Cascade Control

CHAPTER 14

14.1 ▣ INTRODUCTION

Cascade control is one of the most successful methods for enhancing single-loop control performance. It can dramatically improve the performance of control strategies, reducing both the maximum deviation and the integral error for disturbance responses. Since the calculations required are simple, cascade control can be implemented with a wide variety of analog and digital equipment. This combination of ease of implementation and potentially large control performance improvement has led to the widespread application of cascade control for many decades. In this chapter, cascade control is fully explained with special emphasis placed on clear guidelines that, when followed, ensure that the cascade method is properly designed and is employed only where appropriate.

As explained in the introduction to this part, single-loop enhancements take advantage of extra information to improve on the performance of the PID feedback control system. Cascade uses an additional measurement of a process variable to assist in the control system. The selection of this extra measurement, which is based on information about the most common disturbances and about the process dynamic responses, is critical to the success of the cascade controller. Therefore, insight into the process operation and dynamics is essential for proper cascade control design.

The basic concepts of cascade control are presented in the next section. Subsequent sections provide concise explanations of the design criteria, performance expectations, tuning methods, and implementation issues. All of the methods and guidelines are presented for continuous systems but are applicable to digital control systems. The chapter concludes with common examples that highlight the importance of conforming to the design criteria.

14.2 ▣ AN EXAMPLE OF CASCADE CONTROL

The best way to introduce cascade control is with reference to a simple process example, which will be the stirred-tank heat exchanger shown in Figure 14.1. The goal is to provide tight control of the exit temperature. The conventional feedback controller, with integral mode, attempts to maintain the exit temperature near its set point in response to all disturbances and ensures zero steady-state offset for steplike disturbances. Suppose that one particularly frequent and large disturbance is the heating oil pressure. When this pressure increases, the initial response of the oil flow and the heat transferred is to increase. Ultimately, the tank exit temperature increases, and the feedback controller reduces the control valve opening to compensate for the increased pressure. While the effect of the disturbance is ultimately compensated by the single-loop strategy, the response is slow because the exit temperature must be disturbed before the feedback controller can respond.

Cascade control design considers the likely disturbances and tailors the control system to the disturbance(s) that strongly degrades performance. Cascade control uses an additional, "secondary" measured process input variable that has the important characteristic that it indicates the occurrence of the key disturbance. For the stirred-tank heat exchanger, all measured variables are shown in Figure 14.1. The secondary variable is selected to be the heating oil flow, because it responds in a predictable way to the disturbances in the oil pressure, which is not measured in this case. The control objective (tight control of the outlet temperature) and the final element are unchanged.

The manner in which the additional measurement is used is shown in Figure 14.2. The control system employs two feedback controllers, both of which can

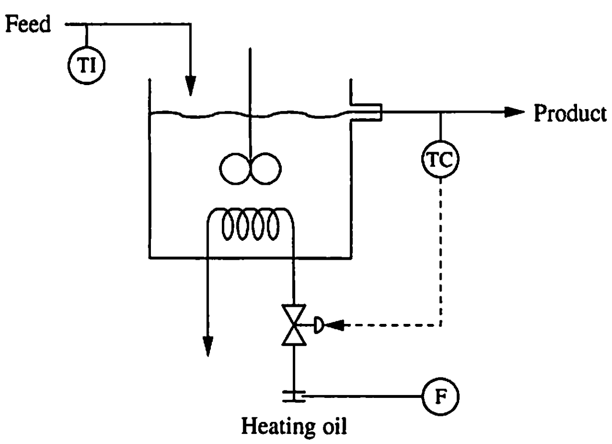

FIGURE 14.1

Stirred-tank heat exchanger with single-loop temperature control.

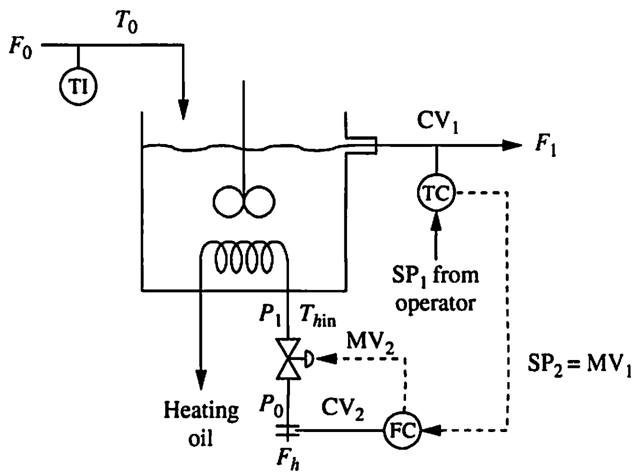

FIGURE 14.2

Stirred-tank heat exchanger with cascade control.

use the standard PID controller algorithm. The important feature in the cascade structure is the way in which the controllers are connected. The output of the exit temperature controller adjusts the set point of the flow controller in the cascade structure; that is, the secondary controller set point is equal to the primary controller output. Thus, the secondary flow control loop is essentially the manipulated variable for the primary temperature controller. The net feedback effect is the same for single-loop or cascade control; in either case, the heating oil valve is adjusted ultimately by the feedback. Therefore, the ability to control the exit temperature has not been changed with cascade.

As described previously, the single-loop structure makes no correction for the oil pressure disturbance until the tank exit temperature is upset. The cascade structure makes a much faster correction, which provides better control performance. The reason for the better performance can be seen by analyzing the initial response of the cascade system to an oil pressure increase. The valve position is initially constant; therefore, the oil flow increases. The oil flow sensor quickly detects the increased flow. Since the flow controller set point would be unchanged, the controller would respond by closing the valve to return the flow to its desired value. Because the sensor and valve constitute a very fast process, the flow controller can rapidly achieve its desired flow of oil. By responding quickly to the pressure increase and compensating by closing the control valve, the secondary controller corrects for the disturbance before the tank exit temperature is significantly affected by the disturbance. Typical dynamic responses of the single-loop and cascade control systems are given in Figure 14.3*a* and *b* for a decrease in oil pressure.

A few important features of the cascade structure should be emphasized. First, the flow controller is much faster than the temperature controller. The improvement results from the much shorter dead time in the secondary loop than in the original single-loop system; as discussed in Chapter 13, shorter dead times improve single-

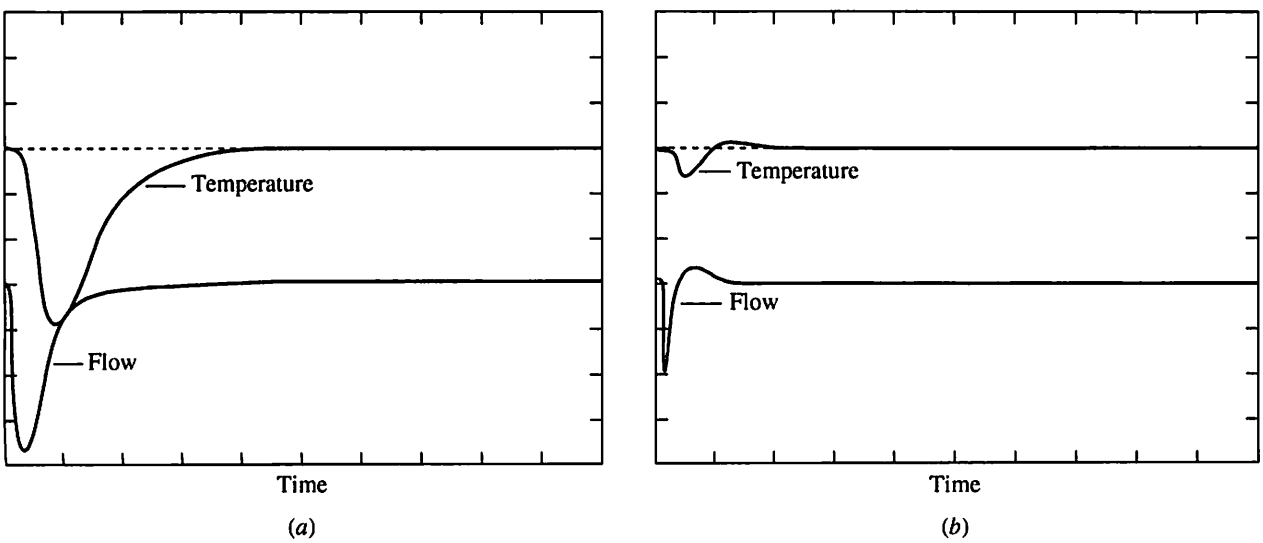

FIGURE 14.3

Dynamic response of stirred-tank heat exchanger to a disturbance in oil pressure: (*a*) with single-loop control; (*b*) with cascade control.

loop control. If the flow controller were not faster, the cascade design would have no advantage. Second, the temperature controller with an integral mode remains in the design to ensure zero offset for all disturbance sources. The primary controller is essential, because (1) the secondary variable may not totally eliminate the effect of the disturbance, (2) other disturbances that are not affected by the cascade will also occur, and (3) the ability to change the primary set point must be retained. Remember that the secondary variable is selected for one (or a few) common disturbances; in the example, a heat exchanger feed temperature disturbance would affect the tank outlet temperature but does not influence the heating oil measurement. Finally, the judicious selection of the secondary variable has made the improvement possible *without using a model* of the effect of pressure on exit temperature in the control calculation; the only models used were the process models used to tune the two feedback controllers. As a result, cascade control is not strongly sensitive to modelling errors, although large errors could lead to oscillations or instability in one of the feedback controllers.

