Process Control Case Study: Two Product Distillation

APPENDIX J

Short examples of many process control designs are presented in the solved examples in the book. In this appendix, the control of a distillation tower is considered *in detail*. Distillation is chosen because it is one of the most important unit operations in the chemical industry. Also, distillation provides excellent learning experiences for nonlinear, multivariable processes with significant interactions. The exercises in this appendix can be completed without the aid of a simulator. However, complementary simulation exercises will substantially enhance the learning experience.*

This appendix enables readers to apply their process and control skills to the control of distillation by performing a series of exercises of increasing complexity. Many of the exercises involve open-ended questions to give you experience in defining and solving realistic problems. Since successful process control relies on knowledge from process technology and instrumentation, readers are encouraged to utilize their library, Internet, and self-study skills to investigate issues raised in these exercises. The references at the end of this appendix provide good initial sources of information and an introduction to the literature on distillation towers and their control.

The exercises in this appendix cover the topics in the same order as in the body of the book. To assist the readers, the exercises are organized according to the six

*A menu-driven, tray-by-tray dynamic distillation simulation is available in the Software Laboratory, Version 3.0 (Marlin, 1999), which runs within the MATLAB™ language (MathWorks, 1998). In addition, commercial flowsheeting programs have the capability to simulate distillation dynamics using standard models and rigorous physical properties; examples are Aspen Dynamics™ (Aspen, 1999) and HYSYS (Hyprotech, 1998).

major parts of the book. The best manner for using this appendix is as "capstone" exercises at the completion of each part of the book. The student should have the opportunity to review solutions to each part before proceeding to the next, so that prior learning provides a solid foundation for future challenges.

PART I: INTRODUCTION

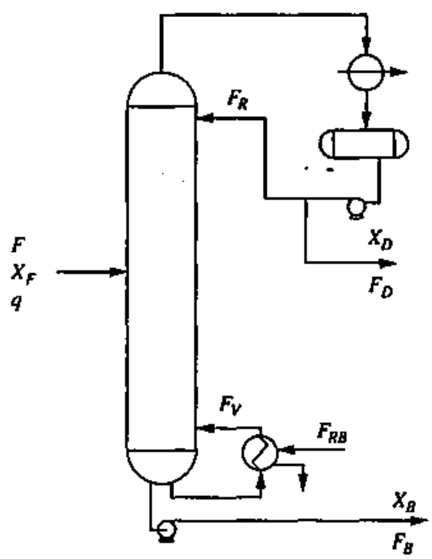
In Part I of the book, control terminology, concepts, and objectives are introduced. The exercises in this section of the appendix enable you to apply these topics to prepare for the study of distillation control. The example two-product distillation tower used in this appendix is shown in Figure J.1.

J.1. Distillation Process Principles

Before beginning control design and implementation, we should always be sure to understand the process technology. The questions in Table J.1 provide this check for the distillation tower.

J.2. Objectives

Present typical process control objectives grouped into the seven objective categories presented in Chapter 2. You should be as specific as possible, not just saying that "The process should remain safe" or "Profit should be maximized." Remember that these objectives must be clear enough to direct the control design and implementation.



Base-Case Data	
Feed rate	8.00 kmole/min
Feed composition, XF	0.45 mol fract L.K.
Feed liquid	1.00 fraction
Feed tray	10
Relative vol.	2.20
Trays	21 + reboiler
Distillate, XD	0.975 mol fract L.K.
FD	3.625 kmole/min
FR	7.487 kmole/min
Bottoms, XB	0.015 mol fract L.K.
FB	4.375 kmole/min
FV	11.11 kmole/min
FRB	6.945 kmole/min
Reflux drum	7.2 min. [Volume/($F_R + F_D$)]
Bottoms holdup	5.3 min [Volume/($F_V + F_B$)]

FIGURE J.1

Two-product distillation tower separating a binary mixture, with base-case data.

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Potential Benefits from Control

Answer the following questions for a simple, two-product distillation tower like the one in Figure J.1 that is separating a binary mixture.

