

HANDBOOK OF INDUSTRIAL DRYING

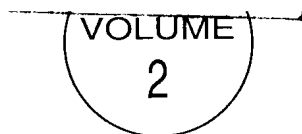
SECOND EDITION
REVISED AND EXPANDED

VOLUME
2

EDITED BY
ARUN S. MUJUMDAR

HANDBOOK OF INDUSTRIAL DRYING

SECOND EDITION
REVISED AND EXPANDED



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Foreword to the Second Edition

The second edition of the *Handbook of Industrial Drying* continues the tradition of the editor and the publisher as international leaders in providing information in the field of industrial drying. The authors are knowledgeable of the subjects and have been drawn from among the world's authorities in industry, academia, government, and consulting. Some fifty authors from fifteen countries have written forty-three chapters plus three appendices. There are twenty-one new chapters, plus two new appendices. All chapters have been updated or revised. There is over sixty percent new material, making this edition practically a new volume.

The mark of an outstanding handbook is that it provides current information on a subject—in this case multidisciplinary in nature—understandable to a broad audience. A balanced approach of covering principles and practices provides a sound basis for the presentations. Students, academics, consultants, and industry people can find information to meet their needs. Researchers, designers, manufacturers, and sales people can benefit from the book as they consider elements or components related to drying as well as the system itself.

New material has been added to provide the latest information on minimizing environmental impacts, increasing energy efficiency, maintaining quality control, improving safety of operation, and improving the control of drying systems. New sections or chapters have been added to cover in detail microwave drying; infrared drying; impinging stream dryers; use of superheated steam and osmotic dehydration; and drying of biotechnological materials, tissue and towels, peat, coal, and fibrous materials.

The information in this book can be categorized as product related, equipment related, and the relationship between the two—the system of drying. For products not specifically covered, or for the design of dryers not detailed, users can select closely related applicable information to meet many needs. The user may want to pursue a subject in considerably more detail. Pertinent references, but not voluminous overwhelming bibliographies, are included at the end of each chapter. An appendix devoted to an annotated bibliography is also included.

Carl W. Hall

Foreword to the First Edition

The *Handbook of Industrial Drying* fills an important need and is of immeasurable value in the field of drying. Academics, students, and industry people—from sales to research—can learn much from the combination of principles and practices used throughout. The presentation of principles does not overwhelm the coverage of equipment and systems. More appropriate theories will develop as a result of the description of equipment and systems. For example, a description of dryers, particularly industrial dryers, is lacking in many research articles; this handbook provides such information.

The authors have distilled much information from extensive literature to provide generic information as contrasted with details of a specific drying system of a particular manufacturer. The users can extrapolate the use of drying systems, by design and management, to a variety of products. As a special feature, a complete listing of books written on the subject of drying is included.

The authors, a blend of students, faculty, and those in industry, represent experience with different kinds of drying systems, different applications of principles, and different products. The book provides excellent coverage of the cross-disciplinary nature of drying by utilizing well-known authors from many countries of the world. Dr. Mujumdar and these associates have assembled an excellent up-to-date handbook.

The common thread throughout the book is the movement of heat and moisture as well as the movement and handling of products. Also included are instrumentation, sensors, and controls that are important for quality control of products and efficiency of operation. The emphasis on the design of equipment to expedite these processes in an economical manner is appropriate and useful.

The word *handbook* is sometimes used disparagingly to describe a reference for quick answers to limited questions or problems. In that sense this book is more than a handbook—the knowledge base provided permits the user to build different systems for products other than those covered.

Carl W. Hall

Preface to the Second Edition

The second edition of the *Handbook of Industrial Drying* is a testimonial to the success of the first edition published in 1987. Interest in the drying operation has continued to increase on a truly global scale over the past decade. For example, over 1500 papers have been presented at the biennial International Drying Symposia (IDS) since its inception in 1978. *Drying Technology—An International Journal* published some 2000 pages in seven issues in 1993 compared with just over three hundred only a decade earlier. The growth in drying R&D is stimulated by the need to design and operate dryers more efficiently and to produce products of higher quality.

