AUTOMATED CONTINUOUS PROCESS CONTROL

AUTOMATED CONTINUOUS PROCESS CONTROL

CARLOS A. SMITH
Chemical Engineering Department
University of South Florida

A Wiley-Interscience Publication
JOHN WILEY & SONS, INC.

This book is printed on acid-free paper. ♾

Published simultaneously in Canada.

For ordering and customer service information please call 1-800-CALL-WILEY.

Library of Congress Cataloging-in-Publication Data Is Available

ISBN 0-471-21578-3

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

This work is dedicated to the Lord our God, for his daily blessings make all our work possible.

To the old generation: Mami, Tim, and Cristina Livingston, and Carlos and Jennifer Smith.

To the new generation: Sophia Cristina Livingston and Steven Christopher Livingston.

To my dearest homeland, Cuba.

CONTENTS

PREFACE

This book was written over a number of years while teaching short courses to industry. Most of the participants were graduate engineers, and a few were instrument technicians. For the engineers, the challenge was to show them that the control theory most of them heard in college is indeed the basis for the practice of process control. For the technicians, the challenge was to teach them the practice of process control with minimum mathematics. The book does not emphasize mathematics, and a serious effort has been made to explain, using readable language, the meaning and significance of every term used: that is, what the term is telling us about the process, about the controller, about the control performance, and so on.

The book assumes that the reader does not know much about process control. Accordingly, Chapter 1 presents the very basics of process control. While several things are presented in Chapter 1, the main goals of the chapter are (1) to present why process control is needed, (2) to present the basic components of a control system, (3) to define some terms, and (4) to present the concept of feedback control with its advantages, disadvantages, and limitations.

To do good process control there are at least three things the practitioner should know and fully understand: (1) the process, (2) the process, and (3) the process! Chapter 2 presents a discussion of processes from a very physical point of view. Everything presented in this chapter is used extensively in all remaining chapters.

Chapter 3 presents a discussion of feedback controllers, and specifically, the workhorse in the process industry: the PID controller. A significant effort is made to explain each tuning parameter in detail as well as the different types of controllers, with their advantages and disadvantages. In the chapter we describe how to tune, adjust, or adapt the controller to the process. Finally, we discuss the important topics of reset windup, tracking, and tuning flow and level loops. Throughout the presentation, the use of distributed control systems (DCSs) is stressed. Problems are presented at the end of Chapters 2 and 3 to practice what was presented.

As discussed in Chapter 1, feedback control has the limitation that in some cases it does not provide enough control performance. In these cases some other control strategy is needed to obtain the control performance required. What is usually done is to provide assistance to feedback control; feedback control is never removed. Cascade control is a common strategy to improve simple feedback control. In Chapter 4 we present the concept and implementation of cascade control.

In Chapter 5 we describe ratio, override (or constraint), and selective control. To implement these strategies, some computing power is needed. The chapter starts with a presentation of how DCSs handle signals as they enter the system and a description of different programming techniques and computing power. Ratio, override, and selective control are presented using examples. The chapter ends with some hints on how to go about designing these strategies. Many problems are given at the end of the chapter.

Once feedback and cascade control have been presented, it is worthwhile to discuss the important subject of control system stability. Chapter 6 starts with the subject of block diagram and continues with the subject of stability. Block diagrams are used in subsequent chapters to explain the implementation of other control strategies. Stability is presented from a very practical point of view without dealing much with mathematics. It is important for the practitioner to understand how each term in the control system affects the stability of the system.

The detrimental effect of dead time on the stability of a control system is presented in Chapter 6. Chapter 7 is devoted exclusively to feedforward control. Various ways to design and implement this important compensation strategy and several examples are presented. Several techniques to control processes with long dead times are described in Chapter 8, and multivariable process control in Chapter 9. Appendix A provides some process examples to design the control strategies for an entire process. Finally, Appendix B describes the processes presented in the compact disk (CD). These processes have been used for many years to practice tuning feedback and cascade controllers as well as designing feedforward controllers.

The author believes that to practice industrial process control (as opposed to "academic" process control), there is generally no need for advanced mathematics. The author is also aware that the reader is interested in learning "just enough theory" to practice process control. The main concern during the writing of this manuscript has been to present the reader with the benefits obtained with good control, and in doing so, to motivate him or her to learn more about the subject. We hope you do so, and now wish you good controlling!

