to reboil two other distillation columns that operate at lower temperatures (Figure 8). The design flow rates through reboilers 1 and 2 are 100 and 150 gpm, respectively. At these flow rates, the pressure drops through the reboilers are 20 and 30 psi. The hot oil pump has a flat pump curve. Size the two control valves and the pump so that:

(a) Maximum flow rates through each reboiler can be at least twice design.

(b) At minimum turndown rates where only half the design flow rates are required, the control valves are no less than 10 percent open.

What is the fraction of valve opening for each valve at design rates?

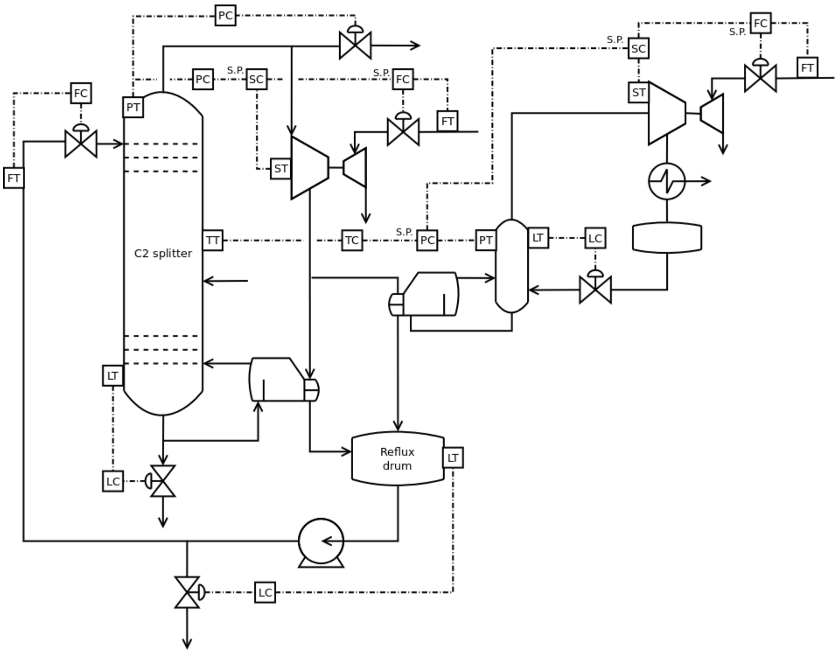


Figure 6: $C_2$ splitter column, proposed control.

## Solution

The reboiler 1 control valve restrictions are:

$$C_{v,1}\sqrt{\Delta P - 20 * 2^2} \geq 200 \quad (1)$$

$$0.10 * C_{v,1}\sqrt{\Delta P - 20 * 0.5^2} \leq 50 \quad (2)$$

So, the value of $C_{v,1}$ must satisfy:

$$\frac{200}{\sqrt{\Delta P - 20 * 2^2}} \leq C_{v,1} \leq \frac{500}{\sqrt{\Delta P - 20 * 0.5^2}}$$

The $\Delta P$ operating region is defined by:

$$\frac{200}{\sqrt{\Delta P - 20 * 2^2}} \leq \frac{500}{\sqrt{\Delta P - 20 * 0.5^2}}$$

and is plotted in Figure 9.
The region corresponds to $\Delta P \geq 94.3$, an equivalent analysis for reboiler 2 control valve gives: $\Delta P \geq 141.4$. The value $\Delta P = 142$ is used to satisfy both boiler restrictions, replacing it in equations (1) and (2) gives: $25.4 \leq C_{v,1} \leq 42.7$. An average value of 34.0 is used. Replacing $\Delta P = 142$ in reboiler 2 control valve restrictions gives: $64.0 \leq C_{v,2} \leq 64.7$. An average value of 64.4 is used. Finally, the trim position at the required values of flow for both control valves are evaluated to check that the restrictions are satisfied:

$$x_{1,Max} = 200/(34.0\sqrt{142 - 20 * 2^2}) = 0.747 \leq 1$$
$$x_{1,Min} = 50/(34.0\sqrt{142 - 20 * 0.5^2}) = 0.126 \geq 0.1$$
$$x_{2,Max} = 300/(64.4\sqrt{142 - 30 * 2^2}) = 0.993 \leq 1$$
$$x_{2,Min} = 75/(64.4\sqrt{142 - 30 * 0.5^2}) = 0.100 \geq 0.1$$

