5.20 Energy recycle occurs when a hot stream leaving a process transfers heat to a colder stream entering the process.

5.21 Material recycle occurs when reactants that were unconverted in going through a reactor are separated and mixed with fresh feed and fed to the reactor.

Analytical Questions and Exercises

5.22 a. Rearranging this equation in the standard form

$$G_p(s) = \frac{0.16}{4.56s+1}$$

Therefore, the steady-state gain is 0.16 and the time constant is 4.56.

b. Rearranging this equation in the standard form

$$G_p(s) = \frac{10}{10s+1}$$

There for the steady-state gain is 10 and the time constant is 10.

c. Rearranging this equation in the standard form

$$G_p(s) = \frac{30}{60s+1}$$

Therefore, the steady-state gain is 30 and the time constant is 60.

d. Rearranging this equation in the standard form

$$G_p(s) = \frac{10}{300s+1}$$

Therefore, the steady-state gain is 10 and the time constant is 300.

5.23 Taking the Laplace transform of this differential equation, the transfer function for this system can be obtained

$$\frac{T_s(s)}{T_p(s)} = \frac{1}{\frac{MC_p}{Ah}s+1}$$

Substituting the numerical values yields a time constant of 3.6 s.

5.24 From Problem 3.36,

$$MC_{mp}\frac{dT_m}{dt}=Q_{stm}-Q$$
$$Q_{stm}=U_{stm}A(T_{stm}-T_m)=K_1(T_{stm}-T_m)$$
$$Q=\frac{UA(T_m-T_{in})}{1+\dfrac{UA}{2FC_p}}=K_2(T_m-T_{in})$$

Combining these equations and transforming into deviation variable form yields

$$MC_{mp}\frac{d\,\Delta T_m}{dt}=(K_2-K_1)\Delta T_m+K_1\Delta T_{stm}-K_2\Delta T_{in}$$

Considering only input changes in T_{stm}, the transfer function is given as

$$G_p(s)=\frac{\dfrac{K_1}{K_1-K_1}}{\dfrac{MC_{mp}}{K_1-K_2}s+1}$$

Therefore, the time constant is

$$\tau_p=\frac{MC_{mp}}{K_1-K_2}$$

From Perry's Handbook, the outside diameter is 0.625 inches and the inside diameter is 0.527 inches (Note that the problem statement incorrectly specified schedule 40 which is for ferrous pipe and the dimensions specified here are for Type K copper water tubing.). Since the outside surface corresponds to A_h, A_h is 1.96 in^2/in and A is 1.65 in^2/in. Also, the metal volume is calculated as 0.0886 in^3/in based upon these dimensions. Also, from Perry's Handbook, the specific gravity of copper is 8.91 and the heat capacity is 0.092 Btu/lb-ºF. From Bird, Stewart, and Lightfoot, the heat transfer coefficient for forced convection of liquids is 100 Btu/h-ft^2-ºF on the low end which will be used for the tube-side. For the shell-side, the heat transfer coefficient for condensing steam is approximately 1000 BTU/h-ft^2-ºF. The values of K_1 and K_2 are calculates as 13.61 and 11.146 BTU/h-in-ºF, respectively. Substituting these values into the previous equation yields the time constant equal to 0.787 s.

5.25 For a first order process, it will attain 95% of its steady-state change in three time constants. For industrial data, identifying the time required for 95% of the change is all that can be expected due to typical noise levels on the process measurement. If the process time constant to deadtime ratio for a FOPDT model is three, then it will take about 4 time constants in order to observe the full effect of a change. If the process time constant-to-deadtime ratio is greater than three, which is the case for most processes, the time for 95% change will be slightly less time than four time constants. While the level of noise and the determination of the time to observe the full effect of the input change as well as the deadtime will affect the accuracy of this approach, this rule of thumb provides a reasonable estimate of the process time constant.

5.26

$$K_p = \frac{\Delta y}{\Delta u} = \frac{20\ psi}{200\ lb/h} = 0.1\ psi \cdot h/lb$$

$$\tau_p \approx 40/4 = 10s$$

$$G_p(s) = \frac{0.1}{10s+1}$$

5.27

$$K_p = \frac{-3\%}{5000\ lb/h} = -0.0006\ \% \cdot h/lb$$

$$\tau_p \approx 120/4 = 30\,\text{min}$$

$$G_p(s) = \frac{-0.0006}{30s+1}$$

5.28

$$K_p = \frac{8\%}{1000\ lb/h} = 0.008\ \% \cdot h/lb$$

$$\tau_p \approx 20/4 = 5\,\text{min}$$

$$G_p(s) = \frac{0.008}{5s+1}$$

5.29

$$K_p = \frac{-10^\circ F}{2000\ lb/h} = -0.005\ {}^\circ F \cdot h/lb$$

$$\tau_p \approx 18/4 = 4.5\ \text{min}$$

$$G_p(s) = \frac{-0.005}{4.5s+1}$$

5.30 Solving Equation 5.16 for decay ratio equal to 0.25 yields $\zeta = 0.2154$.

5.31 From Equation 5.15,

$$\ln(0.6) = \frac{-\pi\zeta}{\sqrt{1-\zeta^2}} = -0.5108$$

Squaring both sides and solving for the damping factor, result in ζ=0.1604

Using Equation 5.16, the decay ratio is 1/2.78.

