DRYING IN THE PROCESS INDUSTRY
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C.M. van ’t Land
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Drying is an important operation in the process industry. This book treats drying as a method for accomplishing liquid–solid separation by other than mechanical means. Usually, heat is supplied, leading to evaporation of a liquid (usually water), and this leaves a solid behind. Drying accomplishes the transformation of a process stream and, as such, often produces a salable product. As drying is an energy-intensive activity and dryers are expensive pieces of equipment, drying must be carried out as economically as possible.

This book is a follow-up to my earlier book, Industrial Drying Equipment: Selection and Application. In comparison to that book, the theoretical basis has been strengthened and the contents have been updated and extended.

The objective of this book is to assist the process development engineer, the process engineer, and the plant engineer in their selection of drying equipment. The theoretical background of drying and criteria to be observed when selecting drying equipment are discussed. Dryer descriptions and procedures for sizing them are treated. The subjects of product quality, process safety, process control, gas cleaning, and dryer feeding complete the book.

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INTRODUCTION

Drying can be defined as a unit operation in which a liquid–solid separation is accomplished by the supply of heat, with separation resulting from the evaporation of liquid. Although in the majority of cases water is the liquid being removed, solvent evaporation is also encountered. The definition may be extended to include the dehydration of food, feed, and salts, and the removal of hydroxyl groups from organic molecules.

This book is based on my personal experience gained in the selection and operation of drying equipment while employed by Akzo Nobel, a multinational company that manufactured, at that time, bulk and fine chemicals, pharmaceuticals, and coatings. Since 2000, I gained experience while working as an independent consultant.

Laboratory measurements and investigations concerning the drying of a product should be the first stage of the selection of a new dryer or the replacement of one. This aspect is discussed in Chapter 3. During the next stage, a person should seek the cooperation of a reputable dryer manufacturer. Close cooperation between the manufacturer and the potential user is essential, because one partner is knowledgeable about the equipment and the other person has expertise regarding the product. Since small-scale testing of drying equipment can be carried out, such testing can provide valuable insight into ultimate dryer selection. However, it is important that each partner have some insight into the other’s field so that the user can develop value judgments on the equipment being recommended by the manufacturer. The size of the equipment must be checked, using various techniques (e.g., estimating methods, rules of thumb, rough-and-ready calculations). This book covers these techniques for each class of dryer.
INTRODUCTION

Various reasons exist for drying materials to a specific level or range:

1. It is often necessary to obtain a free-flowing material that can be stored, packed, transported, or dosed.
2. Contractual limits exist for many products (e.g., salt, sand, yarn).
3. Statutory limits are in force for some materials (e.g., tobacco, flour).
4. A moisture content within a specified range may have to be obtained for quality control purposes. For many dried foods and feeds, too much moisture may adversely affect shelf life and nutritional value, whereas a moisture content too low, due to overdrying, may cause the loss of valuable nutrients. Moisture contents that are either too high or too low may render a product less enjoyable.
5. The feasibility of subsequent process steps sometimes requires that the moisture content be between specified limits, as in the milling of wheat or the pressing of pharmaceutical tablets. Another example is the low moisture content of rubber chemicals to be used in the vulcanization process of tires. Too much moisture causes the formation of blisters.
6. The onset of mildew and bacterial growth in such textiles as woolen cloth can be prevented by drying the cloth to a specific moisture content.
7. A drying step can be used as a shaping step. The manufacture of fluid cracking catalysts is an example. A spray-drying step produces hard and dry spheres of average diameter 80 μm. However, next, the spheres are leached with water to remove sodium salts. That step is followed by filtration and flash drying.