The two controllers in the cascade are referred to by various names. The three pairs of names in the most commonly used terminology are presented as they would be applied to the stirred-tank heat exchanger:

Temperature	**Flow**
Primary	Secondary
Outer	Inner
Master	Slave

At first encounter, it may seem improper to use two feedback controllers to achieve one objective; however, the propriety of cascade control can be established by analyzing the degrees of freedom of the system. For the heat exchanger in Figure 14.2, the material and energy balances were derived in Example 3.7 (for cooling) and are repeated here for heating.

$$F_0 = F_1 \tag{14.1}$$

$$V\rho C_p \frac{dT}{dt} = F_1 \rho C_p (T_0 - T) - \frac{a F_h^{b+1}}{F_h + \dfrac{a F_h^b}{2\rho_h C_{ph}}} (T - T_{hin}) \tag{14.2}$$

The heating flow is related to the valve position (v) according to the following general equation:

$$F_h = C_v v \sqrt{\frac{P_0 - P_1}{\rho_h}} \tag{14.3}$$

where we assume that the pressures and the coefficient C_v are constant, although they can be variables (see Chapter 16). The final equations are the two cascade controllers:

$$F_{hsp} = K_{c1} \left[(T_{sp} - T) + \frac{1}{T_{I1}} \int_0^t (T_{sp} - T)\, dt' \right] + I_{Fh} \tag{14.4}$$

$$v = K_{c2}\left[(F_{h\text{sp}} - F_h) + \frac{1}{T_{I2}}\int_0^t (F_{h\text{sp}} - F_h)\,dt'\right] + I_v \qquad (14.5)$$

Variables:	$F_1, F_h, T, (F_h)_{\text{sp}}, v$ DOF $= 5 - 5 = 0$
External variables:	$F_0, T_0, T_{h\text{in}}, T_{\text{sp}}$
Parameters:	$V, \rho, C_p, \rho_h, C_{ph}, a, b, C_v, P_0, P_1, K_{c1}, T_{I1}, K_{c2}, T_{I2}, I_{Fh}, I_v$

The number of degrees of freedom is equal to the number of variables minus the number of equations; thus, the system is exactly specified when the primary temperature controller set point has been defined. Note that the cascade secondary controller was placed between the primary controller output and the valve, which added one variable ($F_{h\text{sp}}$) and one equation (14.5).

14.3 ▪ CASCADE DESIGN CRITERIA

The principles of cascade control have been introduced with respect to the example stirred-tank heater. In Table 14.1, the design criteria are summarized in a concise form so that they can be applied in general. Adherence to these criteria ensures that cascade control is designed properly and used only where appropriate. The first two items address the selection of cascade control. Naturally, only when single-loop control does not provide acceptable control performance is an enhancement such as cascade control necessary. As described in Chapter 13, single-loop control provides good performance when the dynamics are fast, the fraction dead time is small, and disturbances are small and slow. Also, the second criterion requires an acceptable measured secondary variable to be available or added at reasonable cost.

A potential secondary variable must satisfy three criteria. First, it must indicate the occurrence of an important disturbance; that is, the secondary variable must respond in a predictable manner every time the disturbance occurs. Naturally, the disturbance must be important (i.e., have a significant effect on the controlled variable and occur frequently), or there would be no reason to attenuate its effect. Second, the secondary variable must be influenced by the manipulated variable. This causal relationship is required so that a secondary *feedback* control loop

TABLE 14.1

Cascade control design criteria

Cascade control is desired when
1. Single-loop control does not provide satisfactory control performance.
2. A measured secondary variable is available.
A secondary variable must satisfy the following criteria:
1. The secondary variable must indicate the occurrence of an important disturbance.
2. There must be a causal relationship between the manipulated and secondary variables.
3. The secondary variable dynamics must be faster than the primary variable dynamics.

functions properly. Finally, the dynamics between the final element and the secondary must be much faster than the dynamics between the secondary variable and the primary controlled variable. The secondary must be relatively quick so that it can attenuate a disturbance before the disturbance affects the primary controlled variable. A general guideline is that the secondary should be three times as fast as the primary. This could be roughly interpreted as the secondary reaching its steady state in one-third the time of the primary after an open-loop step change in the manipulated variable. A more proper comparison is the critical frequency of each loop; cascade is recommended when the critical frequency of the secondary is at least three times that of the primary. Using critical frequencies accounts for differences in the fraction dead time as well as the speed of response.

> **A cascade control strategy combines two feedback controllers, with the primary controller's output serving as the secondary controller's set point. The design should conform to the design criteria in Table 14.1, which provide a simple, step-by-step procedure for selection.**

14.4 ▫ CASCADE PERFORMANCE

In the introduction to this chapter, cascade was described as simple and effective. The foregoing material has demonstrated how simple a cascade strategy is to design. In this section, its effectiveness is shown by calculating its performance using simulation and frequency response for a few cascade systems and comparing with single-loop control performance on the same systems. Because the number of parameters in a cascade system—primary dynamics, secondary dynamics, disturbance dynamics—make general performance correlations intractable, this section presents sample results for typical process dynamics. The general trends showed by these results should be expected for most realistic processes.

The block diagram in Figure 14.4 presents the structure of a cascade control system, which summarizes the flow of information and can be used to evaluate important properties such as stability and frequency response. Transfer functions can be derived from this block diagram for the relationships between the primary controlled variable $\mathrm{CV}_1(s)$ and the secondary disturbance $D_2(s)$, the primary disturbance $D_1(s)$, and the primary set point $\mathrm{SP}_1(s)$, as follows:

$$\frac{\mathrm{CV}_1(s)}{D_2(s)} = \frac{G_{d2}G_{p1}(s)}{1 + G_{c2}(s)G_v(s)G_{p2}(s)G_{s2}(s) + G_{c1}(s)G_{c2}(s)G_v(s)G_{p1}(s)G_{p2}(s)G_{s1}(s)} \tag{14.6}$$

$$\frac{\mathrm{CV}_1(s)}{D_1(s)} = \frac{G_{d1}(s)[1 + G_{c2}(s)G_v(s)G_{p2}(s)G_{s2}(s)]}{1 + G_{c2}(s)G_v(s)G_{p2}(s)G_{s2}(s) + G_{c1}(s)G_{c2}(s)G_v(s)G_{p1}(s)G_{p2}(s)G_{s1}(s)} \tag{14.7}$$

$$\frac{\mathrm{CV}_1(s)}{\mathrm{SP}_1(s)} = \frac{G_{c1}(s)G_{c2}(s)G_v(s)G_{p2}(s)G_{p1}(s)}{1 + G_{c2}(s)G_v(s)G_{p2}(s)G_{s2}(s) + G_{c1}(s)G_{c2}(s)G_v(s)G_{p1}(s)G_{p2}(s)G_{s1}(s)} \tag{14.8}$$

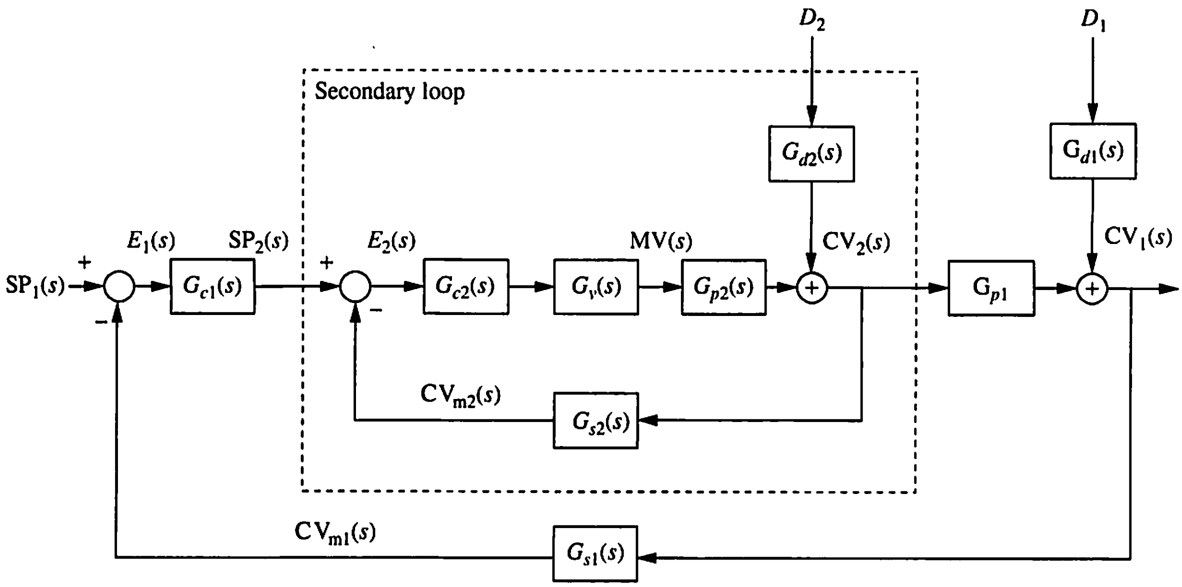

FIGURE 14.4

Block diagram of cascade control.

As apparent from the introductory example, a key factor in cascade control is the relative dynamic responses of the secondary and primary processes. Since the main reason for cascade is secondary disturbances, the studies in this section evaluate the responses to secondary disturbances: step, sine, and stochastic. For these simulation studies, the models for the sensors $G_{si}(s)$ and valve $G_v(s)$ were taken to be unity, and the dynamics of the plant models and disturbance model are given below, with all times scaled so that the process models have a common value of the fraction dead time. The relative dynamics between the secondary and primary are defined by a variable η, which will be allowed to vary in the following models:

Cascade System

	Process	Control
Secondary:	$G_{p2}(s) = \dfrac{1.0e^{(-0.3/\eta)s}}{1+(0.7/\eta)s}$	PI controller tuned accordingly
Primary:	$G_{p1} = \dfrac{1.0e^{(-0.3)s}}{1+0.7s}$	PI controller tuned accordingly

Single-Loop System

Process	Control
$G_p = \dfrac{1.0e^{-(0.3+0.3/\eta)s}}{[1+(0.7/\eta)s](1+0.7s)}$	PI controller tuned accordingly

For All Cases

Disturbance: $G_{d2}(s) = \dfrac{1.0}{1 + (0.7/\eta)s}$

Instrumentation: $G_{s1}(s) = G_{s2}(s) = G_v(s) = 1.0$

Response to Step Disturbance in D_2

In the first cascade system studied, a step disturbance was introduced in the secondary loop, and no noise was added to the measurements, so that only the effect of the cascade could be determined. Both primary and secondary controllers used PI algorithms with conventional tuning. The control performance measure is the integral of the absolute value of the error, IAE, of the primary controlled variable; it is reported as a ratio of cascade to single-loop IAE to characterize the improvement achieved through cascade. The resulting control performance is shown in Figure 14.5 as a function of the relative secondary/primary process dynamics, η. As expected, the performance is very good when the secondary is fast. For example, the integral error is reduced by 95 percent or more for cascade versus single-loop control when the secondary is more than 20 times faster. This large ratio in primary to secondary dynamics is typical when the secondary is a fast loop such as a flow or pressure controller, which is often the case. However, many cascade control systems cannot achieve such a remarkable improvement because the secondary loop is not so fast, and some potential secondary loop dynamics are so slow as to prohibit cascade control.

