FOURTH EDITION

COULSON & RICHARDSON'S

CHEMICAL ENGINEERING

化学工程

J M Coulson & J F Richardson
with J R Backhurst & J H Harker

第2卷 第4版

2 VOLUME 2

Particle Technology & Separation Processes

Butterworth Heinemann
世界图书出版公司

CHEMICAL ENGINEERING

VOLUME 2

FOURTH EDITION

Particle Technology and Separation Processes

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Preface to the Fourth Edition

Details of the current restructuring of this Chemical Engineering Series, coinciding with the publication of the Fourth Edition of Volumes 1 and 2 and to be followed by new editions of the other volumes, have been set out in the Preface to the Fourth Edition of Volume 1. The revision involves the inclusion in Volume 1 of material on non-Newtonian flow (previously in Volume 3) and the transference from Volume 2 to Volume 1 of *Pneumatic and Hydraulic Conveying* and *Liquid Mixing*. In addition, Volume 6, written by Mr. R. K. Sinnott, which first appeared in 1983, nearly thirty years after the first volumes, acquires some of the design-orientated material from Volume 2, particularly that related to the hydraulics of packed and plate columns.

The new sub-title of Volume 2, *Particle Technology and Separation Processes*, reflects both the emphasis of the new edition and the current importance of these two topics in Chemical Engineering. *Particle Technology* covers the basic properties of systems of particles and their preparation by comminution (Chapters 1 and 2). Subsequent chapters deal with the interaction between fluids and particles, under conditions ranging from those applicable to single isolated particles, to systems of particles freely suspended in fluids, as in sedimentation and fluidisation; and to packed beds and columns where particles are held in a fixed configuration relative to one another. The behaviour of particles in both gravitational and centrifugal fields is also covered. It will be noted that *Centrifugal Separations* are now brought together again in a single chapter, as in the original scheme of the first two editions, because the dispersal of the material between other chapters in the Third Edition was considered to be not entirely satisfactory.

Fluid–solids Separation Processes are discussed in the earlier chapters under the headings of Sedimentation, Filtration, Gas Cleaning and Centrifugal Separations. The remaining separations involve applications of mass-transfer processes, in the presence of solid particles in Leaching (solid–liquid extraction), Drying and Crystallisation. In Distillation, Gas Absorption and Liquid–Liquid Extraction, interactions occur between two fluid streams with mass transfer taking place across a phase boundary. Usually these operations are carried out as continuous countercurrent flow processes, either stagewise (as in a plate-column) or with differential contacting (as in a packed-column). There is a case therefore for a generalised treatment of countercurrent contacting processes with each of the individual operations, such as Distillation, treated as particular cases. Although this approach has considerable merit, both conceptually and in terms of economy of space, it has not been adopted here, because the authors' experience of teaching suggests that the student more readily grasps the principles involved, by considering each topic in turn, provided of course that the teacher makes a serious attempt to emphasise the common features.

The new edition concludes with four chapters which are newcomers to Volume 2, each written by a specialist author from the Chemical Engineering Department at Swansea—

Adsorption and Ion Exchange (Chapters 17 and 18)
(topics previously covered in Volume 3)
by J. H. Bowen

Chromatographic Separations (Chapter 19)
by J. R. Conder

and

Membrane Separations (Chapter 20)
by W. R. Bowen.

These techniques are of particular interest in that they provide a means of separating molecular species which are difficult to separate by other techniques and which may be present in very low concentrations. Such species include large molecules, sub-micrometre size particles, stereo-isomers and the products from bioreactors (Volume 3). The separations can be *highly specific* and may depend on molecular size and shape, and the configuration of the constituent chemical groups of the molecules.

Again I would express our deep sense of loss on the death of our colleague, Professor John Coulson, in January 1990. His two former colleagues at Newcastle, Dr. John Backhurst and the Reverend. Dr. John Harker, have played a substantial part in the preparation of this new edition both by updating the sections originally attributable to him, and by obtaining new illustrations and descriptions of industrial equipment.

