9 Drum Dryers

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CONTENTS

9.1 INTRODUCTION

The drum dryer is commonly used to dry viscous, concentrated solutions, slurries or pastes on rotating steam-heated drums.[1,2] It can also be used to dry concentrated solutions or slurries that become more viscous or pasty because of flashing or boiling off of moisture or of irreversible thermochemical transformations of their content that occur on their first contact with the hot drum surface.[3–5]

The viscous slurry or paste is mechanically spread by the spreading action of two counter-rotating drums into a thin sheet that adheres on the hotter drum in single drum dryers or split sheets on both hot cylinders in double drum dryers. The adhering thin sheet of paste is then rapidly dried conductively by the high heat flux of the condensing steam inside the drum. For very wet slurries that produce wet sheets, the drying of the wet thin sheet can be further enhanced by blowing hot dry air on the sheet surface. The thin sheet containing heat-sensitive materials, such as vitamins, can also be dried at a lower temperature in a vacuum.

The irreversible thermochemical transformations during the slurry's first contact with the hot drum can also be used to simultaneously impart certain required quality of the dried product.[6] Starch slurries can be gelatinized or "cooked" before the sheet is

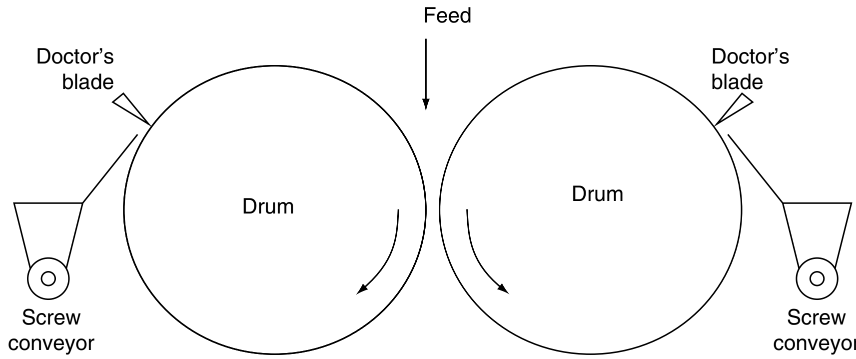

FIGURE 9.1 Double drum dryer with nip feed.

dried to produce pregelatinized or "precooked" starch for instant food formulations. Exposure of the thin sheet to the high heat flux and high temperature for a short period of time can also impart a porous structure to the dried sheet because of the rapid formation of vapor bubbles within the sheet during "boiling-like" drying. Porous products are excellent in instant food formulations because they are more readily wetted and can be easily rehydrated. It is for these reasons that the drum dryer is widely used around the world in the production of pregelatinized starch for instant food formulations.

9.2 TYPES OF DRUM DRYERS

The drum dryer was first patented for use in the manufacture of pregelatinized starch in Germany by Mahler and Supf in 1921. Since then a host of other patents have appeared especially in the United States where extensive variations of feeding methods, number and configuration of drums, heating system and product removal were considered. The diameter of the drum varies from 0.45 to 1.5 m and its length varies from 1 to 3 m. The thickness of the drum wall is between 2 and 4 cm. The drum dryer is classified according to the number and configuration of the steam-heated drums and the pressure of the atmosphere around the drying sheet.

9.2.1 Atmospheric Double Drum Dryer

This type of dryer has a higher production rate, can handle a wider range of products, and is more efficient.[1–3,7] The slurry or paste is fed through a pendulum nozzle or through a header with multiple nozzles on to the nip of two steam-heated drums counter-rotating toward each other, forming a boiling pool at the nip (Figure 9.1). The feed can also be fed at the nips of applicator rollers and the drums (Figure 9.2). Starch slurries gelatinize in the boiling pool forming pastes that become more viscous. The counter-rotation of the drums spread the slurry or paste into two thin sheets on both drums that consequently dry conductively.