Sample dynamic responses from cascade control are shown in Figure 14.6*a* and *b* for a step disturbance in the secondary loop, $D_2(s) = -1/s$ at time = 10.

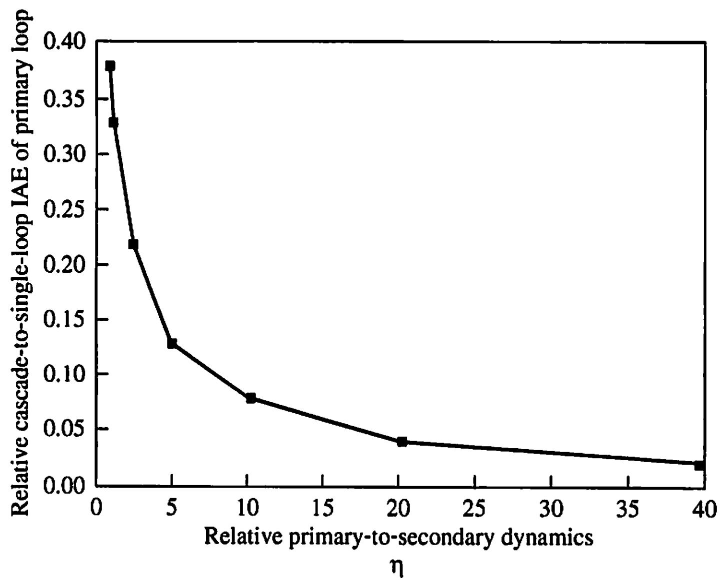

FIGURE 14.5

Relative performance (IAE_{casc}/IAE_{sl}) of cascade and single-loop control for a step disturbance in the secondary loop.

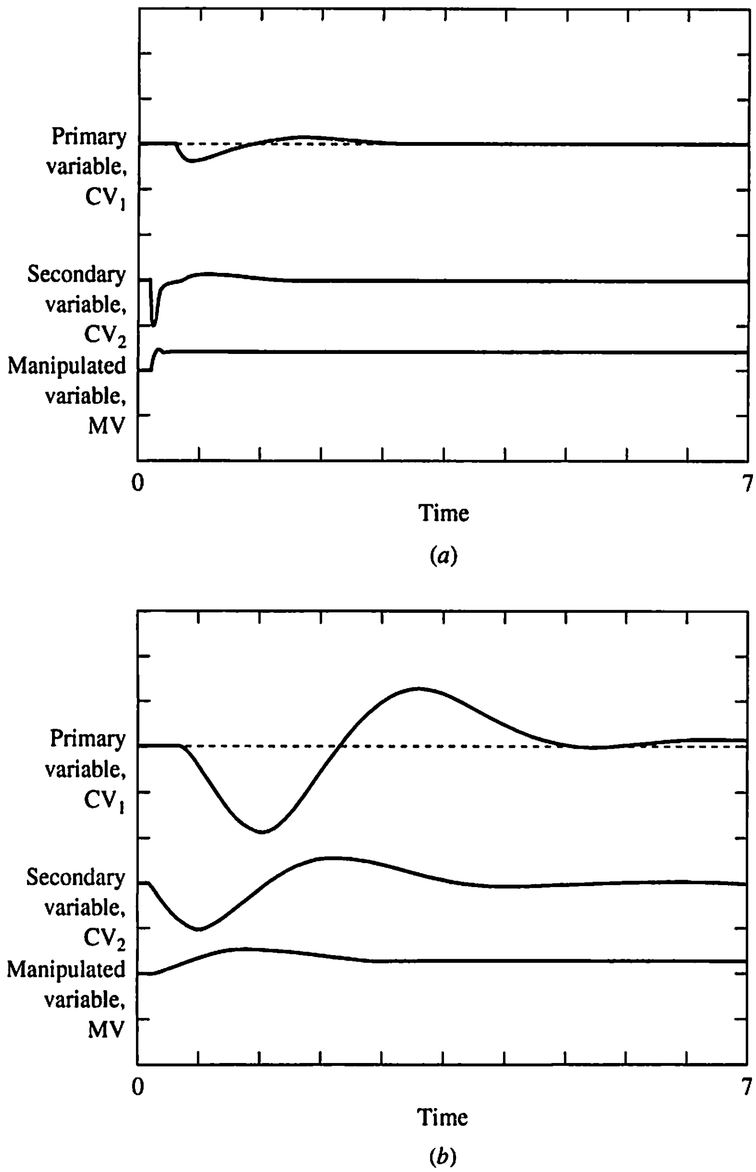

FIGURE 14.6

Performance of cascade control for a disturbance in the secondary loop: (*a*) with $\eta = 10$; (*b*) with $\eta = 1.0$. [Scales for the plots: One tick (10%) is 0.15 for primary, 0.50 for secondary, and 2.5 for manipulated variable.]

The case with a very fast secondary demonstrates how quickly the secondary controller attenuates the effect of the disturbance. The case of a much slower secondary shows much poorer performance, especially the highly oscillatory response. These oscillations, which are more troublesome with the continuous disturbances experienced in industrial plants, usually prohibit the use of cascades with PID controllers when η is less than about 3, although Figure 14.5 shows that some improvement in performance may be possible. (See Chapter 19 for the use of predictive controllers in cascade control, which can increase the region of acceptable cascade performance.)

Response to Stochastic Disturbance in D_2

In a second study, the same process was considered with a stochastic disturbance, which is more representative of the responses encountered in a continuously operating plant. The block diagram and models were the same as for the step disturbance, and the disturbance enters in the secondary loop. Again, the system was simulated with single-loop PI control and cascade control tuning. The control performance in Figure 14.7 is expressed as standard deviation from the set point

$$\sigma_{sp} = \sqrt{\sum_{i=0}^{n} \frac{(SP_i - CV_i)^2}{n}}$$

The standard deviation of the primary variable is plotted as a function of the relative secondary/primary dynamics, η. Again, the faster the secondary, the better the performance of the cascade. Dynamic responses for this system are given for $\eta = 10$ in Figure 14.8*a* through *c* for open-loop, single-loop, and cascade control, respectively. It is important to recognize that the results in Figure 14.7 are limited to the *specific process and disturbance studied;* other disturbances, with different frequency components, would give different results, although the general trend would be unchanged.

Response to Sine Disturbance in D_2

The third cascade study investigates the frequency response, which evaluates the control performance of a cascade control system for a range of disturbance frequencies. As described in Chapter 13, the amplitude ratio gives the magnitude of the variation in the controlled variable for a unit sine input; thus, the smaller the amplitude ratio for a disturbance response, the better the control performance.

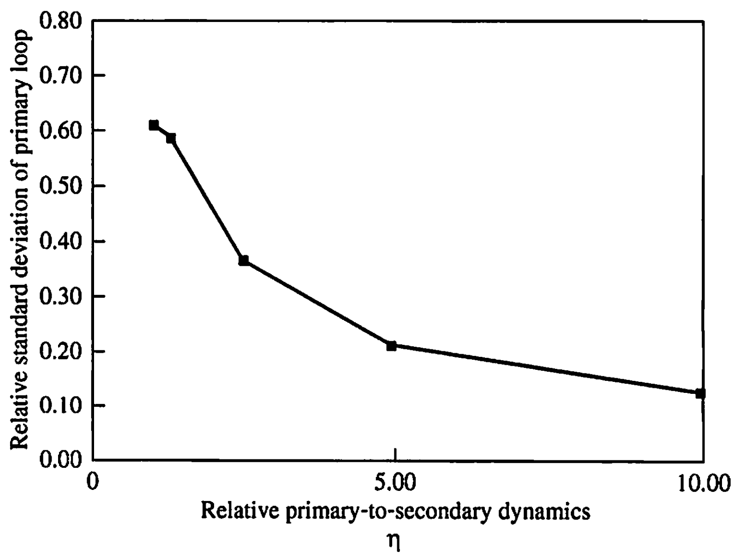

FIGURE 14.7

Relative control performance of single-loop and cascade ($\sigma_{casc}/\sigma_{sl}$) for a stochastic disturbance in the secondary loop.

The amplitude ratios for the cascade control system were calculated for a range of frequencies using equation (14.6). Because of the complexity of the algebra, the amplitude ratios were evaluated using a computer program similar to the one in Table 13.1, and the results are plotted in Figure 14.9.

The smaller amplitude ratio for cascade clearly demonstrates the advantage of cascade control, especially when the secondary process is much faster than the primary (here, $\eta = 10$). The cascade system is very effective for slower disturbance frequencies. Both systems have little deviation for very fast disturbances, because the process attenuates these disturbances. Also, the effect of the resonant frequency, which was discussed in Chapter 13, is attenuated but not eliminated by the cascade system.