Finally, may I again thank our readers who, in the past, have made such helpful suggestions and have drawn to our attention errors, many of which would never have been spotted by the authors. Would they please continue their good work!

Swansea
July 1990

J. F. RICHARDSON

Note to Fourth Edition—Revised Impression 1993

In this reprint corrections and minor revisions have been incorporated. The principal changes are as follows:

(1) Addition of an account of the construction and operation of the Szego Grinding Mill (Chapter 2).

(2) Inclusion of the Yoshioka method for the design of thickeners (Chapter 5).

(3) Incorporation of Geldart's classification of powders in relation to fluidisation characteristics (Chapter 6).

(4) The substitution of a more logical approach to filtration of slurries yielding compressible cakes and redefinition of the specific resistance (Chapter 7).

(5) Revision of the nomenclature for the underflow streams of washing thickeners to bring it into line with that used for other stagewise processes, including distillation and absorption (Chapter 10).

(6) A small addition to the selection of dryers and the inclusion of Examples (Chapter 16).

JFR

Preface to the 1983 Reprint of the Third Edition

In this volume, there is an account of the basic theory underlying the various Unit Operations, and typical items of equipment are described. The equipment items are the essential components of a complete chemical plant, and the way in which such a plant is designed is the subject of Volume 6 of the series which has just appeared. The new volume includes material on flowsheeting, heat and material balances, piping, mechanical construction and costing. It completes the Series and forms an introduction to the very broad subject of Chemical Engineering Design.

Preface to Third Edition

In producing a third edition, we have taken the opportunity, not only of updating the material but also of expressing the values of all the physical properties and characteristics of the systems in the SI System of units, as has already been done in Volumes 1 and 3. The SI system, which is described in detail in Volume 1, is widely adopted in Europe and is now gaining support elsewhere in the world. However, because some readers will still be more familiar with the British system, based on the foot, pound and second, the old units have been retained as alternatives wherever this can be done without causing confusion.

The material has, to some extent, been re-arranged and the first chapter now relates to the characteristics of particles and their behaviour in bulk, the blending of solids, and classification according to size or composition of material. The following chapters describe the behaviour of particles moving in a fluid and the effects of both gravitational and centrifugal forces and of the interactions between neighbouring particles. The old chapter on centrifuges has now been eliminated and the material dispersed into the appropriate parts of other chapters. Important applications which are considered include flow in granular beds and packed columns, fluidisation, transport of suspended particles, filtration and gas cleaning. An example of the updating which has been carried out is the addition of a short section on fluidised bed combustion, potentially the most important commercial application of the technique of fluidisation. In addition, we have included an entirely new section on flocculation, which has been prepared for us by Dr. D. J. A. Williams of University College, Swansea, to whom we are much indebted.

Mass transfer operations play a dominant role in chemical processing and this is reflected in the continued attention given to the operations of solid–liquid extraction, distillation, gas absorption and liquid–liquid extraction. The last of these subjects, together with material on liquid–liquid mixing, is now dealt within a single chapter on liquid–liquid systems, the remainder of the material which appeared in the former chapter on mixing having been included earlier under the heading of solids blending. The volume concludes with chapters on evaporation, crystallisation and drying.

Volumes 1, 2 and 3 form an integrated series with the fundamentals of fluid flow, heat transfer and mass transfer in the first volume, the physical operations of chemical engineering in this, the second volume, and in the third volume, the basis of chemical and biochemical reactor design, some of the physical operations which are now gaining in importance and the underlying theory of both process control and computation. The solutions to the problems listed in Volumes 1 and 2 are now available as Volumes 4 and 5 respectively. Furthermore, an additional volume in the series is in course of preparation and will provide an introduction to chemical engineering design and indicate how the principles enunciated in the earlier volumes can be translated into chemical plant.

