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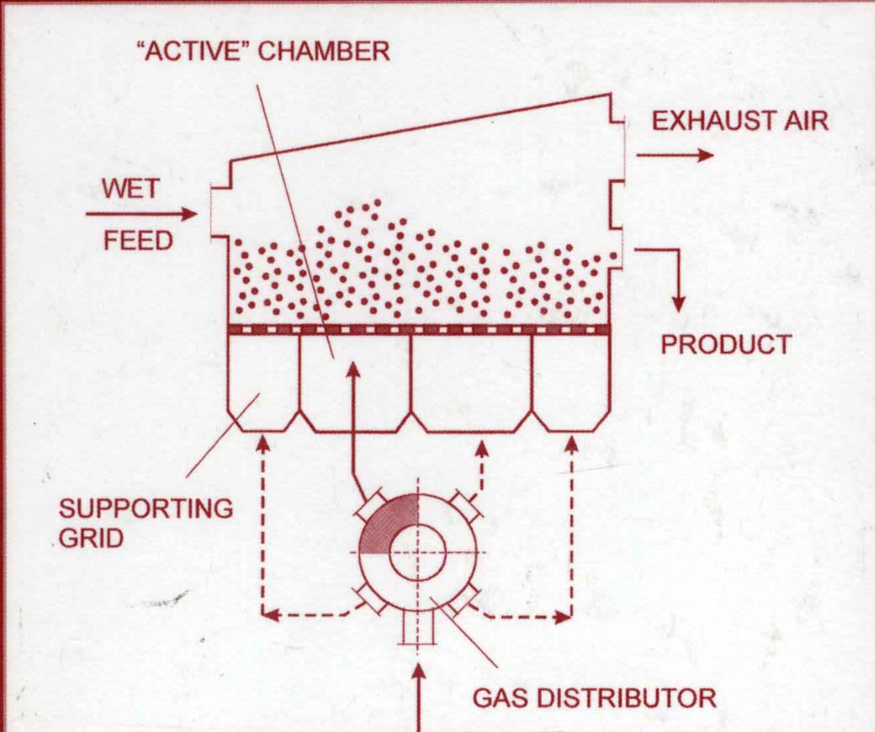
Tadeusz Kudra
Arun S. Mujumdar



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Tadeusz Kudra
CANMET
Varennes, Quebec, Canada
and McGill University
Montreal, Quebec, Canada

Arun S. Mujumdar
National University of Singapore
Singapore
and McGill University
Montreal, Quebec, Canada

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Preface

Drying is a ubiquitous operation found in almost all industrial sectors, ranging from agriculture to pharmaceuticals. It is arguably the oldest, most common, most diverse, and most energy-intensive unit operation—and, coincidentally, is also one of the least understood at the microscopic level. Drying technology is an amalgamation of transport phenomena and material science since it deals not only with the removal of a liquid to produce a solid product but also with the extent to which the dried product meets the necessary quality criteria.

Until a little over two decades ago, developments in drying occurred at a remarkably slow pace. Indeed, one wondered if the field showed any visible signs of progress. Spurred by the energy crisis, consumer demand for better quality, and the initiation of the biennial International Drying Symposium series, advances on both the fundamental and applied fronts began by leaps and bounds. Literally thousands of technical papers of archival interest were published and made widely available. This had a synergistic effect of promoting further advances in the truly inter- and multidisciplinary field of drying technology.

This book is a direct outcome of the phenomenal growth in drying literature as well as new drying hardware. It is now virtually impossible for academic and industry personnel to keep abreast of the developments and evaluate them logically. Therefore, the main objective of this book is to provide an evaluative overview of the new and emerging technologies in drying that are not readily accessible through conventional literature. We have attempted to provide a glimpse of the developments that have taken place in the past two decades and the direction toward which we see these technologies heading. We have included some well-established new technologies that are already commercialized, such as the superheated steam drying of pulp in flash or pressurized fluidized bed dryers, and laboratory curiosities, such as the displacement drying of wood (displacing water with the more volatile alcohol). Our hope is that some of the laboratory curiosities of today will lead to truly revolutionary drying technologies in the future; a systematic classification and evaluation of current technologies will hopefully lead to new ideas.