9.2.2 Atmospheric Single Drum Dryers

The slurry or paste is fed through a pendulum nozzle or through a header with multiple nozzles similar to those of the double drum dryers, on to the nip of a

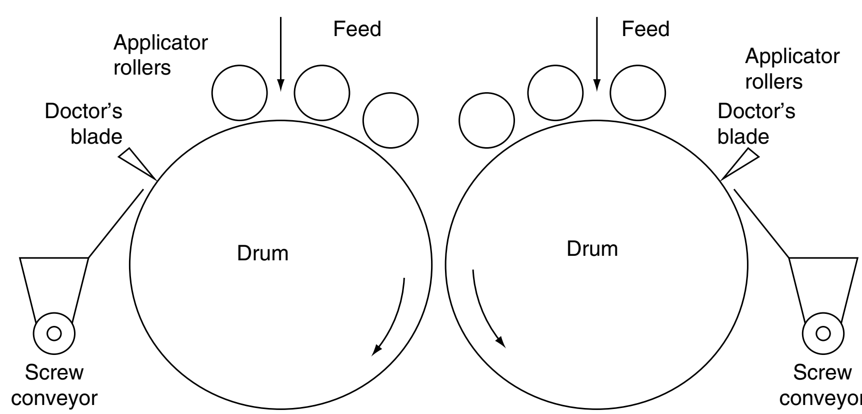

FIGURE 9.2 Twin drum dryer with applicator roller feeds.

steam-heated drum and a much cooler applicator roller counter rotating toward each other, forming a boiling pool at the nip (Figure 9.3).[1–3,7] Starch slurries gelatinize in the boiling pool, forming pastes that become more viscous. The counter-rotation of the drum and applicator roller spread the slurry or paste into a thin sheet on the hot drum that consequently dries conductively. Alternatively, the slurry can be fed by dip coating a dip or applicator roller in a feed tray at the bottom of the dryer and then roller-coated on the drum (Figure 9.4). The slurry can also be fed by dip coating the drum directly in the feed tray (Figure 9.5) or sprayed or splashed from a feed tray (Figure 9.6).

9.2.3 Atmospheric Twin Drum Dryers

The slurry is applied by direct dip coating of the twin drums in the feed tray at the bottom of the dryer (Figure 9.7) or by splash or spray feeders from a feed reservoir at the bottom of the dryer (Figure 9.8) on to the surface of the two steam-heated drums that are counter-rotating away from each other.[1–3,7] The sheet is formed by adhesion on to the drum surface and is held up against gravity by its surface tension. The sheets consequently dry conductively. This type of dryer is suitable for solutions that produce a dusty product.

9.2.4 Enclosed Drum Dryers

If solvent vapor other than water released during drum drying needs to be recovered or if the dried products generate a lot of dust, atmospheric double- or twin-drum dryers can be enclosed in vapor or dust-tight enclosures.[1–3,7] The vapor can be recovered by using a suitable condenser and the dust can be removed by using a wet scrubber.

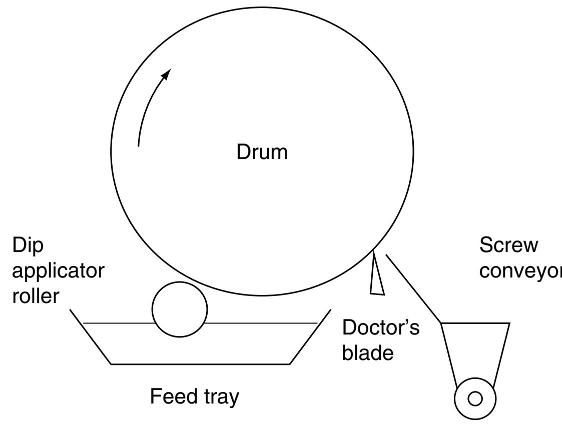

FIGURE 9.4 Single drum dryer with dip roller feed.

9.2.5 Vacuum Double Drum Dryer

Heat-sensitive materials can be dried in a vacuum double drum dryer where the dryer is enclosed in an airtight enclosure under vacuum (Figure 9.9).[1–3,7] This type of dryer is also fitted with a condenser, a scrubber, and a vacuum pump. The operation of the dryer is similar to its atmospheric version except that there are two product troughs, namely one for breaking the vacuum and the other for product discharge.

