PROCESS SYSTEMS ANALYSIS AND CONTROL

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Second Edition

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ABOUT THE AUTHOR

Donald R. Coughanowr is the Fletcher Professor of Chemical Engineering a Drexel University. He received a Ph.D. in chemical engineering from the Uni versity of Illinois in 1956, an M.S. degree in chemical engineering from th University of Pennsylvania in 1951, and a B.S. degree in chemical engineerin from the Rose-Hulman Institute of Technology in 1949. He joined the facult at Drexel University in 1967 as department head, a position he held until 1988 Before going to Drexel, he was a faculty member of the School of Chemica Engineering at Purdue University for eleven years.

At Drexel and Purdue he has taught a wide variety of courses, which in clude material and energy balances, thermodynamics, unit operations, transpor phenomena, petroleum refinery engineering, environmental engineering, chemica engineering laboratory, applied mathematics, and process dynamics and control At Purdue, he developed a new course and laboratory in process control and col laborated with Dr. Lowell B. Koppel on the writing of the first edition of *Proces Systems Analysis and Control*.

His research interests include environmental engineering, diffusion wit chemical reaction, and process dynamics and control. Much of his research i control has emphasized the development and evaluation of new control algorithm for processes that cannot be controlled easily by conventional control; some o the areas investigated are time-optimal control, adaptive pH control, direct digita control, and batch control of fermentors. He has reported on his research in nu merous publications and has received support for research projects from the N.S.F and industry. He has spent sabbatical leaves teaching and writing at Case-Wester Reserve University, the Swiss Federal Institute, the University of Canterbury, th University of New South Wales, the University of Queensland, and Lehigh Uni versity.

Dr. Coughanowr's industrial experience includes process design and pilo plant at Standard Oil Co. (Indiana) and summer employment at Electronic Asso ciates and Dow Chemical Company.

He is a member of the American Institute of Chemical Engineers, the Instrument Society of America, and the American Society for Engineering Education. He is also a delegate to the Council for Chemical Research. He has served the AIChE by participating in accreditation visits to departments of chemical engineering for ABET and by chairing sessions of the Department Heads Forum at the annual meetings of AIChE.

PREFACE

Since the first edition of this book was published in 1965, many changes have taken place in process control. Nearly all undergraduate students in chemical engineering are now required to take a course in process dynamics and control. The purpose of this book is to take the student from the basic mathematics to a variety of design applications in a clear, concise manner.

The most significant change since the first edition is the use of the digital computer in complex problem-solving and in process control instrumentation. However, the fundamentals of process control, which remain the same, must be acquired before one can appreciate the advanced topics of control.

In its present form, this book represents a major revision of the first edition. The material for this book evolved from courses taught at Purdue University and Drexel University. The first 17 chapters on fundamentals are quite close to the first 20 chapters of the first edition. The remaining 18 chapters contain many new topics, which were considered very advanced when the first edition was published.

A knowledge of calculus, unit operations, and complex numbers is presumed on the part of the student. In certain later chapters, more advanced mathematical preparation is useful. Some examples would include partial differential equations in Chap. 21, linear algebra in Chaps. 28–30, and Fourier series in Chap. 33.

Analog computation and pneumatic controllers in the first edition have been replaced by digital computation and microprocessor-based controllers in Chaps. 34 and 35. The student should be assigned material from these chapters at the appropriate time in the development of the fundamentals. For example, obtaining the transient response for a system containing a transport lag can be obtained easily only with the use of computer simulation of transport lag. Some of the software now available for solving control problems should be available to the student; such software is described in Chap. 34. To understand the operation of modern microprocessor-based controllers, the student should have hands-on experience with these instruments in a laboratory.

Chapter 1 is intended to meet one of the problems consistently faced in presenting this material to chemical engineering students, that is, one of perspective. The methods of analysis used in the control area are so different from the previous experiences of students that the material comes to be regarded as a sequence of special mathematical techniques, rather than an integrated design approach to a class of real and practically significant industrial problems. Therefore, this chapter presents an overall, albeit superficial, look at a simple control-system design problem. The body of the text covers the following topics:

1. Laplace transforms, Chaps 2 to 4.
2. Transfer functions and responses of open-loop systems, Chaps. 5 to 8.
3. Basic techniques of closed-loop control, Chaps. 9 to 13.
4. Stability, Chap. 14.
5. Root-locus methods, Chap. 15.
6. Frequency-response methods and design, Chaps. 16 and 17.
7. Advanced control strategies (cascade, feedforward, Smith predictor, internal model control), Chap. 18.
8. Controller tuning and process identification, Chap. 19.
9. Control valves, Chap. 20.
10. Advanced process dynamics, Chap. 21.
11. Sampled-data control, Chaps. 22 to 27.
12. State-space methods and multivariable control, Chaps. 28 to 30.
13. Nonlinear control, Chaps. 31 to 33.
14. Digital computer simulation, Chap. 34.
15. Microprocessor-based controllers, Chap. 35.