1. Explain input variables and equipment performance factors that are likely to affect the profit of an operating distillation tower; do not include design decisions like the number of trays that cannot be changed during normal operation.
2. What information is required to determine the costs for the energy used in condensing and reboiling?
3. Some data is provided for the distillation tower in Figure J.2. For this question, assume that the light key in the bottoms should never exceed 0.016 mole

TABLE J.1

Questions on distillation process principles

1. Sketch the design for two heat exchangers that can be used as condensers. For each design, explain how the heat transfer can be changed and indicate a valve or other element of the design that could be manipulated to change the heat transferred. What fluid medium is normally used for heat exchange in the condenser and why?
2. Repeat question 1 for a reboiler.
3. Discuss the purpose of the overhead accumulator. How much liquid should be contained in the overhead accumulator.
4. Repeat (3) for the bottoms accumulator.
5. What determines the amount of liquid on each tray? Is level control needed?
6. Define constant relative volatility and give an example of components for which this is a good approximation.
7. For what conditions is constant molal overflow a valid approximation?
8. How would you define the best feed tray? How is the best feed tray determined?
9. (a) What factors are considered when determining a "good" pressure for a distillation tower during design?
   (b)What determines the maximum pressure for an operating distillation tower?
   (c) What determines the minimum pressure for an operating distillation tower?
   (d) What physical device should be provided to prevent excessive pressures?
10. (a) What determines the maximum vapor boilup in an operating distillation tower?
   (b) What determines the minimum vapor boilup in an operating distillation tower?
11. Describe likely disturbances that would influence product compositions and would be compensated by feedback control.

Summary of Historical Data

Fraction of Time	X_B (mole fraction L.K.)
0.10	0.013
0.12	0.011
0.23	0.009
0.20	0.007
0.27	0.005
0.08	0.003

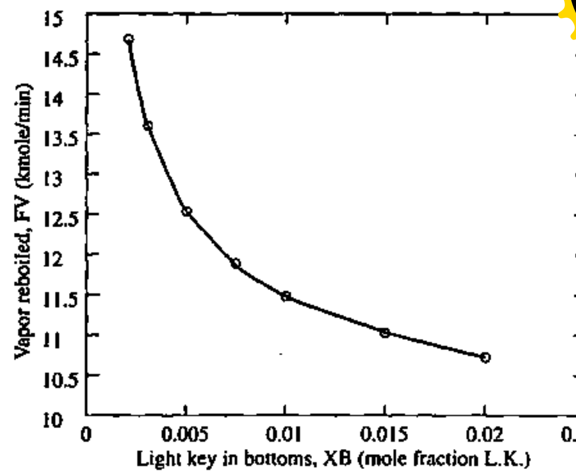

FIGURE J.2

Operating data for the distillation tower.

fraction. From this data, determine the following values for the reboiler energy consumption: (*a*) the average over the period of the data and (*b*) the absolute minimum. (For this question, assume that the heavy key is butane.)

4. With perfect separation, all light key material could have been recovered in the overhead product. Using the tabular data in Figure J.2, determine the amount of light key material in the bottoms that ideally could have been recovered in the top product.

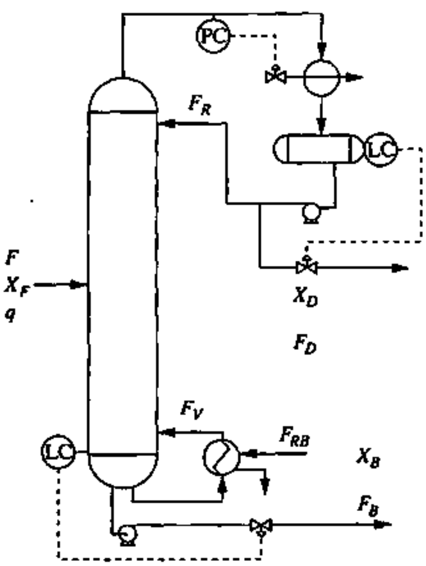

FIGURE J.3

Distillation tower with typical pressure and level controls.

