Handbook of Industrial Drying

edited by

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Foreword

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.

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Preface

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 International 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 severalfold 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.

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Part I

Fundamental Aspects

1

Drying of Solids: Principles, Classification, and Selection of Dryers

Anilkumar S. Menon* and Arun S. Mujumdar

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1. INTRODUCTION

Drying commonly describes the process of thermally removing volatile substances (moisture) to yield a solid product. Moisture held in loose chemical combination, present as a liquid solution within the solid or even trapped in the microstructure of the solid, which exerts a vapor pressure less than that of pure liquid, is called *bound* moisture. Moisture in excess of bound moisture is called *unbound* moisture.

When a wet solid is subjected to thermal drying, two processes occur simultaneously:

1. Transfer of energy (mostly as heat) from the surrounding environment to evaporate the surface moisture
2. Transfer of internal moisture to the surface of the solid and its subsequent evaporation due to process 1

The rate at which drying is accomplished is governed by the rate at which the two processes proceed. Energy transfer as heat from the surrounding to the wet solid can occur as a result of convection, conduction, or radiation and in some cases as a result of a combination of these effects. Industrial dryers differ in type and design, depending on the principal method of heat transfer employed. In most cases heat is transferred to the surface of the wet solid and thence to the interior. However, in dielectric, radiofrequency or microwave freeze drying, energy is supplied to generate heat internally within the solid and flows to the exterior surfaces.

Process 1, the removal of water as vapor from the material surface, depends on the external conditions of temperature, air humidity and flow, area of exposed surface, and pressure.

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Process 2, the movement of moisture internally within the solid is a function of the physical nature of the solid, the temperature, and its moisture content. In a drying operation any one of these processes may be the limiting factor governing the rate of drying, although they both proceed simultaneously throughout the drying cycle. In the following sections we shall discuss the terminology and some of the basic concepts behind the two processes involved in drying.

2. EXTERNAL CONDITIONS (PROCESS 1)

Here the essential external variables are temperature, humidity, rate and direction of air flow, the physical form of the solid, the desirability of agitation, and the method of supporting the solid during the drying operation (1). External drying conditions are especially important during the initial stages of drying when unbound surface moisture is being removed. In certain cases, for example, in materials like ceramics and timber in which considerable shrinkage occurs, excessive surface evaporation after the initial free moisture has been removed sets up high moisture gradients from the interior to the surface. This is liable to cause overdrying and excessive shrinkage and consequently high tension within the material, resulting in cracking and warping. In these cases surface evaporation should be retarded through the employment of high air relative humidities while maintaining the highest safe rate of internal moisture movement by heat transfer.

Surface evaporation is controlled by the diffusion of vapor from the surface of the solid to the surrounding atmosphere through a thin film of air in contact with the surface. Since drying involves the interphase transfer of mass when a gas is brought in contact with a liquid in which it is essentially insoluble, it is necessary to be familiar with the equilibrium characteristics of the wet solid. Also, since the mass transfer is usually accompanied with the simultaneous transfer of heat, due consideration must be given to the enthalpy characteristics.

2.1. Vapor-Liquid Equilibrium and Enthalpy for a Pure Substance Vapor-Pressure Curve

When a liquid is exposed to a dry gas, the liquid evaporates, that is, forms vapor and passes into the gaseous phase. If m_W is the mass of vapor in the gaseous phase, then this vapor exerts a pressure over the liquid, the *partial pressure*, which, assuming ideal gas behavior for the vapor, is given by

$$P_W V = \frac{m_W}{M_W} RT \qquad \text{or} \qquad P_W V_W = RT \qquad [1]$$

The maximum value of P_W that can be reached at any temperature is the saturated vapor pressure P_W^0. If the vapor pressure of a substance is plotted against temperature, a curve such as TC of Fig. 1 is obtained. Also plotted in the figure are the solid-liquid equilibrium curve (melting

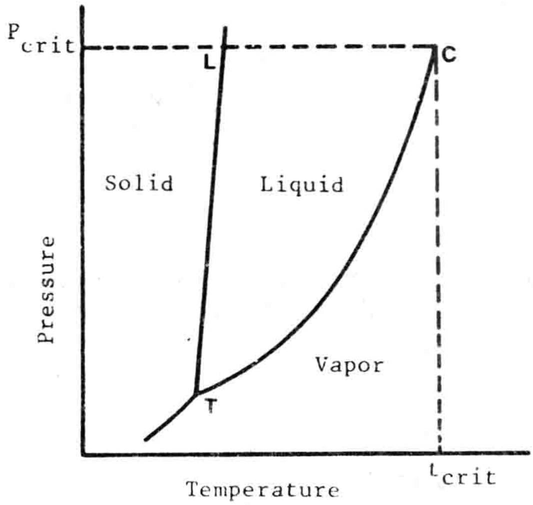

FIG. 1 Vapor pressure of a pure liquid.

curve) and the solid-vapor (sublimation) curve. The point T in the graph at which all three phases can coexist is called the *triple point*. For all conditions along the curve TC, liquid and vapor may coexist, and these points correspond with the *saturated liquid* and the *saturated vapor state*. Point C is the critical point at which distinction between the liquid and vapor phases disappears, and all properties of the liquid, such as density, viscosity, and refractive index, are identical with those of the vapor. The substance above the critical temperature is called a gas, the temperature corresponding to a pressure at each point on the curve TC is the *boiling point*, and that corresponding to a pressure of 101.3 kPa is the *normal boiling point*.

The Clausius-Clapeyron Equation

Comprehensive tables of vapor pressure data of common liquids, such as water, common refrigerants, and others, may be found in Refs. 2 and 3. For most liquids, the vapor pressure data are obtained at a few discrete temperatures, and it might frequently be necessary to interpolate between or extrapolate beyond these measurement points. At a constant pressure, the Clausius-Clapeyron equation relates the slope of the vapor pressure-temperature curve to the latent heat of vaporization through the relation

$$\frac{dP_W^0}{dT} = \frac{\Delta H_W}{T(V_W - V_L)} \qquad [2]$$

where V_W and V_L are the specific molar volumes of saturated vapor and saturated liquid, respectively, and ΔH_W is the molar latent heat of vaporization. Since the molar volume of the liquid is very small compared with that of the vapor, we neglect V_L and substitute for V_W from Eq. [1] to obtain