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Drying and Storage of Grains and Oilseeds

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TABLE 1-4 Percentage of Corn Harvesting and Drying Techniques Employed in the Eighties in the State of Indiana

	1984	1986
Harvesting		
Shelled w/combine	92.3	91.8
Shelled w/picker sheller	1.2	2.4
On ear	6.2	5.3
Drying (corn stored on farms)		
None	6.1	10.1
On-farm	93.9	89.2
Off-farm	0.0	0.7

Source: Indiana Agricultural Statistics (1986).

the United States is harvested with combines and is dried on farms. Less than 5% is dried at local elevators or terminals; typical is the harvesting and drying data in Table 1-4 for the state of Indiana. In some countries (e.g., France) the situation is reversed, as most of the drying takes place at the elevator level. In the Third World, the bulk of the grain is still dried by spreading the wet grain in thin layers on the ground in the open air to be dried by the sun.

On-Farm Drying

On-farm dryers fall into three categories: bin, non-bin, and combination dryers. Bin dryers are, in general, low-capacity, low-temperature systems, able to produce excellent quality grain. Non-bin dryers, the most popular dryer type in the United States, are high-capacity, high-temperature

TABLE 1-5 Percentage of On-Farm Dryer Types Used in Drying Farm-Stored Corn in the State of Indiana in the Eighties

Dryer Type	1985	1986
Batch dryer	24.7	25.9
Continuous-flow dryer	27.9	29.4
Batch-in-bin dryer	9.4	9.4
Continuous-flow bin dryer	13.2	10.2
Bin dryer with stirrers	24.8	25.1

Source: Indiana Agricultural Statistics (1986).

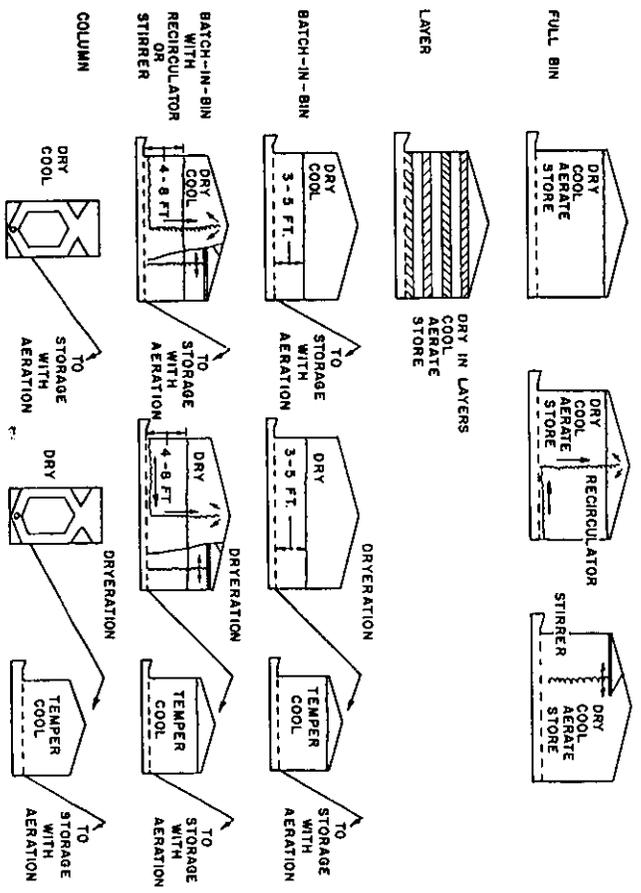


FIGURE 1-4. On-farm grain drying systems.

systems that frequently overheat and overdry the grain, thereby causing grain quality deterioration. Combination drying uses the non-bin high-temperature dryer to dry the grain from its harvest moisture content to 16-20% moisture and completes the drying process with in-bin drying. Combination drying has the advantages of both systems (i.e., high capacity and high quality), but requires additional investment and is logistically more complicated.

On-farm dryers are generally considered to have a throughput of less than 12.5 tonnes (500 bushels) per hour. Table 1-5 lists the most common on-farm dryer types used in the Midwest. Figure 1-4 illustrates the common on-farm grain drying systems.

Off-Farm Drying

Off-farm or elevator grain dryers are high-capacity, high-temperature units that fall into three categories: crossflow, concurrent flow, and mixed flow. Crossflow models dry grain nonuniformly, causing considerable stress cracking of the grain kernels. Mixed-flow dryers dry the grain more uniformly; the dried grain is usually of higher quality than that dried in crossflow models. Concurrent-flow dryers have counterflow coolers and

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Grain Structure, Composition, and Properties

A knowledge of the structure, composition, and property values is useful in understanding the drying and storage characteristics of grains. The kernel structure may affect the drying rate; an example is the rapid loss of moisture from a corn kernel of which the tip cap is broken off. The kernel composition may influence the moisture adsorption characteristics; the low moisture equilibrium content of a high-fat-content grain such as soybeans is an example. Finally, a kernel property may control the airflow resistance; an example is the effect of grain bed porosity on the pressure drop through a layer of grain.

Cereal grains belong to the grass family, each member of which produces fruits in the form of kernels. The kernel or caryopsis is surrounded by a hull. The major parts of the kernel are the endosperm, the germ (embryo), and the pericarp. Detailed information on wheat, rice, and corn can be found in Pomeranz (1988), Juliano (1985), and Watson and Ramstad (1987), respectively. In the threshing process, the hulls are separated from the naked seeds, such as wheat and corn, but not from rice, a covered seed. The presence of a hull affects (slows down) the drying rate of a grain kernel.

The structure, composition, and properties of the three major grains—wheat, corn, and rice—are presented in this chapter. Longitudinal cross sections are shown in Figures 2-1, 2-2, and 2-3.

GRAIN STRUCTURE

Data on dimensions and weights are tabulated in Table 2-1; the weight proportions of the principal parts of each grain are shown in Table 2-2.

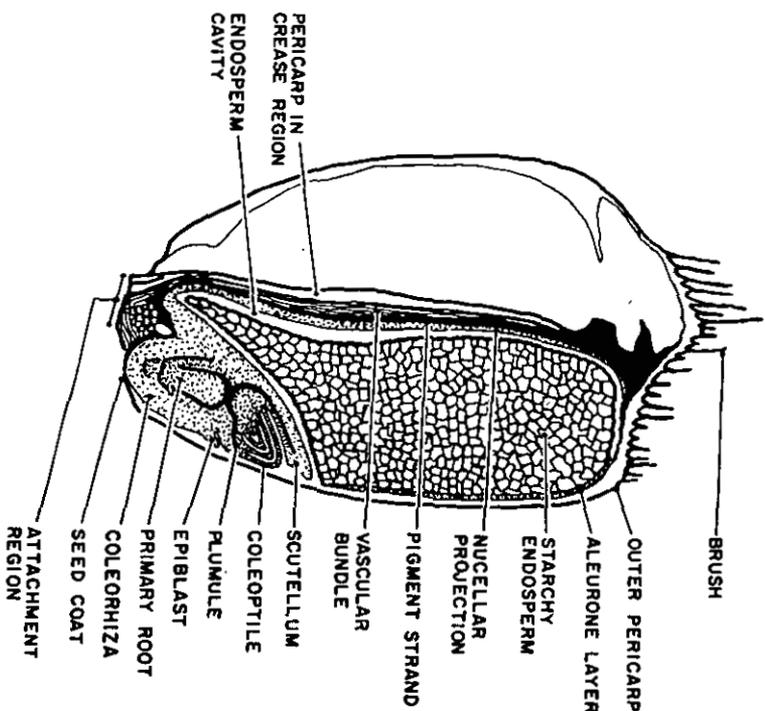


FIGURE 2-1. Cross section of a wheat kernel.

Wheat kernels are 5–8 mm in length and weigh 30–45 mg; for drying calculations, the equivalent spherical diameter is 3.7–4.5 mm. Although wheat varieties differ in hardness (and in color), there is little difference in drying rate. The pericarp of wheat is removed in the milling process along with the outer endosperm (or aleurone) layer; the removed portion is called bran and constitutes 13–15% of the weight of the wheat kernel. The germ is also extracted during milling; it is 2–3% of the kernel in weight. The endosperm forms 82–85% of the kernel, and is the major end product of a wheat flour mill (see Chap. 5).

Corn kernels are 8–17 mm in length and weigh 150–600 mg; the equivalent spherical diameter is 7.8–9.8 mm. There is a significant difference in drying rate among different varieties and hybrids. In addition to the pericarp, germ, and endosperm, corn kernels contain a tip cap; the tip cap is often separated from the kernels during the shelling process. The pericarp of corn is removed in the dry-milling process along with the

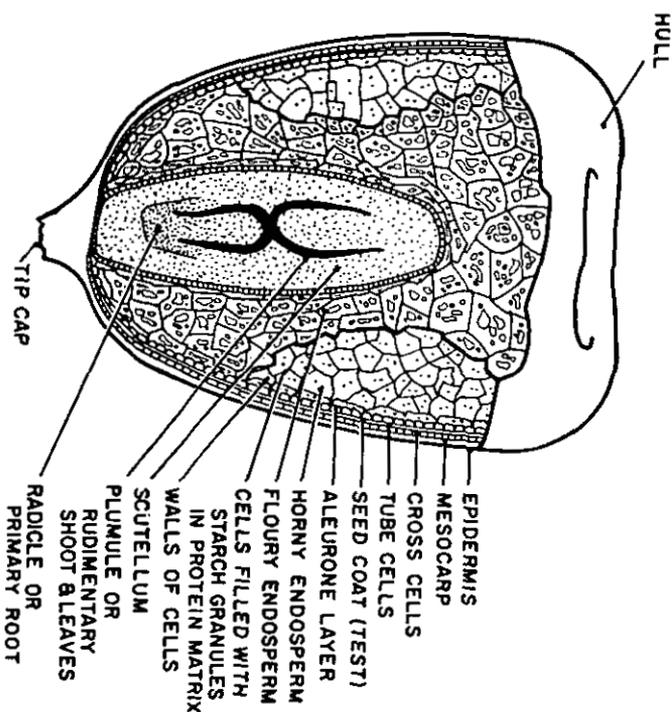


FIGURE 2-2. Cross section of a corn kernel.

aleurone layer; they constitute about 5–7% of the weight. The germ, which is also extracted during dry milling, makes up about 10–12% of the corn kernel. The endosperm of the corn forms 82–84% of the weight of corn; rather than corn flour, grits is the major endosperm product of a corn dry-milling plant. The dry milling and wet milling of corn are discussed in detail in Chapter 5.

TABLE 2-1 Dimensions and Weights of Corn, Rice, and Wheat*

	Length (mm)	Width (mm)	Equiv. Diam. (mm)	Kernel Weight (mg)
Corn	8–17	5–15	7.8–9.8	150–600
Rice (paddy)	5–10	1.5–5	4.2–4.6	23–27
Wheat	5–8	2.5–4.5	3.7–4.5	30–45

Source: Data from Y. Pomeranz, 1981. Composition of cereal grains. In *CRC Handbook of Transportation and Marketing in Agriculture*, vol. 2, Field Crops, Essex E. Finney, Jr., ed. CRC Press, Boca Raton, FL; copyright © 1981 by CRC Press.
* At 12–15% moisture content (w.b.).

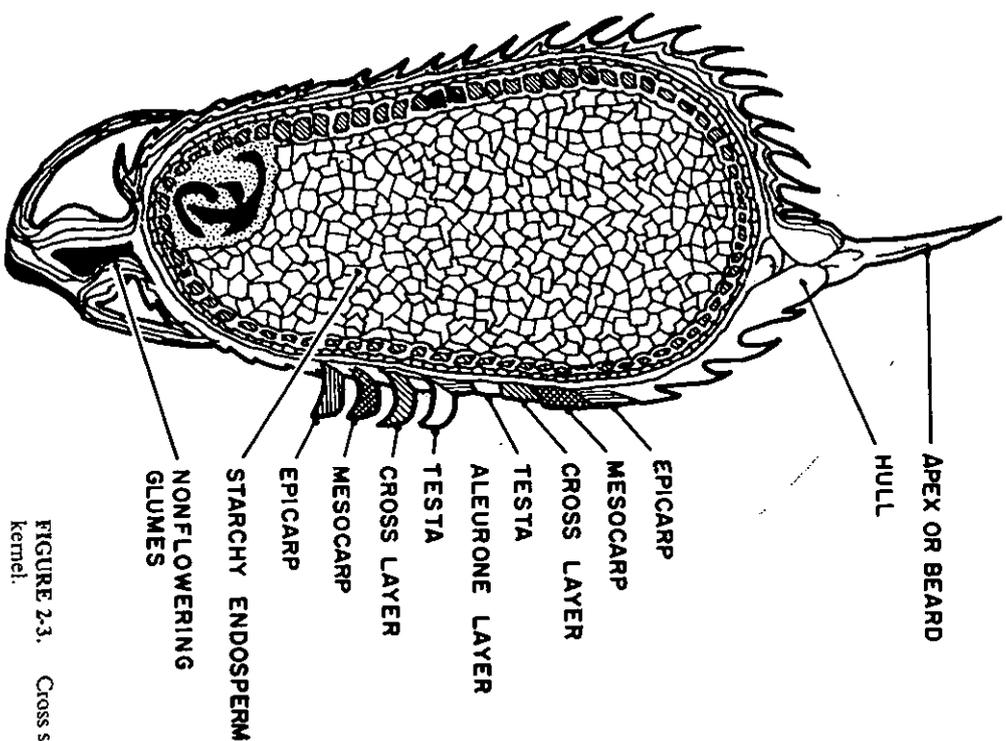


FIGURE 2-3. Cross section of a rice kernel.

Rice kernels with attached hulls (so-called paddy or rough rice) are 5–10 mm in length and weigh 23–27 mg; the equivalent spherical diameter is 4.2–4.6 mm. Three types of rice are grown worldwide: long-grain, medium grain, and short-grain. The classification is based on the length-to-width ratio of the kernels (see Chap. 11). The physical data for rice in Table 2-1 constitute the values for a typical medium-grain variety. A paddy rice kernel is made up of the hull (about 20% in weight) and the brown rice kernel (i.e., the rice kernel without the hull). The pericarp

TABLE 2-2 Weight Proportions of Principal Parts of Corn, Rice, and Wheat

	Pericarp ^a (%)	Germ (%)	Endosperm (%)
Corn	5-7	10-12	82-84
Rice (brown)	5-7	3-4	89-92
Wheat	13-15	2-3	82-85

Source: Data from Y. Pomeranz, 1981. Composition of cereal grains. In *CRC Handbook of Transportation and Marketing in Agriculture*, vol. 2. Field Crops, Essex E. Finney, Jr., ed. CRC Press, Boca Raton, FL, copyright © 1981 by CRC Press.