It has been my experience that the book covers sufficient material for a one-semester (15-week) undergraduate course and an elective undergraduate course or part of a graduate course. In a lecture course meeting three hours per week during a 10-week term, I have covered the following Chapters: 1 to 10, 12 to 14, 16, 17, 20, 34, and 35.

After the first 14 chapters, the instructor may select the remaining chapters to fit a course of particular duration and scope. The chapters on the more advanced topics are written in a logical order; however, some can be skipped without creating a gap in understanding.

I gratefully acknowledge the support and encouragement of the Drexel University Department of Chemical Engineering for fostering the evolution of this text in its curriculum and for providing clerical staff and supplies for several editions of class notes. I want to acknowledge Dr. Lowell B. Koppel's important contribution as co-author of the first edition of this book. I also want to thank my colleague, Dr. Rajakannu Mutharasan, for his most helpful discussions and suggestions and for his sharing of some of the new problems. For her assistance in typing, I want to thank Dorothy Porter. Helpful suggestions were also provided by Drexel students, in particular Russell Anderson, Joseph Hahn, and Barbara Hayden. I also want to thank my wife Effie for helping me check the page proofs by reading to me the manuscript, the subject matter of which is far removed from her specialty of Greek and Latin.

McGraw-Hill and I would like to thank Ali Cinar, Illinois Institute of Technology; Joshua S. Dranoff, Northwestern University; H. R. Heichelheim, Texas Tech University; and James H. McMicking, Wayne State University, for their many helpful comments and suggestions in reviewing this second edition.

Donald R. Coughanowr

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Part VIII Nonlinear Control

Part IX Computers in Process Control

CHAPTER 1

AN INTRODUCTORY EXAMPLE

In this chapter we consider an illustrative example of a control system. The goal is to introduce some of the basic principles and problems involved in process control and to give the reader an early look at an overall problem typical of those we shall face in later chapters.

The System

A liquid stream at temperature T_i is available at a constant flow rate of w in units of mass per time. It is desired to heat this stream to a higher temperature T_R. The proposed heating system is shown in Fig. 1.1. The fluid flows into a well-agitated tank equipped with a heating device. It is assumed that the agitation is sufficient to ensure that all fluid in the tank will be at the same temperature, T. Heated fluid is removed from the bottom of the tank at the flow rate w as the product of this heating process. Under these conditions, the mass of fluid retained in the tank remains constant in time, and the temperature of the effluent fluid is the same as that of the fluid in the tank. For a satisfactory design this temperature must be T_R. The specific heat of the fluid C is assumed to be constant, independent of temperature.

Steady-State Design

A process is said to be at steady state when none of the variables are changing with time. At the desired steady state, an energy balance around the heating process may be written as follows:

$$q_s = wC(T_s - T_{i_s}) \tag{1.1}$$

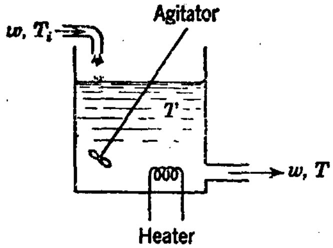

FIGURE 1-1
Agitated heating tank.

where q_s is the heat input to the tank and the subscript s is added to indicate a steady-state design value. Thus, for example, T_{i_s} is the normally anticipated inlet temperature to the tank. For a satisfactory design, the steady-state temperature of the effluent stream T_s must equal T_R. Hence

$$q_s = wC(T_R - T_{i_s}) \tag{1.2}$$

However, it is clear from the physical situation that, if the heater is set to deliver only the constant input q_s, then if process conditions change, the tank temperature will also change from T_R. A typical process condition that may change is the inlet temperature, T_i.

An obvious solution to the problem is to design the heater so that its energy input may be varied as required to maintain T at or near T_R.

Process Control

It is necessary to decide how much the heat input q is to be changed from q_s to correct any deviations of T from T_R. One solution would be to hire a process operator, who would be responsible for controlling the heating process. The operator would observe the temperature in the tank, presumably with a measuring instrument such as a thermocouple or thermometer, and compare this temperature with T_R. If T were less than T_R, he would increase the heat input and vice versa. As he became experienced at this task, he would learn just how much to change q for each situation. However, this relatively simple task can be easily and less expensively performed by a machine. The use of machines for this and similar purposes is known as *automatic process control.*

The Unsteady State

If a machine is to be used to control the process, it is necessary to decide in advance precisely what changes are to be made in the heat input q for every possible situation that might occur. We cannot rely on the judgment of the machine as we could on that of the operator. Machines do not think; they simply perform a predetermined task in a predetermined manner.