It is impossible to write a book like this one without receiving help and encouragement from other people. The author would first like to acknowledge the encouragement received from the hundreds of engineers and technicians who have attended the short courses and offered suggestions and examples. The author would also like to sincerely thank his friends, colleagues, and most outstanding chemical engineers, J. Carlos Busot and Armando B. Corripio (coauthor of *Principles and Practice of Automatic Process Control*). Their friendship, human quality, professional quality, and ability to frustrate the author have had a great positive impact in my life. Thanks to both of you! ABC also provided the material presented in Section 8-2. The author also remembers very dearly his former student, the late Dr. Daniel Palomares, for his contributions to the simulations presented in the CD

accompanying this book. Finally, the author would like to thank his graduate student and friend, Dr. Marco Sanjuan. Marco's friendship, support, and continuous encouragement have made these past years a tremendous pleasure. Marco also put the final touches to the CD.

Tampa, FL
2001

CARLOS A. SMITH, PH.D., P.E.

Automated Continuous Process Control. Carlos A. Smith
Copyright © 2002 John Wiley & Sons, Inc. ISBN: 0-471-21578-3

CHAPTER 1

INTRODUCTION

Automatic process control is concerned with maintaining process variables, temperatures, pressures, flows, compositions, and the like, at a desired operating value. As we shall see in the ensuing pages, processes are dynamic in nature. Changes are always occurring, and if actions are not taken, the important process variables—those related to safety, product quality, and production rates—will not achieve design conditions.

1-1 PROCESS CONTROL SYSTEM

To fix ideas, let us consider a heat exchanger in which a process fluid is heated by condensing steam; the process is sketched in Fig. 1-1.1. The purpose of this unit is to heat the process fluid from some inlet temperature, $T_i(t)$, up to a desired outlet temperature, $T(t)$. The energy gained by the process fluid is provided by the latent heat of condensation of the steam.

In this process many variables can change, causing the outlet temperature to deviate from its desired value. If this happens, some action must be taken to correct for this deviation. The objective is to maintain the outlet process temperature at its desired value. One way to accomplish this objective is to first measure the temperature, $T(t)$, compare it to its desired value, and based on this comparison, decide what to do to correct for any deviation. The steam valve can be manipulated to correct for the deviation. That is, if the temperature is above its desired value, the steam valve can be throttled back to cut the steam flow (energy) to the heat exchanger. If the temperature is below its desired value, the steam valve could be opened more to increase the steam flow to the exchanger. The operator can do all of this manually, and since the procedure is fairly straightforward, it should present no problem. However, there are several problems with this *manual process control*. First, the job requires that the operator look frequently at the temperature to take

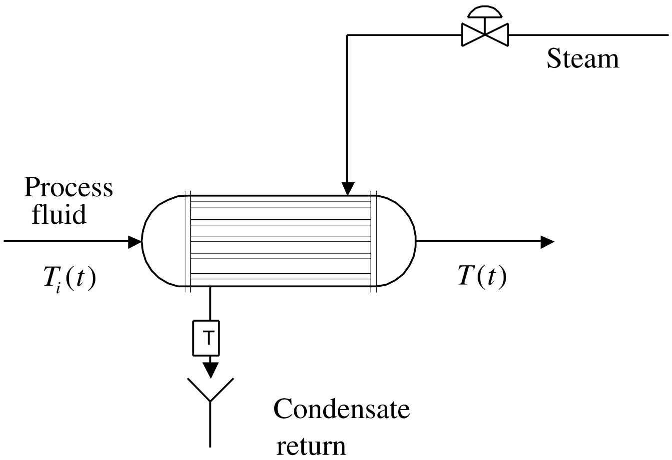

Figure 1-1.1 Heat exchanger.

corrective action whenever it deviates from the value desired. Second, different operators would make different decisions as to how to move the steam valve, resulting in inconsistent operation. Third, since in most process plants hundreds of variables must be maintained at a desired value, this correction procedure would require a large number of operators. Consequently, we would like to accomplish this control automatically. That is, we would like to have systems that control the variables without requiring intervention from the operator. This is what is meant by *automatic process control*.

To accomplish this objective, a control system must be designed and implemented. A possible control system and its basic components are shown in Fig. 1-1.2. The first thing to do is to measure the outlet temperature of the process stream. This is done by a sensor (thermocouple, resistance temperature device, filled system thermometers, thermistors, etc.). Usually, this sensor is connected physically to a transmitter, which takes the output from the sensor and converts it to a signal strong enough to be transmitted to a controller. The controller then receives the signal, which is related to the temperature, and compares it with the value desired. Depending on this comparison, the controller decides what to do to maintain the temperature at its desired value. Based on this decision, the controller sends a signal to the final control element, which in turn manipulates the steam flow. This type of control strategy is known as *feedback control*.