^aIncludes the aleurone layer.

comprises 5–7% of brown rice; it is removed during the milling process in order to produce white rice. The endosperm and germ together constitute 93–95% of brown rice.

The weight, dimensions, and structure of wheat, corn, and rice affect their drying behavior. Individual corn kernels dry slowest due to their large weight and equivalent spherical diameter, but wheat kernels reach the highest equilibrium moisture content because of their low percentage of germ tissue. The bulk density of paddy rice is significantly lower than that of corn and wheat; therefore, the grain velocity of paddy rice through a grain dryer is larger than that of corn and wheat at constant dryer throughput. Thus, it is important for the dryer designer or operator to recognize the importance of the data in Tables 2-1 and 2-2.

GRAIN COMPOSITION

The chemical composition of corn, rice (brown), and wheat at 14% moisture content is given in Table 2-3. Wheat and corn contain approximately 10% protein, rice about 7%. Corn has a fat content of about 5%,

TABLE 2-3 Chemical Composition of Corn, Rice, and Wheat^a

	Protein (%)	Fat (%)	Starch (%)	Fiber (%)
Corn	9.8	4.9	63.6	2.0
Rice (brown)	7.3	2.2	64.3	0.8
Wheat	10.6	1.9	69.7	1.0

Source: Reprinted with permission from Rice: *Chemistry and Technology*, B. O. Juliano, ed. Am. Assoc. Cereal Chemists, St. Paul, MN.

^aAt 14% moisture content (w.b.).

TABLE 2-4 Moisture Contents (% w.b.) for Corn, Rice, and Wheat at Harvest and for Safe Storage

Cereal	Maximum Harvest Moisture	Optimum Harvest Moisture	Storage	
			6-12 months	Over 1 year
Corn	25	23	14.5	13
Rice (paddy)	38	22	14	13
Wheat	20	18	14	13

wheat and rice contain close to 2%. The starch content of the three grains is similar, between 64% and 70%, with their fiber content between 0.8% and 2.0%.

The three major grains are usually harvested at moistures between 18% and 35% (w.b.). As the data in Table 2-4 show, the proper moisture content of corn, wheat, and rice for storage is about 14%. For long-term storage of over one year, somewhat lower moistures are recommended to prevent mold growth. For short-term storage of 1-3 months, the moisture contents can be slightly higher.

The maximal and optimal moisture contents of the three grains at harvest are also tabulated in Table 2-4. Corn is usually harvested at considerably higher moisture contents than wheat, especially at higher latitudes; in the northern Corn Belt of the United States, corn is frequently at 30-35% moisture at the time of harvest. In Eastern Europe, corn is harvested at 35-45% moisture. It is advantageous to harvest a crop close to the optimal moisture content in order to minimize kernel damage during harvesting and fuel consumption during drying.

At the time of harvest the moisture content distribution in the grain kernels is not uniform. This is illustrated in Table 2-5 for corn. At an average whole-kernel moisture content of 36.0% (w.b.), the germ contains 48.2% water and the endosperm contains only 30.7%.

TABLE 2-5 Moisture Distribution in a Freshly Harvested Corn Kernel

Kernel Part	MC (% w.b.)
Whole kernel	36.0
Germ	48.2
Endosperm	30.7
Pericarp	52.6

Source: Rossmann (1949).

During the drying process, moisture leaves the grain kernels mainly through the region around the germ; only a small amount of moisture diffuses through the pericarp (Nagato et al. 1964). Therefore, cracked and broken grain kernels dry more rapidly than sound kernels.

GRAIN PROPERTIES

Several physical properties of corn, rice, and wheat are tabulated in Table 2-6. Each property has a significant effect on the drying rate of single grain kernels or a bed of grain kernels.

The bulk density of grain determines the bin volume required to store a certain mass of grain. The grain velocity in a continuous-flow grain dryer at a certain capacity is also affected by the bulk density of the grain. Wheat has the highest bulk density, rice the lowest.

The 1,000-kernel weight of corn is about an order of magnitude larger than that of rice and wheat. This translates to a lower drying rate for corn than for rice and wheat kernels.

The void space in a mass of grain is expressed as a percentage of the total volume of the grain, and is called the porosity. The range of porosity of the three grains, 40-48%, is typical of cereal grains. Resistance of bulk grain to airflow is, in part, a function of the porosity and the kernel size.

The specific heat expresses the energy required by a unit mass of grain to increase in temperature by 1°. Of the three grains, corn requires the most energy to reach the desired temperature at which the optimal evaporation rate of water occurs.

TABLE 2-6 Physical Properties of Corn, Paddy Rice, and Wheat at 12-16% Moisture Content (w.b.)

Property	Corn	Rice	Wheat
Bulk density (kg/m ³) (lb/ft ³)	745 46.5	590 36.8	805 50.3
1000-Kernel weight (g) (lb)	325 0.72	27 0.06	32 0.07
Porosity (%)	40	48	41
Specific heat (kJ/kg · °C) (Btu/lb · °F)	2.01 0.48	1.51 0.36	1.67 0.40
Conductivity (W/m · °C) (Btu/hr · ft · °F)	0.159 0.092	0.106 0.061	0.137 0.079
Repose angle (deg)	35	36	31
Sp. surface area (m ² /m ³) (ft ² /ft ³)	784 238	1132 345	1181 360

Source: Brooker et al. (1974).

The conductivity (also called the thermal conductivity) is a measure of the resistance to the conduction of thermal energy (heat) within individual grain kernels. In grain with high conductivity, the thermal gradients in the kernels disappear faster during drying than in equal sized kernels of another grain with lower conductivity.

The angle of repose determines the maximum angle of a pile of grain with the horizontal plane. It is important in the filling of a flat storage facility when grain is not piled at a uniform bed depth but rather is peaked.

The specific surface area refers to the kernel surface area per unit volume of grain that exchanges energy and moisture with the air during the drying process. Thus, for equal volumes, there is more heat and mass transfer area for wheat and rice than for corn.

Properties of grains other than corn, rice, and wheat are contained in Appendix D.

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3

Drying-Air Properties

The drying medium used in drying cereal grains is moist air, which is a mixture of dry air and water vapor. Dry air consists of a number of gases, mainly oxygen and nitrogen plus minor components such as argon, carbon dioxide, and neon. Goff (1949), in determining the thermodynamic properties of moist air, arbitrarily defined dry air as a gaseous mixture with a molecular weight of 28.966 and a mole fraction composition of 0.2095 oxygen, 0.7809 nitrogen, 0.0093 argon, and 0.0003 carbon dioxide. Dry air may vary slightly from these proportions at a given location; however, the Goff figures are sufficiently accurate for engineering calculations.

In addition to the dry-air gases, moist air contains a varying amount of water vapor. Although the weight fraction of water vapor in the air used for grain drying is always less than one tenth, the presence of water vapor molecules has a profound effect on the drying process. Several terms are used to express the amount of water vapor in moist air. These and other thermodynamic terms employed in describing moist-air properties are defined in the following section.

DEFINITION OF PSYCHROMETRIC TERMS*

Three humidity terms are used in the grain drying literature to describe the amount of water vapor held in the drying air: vapor pressure, relative humidity, and humidity ratio. The temperatures of moist air may refer to the dry-bulb, dew point, or wet-bulb temperatures. Two additional moist-

* An explanation of symbols used appears at the end of the chapter.

Waite, P. J. and C. J. Bern. 1987. Wet-bulb temperature and wet-bulb depressions in the United States and Southern Canada. *Trans. ASAE* 30: 1827-1832.

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10

High-Capacity Grain-Drying Systems

In the previous chapter, low-capacity grain drying systems were discussed; they are mostly in-bin, low-temperature systems. This chapter covers high-capacity grain dryers; the majority of these systems are of the continuous-flow, high-temperature type. Both off-farm and on-farm high-capacity dryers are considered.

High-capacity dryers employ high drying-air temperatures. Depending on the dryer type, the crop to be dried, and the grain quality requirements, the air temperature varies from 50°C to 300°C (122-572°F). In general, the specific energy consumption of a grain dryer decreases with an increase in the temperature of the inlet air and with an increase in the relative humidity of the exhaust air. This phenomenon is illustrated in Figure 10-1, in which the specific energy requirement of the adiabatic drying process is plotted against the drying-air temperature for different air exhaust relative humidities; the initial conditions of the air in the diagram are 10°C and 80% relative humidity. The specific energy requirement is defined as the sum of the fuel and electric energy needed in a particular dryer (or drying system) to evaporate a unit quantity of water. It is usually expressed in megajoules per kilogram of water (MJ/kg) or in British thermal units per pound of water (Btu/lb).

Figure 10-1 quantifies the effect of the relative humidity of the exhaust air on the energy requirement of grain drying. As the drying-air temperature is increased from 120°C (248°F) to 200°C (392°F) and above, the effect of the degree of saturation of the exhaust air on the energy consumption is greatly diminished. For grain dryers operating in the 50-200°C (122-392°F) range, the specific energy requirement can be expected to fall between 3.0 MJ/kg and 10.0 MJ/kg (1,290-4,299 Btu/lb). This

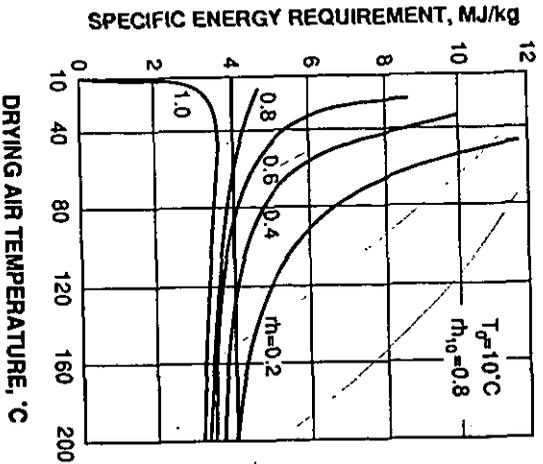


FIGURE 10-1. The effect of drying-air temperature and exhaust air relative humidity on the specific energy requirement of the grain drying process (ambient air conditions are 10°C and 80% RH). (From Isaacs and Mühlbauer, 1975.)

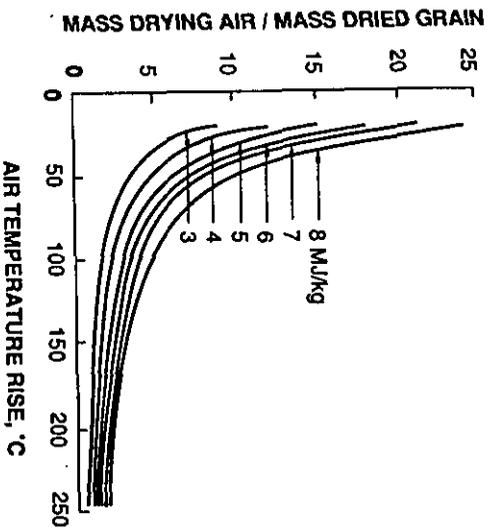


FIGURE 10-2. The effect of drying-air temperature and specific energy consumption on the mass of air required to dry a unit mass of grain from 20% to 15% (w.b.). (From Isaacs and Mühlbauer, 1975.)

compares with a value of 2.45 MJ/kg (1,053 Btu/lb) for the evaporation of pure water at 100°C (212°F).

As the temperature of air rises, it can absorb more moisture. Thus, the required airflow rate per unit mass of grain is less for high-temperature than for low-temperature grain dryers. This is shown in Figure 10-2 in which the ratio of the mass of drying air to the mass of dried grain is plotted versus the air temperature for different specific energy requirement values. A lower airflow rate is advantageous because it reduces the size of the fan motor and limits the air pollution.

Figures 10-1 and 10-2 show that it is cost-efficient to operate high-capacity grain dryers at the highest temperature and the lowest airflow rate commensurate with the maintainance of grain quality. Since the grain quality requirements depend on the utilization of the grain, the optimal temperature-airflow settings of high-capacity dryers differ for seed grain, food grain, and feed grain dryers.

OFF-FARM SYSTEMS

Various high-temperature dryers are employed in the grain industry. The recommended air temperatures and airflow rates vary among dryer types. The basic off-farm continuous-flow dryer designs are (1) crossflow, (2) concurrent-flow, (3) counterflow, (4) mixed-flow, (5) rotary, (6) fluidized-bed, and (7) spouted-bed. The first four types are discussed in detail because of their commercial importance. The last three are summarized more briefly because they are at present employed only to a limited extent in the grain industry.

The four major continuous-flow grain drying systems—crossflow, concurrent-flow, counterflow, and mixed-flow—are classified by the relative direction of the grain and air movement through the dryer. Each is illustrated in Figure 10-3; the moisture and grain temperature distributions of each dryer type are shown in Figure 10-4. The air and grain move in perpendicular directions in crossflow dryers, in parallel directions in concurrent-flow dryers, and in opposite directions in counterflow dryers. The flow of the air and grain in mixed-flow dryers is a combination of crossflow, concurrent-flow, and counterflow.

