CHAPTER
TWO

CLASSIFICATION AND SELECTION OF INDUSTRIAL DRYERS

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1. INTRODUCTION

Dryer selection has long been practiced as an art rather than science depending more on prior experience and vendors' recommendations. As drying technologies have evolved and become more diverse and complex, this has become an increasingly difficult and demanding task for the non-expert not conversant with the numerous types of equipment, their pros and cons, etc. Further, the task is exasperated by the need to meet stricter quality specifications, higher production rates, higher energy costs and stringent environmental regulations. In the absence of in-house experts in drying, there have been some attempts, albeit not fully successful, to develop expert systems for a non-expert to use. It is therefore necessary for an engineer responsible for selection of a dryer or, more appropriately, a drying system to be aware of what is available in the market, what the key criteria are in the selection process and thus arrive at alternative possibilities before going to vendors of such equipment for comparative quotes. It is time and effort well spent since the cost of incorrect selection can be very high.

This chapter is intended to give an introduction to this subject; the reader is referred to Mujumdar (1995) for further details. Note that over 80 percent of major chemical companies in Europe – each using over 1000 dryers in their production facilities – made errors in selecting dryers in the past year alone. What is optimal choice in one location at one point in time may be a wrong choice for another geographic location some years later. Prior use is a definite help but not the only criterion to be used in selecting drying systems.

As an example, concentrated nickel ore is dried in different parts of the world at very high production rates (20-75 t/h) using flash dryers, fluid bed dryers, rotary dryers as well as spray dryers. It is thus not a simple task to select a dryer for such applications based on what is done elsewhere.

Over 400 dryer types have been cited in the technical literature although only about 50 types are commonly found in practice. In this chapter, we will examine the key classification criteria for industrial dryers and then proceed to selection criteria with the explicit understanding that the latter is a complex process, which is not entirely scientific but also involves subjective judgment as well as considerable empiricism. It should also be noted that the pre-drying as well as post-drying stages have important bearing on the selection of appropriate dryer types for a given application. Indeed, for an optimal selection of process, one must examine the overall flowsheet as well as the “drying system.” This chapter will be confined, however, only to the classification and selection of dryers.

Another important point to note is that several dryer types (or drying systems) may be equally suited (technically and economically) for a given application. A careful evaluation of as many of the possible factors affecting the selection will help reduce the number of options. For a new application (new product or new process), it is important to follow a careful procedure leading to the choice of the dryers. Characteristics of different dryer types should be recognized when selecting dryers. Changes in operating conditions of the same dryer can affect the quality of the product. So, aside from the dryer type, it is also important to choose the right operating conditions for optimal quality and cost of thermal dehydration.

According to a very recent survey conducted by SPIN (Solids Processing Industrial Network, UK, founded by 14 large chemical companies based in Europe) selection of dryers is a key problem faced by all companies (Slangen, 2000). Over ninety percent of the companies had made errors in selection of their new dryers. Sometimes the selection is easy but when a new product is involved or the production capacity required for exceeds current practice, it is not always an easy task. New requirements on safety and environmental aspects can also make the selection more difficult. The SPIN report recommends development of user-friendly expert systems and better standardization to assist with this complex selection process. It should be noted that the selection process is further complicated by the fact that each category of dryers (e.g., fluid bed, flash, spray, rotary) has a wide assortment of sub-classes and, furthermore, each must be operated at optimal conditions to benefit from appropriate selection.

Baker (1997) has presented a “structural approach” for dryer selection, which is iterative. It includes the following steps:

- List all key process specifications
- Carry out preliminary selection
- Carry out bench scale tests including quality tests
- Make economic evaluation of alternatives
- Conduct pilot-scale trials
- Select most appropriate dryer types

Often, for same materials, a specific dryer type is indicated from the outset. If selection is based exclusively on past experience, it has some limitations:

- If the original selection is not optimal (although it works satisfactorily), the new choice will be less-than-optimal
- No new drying technologies are considered by default
- It is implicitly assumed the "old" choice was arrived at logically, which is often not the case

2. CLASSIFICATION OF DRYERS

There are numerous schemes used to classify dryers (Mujumdar, 1995; van't Land, 1991). Table 1 lists the criteria and typical dryer types. Types marked with an asterisk (*) are among the most common in practice.