At design, the trim positions are $x_1 = 0.266$ and $x_2 = 0.220$.
Code(s) used: P21PlotRegion.py

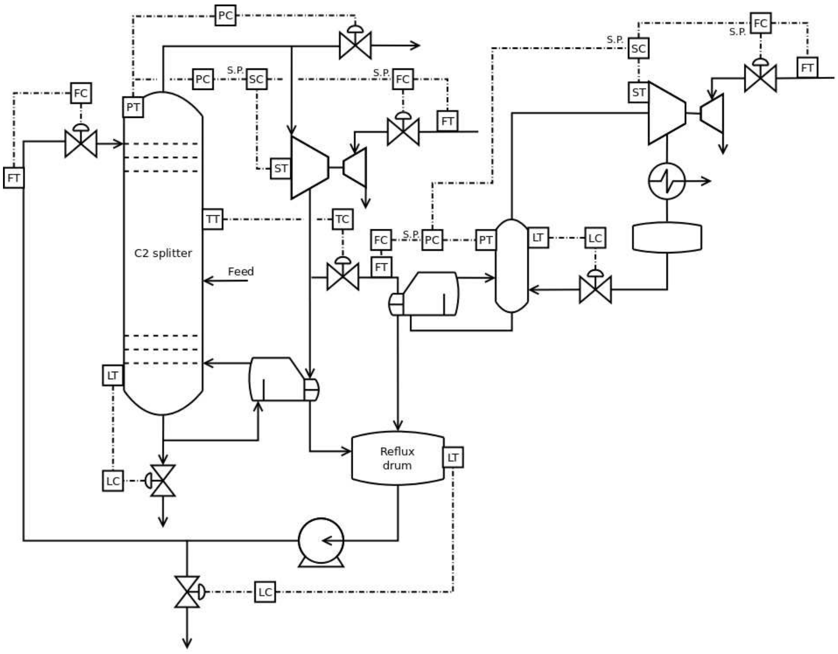


Figure 7: $C_2$ splitter column, improved control.

## Problem 22

A reactor is cooled by circulating liquid through a heat exchanger that produces low pressure (10 psig) steam (Figure 10). This steam is then split between a compressor and a turbine. The portion that goes through the turbine drives the compressor. The portion through the compressor is used by 50 psig steam users. 100 psig steam can also be used in the turbine to provide power required beyond that available in the 10 psig steam.
Sketch a control concept diagram that includes all valve actions and the following control strategies:

(a) Reactor temperature is controlled by changing the setpoint of the turbine speed controller.

(b) Turbine speed is controlled by two split range valves, one on the 10 psig inlet to the turbine and the other on the 100 psig steam that can also be used to drive the turbine. Your instrumentation system should be designed so that the valve on the 10 psig steam is wide open before any 100 psig steam is used.

(c) Liquid circulation from the reactor to the heat exchanger is flow controlled.

(d) Condensate level in the condensate drum is controlled by manipulating BFW (boiler feed water).

(e) Condensate makeup to the steam drum is ratioed to the 10 psig steam flow rate from the steam drum. This ratio is then reset by the steam drum level controller.

(f) Pressure in the 50 psig steam header is controlled by adding 100 psig steam.

(g) A high pressure controller opens the vent valve on the 10 psig header when the pressure in the 10 psig header is too high.

(h) Compressor surge is prevented by using a low flow controller that opens the valve in the spill back line from compressor discharge to compressor suction.

## Solution

The diagram is shown in Figure 11.