Finally, the performance of a cascade control strategy must be evaluated for circumstances for which this enhancement was not specifically designed—that is,

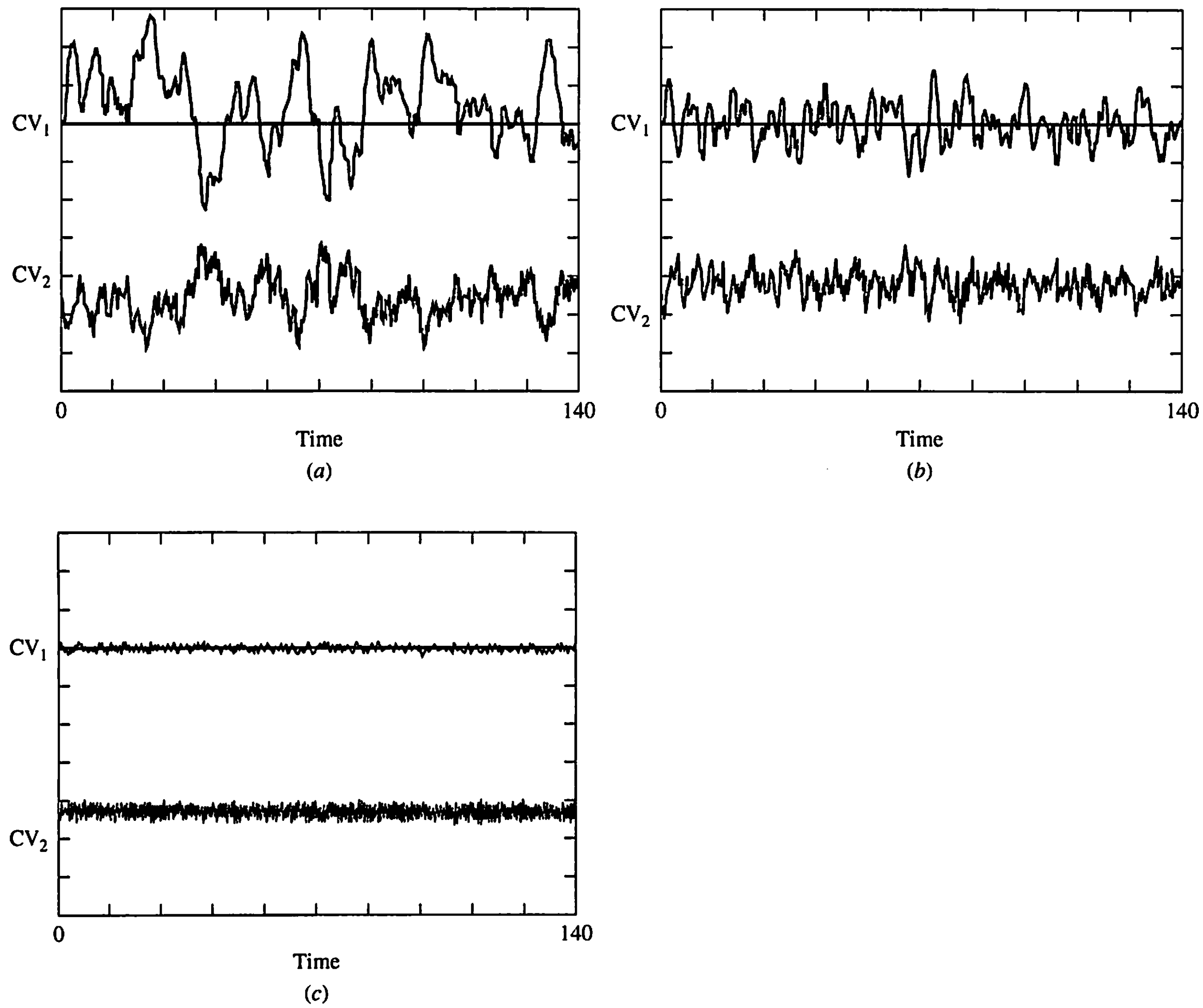

FIGURE 14.8

Dynamic responses for stochastic secondary disturbance with $\eta = 10$: (*a*) open-loop process; (*b*) single-loop control; (*c*) cascade control.

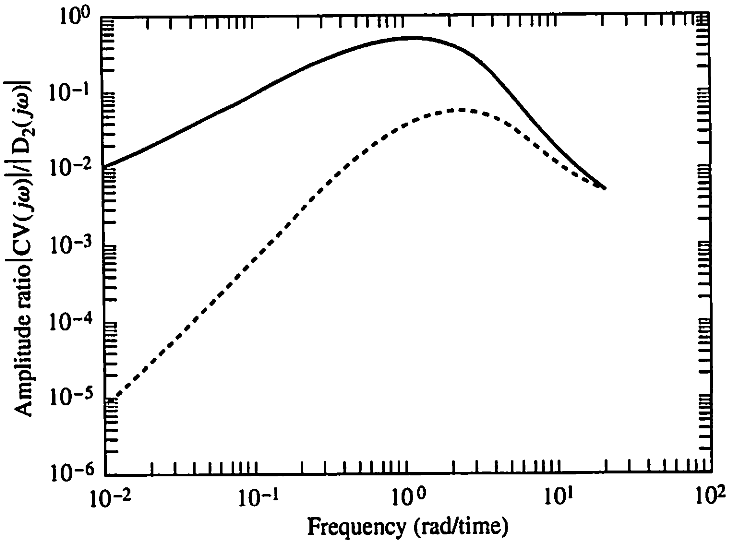

FIGURE 14.9

Closed-loop frequency responses for single-loop (solid curve) and cascade (dotted curve) control with $\eta = 10$.

primary disturbances that do not directly affect the secondary variable and changes to the primary set point. By analyzing the cascade block diagram, it is apparent that the primary controller can respond to other types of disturbance in the cascade design; the only difference is that it manipulates the secondary set point rather than the valve directly. One would expect that the responses to unmeasured disturbances and set points are not substantially changed. This is the case, with cascade providing slightly better performance because it increases the critical frequency of the secondary loop (Krishnaswamy et al., 1990). In conclusion,

> Cascade control can substantially improve control performance for disturbances entering the secondary loop and is recommended for use when the secondary loop is much faster than the primary loop.

14.5 ▫ CONTROLLER ALGORITHM AND TUNING

Cascade control can use the standard feedback control PID algorithm; naturally, the correct modes must be selected for each controller. The secondary must have the proportional mode, but it does not require the integral mode, because the overall control objective is to maintain the *primary* variable at its set point. However, integral mode is often used in the secondary, for two reasons. First, since a proportional-only controller results in offset, the secondary must have an integral mode if it is to attenuate the effect of a disturbance completely, preventing the disturbance from propagating to the primary. Second, the cascade is often operated in a partial manner with the primary controller not in operation, for example, when the primary sensor is not functioning or is being calibrated. A negative side of including integral mode in the secondary controller is that it tends to induce oscillatory behavior in the cascade system, but the result is not significant when the secondary is much faster than the primary. Studies have demonstrated the effectiveness of the integral mode in the secondary loop (Krishnaswamy et al., 1992). The secondary may have derivative mode if required, but the fast secondary loop almost never has a large enough fraction dead time to justify a derivative mode.

The modes of the primary controller are selected as for any feedback PID controller. It is again emphasized that the integral mode is essential for zero offset of the primary variable.

The cascade strategy is tuned in a sequential manner. The secondary controller is tuned first, because the secondary affects the open-loop dynamics of the primary, $CV_1(s)/SP_2(s)$. During the first identification experiment (e.g., process reaction curve), the primary controller is not in operation (i.e., the primary controller is in manual or the cascade is "open"), which breaks the connection between the primary and secondary controllers. The secondary is tuned in the conventional manner as described in Chapter 9. This involves a plant experiment, initial tuning calculation, and fine tuning based on a closed-loop dynamic response.

When the secondary has been satisfactorily tuned, the primary can be tuned. The initial plant experiment perturbs the variable that the primary controller adjusts; in this case, the *secondary set point* is perturbed in a step for the process reaction curve. The calculation of the initial tuning constants and the fine tuning follow the conventional procedures. Naturally, the secondary must be tuned satisfactorily before the primary can be tuned.

> Tuning a cascade control system involves two steps; first, the secondary controller is tuned; then, the primary controller is tuned. Conventional initial tuning guidelines and fine-tuning heuristics apply.

14.6 IMPLEMENTATION ISSUES

When properly displayed for the operator, cascade control is very easy to understand and to monitor. Since it uses standard PID control algorithms, the operator displays do not have to be altered substantially. The secondary controller requires one additional feature: a new status termed "cascade" in addition to automatic and manual. When the status switch is in the cascade position (cascade closed), the secondary set point is connected to the primary controller output; in this situation the operator cannot adjust the secondary set point. When the status switch is in the automatic or manual positions (cascade open), the secondary set point is provided by the operator; in this situation the cascade is not functional.

Cascade control is shown in a very straightforward way in engineering drawings. Basically, each controller is drawn using the same symbols as a single-loop controller, with the difference that the primary controller output is directed to the secondary controller as shown in Figure 14.2. Often, the signal from the primary controller output is annotated with "reset" or "SP" to indicate that it is adjusting or resetting the secondary set point.

The calculations required for cascade control, basically a PID control algorithm, are very simple and can be executed by any commercial analog or digital control system. Two special features contribute to the success of cascade. The first is anti-reset windup. The potential exists for any controller in a cascade to experience integral windup due to a limitation in the control loop. Analysis for the secondary is the same as for a single-loop design; however, reset windup can occur for one of several reasons in the primary controller. The primary controller output can fail to move the valve because of limits on (1) the secondary set point, (2) the secondary controller output, or (3) the valve (fully opened or closed). Thus, the potential for reaching limits and encountering reset windup, along with the need for anti-reset windup, is *much greater in cascade designs.* Standard anti-reset windup methods described in Chapter 12 provide satisfactory anti-reset windup protection.