The preceding paragraph presented the three basic components of all control systems:

1. *Sensor/transmitter*: also often called the *primary* and *secondary elements*
2. *Controller*: the "brain" of the control system
3. *Final control element*: often a control valve, but not always.

Other common final control elements are variable-speed pumps, conveyors, and electric motors.

The importance of these components is that they perform the three basic operations that must by present in every control system:

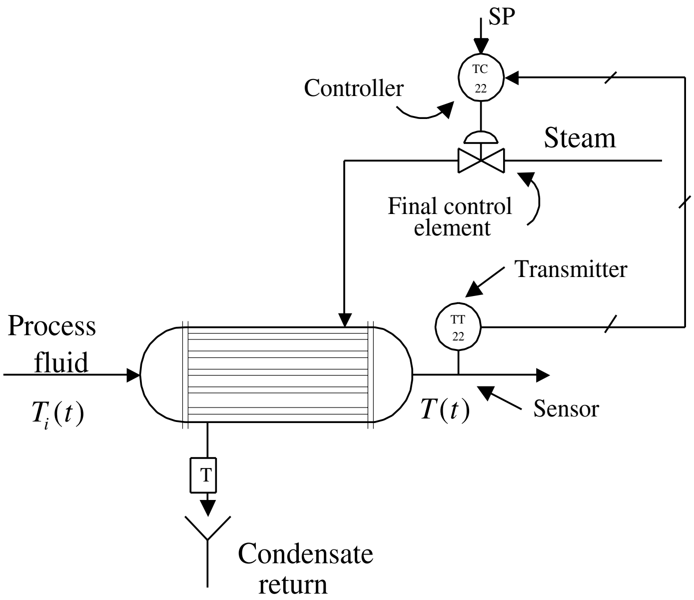

Figure 1-1.2 Heat exchanger control loop.

1. *Measurement* (M). Measuring the variable to be controlled is usually done by the combination of sensor and transmitter.
2. *Decision* (D). Based on the measurement, the controller decides what to do to maintain the variable at its desired value.
3. *Action* (A). As a result of the controller's decision, the system must then take an action. This is usually accomplished by the final control element.

These three operations, M, D, A, are always present in every type of control system. It is imperative, however, that the three operations be in a loop. That is, based on the measurement, a decision is made, and based on this decision, an action is taken. *The action taken must come back and affect the measurement*; otherwise, there is a major flaw in the design and control will not be achieved; when the action taken does not affect the measurement, an open-loop condition exists. The decision making in some systems is rather simple, whereas in others it is more complex; we look at many of them in this book.

1-2 IMPORTANT TERMS AND OBJECTIVE OF AUTOMATIC PROCESS CONTROL

At this time it is necessary to define some terms used in the field of automatic process control. The first term is *controlled variable*, which is the variable that must be maintained, or controlled, at some desired value. In the preceding discussion, the process outlet temperature, $T(t)$, is the controlled variable. Sometimes the terms *process variable* and/or *measurement* are also used to refer to the controlled variable. The *set point* is the desired value of the controlled variable. Thus the job of a control system is to maintain the controlled variable at its set point. The *manipulated variable* is the variable used to maintain the controlled variable at its set point. In the example, the steam valve position is the manipulated variable. Finally, any variable that causes the controlled variable to deviate away from the set point is defined as a *disturbance* or *upset*. In most processes there are a number of different disturbances. As an example, in the heat exchanger shown in Fig. 1-1.2, possible disturbances are the inlet process temperature $T_i(t)$, the process flow $f(t)$, the energy content of the steam, ambient conditions, process fluid composition, and fouling. It is important to understand that disturbances are always occurring in processes. Steady state is not the rule; transient conditions are very common. It is because of these disturbances that automatic process control is needed. If there were no disturbances, design operating conditions would prevail and there would be no necessity of continuously "monitoring" the process.

With these terms defined, we can simply state the following: *The objective of an automatic process control system is to adjust the manipulated variable to maintain the controlled variable at its set point in spite of disturbances.*

It is wise to enumerate some of the reasons why control is important. These are based on our industrial experience and we would like to pass them on to the reader. They may not be the only ones, but we feel they are the most important.

1. Prevent injury to plant personnel, protect the environment by preventing emissions and minimizing waste, and prevent damage to the process equipment. *Safety* must always be in everyone's mind; it is the single most important consideration.
2. Maintain product quality (composition, purity, color, etc.) on a continuous basis and with minimum cost.
3. Maintain plant production rate at minimum cost.