We welcome the collaboration of J. R. Backhurst and J. H. Harker as co-authors in the preparation of this edition, following their assistance in the editing of the latest edition of Volume 1 and their authorship of Volumes 4 and 5. We also look forward to the appearance of R. K. Sinnott's volume on chemical engineering design.

Preface to Second Edition

This text deals with the physical operations used in the chemical and allied industries. These operations are conveniently designated "unit operations" to indicate that each single operation, such as filtration, is used in a wide range of industries, and frequently under varying conditions of temperature and pressure.

Since the publication of the first edition in 1955 there has been a substantial increase in the relevant technical literature but the majority of developments have originated in research work in government and university laboratories rather than in industrial companies. As a result, correlations based on laboratory data have not always been adequately confirmed on the industrial scale. However, the section on absorption towers contains data obtained on industrial equipment and most of the expressions used in the chapters on distillation and evaporation are based on results from industrial practice.

In carrying out this revision we have made substantial alteration to Chapters 1, 5, 6, 7, 12, 13 and 15* and have taken the opportunity of presenting the volume paged separately from Volume 1. The revision has been possible only as the result of the kind co-operation and help of Professor J. D. Thornton (Chapter 12), Mr. J. Porter (Chapter 13), Mr. K. E. Peet (Chapter 10) and Dr. B. Waldie (Chapter 1), all of the University at Newcastle, and Dr. N. Dombrowski of the University of Leeds (Chapter 15). We want in particular to express our appreciation of the considerable amount of work carried out by Mr. D. G. Peacock of the School of Pharmacy, University of London. He has not only checked through the entire revision but has made numerous additions to many chapters and has overhauled the index.

We should like to thank the companies who have kindly provided illustrations of their equipment and also the many readers of the previous edition who have made useful comments and helpful suggestions.

Chemical engineering is no longer confined to purely physical processes and the unit operations, and a number of important new topics, including reactor design, automatic control of plants, biochemical engineering, and the use of computers for both process design and control of chemical plant will be covered in a forthcoming Volume 3 which is in course of preparation.

Chemical engineering has grown in complexity and stature since the first edition of the text, and we hope that the new edition will prove of value to the new generation of university students as well as forming a helpful reference book for those working in industry.

In presenting this new edition we wish to express our gratitude to Pergamon Press who have taken considerable trouble in coping with the technical details.

J. M. Coulson
J. F. Richardson

* N.B. Chapter numbers are altered in the current (third) edition.

Preface to First Edition

In presenting Volume 2 of *Chemical Engineering*, it has been our intention to cover what we believe to be the more important unit operations used in the chemical and process industries. These unit operations, which are mainly physical in nature, have been. classified, as far as possible, according to the underlying mechanism of the transfer operation. In only a few cases is it possible to give design procedures when a chemical reaction takes place in addition to a physical process. This difficulty arises from the fact that, when we try to design such units as absorption towers in which there is a chemical reaction, we are not yet in a position to offer a thoroughly rigorous method of solution. We have not given an account of the transportation of materials in such equipment as belt conveyors or bucket elevators, which we feel lie more distinctly in the field of mechanical engineering.

In presenting a good deal of information in this book, we have been much indebted to facilities made available to us by Professor Newitt, in whose department we have been working for many years. The reader will find a number of gaps, and a number of principles which are as yet not thoroughly developed. Chemical engineering is a field in which there is still much research to be done, and, if this work will in any way stimulate activities in this direction, we shall feel very much rewarded. It is hoped that the form of presentation will be found useful in indicating the kind of information which has been made available by research workers up to the present day. Chemical engineering is in its infancy, and we must not suppose that the approach presented here must necessarily be looked upon as correct in the years to come. One of the advantages of this subject is that its boundaries are not sharply defined.