5.35 From Equation 5.16,

$$\ln(1/10) = \frac{-2\pi\zeta}{\sqrt{1-\zeta^2}} = -2.303$$

Squaring both sides and solving for the damping factor, result in ζ=0.3441

Using Equation 5.15, the percentage overshoot is 31.62%.

5.36 From Equation 5.15,

$$\ln(0.2) = \frac{-\pi\zeta}{\sqrt{1-\zeta^2}} = -1.609$$

Squaring both sides and solving for the damping factor, result in ζ=0.4559

Using Equation 5.16, the decay ratio is 1/25.

5.37 Since there is no offset for this temperature controller, the process gain is one. The damping factor can be determined from Equation 5.15 using the specified percentage overshoot, and the time constant can be determined from Equation 5.17. Since Equation 5.17 depends on ζ, Equation 5.15 should be solved first to determine the value for ζ. Rearranging Equation 5.16 and using the specified 10% overshoot yields ζ equal to 0.591. Rearranging Equation 5.17 and using the value of T and ζ yields τ_p equal to 0.128 minutes; therefore, the transfer function for this closed-loop process is

$$G(s) = \frac{1}{0.01638 s^2 + 0.1517 s + 1}$$

where the time constant is expressed in minutes and the gain is in psi/psi.

5.38 Since there is no offset for this temperature controller, the process gain is one. The damping factor can be determined from Equation 5.16 using the specified decay ratio, and the time constant can be determined from Equation 5.17. Since Equation

5.17 depends on ζ, Equation 5.16 should be solved first to determine the value for ζ. Rearranging Equation 5.16 and using the specified ¼ decay ratio, ζ equal to 0.2154. Rearranging Equation 5.17 and using the value of T and ζ yields τ_p equal to 9.325 minutes; therefore, the transfer function for this closed-loop process is

$$G(s) = \frac{1}{86.96s^2 + 4.017s + 1}$$

where time constant is expressed in minutes and the gain is in $\frac{gmoles / L}{gmoles / L}$.

5.39 Since there is no offset for this temperature controller, the process gain is one. The damping factor can be determined from Equation 5.16 using the specified decay ratio, and the time constant can be determined from Equation 5.17. Since Equation 5.17 depends on ζ, Equation 5.16 should be solved first to determine the value for ζ. Rearranging Equation 5.16 and using the specified 1/8 decay ratio, ζ equal to 0.3142. Rearranging Equation 5.17 and using the value of T and ζ yields τ_p equal to 2.115 minutes; therefore, the transfer function for this closed-loop process is

$$G(s) = \frac{1}{4.475s^2 + 1.329s + 1}$$

where time constant is expressed in minutes and the gain is in deg/deg.

5.40 Since there is no offset for this temperature controller, the process gain is one. The damping factor can be determined from Equation 5.15 using the specified percentage overshoot, and the time constant can be determined from Equation 5.17. Since Equation 5.17 depends on ζ, Equation 5.15 should be solved first to determine the value for ζ. Rearranging Equation 5.15 and using the specified 25% overshoot yields ζ equal to 0.4037. Rearranging Equation 5.17 and using the value of T and ζ yields τ_p equal to 1.165 s; therefore, the transfer function for this closed-loop process is

$$G(s) = \frac{1}{1.357s^2 + 0.9405s + 1}$$

where time constant is expressed in seconds and the gain is in $\frac{lb / h}{lb / h}$.

5.41 The transfer function for this equation is

$$G_p(s) = \frac{1}{s^2 + K s + 1}$$

The poles of this transfer function are

$$p = \frac{-K \pm \sqrt{K^2 - 4}}{2}$$

Therefore, the process is unstable for $K < 0$. The process is oscillatory for $K < 2$ and for $K > -2$.

5.42 The slope of the level is 3.33 %/min. The transfer function for this integrating process is

$$G_p(s) = \frac{0.006667}{s}$$

With units of %-h/lb.

5.43 The slope of the level is 1.133 %/min. The transfer function for this integrating process is

$$G_p(s) = \frac{0.0005667}{s}$$

With units of %-h/lb.

