COULSON & RICHARDSON'S

CHEMICAL ENGINEERING

Heat Transfer and Mass Transfer

VOLUME 1B

化学工程 传热与传质

第 1 卷 B

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

SIXTH EDITION

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Professor J. M. Coulson Coulson 教授介绍

John Coulson, who died on 6 January 1990 at the age of 79, came from a family with close involvement with education. Both he and his twin brother Charles (renowned physicist and mathematician), who predeceased him, became professors. John did his undergraduate studies at Cambridge and then moved to Imperial College where he took the postgraduate course in chemical engineering—the normal way to qualify at that time—and then carried out research on the flow of fluids through packed beds. He then became an Assistant Lecturer at Imperial College and, after wartime service in the Royal Ordnance Factories, returned as Lecturer and was subsequently promoted to a Readership. At Imperial College he initially had to run the final year of the undergraduate course almost single-handed, a very demanding assignment. During this period he collaborated with Sir Frederick (Ned) Warner to write a model design exercise for the I. Chem. E. Home Paper on "The Manufacture of Nitrotoluene". He published research papers on heat transfer and evaporation, on distillation, and on liquid extraction, and co-authored this textbook of Chemical Engineering. He did valiant work for the Institution of Chemical Engineers which awarded him its Davis medal in 1973, and was also a member of the Advisory Board for what was then a new Pergamon journal, *Chemical Engineering Science*.

In 1954 he was appointed to the newly established Chair at Newcastle-upon-Tyne, where Chemical Engineering became a separate Department and independent of Mechanical Engineering of which it was formerly part, and remained there until his retirement in 1975. He took a period of secondment to Heriot Watt University where, following the splitting of the joint Department of Chemical Engineering with Edinburgh, he acted as adviser and *de facto* Head of Department. The Scottish university awarded him an Honorary D. Sc. in 1973.

John's first wife Dora sadly died in 1961; they had two sons, Anthony and Simon. He remarried in 1965 and is survived by Christine.

John Coulson,逝世于 1990 年 1 月 6 日,享年 79 岁,出生于与教育事业有紧密联系的家庭。他与其孪生兄弟 Charles(著名的物理学家与数学家,先他去世)生前都是教授。John 本科就读剑桥大学,然后转到帝国理工,学习化学工程研究课程——当时取得研究资格的通常方式——然后在那里开展填充床的流体流动的研究。之后,他成为帝国理工的副讲师,战时服役于皇家军工厂,之后返校成为讲师,随后就任高级讲师。在帝国理工时,最初他只能独自进行本科生最后一年的课程,这是一项要求苛刻的任务。在此期间,他与 Frederick(Ned) Warner 合作为英国化学工程师协会写了"硝基甲苯制造"的模型设计习题。出版了关于热量传递和蒸发、蒸馏、液相萃取方面的研究论文,合著了这本《化学工程》教科书。他为英国化学工程师协会做出了卓著的工作,为此 1973 年获得了本协会颁发的戴维斯奖,他还是《化学工程科学》杂志顾问委员会的一员,此杂志后来成为新的 Pergamon 期刊。

1954 年,他被任命为当时新建立的纽卡斯尔大学的教授。在那里,化学工程从机械工程系独立出来,成为化学工程系。他在纽卡斯尔大学工作直到 1975 年退休。他曾被短期借调到赫瑞瓦特大学,作为顾问,接手将与爱丁堡大学联办的化学工程系独立出来的工作,它事实上是系里的领导。1973 年,苏格兰大学授予他荣誉科学博士学位。

John 的第一任夫人 1961 年去世,他们有两个儿子,Anthony 和 Simon. 他 1965 年再婚,先夫人 Christine 而去。

JFR

Preface to Sixth Edition 第 6 版序言

It is somewhat sobering to realise that the sixth edition of Volume 1 appears 45 years after the publication of the first edition in 1954. Over the intervening period, there have been considerable advances in both the underlying theory and the practical applications of Chemical Engineering ; all of which are reflected in parallel developments in undergraduate courses. In successive editions , we have attempted to adapt the scope and depth of treatment in the text to meet the changes in the needs of both students and practitioners of the subject.

Volume 1 continues to concentrate on the basic processes of Momentum Transfer (as in fluid flow), Heat Transfer, and Mass Transfer, and it is also includes examples of practical applications of these topics in areas of commercial interest such as the pumping of fluids, the design of shell and tube heat exchangers and the operation and the performance of cooling towers. In response to the many requests from readers (and the occasional note of encouragement from our reviewers), additional examples and their solutions have now been included in the main text. The principle areas of application, particularly of the theories of the Mass Transfer across a phase boundary, form the core material of Volume 2 however, whilst in Volume 6, material presented in other volumes is utilised in the practical design of process plant.

