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Review Article

Advances in the Application of a Rotary Dryer for Drying of Agricultural Products: A Review

M. A. Delele, F. Weigler, and J. Mellmann
Department of Postharvest Technology, Leibniz Institute of Agricultural Engineering, Potsdam, Germany

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Agricultural products are highly perishable and drying of the product after harvest has been proved as one of the methods to minimize postharvest losses. Different studies have been conducted to evaluate the performance of a rotary dryer for drying of agricultural products. The advantages and the challenges of rotary dryers in drying of agricultural products are discussed. This study discusses the effects of product and drying air properties, and dryer design and operation parameters, on dryer performance and product quality. Rotary dryers are capable of processing a variety of agricultural products with a wide range of thermo-physical and flow properties. Rotary dryers have been used for drying of grains, beans, nuts, vegetables, herbs, woody biomass, animal feeds, agricultural wastes, and by-products. This review paper summarizes the advances in the application of rotary dryers in drying of different agricultural products and recommends future research into the use of rotary dryers to improve the efficiency of the drying process.

Keywords Agricultural products; Drying; Postharvest; Rotary dryer

INTRODUCTION

Most agricultural products contain a significant amount of moisture during the harvesting stage. The presence of this moisture increases the deterioration rate of the products during storage, handling, and processing periods. The primary objective of drying is to reduce the moisture content of the product so as to retard adverse biological (such as growth of spoilage microorganisms, germination, insect attack, etc.), chemical, and enzymatic processes.[1–4] In addition, drying reduces the bulk weight of the produce, which helps to reduce the costs of transportation.

There are challenges that are commonly encountered during drying of agricultural products. Inhomogeneous drying results in over- and under-dried parts and affects the overall efficiency of the drying process and the quality of the product. Under-dried product is susceptible to spoilage during storage while over-drying is costly in terms of energy input, weight loss, product brittleness, and overall product quality.[5] It is also reported that suboptimal drying affected texture, color, taste, and physical and chemical attributes of the product. The development of new drying technologies that have a capacity for mitigating these adverse effects is very important.[3,6]

Several review papers on the drying of particulate solids have been published.[3,7,8] The rotary dryer is one of the dryers that have been discussed.[5,7,9–12] A review on aerodynamic separation and fractional dying of alfalfa stems and leaves using a rotary dryer was published by Arinze et al.[5] Wu[10] presented a review of alfalfa drying properties and technologies and stated that alfalfa drying is commonly done using rotary dryers. In 2010, Fagernäs et al.[11] and Pang and Mujumdar[12] did a review of the technologies for drying of biomass materials and reported that rotary dryers are one of the available technologies and commonly used dryer types. Papers have been published on the application of rotary dryers for specific products but, to our knowledge, a comprehensive review on rotary dryers in drying of different agricultural products is not yet available. The objective of this review paper is to present the state of the art in the application of a rotary dryer in drying of different agricultural products and recommend future research to improve the drying performance of rotary dryers.

The paper first describes the different types of dryers that have been used in drying of agricultural products. Then, a detailed review on rotary dryer design and transport phenomena inside the rotary dryer and dryer control is presented. The subsequent section discusses the application of rotary dryers in drying of different agricultural products. Concluding remarks and recommendations for future research are given in the last section.

Correspondence: J. Mellmann, Department of Postharvest Technology, Leibniz Institute of Agricultural Engineering (ATB) Potsdam-Bornim, Max-Eyth-Allee 100, 14469 Potsdam, Germany; E-mail: jmellmann@atb-potsdam.de

DRYERS FOR AGRICULTURAL PRODUCTS

There are different types of dryers that have been applied in agricultural drying. The important benefits and the associated challenges of each type of dryer are highlighted in Table 1. It is common to find different types of dryers for drying of the same product. Mujumdar[13] recommended that, to select the correct dryer type, at least the following parameters should be taken into account: dryer throughput, mode of operation, wet feed properties (physical, chemical, and biochemical), operating condition, moisture content of the feed and the final product, drying kinetics, required product quality, dryer safety, product

TABLE 1
Benefits and challenges of dryers that are commonly used for drying of agricultural products[3,7,8,14]

Dryer type	Important benefits	Challenges	Common product type
Sun drying	• Cheap	• Inhomogeneous drying • Low drying rate • Weather dependent • Susceptibility for spoilage • Risk of contamination and loss (particularly when it is open sun drying)	• Almost all products
Tray dryer	• Flexible • Easy to control	• Inhomogeneous drying • Low capacity	• Fruit, vegetables
Tunnel dryer	• Flexible • Easy to control	• Inhomogeneous drying	• Fruit, vegetables
Conveyor belt dryer	• Gentle handling of soft products	• Sticking of the product over the belt surface • Inhomogeneous drying • Low performance for products with wide size distribution	• Fruit, vegetables, grain, nut, herbs
Column dryer	• Mainly used in grain drying	• Inhomogeneous drying	• Grain
Rotary dryer	• Suitable for products with diverse shapes, sizes, and size distribution • It can handle high to low moisture content products • Suitable for sticky and hard to flow materials • High drying uniformity • Highly flexible • Large turndown ratio • Can give high production rate	• High capital and maintenance cost • Cannot be used for highly fragile material	• Biomass, animal feed, by-products and wastes, grain, herbs, vegetables
Fluidized bed dryer	• High drying uniformity • High drying rate • Easy to control	• Low performance for products with wide size distribution • Limited product particle size (10–2000 μm) • Product should have regular shape	• Fruit, vegetables, peas, grain, herbs, biomass
Spouted bed dryer	• High drying uniformity • High drying rate	• Low performance for products with wide size distribution	• Grain, biomass
Flash dryer	• High drying uniformity • High drying rate	• Suitable mainly for fine particles	• Grain, biomass, fruit, vegetables
Vacuum dryer	• Minimum heat degradation of nutrients	• Very expensive • Dried products are highly hygroscopic	• Fruit, vegetables
Freeze dryer	• Minimum heat degradation of nutrients	• Very expensive • Feasible only for highly valued products	• Fruit, vegetables

value, process control requirement, dryer flexibility, product toxicity, capital and operating cost, space requirement, and environmental regulation.

Slight changes in feed or final product characteristics could cause an adverse effect on the performance of the dryer and a different dryer type could be the appropriate choice.[13] In the selection and design of dryers for agricultural products, it is important to select and design the dryer that is adjustable and can handle different agricultural products with different properties. As compared to other types of dryers, the rotary dryer is more flexible and useable for agricultural products varying in consistency, moisture content, size, and flow properties. Especially for applications at the farm level, universal dryers are needed for preserving different farm products to save investment and operational costs.

Rotary Dryer

A rotary dryer is made up of a cylindrical shell that is rotating around its axis. Depending on the type of heat supply, rotary dryers are divided into direct and indirect types.[9,14] In a direct dryer, there is a direct contact of the product with the drying medium (mainly hot air) and convection is the main heat transfer mechanism. The use of superheated steam as drying medium was also reported.[3,15,16] In the case of an indirect dryer, the product is isolated from the drying medium. In most cases, the drying medium (mainly hot air and steam) passes through a series of tubes, coils, or jackets that are installed inside the shell and the heat is transferred from the hot tube surface to the product, mainly by conduction and radiation. In a one-pass continuous rotary dryer, the material to be dried is fed from one end and is discharged at the other end, while the drying medium is flowing either in the concurrent or countercurrent direction (Fig. 1). To facilitate the flow of the solid material, the shell is usually slightly inclined to the horizontal. For drying of heat-sensitive products, the concurrent dryer gives a better result and higher drying rate.[7] There are also cases where multiple-pass rotary dryers are applied, particularly in the case of animal forage and wood chips.[5,17–19] Industrial rotary dryers have a shell in the range of 0.3–3 m, 1.2–30 m, and 0–4° in diameter, length, and inclination, respectively. Commonly, the shell rotates at 4–8 rpm, the drying air has a temperature of 121–288°C, and air mass velocity in the rotary dryers is in the range of 0.5–5 kg/s.m^2.[7,14]

