THIRD EDITION

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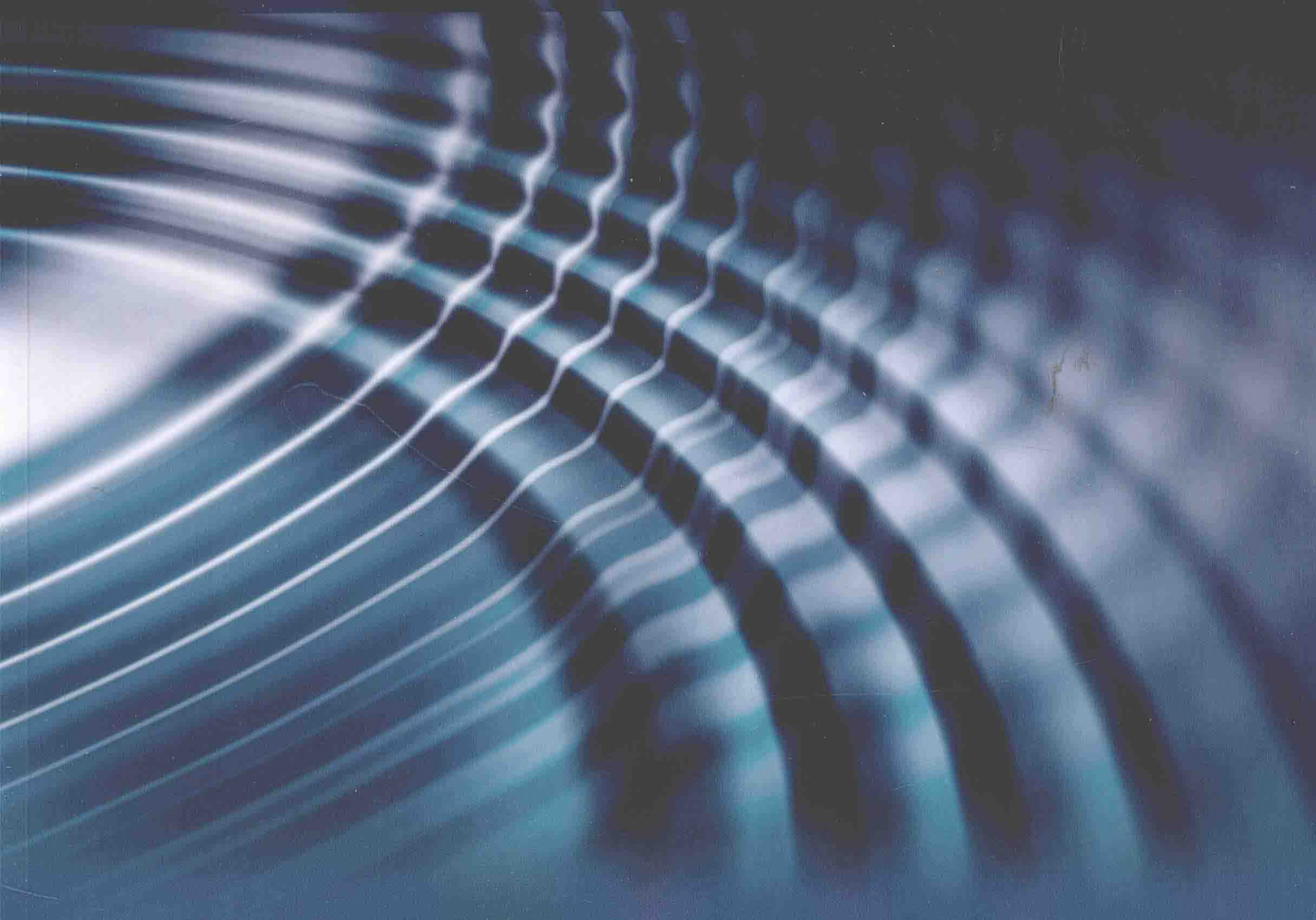

Process Dynamics and Control

International Student Version

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Third Edition

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To our wives, children, and parents

About the Authors

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Duncan A. Mellichamp is professor Emeritus and founding member of the faculty of the chemical engineering department at the University of California, Santa Barbara. He is editor of an early book on data acquisition and control computing and has published more than one hundred papers on process modeling, large scale/plantwide systems analysis, and computer control. He earned a B.S. degree from Georgia Tech and a Ph.D. from Purdue University with intermediate studies at the Technische Universität Stuttgart (Germany). He worked for four years with the Textile Fibers Department of the DuPont Company before joining UCSB. Dr. Mellichamp has headed several organizations, including the CACHE Corporation (1977), the UCSB Academic Senate (1990–92), and the University of California Systemwide Academic Senate (1995–97), where he served on the UC Board of Regents. He presently serves on the governing boards of several nonprofit organizations.