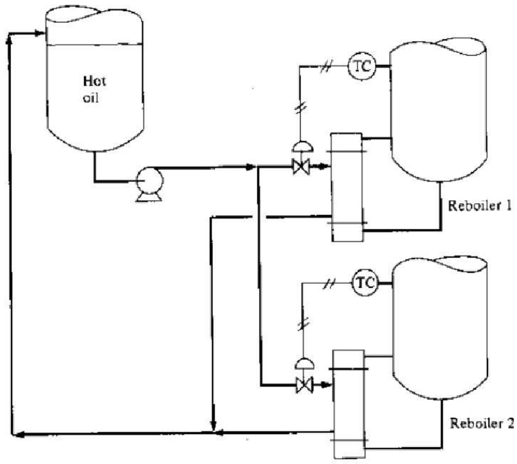


Figure 8: Distillation column base.

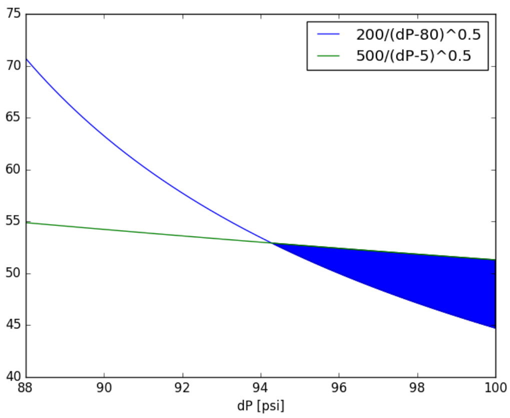


Figure 9: $\Delta P$ operating region for reboiler 1 control valve.

## Problem 23

Water is pumped from an atmospheric tank, through a heat exchanger and a control valve, into a pressurized vessel. The operating pressure in the vessel can vary from 200 to 300 psig, but is 250 psig at design. Design flow rate is 100 gpm with a 20 psi pressure drop through the heat exchanger. Maximum flow rate is 150 gpm. Minimum flow rate is 25 gpm. A centrifugal pump is used which has a straight line pump curve with a slope of -0.1 psi/gpm.
Design the control valve and pump so that both the maximum and minimum flow rates can be handled with the valve never less than 10 percent open.

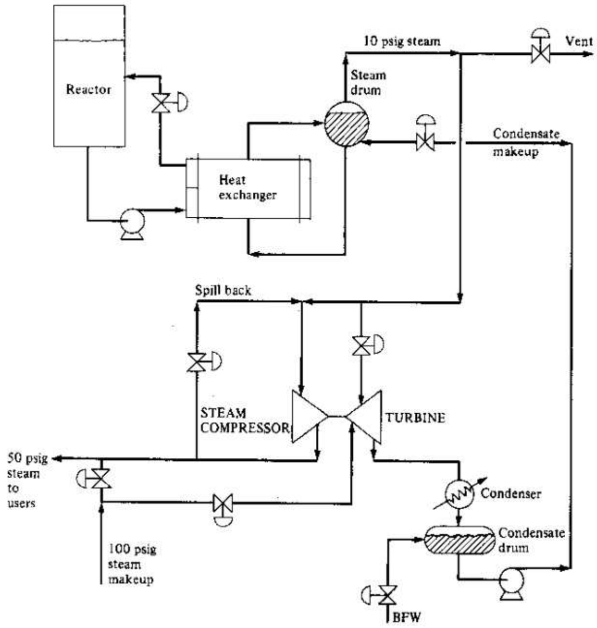


Figure 10: Reactor cooling system.

## Solution

The valve coefficient and total pressure drop at design ($\Delta P$) must satisfy:

$$\frac{150}{C_v\sqrt{\Delta P - 0.1(150-100) - 20(150/100)^2 - 200}} = \frac{150}{C_v\sqrt{\Delta P - 250}} \leq 1$$

$$\frac{25}{C_v\sqrt{\Delta P - 0.1(25-100) - 20(25/100)^2 - 200}} = \frac{25}{C_v\sqrt{\Delta P - 193.75}} \geq 0.1$$

$$\frac{150}{C_v\sqrt{\Delta P - 0.1(150-100) - 20(150/100)^2 - 300}} = \frac{150}{C_v\sqrt{\Delta P - 350}} \leq 1$$

$$\frac{25}{C_v\sqrt{\Delta P - 0.1(25-100) - 20(25/100)^2 - 300}} = \frac{25}{C_v\sqrt{\Delta P - 293.75}} \geq 0.1$$

