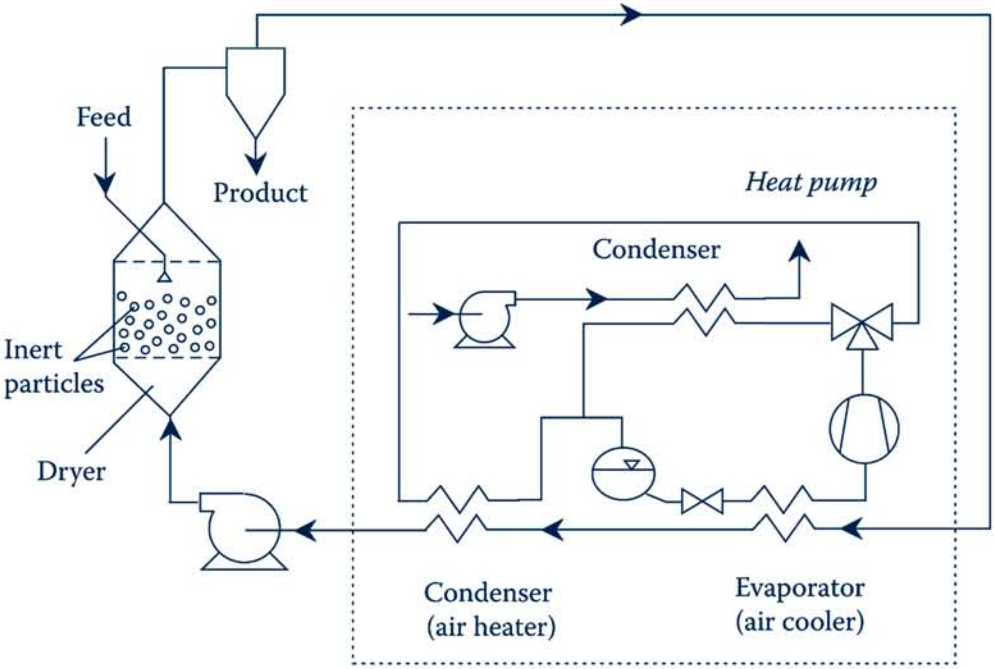
Second Edition

Advanced Drying Technologies



Tadeusz Kudra
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Cover: Front Cover presents the heat-pump drying in a fluidized bed of inert particles originated by Dr. Odilio Alves-Filho from NTNU in Trondheim, Norway (with permission).

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Contents

Preface to the First Edition

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—coincidentally it is also one of the least understood at the microscopic level. Drying technology is an amalgamation of transport phenomena and material science as it deals not only with the removal of a liquid to produce a solid product but also with the extent to which the dry product meets the necessary quality criteria.

About 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 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 on 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 in 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, which 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 directions 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). We hope that some of the laboratory curiosities of today will lead to truly revolutionary novel 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 have 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 this book's Contents, we have included dryers for all types of materials—from slurries and suspensions to continuous sheets such as paper and textiles. We have covered from low-tech, low-value products such as waste sludge to high-tech advanced materials, biotechnology products, and ceramics. We have included production rates that range from fractions of a kilogram per hour (some pharmaceuticals) to tens of tons per hour (paper, milk, etc.). Furthermore, we have dealt 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 the day without being appropriately supported by research and development (R&D). We have therefore tried to identify loopholes in our current knowledge regarding drying and dryers, which will provide new challenges to the new generation of academic and industrial researchers, eventually leading to better drying technologies.

Dr. Tadeusz Kudra
Dr. Arun S. Mujumdar

Preface to the Second Edition

As noted in the "Preface to the First Edition" of this book, drying is a ubiquitous operation found in almost all industrial sectors ranging from agriculture to pharmaceuticals. Drying technology involves the coupling of transport phenomena and material science, as it deals not only with the removal of liquid to produce a solid product, but also with the development of necessary quality criteria in the dried product. Often, what is optimal for heat and mass-transfer rates is not appropriate for drying wet material. Selection of optimal dryers or, more appropriately, drying systems, is a complex task because of the diverse physical and chemical characteristics of both the wet material and the dry product; possibilities of heat supply by convection, conduction, radiation; and radiation including volumetric heat generation by microwave or radio frequency fields, as well as the quality, costs, energy, and environmental constraints. Several hundred types of dryers have been examined in the literature; thus, selecting the right dryer is very challenging indeed.

The rising global population, combined with their aspirations for enhanced standards of living, will continue to place very high demands on energy resources. This will require industry to be more energy-efficient in all its operations. As a particularly energy-intensive unit operation, drying technologies can be expected to be re-examined in the years to come. Because most dryers still use fossil fuels, there is a serious environmental impact of very large-scale drying operations. The rapidly escalating energy costs and the potential for energy shortages provide incentives for increased attention to use renewable energy sources such as solar, wind energy, and biomass for agricultural and industrial drying operations.

This second edition is a result of the increased industry interest in the technical literature on drying technologies. Over the past three decades, there has been an explosive growth in the technical literature dealing with both basic and applied aspects of thermal drying. Therefore, as with the first edition, the main objective of this book is to provide, in a capsule form, an evaluative overview of the new and emerging technologies in drying, which is not readily accessible in the conventional literature such as handbooks or textbooks. Here, we have attempted to provide to the reader a glimpse at the key developments that have taken place in the past two decades. We have included some well-established relatively 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 where water is displaced with the more volatile alcohol. We hope that both incremental and radical innovations in drying technologies will lead to improved drying technologies in the coming decades.