The more important additions and modifications which have been introduced into this sixth edition of Volume 1 are:

Dimensionless Analysis, The idea and advantages of treating length as a vector quantity and of distinguishing between the separate role of mass in representing a quantity of matter as opposed to its inertia are introduced.

Fluid Flow. The treatment of the behaviour of non-Newtonian fluids is extended and the methods used for pumping and metering of such fluids are updated.

Heat Transfer. A more detailed discussion of the problem of unsteady-state heat transfer by conduction where bodies of various shapes are heated or cooled is offered together with a more complete treatment of heat transfer by radiation and a re-orientation of the introduction to the design of shell and tube heat exchangers.

Mass Transfer. The section on mass transfer accompanied by chemical reaction has been considerably expanded and it is hoped that this will provide a good basis for the understanding of the operation of both homogeneous and heterogeneous catalytic reactions.

As ever, we are grateful for a great deal of help in the preparation of this new edition from a number of people. In particular, we should like to thank Dr. D. G. Peacock for the great enthusiasm and dedication he has shown in the production of the index, a task he has undertaken for us over many years. We would also mention especially Dr. R. P. Chhabra of the Indian Institute of Technology at Kanpur for his contribution on unsteady-state heat transfer by conduction, those commercial organisations which have so generously contributed new figures and diagrams of equipment, our publishers who cope with our perhaps overwhelming number of suggestions and alterations with a never-failing patience and, most of all, our readers who with great kindness, make so many extremely useful and helpful suggestions all of which, are incorporated wherever practicable. With their continued help and support, the signs are that this present work will continue to be of real value as we move into the new Millenium.

我们突然意识到本书自 1954 年出版第 1 版至今第六版的诞生已有 45 年了。在此期间，化学工程的基本理论和实际运用都取得了长足进步；大学本科课程也随之发生了很大变化，我们一直试图在教科书的广度和深度方面适应这种变化，以满足学生和相关从业人员的要求。

第 1 卷仍然着重讲述动量传递（如流体流动）、热量传递和质量传递的基本过程，还包括管壳式换热器的实际应用以及冷凝塔的操作和性能。应读者请求（包括来自评论家鼓励性的评论），书中还包括了附加的例题及解答。关于原理的应用，尤其是通过相界面的质量传递理论，

是第 2 卷的核心内容，而第 6 卷的主要内容是利用其他卷相关理论，进行实际工厂的设计。

第 1 卷第 6 版的重要的增加和修改有：

无因次分析。

流体流动。扩展了非牛顿流体行为的处理，更新了非牛顿流体的泵送和计量方法。

热量传递。更详细地讨论了各种形状物体加热或冷却过程的非稳态传导传热问题，而且对于辐射传热也有了更全面的处理，对管壳式热交换器设计的介绍进行了重新定位。

质量传递。将伴随化学反应的质量传递部分进行了较大的扩充，我们希望这将为更好地理解均相和非均相催化反应提供良好基础。

如同以往，我们要感谢许多在此次新版中给我们很大帮助的人。尤其是要感谢 D. Peacock 博士，他在完成索引时表现出极大的热情和贡献，多年来他一直承担着这项任务。我们还要特别提到坎普尔市印度理工学院的 R. P. Chhabra 博士对非稳态传导传热部分的贡献；还有那些商业机构，他们慷慨地提供了新图标和设备图；我们的出版商，他们以极大的耐心，处理了无数的建议和更改；最重要的是我们的读者，给我们提供了许多极其重要的有帮助的建议；所有这一切，我们当竭尽所能。有了他们的继续帮助和支持，我们坚信，进入新千年后，我们的工作将继续拥有存在的价值。

Swansea 1999
Newcastle upon Tyne, 1999
JFR
JRB
JHH

Preface to Fifth Edition 第 5 版序言

This textbook has been the subject of continual up-dating since it was first published in 1954. There have been numerous revised impressions and the opportunity has been taken on the occasion of each reprinting to make corrections and revisions, many of them in response to readers who have kindly pointed out errors or who have suggested modifications and additions. When the summation of the changes has reached a sufficiently high level, a new edition has been produced. We have now reached this point again and the fifth edition incorporates all the alterations in the 1993 revision of the fourth edition, together with new material, particularly on simultaneous mass transfer and chemical reaction for unsteady-state processes.

There have been changes in publisher too. Since the appearance of the fourth edition in 1990, Pergamon Press has become part of Elsevier Science and now, following a reorganisation in the Reed Elsevier group of companies, the responsibility for publishing the Chemical Engineering series has passed to Butterworth-Heinemann, another Reed Elsevier company,

We are grateful to our readers for their interest and very much hope they will continue to make suggestions for the improvement of the series.

