COULSON & RICHARDSON'S

CHEMICAL ENGINEERING

Particle Technology

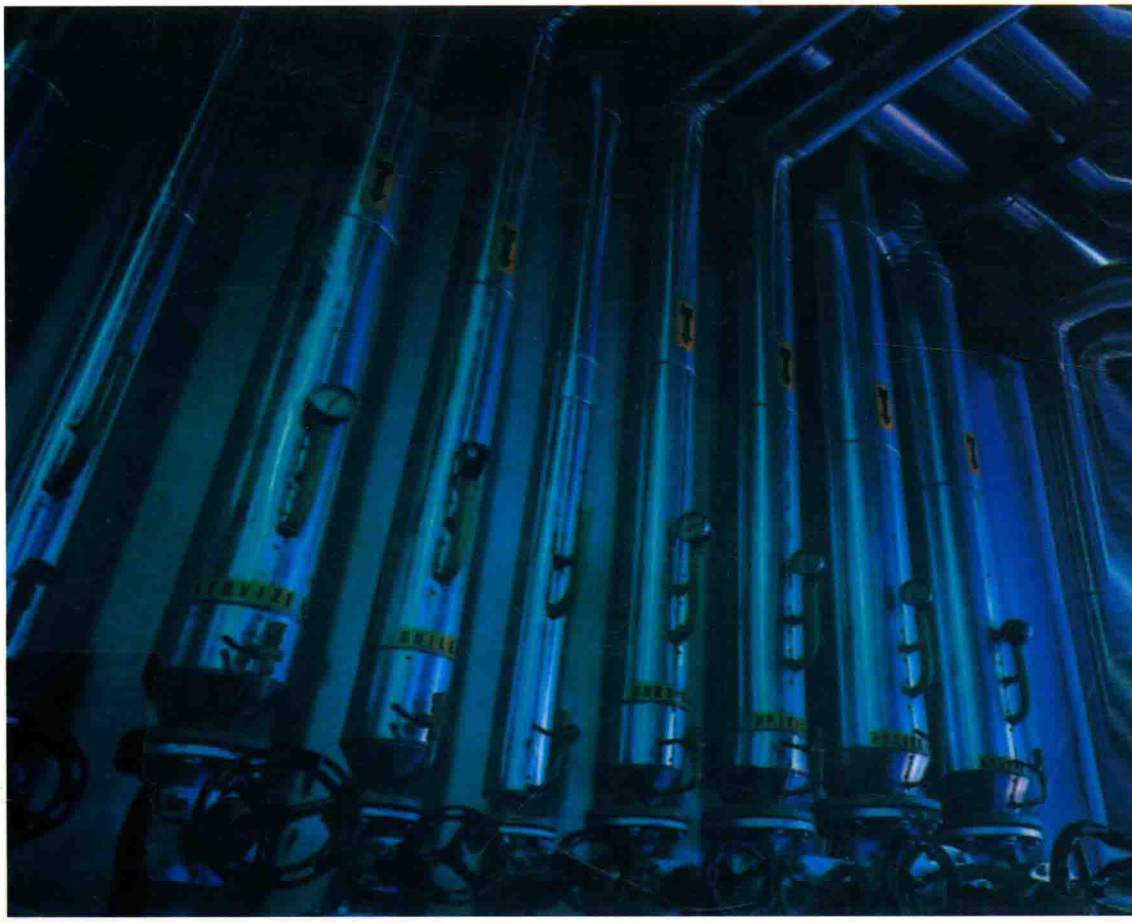
VOLUME 2A

化学工程 颗粒技术

第 2 卷 A

J F Richardson & J H Harker
with J R Backhurst 著

FIFTH EDITION



大连理工大学出版社

Coulson and Richardson's

CHEMICAL ENGINEERING

VOLUME 2A

FIFTH EDITION

Particle Technology

化学工程

颗粒技术

第2卷A

J. F. RICHARDSON

J. H. HARKER

J. R. BACKHURST

大连理工大学出版社

图书在版编目(CIP)数据

化学工程. 第 2 卷 A, 颗粒技术(5 版) = Chemical Engineering. 2A, Partical Technology(5th ed.):英文/(英)理查森(Richardson, J. F.),(英)哈克(Harker, J. H.)著.
影印本. —大连:大连理工大学出版社, 2008. 6
ISBN 978-7-5611-4157-1