As was the case with the first edition, we have covered dryers for the whole range of wet materials ranging from liquids through semisolids to solids. Thus, the scope of coverage is broad and, as the reader will find out, the range of innovations is truly breathtaking. With 10–20% of national industrial energy consumption attributed to industrial drying in developed nations, it is very important for industry and academia alike to seek better ways of thermal dehydration. As the quality of living in the populous nations such as China, India, Indonesia, and Brazil rises, the energy demand for agricultural and industrial drying will necessarily rise. We hope that this will also lead to more efficient drying systems. This book provides a panorama of ideas that can be applied toward this effort.

We hope that this new edition of *Advanced Drying Technologies* will also help trigger further industry interest in supporting R&D in this important area and also in joining hands with academia to carry out cost-effective R&D in a collaborative manner. Such interaction is key to the effective and rapid transfer of technology from R&D laboratories to industrial practice.

Dr. Tadeusz Kudra
Dr. Arun S. Mujumdar

Authors

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Dr. Arun S. Mujumdar is professor of mechanical engineering and director of the Minerals, Metals and Materials Technology Centre at the National University of Singapore (NUS). He is also an adjunct professor at McGill University, Montreal, Canada, where he was professor of chemical engineering before moving to NUS in 2000. Dr. Mujumdar is well known worldwide for his extensive and impactful contributions to drying R&D, professional service to the community through the establishment of the IDS series, and for mentoring more than 45 PhD students and 30 post-doctoral fellows. He is the editor-in-chief of *Drying Technology*—an international journal. He has edited 50 books on drying as well as on heat and mass transfer including the *Handbook of Industrial Drying* (Taylor & Francis/CRC Press, Boca Raton, Florida, 2007), now in its third edition. He has authored more than 360 papers and 100 book chapters and has delivered more than 300 conference presentations and 60 keynote and plenary lectures. Being the winner of numerous international awards, Dr. Mujumdar was recently conferred with *Doctor Honoris Causa* by the Technical University of Lodz, Poland, and awarded a Platinum Jubilee Distinguished Visiting Professorship by the University of Mumbai

Institute of Chemical Technology (MUICT). His research theme has focused on the development of novel dryers including intensification of innovation in drying technologies through mathematical modeling. Dr. Mujumdar earned his BChemEng in Chemistry with distinction from the University of Mumbai, India, and obtained his MEng and PhD degrees from McGill University, Montreal, Canada.

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 research and development (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; hence, the interested reader will have 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

Need for Advanced Drying Technologies

1.1 Why New Drying Technologies?

Authors of a book such as this must answer a 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 research and development (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 the 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, were built 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 their 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 30–40 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.

A conventional dryer may be admirably suited for a specific application, whereas another may need one to look outside the conventional set of dryers. One must set the criteria for selection and then see which one suits them better and is more cost-effective. There is a cost associated with the risk accompanying the technology not verified at the pilot scale and even the full scale. Most companies shun this risk 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. This is a complex and expensive task in view of the very high investment and operating costs required at the mill scale.

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 the initial capital cost. Although this should not be a deciding factor in the selection of an individual dryer, as only 10–15% of the life-cycle cost of a direct dryer is typically 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 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 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 that the dryer volume can be reduced significantly as compared to the conventional spray dryer of the same throughput.

In general, the feedstock to be dried contains 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 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. Of course, there are exceptions, for example, intense drying may cause case-hardening and reduce drying rates or it may cause extreme shrinkage and cracking, which are undesirable phenomena. Thus, an increase of free-stream turbulence, application of mechanical vibration, or oscillation of 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 (SHS) drying than in hot-air drying (see Chapter 7). This is due to the superior thermal properties of SHS. At lower temperatures, the reduced temperature difference between the drying medium and the drying surface for SHS 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 SHS drying, it is the saturation temperature of steam, that is, 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- 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 [MW] or radio-frequency radiation) can heat up volumetrically the polar liquid to be vaporized (e.g., water). This practically eliminates the resistance to transfer heat into the material; the transport of moisture out through the material is also enhanced to some extent 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 SHS 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 sludge-like material is dispersed in it, the turbulence field tends to de-agglomerate 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 impinging flow configuration rather than a parallel flow configuration can increase the evaporation rate severalfold while 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 (SD), recirculation of fines can result in better drying rates.

Finally, as 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 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 use of enhancement techniques in a given application. The application areas for some of these enhancement techniques are given in Table 1.1.

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

1.3 Multistage Dryers

If a material has both surface and internal moistures, that is, 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 a dryer in some cases, should be different to remove these two distinctively different types of moisture. For cost reasons, often it is 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, that is, 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 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 1–45 s, 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. SD 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 contrary, 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 the types of moisture in significant amounts, so that 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).

TABLE 1.2

Selected Examples of Two-Stage Drying

Stage 1	Stage 2	Advantages	Applications
Spray dryer $t \sim O$ 10 s	Fluid bed dryer $t \sim O$ 10 min	Reduces overall size of dryer, hence better technoeconomics	Spray Fluidizer (Niro)
		Product is granulated (instantized), if necessary	Drying of slurries, for example, coffee, detergent, and milk
Spray dryer $t \sim O$ 10 s	Vibrofluid bed dryer $t \sim O$ 10 min	Reduces overall size of dryer, hence better technoeconomics Product is granulated (instantized), if necessary	Drying of coffee, milk, etc.
Spray dryer $t \sim O$ 10 s	Through circulation conveyer dryer with temperature zoning	Drying at moderate conditions for heat-sensitive materials; high-sugar content sticky solids	Filtermat—commercial name—can handle drying of juices, for example, orange
Flash dryer $t \sim O$ 1–10 s	Fluid bed dryer $t \sim O$ 10 min	Surface moisture removed in flash dryer; internal moisture removed in long-residence time fluid bed	
Fluid bed dryer $t \sim O$ 1 min	Tower/packed bed dryer $t \sim O$ 10 h	Surface moisture removed fast in a fluid bed—long residence time obtained in a tall tower	Polymer suspension
Through dryer $t \sim O$ 0.1 s	Impingement dryer $t \sim O$ 0.1 s	Through dryer helps produce a structure of tissue paper that is *soft*	Drying of tissue paper, exceptional application for two-stage drying. The same order of residence times and drying rates in each stage

Note: O, on the order of; t, dwell time in dryer.