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Preface

Process control has become increasingly important in the process industries as a consequence of global competition, rapidly changing economic conditions, faster product development, and more stringent environmental and safety regulations. Process control and its allied fields of process modeling and optimization are critical in the development of more flexible and more complex processes for manufacturing high-value-added products. Furthermore, the rapidly declining cost of digital devices and increased computer speed (doubling every 18 months, according to Moore's Law) have enabled high-performance measurement and control systems to become an essential part of industrial plants.

It is clear that the scope and importance of process control technology will continue to expand during the 21st century. Consequently, chemical engineers need to master this subject in order to be able to design and operate modern plants. The concepts of dynamics, feedback, and stability are also important for understanding many complex systems of interest to chemical engineers, such as in bioengineering and advanced materials. An introductory course should provide an appropriate balance of process control theory and practice. In particular, the course should emphasize dynamic behavior, physical and empirical modeling, computer simulation, measurement and control technology, basic control concepts, and advanced control strategies. We have organized this book so that the instructor can cover the basic material while having the flexibility to include advanced topics. The textbook provides the basis for 10 to 30 weeks of instruction for a single course or a sequence of courses at either the undergraduate or first-year graduate levels. It is also suitable for self-study by engineers in industry. The book is divided into reasonably short chapters to make it more readable and modular. This organization allows some chapters to be omitted without a loss of continuity.

The mathematical level of the book is oriented toward a junior or senor student in chemical engineering who has taken at least one course in differential equations. Additional mathematical tools required for the analysis of control systems are introduced as needed. We emphasize process control techniques that are used in practice and provide detailed mathematical analysis only when it is essential for understanding the material. Key theoretical concepts are illustrated with numerous examples and simulations.

The textbook material has evolved at the University of California, Santa Barbara, and the University of Texas at Austin over the past 40 years. The first edition (SEM1) was published in 1989, adopted by over 80 universities worldwide, and translated into Korean and Japanese. In the second edition (SEM2, 2004), we added new chapters on the important topics of process monitoring (Chapter 21), batch process control (Chapter 22), and plantwide control (Chapters 23 and 24). Even with the new chapters, the length of the second edition was about the same as SEM1. Interactive computer software based on MATLAB® and Simulink® software was extensively used in examples and exercises. The second edition was translated into Chinese in 2004.

For the third edition (SEMD3), we are very pleased to have added a fourth co-author, Professor Frank Doyle (UCSB), and we have made major changes that reflect the evolving field of chemical and biological engineering, as well as the practice of process control, which are described in the following.

The book is divided into five parts. Part I provides an introduction to process control and an in-depth discussion of process modeling. Control system design and analysis increasingly rely on the availability of a process model. Consequently, the third edition includes additional material on process modeling based on first principles, such as conservation equations and thermodynamics. Exercises have been added to several chapters based on MATLAB® simulations of two physical models, a distillation column and a furnace. These simulations are based on the book, *Process Control Modules*, by Frank Doyle, Ed Gatzke, and Bob Parker. Both the book and the MATLAB simulations are available on the book Web site (*www.wiley.com/go/global/seborg*). National Instruments has provided multimedia modules for a number of examples in the book based on their LabVIEW™ software.

Part II (Chapters 3 through 7) is concerned with the analysis of the dynamic (unsteady-state) behavior of processes. We still rely on the use of Laplace transforms and transfer functions, to characterize the dynamic behavior of linear systems. However, we have kept analytical methods involving transforms at a minimum and prefer the use of computer simulation to determine dynamic responses. In addition, the important topics of empirical models and their development from plant data are presented.

Part III (Chapters 8 through 15) addresses the fundamental concepts of feedback and feedforward control. The topics include an overview of the process instrumentation (Chapter 9) and control hardware and software that are necessary to implement process control (Chapter 8 and Appendix A). Chapter 13 (new) presents the important topic of process control strategies at the unit level, and additional material on process safety has been added to Chapter 10. The design and analysis of feedback control systems still receive considerable attention, with emphasis on industry-proven methods for controller design, tuning, and troubleshooting. The frequency response approach for open and closed-loop processes is now combined into a single chapter (14), because of its declining use in the process industries. Part III concludes with a chapter on feedforward and ratio control.

