Chapter 10

Rev: 12-6-03

10.1

According to Guideline 6, the manipulated variable should have a large effect on the controlled variable. Clearly, it is easier to control a liquid level by manipulating a large exit stream, rather than a small stream. Because $R/D>1$, the reflux flow rate R is the preferred manipulated variable.

10.2

Exit flow rate w_4 has no effect on x_3 or x_4 because it does not change the relative amounts of materials that are blended. The bypass fraction f has a dynamic effect on x_4 but no steady-state effect because it also does not change the relative amounts of materials that are blended. Thus, w_2 is the best choice.

10.3

Both the steady-state and dynamic behavior needs to be considered. From a steady-state perspective, the reflux stream temperature T_R would be a poor choice because it is insensitive to changes in x_D, due to the small nominal value of 5 ppm. For example, even a 100% change from 5 to 10 ppm would result in a negligible change in T_R. Similarly, the temperature of the top tray would be a poor choice. An intermediate tray temperature would be more sensitive to changes in the tray composition but may not be representative of x_D. Ideally, the tray location should be selected to be the highest tray in the column that still has the desired degree of sensitivity to composition changes.

The choice of an intermediate tray temperature offers the advantage of early detection of feed disturbances and disturbances that originate in the stripping (bottom) section of the column. However, it would be slow to respond to disturbances originating in the condenser or in the reflux drum. But on balance, an intermediate tray temperature is the best choice.

10.4

For the flooded condenser in Fig. E10.4, the area available for heat transfer changes as the liquid level changes. Consequently, pressure control is easier when the liquid level is low and more difficult when the level is high. By contrast, for the conventional process design in Fig. 10.5, the liquid level has a very small effect on the pressure control loop. Thus, the flooded condenser is more difficult to control because the level and pressure control loops are more interacting than they are for the conventional process design in Fig. 10.5.

10.5

(a) The larger the tank, the more effective it will be in "damping out" disturbances in the reactor exit stream. A large tank capacity also provides a large feed inventory for the distillation column, which is desirable for periods where the reactor is shut down. Thus a large tank is preferred from a process control perspective. However a large tank has a high capital cost, so a small tank is appealing from a steady-state, design perspective. Thus, the choice of the storage tank size involves a tradeoff of control and design objectives.

(b) After a set-point change in reactor exit composition occurs, it would be desirable to have the exit compositions for both the reactor and the storage tank change to the new value as soon as possible. But the concentration in the storage tank will change gradually due to its liquid inventory. The time constant for the storage tank is proportional to the mass of liquid in the tank (cf. blending system models in Chapters 2 and 4). Thus, a large storage tank will result in sluggish responses in its exit composition, which is not desirable when frequent set-point changes are required. In this situation, the storage tank size should be smaller than for case (a).

10.6

<u>Variables</u> : $q_1, q_2, \ldots q_6, h_1, h_2$ $N_V = 8$

<u>Equations</u> :

3 flow-head relations: $q_3 = C_{v1}\sqrt{h_1}$

$$q_5 = C_{v2}\sqrt{h_2}$$
$$q_4 = K(h_1 - h_2)$$

2 mass balances:

$$\rho A_1 \frac{dh_1}{dt} = \rho(q_1 + q_6 - q_3 - q_4)$$
$$\rho A_2 \frac{dh_2}{dt} = \rho(q_2 + q_4 - q_5)$$

Thus $N_E = 5$

<u>Degrees of freedom:</u> $N_F = N_V - N_E = 8 - 5 = 3$

Disturbance variable : q_6 $N_D = 1$

$N_F = N_{FC} + N_D$
$N_{FC} = 3 - 1 = 2$

10.7

Consider the following energy balances assuming a reference temperature of $T_{ref} = 0$:

Heat exchanger:

$$C_c(1-f)w_c(T_{C0} - T_{C1}) = C_h w_h(T_{h1} - T_{h2}) \qquad (1)$$

Overall:

$$C_c w_c(T_{C2} - T_{C1}) = C_h w_h(T_{h1} - T_{h2}) \qquad (2)$$

Mixing point:

$$w_c = (1-f)w_c + fw_c \qquad (3)$$

Thus,

$N_E = 3$, $N_V = 8$ $(f, w_c, w_h, T_{c1}, T_{c2}, T_{c0}, T_{h1}, T_{h2})$

$N_F = N_V - N_E = 8 - 3 = 5$

$N_{FC} = 2$ (f, w_h)

also

$N_D = N_F - N_{FC} = 3$ (w_c, T_{c1}, T_{c2})

The degrees of freedom analysis is identical for both cocurrent and countercurrent flow because the mass and energy balances are the same for both cases.