5.44 The slope of the level is 1.0 %/min. The transfer function for this integrating process is

$$G_p(s) = \frac{0.00125}{s}$$

With units of %-h/lb.

5.45 The slope of the level is -0.5625 %/min. The transfer function for this integrating process is

$$G_p(s) = -\frac{0.000375}{s}$$

With units of %-h/lb.

5.46 Transforming the equation into the standard form yields

$$G_p(s) = \frac{80.75\, e^{-3s}}{s^2 + 4s + 1}$$

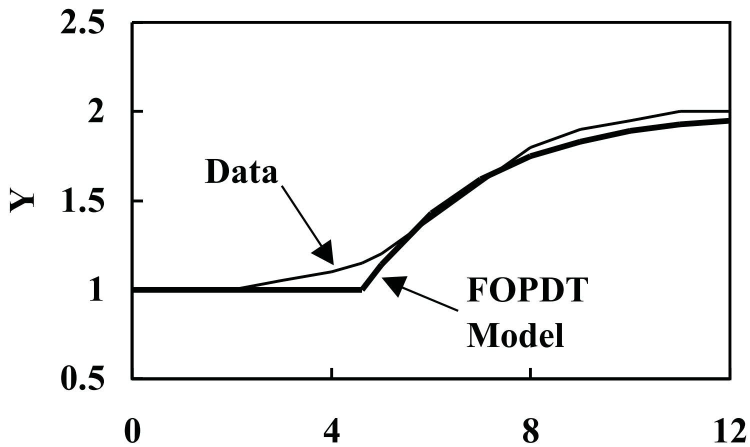

Figure P5.49 Comparison between data and FOPDT model for Problem 5.49.

The poles of this transfer function are real and negative indicating overdamped behavior. The steady-state gain is 80.75 and the deadtime is 3. The time constant is 1 and ζ is equal to 2 which also indicates overdamped behavior.

5.47 The transfer function for the actuator/process/sensor model is third order since the overall transfer function is the product of the individual transfer functions. If an additional mixing tank is added, which is a first order process by itself, the overall process would become a fourth order overdamped process.

5.48 Neglecting the dynamics of the sensor and the actuator, the order of the overall process will be fourth order since for a first order irreversible reaction a single reactor behaves as a first order process.

5.49 From a plot of the step response data, $t_{1/3}$ is 3.6 and $t_{2/3}$ is 5.3. Using Equation 5.25, τ_p is 2.43, θ_p is 2.62, and K_p is 1.0. **Note that since the input change did not occur until time equal to 2, $t_{1/3}$ and $t_{2/3}$ are smaller than one would otherwise calculate.** For example, the time for 1/3 of the response to occur is 5.6 but since the input change did not occur until time equal to 2, $t_{1/3}$ is 3.6. Note that this distinction only affects the value of the deadtime and not the time constant because the time constant is based on the difference between $t_{1/2}$ and $t_{2/3}$. Also note that the FOPDT model and the data do not agree at the end of the data. This results because time scale is not long enough for the FOPDT model to adequately approach steady state. That is, for 98% of the change to occur, the time should be 14.4 ($2+\theta_p+4\tau_p$).

5.50 From an inspection of the data, particularly if the data is plotted, one can see that the data follows an integrator plus deadtime model. The following transfer function approximates this data:

$$G(s) = \frac{0.1\, e^{-3s}}{s}$$

Note that since the input is not changed until time equal 2 and the process start to change after time equal to 5, the deadtime is equal to 3.

5.51 From a plot of the step response data, $t_{1/3}$ is (6.74-3) and $t_{2/3}$ is (8.125-3). Using Equation 5.25, τ_p is 1.979, θ_p is 2.95, and K_p is -9.375.

5.52 From a plot of the step response data, $t_{1/3}$ is (6.4-2) and $t_{2/3}$ is (8.0-2). Using Equation 5.25, τ_p is 2.286, θ_p is 5.49, and K_p is 0.0857.

5.53 a.

$$2s^2 + 5s - 3 = 0$$
$$s = -3, 0.5 \quad Therefore, inverse\ acting$$

b.

$$2s^2 + 7s + 3 = 0$$
$$s = -3, -0.5 \quad Therefore,\ no\ inverse\ acting$$

c.

$$s^2 + 9.99s - 0.01 = 0$$
$$s = -9.991,\ 0.001 \quad Therefore, inverse\ acting$$

d.

$$s^2 - 4s + 3 = 0$$
$$s = 3, 1 \quad Therefore,\ inverse\ acting$$

e.

$$s^3 - 3s - 2 = 0$$
$$s = -1, -1, 2 \quad Therefore, inverse\ acting$$

f.

$$s^3 + 3s^2 - s - 3 = 0$$
$$s = -1, -3, 1 \quad Therefore, inverse\ acting$$