So it can be said that the reasons for automation of process plants are to provide safety and at the same time maintain desired product quality, high plant throughput, and reduced demand on human labor.

The following additional terms are also important. *Manual control* refers to the condition in which the controller is disconnected from the process. That is, the controller is not making the decision as to how to maintain the controlled variable at the set point. It is up to the operator to manipulate the signal to the final control element to maintain the controlled variable at the set point. *Automatic* or *closed-loop control* refers to the condition in which the controller is connected to the process, comparing the set point to the controlled variable, and determining and taking corrective action.

1-3 REGULATORY AND SERVO CONTROL

In some processes the controlled variable deviates from the set point because of disturbances. *Regulatory control* refers to systems designed to compensate for these disturbances. In some other instances the most important disturbance is the set point itself. That is, the set point may be changed as a function of time (typical of this is a batch reactor where the temperature must follow a desired profile), and therefore the controlled variable must follow the set point. *Servo control* refers to control systems designed for this purpose.

Regulatory control is far more common than servo control in the process industries. However, the basic approach to designing them is essentially the same. Thus the principles discussed in this book apply to both cases.

1-4 TRANSMISSION SIGNALS, CONTROL SYSTEMS, AND OTHER TERMS

There are three principal types of signals in use in the process industries. The pneumatic signal, or air pressure, ranges normally between 3 and 15 psig. The usual representation in piping and instrument diagrams (P&IDs) for pneumatic signals is —//——//—. The electrical signal ranges normally between 4 and 20 mA; 1 to 5 V or 0 to 10 V are also used. The usual representation for this signal is a series of dashed lines such as – — — —. The third type of signal is the digital, or discrete, signal (zeros and ones); a common representation is ○—○—○—. In these notes we show signals as —/——/— (as shown in Fig. 1-1.2), which is the representation proposed by the Instrument Society of America (ISA) when a control concept is shown without concern for specific hardware. Generally, we refer to signals as a percent, 0 to 100%, as opposed to psig or mA. That is, 0 to 100% is equivalent to 3 to 15 psig or 4 to 20 mA.

It will help in understanding control systems to realize that signals are used by devices (transmitters, controllers, final control elements, etc.) to communicate. That is, signals are used to convey information. The signal from the transmitter to the controller is used by the transmitter to inform the controller of the value of the controlled variable. It is not the measurement in engineering units, but rather, a mA, psig, volt, or other signal that is proportional to the measurement. The relationship to the measurement depends on the calibration of the sensor/transmitter. The controller uses its output signal to indicate to the final control element what to do (i.e., how much to open if it is a valve, how fast to run if it is a variable-speed pump, etc.). Thus every signal is related to some physical quantity that makes sense from an engineering point of view. The signal from the temperature transmitter in Fig. 1-1.2 is related to the outlet temperature, and the signal from the controller is related to the steam valve position.

It is often necessary to change one type of signal into another type. A *transducer* or *converter* does this. For example, there may be a need to change from an electrical signal, mA, to a pneumatic signal, psig. This is done by the use of a current (I) to pneumatic (P) transducer (I/P). The input signal may be 4 to 20 mA and the output 3 to 15 psig. An analog-to-digital (A to D) converter changes from an mA or volt signal to a digital signal. There are many other types of transducers: digital to analog (D to A), pneumatic to current (P/I), voltage to pneumatic (E/P), pneumatic to voltage (P/E), and so on.

The term *analog* refers to the controller, or any other instrument, which is pneumatic, electrical, hydraulic, or mechanical. Most controllers however, are *computer-based*, or *digital*. By computer-based we don't necessarily mean a mainframe computer but rather, anything starting from a microprocessor. In fact, most controllers are microprocessor-based.

1-5 CONTROL STRATEGIES

1-5.1 Feedback Control

The control scheme shown in Fig. 1-1.2 is referred to as *feedback control*, also called a *feedback control loop*. One must understand the working principles of feedback control to recognize its advantages and disadvantages; the heat exchanger control loop shown in Fig. 1-1.2 is presented to foster this understanding.

If the inlet process temperature decreases, thus creating a disturbance, its effect must propagate through the heat exchanger before the outlet temperature decreases. Once this temperature changes, the signal from the transmitter to the controller also changes. It is then that the controller becomes aware that a deviation from set point has occurred and that it must compensate for the disturbance by manipulating the steam valve. The controller then signals the valve to increase its opening and thus increase the steam flow. Figure 1-5.1 shows graphically the effect of the disturbance and the action of the controller.