Table 1 Classification of dryers

Criterion	Types
Mode of operation	• Batch • Continuous*
Heat input-type	• Convection*, conduction, radiation, electromagnetic fields, combination of heat transfer modes • Intermittent or continuous* • Adiabatic or non-adiabatic
State of material in dryer	• Stationary • Moving, agitated, dispersed
Operating pressure	• Vacuum* • Atmospheric
Drying medium (convection)	• Air* • Superheated steam • Flue gases
Drying temperature	• Below boiling temperature* • Above boiling temperature • Below freezing point
Relative motion between drying medium and drying solids	• Co-current • Counter-current • Mixed flow
Number of stages	• Single* • Multi-stage
Residence time	• Short (< 1 minute) • Medium (1 – 60 minutes) • Long (> 60 minutes)

* Most common in practice

The above classification is rather coarse. Just the fluidized bed dryer can be sub-classified into over thirty types depending on additional criteria.

Each type of dryer has specific characteristics, which make it suited or unsuitable for specific applications. Details can be found in Mujumdar (1995). Certain types are inherently expensive (e.g., freeze dryers) while others are inherently more efficient (e.g., indirect or conductive dryers). Thus, it is necessary to be aware of the wide variety of dryers available in the market as well as their special advantages and limitations. It should be noted that the aforementioned classification does not include most of the novel drying technologies, which are applicable for very specific applications. The reader is referred to Kudra and Mujumdar (1995) for details on novel drying technologies.

Following is a general scheme proposed by Baker (1997) for classification of batch and continuous dryers. Note that there is a more limited choice of batch dryers – only a few types can be operated in both batch and continuous modes.

Batch Dryers: Classification (Baker, 1997)
(Particulate Solids)
Major Classes: Layer (packed bed); Dispersion type

1. Layer type:
    a. Contact (conductive or indirect type), e.g., vacuum tray, agitated bed, rotary batch
    b. Convective (atmospheric tray)
    c. Special types (e.g., microwave, freeze, solar)
2. Dispersion type:
    a. Fluidized bed/spouted bed
    b. Vibrated bed dryer

Continuous Dryers: Classification
Major Classes: Layer; Dispersion type

1. Layer type:
    a. Conduction, e.g., drum, plate, vacuum, agitated bed, indirect rotary
    b. Convective, e.g., tunnel, spin-flash, throughflow, conveyor
    c. Special, e.g., microwave, RF, freeze, solar
2. Dispersion type:
    a. Fluid bed, vibrated bed, direct rotary, ring, spray, jet-zone

Classification of dryers on the basis of the mode of thermal energy input is perhaps the most useful since it allows one to identify some key features of each class of dryers.

Direct dryers – also known as convective dryers – are by far the most common. About 85 percent of industrial dryers are estimated to be of this type despite their relatively low thermal efficiency caused by the difficulty in recovering the latent heat of vaporization contained in the dryer exhaust in a cost-effective manner. Hot air produced by indirect heating or direct firing is the most common drying medium although for some special applications superheated steam has recently been shown to yield higher efficiency and often higher product quality. Flue gases may be used when the product is not heat-sensitive or affected by the presence of products of combustion. In direct dryers, the drying medium contacts the material to be dried directly and supplies the heat required for drying by convection; the evaporated moisture is carried away by the same drying medium.