In most cases, rotary dryers are equipped with lifting flights. The flights lift the product during the rotation of the shell, release it at some height, and then allow it to fall as a rain of solid material through the flowing drying air (Fig. 1). These lifting flights assist the movement of the material and increase the contact area between the drying air and the drying material. The majority of the drying happens during this product-cascading period.[20–22] The flow behavior of solid products within the rotary dryer depends on shell and flight designs, operating parameters, and the flow properties of the product.[21,23,24] Figure 2 shows different types of flight designs and arrangements that are commonly available in standard dryers.[14]

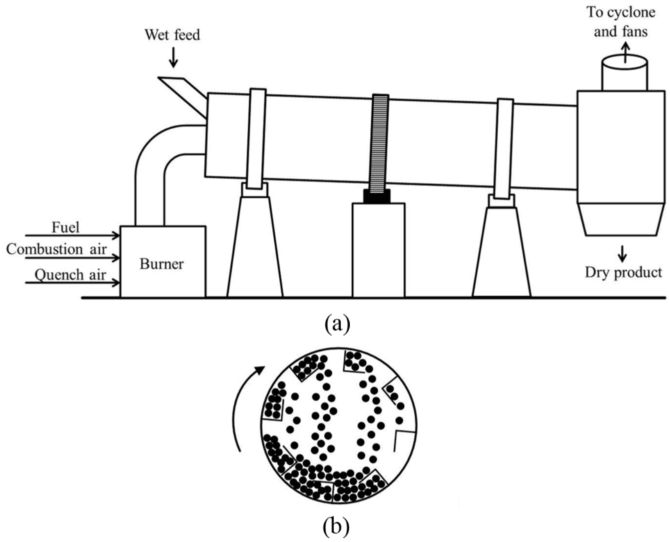

FIG. 1. (a) Diagram showing a typical concurrent rotary dryer. (b) Diagram showing the cascading effect of the flights.

There are modified designs of the conventional rotary dryer that have been reported in the literature. In the first modification, the drying air is supplied using an axial central pipe from which a series of small pipes are attached, distributing the drying air into the product bed.[25,26] This dryer works without lifting flights. Arruda et al.[25] evaluated the performance of such a dryer on drying of

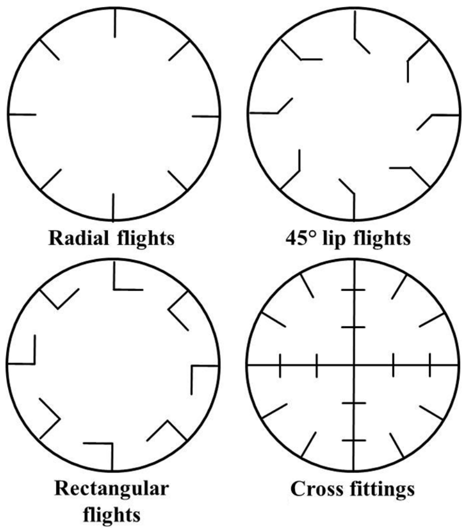

FIG. 2. Alternative direct-heat rotary dryer flight designs and arrangements.

fertilizer and found it to have a 48% lower residence time and a 3.1 to 4.9 higher drying rate as compared to conventional dryers. The heat and mass transfer coefficients obtained in this dryer were up to two times higher than those measured in conventional cascading dryers.[7] However, this design is not suited for all types of bed materials. For the conventional cascading rotary dryer, Saemen[27] reported volumetric heat transfer coefficients in the range of 112–634 W/m^3K for gas mass fluxes of 0.6–2.3 kg/sm^2. The roto-louvre dryer is another type of a rotary dryer where a horizontal drum is fitted with longitudinal louvres, forming a tapered drum within the external drum. The dryer does not have any flights and the hot air passes through the louvers and fluidizes the bed at the bottom of the inner drum.[7] This dryer produces better heat and mass transfer rates than the conventional rotary dryer. As compared to the conventional cascading rotary dryers, these dryers are more compact. Due to a gentle handling of the product, the roto-louvre dryers result in less attrition and are suitable for highly fragile material, but they are higher in capital cost. Studying the breakability of potash particles in a cascading rotary dryer with two straight flights, Grant and Kalman[28] found that particle breakage increased with an increase in rotational speed up to a certain critical value (breakage of 14.5% for a drum with diameter of 265 mm and rotational speed of 30 rpm). Beyond this point, the centrifugal forces became more dominant and the breakage rate decreased. In addition to the rotational speed, the point of particle detachment from the flight and falling path was affected by flowability, adherence of particles to the flights, and cohesiveness. There is also a report on the use of heated solid particles in direct contact dryers as a heat source instead of drying air.[29]

Different studies discussed the advantages and disadvantages of rotary dryers (Table 1).[7,10,21,30,31] Li et al.[32] reported a summary of the specific energy consumption of dryers that are commonly used in drying of biomass. The typical ranges for rotary, flash, conveyor belt, and fluidized bed dryers were 3000–4000, 2700–2800, 1260–2500, and 2200 kJ/kg of water removed, respectively. The conveyor belt and fluidized bed dryers were equipped with heat recovery systems. The information for rotary and flash dryers was taken from dryer manufacturer data. Law and Mujumdar[33] presented a qualitative comparison of rotary, flash, conveyor belt, and fluidized bed dryers in terms of different design and operational parameters. Regarding the power consumption, rotary, flash, conveyor belt, and fluidized bed dryers were classified as high, low, low, and medium, respectively. Kiranoudis et al.[34,35] studied design and operation of convective dryers and compared the capital and operational cost of rotary dryers, fluidized bed and conveyor belt dryers. The rotary dryer turned out to be the most expensive in capital cost. However, due to the favored heat transfer that was achieved, the rotary dryer was the lowest in operational cost, whereas the fluidized bed dryer was the lowest in capital cost but the highest in operational costs. Regarding capital and operational costs, the conveyor belt dryer was in between the rotary and fluidized bed dryers. Simeng[36] discussed different types of grain dryers that have been used in China. As Simeng revealed, rotary dryers consumed relatively lower energy. In general, there is inconsistency in the available information about the operational cost/specific energy consumptions of rotary dryers relative to the other competent dryers. This could be due to differences in the thermal efficiency of the rotary drying systems that have been used for different studies. It is known that the specific energy consumption depends on several factors, such as dryer design, temperature and humidity of ambient and exhaust air, feed rate, etc.[37,38] This shows that there is an opportunity to minimize the operational cost of rotary dryers by attaining the optimum design and operation of dryer.

According to Mujumdar,[7] the thermal efficiency of the rotary dryers is in the range of 30–60%. There are measures that could be taken to improve the thermal efficiency of rotary dryers, such as installing heat recovery systems, minimizing the heat loss, applying dehumidified drying air, improving the instrumentation and control system, knowing the optimum hold-up volume and flight design, installing additional product heating systems, and using a two-stage drying system. Dryer heat recovery can be performed by either recycling the exhaust air or a portion of it to the dryer or by using a recuperator system. Heat loss from the dryer can be minimized by reducing leakage, surface radiation, applying appropriate insulation (where there is no danger of drum overheating), and product discharge temperature. The efficiency of rotary dryers can be improved by using an optimum product hold-up volume (typically 10–15% of volume) that should be enough to cover the flights fully. For non-sticky materials, the inclusion of steam-heated tubes within the shell can improve the dryer performance.[7] Integrating novel product heating methods such as microwave and radio frequency techniques can also improve the thermal efficiency.

Transport Phenomena Inside a Rotary Dryer

The drying of solids in rotary dryers involves simultaneous momentum, heat, and mass transfer processes giving a highly nonlinear set of governing equations. To describe its complexity, Kemp and Oakley[39] expressed drying as the graveyard of academic theory.