It is instructive to note that at first the outlet temperature decreases, because of the decrease in inlet temperature, but it then increases, even above the set point and continues to oscillate until it finally stabilizes. This oscillatory response is typical of feedback control and shows that it is essentially a trial and error operation. That is, when the controller notices that the outlet temperature has decreased below the set point, it signals the valve to open, but the opening is more than required. Therefore, the outlet temperature increases above the set point. Noticing this, the controller signals the valve to close again somewhat to bring the temperature back down. This trial and error continued until the temperature reached and stayed at set point.

The *advantage* of feedback control is that it is a very simple technique that compensates for all disturbances. Any disturbance affects the controlled variable, and once this variable deviates from the set point, the controller changes its output to return the controlled variable to set point. The feedback control loop does not know, nor does it care, which disturbance enters the process. It only tries to maintain the controlled variable at set point and in so doing compensates for all disturbances. The feedback controller works with minimum knowledge of the process. In fact, the only information it needs is in which direction to move. How much to move is usually adjusted by trial and error. The *disadvantage* of feedback control is that it can compensate for a disturbance only after the controlled variable has deviated from the set point. That is, the disturbance must propagate through the entire process before the feedback control scheme can compensate for it.

The job of the engineer is to design a control scheme that will maintain the controlled variable at its set point. Once this is done, the engineer must then adjust, or tune, the controller so that it minimizes the trial-and-error operation required to control. Most controllers have up to three terms used to tune them. To do a creditable job, the engineer must first know the characteristics of the process to be controlled. Once these characteristics are known, the control system can be designed, and the controller can be tuned. What is meant by process characteristics

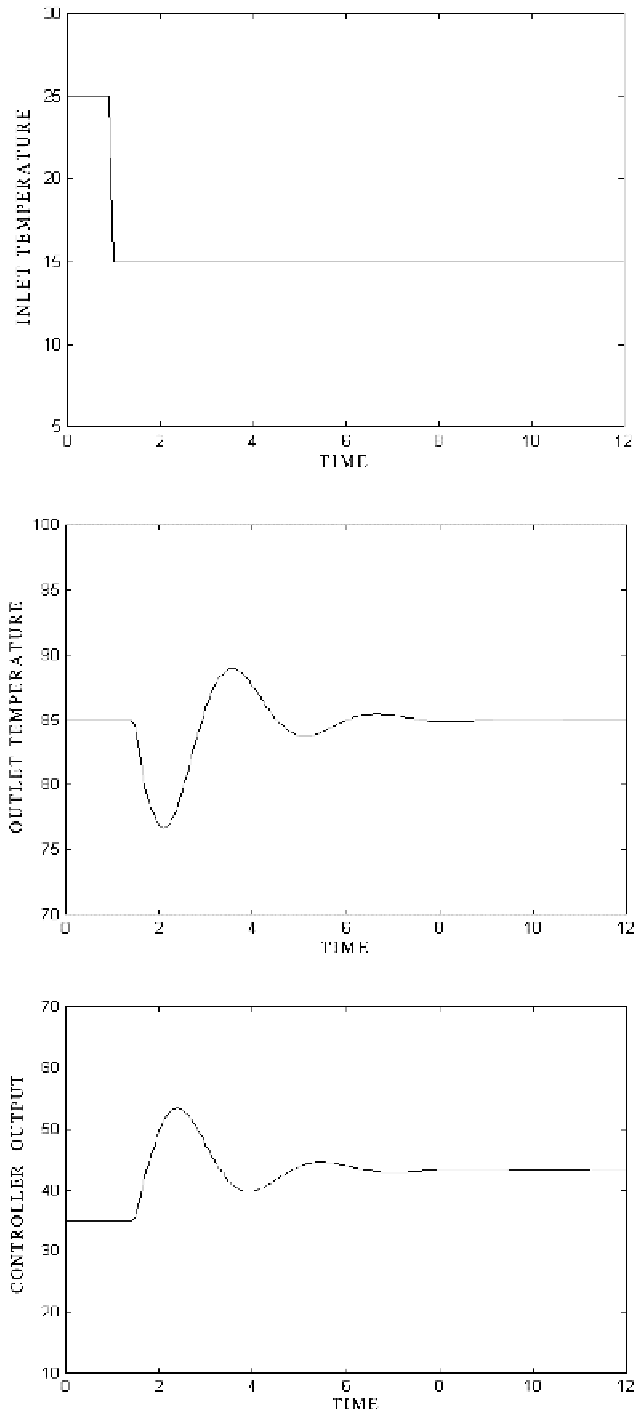

Figure 1-5.1 Response of feedback control.