Each continuous-flow grain dryer is supplied with a cooling section in which the hot, dried grain is cooled to within 5°C (9°F) of the ambient dry-bulb temperature. During the cooling process, 0.5–1.0% of moisture is removed, depending mainly on the retention time of the grain in the cooler. In a standard design, the grain remains in the drying section about twice as long as in the cooling section of the dryer. The relative directions of the grain and the air in the drying and cooling sections is the same in

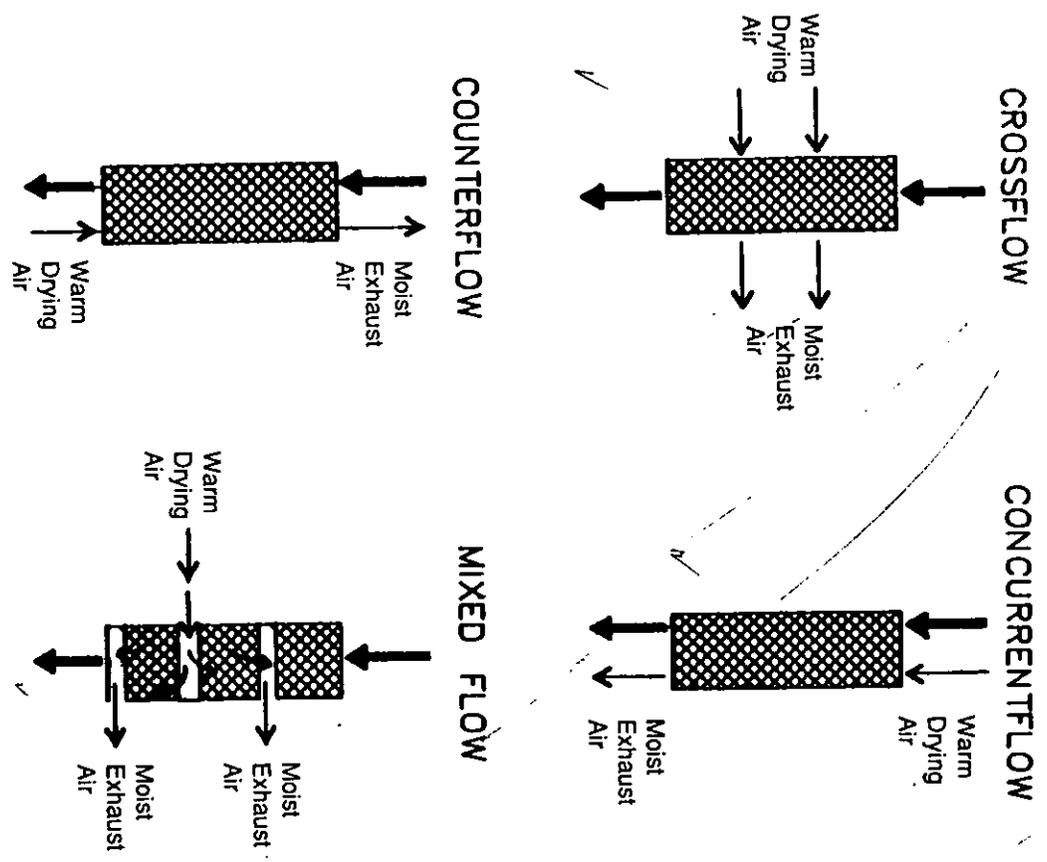


FIGURE 10-3. Schematics of the four major types of high-temperature grain dryers: crossflow, concurrent-flow, counterflow, and mixed flow.

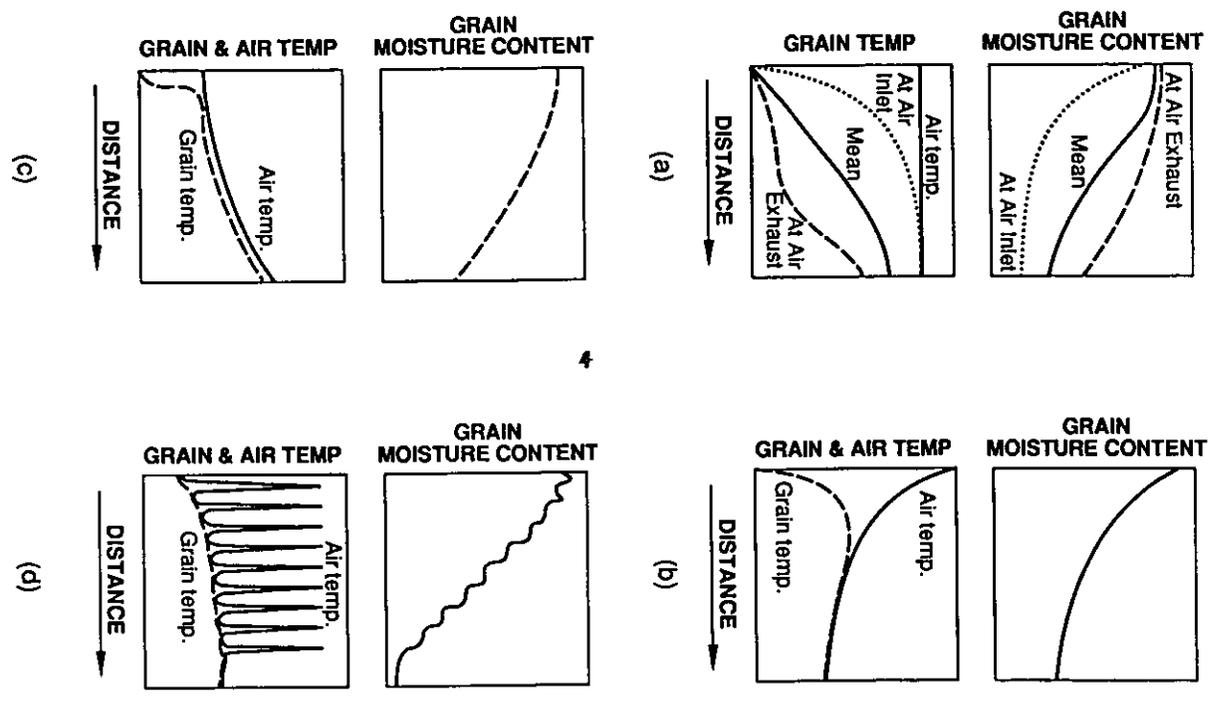


FIGURE 10-4. Moisture and temperature changes during: (a) crossflow drying; (b) concurrent-flow drying; (c) counterflow drying; and (d) mixed-flow drying.

the major dryer types except in concurrent-flow dryers (in which the grain is cooled by counterflow).

In the United States, the crossflow dryer is the most prevalent high-temperature continuous-flow type; elsewhere in the world, the mixed-flow dryer is more common. The concurrent-flow dryer is a recent design; counterflow is mainly used for the cooling of grain, and drying with the in-bin continuous flow dryer (see Chap. 9).

Crossflow Dryers

Figure 10-5 is a schematic of a conventional continuous-flow crossflow grain dryer. The grain flows by gravity from a wet-holding bin into the drying zone consisting of one or several screened grain columns; heated drying air is forced perpendicularly from the air plenum through the grain in the columns. A similar process occurs in the cooling section where ambient air is employed. The thickness of the grain columns is 0.25–0.45 m (0.8–1.5 ft); the length of the grain columns in the drying section is 3–30 m (9–100 ft), and in the cooling section about 1–10 m (3–30 ft).

The drying-air temperatures depend on the grain to be dried and on the grain quality requirements. Typically for food grains, the temperature ranges between 60°C and 75°C (140–165°F), for feed grains between 80°C–110°C (180–230°F).

Two fans are employed in a conventional crossflow dryer: a heating fan and a cooling fan. The air from both fans passes through the grain and is exhausted directly to the atmosphere. The drying and cooling airflow rates range from 15 m³ to 30 m³ air/min·m² screen area (50–100 cfm/ft²) or 83–140 m³/min·tonne (75–125 cfm/bu). The static pressures are a relatively low 0.5–1.2 kPa (2–5 in. H₂O).

The grain velocity in the grain columns, and thus the retention time of the grain in a crossflow dryer, is controlled by the revolutions per minute (rpm) of the unloading or discharge augers. The grain velocity and the retention time depend on the initial moisture content of the grain, the drying-air temperature and airflow rate, and the dimensions of the dryer. Thus, no definite numbers can be quoted for these quantities for crossflow dryers.

The drying characteristics of the conventional crossflow dryer in the drying section are shown in Figure 10-4a; the air–grain temperatures and the grain moisture content are plotted versus location in the grain column. The curves show that the grain is dried nonuniformly; that the grain at the air inlet side of the grain column is overdried and exits from the dryer nearly at the inlet air temperature; and that the grain at the air exhaust side of the column remains well below the inlet air temperature

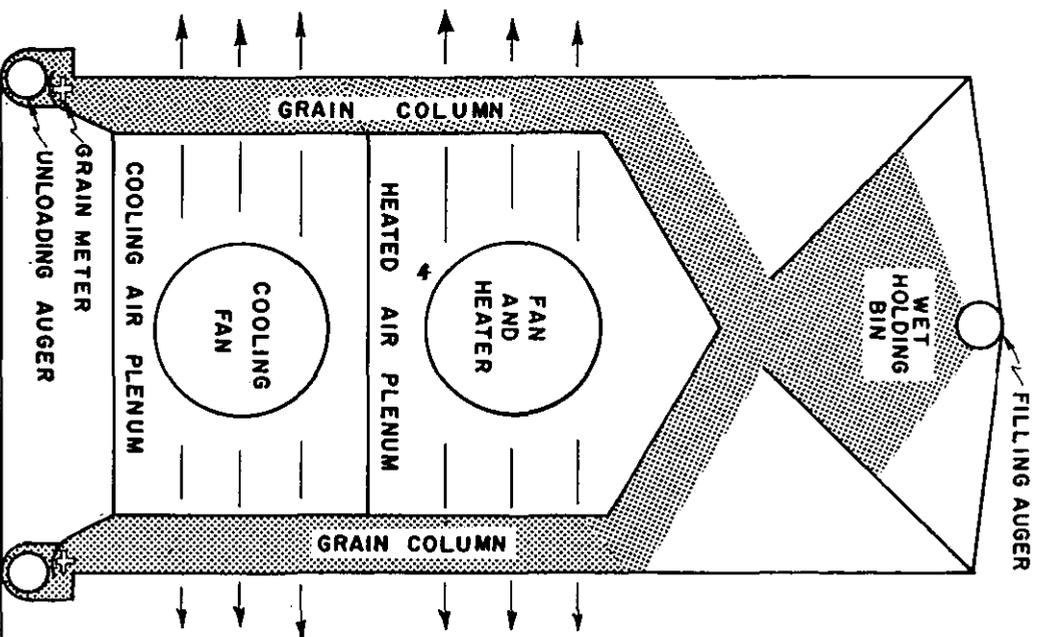


FIGURE 10-5. Conventional crossflow dryer with forced-air drying and cooling.

and is underdried. Mixing of the low-moisture–high-temperature grain with the high-moisture–low-temperature material in the unloading augers of the dryer produces grain at the desired average moisture content and temperature. As explained in Chapters 4 and 5, the mixing of the grain kernels at different moisture contents does not lead to a mixture in which all kernels equilibrate to a uniform moisture content. Crossflow-dried

TABLE 10-1 Moisture Content Gradient in Grain Columns of a Conventional Crossflow Dryer after Drying Corn from 25.5% to 16.0% (w. b.) without and with Cooling

Air Temp. °C	°F	MC Gradient	
		Without Cooling (%)	With Cooling (%)
82	180	9.7	8.6
110	230	14.2	12.2
138	280	19.4	16.6

Source: Gustafson et al. (1981).

grain always remains nonuniform in moisture content and, thus, in grain quality.

The moisture gradient in the grain columns of a conventional crossflow dryer is given in Table 10-1 for a dryer with 0.3-m- (1-ft) wide grain columns in which corn is dried from 25.5% to 16.0% (w. b.) with and without cooling. Drying at 82°C (180°F) results in a moisture content gradient of 9.7% before the cooler, and of 8.6% after the grain exits the dryer. At higher drying temperatures, the moisture gradients are even larger.

Due to the gradient in the moisture content of the grain across the grain columns of a crossflow dryer, the quality of the grain varies. This is shown in Table 10-2 for corn. The grain near the air inlet side of the columns has overdried and has greatly increased in breakage susceptibility, compared with the remaining grain in the grain column. The figures in

TABLE 10-2 Grain Temperature, Moisture Content, and Breakage Susceptibility at Different Locations in Grain Columns of a Conventional Crossflow Dryer after Drying Corn without Cooling from 25.5% to an Average of 19% (w. b.) at 110°C (230°F)

Distance from Air Inlet (cm)	Grain Temp		Moisture Content (% w. b.)	Breakage Susceptibility (%)
	°C	°F		
1.25	102	215	10	48
7.50	78	172	20	11
13.75	51	124	24	10

Source: Gustafson et al. (1981).

TABLE 10-3 Effect of the Average Final Moisture Content on Breakage Susceptibility of 25% Moisture Content (w. b.) Corn Dried in a Conventional Crossflow Dryer at 110°C (230°F)

Final Average Moisture Content (% w. b.)	Breakage Susceptibility (%)
18	11
15	18
13	27
11	39

Source: Gustafson et al. (1981).

Table 10-3 indicate the damaging effect of overdrying on the breakage susceptibility of corn.

The relative humidity of the air exhausted from a conventional crossflow dryer varies along the drying column. Near the grain inlet, the air approaches saturation. In contrast just before the grain reaches the cooling section, the drying potential of the exhaust air is still considerable due to its low relative humidity. The exhausting of low relative humidity air along part of the drying column is a major reason for the high specific energy requirement (i.e., 7–10 MJ/kg or 3,000–4,300 Btu/lb) of conventional crossflow dryers.

To offset the two major disadvantages of the conventional crossflow design, namely, the large moisture differential across the grain columns and the high specific energy requirement, a number of modified crossflow dryers have been developed. In the crossflow dryer shown in Figure 10-6, the cooling air is drawn through the grain of the cooling section and through the fan-heater combination into a heated air plenum. From there, the heated air is passed through the moist grain and is exhausted to the ambient. Thus, the crossflow dryer in Figure 10-6 has so-called reverse-airflow cooling.

The reverse-airflow design has the following characteristics:

1. Part of the sensible heat of the dried grain is reclaimed, thereby decreasing the specific energy requirement by 10–20%.
2. The ambient cooling air enters the grain column where the grain temperature is a minimum, thus minimizing the grain-air temperature difference and the resulting temperature shock and accompanying development of stress cracks of the grain.