Solid Flow Behavior

Rotary dryers are characterized by a complex combination of solid material flow behaviours.[9,16,40–42] There are three distinct components of particle flow observed inside a rotary dryer: cascading, kiln, and bouncing/rolling motions. The cascading motion is the behavior of the

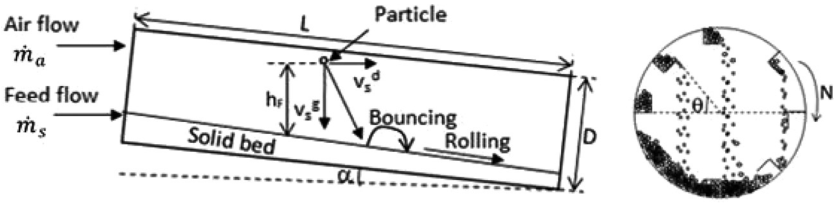

FIG. 3. Diagram showing solid particle flow behavior inside a rotary dryer: side view (left), front view (right).

material that is lifted by the flights, discharged at some height, and falls down as a curtain through the gas zone. The kiln motion is the flow of the solid material at the bottom of the shell due to gravity. Both components of the motion are advanced by drum inclination. Bouncing/rolling motion is the result of particle collision with the bottom solid bed or the inner surface of the shell (Fig. 3).

The residence time of the drying solid is one of the most important parameters that affect product quality, production capacity, and operating cost of the dryers. The average residence time (τ) of the bed material is expressed as total drum hold-up (M_s) divided by the feed rate of solids ($\dot{m}_s$) as:

$$\tau = \frac{M_s}{\dot{m}_s} \tag{1}$$

The mean residence time can be determined by measuring the dryer hold-up at steady-state operating condition. It is difficult to find analytical expressions for the solids' residence time.[43] Several model equations have been reported to calculate the residence time as a function of the dryer geometry, operating conditions (rotational speed, drum inclination, solids feed rate, airflow rate), product flow behavior, and flight characteristics. The most commonly used equations are presented in Table 2. Equations (2), (3), and (6) are empirical models, while Eqs. (4) and (5) are mechanistic models. The ± sign in Eqs. (1) and (2) represents the effect of airflow direction (+ for countercurrent and – for concurrent flow). The physical representations of some of the parameters are shown in Fig. 3. The mechanistic models were developed based on physical and mathematical analysis of the particle flow behavior inside the dryer, and these models were proved to be more accurate than the empirical models.[39,42]

Drying Behavior

In drying, the supplied heat is mainly used for the evaporation of water from the solid product. At the initial stage of drying, as the wet product comes in contact with the heat source, the product is heated up and water vapor is released from the surface of the particle. The initial stage of drying is controlled by the heat and mass transfer

TABLE 2
Different expressions of solid residence time (τ) in a rotary dryer that are available in the literature

Equation	Equation number	Source	Studies that applied similar models for drying of agricultural products
$\tau = \frac{0.23L}{N^{0.9} D tan\,\alpha} \pm \frac{9.84 L \dot{m}_a}{{d_p}^{0.5} \dot{m}_s}$	(2)	Friedman and Marshall[63]	• Xu and Pang[41] for woody biomass • Cao and Langrish[42] for sorghum • Lus et al.[47] for soybean meal • Canales et al.[44] for fish meal • Krokida et al.[46] for olive cake • Iguaz et al.[86] for vegetable wholesale by-products
$\tau = \frac{L}{f(H_s) N D (tan\,\alpha \pm k_r v_a)}$	(3)	Saeman and Mitchell[62]	• Arinze et al.[5] for alfalfa • Cao and Langrish[42] for sorghum • Zabaniotou[83] for forestry biomass
$\tau = \frac{L}{h_F(sin\ \alpha - k_d {v_a}^2/g)} \left(\frac{\theta}{180N} + \left(\frac{2h_F}{g} \right)^{0.5} \right)$	(4)	Schofield and Glikin[92]	• Arinze et al.[17] for alfalfa • Mani et al.[18] for forage
$\tau = \frac{L(1+2Nt_a)}{2Nt_a \left(v_s + \frac{aD tan\,\alpha}{2t_a} \right)}$	(5)	Matchett and Baker[61]	• Cao and Langrish[42] for sorghum
$\tau = \rho_p \left(\frac{0.151}{{\dot{m}_s}^{0.8} N^{0.6}} \right) (1 - 11.97 tan\,\alpha)(1 - 5.4\dot{m}_a)$	(6)	Thibault et al.[40]	• Thibault et al.[40] for fish meal, soybean meal and sawdust

between hot air (or heated surface) and solid. This first stage is called the constant or unhindered drying period and is mainly governed by the properties of the surrounding air (temperature, humidity, and velocity). As drying continues, the rate is dominated by the transport of moisture from the interior to the surface of the particle, which is a complex combination of competing processes; diffusion and convection in both liquid and vapor phases, and capillary movement in pores and adsorption.[39] This stage of drying is known as the falling rate period and is mainly controlled by the nature (particularly the internal structure) of the material being dried. Due to the high biological variability that is commonly observed in agricultural products, it is not easy to predict this stage of drying from theory or to take the data from existing databanks; rather, every case needs its own practical measurement. Drying of agricultural products mainly occurs in the falling rate period.

Mathematically, the two drying stages are expressed as:

$$D_r = -\frac{dX}{dt} = k_{mc} \quad \text{constant rate period} \tag{7}$$

$$D_r = -\frac{dX}{dt} = k_{mf}(X - X_e) \quad \text{falling rate period} \tag{8}$$

The drying rate constants (k_{mc} and k_{mf}) are usually determined using drying experiments. Different studies expressed the drying rate constant as a function of drying air and material properties. Most of these studies did not present separate expressions for constant and falling drying rate constants, but rather presented a single equation representing both drying stages. The constant rate drying period is relatively short. The equilibrium moisture content of the product was usually expressed as a function of drying air temperature and humidity (water activity). Table 3 contains expressions for drying rate constant (k_m) and equilibrium moisture content (X_e) that have been developed from drying studies of agricultural products. Equations (12), (16), and (19)–(25) were developed from rotary dryer studies, whereas the rest of the equations were developed from thin-layer drying studies. The results of thin-layer drying studies have successfully been applied in the modelling of cascading rotary dryers.[17,18,45,47,57,60]

To understand and optimize the design and operation of rotary dryers in agricultural application, 1-D mathematical models of heat and mass transfer have been extensively used.[17,18,39,43–47] In most cases, the models assumed steady-state flows of solid particles and drying air. For instance, the heat and mass transfer equations for a concurrent direct rotary dryer without heat loss are given below. For a dryer with total length of L, the volume is divided into N elementary control volumes of length dL (Fig. 4). Heat transfer by convection is dominating, whereas the effects of radiation and conduction are neglected.

$$\dot{m}_{ds}\frac{dX}{dL} + \dot{m}_{da}\frac{dY}{dL} = 0 \tag{26}$$

$$\begin{aligned} &\dot{m}_{ds}C_{pds}\frac{dT_s}{dL} + \dot{m}_{ds}C_{pw}\frac{d(XT_s)}{dL} - U_vA(T_a - T_s) \\ &\quad - \lambda_{fg}\dot{m}_{ds}\frac{dX}{dL} = 0 \end{aligned} \tag{27}$$

$$\begin{aligned} &\dot{m}_{da}C_{pda}\frac{dT_a}{dL} + \dot{m}_{da}C_{pv}\frac{d(YT_a)}{dL} + U_vA(T_a - T_s) \\ &\quad + \lambda_{fg0}\dot{m}_{da}\frac{dY}{dL} = 0 \end{aligned} \tag{28}$$

Process Control of Rotary Dryers

The selection and design of dryers with an appropriate process control system can maximize product quality, throughput, and dryer safety, and can minimize production cost and environmental pollution.[48,49] The tuning of on-line dryer control systems can be performed either manually or automatically. Manual operation is simple and cheap. However, due to the complex and multivariate behavior of the drying process, it is not easy to control the process manually. Automatic controllers can easily handle multivariate behavior and improve the dryer performance.[48–50]

The feedback controller is one of the most commonly used dryer control techniques.[48,50,51] In feedback control systems, sensors are used to measure the control variable (e.g., product moisture content, exhaust air temperature, etc.) and to compare it with the set point value and calculate the error. In the case of a feedforward controller, system models are used to predict and eliminate the impact of the disturbance variables on the control variables. The effectiveness of the feedforward controller depends on the accuracy of the mathematical system model. The dryer performance was improved by combining feedforward with feedback controllers (feedforward-feedback controller).[48–50] The feedforward control system monitors the disturbances in the input variables and uses them to tune the manipulated variables before the control variables are affected. The function of the feedback controller is to correct the action of the feedforward system in case of measurement and modelling inaccuracies.