Finally, we should like to thank the following friends for valuable comments and suggestions: Mr. G. H. Anderson, Mr. R. W. Corben, Mr. W. J. De Coursey, Dr. M. Guter, Dr. L. L. Katan, Dr. R. Lessing, Dr. D. J. Rasbash, Dr. H. Sawistowski, Dr. W. Smith, Mr. D. Train, Mr. M. E. O'K. Trowbridge, Mr. F. E. Warner and Dr. W. N. Zaki.

Acknowledgements

The authors and publishers acknowledge with thanks the assistance given by the following companies and individuals in providing illustrations and data for this volume and giving their permission for reproduction. Everyone was most helpful and some firms went to considerable trouble to provide exactly what was required. We are extremely grateful to them all.

Christison Scientific Equipment Ltd, Gateshead for Figs. 1.2, 2.9.
Robinson Milling Systems Ltd for Figs. 1.11, 1.12.
Baker Perkins Ltd for Figs. 1.18, 2.7, 2.32, 2.33, 13.35, 13.36.
Buss (UK) Ltd, Cheadle Hulme, Cheshire for Figs. 1.19, 14.23, 16.26.
Dorr-Oliver Co Ltd, Croydon, Surrey for Figs. 1.21, 1.24, 1.33, 5.18, 7.17, 7.20, 7.23, 7.24, 10.5, 10.10, 10.11.
Denver Process Equipment Ltd, Leatherhead, Surrey for Figs. 1.25, 1.27, 1.42, 1.43.
Wilfley Mining Machinery Co Ltd for Fig. 1.28.
NEI International Combustion Ltd, Derby for Figs. 1.29, 1.30, 1.31, 1.33, 2.9, 2.19–2.24, 2.26, 2.29, 14.18, 16.23.
Lockers Engineers Ltd, Warrington for Figs. 1.35, 1.36, 1.37.
Master Magnets Ltd, Birmingham for Figs. 1.38, 1.39, 1.40.
Vaba Process Plant Ltd, Rotherham, Yorks, successors to Edgar Allen Co Ltd for Figs. 2.3, 2.6, 2.10, 2.12, 2.13, 2.28.
Hadfields Ltd for Fig. 2.4.
Hosokawa Micron Ltd, Runcorn, Cheshire for Figs. 2.10, 2.11.
Babcock & Wilcox Ltd for Fig. 2.18.
Premier Colloid Mills for Figs. 2.32,
McGraw-Hill Book Co for Fig. 3.3.
Norton Chemical Process Products (Europe) Ltd, Stoke-on-Trent, Staffs for Figs. 4.10–4.15, 4.17, 4.22, 4.23, Table 4.3.
Glitsch UK Ltd, Kirkby Stephen, Cheshire for Figs. 4.16, 11.51, 11.52, 11.53.
KnitMesh Ltd, S. Croydon, Surrey for Figs. 4.17, 13.24.
Visco Ltd, Croydon, Surrey for Fig. 4.18.
Sulzer (UK) Ltd, Farnborough, Hants for Figs. 4.19, 8.18, 14.23.
Johnson-Progress Ltd, Stoke-on-Trent, Staffs for Figs. 7.6, 7.7, 7.8, 7.9.
Filtration Systems Ltd, Mirfield, W. Yorks, for Fig. 7.10.
Stockdale Filtration Systems Ltd, Macclesfield, Cheshire for Figs. 7.11, 7.12, 7.13, 7.14, 7.21 and Tables 7.1, 7.2, 7.3.
Stella-Meta Filters Ltd, Whitchurch, Hants for Figs. 7.15, 7.16.
Delfilt Ltd, Bath, Avon for Fig. 7.18.

