Separation Processes

McGraw-Hill Chemical Engineering Series

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McGRAW-HILL BOOK COMPANY
New York San Francisco St. Louis Düsseldorf London
Mexico Panama Sydney Toronto

This book was set in Monotype Times Roman by William Clowes & Sons, Ltd., and printed on permanent paper and bound by The Maple Press Company. The designer was Janet Bollow; the drawings were done by John Foster. The editors were B. J. Clark and Marge Eakins. Charles A. Goehring supervised production.

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Printed in the United States of America.

Library of Congress catalog card number: 70-130676

1234567890 MAMM 7987654321

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Preface

This book is intended as a college or university level text for chemical engineering courses. It should be suitable for use in any of the various curricular organizations, in courses such as separation proeesses, mass-transfer operations, unit operations, distillation, etc. A primary aim in the preparation of the book is that it be complementary to a transport phenomena text so that together they can serve effectively the needs of the unit operations or momentum-, heat-, and mass-transfer core of the chemical engineering curriculum.

It should be possible to use the book at various levels of instruction, both undergraduate and postgraduate. Preliminary versions have been used for a junior-senior course and a graduate course at Berkeley, for a sophomore course at Princeton, for a senior course at Rochester, and for a graduate course at the Massachusetts Institute of Technology. A typical undergraduate course would concentrate on Chapters 1 through 7 and on some or all of Chapters 8 through 11. In a graduate course one could cover Chapters 1 through 6 lightly and concentrate on Chapters 7 through 15. There is little that should be considered as an absolute prerequisite for a course based upon the book, although a physical chemistry course emphasizing thermodynamics should probably be taken at least concurrently. The text coverage of phase equilibrium thermodynamics and of basic mass-transfer theory is minimal, and the student should take additional courses treating these areas.

Practicing engineers who are concerned with the selection and evaluation of alternative separation processes or with the development of computational algorithms should also find the book useful; however, it is not intended to serve as a comprehensive guide to the detailed design of specific items of separation equipment.

The book stresses a basic understanding of the concepts underlying the selection, behavior, and computation of separation processes. As a result several chapters are almost completely qualitative. Classically, different separation processes, such as distillation, absorption, extraction, ion exchange, etc., have been treated individually and sequentially. In a departure from that approach, this book considers separations as a general problem and emphasizes the many common aspects of the functioning and analysis of the different separation processes. This generalized development is designed to be more efficient and should create a broader understanding on the part of the student.

The growth of the engineering science aspects of engineering education has created a major need for making process engineering and process design sufficiently prominent in chemical engineering courses. Process thinking should permeate the entire curriculum rather than being reserved for a final design course. An important aim of this textbook is to maintain a flavor of real processes and of process synthesis and selection, in addition to presenting the pertinent calculational methods.

The first three chapters develop some of the common principles of simple separation processes. Following this, the reasons for staging are explored and the McCabe-Thiele graphical approach for binary distillation is developed. This type of plot is brought up again in the discussions of other binary separations and multicomponent separations and serves as a familiar visual representation through which various complicated effects can be more readily understood. Modern computational approaches for single-stage and multistage separations are considered at some length, with emphasis on an understanding of the different conditions which favor different computational approaches. In an effort to promote a fuller appreciation of the common characteristics of different multistage separation processes, a discussion of the shapes of flow, composition, and temperature profiles precedes the discussion of computational approaches for multicomponent separations; this is accomplished in Chapter 7. Other unique chapters are Chapter 13, which deals with the factors governing the energy requirements of separation processes, and Chapter 14, which considers the selection of an appropriate separation process for a given separation task.