9.3 PRINCIPLES OF OPERATION OF THE DRUM DRYER

The drum dryer is a highly flexible equipment because its operational variables like the steam pressure, the drum rotational speed, the nip width, and the ratio of drum rotational speeds can be regulated independently. The steam pressure ranges from 2 to 7 bar, the drum rotational speed varies from 2 to 30 rpm, the nip width ranges from 0.05 to 0.5 mm, and the ratio

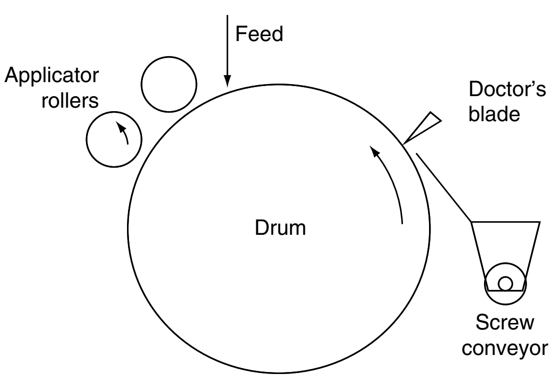

FIGURE 9.3 Single drum dryer with applicator roller feed.

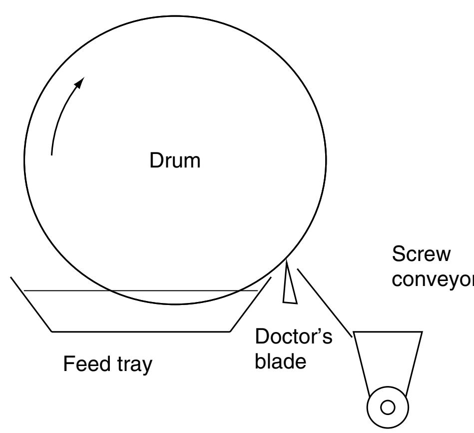

FIGURE 9.5 Single drum dryer with dip feed.

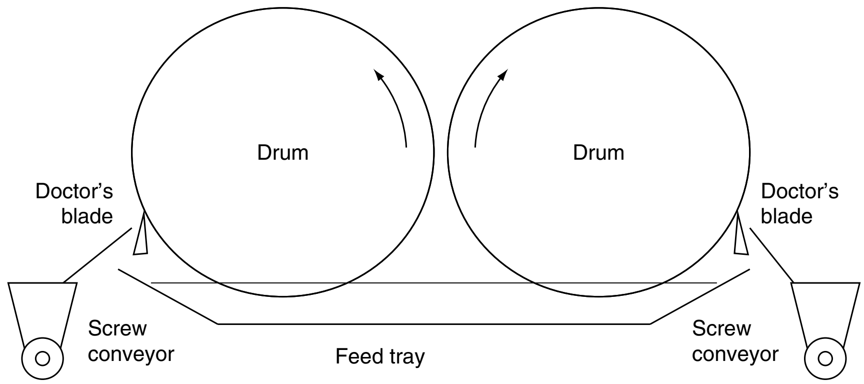

FIGURE 9.6 Twin drum dryer with dip feed.

of drum rotational speeds is from unity to 5. The feed can be preconcentrated and preheated to reduce the drying load but there is a limit to the feed concentration beyond which the sheet may not form well.[1,2,8]

9.3.1 Drum Dryer Capacity

The capacity of the drum dryer depends on the drying rate of the thin sheet, the amount of product in the sheet, and hence the sheet thickness and the rotation speed of the drums. The drying rate in turn depends on the sheet temperature and hence the steam pressure in the drum, the sheet material, and to a lesser extent the thickness of the sheet. The thickness of the sheet depends on the relative speeds of rotation of the drums, the depth of the boiling pool at the nip, the nip width, and the rheological properties of the liquid.

However, the wide range of material property values of the different feed materials, the different complex thermochemical processes occurring during drying that may change these property values further, and the wide variety of drying characteristics of sheets of different material make the operation of the drum dryer very complex. In the past, the performance of a drum dryer drying a specific product cannot be adequately predicted by theoretical or semitheoretical models but must be based on drying performance test of the product on a pilot plant drum dryer.