Typical dryer feeds are:

1. Objects (e.g., bricks)
2. Particulate materials (e.g., sodium sulfate crystals)
3. Filter and centrifuge cakes
4. Sheet material (e.g., paper for newspapers)
5. Pastes (e.g., dibenzoyl peroxide paste)
6. Liquids (i.e., solutions, emulsions, or suspensions)

Drying is an energy-intensive process. In general, heating and evaporation require large quantities of energy. An apple of mass 100 g hanging 4 m above the ground has a potential energy of approximately 4 J. Heating 1 kg of water from 15°C to 100°C requires 356,150 J. Evaporating 1 kg of water at 100°C and atmospheric pressure requires 2,285,000 J. Thus, in terms of energy, thermal effects are in general much more important than mechanical effects. This explains why the energy consumption in phase transformation and the heating in a drying operation exceeds the energy consumption of electromotors. In this respect, there is one more important aspect. The energy to evaporate 1 kmol of liquid is approximately constant for all liquids. Thus, it is possible to evaporate 18 kg of water (which has a kilomolecular weight of
18 kg·kmol⁻¹) with this heat of evaporation. However, it is also possible to evaporate 92 kg of toluene (which has a kilomolecular weight of 92 kg·kmol⁻¹) with this amount of heat. The explanation is that kilomoles of different substances contain the same number of molecules: 6.023·10²³ (Avogadro’s number). Thus, on evaporating 1 kmol of a substance, the bonds between this number of molecules must be broken. The bonds between the molecules are relatively weak Van der Waals forces and are approximately equal. The evaporation of water occurs more frequently than the evaporation of organic liquids.

The energy consumption of the drying operation in the UK has been reviewed by Bahu and Kemp [1]:

- The energy consumption of drying is 8% of the industrial energy consumption. The industrial energy consumption comprises both processes and buildings.
- The annual water evaporation amounts to 2·10¹⁰ kg. This is equivalent to 100-m water columns on 27.2 soccer fields (70-105 m²). As the U.S. economy is about 5.5 times larger than the UK economy, the annual water evaporation in the United States due to drying could be 1.1·10¹¹ kg.
- In 1981, drying required 1.622·10¹⁴ kJ. This figure was possibly 10 to 20% lower in 1991.
- (1.622·10¹⁴)/(2·10¹⁰) = 8110 kJ per kilogram of evaporated water. This consumption figure includes electricity. Excluding electricity, the consumption figure is possibly 7000 kJ·kg⁻¹. Compared to the heat of evaporation of water at 0°C and atmospheric pressure (i.e., 2500 kJ·kg⁻¹), the consumption figure is quite high. In the chapters to come, the background of this state of affairs is discussed.
- Annual costs are determined by taking 32,000 kJ·nm⁻³ as the lower heating value of natural gas. The lower heating value is relevant if the heat of condensation of the water vapor in the combustion gases is not recovered. In the UK, an industrial price of €0.30 is typical:

\[
\frac{1.622\cdot10^{14}\cdot0.30}{32,000} = \text{€1,520,625,000}
\]

These calculations illustrate that drying is an expensive means of accomplishing a liquid–solid separation; as a rule of thumb, 2 to 3 kg of steam is required for the evaporation of each kilogram of water. In a four-effect evaporation plant, approximately 4 kg of water can be evaporated with 1 kg of steam. Furthermore, performing a solid–liquid separation by means of a centrifuge or filter is usually much cheaper than using a dryer. Calculations concerning the energy required by the drying process begin with an assessment of the enthalpy difference between the process flows leaving the dryer and the process flow entering the dryer. Enthalpy differences are heat effects at constant pressure. In convective drying processes, the drying gas should be excluded from these calculations. Thus, the net heat is arrived at.
INTRODUCTION

The heat required for drying can be supplied by the fundamentally different mechanisms of convection, conduction, and radiation:

1. **Convection.** A carrier gas (usually, air) supplies the heat for the evaporation of the liquid by the conversion of sensible heat into latent heat. The carrier gas subsequently entrains the volatile matter.

2. **Conduction.** The heat is supplied indirectly and the carrier gas serves only to remove the evaporated liquid. Typically, the airflow is approximately 10% of the airflow used in a convective process. Conduction of heat is the heat transport mechanism at contact drying.

3. **Radiation.** This type of drying can, in principle, be nonpenetrating, such as the drying of paint by infrared radiation, or penetrating, such as the drying of food or pharmaceuticals by dielectric drying. Dielectric drying (radio-frequency drying and microwave drying) is the only process in which heat is developed in the material being dried rather than having heat diffused into the material. Again a carrier gas is required to remove the evaporated liquid.

A combination of two mechanisms may be encountered in some dryer types.

