SIXTH EDITION

COULSON & RICHARDSON'S

# CHEMICAL ENGINEERING

# 化学工程

第1卷 第6版

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

VOLUME 1

## Fluid Flow, Heat Transfer and Mass Transfer

Butterworth Heinemann 世界图书出版公司

Coulson & Richardson's

# CHEMICAL ENGINEERING

**VOLUME 1**

**SIXTH EDITION**

## *Fluid Flow, Heat Transfer and Mass Transfer*


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Coulson & Richardson's

# CHEMICAL ENGINEERING

## VOLUME 1

*Fluid Flow, Heat Transfer and Mass Transfer*

**Coulson & Richardson's Chemical Engineering**

Chemical Engineering, Volume 1, Sixth edition
Fluid Flow, Heat Transfer and Mass Transfer
J. M. Coulson and J. F. Richardson
with J. R. Backhurst and J. H. Harker

Chemical Engineering, Volume 2, Fourth edition
Particle Technology and Separation Processes
J. M. Coulson and J. F. Richardson
with J. R. Backhurst and J. H. Harker

Chemical Engineering, Volume 3, Third edition
Chemical & Biochemical Reactors & Process Control
Edited by J. F. Richardson and D. G. Peacock

Chemical Engineering, Volume 4, Second edition
Solutions to the Problems in Volume 1
J. R. Backhurst and J. H. Harker

Chemical Engineering, Volume 5, Second edition
Solutions to the Problems in Volumes 2 and 3
J. R. Backhurst and J. H. Harker

Chemical Engineering, Volume 6, Third edition
Chemical Engineering Design
R. K. Sinnott

# *Professor J. M. Coulson*

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 war-time 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.

JFR

# Preface to Sixth Edition

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 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 principal areas of application, particularly of the theories of 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.

*Swansea, 1999* J.F. RICHARDSON
*Newcastle upon Tyne, 1999.* J.R. BACKHURST
J.H. HARKER

# *Preface to Fifth Edition*

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.

JFR

# *Preface to Fourth Edition*

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 1 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.

*June 1990* JFR

## NOTE TO REVISED REPRINT 1993

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.

# *Preface to Third Edition*

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.

*January 1976*

JMC
JFR

# *Preface to Second Edition*

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.

J. M. COULSON
J. F. RICHARDSON

# Preface to First Edition

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 major 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 essential 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.

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*London S.W.7*
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