PART II: PROCESS DYNAMICS

Process control requires an excellent understanding of the dynamic behavior of the plant. This knowledge is used to

1. Build plants that are easy to control.
2. Design control systems
3. Determine the effects of operations changes (production rate, product quality, etc.) on control performance to decide, for example, when adjustments in the computer control calculations are required

Here, questions are presented to help the reader understand the dynamics of a distillation tower. It would be helpful if the reader would review Section 5.6 on distillation modelling before proceeding with these exercises. Some further material on multicomponent distillation dynamic modelling and numerical simulation is available from Tyreus et al. (1975).

J.4. Process Reaction Curves

The tower in Figure J.3 is considered for this exercise with controllers maintaining the pressure and accumulator levels essentially constant. Process reaction curves are presented in Figure J.4.

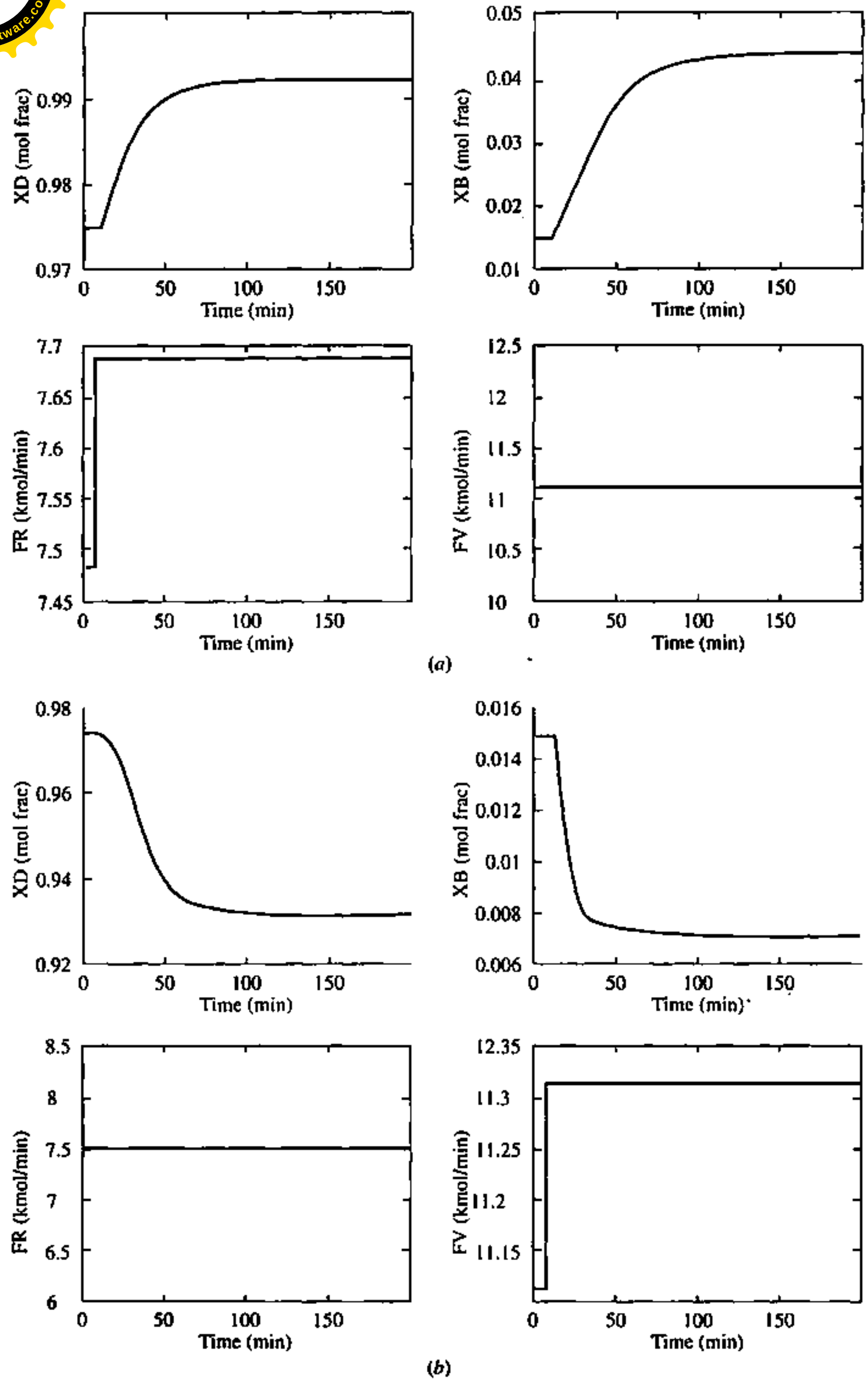

FIGURE J.4

(*a*) Dynamic response for a reflux (F_R) step of 0.20 kmole/min occurring at 6 minutes. (*b*) Dynamic response for a reboiler heating medium (F_{RB}) step of 0.125 kmol/min, causing a reboiled vapor (F_V) step of 0.20 kmole/min occurring at 6 minutes.

