

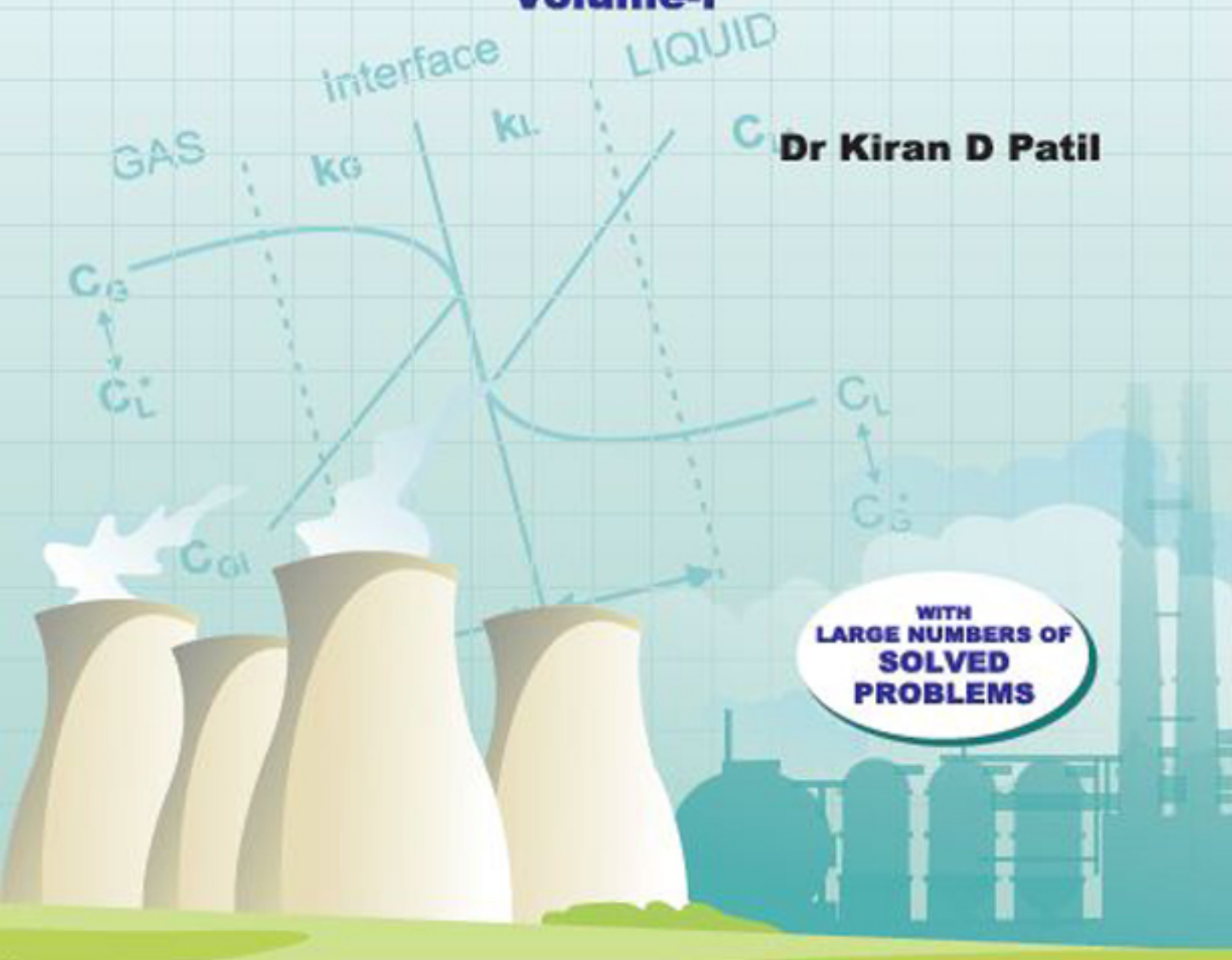
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PRINCIPLES AND FUNDAMENTALS OF

# MASS TRANSFER OPERATIONS-I

Volume-I

Dr Kiran D Patil



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## FOREWORD

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The subject of 'Mass Transfer' forms an essential part of the syllabi of undergraduate courses in Chemical Engineering and other diversified courses such as Polymer Engineering, Petroleum Engineering and Petrochemical Engineering. A textbook on 'Mass Transfer' is therefore always welcome, if it is comprehensive and yet easy to understand.

Fundamental concepts in mass transfer and their mathematical relationships are difficult to understand for an average student. However without the understanding of these basic concepts, it is difficult to appreciate their applications in chemical engineering unit operations, processes, including their design and maintenance.