TABLE 1.3

Multistage Drying in the Dairy Industry: Combination of Conventional Technologies

Dryer	Energy Savings	Powder Characteristics
One-stage: spray dryer	Reference value	Nonagglomerated (~0.2 mm) Wide size distribution Significant fraction of fines
Two-stage: spray dryer + internal fluid bed	~18%	Instantized agglomerated powder Small fines fraction Nondusting
Three-stage: spray dryer + fluid bed + external fluid bed	~30%	Agglomerated and granulated Good flowability Narrow size distribution

Source: From Mujumdar, A. S. and Passos, M. L., *Developments in Drying*., Kasetsart University Press, Bangkok, Thailand, 2000, pp. 235–268.

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

Table 1.2 lists selected commercially viable two-stage drying technologies. Some of these technologies and three-stage dryers are covered elsewhere in this book. It is important to note that the multistage dryers represent nothing but an intelligent combination of well-established conventional technologies. However, such a combination usually offers unique advantages not possible with the component technologies separately (Table 1.3) (Mujumdar and Passos, 2000).

Reference

Mujumdar, A. S. and Passos, M. L. 2000. Drying: Innovative technologies and trends in research and development. In: *Developments in Drying*. A. S. Mujumdar and S. Suvachittanont (Eds.). Kasetsart University Press, Bangkok, Thailand, pp. 235–268.

2

Classification and Selection Criteria: Conventional versus Novel Technologies

Mujumdar and Menon (1995) as well as Mujumdar (2000) provided detailed classification schemes for industrial dryers along with numerous criteria that are important in making an appropriate selection. It is noted that one should select a drying system—including predrying and post-drying equipment—that can influence the choice of the dryer itself as well as its operating conditions. More information on this subject along with detailed information on numerous conventional industrial dryers can be found in the handbook by Mujumdar (2007).

Table 2.1 summarizes the key criteria often used in classifying dryers. A finer classification is also possible, but is not relevant here.

Table 2.2 is a typical checklist for selection of industrial dryers. In addition, the following information should be considered in specifying possible dryer types for a given application.

As a minimum, the following quantitative information is necessary to arrive at a suitable dryer:

- Dryer throughput; mode of feedstock production (batch/continuous)
- Physical, chemical, and biochemical properties of the wet feed as well as desired product specifications; expected variability in feed characteristics
- Upstream and downstream processing operations
- Moisture content of the feed and product
- Drying kinetics, sorption isotherms
- Quality parameters (physical, chemical, and biochemical)
- Safety aspects, for example, fire and explosion hazards, biohazards
- Value of the product
- Need for automatic control
- Toxicological properties of the product
- Turndown ratio, flexibility in capacity requirements
- Type and cost of fuel, cost of electricity

TABLE 2.1

Classification of Dryers

Criterion	Types
Mode of operation	Batch
	Continuous[a]
Heat input type	Convection,[a] conduction, radiation, electromagnetic fields, combination of heat-transfer modes
	Intermittent or continuous[a]
	Adiabatic or nonadiabatic
State of material in dryer	Stationary
	Moving, agitated, or dispersed
Operating pressure	Vacuum[a]
	Atmospheric
Drying medium (convection)	Air[a]
	Superheated steam
	Flue gases
Drying temperature	Below boiling temperature[a]
	Above boiling temperature
	Below freezing point
Relative motion between drying medium and drying solids	Concurrent
	Countercurrent
	Mixed flow
Number of stages	Single[a]
	Multistage
Residence time	Short (<1 min)
	Medium (1–60 min)
	Long (>60 min)

[a] Most common in practice.

- Environmental regulations
- Space in plant

Mujumdar (2000) presents cases where the choice of dryer is also governed by the quantity produced and the quality of the dried material.

Table 2.3 compares possible types of conventional and new drying technologies for various physical forms of wet materials. This list is not all-inclusive; it is given only for illustrative purposes. One can arguably place some of the dryers from the new to the conventional category, as their use becomes more commonplace.

As expected, there is a preference by industry to use conventional dryers due to their mature status and familiarity. Dryer vendors also prefer such technologies due to the low risk factor in design and scale-up. Also, the cost of developing new technologies may discourage offering quotes involving guaranteed performance. New drying technologies must offer significant advantages over the existing ones to find industrial acceptance.

TABLE 2.2

Typical Checklist for Selection of Industrial Dryers

Physical form of feed	Granular, particulate, sludge, crystalline, liquid, pasty, suspension, solution, continuous sheets, planks, odd shapes (small/large)
	Sticky, lumpy
Average throughput	Kilograms per hour (dry/wet); continuous Kilograms per batch (dry/wet)
Expected variation in throughput (turndown ratio)	Small
	High
Fuel choice	Oil
	Gas
	Electricity
Predrying and postdrying operations (if any)	Preforming, backmixing, grinding, milling, screening, standardizing
For particulate feed products	Mean particle size
	Size distribution
	Particle density
	Bulk density
	Rehydration properties
Inlet/outlet moisture content	Dry basis
	Wet basis
Chemical/biochemical/ microbiological activity	Active
	Inactive
Heat sensitivity	Melting point
	Glass transition temperature
Sorption/desorption isotherms	Shape, hysteresis
	Equilibrium moisture content
Drying time	Drying curves
	Effect of process variables
Special requirements	Material of construction
	Corrosion
	Toxicity
	Nonaqueous solution
	Flammability limits
	Fire hazard
	Color/texture/aroma requirements (if any)
Foot print of drying system	Space availability for dryer and ancillaries

Legislative requirements may change this picture in the future in many parts of the world. For example, the imposition of carbon tax and severe restrictions on the emission of greenhouse gases—particularly CO_2—will force industry to consider superheated steam (SHS) drying where it is feasible. High fuel costs and high insurance rates reigning safe operation may also make steam drying more attractive in the future.