For automatic control of rotary dryers, it is possible to manipulate solid feed rate, inlet gas temperature, inlet gas flow rate, and rotational speed of the drum. Usually, the objective of the controller is to keep the product moisture content at the required level. However, it is not easy to realize an online measurement of the product moisture content; hence, in most cases, the control is made by measuring

TABLE 3

Different expressions of drying rate constant (k_m) and equilibrium relative humidity (X_e) for different agricultural products that are available in the literature [Eqs. (12), (16), (19)–(25) were developed from rotary dryer studies, whereas the rest of the equations were developed from thin-layer drying studies.]

Product	Equation	Equation number	Source
Barley	$k_m = 84.94\,exp\left(\frac{-3258}{T_a}\right)$	(9)	Sun and Wood[95]
Barley	$X_e = -5.747ln\left(\frac{-(T_a-248.7)ln(RH)}{393.6}\right)$	(10)	Sun and Wood[95]
Paddy rice	$k_m = 0.24261exp\left(\frac{-2530.2}{T_a}\right)$	(11)	Iguaz et al.[93]
Red chillies	$k_m = 0.0021(T_a - 273.15) - 0.0554$	(12)	Kaleemullha and Kailappan[70]
Alfalfa chop	$k_m = 0.0176exp(-0.123X_0 + 0.044 (T_a - 273.15) - 5.79 \times 10^{-5} (T_a - 273.15)^2 - 3.24 \times 10^{-3} X_0 (T_a - 273.15))$	(13)	Sokhansanj and Patil[96]
Alfalfa stem	$k_m = 0.041exp(-0.409X_0 + 0.409 (T_a - 273.15) - 3.06 \times 10^{-5} (T_a - 273.15)^2)$	(14)	Sokhansanj and Patil[96]
Alfalfa leaf	$k_m = 0.014exp(0.0585(T_a - 273.15) - 6.27 \times 10^{-5}(T_a - 273.15)^2 - 0.00668X_0(T_a - 273.15)$	(15)	Sokhansanj and Patil[96]
Alfalfa chop	$X_e = \frac{C_m CRH}{(1-RH)[1+(C-1)RH]}$ where $C_m = 3.293 \times 10^{-4} exp\left(\frac{1858.8}{T_a}\right)$ $C = 323.177exp\left(\frac{974.6}{T_a}\right)$	(16)	Iguaz et al[94]
Ryegrass	$k_m = -0.0005(T_a - 273.15)^2 + 0.0901(T_a - 273.15) - 2.413$	(17)	Osorno and Hensel[80]
Clover	$k_m = -0.0022(T_a - 273.15)^2 + 0.2952(T_a - 273.15) - 7.806$	(18)	Osorno and Hensel[80]
Clover and ryegrass	$k_m = m.N + b$ For constant temperature	(19)	Osorno and Hensel[80]
Olive cake	$k_m = 1.04\left(\frac{T_a-273.15}{70}\right)^{1.55}\left(\frac{Y}{0.01}\right)^{-0.17}\left(\frac{v_a}{1}\right)^{0.65}$	(20)	Krokida et al.[46]
Olive cake	$X_e = 1.0012exp\left(\frac{1099}{T_a}\right)\left(\frac{a_w}{1-a_w}\right)^{0.62}$	(21)	Krokida et al.[46]
Soybean meal	$k_m = 5.67 \times 10^{-4} log\left(\frac{18.08}{T_s - 273.15}\right)X + \left(4.78 \times 10^{-7}(T_s - 273.15) + 3.75 \times 10^{-6}\right)X^2 + 9.98 \times 10^{-5}(T_s - 273.15)$	(22)	Luz et al.[47]

(*Continued*)

TABLE 3
Continued

Product	Equation	Equation number	Source
Soybean meal	$X_e = 0.066\left(ln\left(\frac{1}{RH}\right)\right)^{-0.867}$	(23)	Luz et al.[47]
Vegetable by-products	$k_m = 0.00719exp\left(-\frac{130.64}{T_a - 273.15}\right)$	(24)	Iguaz et al.[86]
Vegetable by-products	$X_e = \frac{W_m W K a_w}{(1 - K a_w)[1 + (W - 1) K a_w]}$ where $W_m = 0.001426exp\left(\frac{1193.2}{T_a}\right)$ $W = 0.592384exp\left(\frac{1072.5}{T_a}\right)$ $K = 1.007799exp\left(-\frac{43.146}{T_a}\right)$	(25)	Iguaz et al.[86]

exhaust gas temperature and humidity and product temperature.[52] Due to the complexity of the interaction between the momentum, heat and mass transfer phenomena, and the relatively long residence time, it is very challenging to attain the optimum process condition for rotary dryers.[53,54,55] Accidental variation in input variables such as feed moisture content, temperature, flow rate, and humidity will disturb the process for a long time before it is observed in the control variable. This makes clear that conventional feedback controllers are inadequate for monitoring the drying of highly variable agricultural products using rotary dryers.

Recently, there has been a lot of interest in the application of predictive controllers that are based on numerical models of the drying process. Due to the availability of high-capacity computers at reasonable cost over the past two decades, the development and application of numerical models became possible and cost-effective.[31,51] The models are developed either from first principles or from prior knowledge.[48] The former type of models are explicit models that consist of a set of static and/or dynamic, ordinary and/or partial, linear and/or nonlinear differential equations which are based on momentum, heat, and mass transfer phenomena. It is easy to extrapolate these models for predicting a new drying condition. The challenge in the application of these types of models for online process control is the relatively long computational time. Knowledge-based control models are based on a large number of process data; these include the neural network model, fuzzy model, and genetic algorism model. These models require a relatively short time to be formulated, but the models have some drawbacks that include the choice and use of the initial data set and the difficulty of conducting model extrapolations outside of the data set.[48,50]

Didriksen[53] developed a model-based predictive control (MPC) system for a rotary dryer using a first principles model. The model was applied in the process control of an industrial dryer for sugar beet shreds. The system took the feed rate of the wet sugar beet shreds and moisture content of the product/exhaust gas temperature as manipulated and control variables, respectively. As compared to the

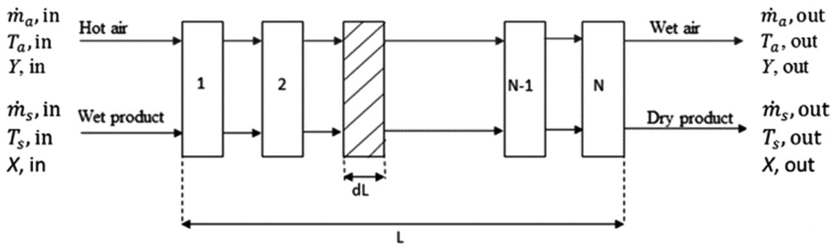

FIG. 4. Flow diagram of a concurrent direct rotary dryer.

traditional feedback controller, the performance of the MPC system was superior. Pérez-Correa[51] used a dynamic model of the rotary dryer to assess the performance of conventional PID and adaptive control algorisms. The model was developed using first principles, and inlet gas temperature and product moisture content were taken as manipulated and control variables, respectively. Since it was capable of capturing the nonlinearity and the dynamic variation of the drying process, the adaptive controller was more effective than the conventional PID controller. Ortega[55] analyzed and designed a multivariable robust control of a rotary dryer by using two manipulated (the flow of wet feed and fuel) and two control variables (product moisture content and exhaust gas temperature). As compared to the single-input single-output systems, such multiple-input multiple-output MPC systems were reported to be robust, fast, and stable. Yliniemi[50] evaluated the performance of conventional feedback-PI, combined feedforward-feedback, hybrid fuzzy logic-PI, and hybrid neural network-PI controllers in terms of accuracy, stability, speed of control, and cost of control. The combined feedforward-feedback controller based on the first principles model was superior in all aspects, followed by the hybrid fuzzy logic-PI controller and the conventional feedback-PI controller.