9.3.2 Steam Consumption

Typical specific steam consumption of the drum dryer varies from 1.3 to 1.5 kg steam per kg water removed or a steam economy of 0.66 to 0.76 kg water removed per kg steam.[1–4] It means that the specific heat consumption is typically about 3000 to 3500 kJ/kg water removed. The specific evaporation rate is 10 to 30 kg water evaporated per m^2/h for difficult to dry materials and 40 to 50 kg water evaporated per m^2/h for easy to dry materials. Recent studies have increased the understanding of the processes in the drum dryer but it is still a long way before the drum dryer can be modeled completely.

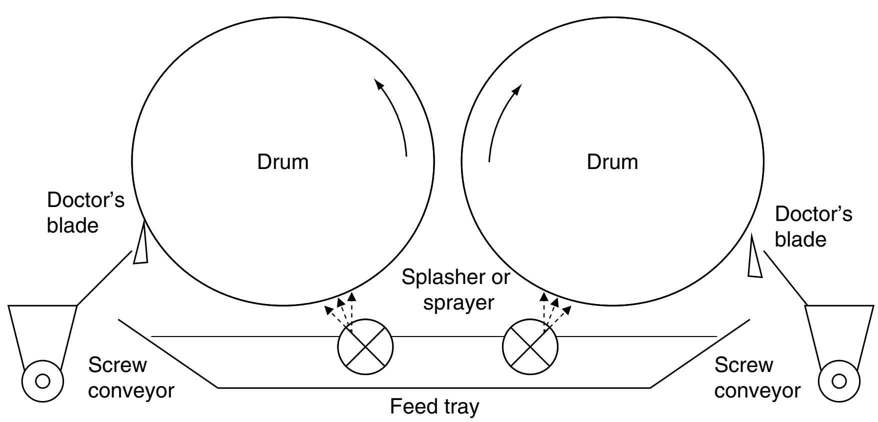

FIGURE 9.7 Twin drum dryer with splasher or sprayer feed.

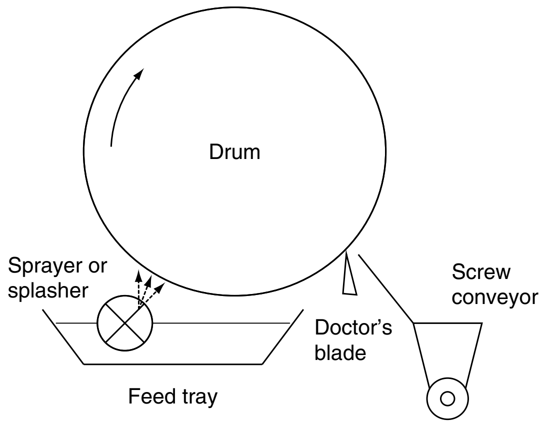

FIGURE 9.8 Single drum dryer with splasher or sprayer feed.

9.3.3 Feeding and Spreading of Liquid into a Thin Sheet

9.3.3.1 Nip Feeding

Double and single drum dryers are usually fed at the nip between the drums by either a pendulum nozzle or multiple nozzles in a header (Figure 9.1 through Figure 9.3).[1–3,7] The sudden exposure of the liquid pool to the high temperature and intense heat flux causes the pool to boil and may also cause irreversible thermochemical transformations of the liquid content that may also change the rheological property of the liquid pool. For example, the gelatinization of starch in the boiling pool of starch slurry changes the Newtonian slurry into a non-Newtonian, shear-thinning power law paste. It also swells up several times its original volume. In this case, the boiling pool is transformed into a rotating, asymmetric cylinder of paste at the nip.