New technologies that are likely to find acceptance over shorter time frames include combinations of well-known conventional technologies as noted earlier. Use of heat pumps, multistage operation, better control at optimum conditions, model-based control, etc., will find—and indeed

TABLE 2.3

Conventional versus Innovative Drying Techniques

Feed Type	Dryer Type	New Techniques[a]
Liquid suspension	Drum	Fluid/spouted beds of inert particles
	Spray	Spray/fluid bed combination
		Vacuum belt dryer
		Pulse combustion dryers
Paste/sludge	Spray	Spouted bed of inert particles
	Drum	Fluid bed (with solids backmixing)
	Paddle	Superheated steam dryers
Particles	Rotary	Superheated steam fluid bed dryer
	Flash	Vibrated bed
	Fluidized bed (hot air or combustion gas)	Ring dryer
		Pulsated fluid bed
		Jet-zone dryer
		Yamato rotary dryer
Continuous sheets (coated paper, paper, textiles)	Multicylinder contact dryers	Combined impingement/radiation dryers
	Impingement (air)	Combined impingement and through dryers (textiles, low-basis-weight paper)
		Impingement and microwave or radio frequency

[a] New dryers do not necessarily offer better technoeconomic performance for all products.

have already found—many applications. With government incentives, use of renewable energy for drying may prove cost-effective, especially if the fossil fuel costs double in the next decade as is currently projected. Indeed, use of solar energy and wind energy to offset the need for energy from fossil fuels and electricity may be worth considering even now at several geographical locations around the world.

The selection criteria for new technologies remain the same as those for conventional ones with the possible exception of risk management. With time, the risk factor will decrease and such technologies will become mainstream technologies.

Tables 2.4 and 2.5 compare the features of conventional and modified fluidized bed and spouted bed dryers, respectively. To choose between them, one must know and compare the specific merits and demerits of each type of gas–solid contactor. With the new devices, often the data available in the literature are obtained at laboratory scale—only in a few cases, it may be pilot scale. The scale-up is, therefore, difficult and uncertain. One must objectively evaluate the potential offered by the new technology and, if justified, carry out a systematic pilot-scale study. Often, it

TABLE 2.4

Fluidized Bed Dryers: Conventional versus Innovative Concepts

Conventional	Innovative
Convective heat transfer	Convection + conduction (immersed heaters in bed)
Steady gas flow	Pulsed gas flow
Constant gas temperature	Variable gas temperature
Pneumatic fluidization	Mechanically assisted fluidization (vibration/agitation)
Used for drying of particles	Drying pastes, slurries using inert media
Air/combustion gas as drying medium	Superheated steam for fluidization/drying
Air drag resisted by gravity	Centrifugal fluid beds (artificial gravity generated by rotation)
Single-stage/multistage fluid beds	Multistage with different dryer types
Simultaneous fluidization of entire bed	Moving fluidization zone (pulsating fluidized bed)

TABLE 2.5

Spouted Bed Dryers: Conventional versus Innovative Concepts

Conventional	Innovative
Pneumatic spouting	Mechanical spouting (screw, vibration)
Single spout	Multiple spouts
Constant gas flow/continuous spouting	Variable gas flow/pulsed gas flow
Constant gas temperature	Variable gas temperature
Drying particles	Drying pastes, slurries using inert media
Spatially fixed spout	Moving spout (rotation, oscillation)
Convective drying	Combined convection and conduction
Axisymmetric	Two-dimensional, annular, hexagonal, etc.

may be possible to scale up the heat and mass transfer characteristics. However, the quality of the dried product is difficult to predict: actual experimental testing is therefore a necessity. One advantage of the so-called "Digital Big Bang" is that advanced mathematical models of various dryers can be used as a tool to foster innovation. Such models, once validated, can be used to evaluate novel designs and optimize operating parameters to reduce the cost as well as the risk involved in using novel drying technologies. Since we do not yet have a general drying theory and the flow conditions in most dryers are extremely complex to be amenable to precise mathematical description, this approach has a long way to go before industry can benefit from it.

TABLE 2.6

Conveyor (or Apron) Dryers: Conventional versus Innovative Concepts

Conventional	Innovative
Fixed gas flow (within each zone)	Variable gas flow along length
Fixed layer thickness	Variable layer thickness along length (between zones)
Fixed (within each zone) temperature	Variable gas temperature
Hot air or flue gases as drying medium	Superheated steam as drying medium
Unidirectional gas flow	Reverse drying air flow direction between zones
Fix bed—no mixing along bed depth	Mix or mechanically agitate bed between fixed bed zones (e.g., vibrated or fluid bed between two fixed zones)
Air flow in bed thickness direction only	Air flow in cross-flow direction between zones of conventional axial flow (to reduce nonhomogeneity in drying rates)
Single-stage conveyor dryer	Use of flash or fluid bed to remove surface moisture followed by conveyor dryer (reduce attrition, etc.)
Continuous heating	Tempering zone between heating zones (interrupted drying when internal heat/mass transfer resistance is high)
Purely convective heating	Combined convective and microwave heating to reduce drying time
Atmospheric pressure	Vacuum or high pressure (with steam drying)
Fixed total pressure	Oscillating pressure between low and atmospheric (when convective heat is supplied)

It is important to reemphasize that general statements regarding the superiority of otherwise different dryers, whether conventional or novel, are not possible. A dryer may be better for one product but not for another. Operating conditions chosen affect dryer performance significantly. The relative cost of fossil fuel and electricity can change the cost-effectiveness of some dryers. Hence, readers should guard against copying dryers or drying systems from one geographic location to another as their cost-effectiveness is typically influenced by local conditions including legislative requirements.