1. What can you conclude about the linearity of the process?
2. Based on your understanding of distillation, confirm the directions of the changes in the distillate and bottoms compositions in Figure J.4.
3. Discuss the causal relationships between inputs (F_R and F_{RB} or F_V) and outputs (X_D and X_B). Looking ahead, what important features in these responses would make feedback control potentially easy or difficult?

J.5. Distillation Dynamics

The following questions provide thought exercises on the effects of equipment and operating parameters on distillation dynamics.

1. The responses in Figure J.4 are for a distillation tower with the pressure and accumulator levels (controlled) to constant values. Is the distillation tower stable or unstable when *no* controllers are in operation? Explain for all important variables.
2. The dynamic response of the compositions for a change in reboil takes many minutes to reach steady state in spite of the very fast change in vapor flow rate. Why?

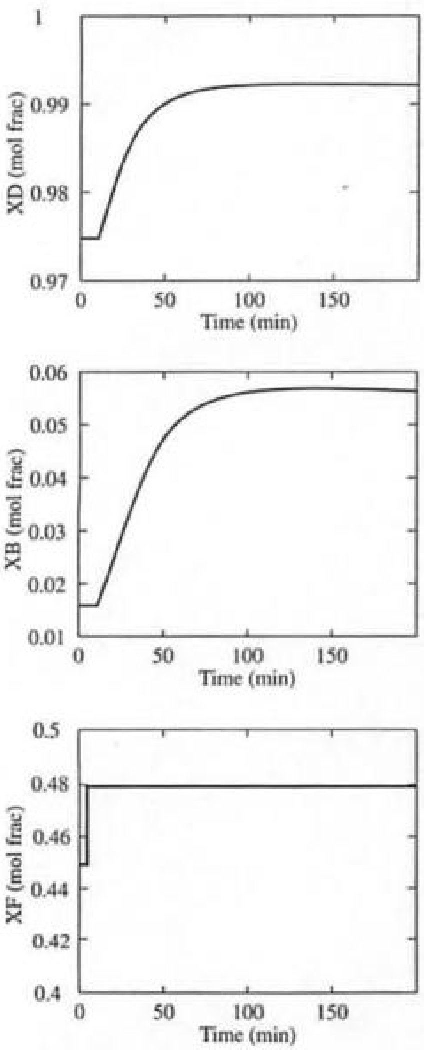

FIGURE J.5

Dynamic response for a feed composition (X_F) step of 0.03 fraction light key occurring at 6 minutes.

J.6. Disturbance Responses

Disturbance responses are presented in Figure J.5 for the tower in Figure J.3 with controllers maintaining the pressure and accumulator levels essentially constant.