自从 1954 第 1 版发行以来，本教科书得到了持续更新。书里修订处众多，每次重印，我们都进行修订和改错，其中许多改错是由善意的读者指出的，我们也根据读者的反馈进行了许多内容的修订和增删。当修订量达到一定程度时，就诞生了新版。第 5 版根据 1993 年第 4 版进行修订，特别是增加了伴随化学反应的非稳态过程的传质的内容。

出版人也有所变化。自从 1990 年的第 4 版出版以后，Pergamon 已经成为 Elsevier Science 的一部分，之后，Reed Elsevier 集团公司重组，出版化学工程图书的业务转到了 Reed Elsevier 的另一个公司 Butterworth-Heinemann。

感谢读者对我们图书的厚爱，而且非常希望他们继续对此系列图书提供改进意见。

JFR

Preface to Fourth Edition 第 4 版序言

The First Edition of Volume 1 was published in 1954 and Volume 2 appeared a year later. In the intervening 35 years or so, there have been far-reaching developments in Chemical Engineering and the whole approach to the subject has undergone a number of fundamental changes. The question therefore arises as to whether it is feasible to update a textbook written to meet the needs of the final year students of an undergraduate course in the 1950s so that it can continue to fulfil a useful purpose in the last decade of the century. Perhaps it would have been better if a new textbook had been written by an entirely new set of authors. Although at one stage this had seemed likely through the sponsorship of the Institution of Chemical Engineers, there is now no sign of any such replacement book appearing in the United Kingdom.

In producing the Fourth Edition, it has been necessary to consider whether to start again with a clean sheet of paper—an impossibly daunting task—or whether to retain the original basic structure with relatively small modifications. In following the latter course, the authors were guided by the results of a questionnaire sent to a wide range of University (and Polytechnic) Departments throughout the English-speaking-world. The clear message which came back was "Do not tamper over-much with the devil we know, in spite of all his faults!"

It was in 1971 that Volume 3 was added to the series, essentially to make good some of the more glaring omissions in the earlier volumes, Volume 3 contains a series of seven specialist chapters written by members of the staff of the Chemical Engineering Department at the University College of Swansea, with Dr D. G. Peacock of the School of Pharmacy, London as a joint editor. In 1977/9, as well as contributing significantly to the new editions of Volumes 1 and 2, two colleagues at the University of Newcastle-upon Tyne, Dr J. R. Backhurst and The Revd. Dr J. H. Harker, prepared Volumes 4 and 5, the solutions to the problems in Volumes 1 and 2, respectively. The final major development was the publication of Volume 6 on Chemical Engineering Design by Mr R. K. Sinnott in 1983. With the preparation of a Fourth Edition, the opportunity has presented itself for a degree of rationalisation, without introducing major changes to the structure. This has led to the following format:

Volume 1 Fluid Flow, Heat Transfer and Mass Transfer
Volume 2 Particle Technology and Separation Processes
Volume 3 Chemical and Biochemical Reactor Engineering and Control
Volume 4/5 Solutions to the Problems in Volumes 1, 2 and 3
Volume 6 Chemical Engineering Design

The details of this new arrangement are as follows:

1. Volume I has acquired an abbreviated treatment of non-Newtonian Flow, formerly in Volume 3.
2. Liquid Mixing appears as a new Chapter in Volume 1, which incorporates the relevant material formerly in Volumes 2 and 3.
3. Separate chapters now appear in Volume 1 on Compressible Flow and on Multiphase Flow, the latter absorbing material previously scattered between Volumes 1 and 2.
4. New chapters are added to Volume 2 to cover four separation processes of increasing importance—Adsorption (from Volume 3), Ion Exchange, Chromatographic Separations and Membrane Separations.
5. Volume 3 is now devoted to various aspects of Reaction Engineering and Control, material which is considerably expanded.
6. Some aspects of design, previously in the earlier volumes, are now transferred to a more appropriate home in Volume 6.

As far as Volume 1 is concerned, the opportunity has been taken to update existing material. The major changes in Fluid Flow include the incorporation of non-Newtonian Flow, an extensive revision of Compressible Flow and the new chapters on Multiphase Flow and Liquid Mixing. Material for this

last chapter has been contributed by Dr R P Chhabra of the Indian Institute of Technology at Kanpur. There has also been a substantial revision of the presentation of material on Mass Transfer and Momentum, Heat and Mass Transfer. To the Appendix have been added the Tables of Laplace Transform and Error Functions which were formerly in Volume 3, and throughout this new edition, all the diagrams have been redrawn. Some further problems have been added at the end.

Sadly, John Coulson was not able to contribute as he had done previously and his death in January 1990 leaves us with a gap which is difficult to fill. John Backhurst and John Harker, who made a substantial contribution to the preparation of the Third Edition in 1977, have taken an increased share of the burden of revising the book and contributing new material, and have taken a special responsibility for those sections which originated from John Coulson, in addition to the special task of up-dating the illustrations. Without their continued support and willing co-operation there would have been no Fourth Edition.