Finally, Table 2.6 lists the attributes of the conventional conveyor (or apron) dryer and compares them with some innovative concepts. Note that many of the new concepts are proposed here for the first time; they do provide some potential advantages, but need to be tested at both laboratory and pilot scales. For a more detailed discussion, the reader is referred to Mujumdar (2000).

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3

Innovation and Trends in Drying Technologies

3.1 Introduction

As an operation of prehistoric origin, drying is not normally associated with innovation. As whatever products need to be dried currently are dried using existing technologies, it is often hard to justify the need for innovation and the concomitant need for research and development (R&D) in drying and dewatering. This is reflected in the relatively low level of R&D resources that drying is able to attract as opposed to some of the exotic bioseparation processes, which on an economic scale may be an order of magnitude less significant. It is interesting to note, however, that about 250 patents—the titles of which contain the words "dryer," "drier," or "drying"—are issued by the U.S. Patent Office every year. Only 10% or less of this number of U.S. patents is being issued per year in some of the other key unit operations such as membrane separations, crystallization, adsorption, and distillation. A negative correlation appears to exist between the current level of industrial interest and the level of academic research activity, at least as measured by the number of publications in the archives of literature.

It is instructive to start this discussion with a definition of innovation, describing types of innovation, and then identifying the need for innovation in drying as well as the features common to some of the novel drying technologies. At the outset, it is important to recognize that novelty *per se* is not adequate justification for embracing new technology; it must be technically superior and cost-effective compared to the current technology. In some instances, the newer technologies may offer advantages over the conventional ones only for specific products or specific rates of production.

3.2 Innovation: Types and Common Features

It is interesting to begin with *Webster Dictionary's* meaning of innovation, which is as follows:

Innovation, n.

- The introduction of something new
- A new idea, method, or device

Notice that it does not use adjectives such as "better," "superior," "improved," "more cost-effective," and "higher quality" to qualify as an innovation. In our vocabulary, however, we are not interested in innovation for the sake of novelty or even originality of concept but for the sake of some other positive technoeconomic attributes.

The following definition given by Howard and Guile (1992) appears to be more appropriate here: "A process that begins with an invention, proceeds with development of the invention, and results in the introduction of the new product, process or service in the marketplace."

To make it into a free marketplace, the innovation must be cost-effective. What are the motivating factors for innovation? For drying technologies, one or more of the following attributes may call for an innovative replacement of existing products, operations, or processes:

- New product or process not made or invented heretofore
- Higher capacities than current technology permits
- Better quality and quality control than currently feasible
- Reduced environmental impact
- Safer operation
- Better efficiency (resulting in lower cost)
- Lower cost (overall)
- Better control, more flexibility, ability to handle different products, etc.

Innovation is crucial for the survival of industries with short time scales (or life cycles) of products/processes, that is, a short half-life (less than 1 year, as in the case of most electronic and computer products). For longer half-lives (e.g., 10–20 years—typical of drying technologies), innovations come slowly and are less readily accepted.

The management of innovation depends on the *stage* it is at. Thus,

- Initially, value comes from rapid commercialization.
- Later, value comes from enhancing the product, process, or service.
- At maturity, value may come from discontinuing and embracing newer technology. It is important to recognize when a current technology is due for replacement.

Note that management must be agreeable to discontinue a currently viable technology in the interest of the company's future if the technology has reached its asymptotic limit of performance. This principle applies to all technologies.

Numerous studies have appeared in the literature on the fundamental aspects of the process of innovation. One of the models of the innovation process assumes a linear progress from (a) discovery of laws of nature to

(b) invention to (c) development of a marketable product or process, in this order. It is well known, however, that some of the truly remarkable revolutionary technologies evolved well before the fundamental physics or chemistry responsible for their success was worked out. True innovation is most likely to be a nonlinear—even chaotic—trial-and-error, serendipitous process. Therefore, it is difficult to teach innovation in a logical sense although one could presumably encourage creativity or try to remove blockages in the process of creativity.

What may be classified as innovation can represent different characteristics. A list of the quality parameters of innovations in general (Howard and Guile, 1992) is as follows:

- Innovation establishes an entirely new product category.
- Innovation is the first of its type in a product category already in existence.
- Innovation represents significant improvement in existing technology.
- Innovation is a modest improvement in existing product/process.

Innovations trigger technological changes, which may be revolutionary or evolutionary. From our experience, we know that the latter are more common. They are often based on adaptive designs, have shorter gestation periods and shorter times for market acceptance, and are typically a result of "market-pull"—something the marketplace demands, that is, a need exists currently for the product or process. These usually result from a linear model of the innovation process (an intelligent modification of the dominant design is an example). Revolutionary innovations, on the contrary, are few and far between, have longer gestation periods, may have larger market resistance, and are often a result of "technology-push," where the development of a new technology elsewhere prompts the design of a new product or process for which market demand may have to be created. They are riskier and often require larger R&D expenditures as well as sustained marketing efforts. The time from concept to market can be very long for some new technologies. It is well known that the concept of a helicopter appeared some 500 years before the first helicopter took to the air. The idea of using superheated steam (SHS) as the drying medium was well publicized over 100 years ago, yet its real commercial potential was first realized only about 50 years ago, and that too not fully. In fact it is not fully understood even today. A recent example of this long gestation period is the Condebelt drying process for high-basis-weight (thick grades) paperboard proposed and developed by the late Dr. Jukka Lehtinen of Valmet Oy in Finland (Lehtinen, 1998). It took a full 20 years of patient, expensive, and high-quality R&D before the process