10.8

The dynamic model consists of the following material balances:

Mass balance on the tank:

$$\rho A \frac{dh}{dt} = (1 - f)w_1 + w_2 - w_3 \tag{1}$$

Component balance on the tank:

$$\rho A \frac{d(hx_3)}{dt} = (1 - f)x_1 w_1 + x_2 w_2 - x_3 w_3 \tag{2}$$

Mixing point balances:

$$w_4 = w_3 + fw_1 \tag{3}$$

$$x_4 w_4 = x_3 w_3 + f x_1 w_1 \tag{4}$$

Thus,

$N_E = 4$ (Eqs.1-4)

$N_V = 10$ $(h, f, w_1, w_2, w_3, w_4, x_1, x_2, x_3, x_4)$

$N_F = N_V - N_E = 6$

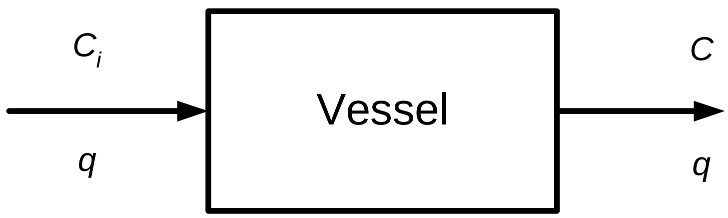
Because two variables (w_2 and f) can be independently adjusted, it would appear that there are two control degrees of freedom. However, the fraction of bypass flow rate, f, has no steady-state effect on x_4. To confirm this assertion, consider the overall steady-state component balance for the tank and the mixing point:

$$x_1 w_1 + x_2 w_2 = x_4 w_4 \tag{5}$$

This balance does not depend on the fraction bypassed, f, either directly or indirectly,

Conclusion : $N_{FC} = 1$ (w_2)

10.9



Let C_i = concentration of N_2 in the inlet stream = 100%
C = concentration in the vessel = exit concentration (perfect mixing)

Assumptions:

1. Perfect mixing
2. Initially, the vessel contains pure air, that is, $C(0)$ = 79%.

N_2 balance on the vessel:

$$V\frac{dC}{dt} = q(C_i - C) \tag{1}$$

Take Laplace transforms and let $\tau = V/q$:

$$\tau[sC(s) - C(t=0)] = \frac{C_i}{s} - C(s)$$

Rearrange,

$$C(s) = \frac{C_i}{s(\tau s+1)} + \frac{C(t=0)}{\tau s+1}$$

Take inverse Laplace transforms (cf. Chapter 3),

$$C(t) = C_i(1-e^{-t/\tau}) + C(t=0)e^{-t/\tau} \qquad (2)$$

Also,

$$\tau = \frac{V}{q} = \left(\frac{20,000 \text{ L}}{0.8\,\text{m}^3/\text{min}}\right)\left(\frac{1\,\text{m}^3}{1000 \text{ L}}\right) = 25\,\text{min}$$

Substitute for τ, C_i and $C(0)$ into (2) and rearrange

$$t = (25\,\text{min})\ln\left[\frac{21\%}{100\% - C(t)}\right] \qquad (3)$$

Let $C(t)$ = 98% N_2 (i.e., 2% O_2). From (3),

t = 58.7 min

10.10

Define k as the number of sensors that are working properly. We are interested in calculating $P(k \geq 2)$, when $P(E)$ denotes the probability that an event, E, occurs.