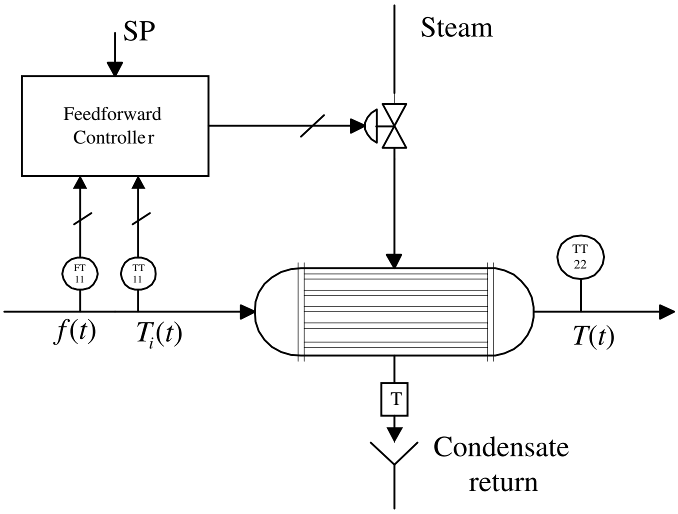

Figure 1-5.2 Feedforward control.

is explained in Chapter 2; in Chapter 3 we present various methods to tune controllers.

1-5.2 Feedforward Control

Feedback control is the most common control strategy in the process industries. Its simplicity accounts for its popularity. In some processes, however, feedback control may not provide the control performance required. For these processes, other types of control may have to be designed. In Chapters 5 and 7 we present additional control strategies that have proven to be profitable. One such strategy is *feedforward control*. The objective of feedforward control is to measure the disturbances and compensate for them before the controlled variable deviates from the set point. If applied correctly, the controlled variable deviation would be minimum.

A concrete example of feedforward control is the heat exchanger shown in Fig. 1-1.2. Suppose that "major" disturbances are the inlet temperature $T_i(t)$ and the process flow $f(t)$. To implement feedforward control these two disturbances must first be measured and then a decision made as to how to manipulate the steam valve to compensate for them. Figure 1-5.2 shows this control strategy. The feedforward controller makes the decision about how to manipulate the steam valve to maintain the controlled variable at set point, depending on the inlet temperature and process flow.

In Section 1-2 we learned that there are a number of different disturbances. The feedforward control system shown in Fig. 1-5.2 compensates for only two of them. If any of the other disturbances enter the process, this strategy will not compensate for it, and the result will be a permanent deviation from set point of the controlled variable. To avoid this deviation, some feedback compensation must be added to feedforward control; this is shown in Fig. 1-5.3. Feedforward control now compen-

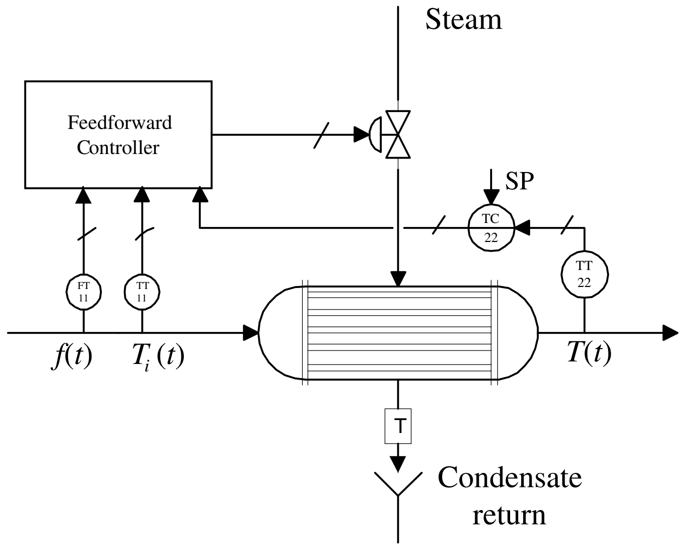

Figure 1-5.3 Feedforward control with feedback compensation.

sates for the "major" disturbances; feedback control compensates for all other disturbances. In Chapter 7 we present the development of the feedforward controller. Actual industrial cases are used to discuss this important strategy in detail.