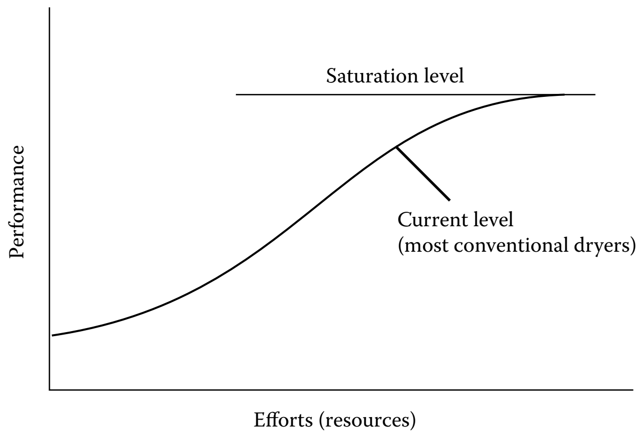

FIGURE 3.1
Foster's S-curve.

was first deployed successfully. The vision required by the management teams of such organizations must be truly farsighted to permit successful implementation of a revolutionary process.

It is natural to inquire whether it is possible to predict or even estimate the best time when the marketplace requires an innovative technology or the mature technology of the day is ripe for replacement. Foster's well-known "S-curve", shown in Figure 3.1 (Foster, 1986), which gives a sigmoid relationship between product or process performance indicators and resources devoted to develop the corresponding technology, is a valuable tool for such tasks. When the technology matures (or is *saturated* in some sense), no amount of further infusion of R&D resources can enhance the performance level of that technology. When this happens (or even somewhat sooner), the time is right to look for alternate technologies—which should not be incremental improvements on the dominant design but truly new concepts—that, once developed to their full potential, will yield a performance level well above that of the current one. As proven by Foster with the help of real-world examples, the performance-versus-effort (resources) curve occurs in pairs when one technology is replaced by another. They represent discontinuity when one technology replaces another and industry moves from one S-curve onto another. As indicated in Figure 3.1, most well-established drying technologies are very close to their asymptotic performance level if they are well designed and operated under optimal conditions.

Table 3.1 lists examples of some new drying technologies that were developed through technology-push versus market-pull. In some cases, a sharp distribution of grouping in just two types is not possible because a "market-pulled" development may require a "technology-push" to succeed.

TABLE 3.1

Examples of New Drying Technologies Developed through Technology-Push and Market-Pull

Technology-Push[a]	Market-Pull[b]
Microwave/RF/induction/ultrasonic drying	Superheated steam dryers—enhanced energy efficiency, better-quality product, reduced environmental impact, safety, etc.
Pulse combustion drying—PC developed for propulsion and later for combustion applications	Impulse drying/Condebelt drying of paper (also need technology-push)
Vibrating bed dryers—originally developed for conveying solids	Combined spray-fluid bed dryers—to improve economics of spray drying
Impinging streams (opposing jets)—originally developed for mixing, combustion applications	Intermittent drying—enhance efficiency

[a] Technology originally developed for other applications and applied to drying.
[b] Developed to meet current or further market demand.

3.3 Development of Improved Drying Technologies

New developments in any field may occur as a result of either an evolutionary or revolutionary process. Most developments follow the evolutionary path involving incremental improvements to offset one or more of the limitations of the contemporary technology. Such technologies are more readily accepted by industry since the risk associated with the adoption of such technologies is generally minimal and the cost-to-benefit ratio is favorable. Often, the new technologies are intelligent combinations of traditional technologies necessitated by changes in the marketplace.

The following list illustrates the evolutionary developments that have occurred over the past five decades in two commonly used industrial dryers: rotary and flash dryers. Similar evolutionary development trends can be traced for most other dryer types, as well.

Rotary dryer

1. Purely convective, axial gas flow
2. Internal heaters (tubes or coils) or external heating of the shell to improve efficiency and capacity
3. Direct drying by air injection into the rolling bed of particles in the rotating shell through tubes connected to a central header (Yamato dryer)

Flash dryer

1. Single-pass, vertical, round, insulated tube (adiabatic)
2. Single-pass, jacketed tube for increasing heat input, faster drying (nonadiabatic)
3. Flash dryer tubes of variable cross sections along its length (with delayed chambers)
4. Multipass, automatic, aerodynamic classification in *ring*-shaped dryer tubes to process particles with broader size distribution and cohesive particles prone to form lumps
5. Use of SHS as carrier gas–adiabatic/nonadiabatic designs
6. Use of inert carrier particles in a pneumatic tube to dry slurries

3.4 Trends in Drying Research and Development

It is extremely difficult, if not impossible, to make definitive statements about the direction drying technologies will take in the next several decades. Most of the developments in this field have occurred in the past three or four decades. As the general standard of living around the world rises along with the population of the world, it is obvious that the need for drying technologies will increase. New demands will be made on better energy efficiency, lower environmental impact through legislative measures, utilization of renewable energy for drying, and better-quality products at lower total costs. Currently, the major driving force for innovative drying techniques is the need to produce better-quality products at higher throughputs. If the price of fossil fuels rises rapidly and the scenarios proposed regarding the impending shortage of oil and the resulting skyrocketing price of oil, then the R&D in drying will again be driven by the need to enhance efficiency. Some of the energy-saving measures that are not cost-effective now would become very attractive if the price of oil doubles or triples in the next one or two decades.