Considering that:

$$\frac{150}{\sqrt{\Delta P - 250}} < \frac{150}{\sqrt{\Delta P - 350}}$$

And:

$$\frac{25}{\sqrt{\Delta P - 193.75}} < \frac{25}{\sqrt{\Delta P - 293.75}}$$

All four restrictions are satisfied if:

$$\frac{25}{C_v\sqrt{\Delta P - 193.75}} \geq 0.1 \tag{1}$$

$$\frac{150}{C_v\sqrt{\Delta P - 350}} \leq 1 \tag{2}$$

Combining equations (1) and (2) we get:

$$\frac{250}{\sqrt{\Delta P - 193.75}} \leq C_v \leq \frac{150}{\sqrt{\Delta P - 350}} \tag{3}$$

The $\Delta P$ operating region is defined by:

$$\frac{250}{\sqrt{\Delta P - 193.75}} \leq \frac{150}{\sqrt{\Delta P - 350}}$$

$$\Delta P \geq 437.9$$

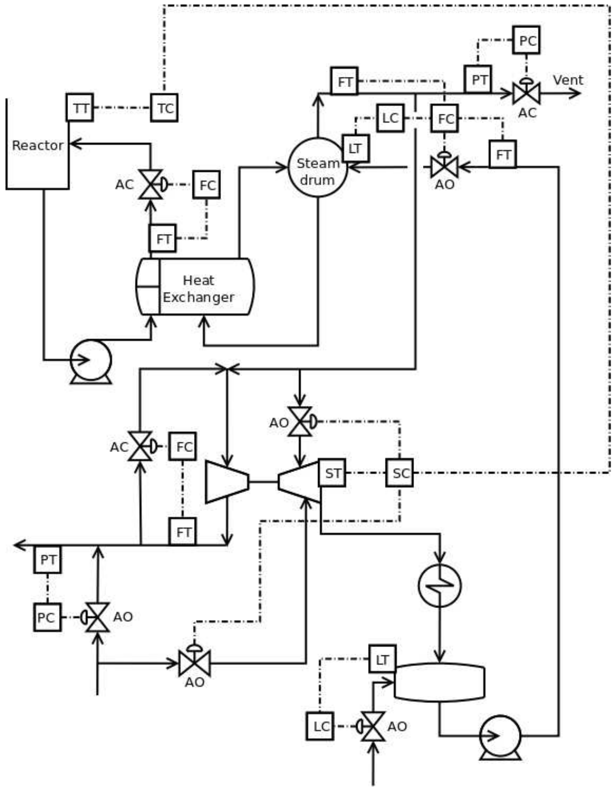


Figure 11: Reactor cooling system control diagram.

A value of $\Delta P = 439$[psi] is used, replacing it in equation (3) gives $15.90 \le C_v \le 15.96$, an average value of $C_v = 15.93$ is used. The valve position values at different conditions are (P: Pressurized vessel pressure):

$$x(F=150, P=200) = 0.685 \le 1$$
$$x(F=25, P=200) = 0.100 \ge 0.1$$
$$x(F=150, P=300) = 0.998 \le 1$$
$$x(F=25, P=300) = 0.130 \ge 0.1$$

## Problem 24

Reactant liquid is pumped into a batch reactor at a variable rate. The reactor pressure also varies during the batch cycle. Specify the control valve size and the centrifugal pump head required. Assume a flat pump curve.

The initial flow rate into the reactor is 20 gpm (sp gr = 1). It is decreased linearly with time down to 5 gpm at 5 hours into the batch cycle. The initial reactor pressure is 50 psig. It increases linearly with time up to 350 psig at 5 hours. The reactant liquid comes from a tank at atmospheric pressure.