Application of Rotary Dryers in Agriculture

Due to their flexibility, simplicity of operation, and high production rate, rotary dryers are highly utilized in chemical and mineral process industries and for drying of sugar particles.[7,31,56] Different studies on the performance and applicability of rotary dryers in drying of agricultural products have been reported.

Drying of Grains

Grains are commonly dried using vertical column-type dryers that are working in concurrent, countercurrent, cross and mixed flow modes. Recently, there has been a limited application of rotary dryers in drying of grains. Simeng[36] presented the characteristics of rotary, fluidized bed, mixed flow, concurrent flow, cross flow, and steam dryers in China's grain system. The specific heat consumption of the dryers were about 4515, 5330, 8163, 8582, and 9418 kJ/kg of water removed for rotary, fluidized bed, mixed flow, concurrent flow, and cross flow dryers, respectively. The rotary dryer was operated at a relatively high air temperature (200°C), attaining a rapid grain drying. However, the paper did not present the details of the operating conditions for the different dryers. In addition to the dryer type, the differences in specific energy consumption may be due to differences in temperature and humidity of the ambient and exhaust air, feed rate, etc.[37,38]

Rotary dryers have been successfully applied in the drying of rice and produced more uniform drying of kernels than conventional dryers.[30] Kameoka and Itou[57] designed and constructed a roto-louvre dryer for brown rice. The drying rate of brown rice was higher than that of rough rice. The drying curve of brown rice was similar to that of thin-layer drying, suggesting that when there is a good fluidization inside the dryer, the drying behavior of brown rice with a rotary dryer can be approximated to thin-layer drying. To minimize the crack of the kernels, a drying air temperature of 30–40°C was recommended. Regaldo and Madamba[58] designed and tested the performance of a combined conduction-convection rotary paddy dryer. In the dryer, a countercurrent ambient air stream was used in the opposite direction to the cascading hot grain. The flow of the ambient air increased the drying rate and resulted in a cooling of the grain discharge. Drum rotational speed and counter flow air velocity affected the final moisture content, drying rate, and drying capacity of the dryer. The overall thermal efficiency of this dryer was about 50% higher than that of the benchmark conduction-type dryer. The benchmark conduction dryer was a continuous-flow conduction-type rotary dyer with 0.6 m diameter and 2.5 m length, drum surface temperature of 100–150°C, and a rotational speed of 6 rpm. Ilangantileke[59] compared the efficiency of direct heated air drying, indirect conduction drying, and a combination of first-stage indirect conduction followed by second-stage direct heated air drying of high moisture paddy. It was revealed that the highest drying rate was obtained with indirect conduction drying, whereas the highest fuel efficiency was obtained by direct heated air drying. Regarding the head yield ratio, no significant differences were found between the three methods.

Soponronnarit and Rodviboonchal[60] modelled a rotary maize dryer using the thin-layer drying principle and studied the effects of feed rate, rotational speed, drum inclination, and air velocity on residence time of maize. Maize residence time decreased with an increase in feed rate, rotational speed, and inclination. Cao and Langrish[42] evaluated the accuracy of the residence time models from Matchett and Baker,[61] Saeman and Mitchell,[62] and Friedman and Marshall[63] using sorghum grain as a test material. As they showed, the model from Matchett and Baker[61] achieved the best accuracy.

Alikhan et al.[29] used heated zeolite granules for drying of corn in a rotary dryer. The drying rate and the effective diffusivity of moisture increased as the zeolite granules' temperature increased. Iqbal et al.[64] designed and developed a continuous-flow rotary grain dryer using heated sand as a heat transfer medium and tested it for the drying of shelled maize. They recommended an optimum sand temperature of 120°C for shelled maize with an initial moisture content of 28% (wet basis). Mittal et al.[65] investigated the drying of wheat in a rotary dryer using different heated inert materials such as sand, steel balls, and granulated salt. The lowest energy consumption was achieved by using sand with a particle size of 0.42–0.84 mm, a sand-to-wheat ratio of 4:1, and an initial sand temperature of 100°C. At higher initial temperatures of the inert material (>120°C), granulated salt was found to be more energy-efficient than the other inert materials. Tessier and Raghavan[66] studied the performance of a rotary dryer for drying of shelled corn using sand with an initial temperature of 150°C. The dryer was capable of drying corn grain from an initial moisture content of 26.5% to 24.0% (wet basis) within 30 s for a grain flow rate of 12 kg/s. A drying efficiency of up to 39% was reported.

Drying of Beans and Nuts

The application of rotary dryers in drying of coffee beans was reported by Mwithiga and Jindal.[67] In this study, an indirect-type rotary dryer was used for drying of coffee from an initial moisture content of about 47.4% down to 9.1% (wet basis). The susceptibility of coffee beans to breakage decreased as the moisture content decreased and reached minimum value when the moisture content was between 10 and 30%. However, as the moisture content further decreased, the breakability of coffee beans again increased. The authors developed a drying model for coffee beans that could be applied to improve the dryer control system.

Noomhorm and Ramakarmer[68] studied the applicability of an indirect rotary dryer for the drying and curing of groundnut. As expected, the drying temperature increased the drying rate. However, increasing the drying temperature also increased the percentage of kernels' breakage and shrivelling and decreased seed weight and flavor. Drying surface temperatures that were capable of producing kernel temperatures of 35–37.5°C gave the best result. According to Ahmed et al.,[69] the free fatty acid and peroxide values of the oil as well as the storability of groundnut that was dried using an indirect rotary dryer were found to be not significantly different from sun-dried groundnut.

Drying of Vegetables and Herbs

Vegetables and herbs are heat-sensitive products; hence, the drying process needs a short drying time and low product temperature. Kaleemullah and Kailappan[70] discussed the advantages of a rotary dryer in keeping quality, minimizing losses, improving uniformity, and increasing capacity relative to the commonly used sun-drying method. The study evaluated the drying kinetics and quality of red chillies during drying in a rotary dryer. Chillies with an initial moisture content of 76.7% (wet basis) and a drying temperature of 50–65°C were applied. As the drying temperature was increased, the capsaicin content, red color value, and drying time decreased. At the same time, the effective moisture diffusivity increased. The drying air temperature of chillies was optimized based on drying time, capsaicin content, and red color. A temperature of 55°C was recommended.

The performance of a rotary dryer that combined infrared and heat pump drying of vegetables and herbs was studied by Pääkkönen.[71] The studies were conducted on herbs (leaves of birch, rosebay willow herb, and dandelion) and vegetables (slices of red beet and slices of carrot). Intermittent irradiation and mixing helped to avoid product overheating. The temperature inside the dryer was maintained at 40–50°C and the relative humidity was in the range of 10.2–16.7%. The relative humidity of the inlet air and the evaporation temperature were considered to be the major factors that controlled the applicability of this system. Drying of vegetable slices from an initial moisture content of about 90% (wet basis) showed the lowest energy consumption (5400 kJ/kg of water evaporated). For herbs, the energy consumption was in the range of 10400–16200 kJ/kg of water evaporated. There was a decrease in energy consumption with an increase of loading. As compared to static (fixed) bed infrared drying, an infrared rotary dryer combining infrared and heat pump drying resulted in energy saving, according to Pääkkönen et al.[74] For the static bed infrared drying experiment with convective air, the average energy consumption was 16560 kJ/kg of water evaporated compared to 11880 kJ/kg of water evaporated for the drum drying experiment that combined infrared and heat pump. As the drying air temperature was increased, the energy consumption decreased but, above a certain value, this increase contributed to a loss of important properties. The drying rates of vegetable slices were higher than those of herbs. This was due to the difference in water-binding behavior and cell structure of the products. Drying at lower temperatures (40°C) favored the growth of microorganisms. Color differences between herbs that were dried at 40°C and 50°C, respectively, were not significant. The differences in color value between fresh and dried carrot slices were higher than between fresh and rehydrated slices, suggesting that the product water content is an important parameter determining the color of food products. The rotation effect of rotary dryers affected the shape of the dried product, whereas it remained unchanged in the cases of static bed drying. Products that were dried using rotary dryers showed a better rehydration capacity than those from static bed drying.