The situation in the United States was analyzed by Strumillo and Lopez-Cacicedo [2], who found that 99% of dryer energy consumption could be attributed to six dryer types. In order of importance:

- Flash dryer
- Spray dryer
- Cylinder dryer for paper
- Convective rotary dryer
- Contact rotary dryer
- Fluid-bed dryer

This list illustrates that in terms of tonnage, convective drying is more important than conduction (contact) drying.

**Dryer Types**

A great variety of dryer types is commercially available. The reasons are as follows:

- Different products have very different drying times.
- The product quality often requires a certain dryer type or mode.
- It is often necessary to transport particulate material through a dryer.

A distinction should be made between free and bound moisture. Initially, free water is evaporated until the critical moisture content is reached. Free water’s latent heat of evaporation is essentially equal to that of water on evaporating from a pool,
with the heat transfer being the rate-determining step. Evaporation occurs at a constant rate if the heat supply is constant. Thus, as long as there is free water, the rate of evaporation is not a function of the water concentration. The order of the process is then zero. Drying to below the critical moisture content requires the evaporation of bound water, with the evaporation rate decreasing if the heat supply is kept constant. Bound water can be present in pores or crevices, can be physically absorbed, or can be present as water of hydration. The latent heat of evaporation of bound water is usually higher than that of free water; for example, the ratio of the latent heats of evaporation of water in wool containing 16 and 30% water by weight (the latter value is the critical moisture content) is approximately 1.1 : 1.

Temperature and Moisture Profiles

In this book we deal only with phenomena related to objects to be dried. Thus, transient temperature and moisture profiles in the product to be dried are not discussed.

Drying Systems

Unlike a centrifuge, for example, a dryer consists of a number of pieces of equipment grouped together in a subsystem. It is therefore more correct to refer to drying systems. Convective drying systems are often more extended than contact or radiation dryer systems. Drying is often the last process step, which is followed by a solids-handling system designed by mechanical engineers. In addition, being an energy-intensive process, drying is sometimes handled by energy specialists. It can therefore be considered a unit operation that falls at the interface of three disciplines: chemical, mechanical, and energy engineering.

In Chapter 2 it is recommended that the drying step not be considered in isolation but rather be reviewed in the context of the entire process. Upstream process modifications can have a great impact on the drying stage, whereas the method of drying is often of paramount importance to product quality.

Procedures for determining the optimum dryer to use are covered in Chapter 3. One scheme is presented for continuous dryers, with a separate scheme for batch dryers. Chapter 4 provides an introduction to convective drying, and Chapters 5 through 8 cover in detail the four main categories of convective dryers. In these chapters, the performance of dryers is analyzed, their literature data interpreted, and design methods are covered. The material that is presented permits an estimation of both fixed and relevant variable costs for convective dryers. In Chapter 9, miscellaneous continuous convective dryers and convective batch dryers are discussed, and atmospheric contact dryers are treated in Chapter 10. Vacuum drying, including freeze-drying, is covered in Chapter 11. Steam drying is treated in Chapter 12. Radiation drying (infrared, radio-frequency, and microwave drying) is dealt with in Chapter 13, and the important issues of product quality and safety are considered in Chapter 14. Fires and dust explosions are treated in the context of safety. Chapter 15 covers continuous solids- and gas-moisture measurement, dryer process control, and energy recovery.
The separation of particulate solid material from spent drying gas by means of cyclones, fabric filters, scrubbers, and electrofilters are the topics in Chapter 16, and the selection of feeders for dryers is taken up in Chapter 17.

One hundred and fifty years ago, drying was often a very time-consuming process. We illustrate this by means of an example, the manufacture of a red dye from madder roots. Madder is a plant with long, thick roots that contain a red dye. From possibly 1400 until approximately 1900, this dye was manufactured industrially in Great Britain and The Netherlands. The roots were harvested and, as a first step, dried in a drying house (see Fig. 1.1). The roots were first laid on the lowest floor and were moved to higher floors as the drying proceeded. An oven at ground level heated the drying house. Control of the drying process was as follows:

- More or less intense fire
- Deposition of stones on the bottom ducts
- Degree of opening of the hatches at the top
The roots contained approximately 80% water by weight. A typical plant’s annual capacity amounted to 100 metric tonnes, with a water evaporation of 400 metric tonnes. The installation of steam tubes around 1850 made possible a more reproducible drying process. The latter meant a switch from convective drying to contact drying. The first drying step was followed by a postdrying step on an oast and a milling step. The practice of manufacturing the red dye from madder was stopped around 1900 because in 1868, Gräbe and Liebermann discovered the synthesis of alizarine from anthracene, and alizarine could replace the red madder dye.