Only a few books on "Mass Transfer" are available in the Indian market. Also these available books are costly and their orientation and presentation may not always suit the needs of Indian students community. The author of present book, *Mr. Kiran Patil* has nicely explained each concept in most logical and systematic manner. The mathematical derivations of several equations have been presented most rigorously and without any ambiguity. This may particularly be seen in chapters 2, 3 and chapter 5, wherein the topics on Diffusion mass transfer, Mass transfer coefficient and Gas absorption have been explained in detail. I appreciate the efforts of author to include a large number of problems with solutions and open-ended exercises with hints.

The author has taken care to incorporate every concept in logical sequence and developed it step by step to its final form. This will facilitate self-learning by the reader and satisfy the long felt need of the students for such a standard textbook.

Mr. Kiran Patil is a senior faculty member of Chemical Engineering Division of the Petrochemical Engineering Department of MAEER's MIT, Pune (M.S.), India. His industrial and teaching experience and ability to effectively communicate with the student is amply revealed in every chapter of the book. I congratulate him for his untiring efforts and dedications in preparing this textbook. I congratulate Mr. Patil for his untiring efforts and dedications dedication in preparing this textbook.

I hope and feel confident that this book will prove to be quite helpful to the engineering students community at large in long run and it will also be quite useful as a noteworthy standard textbook on the subject of "Mass Transfer-I" for chemical engineering courses in the various Universities of India.

**(Prof. Dr. Vishwanath D. Karad)**

Executive President and Director General,  
MAEER'S Maharashtra Institute of Technology,  
Pune-411 038, Maharashtra, India

## **PREFACE TO THE FOURTH EDITION**

---

I am happy to present the Fourth edition of the book, “ **Principles and Fundamentals of Mass Transfer Operations - I**” (VOLUME I) for students of degree courses of Chemical, Petrochemical, Petroleum, and Polymer Engineering and degree courses in Biotechnology of major Universities of India. My purpose in presenting the fourth edition of this book continues to be that of the previous edition: “ to provide a vehicle for teaching, either through a formal course or through self study, the techniques of, principles of equipment design for, the mass transfer operations of chemical engineering”. The enthusiastic response to the third edition of this book has encouraged me to revise this edition, which contains many new features. In this edition simple ideas are treated first, and are then extended to the more complex.

Regarding this new edition: first of all I should say that in spirit it follows the earlier ones, and I try to keep things simple. In fact, I have reorganized materials as per the requirement of topic. I have taken this opportunity to improve and modernize many of the explanations, to modernize the design data, and to lighten the writing as best I could. I feel that problem-solving –the process of applying concepts to new situations –is essential to learning. Consequently this edition includes over 250 solved problems and over 200 homework problems with answers to help the student learn and understand the concepts being taught.

The Fourth edition of book is thoroughly revised and split into two volumes :

- 1. Principles and Fundamentals of Mass Transfer Operations-I (Volume I)**
- 2. Principles and Fundamentals of Mass Transfer Operations-II (Including Separation Processes) (Volume-II)**

**Volume – I consists of following chapters :**

- 1) Overview of Chemical Engineering, Profession, Separation Processes and Mass Transfer Operations
- 2) Diffusion Mass Transfer
- 3) Interphase Mass Transfer
- 4) Convective Mass Transfer
- 5) Absorption and Stripping Operations
- 6) Equipment for Gas-Liquid Mass Transfer Operations
- 7) Humidification and Dehumidification Operations
- 8) Drying Operations

**Volume –II consists of following chapters:**

- 1) Crystallization
- 2) Equilibrium Stage Operations
- 3) Distillation
- 4) Extraction and Leaching Operations
- 5) Adsorption and Ion Exchange
- 6) Membrane Separation Processes
- 7) Mass Transfer with Chemical Reactions

I am grateful to Prof. (Dr.) V.D. Karad, Executive President and Director General, MAEER's, Maharashtra Institute of Technology (MIT), Pune for his constant encouragement and moral support during the preparation of this book. My overwhelming debt is to my colleagues and students in the department. Malik types most of the book, and Angha provided valuable editorial help. I express my appreciation my publisher, Shri Dinesh Furia and Shri. Jignesh Furia for positive attitude for bringing out the Fourth edition of this book with great care and in a very attractive manner.

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 author. Would they please continue their good work!

I am confident that this book will be definitely useful to the teachers and students of Chemical Engineering of major Universities in India.

**Pune**  
**5<sup>th</sup> September 2008**  
**Teachers Day**

**Kiran D. Patil**  
**E-mail: [kiranpatil@mitpune.com](mailto:kiranpatil@mitpune.com)**

## PREFACE TO THE THIRD EDITION

---

I am happy to present the third edition of the book, “Principles of Mass Transfer Operations” for students of degree courses of Chemical, Petrochemical, Petroleum, and Polymer Engineering of major Universities of India. The enthusiastic response to the second edition of this book encouraged me to write this edition, which contains many new features: addition of new chapters (chapter 11, 12, 13 and 14) on Distillation, Extraction and leaching operations, Adsorption and ion exchange and membrane Separation Processes. The new material has been included in keeping with current demands of students.