Pelegrina et al.[72] designed and tested the performance of a semi-continuous rotary dryer for vegetables. The dryer was made of a series of modules; each stage worked as a batch system where the material was dried to a certain moisture content, then passed to the next stage, where the operation was repeated. Hence, the whole set-up operated in a semi-continuous mode, such that the first module received the wet raw material load at regular time intervals, while the last one delivered the dry product. Drying experiments were conducted on cubic onion pieces with an air velocity of 1.8 m/s and 3.6 m/s, while all remaining parameters were kept constant. To reach a moisture content of 5% of the original value, the drying times were independent of the drying air velocity, suggesting that the drying process was controlled by internal diffusion of the water that is bound inside the onion pieces. As the rotational speed of the drum was increased, the moisture content decreased. However, when the rotational speed was higher than 6 rpm, the moisture content of the onion pieces only slightly decreased. The production capacity increased with the rotational speed. The effect of the loading ratio on drying behavior of onion pieces was also studied. For a fixed drying time, it was shown that, as the product loading ratio increased, the final moisture content of the product increased. In the study, a loading ratio of 120 kg/m^3 was used. The optimum shape and size of onion pieces (prismatic, $0.01 \times 0.01 \times 0.03\text{m}^3$) were taken from a work by Elustondo et al.[75] The study described the dynamic behavior of the drying rate as a function of drying air properties (temperature and humidity) and solid moisture content.

Later, Pelegrina et al.[73] used mathematical models to investigate the effect of drying air recycling on the performance of a semi-continuous rotary dryer for vegetables. The recycling part of the exhaust drying air decreased the heat that was delivered to the air supply. The paper presented the total heat amount that was delivered to evaporate one kilogram of water and the minimum was observed for a recycle fraction of 0.8 for a drying time of 7.5 h. However, an increase in the recycle fraction increased the absolute humidity of the drying air and caused a reduction in driving force of the mass transfer inside the drying chamber that caused an increase in drying time. The air recycling created a trade-off between the specific energy consumption and drying time. The specific energy consumption is not the only factor that determines the efficiency and economy of drying. The drying time directly affects the production rate and the final product quality in terms of color and aroma. In addition, recycle ratio affected the final product moisture content, which plays an important role in the quality and stability of the dried product. Thus, the optimum recycling ratio that takes into account energy consumption, production rate, and product quality should be determined. The optimization of such complex systems can be performed by using multiple objective optimization, neural network, and genetic algorisms.[76,77]

Kaensup et al.[78] applied a novel drying technique for chili that combined the advantages of vacuum drying and microwave energy within the rotary dryer. Due to the high pressure difference between the product and the surrounding vacuum, increasing the vacuum pressure of the system increased the drying rate. The drum rotational speed was the critical factor that determined the dead zone effect. Drum speeds that were slower than the optimum value were found to be insufficient to release the water vapor that was entrapped in the space between the products, whereas higher rotational speeds enabled quick convection of the generated heat. The optimum drum rotational speed was found to be 20 rpm. When the moisture content of the product was higher than 0.5% (wet basis), the specific energy consumption of the system was not affected by vacuum pressure level and rotational speed.

The performance of rotary dryers for drying of peppermint was studied by Tarhan et al.[79] The experimental drum was 95 cm in diameter and 130 cm in length. Ambient air was delivered by a fan and heated up to the required temperature. There was a significant difference in drying rate between the leaves and stems; the leaves dried faster than the stems. The drying rate was also affected by the maturity level of the harvested plant. Early harvested peppermint plants dried faster than those harvested later. Drying using a rectangular wave-shaped drying temperature profile (cycle of 36–37°C for 45 min and 52–58°C for 15 min) was more effective than drying at a constant temperature (36°C). Hot-air drying of peppermint in a rotary dryer caused considerable darkening of the dried product. The menthol content of the leaves increased due to drying but the menthone content decreased. Drying did not affect the essential oil content of the product. The specific energy consumption of the process was in the range of 7880–15080 kJ/kg of water removed. This wide variation of the specific energy consumption was attributed to the variation in ambient air conditions. There was a considerable variation of the ambient air condition during the experiment, which affected both energy consumption and moisture transfer rate. Temperature and relative humidity of the ambient air were in the range of 15.2–27.4°C and 36.6–73.5%, respectively.

Drying of Animal Feeds

The application of rotary dryers in drying of animal forage is a common practice. Due to their good mixing and relatively long residence time, direct contact rotary dryers are capable of producing high-quality and uniform forage.[18,80] At harvest, forage has a relatively high moisture content of 70–80% (wet basis). Hence, for proper storage and transportation, a moisture level of about 10–15% is required.[5,18]

One of the most important challenges in drying of forage plants is their inhomogeneity. The leaves and stems have different thermo-physical properties and drying rates. This usually lowers the quality and increases energy waste. Due to their high specific surface area and the presence of open stomata, leaves dry faster than the stems. It was reported that leaves dry up to five times faster than stems.[5] To get a better forage quality and for better understanding of the drying kinetics, a separate drying of the leaves and stems was recommended.[5,10] As the length of the stems was decreased, the drying rate increased. Knowing the optimum length of the stems improved the dryer efficiency. From their study on thin-layer drying of alfalfa, Patil et al.[81] proved that fine stems dried faster than the leaves.

Arinze et al.[5] studied a three-pass rotary dryer that was capable of simultaneously performing drying and separation of alfalfa (Fig. 5). The wet chopped alfalfa was supplied to the dryer, where a stream mostly consisting of completely dried leaves was separated from a wetter product mostly consisting of stems. This separation was performed aerodynamically and the separation of the dried leaves from the air was performed by using a cyclone. Drying of alfalfa from an initial moisture content of 72% (wet basis) was performed using drying air with a flow rate of 0.39 kg/s and inlet temperature of 400–440°C. In the study, a leaf purity in the range of 69–76% at the cyclone and stem purity of 60–79% at the drum exit (purity of 100% means perfect separation; leaves in one fraction and stems in the other) were reported. Later, Arinze et al.[17] developed a validated mathematical model of the dryer and applied it to optimize the drying and separating parameters. The model was capable of predicting drying air, leaf, and stem temperatures and moisture content. The model was also applied to evaluate the performance of a large-scale industrial rotary alfalfa dryer. The drying rate of alfalfa leaves was more than three times faster than that of stems. As the temperature and flow rate of the drying air were increased, the drying rate, product temperature, and exhaust air temperature increased. The drying air temperature was optimized for the small-scale and large-scale industrial rotary alfalfa dryer with wet feed flow rates of 0.039 kg/s and 2.5 kg/s and reported temperatures of 300°C and 900°C, respectively.