Because k = 2 and k = 3 are mutually exclusive events,

$$P(k \geq 2) = P(k=2) + P(k=3) \qquad (1)$$

These probabilities can be calculated from the binomial distribution [1] and the given probability of a sensor functioning properly (p = 0.99):

$$P(k=2) = \binom{3}{2}(0.01)^1\,(0.99)^2 = 0.0294$$

$$P(k=3) = \binom{3}{3}(0.01)^0\,(0.99)^3 = 0.9703$$

where the notation, $\binom{n}{r}$, refers to the number of combinations of n objects taken r at a time, when the order of the r objects is not important. Thus $\binom{3}{2} = 3$ and $\binom{3}{3} = 1$. From Eq.(1),

$$P(k \geq 2) = 0.0294 + 0.9703 = 0.9997$$

[1] See any standard probability or statistics book, e.g., Montgomery D.C and G.C. Runger, *Applied Statistics and Probability for Engineers, 3rd ed.*, John Wiley, NY (2003).

10.11

Assumptions:

1. Incompressible flow.
2. Chlorine concentration does not affect the air sample density.
3. T and P are approximately constant.

The time t_T that is required to detect a chlorine leak in the processing area is given by:

$$t_T = t_{tube} + t_A$$

where:

t_{tube} is the time that the air sample takes to travel through the tubing

t_A is the time that the analyzer takes to respond after chlorine first reaches it.

The volumetric flow rate q is the product of the velocity v and the cross-sectional area A:

$$q = vA \qquad \therefore \qquad v = \frac{q}{A}$$

then:

$$A = \frac{\pi D^2}{4} = \frac{3.14(6.35 - 0.762)^2}{4} = 24.5 \text{ mm}^2$$

$$v = \frac{10 \text{ cm}^3/s}{24.5 \times 10^{-2} \text{ cm}^2} = 40.8 \text{ cm/s}$$

Thus,

$$t_{tube} = \frac{4000 \text{ cm}}{40.8 \text{ cm/s}} = 98.1 \text{ s}$$

Finally,

$$t_T = 98.1 + 5 = 103.1 \text{ s}$$

Carbon monoxide (CO) is one of the most widely occurring toxic gases, especially in confined spaces. High concentrations of carbon monoxide can saturate a person's blood in a matter of minutes and quickly lead to respiratory problems or even death. Therefore, this amount of time is not acceptable if the hazardous gas is CO.

10.12

The key safety concerns include:

1. Early detection of any leaks to the surroundings
2. Over pressurizing the flash drum
3. Maintain enough liquid level so that the pumps do not cavitate.
4. Avoid having liquid entrained in the gas.

These concerns can be addressed by the following instrumentation.

1. *Leak detection*: sensors for hazardous gases should be located in the vicinity of the flash drum.
2. *Over pressurization*: Use a high pressure switch (PSH) to shut off the feed when a high pressure occurs.
3. *Liquid inventory*: Use a low level switch (LSL) to shut down the pump if a low level occurs.

4. *Liquid entrainment*: Use a high level alarm to shut off the feed if the liquid level becomes too high.

This SIS system is shown below with conventional control loops for pressure and liquid level.

