PROCESS DRYING PRACTICE

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To all who have labored to improve drying technology

Preface

Drying is more art than science, they say, and this belief persists with good reason. In most industrial dryers, solid, liquid, and vapor states interact vigorously, and the taking of in-progress measurements is difficult or impossible. Unlike heat exchangers, and most other process equipment, dryers cannot be designed by fitting flow rates and properties into equations derived to suit the equipment's configuration. Instead, designs are based on tests. The result has been an accumulation of know-how by individuals, rather than a spread of general drying knowledge throughout the industry.

Most of the published works on drying report on fundamental studies of the internal conditions of heat and mass transfer, that is, the microscopic behavior of materials while drying. These help in understanding the process, but have limited usefulness in selecting, designing, and operating dryers. Instead, it is the external conditions of temperature, flow rates, and design features, together with experience, that meet industry's needs. This text focuses on these practical considerations.

Our aim is to record our know-how and experience in order to help others design, build, select, operate, and optimize drying systems. We hope to make others more knowledgeable in this puzzling business and guide them out of some of the common pitfalls.

The techniques and information offered either have never been published or are a more complete development of articles by the authors. Since dryer descriptions and theory are readily available, only what is essential for understanding each topic has been included.

The variety of products that have to be dried has evolved an abundance of dryer types, some for quite limited uses—no book could treat all of them in detail. The material here applies in some measure to all dryers, but specific emphasis is on those direct and indirect dryers most widely used for particulate materials—spray, flash, fluid bed, conveyor, tray, rotary, disc, paddle, screw flight, and drum.

Manufacturers of dryers are good sources of practical information, but many are firms with a niche, and are relatively small. Even most larger firms are knowledgeable in only one or two of the dozen or more basic dryer types. It is understandable that some of their information

is biased and some is withheld for competitive reasons. They are limited, for these reasons, in the breadth of knowledge and assistance they offer. Recently their ranks have been thinned out. Most serious has been the loss of some product testing capabilities. Selecting dryers is thus more difficult. Not as tangible, but perhaps as serious, is a lessened incentive to innovate and to price competitively.

In an old technology such as drying, major changes come slowly. But some new approaches have been developed over the past few years to reduce energy use and increase dryer productivity. These techniques have been refined and successfully applied on a variety of drying systems, and they can also be used to improve test methods and results.

For these reasons, this seems a suitable time to disclose the practical side of drying technology. Included are some of the obscure working tools of the industry: scaleup, exposure times, testing methods, relations between drying conditions and product properties, complexities of psychrometric charts, calculation methods for any solvent in any gas, adversities in start-ups, finding leaks, and other items translated from drying folklore.

Chapters 1 through 12 are concerned largely with drying that removes water. The first outlines the internal and external drying conditions—the basic theories. Chapter 2 covers the main types of drying systems and their capabilities. The two chapters that follow describe specific dryers, separating them by heating methods into indirect and direct types.

Next are given the equations needed for the functional design of dryers—the airflow, heat load, and saturation conditions. It is shown how the equations can be used manually or in computer programs. Chapter 6 presents psychrometric charts made just for drying and tells how they are drawn and used.

Then two chapters detail the techniques and instruments needed to measure operating conditions, and how to make computer analyses of these data to improve energy use and productivity. Chapter 9 tells how dryers are selected by product-testing methods and how feed and product properties affect results. The advantages and disadvantages of buying used dryers are weighed in Chapter 10, followed by chapters giving advice and precautions for start-up and troubleshooting.

The realm of drying from nonaqueous solvents is covered in Chapter 13, and some unique estimating charts are presented. The final chapter addresses the reality of four actual installations, and how difficulties were overcome in the steps of testing through operation.

The appendixes list data needed for manual and computer calculations and conversion factors for both individual and combined units to and from U.S. customary and SI units. Throughout the text U.S. units

are used, with SI units added in parentheses wherever practical. Next follows a glossary of terms. Finally, the references are for the most part those that either provided essential data or give useful background information. While some texts have proven invaluable, much more information and know-how has come from personal contacts and experience.

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Much of this book stems from the authors' backgrounds, but some has also come from contacts over a period of years with knowledgeable individuals in the drying industry. Those who helped recently with their specific expertise include David W. Dahlstrom of ABB Raymond, John J. Walsh and Robert A. Nichols of Bepex Corporation, Fred Keill of Proctor & Schwartz, Inc., and Fred A. Aiken of Swenson Process Equipment, Inc.

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Chapter

1

Introduction

Persistent work on drying theory has brought little prospect that it will ever be able to predict dryer designs, and thus open a shortcut to practical solutions. When conditions are complex, theories cannot be made to predict reality. The theory of gravity, for example, predicts poorly the motion of as few as three bodies in space and gets worse as the number of bodies increases. In drying, too, the motion of fluids in solids is complex, and predicting is made more difficult because there are so many solids, each with different properties.

For these and other reasons there is little transfer of technology from drying research to practice. Tests are almost always needed to indicate how a material will behave in an actual unit. This is confirmed by various publications (Keey, 1978; Marshall, 1954; Mujumdar, 1987; Perry and Green, 1984; Reay, 1979). We therefore run tests to find out what works, and we use other practical methods, based largely on know-how and fundamental relations, together with a few basic material properties, to complete our calculations and designs.