It is important to notice that the three basic operations, M, D, A, are still present in this more "advanced" control strategy. The sensors and transmitters perform the measurement. Both feedforward and feedback controllers make the decision; the steam valve takes action.

The advanced control strategies are usually more costly, in hardware, computing power, and personnel necessary to design, implement, and maintain, than feedback control. Therefore, they must be justified (safety or economics) before they can be implemented. The best procedure is first to design and implement a simple control strategy, keeping in mind that if it does not prove satisfactory, a more advanced strategy may be justifiable. It is important, however, to recognize that these advanced strategies still require feedback compensation.

1-6 SUMMARY

In this chapter the need for automatic process control has been discussed. Industrial processes are not static but rather, very dynamic; they are changing continuously because of many types of disturbances. It is principally because of this dynamic nature that control systems are needed on a continuous and automatic basis to watch over the variables that must be controlled.

The working principles of a control system can be summarized with the three letters M, D, and A: M refers to the measurement of process variables, D to the decision to be made based on the measurements of the process variables, and A to the action to be taken based on the decision.

The basic components of a process control system were also presented: sensor/transmitter, controller, and final control element. The most common types of signals—pneumatic, electrical, and digital—were introduced along with the purpose of transducers.

Two control strategies were presented: feedback and feedforward control. The advantages and disadvantages of both strategies were discussed briefly.

Automated Continuous Process Control. Carlos A. Smith
Copyright © 2002 John Wiley & Sons, Inc. ISBN: 0-471-21578-3

CHAPTER 2

PROCESS CHARACTERISTICS

In this chapter we discuss process characteristics and describe in detail what is meant by a process, their characteristics, and how to obtain these characteristics using simple process information. The chapter is most important in the study of process control. Everything presented in this chapter is used to tune controllers and to design various control strategies.

2-1 PROCESS AND IMPORTANCE OF PROCESS CHARACTERISTICS

It is important at this time to describe what a process is from a controls point of view. To do this, consider the heat exchanger of Chapter 1, which is shown again in Fig. 2-1.1*a*. The controller's job is to control the process. In the example at hand, the controller is to control the outlet temperature. However, realize that the controller only receives the signal from the transmitter. It is through the transmitter that the controller "sees" the controlled variable. *Thus, as far as the controller is concerned, the controlled variable is the transmitter output.* The controller only looks at the process through the transmitter. The relation between the transmitter output and the process variable is given by the transmitter calibration.

In this example the controller is to manipulate the steam valve position to maintain the controlled variable at the set point. Realize, however, that the way the controller manipulates the valve position is by changing its signal to the valve (or transducer). Thus the controller does not manipulate the valve position directly; it only manipulates its output signal. Thus, *as far as the controller is concerned, the manipulated variable is its own output.*

If the controller is to control the process, we can therefore define the process as anything between the controller's output and the signal the controller receives. Referring to Fig. 2-1.1*a*, the process is anything within the area delineated by the curve. The process includes the I/P transducer, valve, heat exchanger with

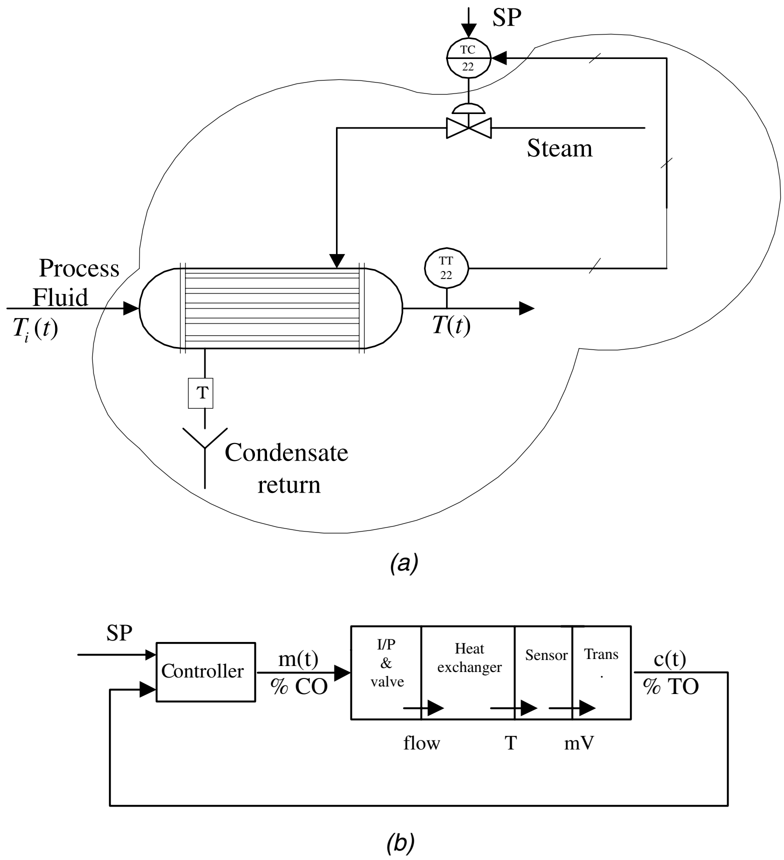

Figure 2-1.1 Heat exchanger temperature control system.