Ⅰ. 化… Ⅱ. ①理…②哈… Ⅲ. ①化学工程 - 英文②颗粒 - 英文 Ⅳ. TQ02

中国版本图书馆 CIP 数据核字(2008)第 068218 号

大连理工大学出版社出版
大连市软件园路 80 号 邮政编码 116023
发行:0411-84708842 邮购:0411-84703636 传真:0411-84701466
E-mail:dutp@ dutp. cn URL:http://www. dutp. cn
大连日升印刷厂 大连理工大学出版社发行

幅面尺寸:175mm × 250mm 印张:35.50 字数:1067 千字
2008 年 6 月第 1 版 2008 年 6 月第 1 次印刷

责任编辑:刘新彦 赵 静 责任校对:黎 玉
封面设计:季 强

ISBN 978-7-5611-4157-1 定价:95.00 元

Preface to the Fifth Edition 第5版序言

It is now 47 years since Volume 2 was first published in 1955, and during the intervening time the profession of chemical engineering has grown to maturity in the UK, and worldwide; the Institution of Chemical Engineers, for instance, has moved on from its 33rd to its 80th year of existence. No longer are the heavy chemical and petroleum-based industries the main fields of industrial applications of the discipline, but chemical engineering has now penetrated into areas, such as pharmaceuticals, health care, foodstuffs, and biotechnology, where the general level of sophistication of the products is much greater, and the scale of production often much smaller, though the unit value of the products is generally much higher. This change has led to a move away from large-scale continuous plants to smaller-scale batch processing, often in multipurpose plants. Furthermore, there is an increased emphasis on product purity, and the need for more refined separation technology, especially in the pharmaceutical industry where it is often necessary to carry out the difficult separation of stereo-isomers, one of which may have the desired therapeutic properties while the other is extremely malignant. Many of these large molecules are fragile and are liable to be broken down by the harsh solvents commonly used in the manufacture of bulk chemicals. The general principles involved in processing these more specialised materials are essentially the same as in bulk chemical manufacture, but special care must often be taken to ensure that processing conditions are mild.

One big change over the years in the chemical and processing industries is the emphasis on designing products with properties that are specified, often in precise detail, by the customer. Chemical composition is often of relatively little importance provided that the product has the desired attributes. Hence *product design*, a multidisciplinary activity, has become a necessary precursor to *process design*.

Although undergraduate courses now generally take into account these new requirements, the basic principles of chemical engineering remain largely unchanged and this is particularly the case with the two main topics of Volume 2, *Particle Mechanics* and *Separation Processes*. In preparing this new edition, the authors have faced a typical engineering situation where a compromise has to be reached on size. The knowledgebase has increased to such an extent that many of the individual chapters appear to merit expansion into separate books. At the same time, as far as students and those from other disciplines are concerned, there is still a need for a an integrated concise treatment in which there is a consistency of approach across the board and, most importanty, a degree of uniformity in the use of symbols. It has to be remembered that the learning capacity of students is certainly no greater than it was in the past, and a book of manageable proportions is still needed.

The advice that academic staffs worldwide have given in relation to revising the book has been that the layout should be retained substantially unchanged—*better the devil we know, with all his faults*! With this in mind the basic structure has been maintained. However, the old Chapter 8 on *Gas Cleaning*, which probably did not merit a chapter on its own, has been incorporated into Chapter 1, where it sits comfortably beside other topics involving the separation of solid particles from fluids. This has left Chapter 8 free to accommodate *Membrane Separations* (formerly chapter 20) which then follows on logically from *Filtration* in Chapter 7, The new Chapter 20 then provides an opportunity to look to the future, and to introduce the topics of *Product Design* and the *Use of Intensified Fields* (particularly centrifugal in place of gravitational) and *miniaturisation*, with all the advantages of reduced hold-up, leading to a reduction in the amount of out-of-specification material produced during the changeover between products in the case multipurpose plants, and in improved safety where the materials have potentially hazardous properties.