Innovation and knowledge are often called the flip sides of the same coin. It is important to know what drives innovative ideas to the marketplace. Here we also tried to look at the process of innovation and compare the innovative technologies with the more conventional ones, noting that novelty per se is not the goal of innovation.

As can be seen readily from a cursory look at the book's contents, we include dryers for all types of materials—from slurries and suspensions to continuous sheets such as paper and textiles. We cover low-tech, low-value products such as waste sludge to high-tech advanced materials, biotechnology products, and ceramics. We include production rates that range from fractions of a kilogram per hour (some pharmaceuticals) to tens of tons per hour (paper, milk, etc.). Further, we deal with drying processes that are completed in a fraction of a second (e.g., tissue paper) to several months (certain species of wood in large-dimension pieces). Thus, the scope is broad and, as the reader will find out, the range of innovations is truly breathtaking.

Finally, no new technology will see the light of day without appropriately supported R&D. We have therefore tried to identify holes in our current knowledge regarding drying and dryers that will provide new challenges to the new generation of academic and industrial researchers, eventually leading to better drying technologies.

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Part I

General Discussion: Conventional and Novel Drying Concepts

This part provides a general discussion of the need for new (advanced) drying technologies, objectives of drying R&D, classification and selection criteria for conventional and advanced drying technologies, as well as some thoughts on innovation and R&D needs. All of these topics are covered briefly; thus, the interested reader will need to refer to the literature cited for details. The objectives of this part of the book are to provide a concise introduction to our philosophy and to assist in using the information provided here.

1

The Need for Advanced Drying Technologies

1.1 WHY NEW DRYING TECHNOLOGIES?

Authors of a book such as this must honestly answer this fair question. It is true that we already have scores of conventional dryers with well-established records of performance for drying most materials. However, not all of these drying technologies are necessarily optimal in terms of energy consumption, quality of dried product, safety in operation, ability to control the dryer in the event of process upsets, ability to perform optimally even with large changes in throughput, ease of control, and minimal environmental impact due to emissions or combustion of fossil fuels used to provide energy for drying. Most drying technologies were developed empirically over sustained periods of time, often by small vendors of drying equipment with little access to R&D resources—human or financial. They were also designed at a time when energy and environmental considerations as well as quality demands were not very stringent. Indeed, many have been upgraded satisfactorily to meet legislative and competitive restrictions. Perhaps most are already designed and operated at their asymptotic limit of performance. However, if for any reason we wish to exceed their current performance in a cost-effective way, we need to look for alternative technologies with a higher asymptotic limit to performance—which is necessarily below the maximum defined by thermodynamic constraints.

The majority of novel drying technologies, which evolved through a process of evolutionary incremental improvements, was built in to offset some or all of the limitations faced in operating conventional dryers. The benefits are typically also incremental rather than dramatic. Some of the new technologies may even start at a performance level below that of a conventional dryer. From this point of view it is not a fair comparison: novel versus conventional might be like comparing apples and oranges. We urge our readers not to be judgmental at this stage and rule on novel dryers simply because they do not have a significantly superior performance at this time, since not much effort has yet been devoted to a greater study of such technologies. Rather, they should study their potential and compare the predicted asymptotic limits of performance. Even on this scale some of these technologies may not turn out to be commercially successful in the long run and may disappear. However, we must give new ideas a chance—some of them definitely will emerge as victors and those choosing them will be the beneficiaries. Note that dryers have a lifetime of 30 to 40 years; a lifetime cost is the only way to really make a proper choice between conventional and new dryers. Novelty should not be the chief criterion in the selection of a dryer—it should be the last, if at all.

A conventional dryer may be admirably suited for a specific application while another may need one to look outside the conventional set of dryers. One must set the criteria for selection and then see which one meets them better and more cost effectively. There is a cost associated with the risk accompanying the technology not verified in pilot scale. Most companies shun this and are prepared to pay a higher cost for a conventional technology—the premium is often considered an insurance premium rather than a cost.

In some cases new drying technologies are sought simply because the current technologies have a limit in terms of the production rates possible. For example, today's modern newsprint machine is limited by the dryer speed. One can make the wet paper sheet faster than it can be dried cost effectively on the current multicylinder dryers. For higher speeds entirely new drying concepts are being evaluated.