While Mass Transfer Operations is a required course in every undergraduate chemical engineering program in the world, there does not exist a comprehensive text on the subject that is specifically tailored to the undergraduate reader. Principles of Mass Transfer Operations responds to this need, providing a thorough, accessible text that presents the latest advances in the science as well as sets of targeted questions that challenge students’ knowledge.

This book is designed to equip the reader with sufficient knowledge on mass transfer operations and face the challenges ahead. The focus throughout author’s peerless study is on making the student consider computation from the start of a mass transfer dilemma. Twenty-five to thirty problems at the end of each chapter ensure that readers will remain actively engaged with the material. The objective of this comprehensive and up-to-date textbook is to teach chemical engineering students the principles involved in analyzing a process and apply the desired mass transfer operation to separate the components involved. Chapters encompass :

- Fundamentals of mass transfer
- Interphase mass transfer
- Convective mass transfer
- Absorption And Stripping
- Equipment For Gas-Liquid Mass Transfer Operations
- Humidification And Dehumidification Operations
- Drying Operations
- Crystallization
- Mass Transfer With Chemical Reactions
- Distillation
- Extraction And Leaching Operations
- Adsorption and Ion Exchange
- Membrane Separation Processes

I express my appreciation and gratefulness to my publisher, Shri Dinesh Furia and Shri. Jignesh Furia and his entire team of Nirali Prakashan, Pune for most co-operative and painstaking attitude with untiring efforts for bringing out the third edition of this book with great care and in a very attractive manner.

Suggestions for improvement in the style and content of the textbook, correction of errors if any will be greatly appreciated from the readers and will be incorporated in future editions.

**Pune**  
**30<sup>th</sup> March 2006**  
**Gudi Padva**

**Mr. Kiran D. Patil**  
**E-mail: kdpatil@mitpune.com**

## **PREFACE TO THE SECOND EDITION**

---

I am happy to present the second edition of the book, “A Text book of Mass Transfer - I” for students of degree courses in Chemical, Petroleum, Petrochemical and Polymer Engineering of major Universities of India. The enthusiastic response to the first edition of this book and its several reprints encouraged me to write this edition, which contains many new features. The significant additions to chapter 2,3, 5 and 9 in greater detail. A new chapter on Mass transfer with chemical reaction is added.

The book is written in simple and easy to follow language to understand the basic principles, fundamental concepts of mass transfer operations for students of chemical engineering. The course contents have been planned in such a way that the general requirements of engineering students are fulfilled. The new material has been included in keeping with current requirements of students.

Over 350 problems (250 solved and 100 unsolved) in this revised edition have been carefully chosen to illustrate the fundamental concepts to help the students to bridge the gap between theory and application of mass transfer. More than 150 quiz questions, 250 study questions from various University question papers and summary notes are given for quick revision of the subject. Additional materials, charts, and data tables have been added, which are equally useful to practicing engineers.

I am thankful to my colleagues, friends and my students for creating the atmosphere of academic excellence, which encouraged me to write this book.

I am grateful to those observant readers who drew my attention to errors in the first edition. I express my appreciation and gratefulness to my publisher, Mr. Jignesh Furia and his team of Nirali Prakashan for most co-operative and painstaking attitude with untiring efforts for bringing out the second edition of this book with great care and in a very attractive manner.

Suggestions for improvement from the readers in the style and content of the textbook, correction of errors if any will be greatly appreciated and will be incorporated in future editions.

I am confident that this book will be definitely useful to the teachers and students of Chemical Engineering of major Universities in India.

**Pune**  
**18<sup>th</sup> September 2004**  
**Ganesh Chaturthi**

**Mr. Kiran D. Patil**  
**E-mail: kiranpatil@mitpune.com**

## PREFACE TO THE FIRST EDITION

---

In view of revised syllabus of Chemical Engineering in all the universities in Maharashtra, Gujarat and other states, there is an urgent need to have standard textbooks for various chemical engineering subjects. When I set to write this book, only a very limited number of books on mass transfer were available in the Indian market. Also based on the market survey of available books in Chemical Engineering, it is observed that the books are written by foreign authors (with a few exceptions), and are often very costly. These are generally written for diploma students. Therefore it is not possible for undergraduate students to understand the basic theory and principles of various chemical engineering subjects to the depth they should. As a result their preparation is not up to the mark. This I have observed, often, in oral examinations. Thus there is a need of good quality undergraduate textbooks in Chemical Engineering subjects which: (i) cover topics in the syllabus up to appropriate details, (ii) discuss adequate problems, (iii) useful to all chemical engineering students in Maharashtra, and (iv) are inexpensive. I hope that the students studying chemical engineering will find the book useful for self-study.