Part IV (Chapters 16 through 22) is concerned with advanced process control techniques. The topics include digital control, multivariable control, and enhancements of PID control, such as cascade control, selective control, and gain scheduling. Up-to-date chapters on real-time optimization and model predictive control emphasize the significant impact these powerful techniques have had on industrial practice. Other chapters consider process monitoring and batch process control. The two plantwide control chapters that were introduced in SEM2 have been moved to the book Web site, as Appendices G and H. We have replaced this material with two new chapters on biosystems control, principally authored by our recently added fourth author, Frank Doyle. Part V (new Chapters 23 and 24) covers the application of process control in biotechnology and biomedical systems, and introduces basic ideas in systems biology.

The following resources for instructors (only) are provided: solutions manual, lecture slides, and figures from the text. Instructors need to visit the book Web site to register for a password to access the protected resources. The book Web site is located at *www.wiley.com/go/global/seborg*.

We gratefully acknowledge the very helpful suggestions and reviews provided by many colleagues in academia and industry: Joe Alford, Anand Asthagiri, Karl Åström, Tom Badgwell, Max Barolo, Larry Biegler, Don Bartusiak, Terry Blevins, Dominique Bonvin, Richard Braatz, Dave Camp, Jarrett Campbell, I-Lung Chien, Will Cluett, Oscar Crisalle, Patrick Daugherty, Bob Deshotels, Rainer Dittmar, Jim Downs, Ricardo Dunia, David Ender, Stacy Firth, Rudiyanto Gunawan, Juergen Hahn, Sandra Harris, Karlene Hoo, Biao Huang, Babu Joseph, Derrick Kozub, Jietae Lee, Bernt Lie, Cheng Ling, Sam Mannan, Tom McAvoy, Greg McMillan, Randy Miller, Samir Mitragotri, Manfred Morari, Duane Morningred, Kenneth Muske, Mark Nixon, Srinivas Palanki, Bob Parker, Michel Perrier, Mike Piovoso, Joe Qin, Larry Ricker, Dan Rivera, Derrick Rollins, Alan Schneider, Sirish Shah, Mikhail Skliar, Sigurd Skogestad, Tyler Soderstrom, Ron Sorensen, Dirk Thiele, John Tsing, Ernie Vogel, Doug White, Willy Wojsznis, Robert Young, and the late Cheng-Ching Yu.

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In the spirit of continuous improvement, we are interested in receiving feedback from students, faculty, and practitioners who use this book. We hope you find it to be useful.

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Appendices F through K are online at *www.wiley.com/go/global/seborg*

Chapter 1

Introduction to Process Control

In recent years the performance requirements for process plants have become increasingly difficult to satisfy. Stronger competition, tougher environmental and safety regulations, and rapidly changing economic conditions have been key factors in tightening product quality specifications. A further complication is that modern plants have become more difficult to operate because of the trend toward complex and highly integrated processes. For such plants, it is difficult to prevent disturbances from propagating from one unit to other interconnected units.

In view of the increased emphasis placed on safe, efficient plant operation, it is only natural that the subject of *process control* has become increasingly important in recent years. Without computer-based process control systems it would be impossible to operate modern plants safely and profitably while satisfying product quality and environmental requirements. Thus, it is important for chemical engineers to have an understanding of both the theory and practice of process control.

The two main subjects of this book are *process dynamics* and *process control*. The term *process dynamics* refers to unsteady-state (or transient) process behavior. By contrast, most of the chemical engineering curricula emphasize steady-state and equilibrium conditions in such courses as material and energy balances, thermodynamics, and transport phenomena. But process dynamics are also very important. Transient operation occurs during important situations such as start-ups and shutdowns, unusual process disturbances, and planned transitions from one product grade to another. Consequently, the first part of this book is concerned with process dynamics.

The primary objective of process control is to maintain a process at the desired operating conditions, safely and efficiently, while satisfying environmental and product quality requirements. The subject of process control is concerned with how to achieve these goals. In large-scale, integrated processing plants such as oil refineries or ethylene plants, thousands of process variables such as compositions, temperatures, and pressures are measured and must be controlled. Fortunately, large numbers of process variables (mainly flow rates) can usually be manipulated for this purpose. Feedback control systems compare measurements with their desired values and then adjust the manipulated variables accordingly.

As an introduction to the subject, we consider representative process control problems in several industries.