## Solution

$C_v$ and $\Delta P$ must be chosen so that the valve stem position $x(t)$ remains between 0.1 and 1 all the time:

$$0.1 \le x(t) = \frac{20 - 3t}{C_v \sqrt{\Delta P - (50 + 60t)}} \le 1$$

This can be accomplished by selecting $\Delta P$ and $C_v$ so that the maximum value of $x(t)$ be smaller than 1, and the minimum value of $x(t)$ be greater than 0.1.

**Interior points**
The critical points of $x(t)$ correspond to a first derivative equal to zero:

$$\begin{aligned} 0 &= \frac{30(20-3t)}{\Delta P-(50+60t)} - 3 \\ \Delta P &= 250+30t \end{aligned}$$

Because $t$ is in the interval [0,5], a critical point will exist if $250 \leq \Delta P \leq 400$ ($\Delta P$ must be greater than 350 in any case). The second derivative of $x(t)$ is:

$$x''(t) = \frac{1}{(\Delta P-(50+60t))^{3/2}} \left( \frac{2700(20-3t)}{\Delta P-(50+60t)} - 180 \right)$$

Evaluating the second derivative with the condition corresponding to the critical point gives:

$$x''(\Delta P = 250+30t) = \frac{1}{(200-30t)^{3/2}} \left( \frac{18000-2700t}{200-30t} \right)$$

Both terms are positive values for t in [0,5], so we conclude that the critical point corresponds to a minimum.

**Interval boundaries**

We continue by analizing the values of $x(t)$ at the extremes of the time interval, we require:

$$\begin{aligned} 0.1 \leq x(0) = 20/(C_v\sqrt{\Delta P-50}) \leq 1 \\ 0.1 \leq x(5) = 5/(C_v\sqrt{\Delta P-350}) \leq 1 \end{aligned}$$

First we determine under what conditions $x(0) < x(5)$:

$$\begin{aligned} 20/(C_v\sqrt{\Delta P-50}) &< 5/(C_v\sqrt{\Delta P-350}) \\ 16 &< (\Delta P-50)/(\Delta P-350) \\ \Delta P &< 370 \end{aligned}$$

Conversely, $x(0) > x(5)$ if $\Delta P > 370$.

**Case** $x(0) < x(5)$

Assuming $\Delta P < 370$, we require:

$$\begin{aligned} 0.1 \leq 20/(C_v\sqrt{\Delta P-50}) \\ 5/(C_v\sqrt{\Delta P-350}) \leq 1 \end{aligned}$$

Combining the previous expressions, we get:

$$5/\sqrt{\Delta P-350} \leq C_v \leq 200/\sqrt{\Delta P-50} \tag{1}$$

So, the operating region for $\Delta P$ is defined by:

$$\begin{aligned} 5/\sqrt{\Delta P-350} &\leq 200/\sqrt{\Delta P-50} \\ \Delta P &\geq 350.19 \end{aligned}$$

A valid solution exits then for $\Delta P$ in [350.19,370[.

**Case** $x(0) > x(5)$

An equivalent analysis for $\Delta P > 370$ allows to conclude that the operating region for $\Delta P$ is $\Delta P$ in $[370, \infty[$.

**Solution**

A value of $\Delta P = 352$ [psi] is used (the smaller feasible value), replacing in equation (1) gives:

$$3.54 \leq C_v \leq 11.50$$

On the other hand, the critical point corresponds to $\Delta P = 250 + 30t$ or t=3.4, because it is a minimun, we require:

$$0.1 \leq x(3.4) = 9.8/(C_v\sqrt{98})$$
$$C_v \leq 9.9$$

We use the average value $C_v = 6.72$ (0.5*(9.9+3.54)). The valve position versus time is shown in Figure 12.