Drying gas temperatures may range from 50 ^{o}C to 400 ^{o}C depending on the material. Dehumidified air may be needed when drying highly heat-sensitive materials. An inert gas such as Nitrogen may be needed when drying explosive or flammable solids or when an organic solvent is to be removed. Solvents must be recovered from the exhaust by condensation so that the inert (with some solvent vapor) can be reheated and returned to the dryer.

Because of the need to handle large volumes of gas, gas cleaning and product recovery (for particulate solids) becomes a major part of the drying plant. Higher gas temperatures yield better thermal efficiencies subject to product quality constraints.

Indirect dryers – involve supplying of heat to the drying material without direct contact with the heat transfer medium, i.e., heat is transferred from the heat transfer medium (steam, hot gas, thermal fluids, etc.) to the wet solid by conduction. Since no gas flow is presented on the wet solid side it is necessary to either apply vacuum or use gentle gas flow to remove the evaporated moisture so that the dryer chamber is not saturated with vapor. Heat transfer surfaces may range in temperature from -40 ^{o}C (as in freeze drying) to about 300 ^{o}C in the case of indirect dryers heated by direct combustion products such as waste sludges. In vacuum operation, there is no danger of fire or explosion. Vacuum operation also eases recovery of solvents by direct condensation thus alleviating serious environmental problem. Dust recovery is obviously simpler so that such dryers are especially suited for drying of toxic, dusty products, which must not be entrained in gases. Furthermore, vacuum operation lowers the boiling point of the liquid being removed; this allows drying of heat-sensitive solids at relatively fast rates.

Heat may also be supplied by radiation (using electric or natural gas-fired radiators) or volumetrically by placing the wet solid in dielectric fields in the microwave or radio frequency range. Since radiant heat flux can be adjusted locally over a wide range it is possible to obtain high drying rates for surface-wet materials. Convection (gas flow) or vacuum operation is needed to remove the evaporated moisture. Radiant dryers have found important applications in some niche markets, e.g., drying of coated papers or printed sheets. However, the most popular applications involve use of combined convection and radiation. It is often useful to boost the drying capacity of an existing convective dryer for sheets such as paper.

Microwave dryers are expensive both in terms of the capital and operating (energy) costs. Only about 50 percent of line power is converted into the electromagnetic field and only a part of it is actually absorbed by the drying solid. They have found limited applications to date. However, they do seem to have special advantages in terms of product quality when handling heat-sensitive materials. They are worth considering as devices to speed up drying in the tail end of the falling rate period. Similarly, RF dryers have limited industrial applicability. They have found some niche markets, e.g., drying of thick lumber and coated papers. Both microwave and RF dryers must be used in conjunction with convection or under vacuum to remove the evaporated moisture. Stand-alone dielectric dryers are unlikely to be cost-effective except for high value products in the next decade. See Schiffmann (1995) for detailed discussion of dielectric dryers.

It is possible, indeed desirable in some cases, to use combined heat transfer modes, e.g., convection and conduction, convection and radiation, convection and dielectric fields, to reduce the need for increased gas flow which results in lower thermal efficiencies. Use of such combinations increases the capital costs but these may be offset by reduced energy costs and enhanced product quality. No generalization can be made a priori without careful tests and economic evaluation. Finally, the heat input may be steady (continuous) or time varying. Also, different heat transfer modes may be deployed simultaneously or consecutively depending on individual application. In view of the significant increase in the number of design and operational parameters it is desirable to select the optimal operating conditions via a mathematical model. In batch drying intermittent energy input has great potential for reducing energy consumption and for improving quality of heat-sensitive products.

3. SELECTION OF DRYERS

In view of the enormous choices of dryer types one could possibly deploy for most products, selection of the best type is a challenging task that should not be taken lightly nor should it be left entirely to dryer vendors who typically specialize in only a few types of dryers. The user must take a proactive role and employ vendors' experience and bench-scale or pilot-scale facilities to obtain data, which can be assessed for a comparative evaluation of several options. A wrong dryer for a given application is still a poor dryer, regardless of how well it is designed. Note that minor changes in composition or physical properties of a given product can influence its drying characteristics, handling properties, etc., leading to a different product and in some cases severe blockages in the dryer itself. Tests should be carried out with the “real” feed material and not a “simulated” one where feasible.