1.1 REPRESENTATIVE PROCESS CONTROL PROBLEMS

The foundation of process control is *process understanding*. Thus, we begin this section with a basic question: what is a process? For our purposes, a brief definition is appropriate:

> ***Process:*** *The conversion of feed materials to products using chemical and physical operations. In practice, the term* process *tends to be used for both the processing operation and the processing equipment.*

Note that this definition applies to three types of common processes: continuous, batch, and semi-batch. Next, we consider representative processes and briefly summarize key control issues.

1.1.1 Continuous Processes

Four continuous processes are shown schematically in Figure 1.1:

(a) ***Tubular heat exchanger.*** A process fluid on the tube side is cooled by cooling water on the shell side. Typically, the exit temperature of the process fluid is controlled by manipulating

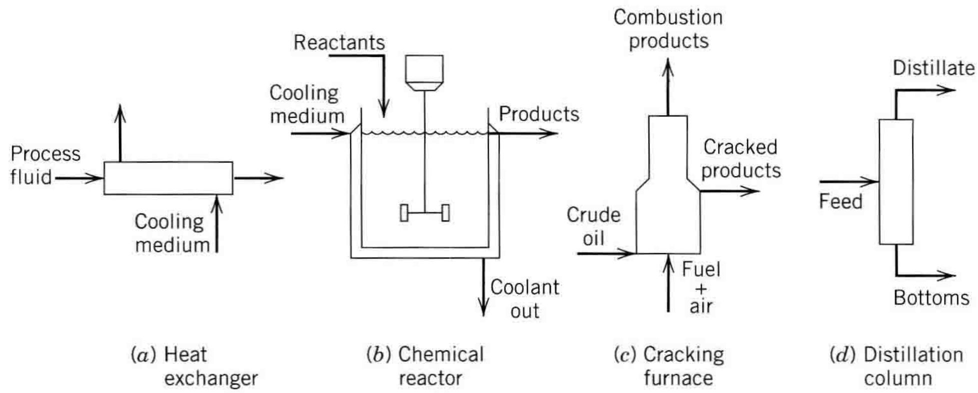

Figure 1.1 Some typical continuous processes.

the cooling water flow rate. Variations in the inlet temperatures and the process fluid flow rate affect the heat exchanger operation. Consequently, these variables are considered to be disturbance variables.

(b) ***Continuous stirred-tank reactor (CSTR).*** If the reaction is highly exothermic, it is necessary to control the reactor temperature by manipulating the flow rate of coolant in a jacket or cooling coil. The feed conditions (composition, flow rate, and temperature) can be manipulated variables or disturbance variables.

(c) ***Thermal cracking furnace.*** Crude oil is broken down ("cracked") into a number of lighter petroleum fractions by the heat transferred from a burning fuel/air mixture. The furnace temperature and amount of excess air in the flue gas can be controlled by manipulating the fuel flow rate and the fuel/air ratio. The crude oil composition and the heating quality of the fuel are common disturbance variables.

(d) ***Multicomponent distillation column.*** Many different control objectives can be formulated for distillation columns. For example, the distillate composition can be controlled by adjusting the reflux flow rate or the distillate flow rate. If the composition cannot be measured on-line, a tray temperature near the top of the column can be controlled instead. If the feed stream is supplied by an upstream process, the feed conditions will be disturbance variables.

For each of these four examples, the process control problem has been characterized by identifying three important types of process variables.

- *Controlled variables (CVs):* The process variables that are controlled. The desired value of a controlled variable is referred to as its *set point*.
- *Manipulated variables (MVs):* The process variables that can be adjusted in order to keep the controlled variables at or near their set points. Typically, the manipulated variables are flow rates.
- *Disturbance variables (DVs):* Process variables that affect the controlled variables but cannot be manipulated. Disturbances generally are related to changes in the operating environment of the process: for example, its feed conditions or ambient temperature. Some disturbance variables can be measured on-line, but many cannot such as the crude oil composition for Process (c), a thermal cracking furnace.

The specification of CVs, MVs, and DVs is a critical step in developing a control system. The selections should be based on process knowledge, experience, and control objectives.