In general, contact drying in steam-heated rotary dryers began in 1830. The development of convective drying began in 1890 when cheap electromotors to drive air fans became available. Spray drying began between 1920 and 1930. Freeze-drying dates back to 1935, and microwave drying was introduced in 1955.

REFERENCES


In the early stages of investigating a drying problem, attention should be given to the entire manufacturing process. This holistic approach may yield one of the following conclusions:

1. The dried product can have a certain residual moisture content.
2. The dewatering step can be optimized.
3. It is possible to simplify the drying step via a process change.
4. The drying step can be combined with one or more other process steps.
5. It is possible to remove the water by a nonthermal method.
6. The drying step can be avoided by changing the process.
7. The product is not dried, whereas the process is not changed.

These seven options are examined below in greater detail.

2.1 RESIDUAL MOISTURE

To dry a product to a very low moisture content often requires a great deal of energy; however, it is sometimes sufficient to dry a product to a specific moisture content before selling it. This would reduce energy costs, and it would be advantageous that more product be sold at the same raw material cost. This option can be useful in combination with a reliable in-plant continuous moisture-monitoring system.
10 DRYING AS PART OF THE OVERALL PROCESS

2.2 OPTIMIZATION OF THE DEWATERING STEP

Before drying, it is generally advantageous to remove as much water as possible by filtration or centrifugation. Centrifugation is in this respect in principle more effective than filtration, but it cannot always be used. Due to the centrifugal force, centrifuge cakes may become impermeable.

Example 2.1 The strong fiber Twaron (trade name of Teijin Twaron) is obtained by spinning a solution of the p-aramid polymer poly(p-phenyleneterephthaloylamide) (PPTA) in concentrated sulfuric acid. On spinning, the aramid molecules are arranged in parallel, which confers strength to the yarn through hydrogen bridges. The polymerization of terephthaloyldichloride and \( p \)-phenylenediamine to PPTA precedes this step. Prior to the dissolution in concentrated sulfuric acid, the polymer crumb is recovered from an aqueous slurry and dried. Initially, dewatering was carried out using a belt filter to produce an intermediate product containing 6.5 kg of water per kilogram of PPTA. In the 1990s the belt filter was replaced by a filter press, producing an intermediate product containing 2 kg of water per kilogram of PPTA.

Example 2.2 Another example of optimization of the dewatering step is that of the leaching of a cake in a liquid–solid separation system at an elevated temperature, which causes a reduction in the viscosity of the adhering liquid and hence leads to more efficient dewatering. This goal can be achieved by, for example, the use of steam in a leaching stage. A dramatic effect in the sugar industry has been described [1]: (1) leaching with cold water yields a sugar cake at 40°C containing about 2% water by weight; (2) treatment with steam results in a sugar cake at 80°C containing about 0.6% water by weight, with the additional benefit that further water loss occurs on the way to the dryer, so that the cake arrives at the dryer containing only 0.2 to 0.3% water by weight. Simons and Dahlstrom [2] reported moisture reductions by steam dewatering exceeding 60% for permeable filter cakes (a crystalline inorganic chemical with 50% by weight > 200 μm and a narrow size distribution). However, impermeable filter cakes cannot readily be dewatered further.

2.3 PROCESS CHANGES TO SIMPLIFY DRYING

Drying can often be simplified by increasing the particle size in the dryer feed. Various techniques, which are covered briefly below, can be used for particle-size enlargement. More detailed information may be found in standard textbooks on crystallization and precipitation (e.g., [3]).

The solubility of the material in the solvent affects the particle size. Materials that have moderate solubility in the solvent system being utilized (e.g., 1 to 30% by weight) are generally obtained in a coarse form with a weight-average particle size of 0.2 to 2 mm. This finding can be explained qualitatively since a small
supersaturation/solubility ratio tends to lead to large crystals. For example, this behavior is found in sodium chloride, potassium chloride, and sugar.