To be able to make these control decisions in advance, we must know how the tank temperature T changes in response to changes in T_i and q. This necessitates writing the *unsteady-state,* or *transient,* energy balance for the process. The input and output terms in this balance are the same as those used in the steady-state balance, Eq. (1.1). In addition, there is a transient accumulation of energy in the tank, which may be written

$$\text{Accumulation} = \rho V C \frac{dT}{dt} \qquad \text{energy units/time}^*$$

where ρ = fluid density
V = volume of fluid in the tank
t = independent variable, time

By the assumption of constant and equal inlet and outlet flow rates, the term ρV, which is the mass of fluid in the tank, is constant. Since

$$\text{Accumulation} = \text{input} - \text{output}$$

we have

$$\rho V C \frac{dT}{dt} = wC(T_i - T) + q \tag{1.3}$$

Equation (1.1) is the steady-state solution of Eq. (1.3), obtained by setting the derivative to zero. We shall make use of Eq. (1.3) presently.

Feedback Control

As discussed above, the controller is to do the same job that the human operator was to do, except that the controller is told in advance *exactly* how to do it. This means that the controller will use the existing values of T and T_R to adjust the heat input according to a predetermined formula. Let the difference between these temperatures, $T_R - T$, be called *error*. Clearly, the larger this error, the less we are satisfied with the present state of affairs and vice versa. In fact, we are completely satisfied only when the error is exactly zero.

Based on these considerations, it is natural to suggest that the controller should change the heat input by an amount *proportional* to the error. Thus, a plausible formula for the controller to follow is

$$q(t) = wC(T_R - T_{i_s}) + K_c(T_R - T) \tag{1.4}$$

where K_c is a (positive) constant of proportionality. This is called *proportional control*. In effect, the controller is instructed to maintain the heat input at the

*A rigorous application of the first law of thermodynamics would yield a term representing the transient change of internal energy with temperature at constant pressure. Use of the specific heat, at either constant pressure or constant volume, is an adequate engineering approximation for most liquids and will be applied extensively in this text.

steady-state design value q_s as long as T is equal to T_R [compare Eq. (1.2)], i.e., as long as the error is zero. If T deviates from T_R, causing an error, the controller is to use the magnitude of the error to change the heat input proportionally. (Readers should satisfy themselves that this change is in the right direction.) We shall reserve the right to vary the parameter K_c to suit our needs. This degree of freedom forms a part of our instructions to the controller.

The concept of using information about the deviation of the system from its desired state to control the system is called *feedback* control. Information about the state of the system is "fed back" to a controller, which utilizes this information to change the system in some way. In the present case, the information is the temperature T and the change is made in q. When the term $wC(T_R - T_{i_s})$ is abbreviated to q_s, Eq. (1.4) becomes

$$q = q_s + K_c(T_R - T) \tag{1.4a}$$

Transient Responses

Substituting Eq. (1.4a) into Eq. (1.3) and rearranging, we have

$$\tau_1 \frac{dT}{dt} + \left(\frac{K_c}{wC} + 1\right)T = T_i + \frac{K_c}{wC}T_R + \frac{q_s}{wC} \tag{1.5}$$

where

$$\tau_1 = \frac{\rho V}{w}$$

The term τ_1 has the dimensions of time and is known as the *time constant* of the tank. We shall study the significance of the time constant in more detail in Chap. 5. At present, it suffices to note that it is the time required to fill the tank at the flow rate, w. T_i is the inlet temperature, which we have assumed is a function of time. Its normal value is T_{i_s}, and q_s is based on this value. Equation (1.5) describes the way in which the tank temperature changes in response to changes in T_i and q.

Suppose that the process is proceeding smoothly at steady-state design conditions. At a time arbitrarily called zero, the inlet temperature, which was at T_{i_s}, suddenly undergoes a permanent rise of a few degrees to a new value $T_{i_s} + \Delta T_i$, as shown in Fig. 1.2. For mathematical convenience, this disturbance is idealized to

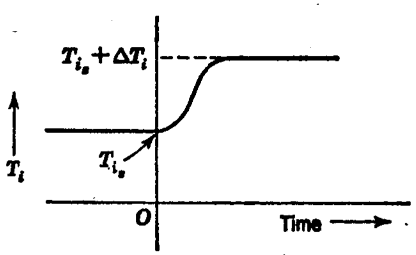

FIGURE 1-2
Inlet temperature versus time.