1.1.2 Batch and Semi-Batch Processes

Batch and semi-batch processes are used in many process industries, including microelectronics, pharmaceuticals, specialty chemicals, and fermentation. Batch and semi-batch processes provide needed flexibility for multiproduct plants, especially when products change frequently and production quantities are small. Figure 1.2 shows four representative batch and semi-batch processes:

(e) ***Batch or semi-batch reactor.*** An initial charge of reactants is brought up to reaction conditions,

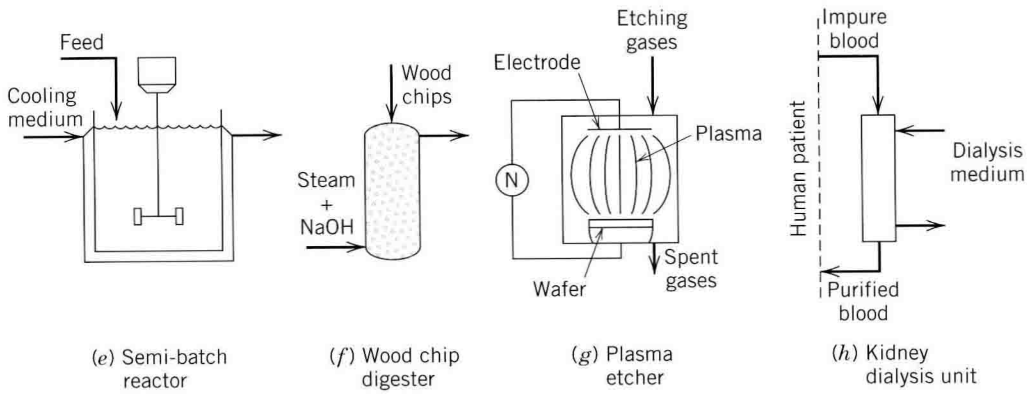

Figure 1.2 Some typical processes whose operation is noncontinuous.

and the reactions are allowed to proceed for a specified period of time or until a specified conversion is obtained. Batch and semi-batch reactors are used routinely in specialty chemical plants, polymerization plants (where a reaction byproduct typically is removed during the reaction), and in pharmaceutical and other bioprocessing facilities (where a feed stream, e.g., glucose, is fed into the reactor during a portion of the cycle to feed a living organism, such as a yeast or protein). Typically, the reactor temperature is controlled by manipulating a coolant flow rate. The end-point (final) concentration of the batch can be controlled by adjusting the desired temperature, the flow of reactants (for semi-batch operation), or the cycle time.

(f) ***Batch digester in a pulp mill.*** Both continuous and semi-batch digesters are used in paper manufacturing to break down wood chips in order to extract the cellulosic fibers. The end point of the chemical reaction is indicated by the kappa number, a measure of lignin content. It is controlled to a desired value by adjusting the digester temperature, pressure, and/or cycle time.

(g) ***Plasma etcher in semiconductor processing.*** A single wafer containing hundreds of printed circuits is subjected to a mixture of etching gases under conditions suitable to establish and maintain a plasma (a high voltage applied at high temperature and extremely low pressure). The unwanted material on a layer of a microelectronics circuit is selectively removed by chemical reactions. The temperature, pressure, and flow rates of etching gases to the reactor are controlled by adjusting electrical heaters and control valves.

(h) ***Kidney dialysis unit.*** This medical equipment is used to remove waste products from the blood of human patients whose own kidneys are failing or have failed. The blood flow rate is maintained by a pump, and "ambient conditions," such as temperature in the unit, are controlled by adjusting a flow rate. The dialysis is continued long enough to reduce waste concentrations to acceptable levels.

Next, we consider an illustrative example in more detail.

1.2 ILLUSTRATIVE EXAMPLE—A BLENDING PROCESS

A simple blending process is used to introduce some important issues in control system design. Blending operations are commonly used in many industries to ensure that final products meet customer specifications.

A continuous, stirred-tank blending system is shown in Fig. 1.3. The control objective is to blend the two inlet streams to produce an outlet stream that has the desired composition. Stream 1 is a mixture of two chemical species, A and B. We assume that its mass flow rate w_1 is constant, but the mass fraction of A, x_1, varies with time. Stream 2 consists of pure A and thus $x_2 = 1$. The mass flow rate of Stream 2, w_2, can be manipulated using a control valve. The mass fraction of A in the exit stream is denoted by x and the desired value (set point) by x_{sp}. Thus for this control problem, the controlled variable is x, the manipulated variable is w_2, and the disturbance variable is x_1.