Finally, we would all like to thank our many readers who have made such helpful suggestions in the past and have pointed out errors, many of which the authors would never have spotted. It is hoped that readers will continue to act in this way as unseen authors.

第 1 卷的第 1 版早在 1954 年就出版了，第 2 卷一年后出版。近 35 年中，化学工程有了长足的发展，本学科的体系方法有了很多本质的变化。因此，提出一个问题，是否有一条可行的路径对本教材进行修订，使得一本满足 20 世纪 50 年代本科最后一年的课程需要的教材，可以适应 20 世纪最后十年的教学需要。或许，完全由一批新的作者编写一本新的教科书效果会更好。尽管在某一阶段，这本书似乎是化学工程师协会的一项任务，然而，目前在英国，没有任何迹象表明将有新的教材替代它。

在第 4 版的出版过程中，我们考虑了是否全盘否定原版——一件令人却步的任务——或者保持最初的架构，只需微小的修改。接下来的过程中，作者们在各个英语国家中大范围选取了大学中的相关院系（包括工科院校）发放了调查问卷，反馈的信息很明确，即“不管它有多少问题，不要过分修改。”

到了 1971，第 3 卷出版，基本上弥补了之前几卷中较明显的漏洞。第 3 卷由 Swansea 大学化工学院教员以及伦敦制药学院的 D. G. Peacock 博士联合编写的共 7 个专门章节组成。1977 年 9 月，纽卡斯尔大学的两位学者 J. R. Backhurst 博士和 J. H. Harker 博士，分别编写了第 4、5 卷，对第 1、2 卷的问题做了解答，他们对第 1 卷和第 2 卷的新版也做出了突出贡献。最后的重大进展是，R. K. Sinnott 先生于 1983 年出版了第 6 卷，化工设计。基于第 4 版的前期工作，该书保持了其相当的合理性，结构没有进行大的调整。此系列书目前结构如下：

第 1 卷：流体流动，热量传递和质量传递

第 2 卷：粒子技术和分离过程

第 3 卷：化学和生物化学反应器工程及其控制

第 4/5 卷：第 1，2，3 卷的问题解答

第 6 卷：化学工程设计

编排细节如下：

1. 第 1 卷包括非牛顿流体的简化处理，之前此内容安排在第 3 卷。

2. 第 1 卷包括了新的一章——液体混合，此章合并了原来出现在第 2 卷和第 3 卷的相关材料。

3. 第 1 卷中包括了可压缩流动和多相流动两章，其中多相流动吸收了原来散落在第 1 卷和第 2 卷的材料。

4. 第 2 卷中引入了新的章节，包含了 4 个日益重要的分离过程：吸收（来自第 3 卷），离子交换，色谱分离法和膜分离。

5. 第 3 卷主要是反应工程和控制各个方面的内容，材料扩展了很多。

6. 在前面几卷中有关设计的问题，现在集中到了第 6 卷。

关于第 1 卷，我们主要是对现有材料进行了更新。“流体流动”的主要变化是合并了非牛顿流体，可压缩流体的扩展、修订以及增加了关于多相流和液体混合的有关章节。最后一章由坎普尔市印度理工大学的 R. P. Chhabra 博士编写。将质量和动量传递、热量和质量传递等内容也进行了修订。附录中添加了原来在第 3 卷的拉普拉斯变换表和误差函数，而且在新版中，所有

图表都进行了重画。全书还未添加提高的问题。

遗憾的是，John Coulson 于 1990 年逝世，他不能再像往常一样为本书做出贡献，留给了我们一个很难完成的缺口。John Backhurst 和 John Harker 为 1977 年的第 3 版的工作做出了很多贡献，他们还担负起了完成 John Coulson 未完成部分的特殊任务以及更新图表的任务。没有他们不断的支持和积极主动的配合，就没有今天的第 4 版。

最后，我们要感谢读者，感谢他们之前提出这么有帮助的建议并指出原书的错误，其中很多是作者们难以发现的问题。希望读者们继续作为大家看不到的作者对该书进行批评指正。

JFR

June，1990

NOTE TO REVISED REPRINT 1993　1993 年修订重印注记

The reprint incorporates corrections and minor amendments, but the opportunity has been taken to effect some re-arrangements and additions, as follows:

Chapter 5 Multiphase Flow

Revision of section on pneumatic conveying.

Chapter 9 Heat Transfer

(i) Re-arrangement of material on plasmas and transfer to particles.

(ii) Inclusion of an Example on lagging.

Chapter 10 Mass Transfer

(i) Re-arrangement at the beginning to give a more logical sequence.

(ii) Revision of final section on practical results.

Chapter 11 Boundary Layer

Addition of section on flow with constant heat flux at surface.