Materials having a solubility of less than about 0.1% by weight tend to be obtained as small particles; for example, on precipitation, gypsum has a weight-average particle size in the range 1 to 100 μm. Particles in the size range 0.2 to 2 mm generally contain 1 to 5% moisture by weight on entering a dryer, whereas smaller particles may retain up to 30 to 40% by weight when discharged from a filter or centrifuge.

Particle size can be increased by changing the solubility of the dissolved material, by changing the solvent or pH, or by increasing the temperature, slurry density, or residence time of the crystallization process. Generally, a decrease in the system velocities of a crystallizer increases the average particle size.

**Example 2.3** An organic acid is produced from an organic salt via acidification, which is followed immediately by precipitation. Process research showed that a good yield was obtained at pH 1.8; however, after filtration the precipitate had a moisture content of up to 40% by weight. On adjusting the pH to 2.3, the precipitate had a moisture content of 20 to 25% by weight, due to a different crystal modification; however, the yield was unsatisfactory. A plant design comprising two continuous-stirred tank reactors in series was chosen. The pH is adjusted to 2.3 in the first reactor, whereas pH 1.8 is selected for the second reactor. The bulk of the product is produced in the first reactor and has good filtration characteristics. The second reactor increases the yield while the good filtration characteristics are retained.

**Example 2.4** Vacuum-pan salt is produced in multiple-effect evaporation plants. Modern salt plants contain crystallizers consisting of three main parts: vapor separator, heater, and pump. The three parts are connected by lines through which a salt slurry circulates. It is also possible to integrate these three parts into one piece of equipment. Plant measurements showed that the first type of crystallizer produces vacuum-pan salt having an average particle size of 450 μm, whereas the second type of crystallizer produces vacuum-pan salt having an average particle size of 650 μm. The difference is caused by the different pump tip velocities and velocities in the heater tubes, being 20 and 2 m·s⁻¹ in the first case and 10 and 1 m·s⁻¹ in the second case.

Combinations of more than one of the parameters cited above can also be used to achieve a desired particle-size distribution. Seeding the crystallizer contents can also increase the particle size. This procedure is applicable to systems that do not nucleate readily because of high viscosity, for example. Up to a certain level, supersaturation increases, at which point many nuclei may be produced. Seeding is practiced to prevent this, in sugar crystallization, for example. Seeding a crystallizer containing a material that nucleates readily (e.g., sodium chloride) can achieve a particle-size decrease.

Sometimes, because of product specification, it is not desirable to alter the average particle size; for example, rapid dissolution or proper dispersion of a product may require a small particle size. The average particle size and particle-size distribution
are not the only factors that influence the moisture-retaining properties of materials; the particle shape (habit) and the specific area can also have a significant influence.

It is also possible to influence the process at the point where the particulate material is formed by replacing conventional crystallization (precipitation), liquid–solid separation, and drying by drum-drying or spray-drying systems. Two possible routes for the processing of clay tile-body suspension in water have been given [4]: (1) filter press–dryer–granulating unit–tile presses, and (2) spray dryer–tile presses. Spray drying and drum drying do not lead to the problem of having to dispose of an impure mother liquor.

The product as produced in a crystallizer or precipitator can be accepted, and an additional step can be introduced prior to liquid–solid separation and drying. Solids with a melting point of less than 100°C can be liquefied by the injection of live steam (i.e., the system is changed from a liquid–solid one to a liquid–liquid one). Subsequent cooling will lead to solidification and, if carried out correctly, can result in a particle-size increase. This process is termed melt granulation.

2.4 COMBINATION OF DRYING AND OTHER PROCESS STEPS

Since many possibilities exist in this category, drying can thus be combined with a chemical reaction, evaporation, mechanical liquid–solid separation, particle-size enlargement, and several other operations.