Osorno and Hensel[80] investigated the effects of the drying air temperature, shell rotational speed, and flight design of a rotary dryer on drying homogeneity of grass mixtures. The mixtures consisted of white clover and ryegrass. The study was conducted in a stainless-steel cylindrical drum with diameter of 480 mm and length of 315 mm. The experiments were performed at drying air temperatures of 40, 60, and 80°C, rotational speeds of 15, 20, and 30 rpm, as well as square and flat flights. The effects of drying air temperature, shell rotational speed, and flight design on the homogeneity of dried grass mixture were not dominant. In all cases, the leaves reached the final moisture content faster than the stems. From all parameters that were analyzed, drying air temperature showed the greatest effect on drying homogeneity. As drying temperature was increased, the drying homogeneity increased. As the drying air temperature and shell rotational speed were increased, the drying time of the grass mixture decreased. The effect of flight geometry on homogeneity and drying rate was not significant. The best homogeneity in moisture content and the shortest drying time were observed for a combination of drying air temperature of 80°C and shell rotational speed of 30 rpm. Xianzhe et al.[82] used a dimensional analysis for studying the performance of an alfalfa rotary dryer. They evaluated the effects of wet alfalfa capacity, dry alfalfa capacity, drum speed, drying air temperature, and number of flights. The drying air temperature was found to be the dominant factor influencing drying rate and product quality of alfalfa hay.

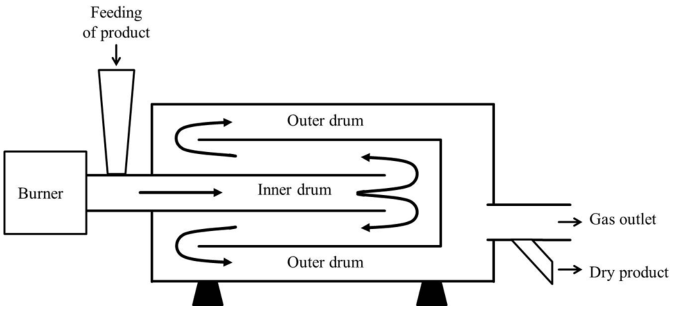

FIG. 5. Schematic diagram of a three-pass rotary dryer.

Drying of Woody Biomass

Drying improves the conversion efficiency of woody biomass to energy and minimizes the emissions. This is due to the fact that, by reducing the water content, the heating value is increased and the combustion behavior is improved. Wood chips, sawdust, bagasse, grass, and agricultural residues are typical biomass materials that are dried and used as alternative energy sources. Drying of such materials is commonly conducted using direct rotary dryers.[11,12,41,83] The dryer feed biomass materials have a moisture content of 30–60% (wet basis). In commercial drying of woody biomass, it is common to use high drying temperatures up to 500°C, thereby increasing the drying rate and drying efficiency.[12]

Zabaniotou[83] investigated the effect of different operating parameters on residence time and product moisture content during the drying of forestry biomass in a rotary dryer. Increasing the drying temperature decreased the final moisture of the biomass. As the drying temperature was decreased, the lengths of preheating and constant drying rate zones increased, while the zone length of the falling rate period decreased. A small increase in drying air flow rate increased the drying rate; however, a large increase in drying air flow rate decreased the residence time and had little influence on final moisture content. Higher rotational speed and drum inclination resulted in lower residence time and higher final moisture content of the produce. It was also reported that the residence time of the particles was more influenced by rotational speed than the drum inclination angle.

Xu and Pang[41] developed a heat and mass transfer model of a rotary dryer for woody biomass. As they revealed, the moisture content of the wood chips exponentially decreased along the dryer length. The final moisture content of the chips from the concurrent mode was higher than that from the countercurrent mode, resulting in a difference of about 7.4% (wet basis). However, the temperature of the particles at the dryer exit was higher in the case of the countercurrent dryer. Due to a better heat transfer from the air to the wood chips and a lower exit air temperature, the countercurrent mode resulted in higher energy efficiency than the concurrent mode. However, the relatively high particle exit temperature from the countercurrent dryer might pose a potential fire hazard. The use of rotary dryers for the drying of bagasse using flue gas was also reported.[84]

Drying of By-Products and Wastes

Rotary dryers have also been used for drying of by-products and wastes from agricultural process industries. The dried by-products and wastes are mainly used as animal feed, energy sources, and feedstock for process industries. The application of indirect contact rotary dryers for drying of soybean meal was investigated by Luz et al.[47] using validated mathematical models. It was reported that the mass transfer inside the particles limited the drying process of soybean meal product. The model was applied to evaluate the performance of the dryer based on the total energy consumption. The efficiency of the dryer was affected by the steam tube wall temperature. For a given feed moisture content and temperature, the optimum wall temperature was determined. During drying of soybean meal with a feed moisture content of 19.4% (wet basis) and temperature of 90°C, the optimum steam tube wall temperature was found to be 86.5°C. In the case of a feed with initial moisture content and temperature of 20.6% and 100°C, respectively, the ideal steam tube wall temperature was 95°C. For a given feed condition, when the wall temperature was higher than the optimum, there was an increase in total energy consumption due to the overheating effect of the product. When the wall temperature was lower than the optimum, there was a similar increase in the total energy consumption due to the heat transfer from the soybean meal to the wall.

Canales et al.[44] developed a validated heat and mass transfer model and predicted the drying behavior of fish meal using an indirect rotary dryer. The model underpredicted the final moisture content of the fish meal; this was attributed to the assumptions that were taken during the model development. The model neglected axial dispersion of solids, particle size distribution, and moisture and temperature gradient within the solid particle. As the particle size was decreased, the final moisture content of the fish meal decreased. However, when the particle size was higher than a certain critical value, the final moisture content asymptotically approached a value of 24.2% (wet basis). In this study, a critical diameter of 3 mm was reported. This is due to the fact that the specific surface area of the particles decreased with an increase in particle diameter but it remained almost the same for larger particles.

The operating characteristics of a pilot-scale corn distillers' grains rotary dryer were studied by Bern et al.[85] The dryer was equipped with a heat recovery system. As compared to conventional grain dryers, the energy consumption of the drying system was relatively low and reported as 2890 kJ/kg of water removed. Stroem et al.[15] evaluated the performance of a pilot-scale superheated steam rotary dryer for drying of brewer's spent grain. The wet product feed rate and the steam temperature were found to be the critical parameters that influenced the product moisture content and the amount of sticky deposit. There was an exponential relationship between the amount of sticky deposit and drum length. The sticking behavior was correlated to moisture content. In this study, 70% of the energy supply was used for drying and the rest was lost due to air infiltration and heat losses through the dryer surface. The study demonstrated the capability of a superheated steam rotary dryer for drying of brewer's spent grain that is wet and sticky.

Iguaz et al.[86] developed a validated dynamic mathematical model to predict the drying behavior of vegetable wholesale by-products using a concurrent rotary dryer. First, the simulation results were analyzed for a fixed simulation time of 5000 s (with a time step of 15 s). As the inlet air temperature and the flow rate were increased, the final product moisture content decreased and the exit air temperature increased. By increasing drum speed and inclination, the final moisture content of the product and the outlet air temperature increased. As the inlet product moisture content and flow rate were increased, the final moisture content of the product increased and the exit air temperature decreased. The inlet air temperature was found to be the parameter with the greatest effect. Next, the model was applied to simulate the dynamic behavior of the dryer by perturbation of the input variables. A 20% step increase in drum rotational speed from steady-state value decreased the dryer hold-up by 18%, but increased the outlet moisture content of the dryer by 37%. Iguaz et al.[87] applied this validated model to study the effect of air recycling on the dryer energy consumption and found energy savings of 21–38.5%. However, for a given final moisture content, as the air circulation ratio was increased, the residence time increased and the production rate decreased.

The use of a rotary dryer for drying of citrus peel from an initial moisture content of about 80% (wet basis) to a final moisture content of about 10% was reported by Bates et al.[88] The application of rotary dryers for drying of olive cake from the olive oil milling industry was also reported.