Other significant changes are the replacement of the existing chapter on *Crystallisation* by an entirely new chapter written with expert guidance from Professor J. W. Mullin, the author of the

standard textbook on that topic. The other chapters have all been updated and additional Examples and Solutions incorporated in the text. Several additional Problems have been added at the end, and solutions are available in the Solutions Manual, and now on the Butterworth-Heinemann website.

We are, as usual, indebted to both reviewers and readers for their suggestions and for pointing out errors in earlier editions. These have all been taken into account. Please keep it up in future! We aim to be error-free but are not always as successful as we would like to be! Unfortunately, the new edition is somewhat longer than the previous one, almost inevitably so with the great expansion in the amount of information available. Whenever in the past we have cut out material which we have regarded as being out-of-date, there is inevitably somebody who writes to say that he now has to keep both the old and the new editions because he finds that something which he had always found particularly useful in the past no longer appears in the revised edition. It seems that you cannot win, but we keep trying!

自从本书第 2 卷 1955 年首次出版以来，已经历经了整整 47 年，这期间化学工程这一行业在整个英国乃至全世界已经发展得非常成熟。例如，1955 年建会 33 年的化学工程师学会现在建会已到 80 年。重化工和石油工业已不再是工业应用的主要领域；与此同时，化学工程已渗入到各个领域，例如药物、医疗保健、食品、生物工艺等；这些领域所生产产品的复杂度已达到相当高的水准，虽然生产规模较小，但产品的单价很高。这导致大规模连续生产向相对小规模批处理过程转变，较多的是多目标生产过程；更进一步，更强调产品的纯度、精制分离工艺，特别是在制药工业，经常需要进行同分异构体的困难分离过程，其中一种同分异构体可能是理想的治疗药物，而另一种则是置人于死地的毒性物质。许多大分子非常脆弱，易于受到粗糙溶剂的破坏，在大批量化学品生产中通常使用这些溶剂。处理特性物料和大批量化学品生产的基本原理是同样的，但必须做些特殊考虑，以确保加工条件适度。

近年来，化学工业及制造工业有一个大的改变，现在更加强调设计产品的性质满足顾客的特殊要求，而且顾客对产品经常有详细的细节要求。只要产品满足所需的品质，其化学组成则就没有那么重要了。因此，产品设计——一种包含各种学科的过程，已经被过程设计所取代。

虽然大学课程里通常会考虑加入这些新的需求，但是化学工程的基本原理的主体没有变化，特别是第 2 卷中两个主要内容——粒子力学及分离过程。进行本次修订时，作者们只能在工程实际需要与本卷片幅之间进行妥协。由于相关知识已经大大增加，以至许多章节都可以独立成书。同时，由于其他学科学生对本课程的需要，我们必须采用统一的方法，有机简洁地呈现完整内容，最重要的是符号的统一。必须记住，现在学生的学习容量肯定不如从前，因此，书本的内容必须均衡并易于应用。

全世界的学术界人士早已给出关于修正本书的建议——Better the devil we know, with all his faults，书的版面的大部分最好不要变。因此，我们保留了本书的基本结构。但是，旧版的第 8 章——气体洗涤，不再独立成章，并入第 1 章，与固体颗粒与流体的分离在一章，这样，给第 8 章的“膜分离”(原第 20 章)部分提供足够的空间，而且使其与第 7 章“过滤”的关系更有逻辑性。在新版第 20 章中，主要是对未来的展望，介绍产品的设计，强化场的使用(离心力取代重力)，微型化——降低停车时间，减少由于生产产品更换导致的不合格原料的量，改善有毒原料存在时的安全性。

其他主要的改变是，结晶一章在 J. W. Mullin 教授指导下重新编写，J. W. Mullin 教授曾写过有关结晶专题的一流的教科书。其他章节也进行了更新，增加了例题及答案。另外，书末增加了习题，答案在解题手册中提供，也可以在 Butterworth-Heinemann 网站上找到。

在此，我们对读者及评论家对本书前一版提出的建议和不足表示感谢。对于这些意见和建议，我们在新版中已经全部考虑。请大家继续支持我们。我们的目标是消除一切错误，尽管有时难以如愿。由于内容的极大扩展，导致新版篇幅比旧版稍长。在过去，每当我们改版时将我们认为已经过时的内容删掉时，总会有人说这部分内容很有用，使得他不得不同时拥有两个版本。不过，我们仍会继续努力！

JFR
JHH

Preface to the Fourth Edition 第 4 版序言

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 Engineerng 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!