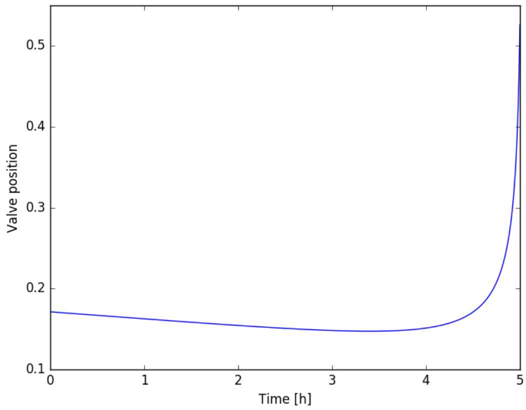


Figure 12: Valve position for $\Delta P = 352[psi]$, $C_v = 6.72$.

Code(s) used: P24MakeFigure.py

## Problem 25

Water is pumped from an atmospheric tank into a vessel at 50 psig through a heat exchanger (Figure 13). There is a bypass around the heat exchanger. The pump has a flat curve. The heat exchanger pressure drop is 30 psi with 200 gpm of flow through it. Size the pump and the two control valves so that:

(a) 200 gpm can be bypassed.

(b) Flow through the heat exchanger can be varied from 75 to 300 gpm.

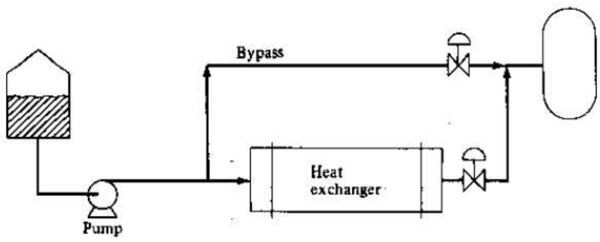


Figure 13: Bypass parallel to heat exchanger.

## Solution

Valve coefficients and total pressure drop must satisfy ($V_1$: Valve in series with heat exchanger, $V_2$: Bypass valve):

$$75 = 0.1C_{v,1}\sqrt{\Delta P - 30(75/200)^2}$$
$$300 = C_{v,1}\sqrt{\Delta P - 30(300/200)^2}$$
$$200 = C_{v,2}\sqrt{\Delta P}$$

The results are: $\Delta P = 79.6$[psi], $C_{v,1} = 86.4$ and $C_{v,2} = 22.4$.

## Problem 26

An engineer from Catasthropic Chemical Company has designed a system in which a positive-displacement pump is used to pump water from an atmospheric tank into a pressurized tank operating at 150 psig. A control valve is installed between the pump discharge and the pressurized tank.
With the pump running at a constant speed and stroke lenght, 350 gpm of water is pumped when the control valve is wide open and the pump discharge pressure is 200 psig.
If the control valve is pinched back to 50 percent open, what will be the flow rate of water and the pump discharge pressure?

## Solution

$$C_v = 350/(\sqrt{200-150}) = 49.5$$

Because the pump is of positive displacement type, the flow remains constant at 350 gpm. When the valve is 50 percent open, the pressure drop over the valve is:

$$\Delta P_v = (350/(0.5 * 49.5))^2 = 200[psi]$$

The pump discharge pressure is then: 200+150=350[psi].

## Problem 27

Hot oil from a tank at 400 °F is pumped through a heat exchanger to vaporize a liquid boiling at 200 °F (Figure 14). A control valve is used to set the flow rate of oil through the loop. Assume the pump has a flat pump curve. The pressure drop over the control valve is 30 psi and the pressure drop over the heat exchanger is 35 psi under the following normal conditions: heat transferred in heat exchanger: $17 * 10^6$ BTU/hr, hot oil inlet temperature: 400 °F, hot oil exit temperature: 350 °F, fraction valve open: 0.8.
The hot oil gives off sensible heat only (heat capacity=0.5 $BTU/lb_m\,^\circ F$, density: 4.58 $lb_m/gal$). The heat transfer area in the exchanger is 652 $ft^2$. Assume the temperature on the tube side of the heat exchanger stays constant at 200 °F and the inlet hot oil temperature stays constant at 400 °F. A log mean temperature difference must be used.
Assuming the heat transfer coefficient does not change with flow rate, what will the valve opening be when the heat transfer rate in the heat exchanger is half the normal design value?