In general, drying techniques designed to enhance quality are very product-specific. For example, high-valued, heat-sensitive products (e.g., pharmaceuticals, nutraceuticals, and some foods) can be dried at low temperatures and under vacuum, albeit at higher costs. As noted elsewhere in this book, two-stage, hybrid heat pump dryers or microwave (MW)-assisted vacuum dryers can compete with freeze-drying (F-D) processes to produce a high-quality dried product at a lower cost. However, these processes are still very expensive for drying of low-value products. Also, scale-up to very high production rates is difficult at this time.

This book focuses on new drying technologies. Where possible, the merits and limitations of various new technologies are proposed in the literature, and novel technologies marketed by vendors around the world are evaluated as objectively as possible. For proprietary reasons, some key details could not be located in some instances. Almost without exception, two key pieces of information are not reported by most authors, that is, the cost-effectiveness of their proposed innovations and the objective comparison with competing current technologies. Readers will have to make such judgments carefully if they wish to use this information in practice. Many of the processes may be protected by patents, as well.

The main goals of new drying technologies are to

- Produce better-quality product
- Operate at higher capacities, safely, and with good control
- Operate at lower total cost by lowering capital as well as running costs (energy, maintenance, emissions, etc.)

One or more of these objectives can be reached in several possible ways. The following is a short list:

- Use of indirect heating mode, where feasible
- Use of heat pumps to save energy
- Use of hybrid dryers
- Use of multistage dryers
- Use of new gas–solids contactors
- Use of SHS as a drying medium where possible
- Use of enhancement techniques such as application of acoustic or ultrasonic fields
- Use of better combustion techniques such as pulse combustion

Note that there is a cost associated with any additional complexity in the drying process. It is imperative to make a technoeconomic evaluation of conventional but more complex as well as newer (advanced) drying technologies before a final choice is made. The outcome will often depend on the

- Value and production rate of the product
- Cost of electricity/fossil fuels (depends on time and geographic location of the plant)
- Risk assessment due to uncertainties of scale-up and life-cycle cost evaluation

- Choice of vendors, delivery times, and performance guarantees
- Expected variability in product characteristics as well as production rates as some techniques are not flexible as far as capacities are concerned

Other factors may also need to be considered for specific applications.

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Part II

Selected Advanced Drying Technologies

This part covers a number of relatively new but not commonly used drying techniques and technologies. Most have found commercial application for selected products in some countries. These technologies have demonstrated their potential to compete with conventional technologies and surpass them in performance in many instances, for example, superheated steam drying, drying of suspensions on inert particles, and heat pump drying. With greater awareness and industrial interest, several of these will become common technologies within the next decade or two.

4

Drying on Inert Particles

4.1 Introduction

Drying of liquid materials on inert solid carriers is a relatively new commercial technology to produce powders from solutions, suspensions, slurries, and pastes. Although this technique was developed in the former Union of Soviet Socialist Republics (USSR) in the 1950s and used for industrial drying of pigments, fine chemicals, pharmaceuticals, and certain materials of biological origin (e.g., Kutsakova et al., 1964; Reger et al., 1967; Minchev et al., 1968; Anonymous, 1992), it was not widespread, mostly because of the language barrier. Over the past two decades, however, drying on inert particles has found a renewed interest mainly because of its ability to produce powders even from the coarsely dispersed liquid feed at evaporation rates competitive to spray, drum, and film-rotary dryers (Strumillo et al., 1983; Adamiec et al., 2007; Kudra and Mujumdar, 2007; Reyes et al., 2008). Extensive studies, carried out in Poland, Brazil, England, New Zealand, and Australia, have resulted in several pilot units and custom-made installations (e.g., Anonymous, 1986; Grbavcic et al., 1998). In addition, fluid bed dryers with inert particles have recently been marketed by companies such as Carrier Vibrating Equipment Co., United States, and Euro-Vent, England, as well as PROKOP INOVA in the Czech Republic that offer dryers utilizing a swirling bed of inert particles (Kutsakova et al., 1990, 1994). Recently, the idea of drying of liquids sprayed on the surface of inert particles has been extended to drying of highly wet materials such as the granules of pressed yeast (70% moisture content), which were dried as a fluidized mixture with inert polyethylene beads (Alsina et al., 2005).

4.2 Drying Mechanism and Process Considerations

Drying on inert particles is typically performed in a variety of fluid beds (classical fluid bed, spouted bed, spout-fluid bed, jet spouted bed, vibrated fluid bed, cyclone dryer, etc.) as well as in other dryers for dispersed materials such as swirling stream dryers, impinging stream dryers, or pneumatic dryers (Figure 4.1). Independent of the hydrodynamic configuration,