A handbook is expected to provide the reader with critical information and advice on appropriate use of such information compiled in a readily accessible form. It is intended to bring together widely scattered information and knowhow in a coherent format. Since drying of solids is a multidisciplinary field—indeed, a discipline by itself—it is necessary to call on the expertise of individuals from different disciplines, different industrial sectors, and several countries. A quick perusal of the list of contributors will indicate a balanced blend of authorship from industry as well as academia. An attempt has been made to provide the key elements of fundamentals along with details of industrial dryers and special aspects of drying in specific industries, e.g., foods, pulp and paper, and pharmaceuticals.

The first edition contained twenty-nine chapters and two appendixes; this one contains forty-three chapters and three appendices. Aside from the addition of new chapters to cover topics missing from the first one, a majority of earlier chapters have been updated—some fully rewritten with new authorship. This edition contains over sixty percent new updated material. Thus, this book will be a valuable addition even to the bookshelves that already hold the first edition.

This revised and expanded edition follows the same general organization as the first with additions made to each of the four parts to eliminate some of the weaknesses of the first edition. For example, an extensive chapter is added in Part I on transport properties needed for dryer calculations. Chapters on infrared drying and the novel impinging stream dryers are added to Part II. Part III contains the largest enhancement with ten

new chapters while Part IV is completely new except for the chapter on humidity measurements.

A two-volume set of this magnitude must depend on the direct and indirect contributions of a large number of individuals and organizations. Clearly it is impossible to name them all. I am grateful to all the contributors for the valuable time and effort they devoted to this project. The companies and publishers who have permitted us to reproduce some of their copyrighted artwork are acknowledged for their support. Appropriate credits are given in the text where applicable. Exergex Corporation, Brossard, Quebec, Canada provided all the secretarial and related assistance over a three-year period. Without it this revision would have been nearly impossible.

Over the past two years most of my graduate students and postdoctoral fellows of McGill University have provided me with very enthusiastic assistance in various forms in connection with this project. In particular, I wish to express my thanks to Dr. T. Kudra for his continued help in various ways. Purnima, Anita, and Amit Mujumdar kindly word-processed numerous chapters and letters and helped me keep track of the incredible paperwork involved. The encouragement I received from Dr. Carl W. Hall was singularly valuable in keeping me going on this project while handling concurrently the editorial responsibilities for *Drying Technology—An International Journal* and a host of other books. Finally, the staff at Marcel Dekker, Inc., have been marvellous; I sincerely appreciate their patience and faith in this project.

Arun S. Mujumdar

Preface to the First Edition

Drying of solids is one of the oldest and most common unit operations found in diverse processes such as those used in the agricultural, ceramic, chemical, food, pharmaceutical, pulp and paper, mineral, polymer, and textile industries. It is also one of the most complex and least understood operations because of the difficulties and deficiencies in mathematical descriptions of the phenomena of simultaneous — and often coupled and multiphase — transport of heat, mass, and momentum in solid media. Drying is therefore an amalgam of science, technology, and art (or know-how based on extensive experimental observations and operating experience) and is likely to remain so, at least for the foreseeable future.

Industrial as well as academic interest in solids drying has been on the rise for over a decade, as evidenced by the continuing success of the Biennial Industrial Drying Symposia (IDS) series. The emergence of several book series and an international journal devoted exclusively to drying and related areas also demonstrates the growing interest in this field. The significant growth in research and development activity in the western world related to drying and dewatering was no doubt triggered by the energy crunch of the early 1970s, which increased the cost of drying several-fold within only a few years. However, it is worth noting that continued efforts in this area will be driven not only by the need to conserve energy, but also by needs related to increased productivity, better product quality, quality control, new products and new processes, safer and environmentally superior operation, etc.

This book is intended to serve both the practicing engineer involved in the selection or design of drying systems and the researcher as a reference work that covers the wide field of drying principles, various commonly used drying equipment, and aspects of drying in important industries. Since industrial dryers can be finely categorized into over two hundred variants and, furthermore, since they are found in practically all major industrial sectors, it is impossible within limited space to cover all aspects of drying and dryers. We have had to make choices. In view of the availability of such publications as *Advances in Drying* and the *Proceedings of the International Drying Symposia*, which emphasize research and development in solids drying, we decided to concentrate on

various practical aspects of commonly used industrial dryers following a brief introduction to the basic principles, classification and selection of dryers, process calculation schemes, and basic experimental techniques in drying. For detailed information on the fundamentals of drying, the reader is referred to various textbooks in this area.