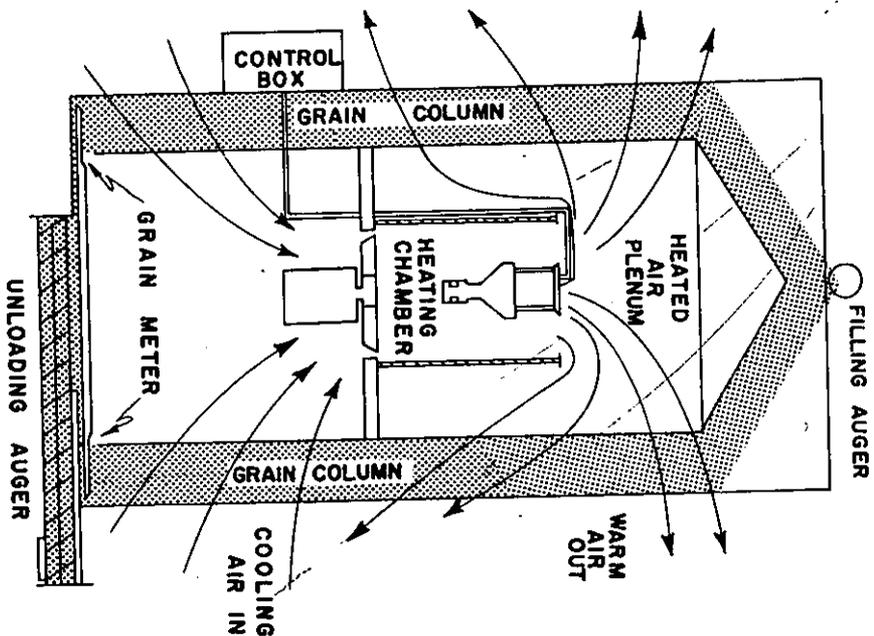


FIGURE 10-6. Modified crossflow dryer with reverse-airflow cooling.

3. A single fan creates the airflows in both the drying and the cooling sections and, thus, has to overcome the static pressures of the grain in the drying and cooling columns.
4. The chaff and fines tend to filter through the screens of the cooling columns and the fan-heater, thus accumulating in the hot-air plenum and necessitating frequent maintenance of the dryer.

Although the design feature of reverse-airflow cooling, as illustrated in Figure 10-6, decreases the moisture differential across the grain columns compared with that of the conventional crossflow design in Figure 10-5, greater improvement is sometimes required. Therefore, in some commercial-size crossflow dryers, a so-called grain exchanger (also called

TABLE 10-4 Operating Conditions of Two Crossflow Dryers Drying Corn from 25% to 15% (w. b.) at the Same Grainflow Rate; Maximum Corn Temperature 60°C (140°F)

Dryer Figures	Drying-Air Temp		Airflow Rate ($\text{m}^3 \text{min}^{-1} \text{m}^{-3}$)	MC Gradient (% w. b.)	Sp. En. Con. (MJ/kg of H_2O evap.)
	°C	°F			
Fig. 10-5	68	154	42	5.0	6.9
Fig. 10-8	65	149	58	1.3	4.9

Source: Pierce and Thompson (1981).

grain inverter) is installed in which the overheated-overdried grain is turned from the air inlet side of the columns to the air outlet side. At the same time, the undertreated-underdried grain is transported from the air exhaust to the air inlet side. Grain exchangers are usually located halfway down a grain column. They are effective in limiting the moisture gradient across a grain column at the dryer exit. However, they slightly increase the specific energy requirement of a dryer due to the lowering of the relative humidity of the dryer-exhaust air. Figure 10-7 illustrates a commercial crossflow dryer with grain exchanger and reverse flow of cooling air.

A very efficient (but expensive) design for decreasing the moisture differential in the dried grain, and simultaneously for improving the energy efficiency of crossflow dryers, is shown in Figure 10-8. The direction of the airflow is reversed at a point midway through the drying column. The air that exhausts from the first drying section is exhausted at a high average relative humidity; that from the second drying section is recycled along with the cooler exhaust air and is mixed and reheated before reuse in the two drying sections. The improvement in the specific energy requirement and in the moisture differential of the dryer pictured in Figure 10-8 is shown in Table 10-4. Compared with the conventional crossflow dryer (Fig. 10-5), the crossflow model with air reversal and air recycle (Fig. 10-8) consumes 42.3% less energy and has a substantially smaller moisture differential (1.3% instead of 5.3%). Note that the two dryers operated at slightly different air temperatures and airflow rates but maintained the same maximum grain kernel temperature.

Further improvement on the crossflow dryer design is shown in Figure 10-9. The dryer contains tapered grain columns, dual variable-speed discharge augers, and a tempering hopper separating the first and second drying zones. The exhaust airstreams from the second drying zone and from the cooling zone are mixed and recycled. The hot grain closest to

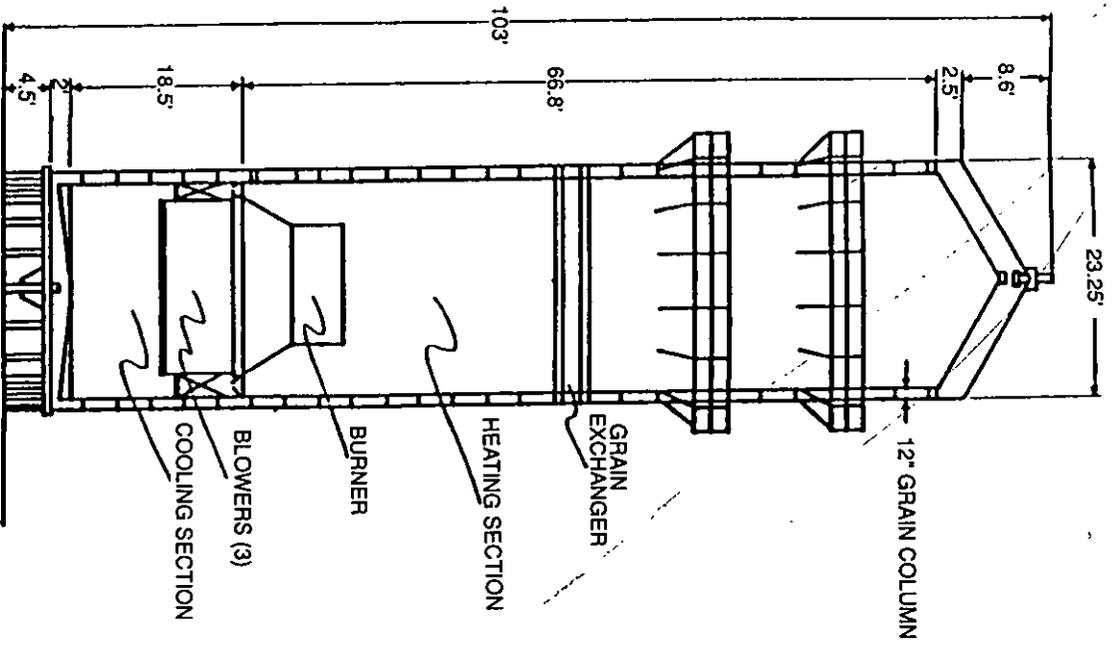


FIGURE 10-7. Commercial-size crossflow dryer with grain exchanger and reverse-airflow cooling.

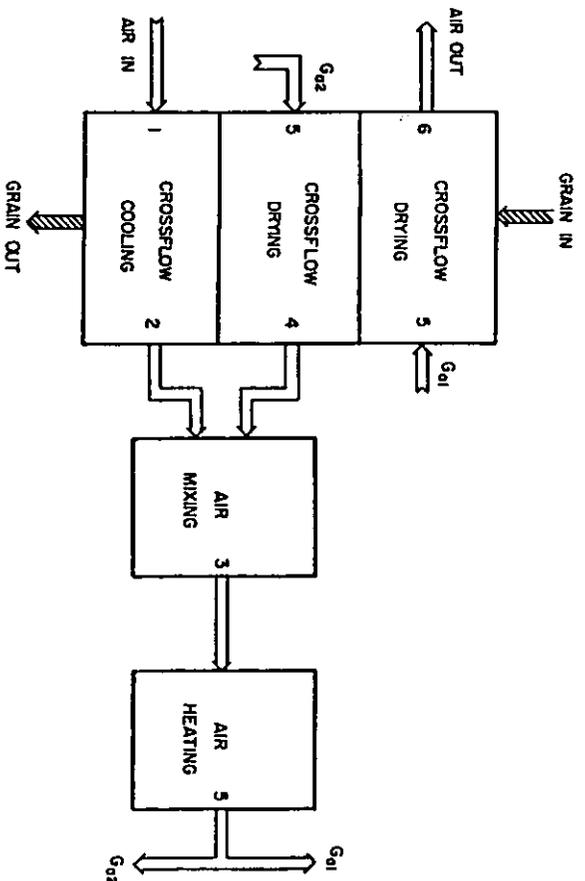


FIGURE 10-8. Schematic of a modified crossflow dryer with air reversal and air recirculation of the cooling and part of the drying air.

the air inlet moves more rapidly through the drying zones than the colder grain located near to the air exhaust side of the grain columns. The varying grain velocity across the columns is the result of the different rpm of the dual variable-speed discharge augers. With proper control of the ratio of the rpm of the two unload augers in each column, the moisture gradient across the columns can theoretically be decreased to zero.

The drying process of the crossflow dryer in Figure 10-9 is interrupted when the partially dried grain reaches the tempering hopper after passing through the first drying zone. During the period of 0.5–1.0 hr of tempering (or steeping), the grain is not subjected to an air treatment, and thus the temperature and moisture gradients within the individual grain kernels are diminished before drying is resumed. The tempering process results in limiting the stress cracking and subsequent breakage of the grain. Tempering between consecutive passes through a dryer has been practiced for years in drying rice to prevent fissuring (see Chap. 11).

Also, tempering between drying zones is a standard feature of multi-stage concurrent-flow dryers (see next section).

Table 10-5 gives the dimensions, airflow, air temperature, and capacity of a typical commercial off-farm crossflow grain dryer with reverse-airflow cooling.

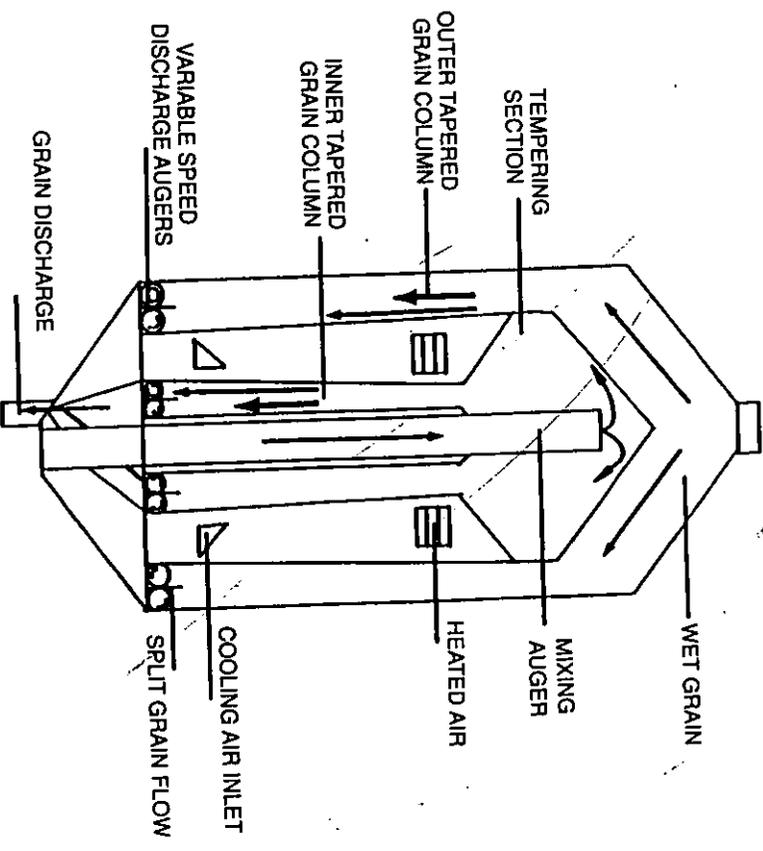


FIGURE 10-9. Modified crossflow dryer with variable-speed discharge augers, tempering section, and air recirculation of the cooling and part of the drying air.

TABLE 10-5 Specifications of Commercial Crossflow Dryer with Grain Exchanger and Reverse-Flow Cooling Shown in Figure 10-7

Airflow heat section	69 cfm/bu	79 m ³ /min · tonne
Airflow cooling section	132 cfm/bu	147 m ³ /min · tonne
Airflow heat section	61 cfm/ft ²	18.6 m ³ /m ² · min
Airflow cooling section	111 cfm/ft ²	33.8 m ³ /m ² · min
Static pressure heat section	1.5 in. WC	0.37 kPa
Static pressure cooling section	1.5 in. WC	0.37 kPa
Column cross-sectional area	70 ft ²	6.5 m ²
Column width	12 in.	0.3 m
Granflow at 5 pnt moisture removal	85.3 ft/h	26.8 m/hr
Recommended drying temperature	180°F	82.2°C
Rated capacity 20–15% MC	5,000 bu/hr	127 t/hr
Retention time at rated capacity	1 hr	1 hr
Burner capacity	54.2 mill Btu/hr	57.2 mill kJ/h
Fuel type	Nat. gas	Nat. gas

Source: Data from Zimmerman, Inc., Litchfield, IL.

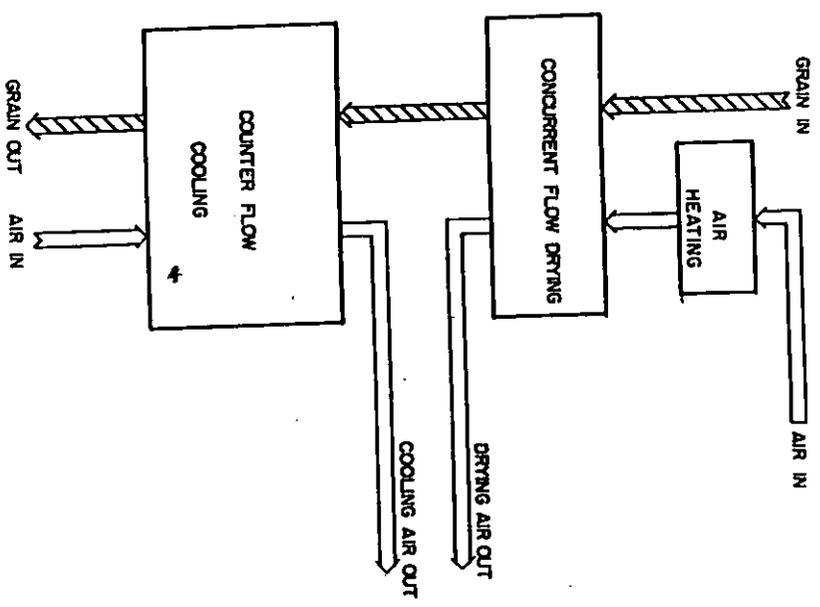


FIGURE 10-10. Schematic of one-stage concurrent-flow dryer with counterflow cooler.