1.1 Scope and Definitions

Of the roughly four million known substances, about 60,000 are processed and sold; many of these must be dried. Sales of chemicals alone have reached about $240 billion a year in the United States, according to the Chemical Manufacturers' Association. Nearly every industry has wet solids that must be dried, some more than once. Most of these are particulates—powders, grains, granules, crystals, pellets, flakes, chips, and other small forms. They range in size from a few microns (micrometers) to about one-half inch (1 cm), and they are generally of rough shapes; sometimes they are cylindrical or spherical. Their size and shape may be formed before the drying operation or by it. For example, when liquid feeds are sprayed, they become spherical droplets,

which may expand as they dry and partially break up while drying or being conveyed and collected.

The great diversity of materials to be dried and the high cost of drying have resulted in the evolution of many dryer designs. Most are for particulates, and most operate continuously at about atmospheric pressure. For a better understanding, they can be divided by heating method into two types, as described in Dittman (1977). The definitions given here are for ideal conditions. Many actual systems are combinations of both types.

1. *Indirect dryers* use a hot surface to heat the solids by conduction or radiation. They use little or no hot gas such as air. This is a solid-liquid-vapor system, and the process is nonadiabatic, that is, heat is added from outside the system.

2. *Direct dryers* heat the solids by contacting them directly with a hot gas (usually air). This is a solid-liquid-vapor-gas system, and the process is adiabatic, that is, all the heat is in the system; none is added to or taken from it, assuming perfect insulation.

The method of heating determines how the drying solids will be agitated, transported, and collected. The split between heating methods is not sharp, however, because most indirect dryers use hot air sometimes, and some direct dryers use indirect heating. The overlap blurs definitions, and comparisons are difficult because few applications fit both types.

Another important distinction is the feed material's physical state. Liquids vary from thin solutions to thixotropic pastes, and solids vary from nearly dry granules to sticky sludges. Spray and drum dryers can be fed only liquids. All other common dryers accept wet solids, although certain liquids can be pumped into some of them, most often through a spray nozzle.

Except for the general discussion of internal and external drying conditions presented in this chapter, no effort is made to cover drying theory. Theoretical drying studies can be found in several texts, such as Keey (1978), Perry and Green (1984), Mujumdar (1987), and elsewhere. But available texts include few of the practical aspects that are dealt with here.

The drying operation is complex and involves a number of chemical engineering operations, including the following:

Vaporization	Diffusion
Flow of heat	Conveying
Flow of fluids	Filtration
Transport of fluids	Mixing

Psychrometry	Crystallization
Combustion	Fluidizing
Size separation	

Also important in drying systems are the solids-handling operations—transporting, mixing, classifying, preforming, grinding, compacting, and packaging. The first three are often performed inside the dryer.

1.2 Why Drying Is Needed

Many materials are processed in the liquid state—ideal for mixing and reacting—but most products are needed or wanted as dry, or relatively dry, solids. Several operations can reduce moisture content at less cost than drying. Some liquids (usually solutions) can be concentrated by evaporating; insolubles can be converted to wet solids by decanting, filtering, or centrifuging. These operations often precede drying to reduce the moisture content, but seldom can anything but drying remove all or most of the moisture.

Classes of products dried in the process industries include polymers, foods, pharmaceuticals, minerals, agricultural products, wastes, ceramics, clays, catalysts, colorants, and various other organic and inorganic chemicals. The most common reasons for drying and some specific examples follow.

1. Preserving. Many solids spoil quickly in water, but last a year or more when packaged dry.
2. Reducing weight for shipping. Clays are dried for shipping, then redispersed in water for paper making.
3. Reducing weight or volume for packaging requirements. Many foods and detergents are dried to suit consumers.
4. Making specific shapes or uniform mixtures for further processing. Ceramics, mixed with additives, are dried into spheres of uniform size and composition for pressing.
5. Recovering solvents for reuse while drying. Abrasives are dried from methanol slurries.
6. Separating a noxious or toxic liquid from a solid.
7. Removing an unwanted solid and recovering the liquid.

1.3 Theoretical Drying Studies versus Design by Testing

For years fundamental research has been conducted on drying to improve understanding and to derive mathematical design methods. The

main interest of this research concerns the internal drying conditions in order to learn what takes place inside solids as they dry. Although much information has been gained, even the theorists conclude that the equations thus far developed are not adequate, and tests must be run to get dryer design data (Dittman, 1977; Mujumdar, 1987; Perry and Green, 1984; Reay, 1979). Even further from reach is the more basic determination of which type of dryer, if any, is the most suitable for a specific material. This, too, requires testing.

Without tests there is no way to tell with confidence whether even closely related feeds will dry in the same manner and at the same conditions. This also applies to broad classes of materials (such as families of inorganic salts, polymers, and ceramics) that have similar chemical and physical properties. Testing is an empirical trial-and-error process that requires know-how. Test results are useful only for a specific application and as a limited guide for other tests, but there is no other way to get the needed information.