Charlestown Engineering Ltd, St Austell, Cornwall for Figs. 7.25, 7.26.
AAF Ltd, Cramlington, Northumberland for Figs. 8.5, 8.19, 8.21.
Institution of Mechanical Engineers for Fig. 8.10.
Sturtevant Engineering Co Ltd for Fig. 8.11.
Thomas Broadbent & Sons Ltd, Huddersfield, Yorks for Figs. 9.6, 9.13, 9.14.
Alfa-Laval Sharples Ltd, Camberley, Surrey, for Figs. 9.8, 9.10, 9.11, 9.12, 9.16, 9.17, 13.37, 14.20.
Sulzer Escher Wyss Ltd, Zurich, Switzerland for Fig. 9.15.
De Smet Rosedowns Ltd, Hull for Fig. 10.4.
APV Mitchell Ltd for Fig. 12.17.
Davy Powergas Ltd for Fig. 13.23.
Swenson Evaporator Co for Figs. 14.16, 14.17, 14.19, 15.13, 15.14.
APV Baker Ltd, Crawley, Sussex for Figs. 14.20, 14.22, 14.24, 14.25.
Robert Jenkins Systems Ltd, Rotherham, Yorks for Fig. 14.21.
The Editor and Publishers of *Chemical and Process Engineering* for Figs. 14.27, 14.32.
Woodhall-Duckham Ltd for Fig. 15.12.
The Girdler Company for Fig. 15.15.
The Power Gas Corporation for Figs. 15.16, 15.17.
APV Pasilac Ltd, Carlisle, Cumbria for Figs. 16.9, 16.10, 16.24.
Buflovak Equipment Division of Blaw-Knox Co Ltd for Figs. 16.16, 16.17, and Table 16.3.
Dr N. Dombrowski for Figs. 16.18, 16.21.
Amicon Ltd for Figs. 20.1 and 20.9*d*.
Anotec Separations Ltd. for Fig. 20.2.
P. C. I. for Fig. 20.9*a*
A/S De Danske Sukkerfabrikker, Denmark for Fig. 20.9*b*

Introduction

The understanding of the design and construction of chemical plant is frequently regarded as the essence of chemical engineering and it is this area which is covered in Volume 6 of this series. Starting from the original conception of the process by the chemist, it is necessary to appreciate the chemical, physical and many of the engineering features in order to develop the laboratory process to an industrial scale. This volume is concerned mainly with the physical nature of the processes that take place in industrial units, and, in particular, with determining the factors that influence the rate of transfer of material. The basic principles underlying these operations, namely fluid dynamics, and heat and mass transfer, are discussed in Volume 1, and it is the application of these principles that forms the main part of this volume.

Throughout what are conveniently regarded as the process industries, there are many physical operations that are common to a number of the individal industries, and may be regarded as *unit operations*. Some of these operations involve particulate solids and many of them are aimed at achieving a separation of the components of a mixture. Thus, the separation of solids from a suspension by filtration, the separation of liquids by distillation, and the removal of water by evaporation and drying are typical of such operations. The problem of designing a distillation unit for the fermentation industry, the petroleum industry or the organic chemical industry is, in principle, the same, and it is mainly in the details of construction that the differences will occur. The concentration of solutions by evaporation is again a typical operation that is basically similar in the handling of sugar, or salt, or fruit juices, though there will be differences in the most suitable arrangement. This form of classification has been used here, but the operations involved have been grouped according to the mechanism of the transfer operation, so that the operations involving solids in fluids are considered together and then the diffusion processes of distillation, absorption and liquid–liquid extraction are taken in successive chapters. In examining many of these unit operations, it is found that the rate of heat transfer or the nature of the fluid flow is the governing feature. The transportation of a solid or a fluid stream between processing units is another instance of the importance of understanding fluid dynamics.

One of the difficult problems of design is that of maintaining conditions of similarity between laboratory units and the larger-scale industrial plants. Thus, if a mixture is to be maintained at a certain temperature during the course of an exothermic reaction, then on the laboratory scale there is rarely any real difficulty in maintaining isothermal conditions. On the other hand, in a large reactor the ratio of the external surface to the volume—which is inversely proportional to the linear dimension of the unit—is in most cases of a different order, and the problem of removing the heat of reaction becomes a major item in design. Some of the general problems associated with *scaling-up* are considered as they arise in many of the chapters. Again, the introduction and removal of the reactants may present difficult problems on the large scale, especially if they contain corrosive liquids or abrasive solids. The general tendency with many industrial units is to provide a continuous process, frequently involving a series of stages. Thus, exothermic reactions may be carried out in a series of reactors with interstage cooling.