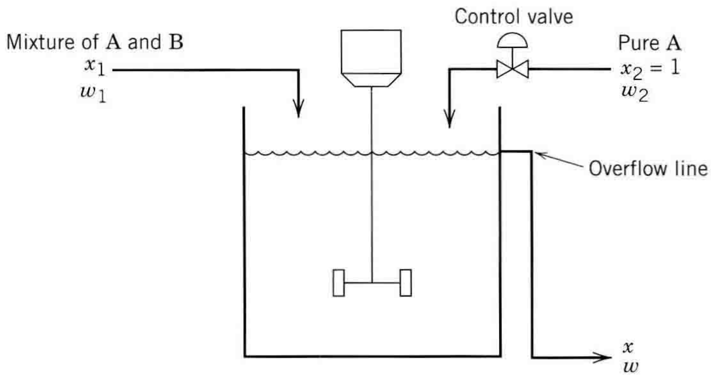

Figure 1.3 Stirred-tank blending system.

Next we consider two questions.

Design Question. *If the nominal value of x_1 is $\overline{x}_1$, what nominal flow rate $\overline{w}_2$ is required to produce the desired outlet concentration, x_{sp}?*

To answer this question, we consider the steady-state material balances:

Overall balance:

$$0 = \overline{w}_1 + \overline{w}_2 - \overline{w} \tag{1-1}$$

Component A balance:

$$0 = \overline{w}_1\overline{x}_1 + \overline{w}_2\overline{x}_2 - \overline{w}\,\overline{x} \tag{1-2}$$

The overbar over a symbol denotes its nominal steady-state value, for example, the value used in the process design. According to the process description, $\overline{x}_2 = 1$ and $\overline{x} = x_{sp}$. Solving Eq. 1-1 for $\overline{w}$, substituting these values into Eq. 1-2, and rearranging gives:

$$\overline{w}_2 = \overline{w}_1 \frac{x_{sp} - \overline{x}_1}{1 - x_{sp}} \tag{1-3}$$

Equation 1-3 is the design equation for the blending system. If our assumptions are correct and if $x_1 = \overline{x}_1$, then this value of w_2 will produce the desired result, $x = x_{sp}$. But what happens if conditions change?

Control Question. *Suppose that inlet concentration x_1 varies with time. How can we ensure that the outlet composition x remains at or near its desired value, x_{sp}?*

As a specific example, assume that x_1 increases to a constant value that is larger than its nominal value, $\overline{x}_1$. It is clear that the outlet composition will also increase due to the increase in inlet composition. Consequently, at this new steady state, $x > x_{sp}$.

Next we consider several strategies for reducing the effects of x_1 disturbances on x.

Method 1. *Measure x and adjust w_2.* It is reasonable to measure controlled variable x and then adjust w_2 accordingly. For example, if x is too high, w_2 should be reduced; if x is too low, w_2 should be increased. This control strategy could be implemented by a person (*manual control*). However, it would normally be more convenient and economical to automate this simple task (*automatic control*).

Method 1 can be implemented as a simple control algorithm (or control law),

$$w_2(t) = \overline{w}_2 + K_c[x_{sp} - x(t)] \tag{1-4}$$

where K_c is a constant called the *controller gain*. The symbols, $w_2(t)$ and $x(t)$, indicate that w_2 and x change with time. Equation 1-4 is an example of *proportional control,* because the change in the flow rate, $w_2(t) - \overline{w}_2$, is proportional to the deviation from the set point, $x_{sp} - x(t)$. Consequently, a large deviation from set point produces a large corrective action, while a small deviation results in a small corrective action. Note that we require K_c to be positive because w_2 must increase when x decreases, and vice versa. However, in other control applications, negative values of K_c are appropriate, as discussed in Chapter 7.

A schematic diagram of Method 1 is shown in Fig. 1.4. The outlet concentration is measured and transmitted to the controller as an electrical signal. (Electrical signals are shown as dashed lines in Fig. 1.4.) The controller executes the control law and sends the calculated value of w_2 to the control valve as an electrical signal. The control

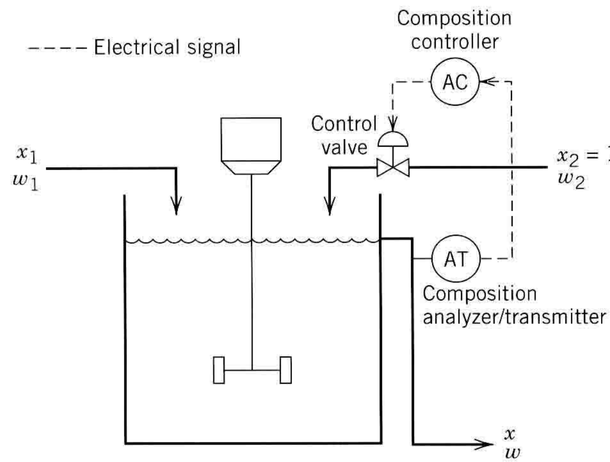

Figure 1.4 Blending system and Control Method 1.

valve opens or closes accordingly. In Chapters 7 and 8 we consider process instrumentation and control hardware in more detail.