The volume is divided into four major parts. Part I covers the basic principles, definitions, and process calculation methods in a general but concise fashion. The second part is devoted to a series of chapters that describe and discuss the more commonly used industrial dryers. Novel and less prevalent dryers have been excluded from coverage; the reader will find the necessary references in Appendix B, which lists books devoted to drying and related areas in English as well as other languages. Part III is devoted to the discussion of current drying practices in key industrial sectors in which drying is a significant if not necessarily dominant operation. Some degree of repetition was unavoidable since various dryers are discussed under two possible categories. Most readers will, however, find such information complementary as it is derived from different sources and generally presented in different contexts.

Because of the importance of gas humidity measurement techniques, which can be used to monitor and control the convective drying operation, Part IV includes a chapter that discusses such techniques. Energy savings in drying via the application of energy recovery techniques, and process and design modifications, optimization and control, and new drying techniques and nonconventional energy sources are also covered in some depth in the final part of the book.

Finally, it is my pleasant duty to express my sincerest gratitude to the contributors from industry and academia, from various parts of the world, for their continued enthusiasm and interest in completing this major project. The comments and criticisms received from over twenty-five reviewers were very valuable in improving the contents within the limitations of space. Many dryer manufacturers assisted me and the contributors directly or indirectly, by providing nonproprietary information about their equipment. Dr. Maurits Dekker, Chairman of the Board, Marcel Dekker, Inc., was instrumental in elevating the level of my interest in drying so that I was able to undertake the major task of compiling and editing a handbook in a truly multidisciplinary area whose advancement depends on closer industry-academia interaction and cooperation. My heartfelt thanks go to Chairman Mau for his kindness, continuous encouragement, and contagious enthusiasm throughout this project.

Over the past four years, many of my graduate students provided me with enthusiastic assistance in connection with this project. In particular, I wish to thank Mainul Hasan and Victor Jariwala for their help and support. In addition, Purnima and Anita Mujumdar kindly word-processed countless drafts of numerous chapters. Without the assistance of my coauthors, it would have been impossible to achieve the degree of coverage attained in this book. I wish to record my appreciation of their efforts. Indeed, this book is a result of the combined and sustained efforts of everyone involved.

Arun S. Mujumdar

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Drying of Pharmaceutical Products

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1. INTRODUCTION

The pharmaceutical industry is one in which quality of the final product cannot be compromised. Any deterioration of the product (e.g., by microbial infection, oxidation, thermal decomposition, contamination by metallic particles or by unremoved organic solvent) must be avoided at any cost. In light of that the GMP (Good Manufacturing Practices) for drug manufacture (see, e.g., Ref. 1) put numerous demands on the drying stage of the drug manufacturing process. Noncontaminating dryer construction materials are used, like polished stainless steel or enameled iron. Closed-cycle dryers are often required as moisture removed is often an organic solvent or their mixture. Drying must be often performed in inert gas to avoid oxidation or explosion if solvent is flammable. To avoid thermal decomposition in many instances vacuum and freeze drying must be employed.

All these requirements put dryers for pharmaceuticals among the most expensive and sophisticated drying equipment. At the same time the wide variety of drugs produced by any pharmaceutical company (tens of thousands of individual drugs are produced worldwide) in many different forms causes dryers in the pharmaceutical industry to encompass a wide range of types, both batch and continuous.

The manufacture of a drug that will be distributed in nonliquid form (tablets, capsules, dragees) is carried out in three subsequent stages:

1. Synthesis of intermediate products
2. Final synthesis of the drug
3. Manufacture of dosage forms

After each stage the products are dried. Selection of a proper dryer for these products depends on the properties of materials such as their form, thermal sensitivity, tonnage, drying kinetics, and so on. Since most pharmaceuticals are low-tonnage and high-value products, considerations of energy saving are usually of secondary importance in the selection of the drying process.