Steam Tables

These have been recast to facilitate interpolation.

在这次重印中包括了错误的订正和少许改正，但是我们利用这次机会做了如下重新的安排和添加：

第 5 章 多相流动

气动输送部分的修改。

第 9 章 热量传递

(i)等离子体粒子传递材料的重新安排。

(ii) 包括了绝缘层材料的实例。

第 10 章 质量传递

(i)开始部分进行了重新整理，使逻辑性更强。

(ii)最后部分的实际结果做了修正。

第 11 章　边界层

添加了表面稳定热流的流动部分。

蒸气表

重新做图以方便插值。

Preface to Third Edition 第3版序言

The introduction of the SI system of units by the United Kingdom and many other countries has itself necessitated the revision of this engineering text. This clear implementation of a single system of units will be welcomed not only by those already in the engineering profession, but even more so by those who are about to join. The system which is based on the c. g. s, and m. k. s, systems using length (L), mass (M), and time (T) as the three basic dimensions, as is the practice in the physical sciences, has the very great advantage that it removes any possible confusion between mass and force which arises in the engineering system from the common use of the term *pound* for both quantities. We have therefore presented the text, problems, and examples in the SI system, but have arranged the tables of physical data in the Appendix to include both SI and other systems wherever possible. This we regard as important because so many of the physical data have been published in c. g. s, units. For similar reasons, engineering units have been retained as an alternative where appropriate.

In addition to the change to the SI system of units, we have taken the opportunity to update and to clarify the text. A new section on the flow of two-phase gas-liquid mixtures has been added to reflect the increased interest in the gas and petroleum industries and in its application to the boiling of liquids in vertical tubes.

The chapter on Mass Transfer, the subject which is so central and specific to chemical engineering, has been considerably extended and modernised. Here we have thought it important in presenting some of the theoretical work to stress its tentative nature and to show that, although some of the theories may often lack a full scientific basis, they provide the basis of a workable technique for solving problems. In the discussion on Fluid Flow reference has been made to American methods, and the emphasis on Flow Measurement has been slanted more to the use of instruments as part of a control system. We have emphasised the importance of pipe-flow networks which represent a substantial cost item in modern large-scale enterprises.

This text covers the physical basis of the three major transfer operations of fluid flow, heat transfer, and mass transfer. We feel that it is necessary to provide a thorough grounding in these operations before introducing techniques which have been developed to give workable solutions in the most convenient manner for practical application. At the same time, we have directed the attention of the reader to such invaluable design codes as TEMA and the British Standards for heat exchanger design and to other manuals for pipe-flow systems.

It is important for designers always to have in their minds the need for reliability and safety; this is likely to follow from an understanding of the basic principles involved, many of which are brought out in the text.

We would like to thank our many friends from several countries who have written with suggestions, and it is our hope that this edition will help in furthering growth and interest in the profession. We should also like to thank a number of industrialists who have made available much useful information for incorporation in this edition; this help is acknowledged at the appropriate point. Our particular thanks are due to Dr B. Waldie for his contribution to the high temperature aspects of heat transfer and to the Kellogg International Corporation and Humphreys and Glasgow Limited for their help. In conclusion, we would like to thank Dr J. R. Backhurst and Dr J. H. Harker for their editorial work and for recalculating the problems in SI units and converting the charts and tables.

Since the publication of the Second Edition of this Volume, Volume 3 of *Chemical Engineering* has been published in order to give a more complete coverage of those areas of chemical engineering which are of importance in both universities and industry in the 1970's.

随着英国及许多其他国家引入国际单位制，本书作为工程类教科书，有必要进行相应的修

订。单一的单位制将不但受到工程领域人们的欢迎，而且必将受到将加入者的欢迎。基于厘米-克-秒和米-千克-秒的单位制系统将长度(L)、质量(M)和时间(T)作为三个基本量纲。正如物理学中所应用的一样，这种单位制可以消除原来工程单位制中由于"磅"同时应用于质量和力而产生的混淆。因此，本书中的正文、习题和例题将以国际单位制给出，附录中的物理数据表同时采用国际单位制和其他可能的单位制。我们认为这样很有必要，因为许多物理数据都是采用 c-g-s 制(厘米-克-秒制)发表的。同样，也保留了工程单位制。

借此推行国际单位制的机会，我们对本书进行了更新和修改。本书新增了气-液两相流的内容，以顺应石油天然气工业对这一问题的日益关注及其在直管内的液体沸腾问题中的具体应用。

基于传质在化工中的重要地位，我们对这一章的内容进行了较大的扩充和更新。我们认为这里强调提供的某些理论工作带有实验性，可能缺乏坚实的科学基础，但仍不失为解决问题的可行方法。在对流体流动问题的讨论中，我们参考了美国的方法，即对于流量测量问题，我们侧重于把测量仪表当作控制系统的组成部分。我们已经强调过流动管网的重要性，在现代化大型企业中，流动管网投资将占其成本的很大比例。