正在修订的化学工程丛书的结构调整的详细情况在第 1 卷第 4 版的序言中已经给出，第 1、2 卷第 4 版以及其他卷的修订都将遵照此原则进行。本次修订，将第 1 卷的非牛顿流体(以前在第 3 卷)调整到此卷，同时把第 2 卷中的气力输送系统和液力输送系统以及液体混合调整到第 1 卷。另外，由 Mr. R. K. Sinnott 编写的第 6 卷，1983 年第 1 版，本套书第 1 卷出版近 30 年后出版，此次加入一些第 2 卷中的面向设计的素材，特别是填料塔和板式塔的水力学相关内容。

新版第 2 卷的副标题，颗粒技术和分离过程，不但反映了新版的重点，也反映出这两个课题在当今化学工程中的重要性。颗粒技术包括颗粒系统的基本特性和其粉碎制备过程(详见第 1 章和第 2 章)，随后的几章将研究流体和颗粒的相互作用，从单一的隔离颗粒，到流体中的悬浮颗粒，沉降、流化；以及颗粒彼此有相对固定结构的填料床和填料塔的情况。也包括颗粒在重力场和离心场中的行为。值得一提的是，如同第 1 版和第 2 版，离心分离此次再次单独形成一章，因为第 3 版把其分散于若干章中并不令人满意。

固-液分离过程在前几章讨论，标题分别为沉降、过滤、气体净化和离心分离。其他分离过程有固体颗粒参与，包括传质过程的应用，如过滤(固-液萃取)、干燥和结晶。在蒸馏中，气体吸收和液-液萃取都发生两股流体在相界面上的传质。通常这些操作采用连续逆流过程，可以分段进行(例如板式塔)，也可以是微分接触(例如填料塔)。在特殊情况下，适用于普通逆流流股接触过程的处理，同时每个流股都为单独操作，例如蒸馏。尽管它在概念上或是在经济上会带来很大好处，但是这个方法在这里一直没有被采纳。因为以作者的教学经验来看，老师一定会尽可能重视其普遍特征，这样学生会依次考虑每一个问题，从而更容易掌握相关原理。

第 2 卷新版的最后 4 章是新加的，每一章分别由来自斯旺西化工学院的专家们编撰。

吸收和离子交换(第 17、18 章，以前在第 3 卷中，J. H. Bowen)

色谱分离(第 19 章，J. R. Conder)

膜分离(第 20 章，W. R. Bowen)

这些技术使人特别感兴趣，因为它们提供了一个分离分子组分的方法，分子组分用其他技术很难分离，而且它们的浓度可能非常低。这种组分包括大分子，次微米颗粒，立体异构体以及生物反应器的产物(第 3 卷)。这种分离可能非常特别，可能依赖于分子的大小、形状或分子官能团的构型。

我们的同事，John Coulson 教授，于 1990 年 1 月逝世。我再次表示深深的惋惜。他以前在纽卡斯尔的两位同事 John Backhurst 博士和 John Harker 博士在本书新版的出版工作中起到重要作用，他们更新了 John Coulson 教授所著部分，添加了新的图例及工业设备的描述。

最后，我想再次感谢我们的读者，他们在过去给我们提出了很多对我们有帮助的建议，让我们发现了不足，而且有些不足凭作者一己之力可能永远不会发现。希望你们能不吝批评指正。

JFR

Swansea, July 1990

Note to Fourth Edition—Revised Impression 1993 第 4 版注记——1993 年修订

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).