The second feature is "bumpless" initialization. Note that changing the secondary status switch to and from the cascade position could immediately change the value of the secondary set point, which is not desired. The desired approach is to recalculate the primary controller output to be equal to the secondary set point on initialization. Many commercial controllers include calculations to ensure that the secondary set point is not immediately changed (bumplessly transferred) when the secondary mode switch is changed.

Digital control equipment can use the standard forms of the PID algorithm presented in Chapter 11 for cascade control. In addition to the execution period of each controller, the scheduling of the primary and secondary influences cascade control performance. To reduce delays due to control processing, the secondary should be scheduled to execute immediately after the primary. Naturally, it makes no sense to execute the primary controller at a higher frequency (i.e., with a shorter period) than the secondary, because the primary can affect the process (move the valve) only when the secondary is executed.

The cascade control system uses more control equipment—two sensors and controllers—than the equivalent single-loop system. Since the cascade requires all of this equipment to function properly, its reliability can be expected to be lower than the equivalent single-loop system, although the slightly lower reliability is not usually a deterrent to the use of cascade. If feedback control must be maintained when the secondary sensor or controller is not functioning, the flexibility to bypass the secondary and have the primary output directly to the valve can be included in the design. This option is shown in Figure 14.10, where the positions of both switches are coordinated.

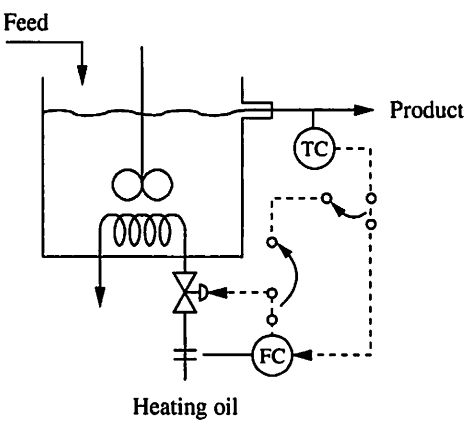

FIGURE 14.10

Control design with a switch to bypass the cascade and convert to single-loop control.

Since the cascade involves more equipment, it costs slightly more than the single-loop system. The increased costs include a field sensor and transmission to the control house (if the variable were not already available for monitoring purposes), a controller (whose cost may be essentially zero if a digital system with spare capacity is used), and costs for installation and documentation. These costs are not usually significant compared to the benefits achieved through a properly designed cascade control strategy.

Cascade control, where applicable, provides a simple method for substantial improvements in control performance. The additional costs and slightly lower reliability are not normally deterrents to implementing cascade control.

14.7 ▫ FURTHER CASCADE EXAMPLES

The concept of cascade control is consolidated and a few new features are presented through further examples in this section.

EXAMPLE 14.1. Packed-bed reactor.

The first example is the packed-bed reactor shown in Figure 14.11. The goal is to tightly control the exit concentration measured by AC-1. Suppose that the single-loop controller does not provide adequate control performance and that the most significant disturbance is the heating medium temperature, T2. The goal is to design a cascade control strategy for this process using the sensors and manipulated variables given. The reader is encouraged to design a cascade control system before reading further.

Since we are dealing with a cascade control strategy, the key decision is the selection of the secondary variable. Therefore, the first step is to evaluate the potential measured variables using the design criteria in Table 14.1; the results of this evaluation are summarized in Table 14.2, with Y(N) indicating that the item is (is not) satisfied. Since *all of the criteria must be satisfied* for a variable to be used as a secondary, only the reactor inlet temperature, T3, is a satisfactory secondary variable.

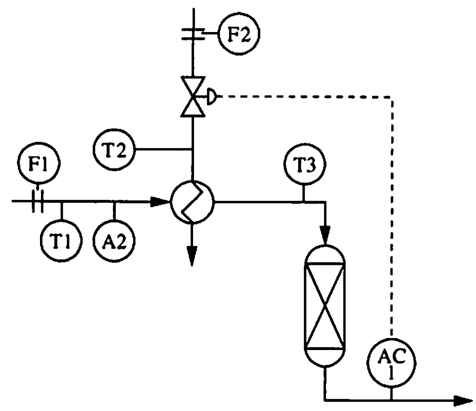

FIGURE 14.11

Single-loop packed-bed reactor control.

The resulting cascade control strategy is shown in Figure 14.12. Given the cascade design, an interesting and important question is, "How well does it respond to other disturbances for which it was not specifically designed?" Several disturbances are discussed qualitatively in the following paragraphs.

Feed temperature, T1. A change in the feed temperature affects the outlet concentration through its influence on the reactor inlet temperature, T3. Therefore, the cascade controller is effective in attenuating the feed temperature disturbance.

Heating oil pressure (not measured). A change in the oil pressure influences the oil flow and, therefore, the heat transferred. As a result the reactor inlet temperature, T3, is affected. Again, the cascade controller is effective in attenuating the oil pressure disturbance.

Feed flow rate, F1. A change in the feed flow rate influences the reactor outlet concentration in two ways: it changes the inlet temperature T3, and it changes the residence time in the reactor. The cascade controller is effective in attenuating the effect of the disturbance on T3 but is not effective in compensating for the residence time change. The residence time effect must be compensated by the primary controller, AC-1.

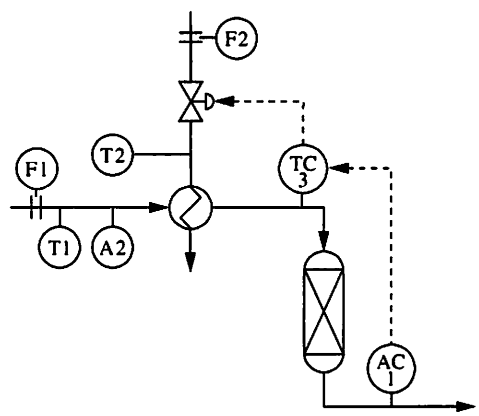

FIGURE 14.12

Cascade packed-bed reactor control.

TABLE 14.2

Evaluation of potential secondary variables

Criterion	A2	F1	F2	T1	T2	T3
1. Single-loop control is not satisfactory	Y	Y	Y	Y	Y	Y
2. Variable is measured	Y	Y	Y	Y	Y	Y
3. Indicates a key disturbance	N	N	N	N	Y	Y
4. Influenced by MV	N	N	Y	N	N	Y
5. Secondary dynamics faster	N/A	N/A	Y	N/A	N/A	Y

Feed composition, A2. A change in the feed composition clearly changes the reactor outlet concentration. The cascade has no effect on the feed composition disturbance, because the composition does not influence T3. Therefore, this disturbance must be totally compensated by the primary feedback controller, AC-1.

> A single cascade control system can be effective in compensating for the effects of several disturbances, and given several possible secondary variables, the one that attenuates the most important disturbances is the best choice.

Conclusions and Tuning. In some cases, the attenuation is complete (at least in the steady-state sense); in other cases, the attenuation is partial. Thus, a well-designed cascade strategy can produce a major improvement in the control system performance. This example is completed by describing the tuning procedure.

1. Both controllers are placed in the manual mode, and a process reaction curve experiment is performed to obtain a model for tuning the secondary controller. The model parameters and tuning based on Figure 9.9*a* and *b* are

Model relating valve to T_3	**T_3 controller**
$K_{p2} = 0.57°C/\%$	$K_{c2} = 2.4\%/°C$
$\theta_2 = 8$ s	$T_{I2} = 23$ s
$\tau_2 = 20$ s	

2. The tuning constants are entered into the secondary controller, which is fine-tuned by placing it in automatic and entering small set point changes.
3. A process reaction curve experiment is performed to obtain the model for tuning the primary controller. The model and parameters are

Model relating T_3 set point to A_1	**A_1 controller**
$K_{p1} = -0.19$ mole/m^3/°C	$K_{c1} = -7.9$°C/mole/m^3 (changed to −3.7 in fine tuning)
$\theta_1 = 20$ s	$T_{I1} = 54$ s (changed to 70 in fine tuning)
$\tau_1 = 50$ s	

4. The tuning constants are entered into the primary controller, and the controller is fine-tuned by placing it in automatic and entering small set point changes. Note that the primary loop was somewhat oscillatory, so that the primary controller gain and time constant were modified as noted in the foregoing list.
5. The response to a disturbance is observed and further fine tuning is applied to improve the response, if necessary. A dynamic response to a disturbance

in the secondary loop is shown in Figure 14.13: $D_2(s) = -1.8/s$; $G_{d2}(s) = 1/(1+20s)$.

Finally, we note that the secondary variable is sensed at the outlet of the heat exchanger. This contributes to its effectiveness, because it can sense the influence of many inlet temperature and flow disturbances. However, the heat exchanger dynamics make the secondary dynamic response somewhat slow. One improvement in the design is to add another level of cascade to compensate for the oil pressure disturbance, which can be sensed by the flow sensor F2. The three-level cascade is shown in Figure 14.14. Industrial designs with three to four cascade levels (and sometimes more) are not unusual and function well.

