A Course in

DISTILLATION DYNAMICS AND CONTROL

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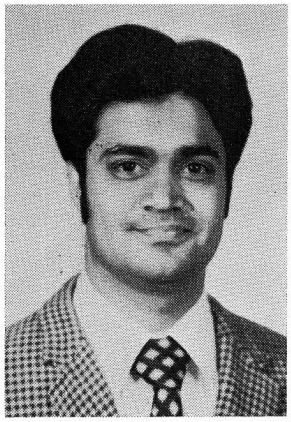
A TYPICAL UNDERGRADUATE curriculum in chemical engineering includes courses in unit operations, process design, and process control. In the first of these, a number of unit operations, e.g., distillation, absorption, extraction, are studied. In distillation, the following topics are usually covered: vapor-liquid equilibria, heat and material balances as applied to multistage columns, determination of the number of stages required for the specified separation of a binary mixture, reflux ratio requirements, and the efficiency of distillation columns. The detailed steady-state design of towers is taken up in process design. The third course, process control, introduces the student to the instrumentation used for the measurement, manipulation, and control of process variables. He learns the Laplace-transform methods for the characterization of processes, measuring elements, controllers, and final control elements. This is followed by the study of frequency response techniques for the design of control systems. Finally, criteria needed to determine the stability of control systems are discussed.



Pradeep Deshpande is an Associate Professor of Chemical Engineering at the University of Louisville. He came to Louisville from Bechtel, Inc. in San Francisco, California where he worked in the area of mathematical modeling, digital and analog/hybrid simulation, and automatic control of process systems. He received a B.S. degree in Chemistry from Karnatak University, Dharwar, India. He completed his B.S. and M.S. degrees in Chemical Engineering at the University of Alabama and his Ph.D. degree (1969) from the University of Arkansas. His background includes six years of academic experience and 2½ years of industrial experience. His current interests are in conventional and computer control, mathematical modeling, and dynamic simulation of process systems, and badminton (not necessarily in that order).

A graduate student with a background in the above courses usually has available to him an advanced course in distillation, which covers topics in multicomponent separations. Thus, he gets a fairly extensive background in the steady-state process design and operation of distillation columns. However, he has relatively little background in the automatic control of towers. For the student who may seek an industrial career in the area of distillation, or for one who plans advanced graduate work in distillation, it is believed that a gap exists which needs to be filled. It was with this in mind that a graduate level course entitled "Distillation Dynamics and Control," was developed. This course has been offered once to a class composed of 12 students, of whom 2 are PhD. students, 6 M.S. students (including 4 part-time students from industry), and 4 M. Eng. students. The reaction of the students to the course has been favorable.

COURSE CONTENT

THE SUGGESTED TOPICS for this course are shown in Table I. There are two ways in which this course can be taught. (1) If the curriculum structure, number of students available, and faculty loads are such that only one course can be offered in the area of distillation, the topics in Table I can be supplemented with steady-state topics. This means that some of the control topics would have to be eliminated, or

only briefly covered. (2) If desired, the entire course can be devoted to control topics. In this case, the course will benefit if it is supplemented with distillation control experiments which demonstrate the operation of control schemes. This approach can also utilize digital computer programs to validate some of the concepts listed in Table I. The course as taught here did include steady-state topics, but did not cover Parts VII-B, VIII-B, and IX. However, when the distillation controls laboratory becomes operational, it is contemplated that the entire course will be devoted to control topics. The course description in this article follows the latter approach.