1. The experiments in Figures J.4 and J.5 both present input-output results. What is the major difference between the input variables in these two figures?
2. Based on your understanding of distillation, confirm the directions of the changes in the distillate and bottoms compositions in Figure J.5.
3. Discuss the causal relationships between disturbance inputs and composition outputs. Looking ahead, what important features in these responses would make feedback control potentially easy or difficult?

PART III: FEEDBACK CONTROL

The process dynamics and disturbance characteristics determine the best possible control performance, but the actual performance is strongly influenced by the control design and implementation. A good design often results in safe and profitable operation providing consistently high product quality. The exercises in this part provide the opportunity to combine the process understanding acquired in Part II with control technology to provide good single-loop feedback control.

J.7. Sensor Selection

Review and enhance the control objectives for the distillation tower you developed in Exercise J.2. For each objective identify one or more sensors required to achieve the objective. Indicate the location of each sensor on a process schematic and indicate the variable range and physical principle. For analyzers, discuss the sample system needed and determine the locations for the "fast loop" withdrawal and return.

J.8. Control Valves

Process control requires manipulated variables, which are most often valves that affect flow rates. Indicate the location of all automated control valves on a process schematic. Determine the maximum flow rating, failure position, and body type. Feedback control tends to transfer variation from the controlled to the manipulated variables; explain briefly why the variation is less costly in the flows affected by these valves than in the controlled variables identified in Exercise J.7.

Part IV: Enhancements to Single-Loop Control

J.9. Control Performance

Suggest quantitative control performance measures that could be calculated from plant data on the controlled and manipulated variables identified in Exercises J.7 and J.8.

J.10. Single-Loop Design

For each of the controlled variables identified in Exercise J.7, select a manipulated variable to adjust from the valves identified in Exercise J.8. Select modes for each controller.

J.11. Controller Tuning

Tune each single-loop PID composition controller, X_D and X_B, using models based on the data in Figure J.4. Estimate the longest digital controller execution periods that would not degrade control performance for each controller.

J.12. Display

Sketch a real-time screen to be displayed by a digital control system to be used by a plant operator to monitor and intervene in the operation of the distillation tower. Indicate what data should be displayed and how (numbers, bar charts, trend plots, etc.) and what parameters could be changed by the plant personnel.

PART IV: ENHANCEMENTS TO SINGLE-LOOP CONTROL

The performance of feedback is limited by the process dynamics in the feedback and disturbance paths. Substantial improvements to control performance are possible through single-loop enhancements that utilize additional sensors and models. The exercises in this part of the appendix enable the reader to apply these enhancements to distillation.

J.13. Cascade Control

List disturbances that will affect the distillation tower. For each, determine whether cascade control would improve the performance of the control design you developed in Exercise J.10. Sketch the cascade controls you recommend on a process schematic.

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J.14. Feedforward Control

Consider the control of the distillate purity, X_D, with the pressure and accumulator levels controlled by separate PI controllers. List disturbances that affect X_D, and for each, determine whether feedforward control would improve the performance provided by the feedback controller of X_D. Sketch the feedback-feedforward controller design for a feed composition disturbance on a process schematic, and design the controller based on the data in Figures J.4 and J.5.

J.15. Ratio Control

A colleague suggests that the reflux flow and reboiler heating medium flow should be adjusted so that they are ratios of the feed flow rate, e.g., F_R/F = constant. Discuss the advantages and disadvantages of this design and how distillate composition (X_D) analyzer feedback could be included in the design. Decide whether you would agree to implement the design.

J.16. Operating Conditions

The distillate and product light key composition set points are changed from their values in Figure J.1 to $X_D = 0.995$ and $X_B = 0.005$. Does anything in the control implementation have to be changed in response?

J.17. Inferential Control

You have learned that an analyzer to measure X_B is very expensive. Discuss alternative control designs and how you would evaluate their likely performance.

J.18. Level Control

Which PID controller modes would you recommend for the accumulator level controllers? Should the levels be tuned for tight or averaging control?