Olive cake contains approximately 65% moisture (wet basis) and there is a need to reduce it to about 8%. Ariona et al.[89] developed and implemented an automatic control system for drying of olive cake in a rotary dryer. Krokida et al.[46] examined the drying kinetics, thermo-physical properties, and cost during drying of olive cake using a rotary dryer. The drying constant of the material was expressed as a function of drying air temperature, humidity, and velocity. The equilibrium moisture content of the material was defined as a function of drying air temperature and water activity. A sensitivity study of the process unit cost indicated that drying air temperature significantly affected the production cost, while the effect of drying air velocity was found to be less significant. The study showed the effectiveness of a rotary dryer to dry such sticky and high-moisture-content material. Yeole and Deshmukh[90] studied the performance of a rotary cotton seed dryer. As the drying air temperature and flow rate were increased, the drying rate and specific energy consumption increased. By increasing the flight number, the drying rate was increased and the specific energy consumption of the dryer was decreased. As the drying air temperature and flow rate and flight number were increased, the pick-up efficiency decreased. The pick-up efficiency was defined as the ratio of the actual mass of moisture removed to the capacity of the drying air to remove moisture. A study of the performance of a rotary dryer for drying of chicken manure for the production of organic fertilizer was reported by Poels et al.[91]

CONCLUSION

Rotary dryers are one of the types of dryer that have been widely used in agricultural drying. In most cases, the dryers consisted of a rotating cylindrical drum, flights, a feeding section, and discharge sections. There are complex transport phenomena happening during drying of solids in rotary dryers that involve simultaneous momentum, heat, and mass transfer processes. The solids flow inside the rotary dryer is characterized by cascading, kiln action, and bouncing/rolling motions. These motions are affected by material properties of the solids and drying air, flight and drum designs, and dryer operating parameters. The residence time of the solids is one of the most important parameters influencing product quality, production capacity, and operating cost of the dryers. It is a common practice to determine the residence time using empirical and mechanistic models that take into account the dryer geometry, product flow characteristics, dryer inclination, rotational speed, flight characteristics, solids flow rate, and air flow rate.

Rotary dryers are capable of drying various agricultural products with a wide range of thermo-physical and flow properties. These dryers have been used in drying of grains, beans, nuts, vegetables, herbs, animal feeds, and woody biomass as well as agricultural wastes and by-products. Rotary dryers are dominant in the drying of animal feed, woody biomass, and agricultural wastes and by-products. However, in the drying of other types of agricultural products, the share of the other dryer types is quite significant. As compared to other types of dryers, rotary dryers are more flexible and useable for agricultural products varying in consistency, moisture content, and flow properties.

In the selection and design of rotary dryers for agricultural products, many parameters have to be taken into account, such as the properties and drying kinetics of the feed material, the required capacity and product quality, dryer flexibility, capital and operating costs, dryer safety, and environmental regulations. As compared to industrial application, where a dryer can be selected and designed for a specific product operating continuously in the respective production chain, the situation in agriculture is completely different. Due to the high dryer capital cost, on the one hand, and the variety of agricultural products on the farm level (type, initial moisture content, physical and biological properties, drying behavior, mechanical and heat sensitivity, etc.), on the other hand, it is important to select and design dryers which are as flexible as possible in order to increase dryer service life. As compared to other types of dryers, the rotary dryer is a good candidate to fulfill these requirements of agricultural drying. The installation of an appropriate control system helps to maintain the optimum product quality, capacity, production cost, safety, and pollution level. There is great interest in the application of predictive control systems using numerical models of the drying process. Currently, the availability of high-capacity computers at a reasonable price makes predictive control systems of rotary dryers feasible.

FUTURE PROSPECTS

As compared to chemical and mineral process industries, the benefits of rotary dryers in drying of agricultural products are not fully exploited. There is a clear indication that, in order to exploit the benefits of rotary dryers in agriculture, more studies on optimizing the design and operation are needed. These investigations can be done using experimental or mathematical modelling techniques. The relatively large biological variability that is commonly seen in agricultural products makes experimental techniques time-consuming, expensive, and difficult to generalize. Validated mathematical models based on physical, chemical, and biological principles are becoming viable alternatives. To investigate compartment processes such as particle flow, airflow, heat and mass transfer, the numerical methods of computational fluid dynamics (CFD) and discrete element method (DEM) are increasingly used in process engineering. Based on them, more advanced mathematical models can be developed, enabling a detailed and more accurate prediction of the processes. To predict the whole process in rotary dryers, coupled CFD-DEM models should be developed, taking into account the interactions between the solid particles and the surrounding gas flow inside the drum. The model should have the capacity of predicting air velocity, air and product temperatures, relative humidity, product moisture content, and product residence time. In the CFD model, the real geometry of the dryer is discretized and the governing partial differential equations (Navier-Stokes equations) for mass, momentum, and energy are solved using the appropriate numerical method. The DEM solves Newton's equations of motion on an individual particle scale, taking into account contact, gravitational, and drag forces. The CFD model predicts the characteristics of the drying air, whereas the DEM predicts the flow behavior of the solid product. The DEM and CFD solvers should be coupled to exchange data at predefined time steps.

It is important to put more focus on improving the thermal efficiency of conventional rotary dryers, such as on energy-saving mechanisms. The performance of different designs of rotary dryers, other than the conventional types, should be assessed. More research focus should be given to rotary dryers that use superheated steam instead of the standard hot air system. Recently, there have been some efforts towards the development of novel rotary dryers that combined microwave, infrared, vacuum, and heat pump technologies with the standard rotary dryers. Especially for the drying of high–value and heat-sensitive products, such novel technologies need more focus and further studies. More emphasis should be given to the development of process control systems for drying agricultural products using rotary dryers, taking into account product quality, dryer capacity, production cost, safety, and pollution. Special attention should be given to the development of universal rotary dryers at the farm level that are capable of preserving different farm products during the harvesting period, such as different types of grain, forage, or different types of medicinal plants and herbs.

NOMENCLATURE

a	dimensionless constant
a_w	water activity
A	heat transfer area, m^2
b	constant
C	constant
C_m	constant
C_{pda}	specific heat of dry air, J/kgK
C_{pds}	specific heat of solid fraction, J/kgK
C_{pw}	specific heat of liquid water fraction, J/kgK
C_{pv}	specific heat of water vapor, J/kgK
d_p	particle diameter, μm
D	shell diameter, m
D_r	drying rate, kg H_2O/kg dry solids
$f(H_s)$	drum-loading factor with a value of π for overloaded drum and 2 for lightly loaded or under-loaded drum.
g	acceleration due to gravity, m/s^2
h_F	height of fall of particles in the drum, m
k_d	dimensionless drag constant
k_m	drying rate constant, 1/s
k_{mc}	drying rate constant for constant rate drying period, kg H_2O/kg dry solids
k_{mf}	drying rate constant for falling rate drying period, 1/s
k_r	constant, s/m
K	constant
L	drum length, m
m	constant
$\dot{m}_a$	drying air flow rate, kg/s
$\dot{m}_{da}$	mass flow rate of dry air, kg/s
$\dot{m}_{ds}$	mass flow rate of dry solid, kg/s
M_s	drum hold-up, kg
$\dot{m}_s$	solid flow rate, kg/s
N	rotational speed of the dryer in rpm
RH	air relative humidity
t_a	average time particles spend in the airborne phase, minute
T_a	air temperature, K
T_s	solid temperature, K
Uv	gas-solid volumetric heat transfer coefficient, W/m^3K
v_a	superficial velocity of the drying air, m/s
v_s	axial velocity of the particles, m/s
$v_s{}^d$	drag component of the velocity, m/s
$v_s{}^g$	gravitational component of the velocity, m/s
W	constant
W_m	constant
X	solid moisture content, kg of H_2O/kg of dry solid
X_e	equilibrium moisture content, kg of H_2O/kg of dry solid
X_0	initial moisture content, kg of H_2O/kg of dry solid
Y	absolute humidity of drying air, kg of H_2O/ kg of dry air

Greek symbols

α	shell inclination, °
θ_s	kinetic angle of repose, °
λ_{fg}	latent heat of vaporization at solid temperature, J/kg
λ_{fg0}	latent heat of vaporization at 0°C, J/kg
ρ_p	particle density, kg/m^3
τ	residence time, minute

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