associated piping, sensor, and transmitter. That is, *the process is everything except the controller*.

A useful diagram is shown in Fig. 2-1.1*b*. The diagram shows all the parts of the process and how they relate. The diagram also clearly shows that the process output is the transmitter output and the process input is provided by the controller output. Note that we refer to the output of the transmitter *as* $c(t)$ to stress the fact that this signal is the real controlled variable; the unit of $c(t)$ is %TO (transmitter output). We refer to the signal from the controller as $m(t)$ to stress the fact that this signal is the real manipulated variable; the unit of $m(t)$ is %CO (controller output).

Now that we have defined the process to be controlled, it is necessary to explain why it is important to understand the terms that describe its characteristics. As we learned in Chapter 1, the control response depends on the tuning of the controller. The optimum tunings depend on the process to be controlled. As we well know, every process is different, and consequently, to tune the controller, the process characteristics must first be obtained. *What we do is to adapt the controller to the process.*

Another way to say that every process has different characteristics is to say that every process has its own "personality." If the controller is to provide good control, the controller personality (tunings) must be adapted to that of the process. It is important to realize that once a process is built and installed, it is not easy to change it. That is, the process is not very flexible. All the flexibility resides in the controller since it is very easy to change its tunings. As we show in Chapter 3, once the terms describing the process characteristics are known, the tuning of the controller is a rather simple procedure. Here lies the importance of obtaining the process characteristics.

2-2 TYPES OF PROCESSES

Processes can be classified into two general types depending on how they respond to an input change: self-regulating and non-self-regulating. The response of a *self-regulating process* to *step change* in input is depicted in Fig. 2-2.1. As shown in the

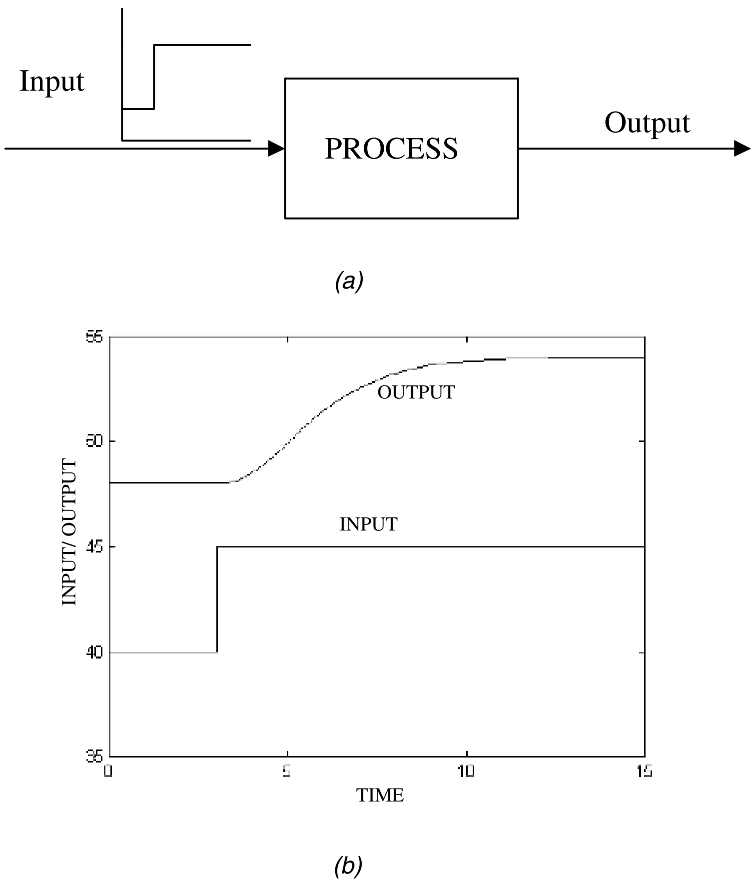

Figure 2-2.1 Response of self-regulating processes.