The planning of a process plant will involve determining the most economic method, and later the most economic arrangement of the individual operations used in the process. This amounts to designing a process so as to provide the best combination of capital and operating costs. In this volume the question of costs has not been considered in any detail, but the aim has been to indicate the conditions under which various types of units will operate in the most economical manner. Without a thorough knowledge of the physical principles involved in the various operations, it is not possible to select the most suitable one for a given process. This aspect of the design can be considered by taking one or two simple illustrations of separation processes. The particles in a soli -solid system may be separated, first according to size, and secondly according to the material. Generally, sieving is the most satisfactory method of classifying relatively coarse materials according to size, but the method is impracticable for very fine particles and a form of settling process is generally used. In the first of these processes, the size of the particle is used directly as the basis for the separation, and the second depends on the variation with size of the behaviour of particles in a fluid. A mixed material can also be separated into its components by means of settling methods, because the shape and density of particles also affect their behaviour in a fluid. Other methods of separation depend on differences in surface properties (froth flotation), magnetic properties (magnetic separation), and on differences in solubility in a solvent (leaching). For the separation of miscible liquids, three commonly used methods are:

1. Distillation—depending on difference in volatility.
2. Liquid–liquid extraction—depending on difference in solubility in a liquid solvent.
3. Freezing—depending on difference in melting point.

The problem of selecting the most appropriate operation will be further complicated by such factors as the concentration of liquid solution at which crystals start to form. Thus, in the separation of a mixture of ortho-, meta-, and para-mononitrotoluenes, the decision must be made as to whether it is better to carry out the separation by distillation followed by crystallisation, or in the reverse order. The same kind of consideration will arise when concentrating a solution of a solid; then it must be decided whether to stop the evaporation process when a certain concentration of solid has been reached and then to proceed with filtration followed by drying, or whether to continue to concentration by evaporation to such an extent that the filtration stage can be omitted before moving on to drying.

In many operations, for instance in a distillation column, it is necessary to understand the fluid dynamics of the unit, as well as the heat and mass transfer relationships. These factors are frequently interdependent in a complex manner, and it is essential to consider the individual contributions of each of the mechanisms. Again, in a chemical reaction the final rate of the process may be governed either by a heat transfer process or by the chemical kinetics, and it is essential to decide which is the controlling factor; this problem is discussed in Volume 3, which deals with both chemical and biochemical reactions and their control.

Two factors of overriding importance have not so far been mentioned. Firstly, the plant must be operated in such a way that it does not present an unacceptable hazard to the workforce or to the surrounding population. *Safety considerations* must be in the forefront in the selection of the most appropriate process route and design, and must also be reflected in all the aspects of plant operation and maintenance. An inherently safe plant is to be preferred to one with inherent hazards, but designed to minimise the risk of the hazard being released. Safety considerations must be taken into account at an early stage of design; they are not an add-on at the end. Similarly control systems, the integrity of which play a major part in safe operation of plant, must be designed into the plant, not built on after the design is complete.

The second consideration relates to the *environment*. The engineer has the responsibility for conserving natural resources, including raw materials and energy sources, and at the same time ensuring that effluents (solids, liquids and gases) do not give rise to unacceptable environmental effects. As with safety, effluent control must feature as a major factor in the design of every plant.

The topics discussed in this volume form an important part of any chemical engineering project. They must not, however, be considered in isolation because, for example, a difficult separation problem may often be better solved by adjustment of conditions in the preceding reactor, rather than by the use of highly sophisticated separation techniques.

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