Example 2.5  The Solvay process is widely used for the manufacture of sodium carbonate (soda). Sodium bicarbonate is an intermediate particulate product separated from the mother liquor by rotary vacuum filters in which the crystals are also leached with water. Centrifuges are also used. The cake from the filters contains about 14% water by weight, whereas from the centrifuges it typically contains about 8%. Calcining of the bicarbonate to soda and drying take place in a single indirectly heated rotary-drum calciner, with the drying preceding the calcining.

$$2\text{NaHCO}_3 \rightarrow \text{CO}_2 \uparrow + \text{H}_2\text{O} \uparrow + \text{Na}_2\text{CO}_3$$

Carbon dioxide is recycled after compression, and steam is generally used as the heating medium. The hot soda ash (ca. 200°C) is cooled, screened, and packaged or shipped in bulk. The product is called light ash because of its low bulk density.

Example 2.6  During the manufacture of potato chips, potatoes are peeled, sliced, and washed in 60°C water. The wet slices are then added to 160°C oil, and curing and drying occur in one step. Salt and spices are added before packaging.

Example 2.7  It is possible to combine liquid–solid separation, leaching, and drying in a single unit that functions batchwise. Such a step is used if, for example, it is desirable to protect the operators from dust. The slurry is pumped to the equipment and the dry solids are discharged at the end of the cycle.
2.4 COMBINATION OF DRYING AND OTHER PROCESS STEPS

In the case of a filter–dryer, the equipment comprises a closed Nutsche-type vacuum filter with options (see Figs. 2.1 and 2.2). A typical cycle is made up of (1) feeding the slurry to the filter, (2) mother liquor removal, (3) leaching (displacement or reslurry), (4) smoothing and compressing the cake to remove liquid, (5) drying (indirect heat transfer, vacuum), and (6) discharge. For further treatment, see Section 11.1.

In the case of a centrifuge–dryer, the equipment consists of a closed filtering centrifuge with options (see Fig. 2.3). A typical cycle consists of (1) feeding the slurry to the centrifuge, (2) mother liquor removal, (3) leaching, (4) breaking up the centrifuge cake by nitrogen or air pressure, (5) convective drying by nitrogen or air circulation, and (6) discharge.

The filter–dryer and the centrifuge–dryer are described in more detail in Chapters 11 and 9, respectively. Possible applications of these pieces of equipment include the automation of existing processes, processing light-sensitive materials, solvent recovery, and handling toxic materials.
Figure 2.2 Vacuum drying step in a closed filter–dryer. (Courtesy of Rosenmund VTA AG, Liestal, Switzerland.)
2.5 NONTHERMAL DRYING

Reference to spray drying and drum drying was made in Section 2.3. With the use of this equipment, evaporation, crystallization, liquid–solid separation, and drying can be combined. The combination is also possible in a thin-film evaporator (see Fig. 2.4). The choice of such a system may not be energetically preferable; however, it can be the best choice if conventional crystallization, liquid–solid separation, and drying are complicated or impossible, or if the resulting product has favorable properties (e.g., the rapid dissolution of spray-dried coffee powder, in which the formed particles appear as hollow spheres).

2.5 NONTHERMAL DRYING

As a general rule, moisture that can be removed mechanically should not be removed thermally. The mechanical removal of moisture is not considered in this section, but physical absorption and chemical reaction, the two principal nonthermal methods for moisture removal, are.

Example 2.8 An inorganic hydrate containing a small percentage of moisture leaves a centrifuge. The material can be admixed in a screw conveyor with a small amount of a lower hydrate that picks up the water and is itself converted to the higher hydrate.

\[ x \cdot aH_2O + bH_2O \rightarrow x \cdot (a + b)H_2O \]

The nonthermal drying of centrifuged soda decahydrate by admixing it with a small amount of anhydrous soda is an application. \( x \) stands for a chemical compound.
Example 2.9  In casting operations for certain pottery objects, such as teapots, gypsum molds are used to dewater a clay stream (slip) in order to produce an article in the correct physical form. The slip typically contains 30 to 40% water by weight. Additives allow the concentrated slurry to flow. A porous gypsum mold absorbs the water and must be dried before it can be reused. After 10 to 20 cycles, the pores of the mold are plugged and it cannot be regenerated further.

Example 2.10  Williams-Gardner has described the use of starch molds for the shaping of confections [4]. Some of the water in the syrup containing dissolved material is absorbed to accomplish product shaping.