Problems are included at the end of each chapter. These have been generated and accumulated by the author over a number of years during courses in separation processes, mass-transfer operations, and the earlier and more qualitative aspects of process selection and design given by him at the University of California and at the Massachusetts Institute of Technology. Many of the problems are of the qualitative discussion type; they are intended to amplify the student's understanding of basic concepts and to increase his ability to interpret and analyze new situations successfully. Calculational time and rote substitution into equations are minimized. Most of the problems are based upon specific real processes or real processing situations. The numbering style of the problems— for example, $5.H_3$—is as follows: The first number represents the chapter, the letter represents the position in sequence, and the numerical subscript represents the degree of difficulty. Subscript 1 denotes a problem which is a straightforward application of material presented in the text. Subscript 2 denotes a problem which involves more insight, but which should still be suitable for undergraduate students. Subscript 3 denotes problems requiring still more insight, which are appropriate for the most part for graduate students.

Donald N. Hanson participated actively in the early planning stages of this book and launched the author onto this project. Substantial portions of Chapters 5, 7, 8, and 9 stem from notes developed by Professor Hanson and used by him for a number of years in an undergraduate course at the University of California. The presentation in Chapter 11 has been considerably influenced by numerous discussions with Edward A. Grens II. The reactions, suggestions, and other contributions of teaching assistants and numerous students over the past few years have been invaluable, particularly those from Romesh Kumar, Roger Thompson, Francisco Barnés, and Raul Acosta. Roger Thompson also assisted ably with the preparation of the index. Thoughtful and highly useful reviews based upon classroom use elsewhere were given by William Schowalter, J. Edward Vivian, and Charles Byers.

Thanks of a different sort go to Edith P. Taylor, who expertly and so willingly prepared the final manuscript, and to her and several other typists who participated in earlier drafts.

Finally, I have three special debts of gratitude: to Charles V. Tompkins, who awakened my interests in science and engineering; to Thomas K. Sherwood, who brought me to a realization of the importance and respectability of process design and synthesis in education; and to the University of California at Berkeley and numerous colleagues there who have furnished encouragement and the best possible surroundings.

C. Judson King

Contents

1
Uses and Characteristics of Separation Processes

Die Entropie der Welt strebt einem Maximum zu.

CLAUSIUS

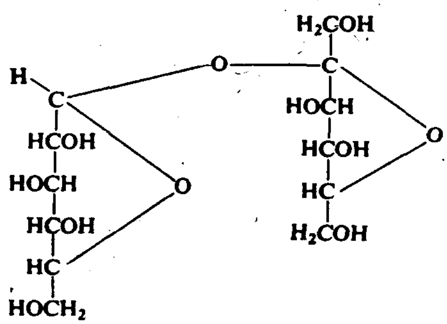
When salt is placed in water it dissolves and tends to form a solution of uniform composition throughout. There is no simple way to separate the salt and the water again. This tendency of substances to mix together intimately and spontaneously is a manifestation of the second law of thermodynamics, which states that all natural processes take place so as to increase the entropy, or randomness, of the universe. In order to separate a mixture of species into products of different composition we must create some sort of device, system, or process which will supply the equivalent of thermodynamic work to the mixture in such a way as to cause the separation to occur.

For example, if we want to separate a solution of salt and water we can (1) supply heat and boil water off, condensing the water at a lower temperature, (2) supply refrigeration and freeze out pure ice, which we can then melt at a higher temperature; (3) pump the water to a higher pressure and force it through a thin solid membrane that will let water through preferentially to salt. All three of these approaches (and numerous others) have been under active study and development for producing fresh water from the sea.

The fact that naturally occurring processes are inherently mixing processes has been recognized for over a hundred years, and has led to the reverse procedure of "unmixing" or *separation processes* becoming one of the most challenging categories of engineering problems. We shall define separation processes as *those operations which transform a mixture of substances into two or more products which differ from one another in composition*. The many different kinds of separation process in use and their importance to mankind should become apparent from the following three examples, which concern basic wants of mankind: food, drink, and clothing.

AN EXAMPLE: CANE SUGAR REFINING

Common white granulated sugar is typically 99.9 percent sucrose, and is one of the



Sucrose

purest of all substances produced from natural materials in such large quantity. Sugar is obtained from both sugar cane and sugar beets.