J.19. Internal Model Control

Design and tune each single-loop IMC composition controller, X_D and X_B, using the data in Figure J.4. Estimate the longest digital controller execution periods that would not degrade control performance for each controller.

PART V: MULTIVARIABLE CONTROL

The dynamic behavior of several single-loop controllers applied to a process differs from the individual loop behavior because of interaction. Interaction affects the controllability, operating window, stability and tuning, and dynamic behavior of the controlled and manipulated variables. The exercises in this part provide the opportunity to consider the effects of interaction on the control of a distillation tower.

J.20. Possible Designs

The control of pressure, two levels, and two compositions with five possible valves provides many opportunities.

1. Determine the maximum number of possible loop pairings for this situation.
2. Determine some of these pairings which can be quickly eliminated from consideration and explain why.

J.21. Operating Window

For the distillation tower in Figure J.1, determine the operating window with the composition (X_D and X_B) set points on the coordinates. For this exercise, the reflux ratio and reboiled vapor are limited by the following values: $5.5 \leq F_R \leq 10.1$ and $75 \leq F_V \leq 140$ kmole/min. (You will need a steady-state simulator for this exercise.)

J.22. Relative Gain

Using the results from the process reaction curve in Figure J.4, calculate the relative gain array. Then, calculate the steady-state gains between the inputs (F_R and F_V) and outputs (X_D and X_B) with sufficient accuracy to reliably evaluate the relative gain array. (You will need a steady-state simulator for this exercise.)

J.23. Controller Tuning

Assume that the multiloop pressure and level control pairings are as shown in Figure J.3. Using the process reaction curves in Figure J.4, calculate the tuning for the two analyzer feedback controllers when implemented simultaneously.

J.24. Decoupling

For the tower in Figure J.3, answer the following questions:

1. Discuss when decoupling might be advantageous.
2. Design decouplers for two-way decoupling using the data in Figure J.4.
3. Discuss the likely errors in the decouplers and the effect of these errors on dynamic performance of PI controllers with decoupling.

J.25. Variable Structure

Discuss why minimum and maximum bounds would exist on allowable reflux flow rates. Design a control system that normally controls X_D to its set point but maintains the reflux flow rate between its minimum and maximum bounds at all times.

PART VI: PROCESS CONTROL DESIGN

Design enables the engineer to "bring it all together." In the design process, the engineer applies analysis methods and guidelines to prepare a complete specification of the control structure, calculations, and equipment. The exercises in this part provide the opportunity to complete the control design for a distillation tower. Since design depends on the context, you will have to make various assumptions when completing the exercises. In contrast the practicing engineer would have

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to determine these factors from market analysis, quality control specifications, ancillary plant equipment layout, and so forth.

J.26. Control Design Form

Prepare a control design form (CDF) for the distillation tower described in Figure J.1. You might prepare a preliminary version, and complete the CDF after preparing answers for the following exercises in this part.

J.27. Sensors

Specify the sensors required for each control objective for the distillation tower. For each sensor, define the physical principle, range, accuracy, and reproducibility, and indicate the location of each sensor on a process schematic. For analyzers, discuss the sample system needed and determine the locations for the "fast loop" withdrawal and return.

J.28. Valves

Specify valves (final control elements) that are needed to control the distillation tower. For each valve, define the capacity (maximum flow), body type, failure position, and the need for block and bypass "hand valves" that can be opened and closed by a plant operator, but not remotely.

J.29. Control Design

Design a closed-loop control system that will achieve the control objectives you specified in Exercise J.26.

J.30. Control for Safety

Perform a safety review of the process with your control design and add control and equipment to ensure safe operation. Your answer should include automated control and provision for operator monitoring of safety-related issues.

J.31. Optimization

Discuss opportunities for optimizing a distillation tower. Define factors that would appear in a calculation of profit for a distillation tower and how these would be measured. Identify variables that can be changed during normal operation that influence profit and what tradeoffs exist that would lead to an optimum, i.e., a maximum when profit is plotted against the variable. Finally, describe a method for optimizing a distillation tower in real time.