Method 2. *Measure x_1, adjust w_2.* As an alternative to Method 1, we could measure disturbance variable x_1 and adjust w_2 accordingly. Thus, if $x_1 > \bar{x}_1$, we would decrease w_2 so that $w_2 < \bar{w}_2$. If $x_1 < \bar{x}_1$, we would increase w_2. A control law based on Method 2 can be derived from Eq. 1-3 by replacing $\bar{x}_1$ with $x_1(t)$ and $\bar{w}_2$ with $w_2(t)$:

$$w_2(t) = \bar{w}_1 \frac{x_{sp} - x_1(t)}{1 - x_{sp}} \tag{1-5}$$

The schematic diagram for Method 2 is shown in Fig. 1.5. Because Eq. 1-3 is valid only for steady-state conditions, it is not clear just how effective Method 2 will be during the transient conditions that occur after an x_1 disturbance.

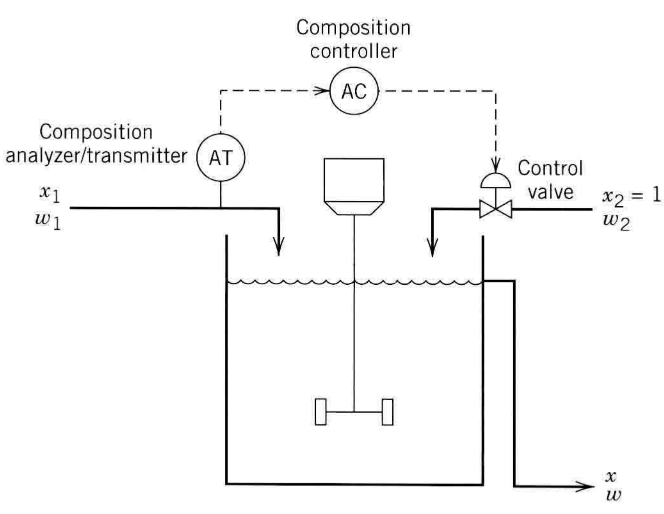

Figure 1.5 Blending system and Control Method 2.

Method 3. *Measure x_1 and x, adjust w_2.* This approach is a combination of Methods 1 and 2.

Method 4. *Use a larger tank.* If a larger tank is used, fluctuations in x_1 will tend to be damped out as a result of the larger volume of liquid. However, increasing tank size is an expensive solution due to the increased capital cost.

1.3 CLASSIFICATION OF PROCESS CONTROL STRATEGIES

Next, we will classify the four blending control strategies of the previous section and discuss their relative advantages and disadvantages. Method 1 is an example of a *feedback control* strategy. The distinguishing feature of feedback control is that the controlled variable is measured, and that the measurement is used to adjust the manipulated variable. For feedback control, the disturbance variable is *not* measured.

It is important to make a distinction between *negative feedback* and *positive feedback*. In the engineering literature, negative feedback refers to the desirable situation in which the corrective action taken by the controller forces the controlled variable toward the set point. On the other hand, when positive feedback occurs, the controller makes things worse by forcing the controlled variable farther away from the set point. For example, in the blending control problem, positive feedback takes place if $K_c < 0$, because w_2 will increase when x increases.[1] Clearly, it is of paramount importance to ensure that a feedback control system incorporates negative feedback rather than positive feedback.

An important advantage of feedback control is that corrective action occurs regardless of the source of the disturbance. For example, in the blending process, the feedback control law in (1-4) can accommodate disturbances in w_1, as well as x_1. Its ability to handle disturbances of unknown origin is a major reason why feedback control is the dominant process control strategy. Another important advantage is that feedback control reduces the sensitivity of the controlled variable to

[1]Note that social scientists use the terms negative feedback and positive feedback in a very different way. For example, they would say that teachers provide "positive feedback" when they compliment students who correctly do assignments. Criticism of a poor performance would be an example of "negative feedback."

unmeasured disturbances and process changes. However, feedback control does have a fundamental limitation: no corrective action is taken until after the disturbance has upset the process, that is, until after the controlled variable deviates from the set point. This shortcoming is evident from the control law of (1-4).