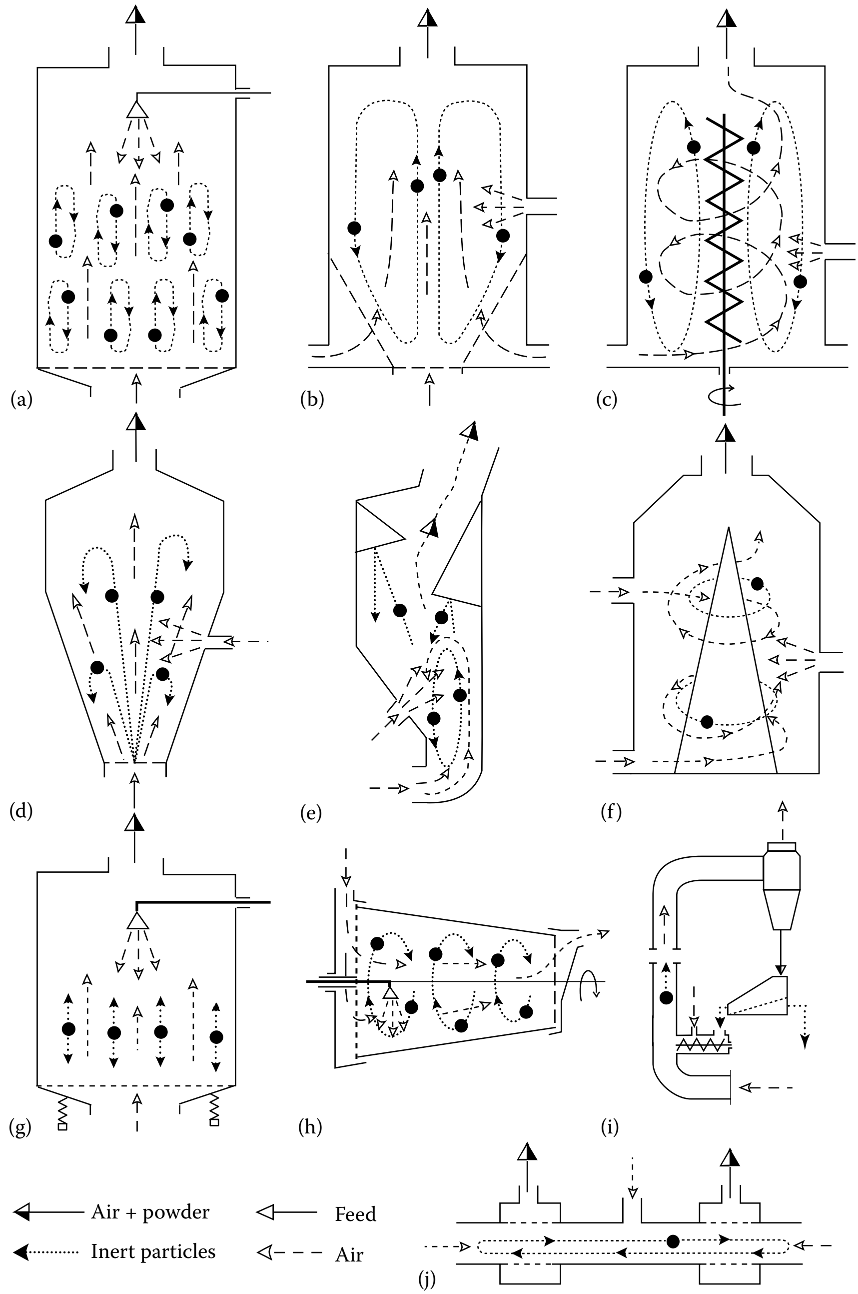

FIGURE 4.1
Basic configurations of dryers with inert carriers: (a) Fluid bed, (b) spout-fluid bed, (c) fluid bed with inner conveyor screw, (d) spouted (jet spouted) bed, (e) vortex bed, (f) swirling streams, (g) vibrofluidized bed, (h) rotary dryer, (i) pneumatic dryer, and (j) impinging stream dryer.

the principle behind this technology lies in dispersing the liquid feed over the surface of an inert solid carrier. This carrier is *fluidized* either by the sole hydrodynamic impact of the hot air stream or by the combined impact of an air stream and a mechanical device such as a screw conveyor, a vibrator, or lifters (Flick et al., 1990; Kudra et al., 1989; Pallai et al., 2007; Erdesz and Ormos, 1986; Kudra and Mujumdar, 1989, 2007; Pan et al., 2000; Limaverde et al., 2000). Particles can also be *fluidized* by an external magnetic field if they are made of ferromagnetic material such as barium ferrite (Kovalev et al., 1989).

Depending on the hydrodynamic conditions, the liquid coat on the particle surface dries by convective heat transfer from hot air and by contact heat transfer due to sensible heat stored in the inert particles. When the coat is dry enough to be brittle, it cracks because of particle-to-particle and particle-to-wall collisions and peels off from the surfaces of inert particles. Because of intense attrition, a dry product is discharged from the dryer with the exhaust air as a fine powder of rounded particles. When chipping due to the impact of inert particles prevails attrition, small flakes are produced, especially when drying brittle materials of biological origin. Small flakes can also be obtained when using inert particles with a corrugated surface. The size of the flakes is then proportional to the size of the grooves on the particle surface (Kutsakova et al., 1985).

Figure 4.2 presents the idealized mechanism of drying on inert particles, which boils down to the following sequence of kinetic processes: heating of inert particles, coating with dispersed liquid, drying of the coat, and cracking and peeling-off the dry product. Because of continuous supply of the liquid feed and a definite material residence time, the liquid spray coats at the same time not only the material-free particles but also particles with a dry but not peeled-off material and particles with a partially dry layer. Thus, quasi-equilibrium is established between the individual rates of the component processes. Stable operation of the dryer requires the combined rate of drying/peeling-off to be greater than the rate of coating. Otherwise, the wet coat would build up on the inert particles and the bed would eventually collapse eventually. The bed would also collapse with excessive saturation of exhaust air (Schneider and Bridgwater, 1989).

Another condition for stable operation of the dryer with inert particles stems from the material properties—no elastic shell should be formed on the solid carrier at any stage of drying as impact due to particle collisions might not be sufficient to crack the shell. Here, the *almond*-shaped inert particles made of two bimetallic canopies, which change their shape when subject to temperature changes during drying, could facilitate cracking of a dry shell (Dmitriev et al., 1989). Fibrous materials (e.g., pulp and paper sludge), which could bridge solid particles and therefore immobilize the bed, are also not good candidates for drying on inert particles. The bed can also collapse when drying sticky materials such as meat-rendering sludge with excessive fat content. In such a case, the melted fat acts as a binder,