1.4 External Conditions

Those conditions that influence the drying but are outside the solid are termed external conditions. They concern the bulk flows of materials—solid, liquid, vapor, and gas (if any)—in contrast to the conditions of the microscopic flows that relate to internal activity. Some conditions concern both internal and external activities.

The important external conditions can be divided into two general groups for a given application.

1. Conditions usually fixed
   - *a.* Properties of the materials
   - *b.* Method of feeding, heating, supporting, and mixing the solids; also the means for transporting them throughout the drying system and removing them
   - *c.* Characteristics of the drying vessel, its heating method, and its provision for removing the vapor
   - *d.* Materials of construction and type of insulation
   - *e.* Operating pressure (usually atmospheric)
2. Variable or elective conditions
   - *a.* Heating temperatures and temperatures of feed, product, and gas
   - *b.* Moisture content in feed, product, and gas
   - *c.* Flow rates of feed, product, and gas, including any recycling of solids or gas
   - *d.* Exposure time and distribution of exposure time between particles
   - *e.* Feed pretreating or backmixing

f. Product transport, collecting, and conditioning (cooling, compacting, and grinding, for example)

Tests are run to find the best set of results. This is done by varying some of the external conditions. The most basic inputs are heating temperatures, exposure time, the flow rate of the solids, and their concentration in the feed. To get the desired results, the test unit may have to be modified, or the feed altered, or another type of dryer tested. The aim is to get design data for scaleup to a commercial system that meets all the product and rate specifications.

The most important of the conditions is the motion of heat. It is very diverse and is both an external and an internal condition. It is transmitted in three modes (McAdams, 1954)—in most dryers by all three, but usually one dominates.

1. *Conduction* moves heat between molecules from higher to lower levels of energy (heat) in solids (and to some extent in fluids). It is the principal heating mode for indirect drying, moving heat from hot metal to the particles and then between particles.

2. *Convection* moves heat between adjacent volumes in flowing fluids, inside of porous solids, and outside of all solids. It is the principal heating mode for direct drying.

3. *Radiation* beams heat through space from each object to all cooler ones in its line of sight. It is important—perhaps dominant, especially at high temperatures—in rotary dryers, but in most others its influence is minor.

1.5 Internal Conditions

Heat enters a wet solid being dried and evaporates some or all of the liquid, thus forming vapor, which is driven out. Heat transfer and mass transfer, and the forces that drive them inside the solids, together with the properties of all the components, are the internal conditions.

Heat and mass transfer occur simultaneously as solids dry. The mechanisms of mass transfer in solids are listed here. At times one will be more active than the others, and, depending on conditions, they may oppose or help each other.

1. Converting liquid to vapor expands the volume (about 1500 times for water in a typical dryer), thus expelling the vapor.

2. Capillarity is the flow of liquid through small pores and other small openings within and around particles. It is induced by molecular forces strong enough to overcome gravity.

3. Diffusion in drying is the flow of liquid or vapor within porous

particles, induced by changes of temperature and pressure. It is also the moving of vapor out of a porous solid and mixing with a gas.

4. Pressure differentials in the fluids in the pores of a solid impel motion. They are caused by temperature differences and by shrinkage and other physical changes during drying.

5. Gravity plays some part in all these actions, most notably in static solids, as in conveyor or tray dryers.

6. Evaporation and condensation are ongoing processes in which condensation in cooler areas and reevaporation move heat and create pressure differences that induce fluid motion.

The transfer of heat into the solid and its entrained liquid and the resulting mass transfer are a cause and effect relationship. The evaporation and other actions that occur are affected by the presence or absence of gas.

For indirect drying little or no gas is present, and the solid and its liquid are heated above the liquid's boiling point. Evaporation causes some degree of expanding, contracting, shrinking, and cracking of the solids, in addition to the great expansion of liquid to vapor. There is also some recondensing of vapor on cool particles—only a few are in contact with the hot surface. In this operation the primary driving force is a temperature difference, and the result is mass transfer. Liquid and vapor move inside the solids by capillarity, diffusion, pressure differences, and gravity. Vapor is moved into the space outside of the solids by pressure differences and diffusion.

When a gas is present, the solid and its entrained liquid are also heated, but to a temperature below the liquid's boiling point. But the lower-temperature driving force is more than offset by the vapor-pressure driving force. The higher vapor pressure of the liquid drives vapor into the gas, which has a lower vapor pressure.

Drying stops when the two pressures are equal. For short exposure time drying this equilibrium is approached but not reached. For any drying, if there is bound moisture in the solids, its vapor pressure is lower than for free liquid, and the equilibrium partial pressure of vapor in the gas is correspondingly lower.

When a porous particle dries, liquid at its surface evaporates, and the amount of remaining liquid as well as the ease of its release depend on the nature of the solid. The full drying range has three overlapping stages in which heat and mass transfer are resisted to varying degrees.

First, liquid vaporizes freely from the exposed wet surfaces at a constant and relatively high rate. Then the rate slows as capillary action within and between the particles brings water to a partially dry sur-