J.32. Monitoring

Identify process equipment and operations factors that should be monitored by plant personnel to ensure proper plant operation. For each factor, define the sensors or laboratory data required, the analysis performed by the personnel, the decision and threshold value that would indicate a change is required, and the time frame for this monitoring, i.e., every half hour, once a month, etc. Discuss the use of statistical monitoring methods in the plant monitoring.

Congratulations! You have now completed an analysis and control design for one distillation tower. Hopefully, these exercises have reinforced the importance of learning the material in the book and improved your ability to apply the principles to realistic challenges. You should not interpret the large number of exercises as an indication of the documentation typically developed in designing controls for a single distillation tower. Here, many exercises have been provided to help you learn. After gaining experience through university education and industrial practice, you will be performing this analysis rapidly, although perhaps on different unit operations.

The exercises in this appendix follow the organization in the book, which introduces topics gradually. Now that you have learned the material, you can apply process control principles and guidelines more directly.

> **Therefore, the control design approaches in Chapters 24 and 25 are recommended when you apply control engineering to real industrial challenges.**

REFERENCE

Mathworks, MATLAB™, 3 Apple Drive, Natick, MA (1998).

Distillation Control

Luyben, W. (ed.), *Practical Distillation Control*, Van Nostrand Reinhold, New York, 1992.

Shinskey, F., *Distillation Control*, McGraw-Hill, New York, 1984.

Distillation Dynamic Simulation

Aspen, Aspen Dynamics™ and Aspen Custom Modeller™, Aspen Technology, 10 Canal Park, Cambridge, MA, 1999.

Holland, C., *Unsteady State Processes with Applications to Multicomponent Distillation*, Prentice-Hall, Englewood Cliffs, 1966.

Hyprotech, HYSYS.PLANT v2.0 *Documentation, Dynamic Modelling Manual*, Hyprotech Ltd., Calgary, 1998.

Marlin, T., *The Software Laboratory, Version 3.0*, McMaster University, Hamilton, 1999.

Tyreus, B., W. Luyben, and W. Schiesser, "Stiffness in Distillation Models and the Use of an Implicit Integration Method to Reduce Computation Times," *Ind. Eng. Chem. PDD, 14*, 427–433 (1975).

Distillation Equipment Design and Operation

Chin, T., "Guide to Distillation Pressure Control Methods," *Hydrocarbon Proc.*, 145–153 (October 1979).

Kister, H., *Distillation Design*, McGraw-Hill, New York, 1992.

Kister, H., *Distillation Process Operations and Applications*, McGraw-Hill, New York, 1990.

Lieberman, N., and E. Lieberman, *A Working Guide to Process Equipment*, McGraw-Hill, New York, 1997.

Ludwig, E., *Applied Process Design for Chemical and Petrochemical Plants* (2nd ed.), Gulf Publishing, Houston, 1979.

Distillation Fundamentals

King, C., *Separation Processes*, 2nd ed., McGraw-Hill, New York, 1980.

Distillation Tray Hydraulics

Barnicki, S., and J. Davis, "Designing Sieve Trays"—Part 1, *Chemical Engineering*, October 1989, 140 (1989).

Barnicki, S., and J. Davis, "Designing Sieve Trays"—Part 2, *Chemical Engineering*, November 1989, 202 (1989).

Lockett, M., *Distillation Tray Fundamentals*, Cambridge University Press, London, 1986.

Industrial Instrumentation

Andrew, W., and H. Williams, *Applied Instrumentation in the Process Industries, Volume I, A Survey* (2nd ed.), Gulf Publishing, Houston, 1979.

Andrew, W., and H. Williams, *Applied Instrumentation in the Process Industries Volume II, Practical Guidelines* (2nd ed.), Gulf Publishing, Houston, 1980.

Driskell, L., *Control Valve Selection and Sizing*, ISA Publishing, Research Triangle Park, NC, 1983.