Concurrent-Flow Dryers

A schematic of a single-stage concurrent-flow grain dryer with counter-flow cooler is shown in Figure 10-10. The grain and the air flow in the same direction through the drying section, and in opposite directions in the cooling section. No screens are employed as in crossflow dryers. The grain flows by gravity from a wet-holding bin into the dryer; the grain velocity in the dryer depends on the rpm of a series of specially designed discharge augers that guarantee uniform movement of the grain bed. The depth of the drying bed is 0.6–0.9 m (2–3 ft), of the cooling bed 1.2–1.8 m (4–6 ft).

A one-stage concurrent-flow dryer has a heating fan and a cooling fan; the drying and cooling sections both exhaust the air directly into the

atmosphere. In the drying section the airflow rate is 30–45 m³ air/min·m² of bed area (100–150 cfm/ft²) or 55–85 m³/min·tonne (50–75 cfm/bu); in the cooling section, 15–23 m³/min·m² (50–75 cfm/ft²) or 16–24 m³/min·tonne (14–21 cfm/bu). The static pressures are considerably higher than in crossflow dryers; in the concurrent-flow drying stage, the pressure is 1.8–3.8 kPa (7–15 in. H₂O).

A characteristic feature of the concurrent-flow dryer is its use of extremely high drying-air temperatures, as high as 230–285°C (445–545°F) for feed grains. The high evaporative and sensible heat loads at the inlet of the drying section prevent the grain kernels from reaching temperatures above 75–95°C (165–200°F) as long as the grain velocity is 4–7 m/hr (12–21 ft/hr). Thus, the retention time of the grain in the drying section is 0.10–0.25 hr, and in the cooling section 0.20–0.50 hr.

The drying characteristics of the concurrent-flow drying process are shown in Figure 10-4b, in which the grain temperature and moisture content, and the air temperature, are plotted versus location in the drying bed. As the wet grain enters the drying section, it encounters the high-temperature air and heats up rapidly while the air cools quickly. After 15–30 s in the dryer, the grain reaches a maximum temperature and maximum drying rate. During the remaining period in the drying zone, the slowly decreasing air and grain temperatures equilibrate while the kernels continue to lose moisture at a decreasing rate in an environment of increasingly high humidity. In Figure 10-4b (for the concurrent-flow dryer) only one moisture content curve is drawn, unlike in Figure 10-4a (for the crossflow dryer), in which curves are drawn for the minimum, maximum, and average moisture contents. Thus, in the concurrent-flow dryer, the minimum–maximum–average moistures are the same since each kernel undergoes the same drying treatment. The uniformity of the concurrent-flow drying treatment is an inherent benefit of its design.

Most commercial concurrent-flow dryers have either two or three drying stages coupled to one counterflow cooler; a tempering section separates two adjoining drying stages. A two-stage concurrent-flow grain dryer is shown in Figure 10-11. A multistage concurrent-flow dryer has several advantages over a single-stage model: (a) higher throughput, (b) improved grain quality as a result of the tempering process, and (c) lower energy consumption through recycling of the exhaust air from the second and/or third drying zones, and from the cooling zone.

The length of the tempering zone in a concurrent-flow dryer is 4.5–5.5 m (15–18 ft), resulting in a retention time of the partially dried grain of 0.75–1.50 hr. This period is adequate to sufficiently reduce the temperature and the moisture content gradients in the kernels before subsequent further drying.

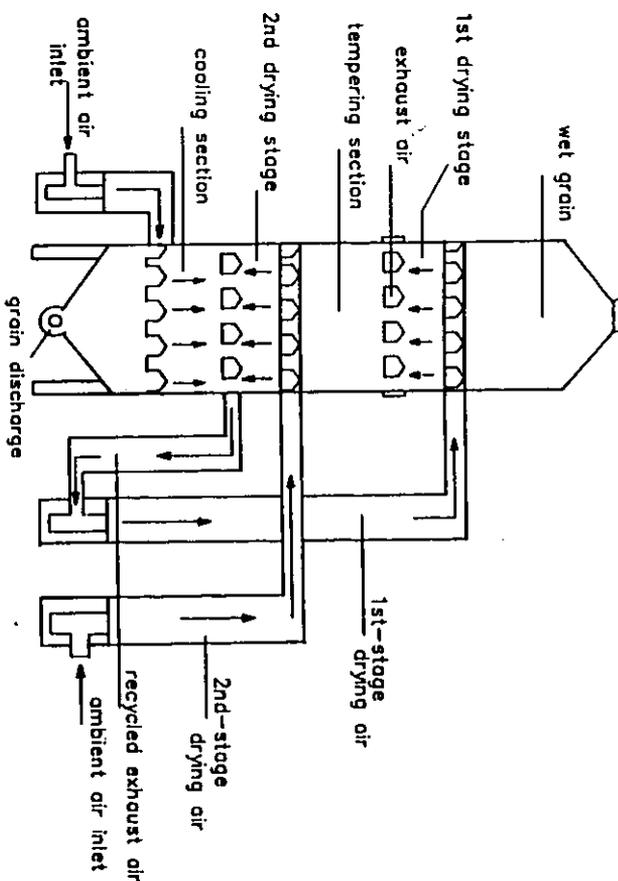


FIGURE 10-11. Two-stage concurrent-flow dryer with counterflow cooler, tempering section, and air recirculation of the cooling air and part of the drying air.

TABLE 10-6 Counterflow Cooling of Corn: Effect of Grain Flow and Airflow Rate on Temperature of Corn Exiting the Dryer

Grain Flow (m/s)	Maize Temperature		Airflow (m ³ /m ² ·s)
	°C	°F	
0.03	24	76	0.28
0.06	38	100	0.28
0.12	48	118	0.28
0.06	41	105	0.21
0.06	34	93	0.39
0.06	32	89	0.44

Source: Bakker-Arkema and Schisler (1984).

As discussed previously, the grain in a concurrent-flow dryer is cooled in a counterflow cooler. The temperature and moisture changes of the air and the grain in this cooler type are illustrated for corn in Table 10-6 and in Figure 10-12. The coldest air in the cooler encounters the coldest grain,

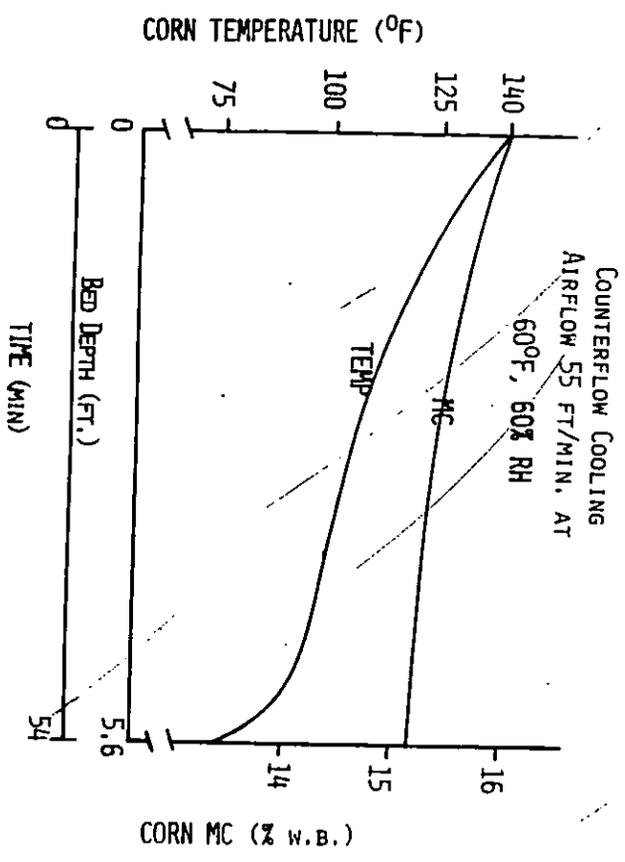


FIGURE 10-12. Corn temperature and moisture content distributions in a counterflow cooler.

and the warmest air cools the warmest grain. Thus, there is only a small temperature difference between the air and the grain (except at the air entry point), and this minimizes the stress cracking of the grain.

Table 10-7 shows the dimensions, airflow, air temperature, and throughput of a typical commercial two-stage concurrent-flow grain dryer, shown in Figure 10-11. The operating conditions are for the drying of soybeans from 14.0% to 10% (w.b.) in a soybean processing plant.

In addition to soybeans, the concurrent-flow dryer is used for corn, rice (See Chap. 11), and wheat. Figure 10-13 shows the moisture content and the grain temperatures profiles in a three-stage concurrent-flow dryer in which 25% corn is dried at 150–230°C. Note the gradual change in moisture contents and the rapid increase/slow decrease in the corn temperatures. Table 10-8 gives test results of the drying of corn in a three-stage concurrent-flow dryer.

The results of the drying of hard spring red wheat in a commercial two-stage concurrent-flow dryer are shown in Table 10-9; although the drying temperature ranged from 149°C to 218°C (300–424°F), the baking quality of the wheat was not affected. These tests show that considerably higher

TABLE 10-7 Specifications of Commercial Concurrent-Flow Dryer with Counterflow Cooler Shown in Figure 10-11, and Employed in Drying Soybeans from 14% to 10% (w.b.)

Bed area (ft ²)	192.0
Throughput [dry bu/hr (soybeans)]	3,000
Inlet moisture content (% w.b.)	14.0
Initial grain temp. (°F)	60
First Stage	
Drying-air temp. (°F)	525
Airflow (cfm/ft ²)	128
Bed depth (ft)	2.8
Tempering stage (ft)	5.3
Second Stage	
Drying-air temp. (°F)	350
Airflow (cfm/ft ²)	103
Bed depth (ft)	2.8

Cooling Stage	
Cooling air temp. (°F)	70
Airflow (cfm/ft ²)	71
Bed depth (ft)	4.0
Outlet moisture content (% w.b.)	10.0
Outlet grain temp. (°F)	105
Fuel consumption (Btu/lb)	1,785

Source: Data from Blount, Inc., Montgomery, AL.

temperatures can be employed in concurrent-flow dryers than in crossflow grain dryers.

Mixed-Flow Dryers

Figure 10-14 shows the features of a mixed-flow grain dryer, also called a cascade or a rack-type dryer. The grain in the dryer flows (cascades) over a series of staggered alternate rows (racks) of horizontal intake and outlet air ducts. The air enters the grain from an open-bottomed intake duct and flows through the grain to the four surrounding exhaust ducts. The ducts are connected to an exhaust plenum fitted with an exhaust fan.

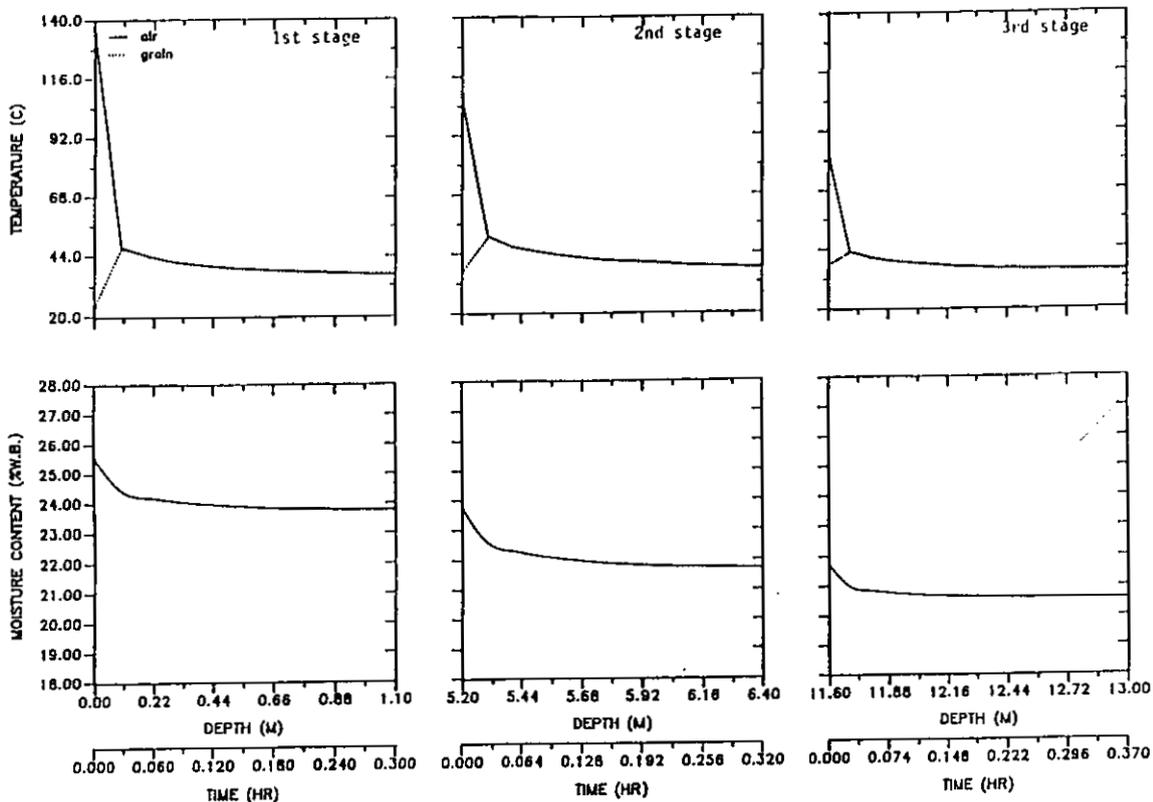


FIGURE 10-13. Corn temperature and moisture content distribution in a three-stage concurrent-flow dryer.