Although here we will focus only on the selection of the dryer, it is very important to note that in practice one must select and specify a drying system which includes pre-drying stages (e.g., mechanical dewatering, evaporation, pre-conditioning of feed by solids backmixing, dilution or pelletization and feeding) as well as the post-drying stages of exhaust gas cleaning, product collection, partial recirculation of exhausts, cooling of product, coating of product, agglomeration, etc. The optimal cost-effective choice of dryer will depend, in some cases significantly, on these stages. For example, a hard pasty feedstock can be diluted to a pumpable slurry, atomized and dried in a spray dryer to produce a powder, or it may be pelletized and dried in a fluid bed or in a through circulation dryer, or dried as is in a rotary or fluid bed unit. Also, in some cases, it may be necessary to examine the entire flowsheet to see if the drying problem can be simplified or even eliminated. Typically, non-thermal dewatering is an order-of-magnitude less expensive than evaporation which, in turn, is many-fold energy efficient than thermal drying. Demands on product quality may not always permit one to select the least expensive option based solely on heat and mass transfer considerations, however. Often, product quality requirements have over-riding influence on the selection process (see Section 4).

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; moist solid sorption isotherms
- Quality parameters (physical, chemical, biochemical)
- Safety aspects, e.g., fire hazard and explosion hazards, toxicity
- 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
- Environmental regulations
- Space in plant

For high value products like pharmaceuticals, certain foods and advanced materials, quality considerations override other considerations since the cost of drying is unimportant. Throughputs of such products are also relatively low, in general.

In some cases, the feed may be conditioned (e.g., size reduction, flaking, pelletizing, extrusion, back-mixing with dry product) prior to drying which affects the choice of dryers.

As a rule, in the interest of energy savings and reduction of dryer size, it is desirable to reduce the feed liquid content by less expensive operations such as filtration, centrifugation and evaporation. It is also desirable to avoid over-drying, which increases the energy consumption as well as drying time.

Drying of food and biotechnological products require adherence to GMP (Good Manufacturing Practice) and hygienic equipment design and operation. Such materials are subject to thermal as well as microbiological degradation during drying as well as in storage.

If the feed rate is low (< 100 kg/h), a batch-type dryer may be suited. Note that there is a limited choice of dryers that can operate in the batch mode.

In less than one percent of cases the liquid to be removed is a non-aqueous (organic) solvent or a mixture of water with a solvent. This is not uncommon in drying of pharmaceutical products, however. Special care is needed to recover the solvent and to avoid potential danger of fire and explosion.

Table 2 presents a typical checklist most dryer vendors use to select and quote an industrial dryer.

Table 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	• kg/h (dry/wet); continuous • kg per batch (dry/wet)
Expected variation in throughput (turndown ratio)	
Fuel choice	• Oil • Gas • Electricity
Pre- and post-drying operations (if any)	
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	
Heat sensitivity	• Melting point • Glass transition temperature
Sorption isotherms (equilibrium moisture content)	
Drying time	• Drying curves • Effect of process variables
Special requirements	• Material of construction • Corrosion • Toxicity • Non-aqueous solution • Flammability limits • Fire hazard • Color/texture/aroma requirements (if any)
Foot print of drying system	• Space availability for dryer and ancillaries

Drying kinetics play a significant role in the selection of dryers. Aside from simply deciding the residence time required, it limits the types of suitable dryers. Location of the moisture (whether near surface or distributed in the material), nature of moisture (free or strongly bound to solid), mechanisms of moisture transfer (rate limiting step), physical size of product, conditions of drying medium (e.g., temperature, humidity, flow rate of hot air for a convective dryer), pressure in dryer (low for heat-sensitive products), etc., have a bearing on the type of suitable dryer as well as the operating conditions. Most often, not more than one dryer type will likely meet the specified selection criteria.