This book presents an elementary treatment of the principles of Mass transfer. A background in ordinary differential equations is helpful for proper understanding of the material. Presentation of the subject follows classical lines of separate discussions for principles of mass transfer operations, Diffusion mass transfer, Mass transfer coefficients, Interphase mass transfer, Gas Absorption, Humidification and dehumidification operations, Equipment for gas-liquid operations, Drying operations and Crystallization. Throughout the book emphasis has been placed on visualization of physical processes while, at the same time, relying on meaningful experimental data in those circumstances that do not permit a simple analytical solution. Theory alone won't do, particularly from the point of view of examination in Indian universities and Engineering colleges. Hence emphasis is given on numerical examples in this book. A liberal number of numerical examples are given which include Diffusion mass transfer, Mass transfer coefficient, Gas absorption. A detailed introduction to diffusion and mass transfer is presented in order to acquaint the reader with these processes and to establish more firmly the important analogies between heat, mass, and momentum transfer. Problems are included at the end of each chapter. Some of these problems are of a routine nature to familiarize the student with the numerical manipulations and orders of magnitude of various parameters that occur in the subject of mass transfer. Other problems extend the subject matter by requiring students to apply the basic principles to new situations and develop their own equations. There is also a section at the end of each problem set designated as *Practice exercise*. The problems in these sections typically are open-ended and do not result in a unique answer. In some cases they are rather extended in length and require judgment decisions during the solution process. Over 100 such problems are included in the text.

The subject of mass transfer is not static. New developments occur quite regularly, and better analytical solutions and empirical data are continuously made available to the professional in the field. Because of the huge amount of information that is available in

the research literature, the beginning student could easily be overwhelmed if too many of the nuances of the subject were displayed and expanded.

The book is designed to serve as an elementary text, so the author has assumed a role of interpreter of the literature with those findings and equations being presented which can be of immediate utility to the reader. It is hoped that the student's attention is called to more extensive works in a sufficient number of instances to emphasize the depth that is available on most of the subjects of mass transfer. A serious student will do well to go through the end-of-chapter reference

I am grateful to Prof. (Dr.) V.D. Karad, Director, Maharashtra Institute of Technology (MIT), Pune for his constant encouragement and moral support during the preparation of this book. I am very grateful to Dr. B.D. Kulkarni, Head, Chemical Engineering Division, National Chemical Laboratory, Pune for writing kind words regarding my book. I am very thankful to Prof. (Dr.) L.K. Kshirsagar for his guidance and suggestions during the preparation of this book. Thanks are due to Prof. Datta. B. Dandge for constructive criticism of the text.

I am very thankful to my publisher M/s Nirali Publishers, Pune and especially to Mr. D.K. Furia for giving the present form to the book in minimum possible time. I am also thankful to most efficient and professional staff of M/s Nirali Publishers, Pune.

I am immensely grateful to the members of my family who were encouraging, tolerant, totally supportive and generous. I am overwhelmingly happy to acknowledge, how much I owe them and how inadequate this sounds from the heart. I would express my sincere gratitude to my parents, who have always been a major source of encouragement in all my academic pursuits. Finally, my wife Varsha gives me a wonderful rich life.

Finally to say, though I have made possible attempts to make this book flawless, yet some errors may surprisingly creep into. Suggestions from the readers regarding improvement of the utility of this book will be gratefully acknowledged and acted upon.

I am confident that this book will be definitely useful to the teachers and students of Chemical Engineering. My efforts will be successful only to that extent to which it receives patronage from the wider section of the students and teachers of Chemical Engineering.

**Pune**  
**15<sup>th</sup> September 2002**

**Mr. Kiran D. Patil**  
**E-mail: kiranpatill@mitpune.com**

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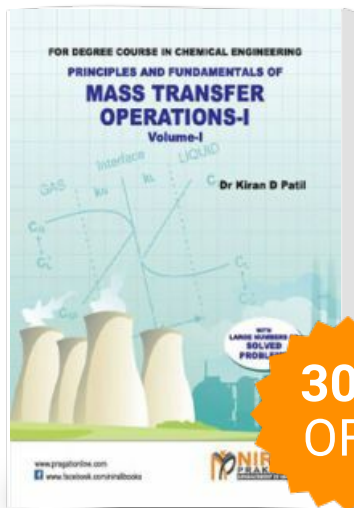
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