这次重印,改正了部分错误,并做了小的修订。主要变化如下:

(1)增加了 Szego 磨碎机的构造和操作(第 2 章)。
(2)增加了增稠器设计的 Yoshioka 方法(第 5 章)。
(3)增加了根据流化性能进行的 Geldart'粉尘分类(第 6 章)。
(4)以一个更符合逻辑的泥浆过滤可压滤饼方法去带来以往的方法,对比阻率进行了重新定义(第 7 章)。
(5)修正了底流洗涤增稠剂命名法,使其与包括蒸馏和吸收等分段式过程一致(第 10 章)。
(6)增加了一小部分有关干燥器的选择的相关内容以及实例(第 16 章)。

JFR

Preface to the 1983 Reprint of the Third Edition 1983 年第 3 版重印序言

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.

在此卷中,主要包括各种单元操作的基本理论,介绍了一些典型设备。设备是一个完整的化工厂的基本部分,化工厂设计方法是刚面世的第 6 卷的主题。第 6 卷内容包括流程设计,热量和物料平衡,管道传输,机械结构及成本。作为本系列书的最后一卷,第 6 卷涉及化工设计的广泛领域。

Preface to Third Edition 第 3 版序言

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 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.

本书第 3 版不仅在内容上进行了部分更新，而且全面采用了 SI 单位制表示物理量及物理性质，如同第 1 卷和第 3 卷。第 1 卷中详细讲述了国际单位制。目前 SI 单位制在欧洲已经得到广泛应用，而且正得到世界各国的支持。然而，由于一些读者还是对基于英尺、磅、秒的英制单位更熟悉，因此，只要不引起混淆，本书尽可能在采用新单位制的同时保留旧的单位制，以供读者选择。

本书在一定程度上进行了重新安排。现在的第 1 章涉及颗粒的特性，颗粒群运动，固体混合及根据颗粒组成和大小进行分类。接下来的几章介绍了颗粒在流体中的运动，离心力和重力

的共同作用，颗粒间的相互作用。删除了原来有关离心分离机的一章，其内容调整到相应章节中。考虑的重要应用包括颗粒通过颗粒床和填料塔的运动，流化，悬浮颗粒的传输，过滤以及气体净化。例如，我们增加了一小节，介绍了流化床燃烧技术，这项技术被认为是最具商业潜力的流化技术。此外，我们还新增了一节，介绍了絮凝作用，由斯旺西大学的 Dr. D. J. A. Williams 所写，在此我们对他深表感谢。

传质操作在化工过程中至关重要，对固-液萃取、精馏、气体吸收以及液-液萃取等操作的持续关注充分说明了这一点。在本书中，液-液萃取和液-液混合独立成为新的一章，即液-液系统，其他材料，以前在有关混合的章节中，现在调整到固体混合章节中。本书的最后一章包括蒸馏、结晶、干燥。

本书 1、2、3 卷构成一个有机整体。其中第 1 卷包括流体流动、热量传递和质量传递基本原理；第 2 卷主要讲述化学工程的物理操作；第 3 卷则讲述化学及生化反应器设计基础，日益重要的物理操作以及过程控制与相关计算的基础。第 1、2 卷的习题答案现在分别列入第 4、5 卷中。此外，即将新增的一卷正在编排中。此卷介绍化工设计，并阐述前几卷讲述的原理如何指导实际操作。

在此感谢 J. R. Backhurst 、J. H. Harker 作为合作者对本版的贡献，第 1 卷修订的帮助以及第 4、5 卷的写作。我们期待 R. K. Sinnott 先生编写的化工设计尽快面世。

在此卷中，主要包含各种单元操作的基本理论以及一些典型实验设备。系统设备是一座完整的化工厂中必不可少的一部分，这些设备的有关设计已经在第 6 卷中讲过。新的一卷内容包括流程模拟、热能、物料平衡、管道传输、机械结构及成本。它对一系列的各个有关化学工程设计学科都作了介绍。

Preface to Second Edition 第 2 版序言

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 15① 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 cooperation 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.