We will not focus on novel or special drying techniques here for lack of space. However, it is worth mentioning that many of the new techniques use superheated steam as the drying medium or are simply intelligent combinations of traditional drying techniques, e.g., combination of heat transfer modes, multi-staging of different dryer types. Superheated steam as the convective drying medium offers several advantages, e.g., higher drying rates under certain conditions, better quality for certain products, lower net energy consumption if the excess steam produced in the dryer is used elsewhere in the process, elimination of fire and explosion hazard. Vacuum steam drying of timber, for example, can reduce drying times by a factor of up to four while enhancing wood quality and reducing net fuel and electricity consumption by up to 70 percent. The overall economics are also highly favorable.

4. SELECTION OF A DRYER BASED ON QUALITY

As the product quality requirements become increasingly stringent and as the environmental legislation becomes more and more demanding it is often found that we need to switch from one drying technology to the others. The rising cost of energy as well as the differences in the cost of fossil fuels versus electrical energy can also affect the choice of a dryer. Since up to 70 percent of the life cycle cost of a convective dryer is due to energy it is important to choose an energy-efficient dryer where possible even at a higher initial cost. Note that energy costs will continue to rise in the future so this will become increasingly important. Fortunately, improved efficiency also translates into better environmental implications in terms of reduced emissions of the greenhouse gas (CO_2) as well as NO_x resulting from combustion.

Following is an example of how selection of the dryer is affected by quality of the dried product that may be used as raw material to produce different consumer products. Shah and Arora (1996) have surveyed the various possible dryers used for crystallization/drying of polyester chips from an initial moisture content of about 0.3-0.5% (w.b.) to under 50 ppm. Aside from low average moisture content it is also necessary to ensure uniform distribution of moisture, especially for some certain products, e.g., production of thin films. The uniformity constraint is less severe if the chips are to be used to make PET bottles. Figure 1 shows schematics of the crystallization/drying steps involved. Generally, it is a two-step process. The material is heat-sensitive. The initial crystallization/drying is faster than the drying step at low moisture levels. A two-stage dryer is indicated and is commonly used. It is possible to use different dryer types for each stage as shown in Figure 2. A single dryer type (e.g., column or packed bed dryer with the chips moving downward slowly under gravity) is cheaper and hence recommended for the lower quality grade but a more expensive fluid bed followed by another fluid bed or column dryer may be needed for the higher quality grade. Note that numerous alternatives are possible in each case. It is also important to operate the dryers at the correct conditions of gas flow rate, temperature and humidity. Dehumidified air is needed to achieve low final moisture contents in accordance with the equilibrium moisture isotherms of the product.