The counter-rotation of the drums toward each other draws the liquid pool into the nip and spreads it into a thin sheet that adheres to the hot drum in a single drum dryer. In the double drum dryer the spreadsheet is split into two sheets that adhere on to both hot drums. Theoretical and empirical studies on the spreading phenomenon show that for a given rotational speed ratio of the drums, the spreadsheet thickness reaches an asymptotic level for a critical height of the boiling pool.[9,10] Although the asymptotic thickness is proportional to the nip width, it also decreases with increasing rotational speed ratio, and to a lesser extent with increasing diameter ratio of the smaller to the larger drum and the ratio of the nip width and the smaller drum. This means that in practice, the nip can be flooded with the feed beyond the critical height and the sheet thickness is controlled by simply varying the nip width.[5] For single drum dryers, the asymptotic thickness of the liquid sheet is about 1.2 times the nip width for Newtonian liquids and up to 1.26 times the nip for shear-thinning liquids. For double drum dryers, both the speed and diameter ratios are usually unity and the ratio of the nip width to the drum is very small. The liquid sheet is then split into two sheets of equal thickness, one for each drum.

The gelatinization of starch slurries into a shear-thinning power law paste also changes the spreading and the mixing regime in the pool.[11] The sheet is thinner for more shear-thinning liquid ($n < 1.0$). The paste material near the surface of the rotating drums experiences a higher shear rate than those further away in the bulk of the pool. The paste nearer the surface is therefore less viscous and readily rotates with the drum. On the other hand, the bulk of the paste is more viscous and may not move at all. This means that the mean residence time of the paste pool is longer than a corresponding Newtonian liquid pool. Heat-sensitive materials therefore degrade to a larger extent in the paste pool. Empirical studies have shown that the residence time distribution of the shear-thinning

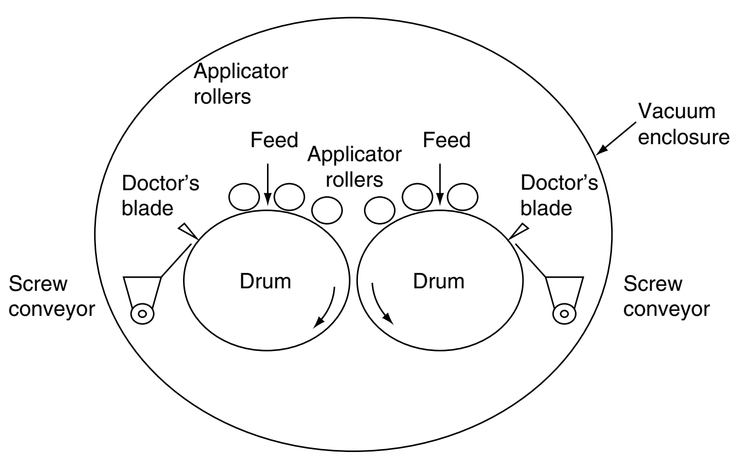

FIGURE 9.9 Vacuum double drum dryer.

paste can be modeled by the Chollete and Coultier model consisting of an equivalent stirred tank and a parallel bypass with a dead region connected to the former.[12–14] Hence for heat-sensitive materials, the mean residence time can be reduced by having a smaller pool at the expense of losing control of the sheet thickness if the pool height is below the critical height for asymptotic sheet thickness. Alternatively the heat-sensitive material can be fed using roller feeding that does not have a large volume of liquid holdup at high temperature as in nip feeding.

9.3.3.2 Roller Feeding

Single drum dryers are often fed by a cooler applicator roller.[1–3,7] The liquid can be fed from the top at the nip between an applicator roller and the hot drum and the liquid sheet is formed by spreading (Figure 9.3). The process is similar to nip feeding (see Section 9.3.3.1). The liquid sheet can be further spread by a succession of rollers to ensure that the thickness of the sheet is uniform.