本书涵盖了流体流动中的"三传"——热量传递、质量传递和动量传递——操作的物理基础。在介绍对于实际应用问题最方便可行的求解方法之前，我们有必要先介绍三传操作的理论基础。同时，我们会给读者介绍一些重要的设计规范，譬如换热器设计的 TEMA 标准和英式标准以及管道流动系统的一些其他准则。

设计者必须时刻将工程的可靠性和安全性需求铭记于心：最好认真理解本书所述的基本原理，其中许多内容涉及到可靠性和安全性。

在此，我们衷心感谢世界各地为本书提供宝贵建议的朋友们，我们希望本次新版能够对化学工业的进一步发展和获利有所帮助。我们还要感谢那些为本次新版提供许多重要信息的实业家们。这些帮助都很有必要。我们要特别鸣谢在高温传热研究方面做出重要贡献的 B. Waldie 博士以及 Kellogg 国际公司、Humphreys 有限公司和 Glasgow 有限公司的帮助。最后，我们还要感谢 J. R. Backhurst 博士和 J. H. Harcker 博士，感谢他们用国际单位制重新计算和修改图表的辛勤工作。

自从本卷第 2 版发行以来，本书第 3 卷也已出版发行，其内容包括对 20 世纪 70 年代的大学和工厂有重要意义的化工领域的介绍。

January 1976
JMC
JFR

Preface to Second Edition 第 2 版序言

In presenting this second edition, we should like to thank our many friends from various parts of the world who have so kindly made suggestions for clarifying parts of the text and for additions which they have felt to be important. During the last eight years there have been changes in the general approach to chemical engineering in the universities with a shift in emphasis towards the physical mechanisms of transport processes and with a greater interest in unsteady state conditions. We have taken this opportunity to strengthen those sections dealing with the mechanisms of processes, particularly in Chapter 7 on mass transfer and in the chapters on fluid mechanics where we have laid greater emphasis on the use of momentum exchange. Many chemical engineers are primarily concerned with the practical design of plant and we have tried to include a little more material of use in this field in Chapter 6 on heat transfer. An introductory section on dimensional analysis has been added but it has been possible to do no more than outline the possibilities opened up by the use of this technique. Small changes will be found throughout the text and we have tried to meet many readers' requests by adding some more worked examples and a further selection of problems for the student. The selection of material and its arrangement are becoming more difficult and must be to a great extent a matter of personal choice but we hope that this new edition will provide a sound basis for the study of the fundamentals of the subject and will perhaps be of some value to practising engineers.

值此再版之际，我们衷心感谢世界各地的朋友们，感谢你们为本书提供修改和增添内容的宝贵建议。在过去的 8 年里，各大学教授的化学工程课程的一般方法发生了一些改变：传输过程的物理机理正越来越受到人们的重视，对于非稳态过程的兴趣也有所增加。因此，我们借此机会改进了过程机理相关内容的介绍。改动最大的是第 7 章——传质以及对动量交换的使用有重要意义的流体动力学的有关章节。许多化学工程师主要关心的是工程项目设计的实际应用，因此在第 6 章——传热里，我们尽量增加了这一领域的相关资料。此外，本书还增加了部分内容，对量纲分析做了初步介绍，尽管可能只是对这种技术使用的可能性作以概括。在全书其他部分还有许多小的改动，以满足许多读者对于增加工程实例的要求，并且给学生们处理问题提供更多的选择。材料的选择和安排正在变得越来越难，选择的结果也必然因人而异，但我们希望本次新版能够给本学科基本原理的研究提供一个良好的基础，并对工程师们的实际应用有所帮助。

JMC
JFR

Preface to First Edition 第 1 版序言

The idea of treating the various processes of the chemical industry as a series of unit operations was first brought out as a basis for a new technology by Walker, Lewis and McAdams in their book in 1923. Before this, the engineering of chemical plants had been regarded as individual to an industry and there was little common ground between one industry and another. Since the early 1920s chemical engineering as a separate subject has been introduced into the universities of both America and England and has expanded considerably in recent years, so that there are now a number of university courses in both countries. During the past twenty years the subject matter has been extensively increased by various researches described in a number of technical journals to which frequent reference is made in the present work.

Despite the increased attention given to the subject, there are few general books, although there have been a number of specialised books on certain sections such as distillation, heat transfer, etc. It is the purpose of the present work to present to the student an account of the fundamentals of the subject. The physical basis of the mechanisms of many of the chemical engineering operations forms a maior feature of chemical engineering technology, Before tackling the individual operations it is important to stress the general mechanisms which are found in so many of the operations. We have therefore divided the subject matter into two volumes, the first of which contains an account of these fundamentals—diffusion, fluid flow and heat transfer. In Volume 2 we shall show how these theoretical foundations are applied in the design of individual units such as distillation columns, filters, crystallisers, evaporators, etc.