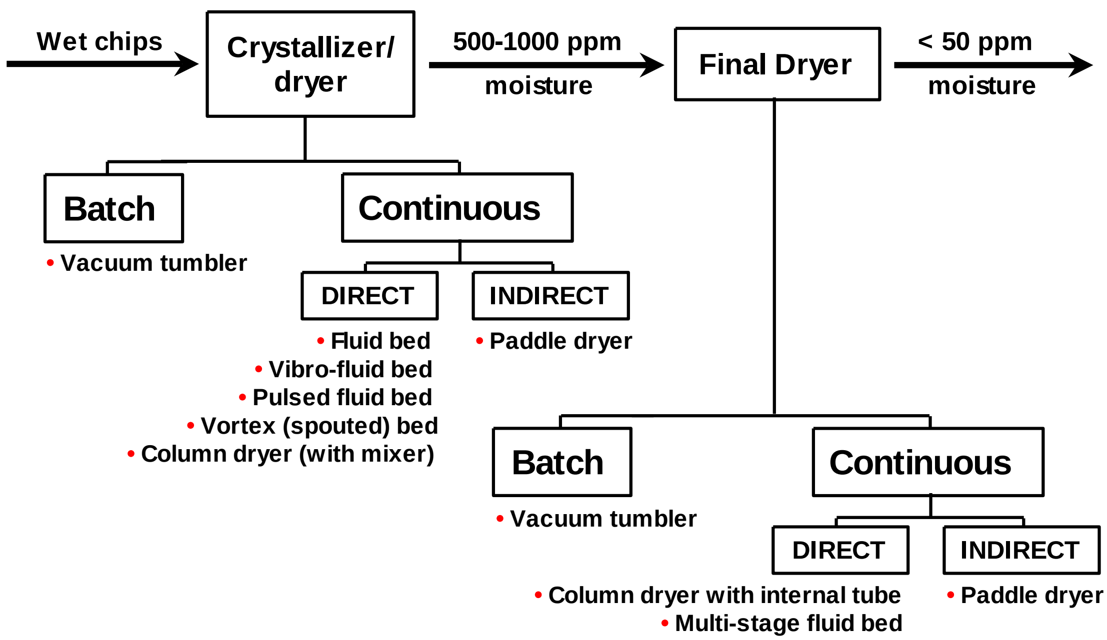

Figure 1 Schematic diagram of crystallization/drying steps in the production of polyester chips

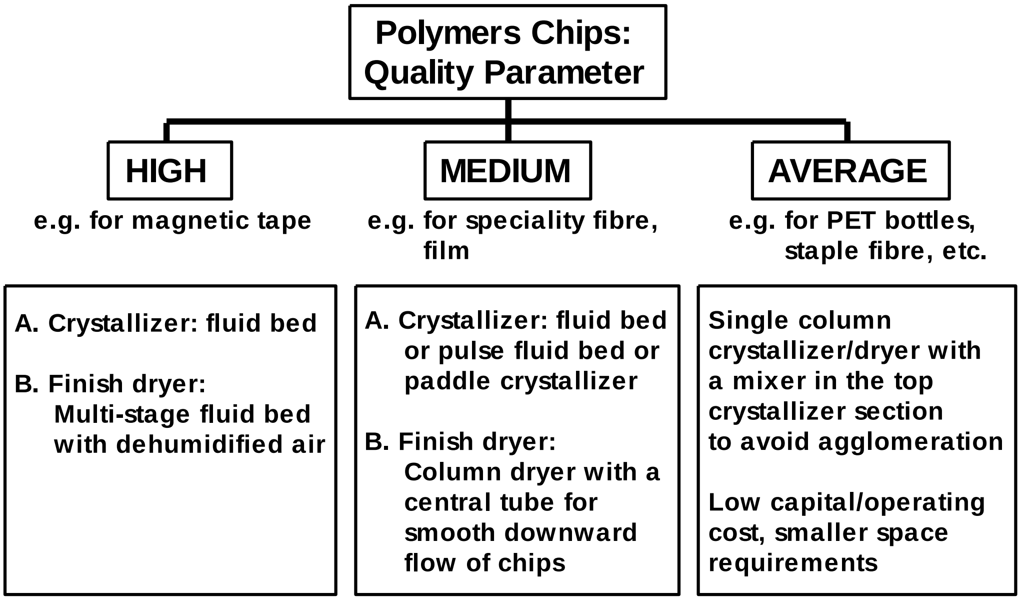

Figure 2 Possible dryer types for drying of polyester chips

Another example of dryer selection is related to the choice of a suitable atomizer for a spray dryer. A spray dryer is indicated when a pumpable slurry, solution or suspension is to be reduced to a free-flowing powder. With proper choice of atomizer, spray chamber design, gas temperature and flow rate it is possible to "engineer" powders of desired particle size and size distribution. Table 3 shows how the choice of the atomizer affects chamber design, size, as well as energy consumption for atomization and particle size distribution. The newly developed two-fluid sonic nozzles appear to be especially attractive choices when nearly monodisperse powders need to be produced from relatively moderate viscosity feeds (e.g., under 250 cp) at capacities up to 80 t/h by using multiple nozzles. More examples may be found in Masters (1985).