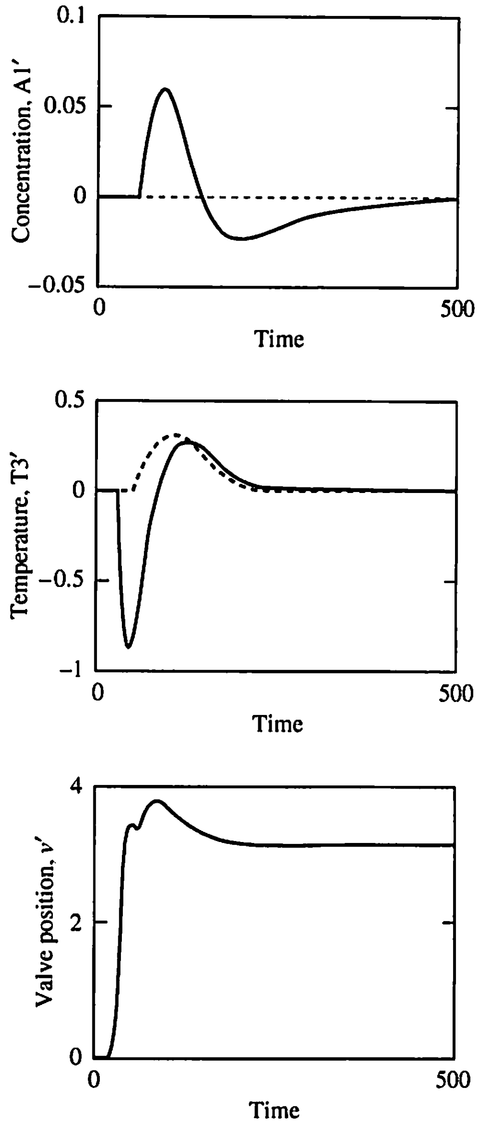

FIGURE 14.13

Dynamic response of the reactor cascade controller to a disturbance in the heating medium temperature in Example 14.1.

There is no theoretical or practical limit to the number of cascade levels used as long as each level conforms to the design criteria in Table 14.1.

Cascade control can be applied to a variety of processes. A few more examples are presented briefly to demonstrate the diversity of the cascade approach. In each case, an analysis similar to the method shown in Table 14.2 was performed to design the cascade strategy.

EXAMPLE 14.2. Fired heater.

Another typical cascade design is given in Figure 14.15 for furnace control. A single-loop temperature controller would adjust the fuel valve directly, making the fuel flow subject to pressure disturbances. A cascade control strategy is possible that satisfies all of the design criteria. In the cascade, the outlet temperature of the fluid in the coil is controlled tightly by adjusting the fuel flow controller set point,

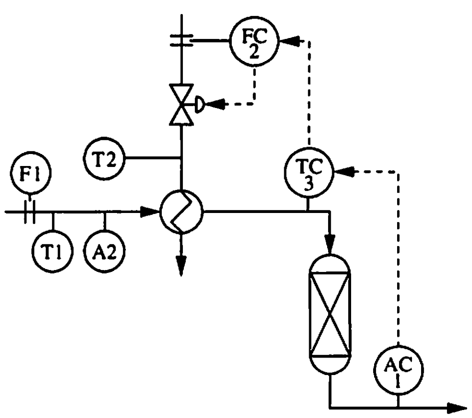

FIGURE 14.14

Three-level cascade control for packed-bed reactor.

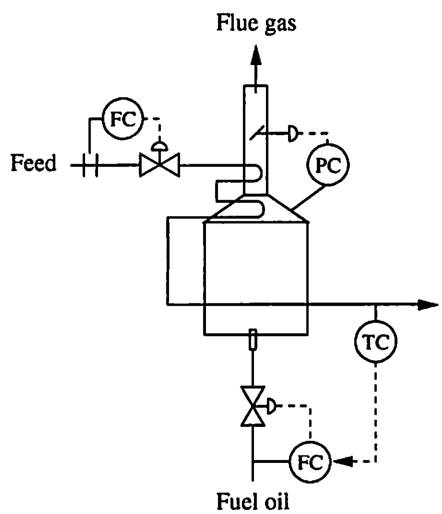

FIGURE 14.15

Cascade control design for outlet temperature.

which adjusts the valve position. An additional advantage of the cascade becomes apparent when considering the performance of many real control valves; the valve does not always move exactly the amount directed by the controller, because friction occasionally causes sticking, which degrades control performance. The cascade design with a flow controller as its fast secondary corrects quickly for both fuel pressure disturbances and the effects of a sticking valve and substantially improves control performance over the single-loop strategy.

EXAMPLE 14.3. Valve positioner.

Cascade control principles are used to enhance the performance of control valves when fast secondary variables cannot be included in the design. Because of a difference between static and dynamic friction, valves often stick and do not exactly achieve the percent stem position demanded by the controller output. The result is that the valve may remain stationary and then "jump" to a value beyond necessary to bring the controlled variable to its set point. A standard control valve can have a dead zone of up to 3 percent (Buckley, 1970), which can lead to poor control and cycling in many control systems. If the valve is being adjusted by a fast control loop (and the process is not sensitive to high-frequency cycling), no corrective action may be necessary; however, valve sticking can lead to severe control performance degradation.

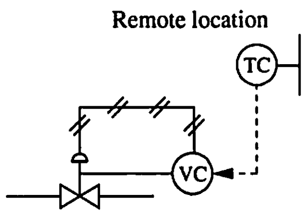

FIGURE 14.16

Schematic of a valve positioner.

The effects of valve sticking can be reduced by including a cascade controller called a *valve positioner,* which is included as part of the valve equipment as shown in Figure 14.16. The primary controller, which can be controlling any measured process variable, sends a signal, which is interpreted as the desired valve stem position (0–100%), to the valve positioner. The positioner senses the *actual valve* stem position and adjusts the air pressure until the desired stem position is (nearly) achieved. Since a valve positioner uses a proportional-only algorithm, it does not give perfect compensation for sticking, but the fast dynamics allow a very high controller gain, which reduces the dead zone to about one-tenth of that experienced without a positioner. It is worth noting that this improvement is achieved with minimal investment.

Other advantages are provided by valve positioners, such as faster valve dynamics and overcoming large pressure drops. They are also used when split range control (see Chapter 22) or changes in the valve characteristic (see Chapter 16) are required. There is no consensus concerning the application of positioners on fast loops; some practitioners recommend them on essentially all control valves, whereas others recommend them only on slow loops.

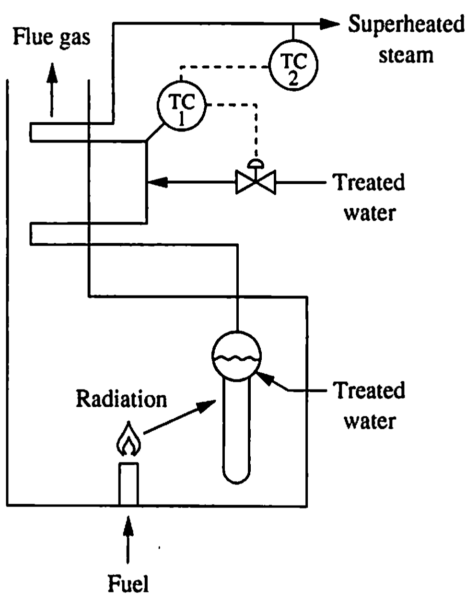

FIGURE 14.17

Cascade control design for boiler superheated steam temperature control.

EXAMPLE 14.4. Steam superheater.

Industrial processes consume large quantities of steam for heating, and machinery consumers require superheated steam for power. As shown in Figure 14.17, steam is generated by vaporizing water in a boiler where the heat transfer is by radiation. The saturated steam temperature is then raised further by convective heat exchange with the hot combustion flue gases. The final steam temperature is controlled by injecting water in the steam. The primary temperature controller could adjust the spray water valve directly, but the control performance would not be good, because of the long dynamic response to disturbances in water flow and heat transfer. The control performance is good for the cascade control with a secondary that responds quickly to both types of disturbances.

EXAMPLE 14.5. Heater exchanger.

A process stream can be cooled by exchanging heat with a refrigerant, which is vaporized in the exchanger. An example is shown schematically in Figure 14.18, which shows that the rate of heat transfer can be controlled by adjusting the heat transfer area (i.e., the liquid refrigerant level in the exchanger). This operating policy is implemented by the cascade control strategy in the figure, where the secondary controller responds quickly to disturbances in liquid flow resulting from pressure variations. An additional advantage is that the level controller maintains the liquid level within acceptable limits; in contrast, a single-loop temperature controller directly adjusting the valve might cause liquid refrigerant to carry over and damage downstream equipment.

EXAMPLE 14.6. Pressure control.

Normally, pressure control involves fast process responses and does not require cascade control. However, processes sometimes have large, integrated systems with a single valve regulating the pressure. An example is shown in Figure 14.19, where the most important pressure is at the initial unit, and the pressure control valve is located far downstream. In this case, pressure disturbances near the control valve can cause a relatively large, prolonged disturbance in the initial unit's pressure. The cascade strategy shown in the figure rapidly senses and corrects for downstream disturbances before they upset the integrated upstream unit.

EXAMPLE 14.7. Jacketed CSTR.

An often-noted example of cascade control is the jacketed continuous-flow stirred-tank reactor shown in Figure 14.20. The dynamics related to the thermal capacitance of the jacket fluid and metal could lead to poor control performance with

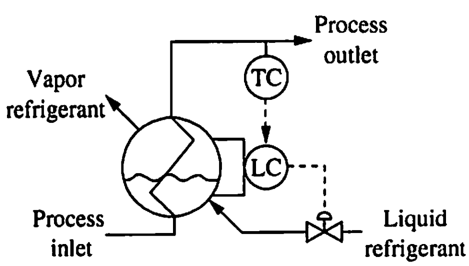

FIGURE 14.18

Cascade control design for temperature control.

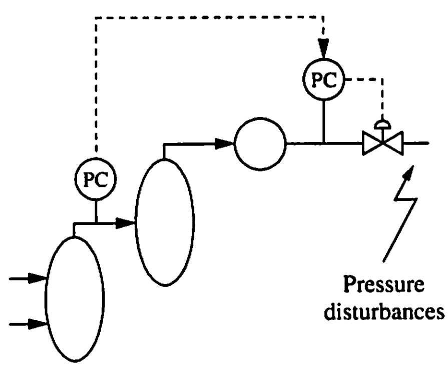

FIGURE 14.19

Cascade control design for pressure control.