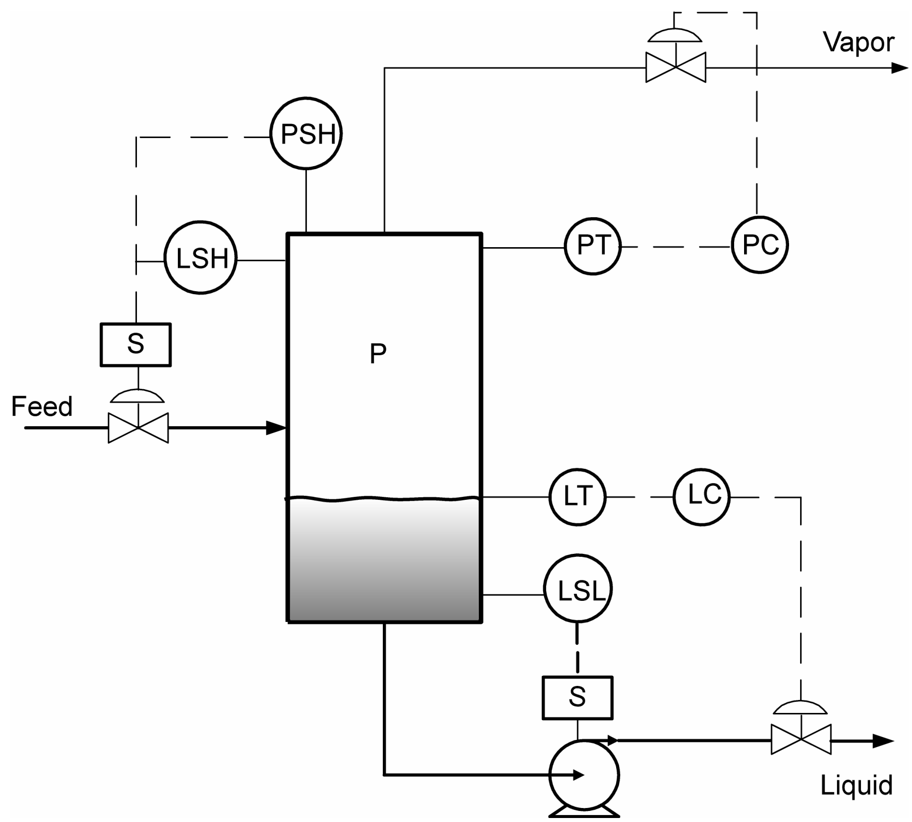


Figure S10.12.

10.13

The proposed alarm/SIS system is shown in Figure S10.13:

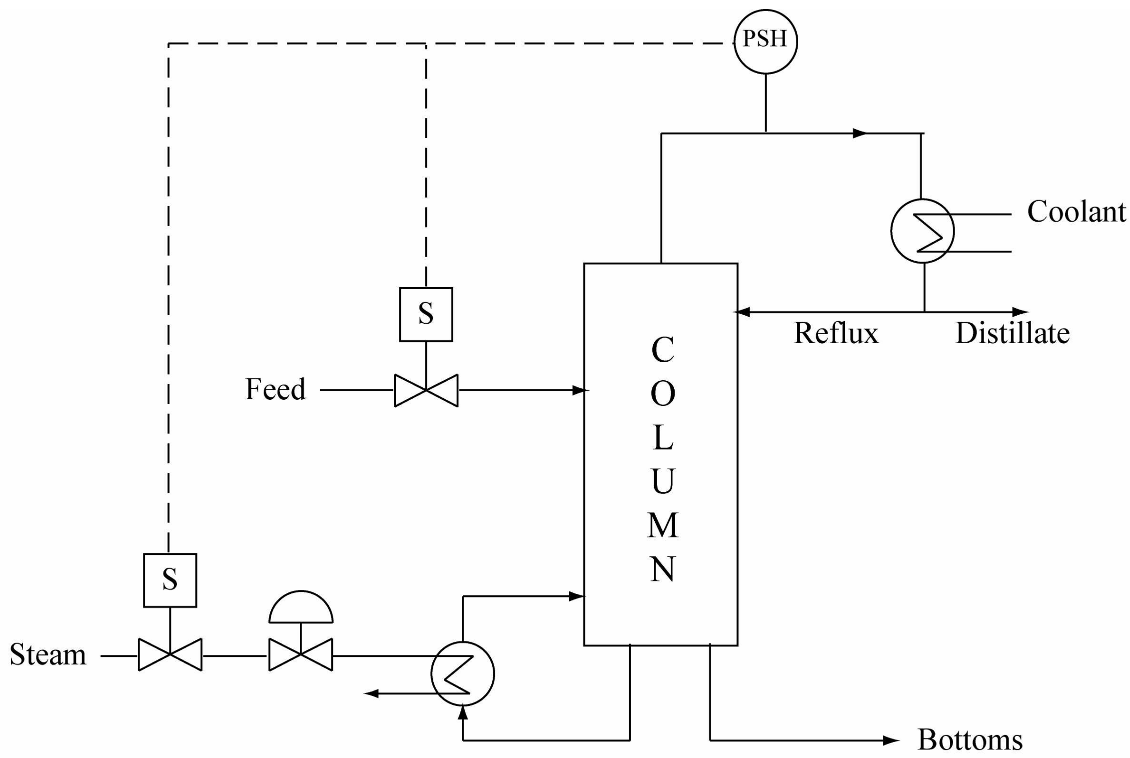


Figure S10.13

The solenoid-operated valves are normally open. If the column pressure exceeds a specified limit, the high pressure switch (PSH) shuts down both the feed stream and the steam flow to the reboiler. Both actions tend to reduce the pressure in the column.