TABLE 10-8 Drying Corn in a Commercial Three-Stage Continuous-Flow Concurrent-Flow Grain Dryer

Dryer Parameters	Test 1	Test 2	Test 3
Ambient temp (°F)	34	33	35
Ambient RH (%)	75-95	77-94	73-97
Corn temp in (°F)	48	59	70
MC in (% w.b.)	26.2	26.5	24.5
Drying air temp. (°F)	550-450-350	550-450-350	500-450-350
MC out (% w.b.)	15.5	14.8	17.4
Corn temp. out (°F)	74	76	79
Test wet in (lb/bu)	50.2	50.9	50.5
Test wet out (lb/bu)	52.2	51.8	52.2
Throughput (wet bu/hr)	1,552	1,375	2,431
Throughput (dry bu/hr)	1,303	1,166	2,150
Fuel cons. (Btu/h)	15,883,000	16,919,000	13,424,000
Elec. cons. (Btu/h)	601,000	601,000	601,000
Water removed (lb)	9,899	9,611	10,568
Fuel eff. (Btu/lb)	1,605	1,760	1,270
Energy eff. (Btu/lb)	1,665	1,824	1,327
Breakage susceptibility increase (%)	3.8	9.5	-0.5

Source: Bakker-Arkema et al. (1981).

TABLE 10-9 Experimental Results of Drying Tests with Hard Spring Red Wheat in Commercial Two-Stage Concurrent-Flow Dryer

Test No.	Stage No.	Air Temp (°C)	Grain Flow (m/hr)	MC In (% w.b.)	MC Out (% w.b.)
1	1	204	4.2	19.8	12.3-14.3
	2	163			
2	1	218	5.9	17.5	13.1-14.1
	2	177			
3	1	149	5.9	17.2	13.0-14.0
	2	149			
4	1	218	7.0	17.7	13.4-14.2
	2	177			
5	1	196	8.9	16.8	13.6-14.1
	2	163			

Source: Bakker-Arkema et al. (1977).

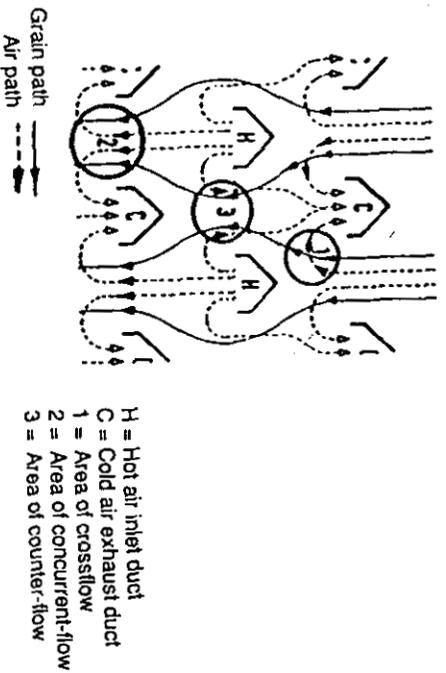


FIGURE 10-14. Duct system and airflow direction through the grain in a mixed-flow grain dryer.

The relative direction of the air and the grain in a mixed-flow dryer is a mixture of concurrent, counter-current, and crossflow. The lateral air distribution ducts can be inverted V-shaped or roof-shaped, as shown in Figure 10-14. The cross-sectional area of the ducts is chosen so that the air velocity does not exceed 7.5 m/s (1,500 ft/min); in some mixed-flow dryers the ducts are tapered in the direction of flow in order to improve the uniformity of the airflow through the grain. The distance between the alternate rows of inlet and exhaust air ducts determines the length of the airflow paths and is kept relatively short (0.3 m or 1.0 ft) to limit the static pressure requirement of the dryer. Air is usually drawn into a mixed-flow dryer to keep the unit under negative pressure to minimize air (and dust) leakage.

The length of the drying and cooling zones depends on the dryer throughput. The total dryer height can vary from 10 m (30 ft) to 60 m (100 ft) with 20–30% of the dryer occupying the cooling section.

The drying temperatures employed in mixed-flow dryers fall between those used in crossflow dryers and in concurrent-flow dryers. The grain in mixed-flow dryers is in contact with the hot air for a shorter period than in crossflow dryers, but for a longer time than in concurrent-flow dryers. Therefore, the air inlet temperature in mixed-flow dryers can be higher than in crossflow models but not as high as in concurrent-flow designs. Drying-air temperatures ranging from 65°C to 85°C (150–185°F) are recommended for food grains in mixed-flow dryers. For feed grains, temperatures between 95°C and 130°C (200–265°F) are employed.

The airflow rates in mixed-flow dryers fall between those required for the other two dryer types. A rate of 45–78 m³ air/min-tonne grain (40–70 cfm/bu) is common in mixed-flow models. The low-airflow, short-path-length combination results in a relatively low static pressure requirement of 0.25–0.50 kPa (1–2 in. H₂O) and affords the opportunity (if no cyclone is used) to employ axial-flow fans rather than the more expensive centrifugal models. An additional inherent advantage of mixed-flow dryers is their moderate electric power requirement compared with that of other high-temperature dryers of similar throughput.

The velocity and the retention time of the grain in a mixed-flow dryer are controlled by a series of discharge augers usually of similar design to those used in the crossflow dryers. The dryer size and grain type determine the grain velocity and retention time. In some mixed-flow dryers, the grain flows intermittently for 20–30 s with the interval of nonmovement adjustable between 0 and 5 min, depending on the initial moisture content of the grain.

The drying characteristics of a mixed-flow dryer are illustrated in Figure 10-4d. As the grain flows through the dryer, it is treated intermittently with bursts of hot air. Therefore, the grain decreases stepwise in moisture content without ever approaching the temperature of the drying air. Because of the cascading and mixing action of the flow, the variation in the kernel moisture content of mixed-flow dried grain is small. This is one of the major advantages of mixed-flow (and concurrent-flow) dryers over crossflow dryers.

Recirculation of the cooling air and part of the dryer exhaust air is common on modern mixed-flow dryers. In principle, the air distribution design is similar to that illustrated for crossflow dryers in Figure 10-8.

The manufacturing cost of mixed-flow dryers is higher than of other dryer types due to the high cost of steel used for the multiple air ducts. Also, special air pollution equipment (i.e. a cyclone or bag filter) is usually required for this dryer type because of the high air exhaust velocity. For these reasons, mixed-flow dryers often have a higher fixed cost than crossflow and concurrent-flow dryers.

Rotary Dryers

A rotary dryer consists of a slightly inclined long cylindrical shell that rotates slowly. The moist grain kernels and the hot drying air are introduced at one end of the shell, and the dried (or partially dried) kernels and the moist air exit at the other end. Thus, the dryer is of the concurrent-flow type. The inside of the shell is fitted with a set of flights that repeatedly lift (cascades) the kernels a certain distance along the peri-

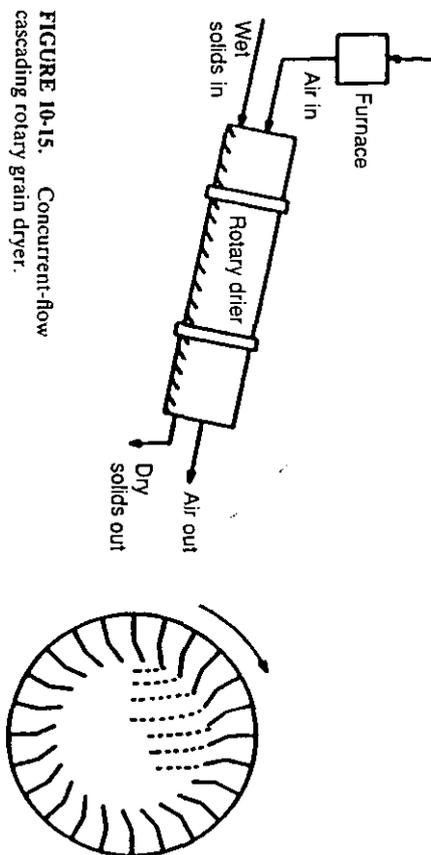


FIGURE 10-15. Concurrent-flow cascading rotary grain dryer.

phery of the rotating shell before they fall back to the bottom of the shell. During each fall, the kernels move closer to the dryer exit. While the kernels are in free fall, they encounter the stream of hot drying air resulting in rapid heat and moisture transfer. Figure 10-15 shows the type of rotary dryer employed for the drying of grains.

Typically, rotary grain dryers have a shell diameter of 1–2 m (3.3–6.6 ft), a length of 15–30 m (49.2–98.4 ft), and a slope of the shell with the horizontal of 2–4°. They are rotated at 4–8 rpm. As in a moving-bed concurrent-flow grain dryer, the drying-air temperatures are high, in the range of 121–288°C (250–550°F). The retention time of a grain kernel in a rotary dryer is a function of the rpm and the shell angle; it usually varies from 10 to 20 mins.

Parboiled rice is one of the grain products dried in rotary dryers in the United States (see Chap. 11 for an explanation of the parboiling process). In some countries (e.g., China), rotary dryers are also used for corn and wheat. In general, their fixed and variable costs are higher than of the three previously discussed dryer types. The major advantage of the rotary dryer is that it is able to dry high-moisture-content kernels that have a tendency to stick together. As with other concurrent-flow dryers, all kernels in a rotary grain dryer undergo the same uniform drying treatment. Rotary dryers are more popular for the drying of chemicals than for agricultural products (Baker 1988).

Table 10-10 shows data on the drying of soaked and steamed parboiled rice. The rice kernels are initially too sticky to allow drying in a cross-flow, concurrent-flow, or mixed-flow dryer. Drying of parboiled rice is accomplished in three rotary dryers placed in series. Note that the specific fuel consumption increases as the inlet moisture content of the rice and the temperature of the drying air decrease.

TABLE 10-10 Experimental Results of Drying Parboiled Rice in a System of Three Commercial Rotary Dryers Placed in Series

Dryer No.	Drying Temperature		Inlet MC Percent (w.b.)	Outlet MC Percent (w.b.)	Fuel Consumption (MJ/kg)
	°C	°F			
1	288	550	34.6	23.3	4.11
2	232	450	23.3	17.8	7.41
3	149	300	17.8	14.1	8.73
System	—	—	34.6	14.1	5.50

Source: Bakker-Arkema et al. (1984).

The simulation model of a rotary grain dryer is the same as that of the concurrent-flow moving-bed dryer (see eq. (8-53) through (8-55)). In the moving-bed dryer, the kernel flow rate through the dryer (G_p) is easily measured. In the rotary dryer, the kernel transport through the dryer is a complicated function of the airflow and of the cascading, bouncing, and rolling actions encountered by the individual kernels. A general expression for the effective flow rate of grain in a rotary dryer can be expressed as (Saeman and Mitchell 1954)

$$G_p = C_1 DN(\tan \alpha + C_2 V_a) \quad (10-1)$$

where D is the inside diameter of the dryer shell, N is the rotational dryer speed, α is the shell slope, V_a is the air velocity, and C_1 and C_2 are constants depending on the flight design and the grain to be dried. Determination of the constants C_1 and C_2 has proven to be difficult (Baker 1983).

Fluidized-Bed Dryers

A fluidized-bed dryer differs from a fixed-bed in-bin dryer only with respect to the velocity of the drying air. Figures 10-16 and 10-17 are schematics of a fluidized-bed grain dryer. The kernels in a fixed-bed dryer remain in place due to the relatively low flow rate of the air; they are suspended in air in a fluidized-bed dryer. As the velocity of the air to a grain bed is increased, the static pressure of the drying air also increases until it reaches the equivalent of the weight of the kernels per unit area of bed, and the kernels become suspended or fluidized in the air. Moderate mixing of the kernels results during the fluidization process. As the air velocity is further increased, air bubbles form within the bed resulting in

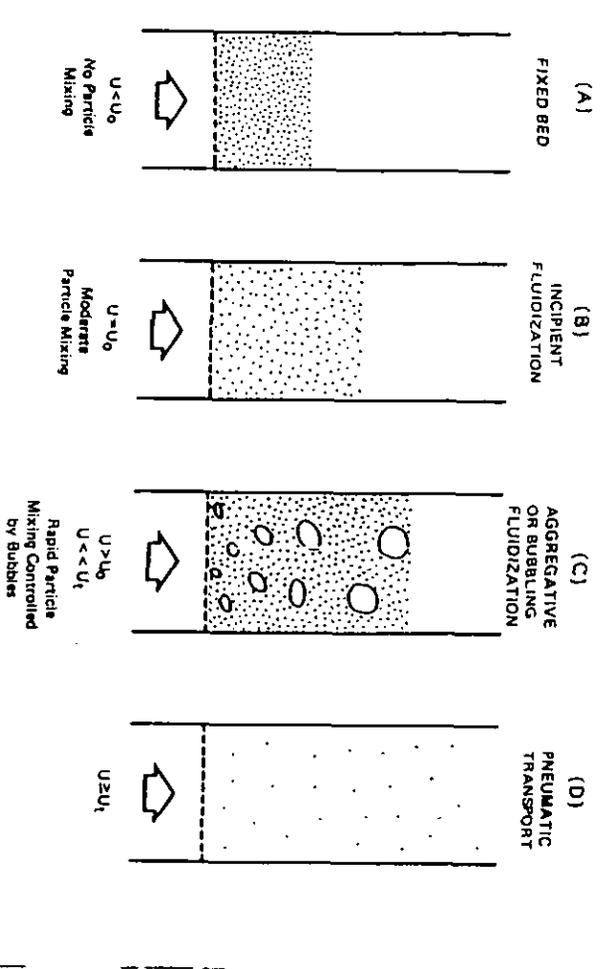


FIGURE 10-16. Regions of fluidization: U = air velocity; U_0 = air velocity for incipient fluidization; U_t = terminal fall velocity for particles; ΔP = pressure drop over particle layer. (From Horvard, 1987.)

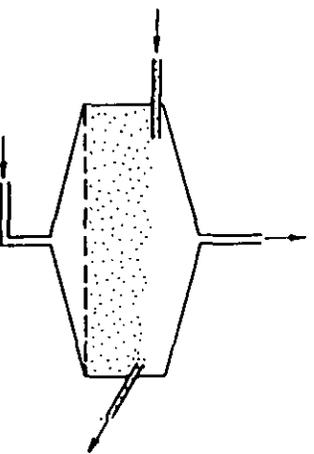


FIGURE 10-17. Continuous-flow fluidization-bed grain dryer.

vigorous mixing of the kernels. At still higher air velocities, the kernels are pneumatically transported from the bed. The interaction between the bed kernels and the bypassing air is illustrated for the four cases in Figure 10-16; also shown is the relationship of the static pressure (ΔP) versus the air velocity (U) for the four processes. Fluidization drying of grain functions best at air velocities slightly above the fluidization velocity (U_0). Excessive bubble forming should be prevented because it results in inefficient use of fuel and of electric power.