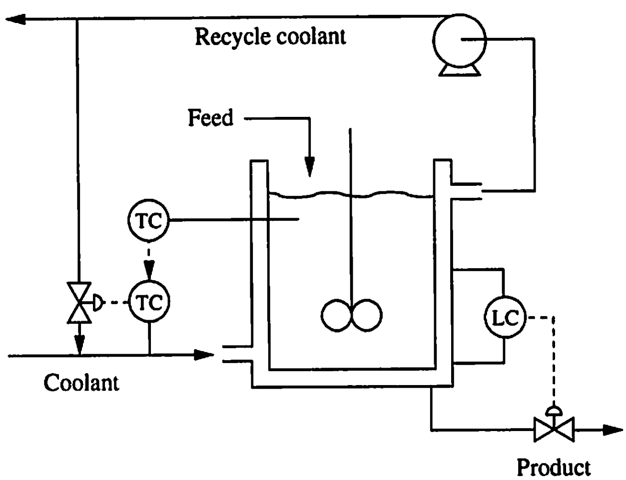

FIGURE 14.20

Cascade control for a stirred-tank reactor with cooling jacket.

single-loop control from the reactor temperature directly to the valve that controls the inlet temperature of the jacket fluid. A cascade controller uses a secondary variable to sense and quickly correct a disturbance in the jacket fluid inlet temperature.

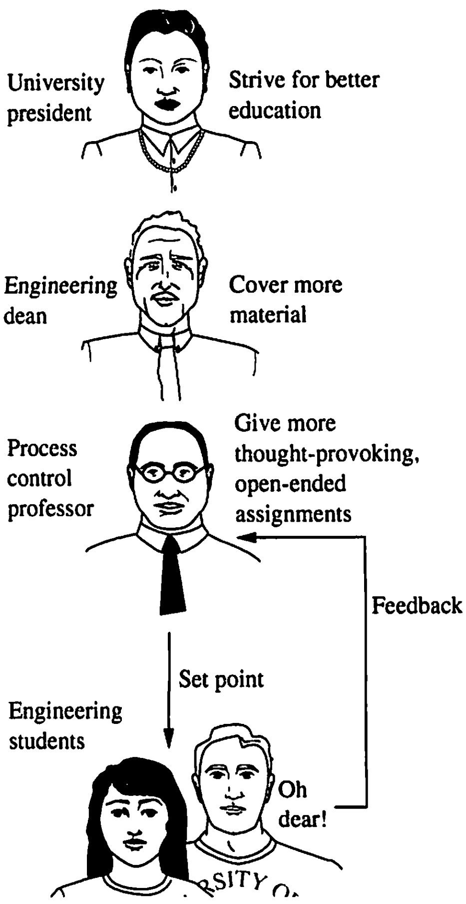

FIGURE 14.21

A cascade process at a university.

14.8 CASCADE CONTROL INTERPRETED AS DISTRIBUTED DECISION MAKING

Cascade control is essentially a way to delegate decision making to the lowest level possible. In the packed bed reactor (Figure 14.12), the outlet analyzer AC-1 determines the desired value for the inlet temperature TC-3. The inlet temperature controller is free to determine the valve position that is required to achieve the desired value of TC-3. Since the T3 measurement provides rapid indication of every effect on the reactor inlet temperature, it can achieve the required inlet temperature control better than AC-1.

Cascade control concepts are not limited to engineering control systems. Social and business organizations also benefit from distributed decision making. A hypothetical example of university decision making is given in Figure 14.21. The president of a university decides to improve the education of the engineering students. Rather than tell each student how and what to learn, the president informs the Dean of Engineering. The Dean of Engineering gives directions to the Process Control professor, who finally gives directions to the students. The students then implement the decision by adjusting their studying to satisfy the requirements set by the professor. This distribution allows quick response to disturbances, such as competing demands of other courses, and provides frequent feedback from class discussion and course quizzes. The distributed system surely functions better than the single-loop feedback approach in which the president would obtain feedback every few years and then give directions to every student in the university. It also might clarify why the secondary controller is sometimes called the "slave"!

14.9 ◻ CONCLUSIONS

In this chapter, the principles of cascade control have been presented, and the excellent performance of cascade control for disturbance rejection has been established. Cascade control employs the principle of *feedback* control, since the secondary variable is a process output that depends on the manipulated variable in a causal manner. Cascade control can improve performance when the dynamics, mainly the dead time, of the secondary loop is much shorter than in the primary. In this situation, some disturbances can be measured and compensated quickly. As shown in Figure 14.3*a* and *b*, this improved performance of the controlled variable is achieved without significantly increasing the variability of the manipulated variable. Based on this performance improvement and simplicity of implementation, the engineer is well advised to evaluate cascade control as the first potential single-loop enhancement.

The first few times new control engineers evaluate cascades, they should perform a careful study like the one in Table 14.2, but after some experience they will be able to design cascade controls quickly by applying the design principles without explicitly writing the criteria and table.

However, cascade control is not universally applicable; the design criteria in Table 14.1 can be used to determine whether cascade is appropriate and if so, select the best secondary variable. If it is not immediately possible and a significant improvement in control performance is desired, the engineer should investigate the possibility of adding the necessary secondary sensor. Even with improved sensors, cascade is not always possible; for example, a causal relationship between the manipulated variable and a measurement indicating the disturbance may not exist. Thus, while cascade is usually the preferred choice for enhancing control performance, further enhancement approaches are often required, and some of these are introduced in subsequent chapters.

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Buckley, P., "A Control Engineer Looks at Control Valves," in Lovett, O. (ed.), Paper 2.1, *Final Control Elements, First ISA Final Control Elements Symposium,* May 14–16, 1970.

Krishnaswamy, P., and G. Rangaiah, "Role of Secondary Integral Action in Cascade Control," *Trans. IChemE., 70,* 149–152 (1992).

Krishnaswamy, P., G. Rangaiah, R. Jha, and P. Despande, "When to Use Cascade Control," *IEC Res., 29,* 2163–2166 (1990).

Verhaegen, S., "When to Use Cascade Control," *In. Tech.*, 38–40 (October 1991).

ADDITIONAL RESOURCES

Cascade control has been used for many decades and seems to have been developed by industrial practitioners, who often do not publish their results. Therefore, the inventor(s) of cascade are not known. A few of the earlier papers are listed here.

Franks, R., and C. Worley, "Quantitative Analysis of Cascade Control," *IEC, 48*, 1074 (1956).

Webb, P., "Reducing Process Disturbances with Cascade Control," *Control Eng.*, *8*, *8*, 63 (1961).

QUESTIONS

14.1. (*a*) In your own words, discuss each of the cascade design criteria. Give a process example in which cascade control is appropriate.
(*b*) Identify the elements of the cascade block diagram in Figure 14.4 that are process, instrumentation, and control calculations.
(*c*) Discuss the topics in Table 13.3 that are influenced by cascade control, explaining how cascade improves performance for each.
(*d*) For the mixing system in Figure 13.4 and a disturbance in the feed concentration, discuss how you would add one sensor to improve control performance through cascade control.

14.2. Derive the transfer function in equations (14.6) to (14.8) based on the block diagram in Figure 14.4.

14.3. Figure 14.9 presents the frequency responses for single-loop and cascade control with a disturbance in the secondary loop.
(*a*) Sketch the general shapes and discuss the frequency responses for cascade and single-loop control for (1) a set point change and (2) a disturbance in the primary loop.
(*b*) Calculate the frequency responses for (*a*), with $G_{d1}(s) = G_{p1}(s)$ and $\eta = 10$.

14.4. Based on the transfer function in equation (14.6), mathematically demonstrate the assertion made in this chapter that cascade control performance for a secondary disturbance improves as the secondary becomes faster. For this question, assume that the secondary controller is a PI. (Hint: Evaluate the amplitude ratio as a function of frequency.)

14.5. Answer the following questions based on the transfer function in equation (14.6).
(*a*) Mathematically demonstrate the assertion made in this chapter that integral mode in the secondary controller is not required for zero offset in the primary.
(*b*) Demonstrate the assertion that the secondary controller must be tuned before the primary is tuned.
(*c*) This question addresses why the integral mode is often included for the secondary controller. Consider the secondary controller and its initial response to a disturbance before any feedback from the primary. Calculate the amount that a P-only and a PI controller attenuate the same disturbance at the limit of *low frequency* (i.e., at steady state). Based on this analysis, which controller is more effective in attenuating a disturbance?
(*d*) When the secondary has an integral mode, the integral error of the primary is zero for a step disturbance. The oscillatory effect of the integral error being zero is apparent in Figure 14.6. For the transfer function in equation (14.6), prove this statement. You may use the

following relationship (see Appendix D, equation (D.4)):

$$\int_0^\infty E_1(t')dt' = E_1(s)|_{s=0}$$

14.6. Discuss the proposed cascade control designs. In particular, apply the cascade control criteria to each proposed design, and estimate whether the cascade design would provide better performance than single-loop for disturbance response. Consider each of the disturbances separately. To assist in the analysis, prepare a block diagram for each process showing the appropriate cascade control systems.

(*a*) Jacketed stirred-tank reactor in Figure 14.20; disturbances are (1) coolant pressure, (2) coolant temperature, (3) recycle pump outlet pressure, (4) reaction rate (e.g., feed concentration), and (5) feed flow rate.

(*b*) Furnace coil outlet temperature control in Figure 14.15; disturbances are (1) fuel pressure, (2) fuel density (composition), (3) valve sticking, and (4) feed temperature.

(*c*) Repeat (*b*) with the temperature controller cascaded to a valve positioner, without the flow controller.

(*d*) Figure Q1.9*a* modified for cascade control with a level to flow to valve control structure; disturbances are (1) pump outlet pressure and (2) second outflow valve percent open.

(*e*) Analyzer to reboiler flow cascade for distillation in Figure Q14.6; disturbances are (1) heating medium temperature, (2) feed temperature, (3) tower pressure, and (4) heating medium downstream pressure.