Volume 1 is divided into four sections, fluid flow, heat transfer, mass transfer and humidification. Since the chemical engineer must handle fluids of all kinds, including compressible gases at high pressures, we believe that it is a good plan to consider the problem from a thermodynamic aspect and to derive general equations for flow which can be used in a wide range of circumstances. We have paid special attention to showing how the boundary layer is developed over plane surfaces and in pipes, since it is so important in controlling heat and mass transfer. At the same time we have included a chapter on pumping since chemical engineering is an essentially practical subject, and the normal engineering texts do not cover the problem as experienced in the chemical and petroleum industries.

The chapter on heat transfer contains an account of the generally accepted techniques for calculation of film transfer coefficients for a wide range of conditions, and includes a section on the general construction of tubular exchangers which form a major feature of many works. The possibilities of the newer plate type units are indicated.

In section three, the chapter on mass transfer introduces the mechanism of diffusion and this is followed by an account of the common relationships between heat, mass and momentum transfer and the elementary boundary layer theory. The final section includes the practical problem of humidification where both heat and mass transfer are taking place simultaneously.

It will be seen that in all chapters there are sections in small print. In a subject such as this, which ranges from very theoretical and idealised systems to the practical problems with empirical or experimentally determined relations, there is much to be said for omitting the more theoretical features in a first reading, and in fact this is frequently done in the more practical courses. For this reason the more difficult theoretical sections have been put in small print and the whole of Chapter 9 may be omitted by those who are more concerned with the practical utility of the subject.

In many of the derivations we have given the mathematical analysis in more detail than is customary. It is our experience that the mathematical treatment should be given in full and that the student should then apply similar analysis to a variety of problems.

We have introduced into each chapter a number of worked examples which we believe are es-

sential to a proper understanding of the methods of treatment given in the text. It is very desirable for a student to understand a worked example before tackling fresh practical problems himself. Chemical engineering problems require a numerical answer and it is essential to become familiar with the different techniques so that the answer is obtained by systematic methods rather than by intuition.

In preparing this text we have been guided by courses of lectures which we have given over a period of years and have presented an account of the subject with the major emphasis on the theoretical side. With a subject that has grown so rapidly, and which extends from the physical sciences to practical techniques, the choice of material must be a matter of personal selection. It is, however, more important to give the principles than the practice, which is best acquired in the factory. We hope that the text may also prove useful to those in industry who, whilst perhaps successfully employing empirical relationships, feel that they would like to find the extent to which the fundamentals are of help.

We should like to take this opportunity of thanking a number of friends who have helped by their criticism and suggestions, amongst whom we are particularly indebted to Mr F. E. Warner, to Dr M. Guter, to Dr D. J. Rasbash and to Dr L. L. Katan. We are also indebted to a number of companies who have kindly permitted us to use illustrations of their equipment. We have given a number of references to technical journals and we are grateful to the publishers for permission to use illustrations from their works. In particular we would thank the Institution of Chemical Engineers, the American Institute of Chemical Engineers, the American Chemical Society, the Oxford University Press and the McGraw-Hill Book Company.

1923 年，Walker、Lewis 和 McAdams 在他们的著作中首次提出把各种化工过程看作一系列单元操作，并以此作为一门新技术的基础。在此之前，各种化工厂曾被当作各自独立的工业来对待，并且彼此之间几乎没有共同点。自 20 世纪 20 年代初起，化学工程开始作为一门独立的学科引入美国和英国的大学。近年来，这门学科扩展范围很大。至今为止，英美的许多大学都开设了很多化学工程类课程。在过去的 20 年里，各种发表在科技期刊上的研究使这门学科的内容得到了广泛的提升，并且经常被实际操作所参考。

化学工程正在受到人们的日益关注，然而，几乎没有关于此方面的综合性书籍，尽管有很多关于精馏、传热等某一专题的书籍。本书的目的是给学生们系统提供化学工程的基本原理。化学工程操作机理的物理基础构成了化学工程技术的主要特点。在关注各单独的操作问题之前，我们有必要先重点介绍许多操作过程中都包含的共同机理。因此，我们根据这门学科的内容，将本书分为如下两卷：第 1 卷主要包括扩散、流体流动和传热的基本原理；第 2 卷主要讲述如何将这些理论基础应用于精馏塔、过滤器、结晶器、蒸发器等独立单元的设计上。