A fluidized-bed grain dryer offers two main advantages over other dryer types:

1. Rapid mixing of the kernels, resulting in nearly homogeneous drying of the grain, thus permitting reliable control of the maximum grain temperature
2. High heat and mass transfer rates between the air and the kernels due to the high air velocity

The disadvantages of a fluidized-bed grain dryer are

1. High electric power requirements because of the high air velocity
2. High specific energy consumption due to the low relative humidity of the exhaust air
3. Dusty environment around the dryer if no air pollution equipment (i.e., a cyclone or bag filter) is employed (assuming the pressure in the dryer is higher than that of the ambient air)
4. Limited allowable size distribution of the kernels
5. Inability to dry very moist sticky kernels (e.g., parboiled rice)

The process of fluidized-bed grain drying can be simulated by a three-equation model. In addition to the assumptions in Chapter 8 for deep-bed grain drying models, it is accepted that the kernels in a fluidized-bed dryer are thoroughly mixed and that the air is leaving the grain bed surface in thermal equilibrium with the kernels. From an energy balance on a layer of grain of depth H , an equation similar to equation (8-39) results:

$$\rho_p(1-\epsilon)HC_p \frac{d\theta}{dt} = \rho_p(1-\epsilon)Hh_{fg} \frac{dM}{dt} + \rho_a V_a C_a (T(in) - T(out)) \tag{10-2}$$

A mass balance on the layer gives

$$\rho_a V_a (W_{out} - W_{in}) = -\rho_p(1-\epsilon)H \frac{dM}{dt} \tag{10-3}$$

A third equation expresses the drying rate of the individual grain kernels:

$$\frac{dM}{dt} = \text{a single-kernel drying equation} \quad (10-4)$$

Consult Chapter 8 for definitions of the symbols.

Solution of the fluidized-bed grain dryer model (eq. (10-2) through (10-4)) requires an expression for the equilibrium moisture content (see Chap. 4), the psychrometric model (see Chap. 3), the initial conditions, and the grain and air parameter values. Refer to Chapter 8 for guidance in the solution of the fluidized-bed grain drying model.

Giner and De Michelis (1988) modeled the drying of wheat from 25% to 15% (w.b.) in a batch fluidized-bed dryer; the maximum kernel temperature was not allowed to exceed 62.5°C in order to prevent deterioration of the baking quality. Different bed depths (H) were analyzed. The superficial air velocity (V_a) was kept constant at 1.2 m/s, which is slightly above the fluidization velocity for wheat. The maximum drying air temperatures and the drying times are tabulated in Table 10-11 for different grain depths; also shown is the relative energy consumption of the various dryer operating conditions. With increasing grain depth the maximum allowable inlet air temperature increases and the specific energy consumption decreases. Although the drying time at the 0.3-m grain depth is the longest, the rate of drying in tonnes per hour is the largest.

No commercial fluidized-bed grain dryer has been marketed in the United States in over a decade. However, the dryer is in use in Australia as a combination grain dryer-insect disinfector (Thorpe 1987). The unit is shown in Figure 10-18 and consists of four fluidized-bed chambers: a

TABLE 10-11 Simulated Drying of Wheat from 25% to 15% (% d.b.) in a Batch Fluidized-Bed Dryer at Different Grain Depths

Grain Depth (m)	Inlet Air Temp. (°C)	Drying Time (min)	Relative Energy Consumption
0.10	65.5	51.8	100
0.15	67.5	53.9	72
0.20	69.0	56.7	58
0.25	70.5	59.2	50
0.30	72.5	61.5	44

Source: Giner and De Michelis (1988).

Note: Superficial air velocity = 1.2 m/s; maximum grain temperature = 62.5°C.

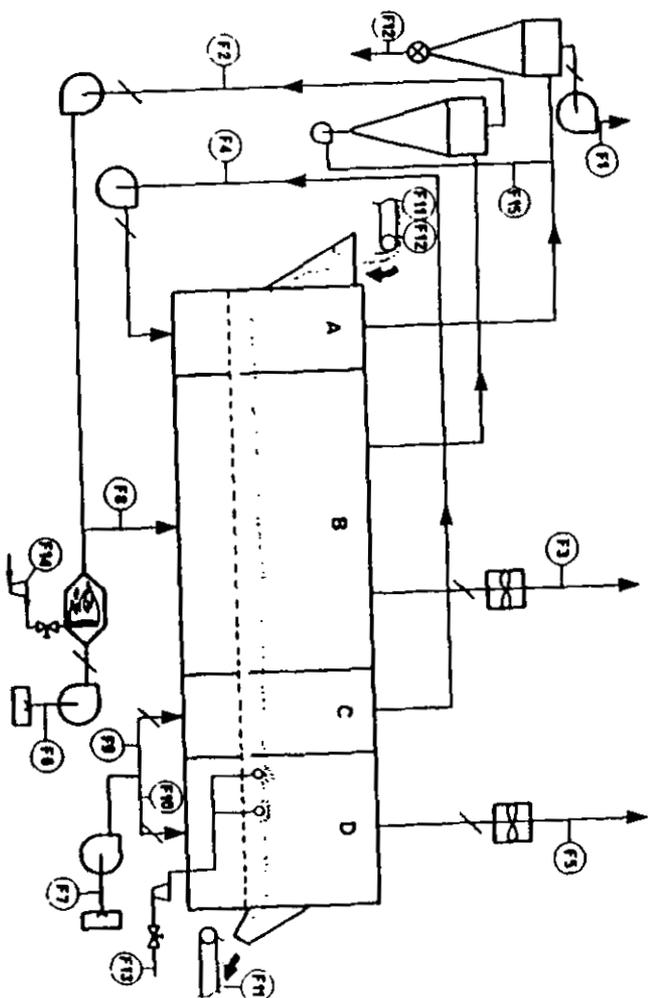


FIGURE 10-18. Process-flow diagram of fluidized-bed continuous-flow high-temperature disinfestation plant: (A) dedusting section; (B) heating section; (C) precooling and heat recovery section; (D) evaporative cooling section. (From Thorpe, 1987.)

preheating and dedusting chamber, a heating chamber, a heat recovery-cooling chamber, and an evaporative-cooling chamber. The grain is cleaned in chamber A, heated to the disinfestation temperature of 65°C (149°F) in chamber B, subsequently partially cooled in the heat-recovery insect disinfestation of grain requires that the grain mass be uniformly heated. This is better accomplished in a fluidized-bed dryer than in other dryer models.

Spouted-Bed Dryers

Spouted-bed drying is a form of fluidized-bed drying (Zabrodsky 1966). A spouted-bed dryer is illustrated in Figure 10-19. A bed of grain is held in a 0.05–1.5-m (0.5–4.9-ft) diameter cylindrical container with a 60–75° conically shaped bottom. The drying air is introduced through an air inlet tube at the cone center. At a sufficiently high air velocity, the kernels above the air inlet move upward in the central spout as in the pneumatic

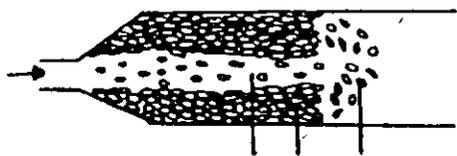


FIGURE 10-19. Conventional spouted-bed grain dryer.

transport regime. Once the kernels reach the top of the bed, they are blown or spouted to the annular portion of the container adjacent to the wall. They settle and slowly begin to descend back to the air inlet, from where they are once more carried upward in the central spout. Thus, the kernels in spouted-bed dryer are constantly circulated from the air inlet to

TABLE 10-12 Minimum Spouting Velocity of Different Grains in a Conventional Spouted-Bed Grain Dryer with 0.08 m (0.26 ft) Internal Tube Diameter and Different Orifice Diameters

Grain Type	Grain Depth (m)	Orifice Diam. (m)	Minimum Spouting Velocity (m/s)
Oats	0.15	0.05	0.52
	0.23	0.05	0.61
	0.31	0.05	0.88
Barley	0.15	0.05	0.79
	0.23	0.05	0.93
	0.31	0.05	1.00
Corn	0.15	0.05	1.12
	0.23	0.05	1.41
	0.15	0.04	0.76
	0.25	0.04	1.00

Source: Swaminathan and Mujumdar (1984).

the air outlet (Pallai and Nemeth 1987). In the core, the kernel air flow is concurrent, whereas in the annulus it is counterflow. The residence time of the grain kernels is determined by the number of times that they are recycled through the dryer and by the time period of each cycle.

The minimum spouting velocity of the air (i.e., the airflow at which the grain above the air inlet orifice begins to spout) depends on the type of grain, the grain depth, and the design specifications of the dryer. The minimum spouting velocities of barley, oats, and corn for several spouted-bed designs are shown in Table 10-12. Corn requires the highest air velocity to initiate spouting, oats the lowest. Also, the smaller the diameter of the air inlet orifice, the lower is the minimum spouting velocity and, thus, the required fan power.

Typical curves for the static pressure versus the air velocity in a spouted-bed grain dryer are shown in Figure 10-20. As the velocity of the air to the bed is increased, the static pressure rises to a maximum value and then suddenly falls as air channels are formed in the core and spouting of the grain commences. A hysteresis loop occurs in the SP-U diagram of a spouted-bed dryer due to the increase in the porosity of a previously spouted grain bed. Figure 10-20 indicates the anomaly that the static pressure requirement for initiating the spouting is larger than for maintaining the actual spouting process.

The spouted-bed dryer has been modeled for wheat by Becker and

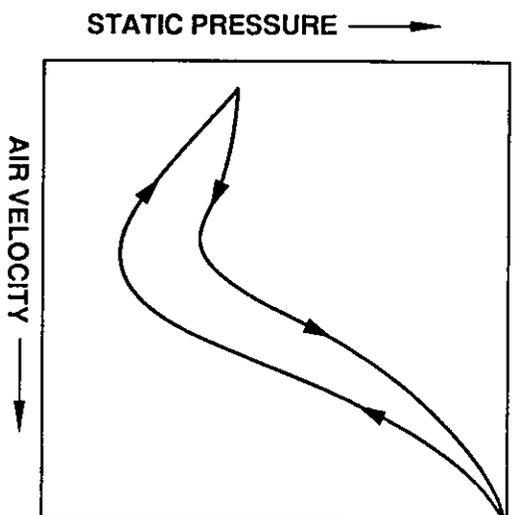


FIGURE 10-20. Typical shape of the static pressure-air velocity curve for a spouted-bed grain dryer.

Sallans (1961). The calculation of the heat and mass transfer coefficients in the annulus, spout, and fountain regions of a spouted-bed dryer has been reviewed by Mathur and Epstein (1974).

In some spouted-bed models, a cylindrical draft tube is installed some distance above the air inlet orifice. The design allows a larger bed depth, initiates spouting at a lower pressure drop, and provides more accurate control of the grain recirculation process and, therefore, of the residence time. A draft tube spouted-bed dryer appears to be particularly suitable for the drying of heat-sensitive grains (Mujumdar 1984). The relatively low capacity of spouted-bed grain dryers has thus far prevented their commercialization.

Spouted-bed grain dryers have the following advantages compared with fluidized-bed dryers (Khoe and Van Brakel 1980): (1) use of higher temperatures due to the short retention time of the kernels in the core and spout, (2) lower static pressure requirement during the drying operation, and (3) lower capital and operating costs.

The effect of the operating conditions of a spouted-bed dryer on the grain quality characteristics of wheat were investigated by Ghaly et al. (1973). Drying wheat from 17% (w.b.) to 12% was achieved at 93°C (200°F) without affecting the baking quality. This result indicates that higher drying-air temperatures can be employed for the spouted-bed drying of a heat-sensitive product than for the fixed-bed and crossflow drying of the same product.

ON-FARM SYSTEMS

The column dryer shown schematically in Figure 10-5 is also used for on-farm drying. The crossflow dryer type shown in Figure 10-6 (reverse-flow cooling) is another type of on-farm dryer. When the dryers are operated as continuous units, the operation and operating characteristics are the same as those for off-farm crossflow dryers and need not be repeated here. For on-farm use, the dryers are smaller than those previously described and ordinarily have capacities of 12.5 metric tons (500 bu) per hour or less. Dryers of this size can be mounted on a wheeled chassis to facilitate movement.

Batch Drying

Single Plenum

When used as a batch dryer, the unit shown in Figure 10-5 may not have a separate cooling section. In that case the fan-heater(s) discharge heated air during the drying process and unheated air during the cooling

process. The fan-heater(s) are shut down during loading and unloading. The entire process of drying, cooling, and unloading is normally automatically controlled.

Multiple Plumens

A separate plenum may be used for cooling and one or more additional plumens used for drying. Each plenum is served by a fan-heater unit. The grain in the lower (cooling) section is separated from the grain in the drying section above by gates in the columns. These gates can be controlled manually or automatically. When operating on automatic control, the grain is augered from the cooling section on a timed basis. Grain is dropped from the drying section to the cooling section when the cooling section is empty, and sensors indicate the grain in the drying section is at the proper moisture level. An optional method of operating column batch dryers is to discharge the grain while it is hot, with cooling accomplished external to the dryer. Such a procedure increases the throughput of the dryer. Typical data for farm-size column batch dryers are given in Table 10-13.

Drying Characteristics

Figure 10-4a shows temperature and moisture changes as a function of the distance traveled by the grain in a crossflow dryer. The same figure indicates moisture and temperature changes in a column batch dryer if the ordinate is changed from distance to time. Therefore, the discussion of temperature gradients, moisture gradients, and grain damage for the crossflow dryer is apropos for the column batch dryer. The equations in Chapter 8 for the fixed-bed process also describe the process in the column batch dryer.

TWO-STAGE DRYING

Dryer capacity and efficiency can be increased if the grain is discharged from the dryer before it is cooled. Discharging hot and partially dried grain from the dryer to a bin for further processing is, to a great extent, a two-stage on-farm practice that is used in three drying processes: dryeration, immediate cooling, or combination drying.

Dyeration

Dyeration is a process that involves drying with a high-temperature dryer, tempering, and finally, cooling. The process is illustrated in Figure 10-21.