In the following sections we will review two evolutionary types of advances in drying technologies, specifically the intensification of drying rates and multistaging of convective dryers.

1.2 INTENSIFICATION OF DRYING RATES

It is obvious that reduction of the size of the dryer will lead to a reduction in initial capital cost. Although this should not be a deciding factor in the selection of an individual dryer, since only 10 to 15 percent of the life-cycle cost of a direct dryer is due to the initial capital cost of the drying system, it is still an important consideration as it can reduce the space requirement, duct sizes, size of ancillary equipment, etc., as well. One must intensify the drying rates without adversely affecting product quality in order to make the equipment smaller.

Reduction of capital and operating costs of dryers clearly depends on the feasibility to enhance drying rates within the limits of product quality requirements. Higher drying rates translate into a smaller physical size of the dryer as well as the associated ancillary equipment. Generally, it is also reflected in lower running costs. An example is drying of liquid feeds in a fluidized or spouted bed of inert particles (see Chapter 4) where highly intensified heat and mass transfer results in high volumetric evaporation rates so the dryer volume can be reduced significantly as compared to the conventional spray dryer of the same throughput.

In general, the feedstock may contain both surface and internal moisture. The rate at which the surface moisture can be removed depends only on the external heat and mass transfer rates since the controlling resistance to drying rate lies outside the material being dried. Thus, enhancing external convective heat and mass transfer rates by increasing the gas velocity and gas temperature and/or reducing gas humidity will lead to increased drying rates for a purely convective (or direct) dryer. Any action that enhances external (gas-side) resistance will yield an increase in the drying rate. Thus, an increase of free-stream turbulence, application of mechanical vibration, or oscillation of the flow yields higher drying rates. Application of ultrasonic or sonic fields is also known to increase the drying rates, but the mechanisms responsible for the augmentation are different (see Chapter 13).

Above a critical temperature, commonly termed the "inversion temperature," the rate of evaporation of the surface moisture is higher in superheated steam drying than in hot-air drying (see Chapter 7). This is due to the superior thermal properties of superheated steam. At lower temperatures the reduced temperature difference between the drying medium and the drying surface for superheated steam results in a lower drying rate for the latter. In purely convective air drying the surface temperature is equal to the wet bulb temperature corresponding to the air humidity and dry bulb temperature, whereas for superheated steam drying it is the saturation temperature of steam, i.e., 100°C for atmospheric pressure.

Enhancement of the falling rate period of drying, which requires faster transport of heat and moisture through the material, is more difficult to achieve. In general, attempts to do so result in a change in product quality. Application of an ultrasonic field can cause high-frequency pressure pulsation resulting in cavitation; the successive generation of high-pressure and low-pressure fields causes rapid vaporization and enhanced transport of the liquid through the material. The use of an electromagnetic field (e.g., microwave or radio-frequency radiation) can heat up volumetrically the polar liquid to be vaporized (e.g., water). This practically eliminates the resistance to transfer of heat into the material; the transport of moisture out through the material is also enhanced somewhat due to the higher mobility of moisture at higher temperatures as well as due to internal pressure gradient toward the material surface. The same mechanism is responsible for the marginally increased drying rates observed in superheated steam drying.

Another possible way of intensifying the drying rate involves increasing the effective interfacial areas for heat and mass transfer. For example, in an impinging stream configuration, the impingement zone generated by the collision of opposing gas–particle streams is one of high shear and high turbulence intensity (see Chapter 5). If a pasty or sludgelike wet material is dispersed in it, the turbulence field tends to deagglomerate the lumps and increase the interfacial area of drying. The drying rate is further intensified by the fact that the heat and mass transfer rates are nearly inversely proportional to the particle or droplet size, all other things being equal. When it is permissible, use of mechanical dispersers or mixers within the dryers results in more rapid drying.

An obvious means of intensifying drying rates is to increase the convective heat/mass transfer rate when feasible. Use of an impinging flow configuration rather than a parallel flow configuration can increase the evaporation rate several-fold when removing surface moisture. A gas–solid suspension flow yields higher heat transfer rate than a single-phase gas flow. For impinging gas–particle flows, the heat transfer rate is two to three times higher than for gas flow alone; the enhancement ratio depends on the flow and geometric parameters as well as particle loading in the gas. In spray drying, recirculation of fines can result in better drying rates.