本书涉及化学及相关工业中的物理操作。这些操作习惯上用"单元操作"表示每个单独的操作，例如，工业上广泛应用的"过滤"，其操作温度和压力是变化的。

自从 1955 年第 1 版出版至今，相关技术文献增加很多，但是主要发展都源于政府和大学实验室中的研究工作，而非工业公司。结果，基于实验室数据的关联式与工业规模条件下应用并不能总保持一致。然而，本书吸收塔部分包括了一些由工业设备得来的数据，并且本书蒸馏和蒸发章节的大多数公式都是根据工业生产结果给出的。

本次修订中，我们对第 1、5、6、7、12、13 和 15 章(章号有所改变)做了实质性的改动，同时，此卷页码与第 1 卷分开，单独编码。本次修订得益于作者们的友好合作及相互帮助，他们是纽卡斯尔大学的 J. D. Thornton 教授(第 12 章)，J. Porter 先生(第 13 章)，K. E. Peet 先生(第 10 章)，B. Waldie 博士(第 1 章)，和里兹大学的 N. Dombrowski 博士(第 15 章)。特此感谢伦敦大

① N. B. Chapter numbers are altered in the current(third)edition.

学药学院的 D. G. Peacock 先生作出的大量工作。他不仅承担了全部修订过程的校对工作，而且还对很多章节做了增补，同时核对了索引。

我们感谢那些给我们提供设备图解的公司以及上一版的读者们，他们给了我们有益的意见和有帮助性的建议。

化学工程已经不再被限制在纯粹的物理过程和单元操作，许多重要的新专题，包括反应器设计，工厂自动控制，生物化工以及化工厂的计算机辅助设计和计算机辅助控制，这些都将在正在准备出版的第 3 卷中讲述。

自本书第 1 版出版以来，化学工程的复杂性和地位日渐增长，为此，我们希望本书新版能成为对工程技术人员有所帮助的参考书，也能满足新一代大学生的要求。

在新版问世之际，我们对 Pergamon 出版社表示感谢，他们不嫌麻烦，处理了很多技术细节问题。

JMC
JFR

Preface to First Edition 第 1 版序言

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 it is 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. Sawistow ski, Dr. W. Smith, Mr. D. Train, Mr. M. E. O'K. Trowbridge, Mr. F. E. Warner and Dr. W. N. Zaki.

在出版本书第 2 卷时，我们的目的是介绍我们认为重要的化工过程中的单元操作。这些单元操作的本质主要是物理过程，尽可能按照传递操作的基本机理进行分类。在极少数情况下，当物理过程伴随化学反应进行时，可能会给出设计程序。此处的难点是，当我们尝试设计诸如有化学反应发生的吸收塔等单元时，我们还不能给出一个完全严格的解决办法。我们没有考虑带式传送机或是链斗式升降机中的物料传输，我们认为这些装置更偏向于机械工程。

本书包括了大量信息，为此我们非常感激 Newitt 教授为我们提供的便利，我们在他所在系工作了很多年。读者会发现很多缺陷，许多理论还不太完善。化学工程领域仍有很多研究有待完成，如果本书会激发人们研究的兴趣，我们将非常欣慰。我们希望本书的出版能反映研究工作者目前的工作。化学工程现在还处于新生阶段，我们不能设想此书给出的方法在未来还一定正确。此学科的一项优势就是它的边界还没有清晰的界定。

最后，我们要感谢那些给我们提出宝贵意见和建议的朋友们。他们是：G. H. Anderson 先生，R. W. Corben 先生，W. J. De Coursey 先生，M. Guter 博士，L. L. Katan 博士，R. Lessing 博士，D. J. Rasbash 博士，H. Sawistowski 博士，W. Smith 博士，D. Train 先生，M. E. O'K. Trowbridge 先生，F. E. Warner 先生和 W. N. Zaki. 博士。

JFR
JHH

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.