Method 2 is an example of a *feedforward control strategy*. The distinguishing feature of feedforward control is that the disturbance variable is measured, but the controlled variable is not. The important advantage of feedforward control is that corrective action is taken *before* the controlled variable deviates from the set point. Ideally, the corrective action will cancel the effects of the disturbance so that the controlled variable is not affected by the disturbance. Although ideal cancelation is generally not possible, feedforward control can significantly reduce the effects of measured disturbances, as discussed in Chapter 14.

Feedforward control has three significant disadvantages: (i) the disturbance variable must be measured (or accurately estimated), (ii) no corrective action is taken for unmeasured disturbances, and (iii) a process model is required. For example, the feedforward control strategy for the blending system (Method 2) does not take any corrective action for unmeasured w_1 disturbances. In principle, we could deal with this situation by measuring both x_1 and w_1 and then adjusting w_2 accordingly. However, in industrial applications it is generally uneconomical to attempt to measure all potential disturbances. A more practical approach is to use a combined feedforward–feedback control system, in which feedback control provides corrective action for unmeasured disturbances, while feedforward control reacts to eliminate measured disturbances before the controlled variable is upset. Consequently, in industrial applications feedforward control is normally used in combination with feedback control. This approach is illustrated by Method 3, a combined feedforward-feedback control strategy because both x and x_1 are measured.

Table 1.1 Concentration Control Strategies for the Blending System

Method	Measured Variable	Manipulated Variable	Category
1	x	w_2	FB
2	x_1	w_2	FF
3	x_1 and x	w_2	FF/FB
4	—	—	Design change

FB = feedback control; FF = feedforward control; FF/FB = feedforward control and feedback control.

Finally, Method 4 consists of a process design change and thus is not really a control strategy. The four strategies for the stirred-tank blending system are summarized in Table 1.1.

1.3.1 Process Control Diagrams

Next we consider the equipment that is used to implement control strategies. For the stirred-tank mixing system under feedback control in Fig. 1.4, the exit concentration x is controlled and the flow rate w_2 of pure species A is adjusted using proportional control. To consider how this feedback control strategy could be implemented, a block diagram for the stirred-tank control system is shown in Fig. 1.6. Operation of the

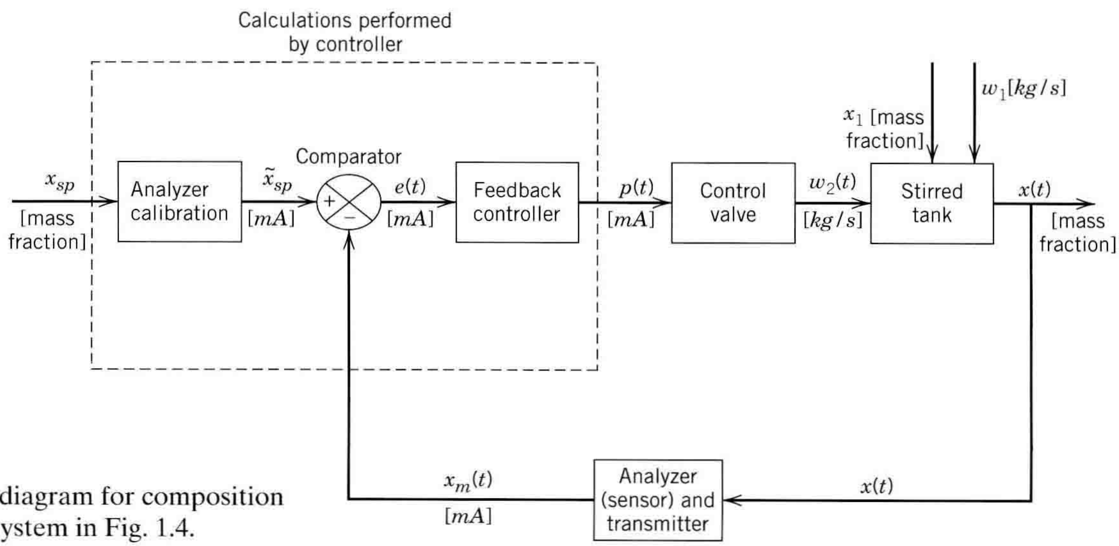

Figure 1.6 Block diagram for composition feedback control system in Fig. 1.4.