Finally, since particle-to-particle heat transfer is more efficient (provided sufficient contact area) than between a gas and particles, the use of immersion drying (e.g., mixing hot inert particles with wet particles) can yield very high

TABLE 1.1 Techniques for Enhancement of Drying Rates

Drying period		
Constant rate only	Both	Falling rate period
Enhance free-stream turbulence	Increase interfacial area for heat and mass transfer	Apply ultrasonic field
Apply oscillation, vibration	Dielectric heating	Dielectric heating
Two-phase (gas–particle) drying medium	Superheated steam drying	Electrokinetic phenomena
Acoustic field of high sound pressure level		Synergistic effects

drying rates. It may be possible to use adsorbent particles so that the heat transfer medium can also effectively enhance the mass transfer potential by lowering the gas humidity concurrently (see Chapter 12).

Most of the drying-rate intensification concepts mentioned here have been tested. These are discussed in some detail in this book. It should be noted that not all ideas might be applicable in a given situation as most of these also result in changes in product quality. There is an increase in the complexity of the equipment as well. A careful technoeconomic evaluation is necessary before one may justify the use of enhancement techniques in a given application. The application areas for some of these enhancement techniques are given in Table 1.1.

1.3 MULTISTAGE DRYERS

If a material has both surface and internal moisture, i.e., both the so-called constant and falling rate periods exist in batch drying, it is logical to believe that for optimal drying the drying conditions, and even the type of dryer in some cases, should be different to remove these two distinctively different types of moisture. For cost reasons it is often preferable to choose a single dryer to accomplish the entire drying by varying the drying conditions spatially for continuous dryers and temporally for batch dryers, i.e., the dryer type is the same. Zoning of the dryers along their length is commonly used in conveyer, continuous fluidized beds, continuous vibrated beds, tunnel dryers, etc., to ensure optimal drying; this is especially true for heat-sensitive materials that could be dried under intense conditions only while surface moisture is being removed. In the falling rate, the drying conditions must be made less intense to ensure that the material temperature remains below the critical temperature above which the material starts to deteriorate (change its color, texture, activity, solubility, etc.). However, for large production rates and for certain materials, it is cost-effective to employ two different dryer types for removal of surface and internal moistures.

Removal of surface moisture is generally a more rapid process requiring a shorter dwell time in the dryer, whereas internal moisture removal is a slower process requiring a longer dwell time and hence a larger dryer. Dryers suited for surface moisture removal are fluid bed, flash, spray dryers, etc. For longer residence times one could employ through circulation, fluid bed, packed bed (or tower), continuous tray dryers, etc. Relative to spray or flash dryers, which have residence times on the order of 1 to 45 seconds, fluid bed or vibrated bed dryers have much longer dwell times. Thus, a spray dryer can be followed with a fluid or vibro-fluidized bed dryer to reduce the overall cost of drying. Indeed, this is a well-established commercial process for drying coffee, detergents, skim milk, etc. Spray drying is an expensive drying process requiring a very large spray chamber size if the entire drying is to be accomplished in the spray dryer alone. On the other hand, if all of the surface moisture is removed along with a small part of the internal moisture in the spray chamber, one can employ a small fluid bed—even as an integral part of the conical bottom of the spray chamber—and the overall dryer becomes cost-effective. Indeed, the fluid bed (or vibrated bed) can be used to instantize (agglomerate) the fine powder produced by the spray dryer. Such hybrid dryers are presented briefly elsewhere in this book.

For successful multistage drying it is important that the wet feed material has both types of moisture in significant amounts and the drying times for the two-stage dryer concept become attractive. In some cases, the first stage may be used simply to remove the surface moisture so that the product becomes nonsticky and suitable for processing in a conventional fluid bed, for example. In some special cases such as tissue paper drying, a two-stage process with through drying as the first stage and hot-air impingement as the second stage is used to obtain softer paper although both stages have comparable drying rates and comparable drying times (in fractions of a second).

Sometimes, a long residence time is needed to accomplish some physical or chemical reactions, which are much slower than the drying kinetics, e.g., crystallization of PET (polyethylene terephthalate resin) is accomplished at a tall tower while the initial drying of surface moisture is done in a small fluid bed dryer in a two-stage drying–crystallization process.