Robinson Milling Systems Ltd for Fig. 1.16.
Baker Perkins Ltd for Figs. 1.23, 2.8, 2.34, 13.39, 13.40.
Buss (UK) Ltd, Cheadle Hulme, Cheshire for Figs. 1.24, 14.24.
Dorr-Oliver Co Ltd, Croydon, Surrey for Figs. 1.26, 1.29, 7.15, 7.22, 10.8, 10.9.
Denver Process Equipment Ltd, Leatherhead, Surrey for Figs. 1.27, 1.30, 1.32, 1.47, 1.48.
Wilfley Mining Machinery Co Ltd for Fig. 1.33.
NEI International Combustion Ltd, Derby for Figs. 1.34, 1.35, 1.36, 1.37, 2.10, 2.20–2.24, 2.27, 2.30, 14.18, 16.23.
Lockers Engineers Ltd, Warrington for Figs. 1.40, 1.41, 1.42.
Master Magnets Ltd, Birmingham for Figs. 1.43, 1.44, 1.45.
AAF Ltd, Cramlington, Northumberland for Figs. 1.54, 1.68, 1.70, 1.72.
Vaba Process Plant Ltd, Rotherham, Yorks, successors to Edgar Allen Co Ltd for Figs. 2.4, 2.7, 2.13, 2.14, 2.29.
Hadfields Ltd for Fig. 2.5.
Hosokawa Micron Ltd, Runcorn, Cheshire for Fig. 2.12.
Babcock & Wilcox Ltd for Fig. 2.19.
Premier Colloid Mills for Figs. 2.33.
Amandus–Kahl, Hamburg, Germany for Fig. 2.35.
McGraw-Hill Book Co for Fig. 3.3.
Norton Chemical Process Products (Europe) Ltd, Stoke-on-Trent, Staffs for Table 4.3.
Glitsch UK Ltd, Kirkby Stephen, Cheshire for Figs. 11.51, 11.52, 11.53.
Sulzer (UK) Ltd, Farnborough, Hants for Figs. 1.67, 4.13, 4.14, 4.15.
Johnson-Progress Ltd, Stoke-on-Trent, Staffs for Figs. 7.6, 7.7, 7.9, 7.10.
Filtration Systems Ltd, Mirfield, W. Yorks, for Fig. 7.11.
Stockdale Filtration Systems Ltd, Macclesfield, Cheshire for Fig. 7.12, and Tables 7.1, 7.2, 7.3.
Stella-Meta Filters Ltd, Whitchurch, Hants for Figs. 7.13, 7.14.
Delfilt Ltd, Bath, Avon for Fig. 7.16.
Charlestown Engineering Ltd, St Austell, Cornwall for Figs. 7.24, 7.25.
Institution of Mechanical Engineers for Fig. 1.59.
Sturtevant Engineering Co Ltd for Fig. 1.60.
Thomas Broadbent & Sons Ltd, Huddersfield, West Yorkshire for Figs. 9.13, 9.14.

Amicon Ltd for Figs. 8.12.
P. C. I. for Fig. 8.9.
A/S De Danske Sukkerfabrikker, Denmark for Fig. 8.10.
Dr Huabin Yin for Fig. 8.1.
Dr Nrdal Hilal for Fig. 8.2.
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.
APV Mitchell Ltd for Fig. 12.17.
Davy Powergas Ltd for Fig. 13.26.
Swenson Evaporator Co for Figs. 14.17, 14.18, 14.19, 14.20.
APV Baker Ltd, Crawley, Sussex for Figs. 14.21, 14.22, 14.23, 14.24, 14.25, 14.26.
The Editor and Publishers of *Chemical and Process Engineering* for Figs. 14.28, 14.30.
APV Pasilac Ltd, Carlisle, Cumbria for Figs. 16.10, 16.11.
Buflovak Equipment Division of Blaw-Knox Co Ltd for Figs. 16.17, 16.18, and Table 16.3.
Dr N. Dombrowski for Figs. 16.19, 16.22.
Ventilex for Fig. 16.29.

INDEX

The authors are indebted to our colleague, Dr. D. G. Peacock, formerly of the School of Pharmacy, University of London, for the skill and patience which has shown in the preparation of the Index.

J.F.R.
J.H.H.

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 Volume 2.

Throughout what are conveniently regarded as the process industries, there are many physical operations that are common to a number of the individual 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 solid-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.