Alternatively the applicator roller can be dip-coated with a liquid sheet from a dipping reservoir or bath below the drum (Figure 9.4).[1–3,7] The roller then transfers some of the liquid to the counter-rotating drum above it, retaining a thinner sheet that goes back into the bath. This feeding method is called roller feeding and is similar to roller coating.[15] The splitting of the liquid sheet is dependent on the ratio of rotational speeds (N_D/N_R), the ratio of the drum and roller diameters (D_D/D_R), and the index of the power law fluid, n, given by[15]

$$\frac{T_D}{T_R} = \left(\frac{N_D}{N_R}\frac{D_D}{D_R}\right)^{2n/(1+2n)} \tag{9.1}$$

The thickness of the liquid sheet on the drum is independent of the pressure applied between the applicator roller and the drum. It depends largely on the viscosity and the surface tension of the liquid as well as on the ratio of rotational speeds of the drum and roller and the nip width. A stable thickness can be achieved for medium viscosity shear-thinning liquids at moderate Reynolds number, *Re* (the ratio between momentum and viscous forces), low capillary number, *Ca* (the ratio of the viscous force and surface tension), and low rotational speed ratio.[15,16] A smaller *Ca* (<0.01) or a larger surface tension extends coating stability to higher rotation speeds. A stable sheet is established between a minimum and a maximum drum speed and at a critical ratio of rotational speeds of the applicator roller and the drum. The sheet formed beyond the critical point is unstable, leading to ribbing and may entrain air bubbles as well especially if the liquid contains excessive surfactants.[15,16] This rarely occurs in drum dryer operation because both the rotation speed and the ratio of rotation speeds are low (linear speed of drum surface rarely exceeds 0.3 m/s).

9.3.3.3 Dip Feeding

Single and double drum dryers can also be dip-coated directly from a reservoir of liquid (Figure 9.5 and Figure 9.6).[1–3,7] Dip coating depends on the surface tension, viscosity, density, and wall adhesion of the liquid as well as on the angle of immersion and rotation speed of the drum.[15,17,18] If the drum is immersed deeper in the bath and the angle of immersion is therefore larger, the sheet would be thinner. Apart from *Re* and the *Ca*, dip coating also depends to a lesser extent on the Froude number (the ratio of momentum to gravity forces). Higher *Re* (>1.0) and higher rotation speed yield thinner sheets (>0.5 m/s). Above a certain critical *Re* (>1), *ca* (>0.2), and drum rotational speed (linear speed >0.5 m/s), the sheet breaks up into rivulets or ribs.[15,17,18] A smaller *ca* or a larger surface tension would extend the critical *Re* and rotation speed. This rarely happens in drum dryer operation because both the rotation speed and the ratio of rotation speeds are low. The linear speed of the drum surface rarely exceeds 0.3 m/s.

9.3.3.4 Spray and Splash Feeding

The slurry or solution can be fed by spraying or splashing of the liquid from a feed tray at the bottom of the drum (Figure 9.7 and Figure 9.8). Spraying and splashing is a highly inefficient coating technique because most of the spray or splash droplets will bounce back into the feeding tray. In the drum dryer, it would also drools back into the tray due to gravity. The spray efficiency can be as low as 20 to 30%, which means that 70 to 80% of sprayed or splashed liquid fall back to the feed tray. An adhesive liquid or a liquid that becomes adhesive on contact with the hot drum surface may have a higher spraying efficiency. The liquid sheet produced is also thinner than those produced by other comparable spreading techniques.

9.3.4 Conductive or Contact Drying of Thin Sheets

9.3.4.1 Initial Application Zone

The sudden exposure of the liquid feed to the high temperature and intense heat flux on the drum surface at the application zone causes it to immediately heat up and boil (Figure 9.10). Most of the free moisture is

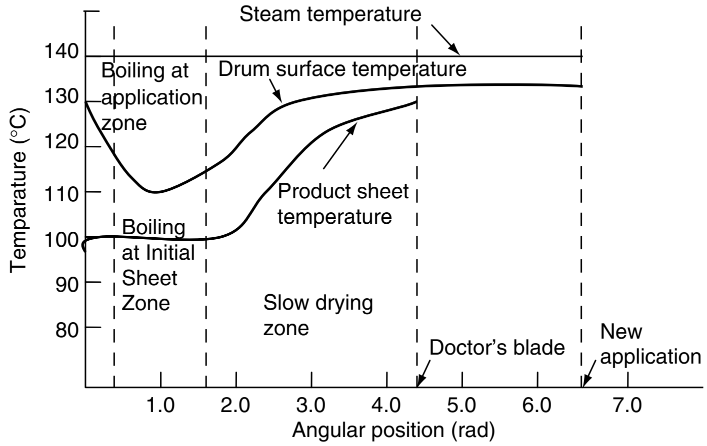

FIGURE 9.10 Temperature profile of the drum dryer.