Table 3 Spray drying of emulsion-PVC. Effect of selection of atomizer on spray dryer performance: A Comparison between different atomizers

Parameter	Rotary disk	Two-fluid (sonic)	Two-fluid (standard)
Dryer geometry	Conical/cylindrical $H/D \approx 1.2$-1.5	Tall-form Cylindrical $H/D \approx 4$	Tall-form Cylindrical $H/D \approx 5$
Evaporation capacity (water)	1600 kg/h	1600 kg/h	1600 kg/h
Chamber ($D \times H$)	6.5 m $\times$ 8 m	3.5 m $\times$ 15 m	3 m $\times$ 18 m
Number of nozzles	1, 175-mm disk 15,000 rpm	16 nozzles 4 bar pressure	18 nozzles 4 bar pressure
Power for atomizer	25 W/kg slurry	20 W/kg slurry	80 W/kg slurry

Capital cost	High	Medium	Medium
Operating cost	Medium	Low	High

New dryers are being developed continuously as a result of industrial demands. Over 250 US patents are granted each year related to dryers (equipment) and drying (process); in the European Community about 80 patents are issued annually on dryers. Kudra and Mujumdar (2000) have discussed a wide assortment of novel drying technologies, which are beyond the scope of this chapter. Suffice it to note that many of the new technologies (e.g., superheated steam, pulse combustion – newer gas-particle contactors as dryers) will eventually replace conventional dryers in the next decade or two. New technologies are inherently more risky and more difficult-to-scale-up. Hence there is natural reluctance to their adoption. Readers are encouraged to review the new developments in order to be sure their selection is the most appropriate one for the application at hand.

Some conventional and more recent drying techniques are listed in the Table 4.

Table 4 Conventional versus innovative drying techniques

Feed type	Dryer type	New techniques*
Liquid Suspension	• Drum • Spray	• Fluid/spouted beds of inert particles • Spray/fluid bed combination • Vacuum belt dryer • Pulse combustion dryers
Paste/sludge	• Spray • Drum • Paddle	• Spouted bed of inerts • Fluid bed (with solid backmixing) • Superheated steam dryers
Particles	• Rotary • Flash • Fluidized bed (hot air or combustion gas)	• Superheated steam FBD • Vibrated bed • Ring dryer • Pulsated fluid bed • Jet-zone dryer • Yamato rotary dryer
Continuous sheets (coated paper, paper, textiles)	• Multi-cylinder contact dryers • Impingement (air)	• Combined impingement/radiation dryers • Combined impingement and through dryers (textiles, low basis weight paper) • Impingement and MW or RF

*New dryers do not necessarily offer better techno-economic performance for all products

CLOSING REMARKS

It is difficult to generate rules for both classification and selection of dryers because exceptions occur rather frequently. Often, minor changes in feed or product characteristics result in different dryer types being the appropriate choices. It is not uncommon to find different dryer types being used to dry apparently the same material. The choice is dependent on production throughput, flexibility requirements, cost of fuel as well as on the subjective judgment of the individual who specified the equipment.

We have not considered novel dryers in this chapter. Kudra and Mujumdar (2000) have discussed in detail most of the non-conventional and novel drying technologies reported in the literature. Most of them have yet to mature; a few have been commercialized successfully for certain products. It is useful to be aware of such advances so that the user can make intelligent decisions about dryer selection. Since dryer life is typically 25-40 years that effect of a poor “prescription” can have a long-term impact on the economic health of the plant. It is typically not a desirable option to depend exclusively on prior experience, reports in the literature or vendors’ recommendations. Each drying problem deserves its own independent evaluation and solution.

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