第 1 卷分为 4 部分：流体流动，传热，传质和增湿。因为化学工程师必须处理包括高压可压缩气体在内的各种流体，我们确信从热力学角度来考虑问题，并推导出具有普遍适用性的流动方程会对解决问题比较有利。我们尤其关注平板表面和圆管内的边界层发展，因为这对于控制传质和传热至关重要。同时，我们还将有专门一章介绍泵，因为化工本质上来说是一门实用学科，而普通工程类课本一般不会涉及此类在化工和石化行业中才会经历的问题。

在传热一章里，针对具有广泛适用性的表面传热系数，我们将介绍一些普遍接受的计算方法。同时，将有部分内容介绍管式换热器的主要结构，不少换热工程采用管式换热器。本章还将对最新式的平板式单元结构的可行性进行讨论。

在第 3 章——传质中，我们将介绍扩散的机理，并对热量传递、质量传递、动量传递的普遍关联以及边界层理论的基础进行说明。本章最后，我们还将介绍一些关于增湿的实际问题，这些问题会涉及到传质和传热的同时作用。

在所有章节中都会有用小号字体打印的部分。有些课题内容跨度很大，包括从非常理论化和理想化的系统，到经验或实验性关联式在内的很多问题。对于此类课题，在初次阅读时可以忽略掉过多的理论细节。事实上，许多注重实际的课程经常会这样处理。因此，我们对于较困难的理论知识采用小号字体来编写。对于主要关注公用工程使用问题的读者，可以忽略掉整个第 9 章。

在许多问题的推导中，我们将给出比以往更详尽的数学分析。这是因为，就我们的经验来

说，给出完整的数学分析，有利于学生们将此类分析方法应用于解决其他问题。

在每一章中，我们都会给出许多工程实例，这对于正确理解课本中给出的问题处理方法来说至关重要。对于每一个学生来说，可取的做法是先了解工程实例，然后再去独自解决新的实际问题。化工问题需要的往往是数值解，因此熟悉各种不同的解题技巧就显得非常重要，只有这样才能系统地而不是靠直觉来得到答案。

在本书编写过程中，我们遵循了多年来教授课程的做法，将侧重点放在理论上。这门学科发展是如此迅速，涵盖范围已经从物理学理论扩展到实际技术应用，相关材料的选择必然因人而异。但是，对于本书，给出基本原理比实际操作更重要，因为后者可以到工厂中去更好地学习。而对于那些在工厂中能成功运用经验公式的读者，我们希望本书同样能够帮助他们尽可能应用基本原理。

我们希望借此机会感谢那些对我们提供批评建议的朋友们，其中我们尤其感谢 F. E. Warner 先生，M. Guter 博士，D. J. Rasbash 博士，L. L. Katan 博士。我们同样要感谢那些允许我们列举他们的操作设备的公司。本书引用了许多在技术性期刊上发表的作品，对此我们对那些允许我们引用文章的出版方表示感谢。特别鸣谢：化学工程师学会、美国化学工程师学会、美国化学会以及牛津大学出版社和麦克米伦图书公司。

South Kensington,
London S. W. 7
1953

写在前面

Without Chemical Engineering, modern society could not exist!

这几乎是我每年进行化工原理教学的开场白，也是激励我为化学工程努力工作、为社会贡献自己一份力量的动力。

没有哪一个学科像化学工程的研究范畴这么宽，研究对象的尺度变化这么大，从原子、分子研究到年产百万吨、千万吨产品的体系；也没有哪一个工程学科像化学工程这样与科学结合得这样紧密……所有这一切都给我们无限的理由要把化学工程学好。

为了使学生在日后的国际舞台上无障碍地交流，争取更多的平等的合作机会，以适应教育国际化的趋势和创新型人才培养的需要，我校自 1993 年开始采用原版教材，使用全方位的英语授课。我校当时经过大量调研，选择本套书作为授课的原版教材。

我校自 1993 年开始使用本教材，至今已有 15 年，我任教化工原理双语课程也已满 15 年，我们见证了本套书作者们精益求精，在保持原有风格基础上的不断修订和再版，使其始终在英国、欧洲，乃至世界保持着无以替代的地位；体会了这套教材内容的丰富和深邃，以及始终伴随着化工发展步伐创新的精神。在我心中，这无疑是一套经典而现代的、永不过时的教材。

我们应该感谢大连理工大学出版社科技教育出版中心负责人的执著努力，使得这套书的最新版得以展现在大家面前。我要感谢我的学生们，正是由于他们的工作，大家才可以看到中文的前言和目录……

这套书涉及动量传递、热量传递和质量传递的基本原理和理论，并讲述如何将这些基础理论应用于精馏、吸收、过滤、膜分离、结晶、蒸发等独立的单元操作中。不仅适宜作双语教学的原版教科书，也是化学工程工作者不可多得的必备参考书。

我衷心希望广大读者能同我们一样喜欢这套书，通过这套书见证我们化学工业的进步和发展。

贺高红

2008 年 6 月 1 日于

大连理工大学