One of the first questions that a control engineer has to address himself to is: "how many variables are available for control?" In order to answer this question, one must consider the analysis of the "degrees of freedom," in which the system equations are developed and compared with the number of unknown variables in order to decide how many variables are available for control, (Part II). Part III-A develops a basis for the control of one or both product compositions. The material balance and the separation factor, S, for a binary tower can be expressed, respectively, as

$$\frac{D}{F} = \frac{Z_F - X_B}{X_D - X_B} \qquad (1)$$

$$S = \frac{X_D\,(1 - X_B)}{X_B\,(1 - X_D)} = f(V/F, n, \alpha) \qquad (2)$$

where

Z_F, X_D, X_B = composition of the more volative component in the feed, distillate and, bottoms, respectively, dimensionless

D = distillate rate, $\frac{\text{moles}}{\text{time}}$

F = feed rate, $\frac{\text{moles}}{\text{time}}$

V = vapor boilup in reboiler, $\frac{\text{moles}}{\text{time}}$

n = no. of theoretical stages

α = relative volatility, dimensionless

For a fixed column operating with a given binary mixture, Equation (2) reduces to

$$S = \frac{X_D\,(1 - X_B)}{X_B\,(1 - X_D)} = f(V/F) \qquad (3)$$

Equations (1) and (3) can be considered together

TABLE I. COURSE OUTLINE

DESCRIPTION	SUGGESTED REFERENCES
I. Introduction	
A. Review of Steady-state Distillation Concepts	
B. Introduction to Automatic Control of Distillation Columns	
II. "Degrees of Freedom Analysis" to Determine the Number of Variables Available for Control	(1) pp. 69-75 (2) pp. 355-65
III. Material Balance Control Schemes	
A. Manipulation of Material Balance and Heat Input	(3) pp. 288-305
B. Pressure Control Methods	(3) pp. 299-302
C. Criteria for Sensor Location	(2) pp. 476-82
D. Control Strategy Analysis on McCabe-Thiele and Ponchon-Savarit Diagrams	(1) pp. 334-39 (2) pp. 417-27 (4) pp. 139-44 (5) pp. 26-29
IV. Dynamic Mathematical Modeling and Simulation of Distillation Columns	
A. Binary and Multicomponent Systems	(1) pp. 69-80
B. Open-Loop and Closed-Loop Responses	(1) pp. 148-59
V. Frequency Response Methods for Control Systems Design	
A. Linearized Models	(1) pp. 267-76
B. Experimental Methods — Pulse Testing	(1) pp. 282-93
VI. Control Over Both Products	
A. The Interaction Problem in Multivariable Control and Bristol's Interaction Measure	(6) pp. 133-34 (3) pp. 188-98
B. Proper Pairing of Variables and Application in Distillation	(3) pp. 305-06 (7) pp. 403-07 (8) pp. 227-36 (9) pp. 52-57
C. Design of Decouplers	(1) pp. 380-84 (10) pp. 198-203
VII. Advanced Control Schemes for Distillation Columns	
A. Feedforward Control	(1) pp. 431-37 pp. 445-47 (11) Tabs 1-4
B. Inferential Control	(12) pp. 614-23; (13) (14) pp. 127-31
VIII. Special Problems	
A. Inverse Response in Distillation Columns	(1) pp. 377-80 (15)
B. Override Control Schemes	(1) pp. 342-44 (16)
IX. Control Instrumentation	
A. Sensors, Controllers, and Control Valves	(1) pp. 305-45 (3) pp. 61-123

for deciding which streams should or need be manipulated in order to control one or both product compositions. Although the development is based on a binary column, the principles may be extended to multicomponent distillation.

In order to exercise proper control, it is essential that column pressure be maintained constant. Therefore, the methods for varying the rate of condensation so as to control column pressure are discussed next in Part III-B.

A graduate student usually gets a fairly extensive background in the steady-state process design and operation of distillation columns. However, he has relatively little background in the automatic control of towers.

Although the objective of most control schemes is to control product compositions, composition analyzers are not widely used for control purposes for reasons of cost and long time-lags. Instead, temperatures at appropriate locations in the column are controlled so as to indirectly control product quality. Thus, it is appropriate at this point to discuss the criteria for the suitable location of temperature sensors (III-C).

Although limited in its concepts to the distillation of binary mixtures, the McCabe-Thiele and Ponchon-Savarit diagrams are helpful in analyzing the effect of various upsets on the composition of product streams. The control strategy analysis on these diagrams is the subject of discussion in Part III-D.