Cane sugar is normally produced in two major blocks of processing operations (Wills, 1954; Spencer & Meade, 1945). Preliminary processing takes place near where the sugar cane is grown (Hawaii, Puerto Rico, etc.) and typically consists of the following basic steps, shown in Figure 1-1.

1. *Washing and Milling*. The sugar cane is washed with jets of water to free it from any field debris and is then chopped into short sections. These sections are passed through high-pressure rollers which squeeze sugar-laden juice out of the plant cells. Some water is added toward the end of the milling to leach out the last portions of available sugar. The remaining cane pulp is known as *bagasse*, and is used for fuel or for the manufacture of insulating fiber board.

2. *Clarification*. Milk of lime [$Ca(OH)_2$] is added to the sugar-laden juice, which is then heated. The juice next enters large holding vessels in which coagulated colloidal material and insoluble calcium salts are settled out. The scum withdrawn from the bottom of the clarifier is filtered to reclaim additional juice, which is recycled.

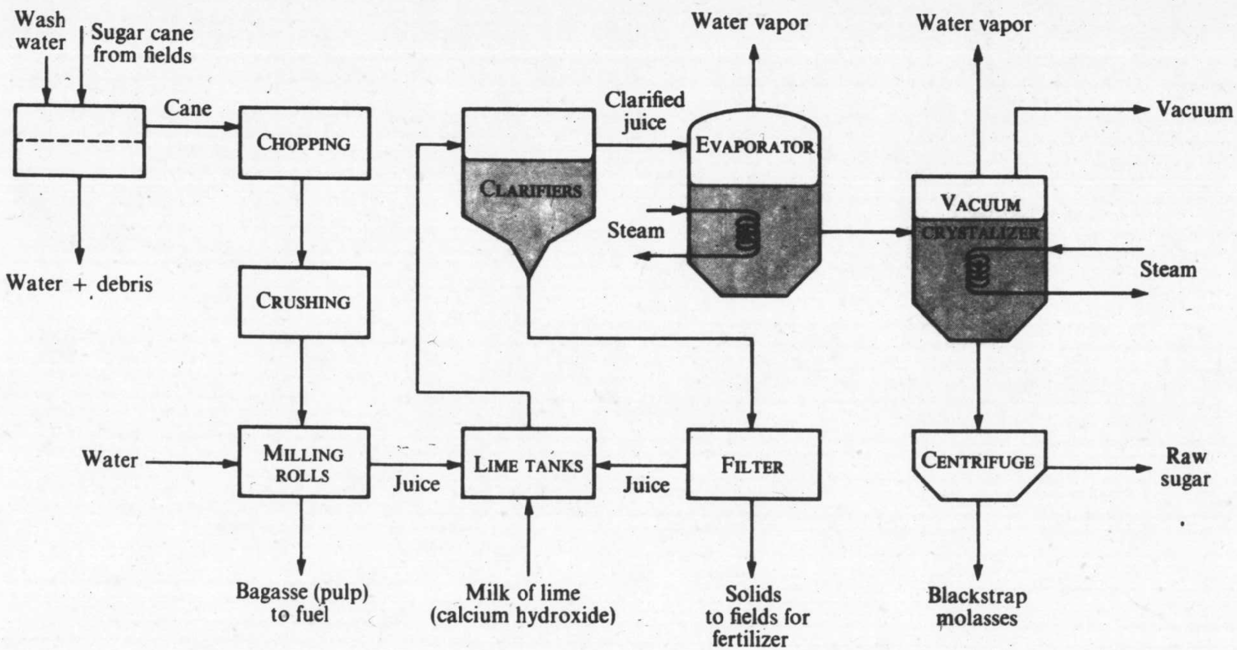


Fig. 1-1 *Processing steps for producing raw sugar from sugar cane.*