## Solution

The log mean temperature difference at design conditions is:

$$LMTD = (200 - 150)/ln(200/150) = 173.8\,^\circ F$$

At constant heat transfer coefficient, the heat transfer rate decreases to half the design value when the LMTD is halved.

$$LMTD = (200 - \Delta T_C)/ln(200/\Delta T_C) = 173.8/2$$

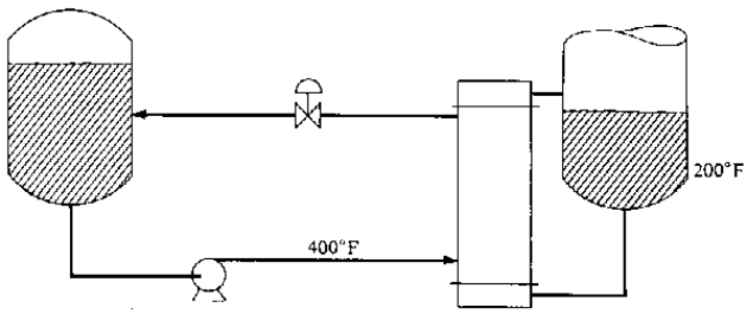


Figure 14: Hot oil boiler.

The equation is solved using the Newthon method, giving $\Delta T_C = 27.5\,°\mathrm{F}$, equivalent to an outlet temperature of 227.5 °F. The flow is:

$$F = 17 * 10^6/(2 * 0.5 * (400 - 227.5)) = 98550[lb_m/h]$$
$$Q = 359[gpm]$$

At design conditions the flow is:

$$F = 17 * 10^6/(0.5 * (400 - 350)) = 680000[lb_m/h]$$
$$Q = 2475[gpm]$$

The valve coefficient is:

$$C_v = 2475/(0.8\sqrt{30/0.55}) = 419$$

Therefore, when the heat transfer rate is halved, the valve position is:

$$x = 359/(419\sqrt{(65 - 35(359/2475)^2)/0.55}) = 0.079$$

Code(s) used: P27NewthonMethod.py

## Problem 28

A control valve/pump system proposed by Connell (Chemical Engineering, September 28, 1987, p. 123) consists of a centrifugal pump, several heat exchangers, a furnace, an orifice, and a control valve. Liquid is pumped through this circuit and up into a column that operates at 20 psig. Because the line running up the column is full of liquid, there is a hydraulic pressure differential between the base of the column and the point of entry into the column of 15 psi.
The pump suction pressure is constant at 10 psig. The design flow rate is 500 gpm. At this flow rate the pressure drop over the flow orifice is 2 psi, through the piping is 30 psi, over three heat exchangers is 32 psi, and over the furnace is 60 psi. Assume a flat pump curve and a specific gravity of 1.
Connell recommends that a control valve be used that takes 76 psi pressure drop at design flow rate. The system should be able to increase flow to 120 percent of design.

(a) Calculate the pressure drop over the valve at the maximum flow rate.

(b) Calculate pump discharge pressure and the control valve $C_v$.

(c) Calculate the fraction that the valve is open at design.

(d) If turndown is limited to a valve opening of 10 percent, what is the minimum flow rate?

## Solution

(a)

$$\Delta P_T = 32 + 60 + 2 + 30 + 76 + 15 + 20 - 10 = 225$$
$$\Delta P_v(F = 600[gpm]) = 225 - 124 * 1.2^2 = 46.4[psi]$$

(b)

$$P_D = 10 + 225 = 235[psi]$$
$$C_v = 1.2 * 500/\sqrt{46.4} = 88.1$$

(c)

$$x_{Design} = 500/(88.1\sqrt{76}) = 0.651$$

(d) The minimum flow rate satisfies the following equation:

$$F = 0.1 * 88.1 * \sqrt{225 - 124(F/500)^2}$$
$$F = 130[gpm]$$

## Conversion Factors

$$1[ft^3] = 7.48[gal]$$
$$1[gal] = 0.003785[m^3]$$
$$1[ft] = 0.3048[m]$$
$$1[psi] = 6895[Pa]$$