Part IV is concerned with dynamic mathematical modeling and digital simulation of distillation towers for separating binary and multicomponent mixtures. The purpose here is to evaluate the open-loop response and the closed-loop response of columns (with specified control schemes), to various upsets. The dynamic models of towers and the associated equipment are developed and the system equations are solved on the digital computer in order to obtain open-loop and closed-loop responses.

CONTROLLER SYNTHESIS

PART V DEALS WITH controller synthesis; analytical and experimental approaches are covered. In the former approach (V-A), the mathematical model developed earlier is linearized, and the resulting system of equations is solved by the "stepping" technique. The results are in the form of frequency response plots (i.e., Bode Plots), from which feedback controllers can be designed.

The experimental technique consists of perturbing a distillation column and recording the outputs as a function of time. Many inputs can be used but a pulse input has many advantages over the others. The presentation in V-B describes how the output data to a pulse input can be analyzed so as to obtain frequency response diagrams.

Both of these methods are based on linear (ized) models, and hence the controllers will be satisfactory in the vicinity of the steady-state operating conditions. It is best to test these controllers on a more rigorous nonlinear model of the column developed in Part IV.

Part VI is devoted to the control of both product compositions and to the problem of interaction. A simple and useful measure of interaction in multivariable control problems is Bristol's Interaction Matrix. This interaction measure is developed and applied to some simple problems in VI-A. Its application to distillation (Part VI-B), assists in the selection of proper pairing of manipulated and controlled variables. This is followed, in Part VI-C, by the design of decouplers for achieving noninteracting feedback control of distillation columns. The design leads to Bode plots from which the transfer functions of decouplers can be approximated for implementation on hardware. This procedure is also based on a linearized model of the process, and the validity of these decouplers should be tested on a nonlinear model of the column developed earlier.

Part VII is concerned with advanced control schemes for distillation columns. Part VII-A discusses the advantages of feedforward control over feedback control. This is followed by the design of feedforward controllers. The gain terms of the feedforward controllers can be obtained from the material balance. In order to include dynamics, analysis of Part V-A (or experimental data), are needed. This analysis leads to Bode plots from which feedforward controller transfer functions can be obtained. The benefits of combined feedback/feedforward over feedforward and feedback control schemes can be demonstrated through simulation.

Part VII-B discusses an advanced scheme in which inexpensive multiple measurements on a

column are used to estimate the product composition. The estimate is then used to manipulate appropriate streams to hold product quality constant. There is scope here also to validate the results through simulation.

Part VIII outlines some special problems in distillation operations. The first of these to be covered is the inverse response in columns. The column base liquid level, for example, may temporarily increase due to an increase in reboiler heat duty. Part VIII-A examined the transfer function of a process, and illustrates how a positive zero can give rise to inverse response. Next, the equations needed to predict inverse response in distillation columns are developed. These equations serve as an aid in checking the design of distillation columns for inverse response. The remedy may consist of an alternate design for new columns or a different control scheme for operating columns.

Part VIII-B discusses override control schemes and the need for them. Often, conventional control schemes are inadequate in the presence of large upsets. In such cases, the override control schemes alter the appropriate streams so as to maintain the column in the safe operating region (or even cause shutdown if warranted). The hardware needed to implement these schemes is also discussed here.

Part IX in this course considers instrumentation hardware. The elements for the measurement of flow, liquid level, pressure, temperature, and composition are covered. This is followed by controller mode selection for loops involving the above variables. Finally, the characteristics and selection of control valves and the effect of characteristics on loop linearity is studied.

The benefits of combined feedback/feedforward control schemes can be demonstrated through simulation.

CONCLUDING REMARKS

IT IS BELIEVED that this course fills the gap between a conventional course on distillation and the dynamic operation of distillation towers. It can be taught as a complete course in distillation controls, or portions of it can be combined with a conventional course on distillation.

The course outline of Table I does not include optimal control and computer control of towers because these topics require an additional background in optimization and the z-transform methods (Perhaps these can be covered in individual courses in optimization and computer process control, respectively). □

ACKNOWLEDGMENT

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