Numerical solution of the sun-drying model of equations (11-7) to (11-10) provides the moisture content of the layer of rice as a function of layer depth (x) and time (t). Subsequently, the average moisture content of the rice layer can be calculated. No solution of the sun-drying model has been published. If the layer of rice is stirred intermittently, the sun-drying model of equations (11-7) to (11-10) has to be modified.

BIN DRYING

The bin drying of rice on the farm is common in many rice producing areas. In Louisiana and Arkansas, 60% of the rice is bin-dried; in California, only 15% (Wailes et al. 1984). Rice is bin-dried in steel bins with full perforated floors (Fig. 11-8) or in flat storage houses in which appropriate air distribution systems are placed (Fig. 11-9).

The major parameters influencing the operation of an in-bin rice drying system are (1) initial rice moisture content, (2) average air inlet temperature and humidity, (3) airflow rate and distribution, (4) grain depth, and (5) grain quality requirements. For rice, these parameters have values different from corn and wheat. Bin drying of rice is frequently accomplished with natural air. Stirrers

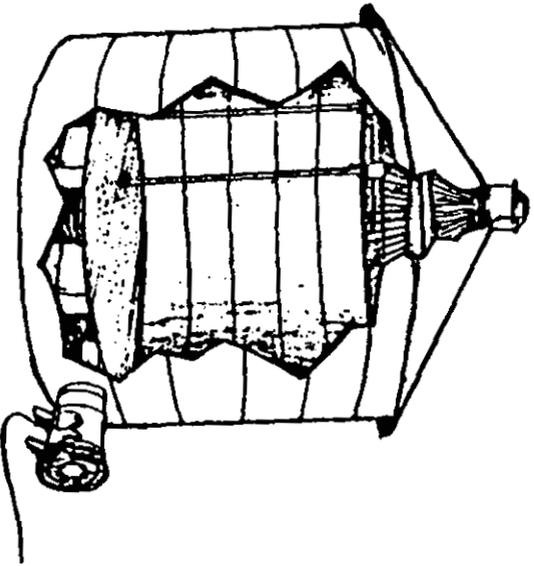


FIGURE 11-8. A circular rice drying-storage bin with a stirring device and perforated floor.

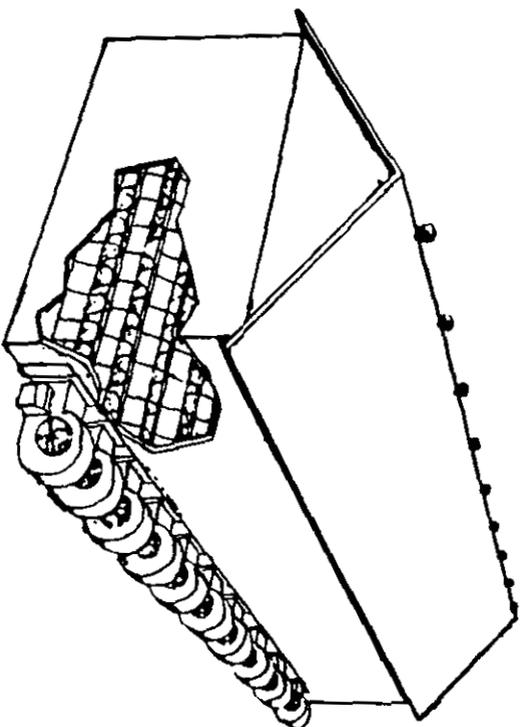


FIGURE 11-9. A flat storage for drying rice.

(see Chap. 9) are used in some installations. Design requirements in the United States for the natural air in-bin drying of rice are (1) reduction of the moisture in the wettest grain layers to 15–16% within 15–18 days, and (2) final drying to 12.5–13.5% during the following month. This combination drying system prevents mold damage and kernel discoloration (USDA 1959).

For natural air, in-bin drying systems, the recommended minimum airflow rate and the maximum grain depth depend on the initial moisture content and climatic conditions. Table 11-10 shows these values for Texas

TABLE 11-10 Recommended Minimum Airflow and Maximum Grain Depth for Natural Air In-bin Drying of Rice in Texas and California as a Function of Initial Moisture Content

Initial Moisture Content (% w.b.)	Texas		California	
	Airflow Rate (m ³ /min · tonne)	Grain Depth (m)	Airflow Rate (m ³ /min · tonne)	Grain Depth (m)
24	5.57	0.91	1.95	4.27
22	3.35	1.52	1.67	4.88
20	2.23	2.13	1.39	5.49
18	1.12	2.44	1.12	6.05

Sources: Chang et al. (1979); USDA (1959).

and California. In California, higher grain depths and lower airflow rates are permissible due to the more favorable natural air drying conditions.

If the relative humidity of the ambient air is high during the drying season, the natural air in-bin drying of rice to 13% moisture is a technical challenge; such is the case in Costa Rica. There, a natural air drying system can only be operated continuously until the wettest layer of rice has reached 16%. Thereafter, the fan is operated intermittently; it should be activated by a humidistat controller only when the relative humidity of the air drops below 65%.

For proper bin drying of rice to 13.0% moisture, the ambient air may have to be slightly heated to keep the relative humidity below 65%. In California, the highest recommended inlet air temperature for supplemental-heat in-bin rice drying is 29.4°C (85°F); in Louisiana, 37.8°C (100°F). Recommended maximum moistures and maximum grain depths are the same as for natural air drying (see Table 11-10).

Stirring devices are frequently used with supplemental-heat in-bin rice dryers. Slightly greater grain depths can be employed than indicated in Table 11-10 due to the decreased static pressure drop of a bed of stirred rice.

The annual costs of an in-bin drying and storage system consist of the annual ownership or fixed costs plus the operating or variable costs. For a 1,000-MT (50,000-bu) in-line bin system with augers, the fixed costs constitute about 60% of the total annual costs (Wailes et al. 1984). Depreciation on the bins, dryer fans, heaters, humidistats and thermostats, and stirrers make up half of the fixed costs, and the interest on the investment is about one fourth. The energy costs are about 10% of the total drying expenses.

HIGH-TEMPERATURE DRYING

Six high-temperature drying systems are employed in the rice industry: crossflow, mixed-flow, concurrent-flow, in-bin counterflow, rotary, and fluidized-grain dryers. Each system has been discussed previously. However, the operating conditions of the dryers for rice are very different than for other grains.

Rice, unlike corn and wheat, usually cannot be dried in one pass through a dryer (Kunze and Calderwood 1985). Instead, multipassing of the rice is practiced, with tempering of the partially dried rice for 1–24 hr between successive drying passes.

The logistics of multipassing is complicated because a sufficient number of bins has to be available to allow rice at different moisture contents to be tempered for the required period of time. Therefore, at high-

temperature rice drying installations, long rows of relatively small tempering bins are found in addition to the larger concrete or steel storage silos.

It is not possible to measure accurately the moisture content of hot rice in an electronic moisture meter immediately after the rice exits a dryer and before it enters a tempering bin. Depending on the true moisture content and temperature of the rice, it may be several hours before the moisture and temperature gradients in the kernels have decreased sufficiently to allow accurate measurement. Immediate measurement results in a reading 1–1.5 percentage points above the true moisture content.

Crossflow and Mixed-Flow Drying

The design of crossflow and mixed-flow grain dryers has been discussed in Chapter 10; illustrations of both dryers are shown in Figures 11-10 and 11-11. Crossflow rice dryers (also called columner dryers in the rice industry) are most popular in the United States; mixed-flow dryers are used elsewhere in the world. Slightly higher drying-air temperatures are used in mixed-flow rice dryers (i.e., 40–45°C or 104–113°F) than in crossflow models (i.e., 35–40°C or 95–104°F).

In general, the amount of moisture removed from rough rice per pass in a crossflow or mixed-flow dryer should be limited to 1.0–2.0 percentage points (w.b.). Only during the first pass, since the rice is cool and relatively high in moisture and the drying-air temperature is 50–60°C (122–140°F), is this value increased to 2.5–3 percentage points. The retention time of the rough rice in these dryers should not exceed 20–30 min per pass; the exit kernel temperature should not surpass 35°C (95°F). Due to the nonuniformity of the dryer-exit kernel moisture content, the tempering time between passes in crossflow and mixed-flow dryers is usually selected to be 6–24 hr.

The drying of medium-grain rice from a moisture content of 24.9% to 13.6% in a commercial crossflow dryer under California conditions is illustrated with an example in Table 11-11. Eight passes were required; in the last pass, the rice was cooled to ambient temperature. The rice remained in the dryer for 21 min during each pass. The drying-air temperature was 36–40°C (97–104°F), except in the first pass when 58°C (136°F) was employed; the average temperature of the rice exiting the dryer was 35°C (95°F). The rice was tempered for at least 24 hr between passes. The head yield decreased from 56.9% to 55.2%; the total yield did not change.

Rice is usually dried in fewer than eight passes. Even 25% moisture content rice is dried by most dryer operators in no more than five or six

FIGURE 11-10. Conventional crossflow rice dryer.

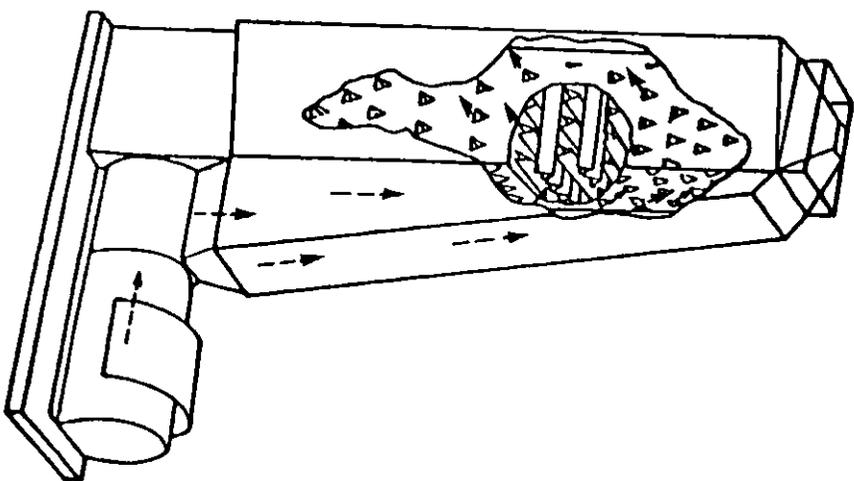


FIGURE 11-11. Mixed-flow rice dryer.

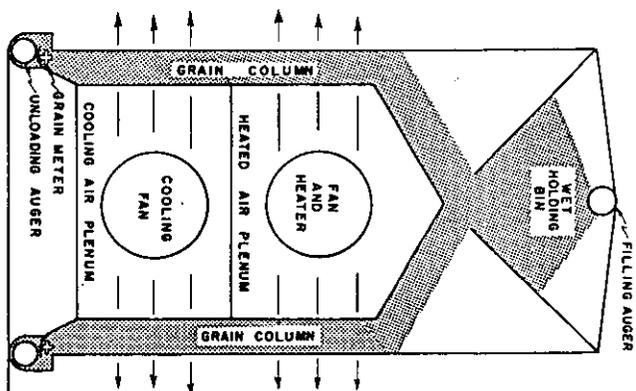


TABLE 11-11 Multipass Drying of Medium-Grain Rice in a Commercial Crossflow Dryer

Pass No.	Air Temperature		MC (% w.b.)	Head Yield (%)	Total Yield (%)
	°C	°F			
0	—	—	24.9	56.9	68.0
1	58	136	22.1	—	—
2	40	104	20.5	—	—
3	38	100	18.8	—	—
4	38	100	17.4	56.6	68.2
5	38	100	16.3	—	—
6	36	92	15.1	—	—
7	36	97	14.2	—	—
8	22	72	13.6	55.2	68.0

Source: Unpublished data of tests by F. W. Bakker-Arkema.

passes, even though the decrease in head yield is, in general, lessened by increasing the number of passes. The additional cost of an extra drying pass has to be weighed against the higher price to be received for an improved quality of the rice.

Concurrent-Flow Drying

The design of concurrent-flow (CCF) grain dryers has been considered in Chapter 10. For rice, two- and three-stage units are employed commercially (see Fig. 11-12). The drying-air temperatures are 65–175°C (150–350°F), and thus are substantially higher than in crossflow and mixed-flow rice dryers (Bakker-Arkema et al. 1983).

To maintain the quality of the rice, the maximum amount of moisture to be evaporated in one CCF drying stage is 1.5–2.0% (w.b.). The time period during which moist rice is subjected directly to the hot drying air should be limited to 15–20 s, and the rice temperature in the tempering zones should not exceed 43°C (110°F). These requirements are met in a three-stage CCF dryer when the air temperatures are limited to 150–175°C (300–350°F), 100–150°C (212–300°F), and 75–125°C (165–255°F), respectively, in the first, second, and third stages, and the grain velocity is maintained at 5–7 m/hr (16–23 ft/hr). The tempering time between drying stages at this grain velocity is approximately 1 hr, which is sufficient due to the uniformity of the average temperature and moisture content of the rice kernels entering the tempering zone.

peratures, the head yield decreased by only 1.3%; the total yield of the rice remained practically constant.

In general, the number of passes to dry rice in a three-stage concurrent-flow dryer is one third of that required in either a crossflow or mixed-flow dryer, assuming the resulting grain quality is comparable.

Symbols

A	surface area of rice (m^2) or product constant
B	product constant
C	water concentration (kg/m^3) or product constant
c	specific heat ($J/kg \cdot ^\circ C$)
D	diffusion coefficient (m^2/hr)
F	percentage fines (%)
H	rate of beam and diffuse solar radiation (W/m^2)
h	convective heat transfer coefficient ($W/m^2 \cdot ^\circ C$)
h_d	convective moisture transfer coefficient (m/s)
h_{fg}	latent heat of vaporization (J/kg)
k	effective thermal conductivity ($W/m \cdot ^\circ C$)
L	thickness of rice layer (m)
M	moisture content (% or dec) dry basis or wet basis
M_e	equilibrium moisture content (dec) dry basis
Q	airflow rate ($m^3/m^2 \cdot s$)
R	equivalent kernel radius (m)
SP	pressure drop per unit length (Pa/m)
T	air temperature ($^\circ C$)
t	time (s or hr)
X	dimension (m)
x	absorptivity (dec)
θ	rice temperature ($^\circ C$)
θ_a	rice temperature (K)
α	absorptivity (dec)
ρ	effective bulk density (kg/m^3)

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