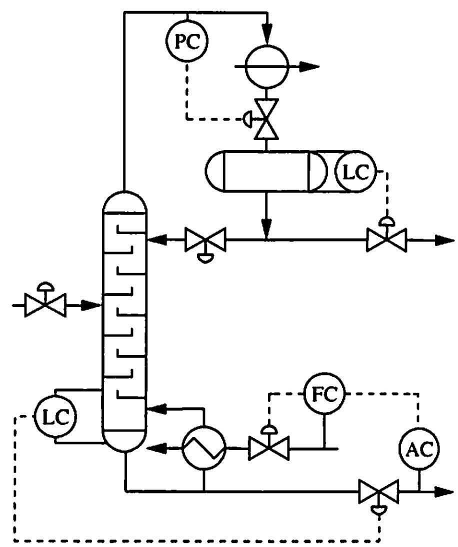

FIGURE Q14.6

14.7. Assume that the dynamic behavior in Figure 14.8*a* through *c* are for a fired heater in Example 2.1 that has the goal of maximizing temperature without exceeding a maximum constraint of 864°C; a performance correlation is provided in the example. The primary variable is temperature, which is plotted as the top variable in Figure 14.8*a* through *c*. Assume that 10 percent of the scale represents 5°C and that the top of the scale is 864°C.

(*a*) Estimate the benefit for (1) single-loop and (2) cascade control due to the reduction in the variability in the temperature using the data in Figure 14.8*a* through *c*.

(*b*) Suggest changes to the operating conditions (set points) for both control designs and repeat the estimation done in (*a*).

14.8. The cascade control design shown in Figure 14.12 should have anti-reset windup protection.

(*a*) Discuss the potential causes for integral windup in this strategy.

(*b*) Assume that the feedback algorithms are of the form that use external feedback, as described in Chapter 12. Which signal should be used for external feedback for each controller? Explain your answer.

(*c*) In Chapter 11, the use of digital PI algorithms was explained. Discuss the performance of the incremental (velocity) algorithm as the primary temperature controller when the valve reaches its maximum or minimum position. Does the velocity form of the PI controller satisfactorily prevent reset windup?

14.9. The initial design for the packed-bed reactor, Figure 14.11, included a controller for the outlet concentration and a single control valve. The cascade control design *added a controller* but did not change the number of control valves. This might seem to violate the degrees of freedom of the process.

(*a*) In your own words, discuss why the cascade is possible.
(*b*) Perform a degrees-of-freedom analysis to demonstrate that the cascade control is possible. You may use the transfer function model of the reactor for this analysis.

14.10. For the following control designs determine which valves should have positioners and explain why: (*a*) Figure 13.19, (*b*) Figure 2.2, (*c*) Figure 14.1, and (*d*) Figure 14.2.

14.11. A stirred-tank chemical reactor is shown in Figure Q14.11 with the following reaction.

$$A \rightarrow B \qquad \Delta H_{rxn} = 0$$

$$r_A = -k_0 e^{-E/RT} \frac{C_A}{1 + kC_x}$$

The available sensors and control valves are shown in the figure, and no changes to these are allowed. The goal is to control the reactor concentration of A tightly by single-loop or cascade control, whichever is better. For each of the following disturbances, design the best control system and explain your design: (*a*) the heating medium pressure (P_1), (*b*) the solvent feed temperature (T_s), (*c*) the reactant feed pressure (P_2), and (*d*) the inhibitor concentration (C_x) which enters in the solvent. (To assist in the analysis, prepare a block diagram for each case showing the appropriate single-loop or cascade control system.)

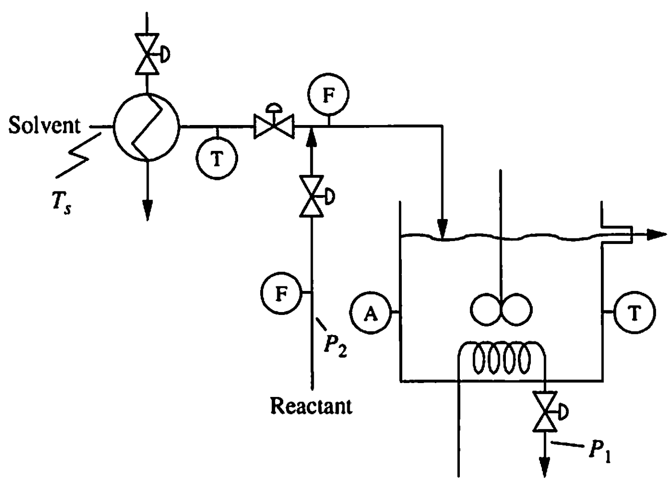

FIGURE Q14.11

14.12. A set of cascade design criteria are presented in an article by Verhaegen (1991). Discuss the similarities and differences between the criteria in this chapter and in the article.

14.13. The chemical reactor with separate solvent and reactant feed flows in Figure Q14.13 has the following properties: well-mixed, isothermal, constant volume, constant density, and $F_s \approx F_A$. The chemical reaction occurring is A $\rightarrow$ B with the reaction rate, $r_A = -kC_A$. The concentrations of the reactant and the product can be measured without delay. Follow the steps in this question to evaluate two possible cascade control designs to select the best for controlling the concentration of product B in the effluent, measured by A2.

(*a*) The total feed flow ($F1$) and the feed concentration (A1) are the potential *secondary* variables for the reactor effluent primary composition control. Construct a control scheme and sketch it on the figure that will control these two variables ($F1$, A1) simultaneously to independent set point values. You must add two feedback controllers. If needed, you may move the locations of the sensors and valves.

(*b*) Derive the dynamic model $C_B(s)/C_{A0}(s)$ [or A2(s)/A1(s)] under the control in (*a*), i.e., with $F1$ constant. Analyze the model regarding (i) order, (ii) stability, (iii) periodicity, and (iv) step response characteristics.

(*c*) Derive the dynamic model for $C_B(s)/F(s)$ [or A2(s)/F1(s)] under the control in (*a*), i.e., with A1 constant. Analyze the model regarding (i) order, (ii) stability, (iii) periodicity, and (iv) step response characteristics.

(*d*) The results in (*b*) and (*c*) provide the dynamics of the primary feedback process for the two designs. Based on these results, select which of the secondary variables would provide the best feedback control for a set point change in A2. Your answer should be either A2 $\rightarrow$ A1 or A2 $\rightarrow$ F1. Sketch the feedback (cascade) structure on the figure prepared in (*a*).

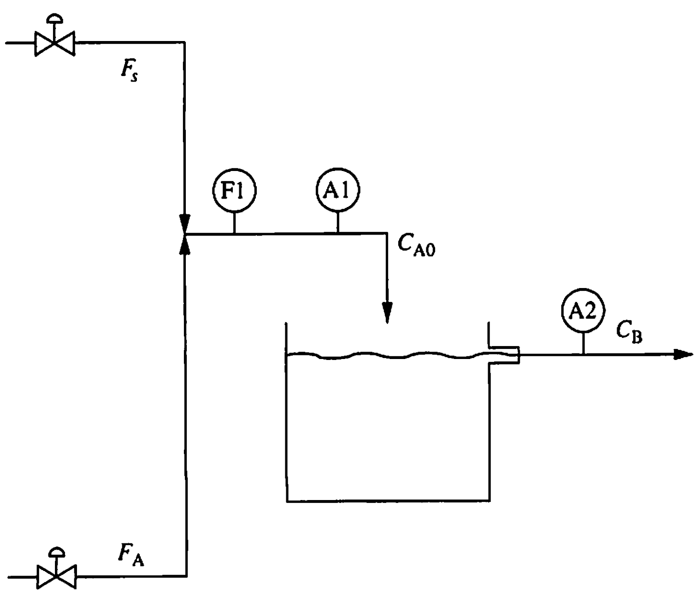

FIGURE Q14.13

(*e*) Compare with the solution in Example 13.8 and discuss whether your design is expected to provide better or worse control performance for A2.

14.14. In the packed-bed reactor example (14.1) an alternative approach would be possible. In the alternative approach, the oil temperature (T2) would be measured and the effect on the outlet analyzer due to changes in oil temperature could be calculated and used to adjust the valve. Which design—cascade control or the alternative described here—would you prefer? Discuss why.

14.15. Prepare a digital computer program to perform the control calculations for the cascade control system in Figure 14.12. Include initialization, reset windup, and other factors required for good implementation.

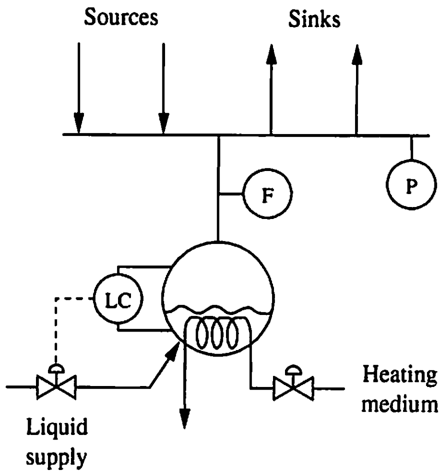

FIGURE Q14.16

14.16. A vaporizer process is shown in Figure Q14.16. The gas pipe (header) has several sources and sinks of gas, and the pressure in the pipe is to be controlled by adjusting the amount vaporized.

(*a*) A cascade control design has been suggested from the pressure to the flow of vapor to the heating medium valve. Evaluate this design using the cascade design criteria. Correct it if necessary.

(*b*) Discuss the response of this cascade design to a disturbance in the heating medium pressure, upstream of the control valve.

(*c*) Discuss the response of this cascade design to a disturbance in one of the source or sink flows.

(*d*) Discuss the response of this cascade design to a disturbance in the liquid temperature.

(*e*) Generalize the results from (*b*) through (*d*) and develop a further cascade design criterion to be added to those in Table 14.1.