evaporated during this initial boiling of the feed (Figure 9.11).[5,19] The boiling removes a large amount of heat from the hot drum surface due to the large latent heat of vaporization of moisture. Since the temperature difference between the feed slurry and the drum is of the order of 30°C, the slurry boils on contact with the drum surface very near the critical point of boiling. The critical boiling flux, E in W/m^2 is given by[20]

$$E = 2.177\rho_v \left[\frac{\sigma g(\rho_1 - \rho_v)}{\rho_v^2}\right]^{0.25} \tag{9.2}$$

where ρ_v is the density of steam (kg/m^3), ρ_1 is the density of water (kg/m^3), σ is the surface tension of water (N/m), and g is gravitational constant (m/s^2). The correlation of heat transfer of vapor condensing inside horizontal tubes is given by[21]

$$h_s = 0.555\left[\frac{g\rho_1(\rho_1 - \rho_s)\Delta H_v \lambda_1^3}{\mu_1 D_i(T_s - T_i)}\right]^{1/4} \tag{9.3}$$

where μ_1 is the viscosity of liquid (Ns/m^2), D_i is the inner diameter of drum (m), T_s is the steam temperature (°C), T_i is the inner drum wall temperature (°C), ΔH_v is the latent heat of vaporization of steam (J/kg), and λ_1 is the thermal conductivity of water (W/m °C). The overall heat transfer coefficient in this zone was reported to be between 2000 and 7000 W/m^2 °C.[6,19] The temperature of the drum surface then drops due to the large removal of heat in the boiling to an extent proportional to the drum rotation speed. The faster the rotation, the smaller is the temperature drop. The temperature of the liquid remains at the boiling point of the solution, which is slightly above the normal boiling point of water due to the presence of dissolved solids.

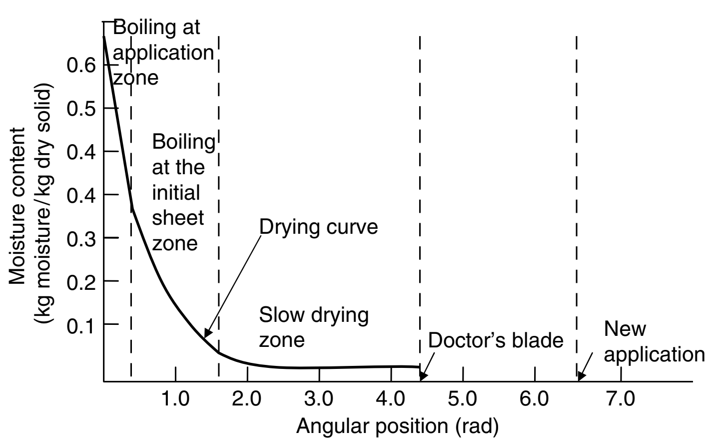

FIGURE 9.11 Moisture content (dry basis) profile of the drum dryer.

9.3.4.2 Initial Sheet Zone

The drying regime of the thin sheet of liquid or paste on the drum surface is dictated by the high temperature and the large heat flux supplied by condensing steam inside the drum (Figure 9.10).[22–26] The heat flux can be as high as 85 kW/m^2.[27] The overall heat transfer coefficient in this zone was reported lower than at the application zone and is between 600 and 1250 W/m^2 °C.[6,19]

Moisture transport in the sheet is predominantly driven by the large temperature gradient and the subsequently large pressure gradient within the sheet (Figure 9.11).[5,22–24,27] Excess surface water in the wet sheet flashes or boils off the sheet and the temperatures of the drum surface continue to fall whereas the product sheet temperature remains constant.[19] The evaporation flux at this point is given by[3]

$$E_1 = 8.64554 \times 10^{-8} u_a^{0.8} (P_p - P_a) \qquad (9.4)$$

where u_a is the velocity of air over the surface of sheet (m/s), P_p is the vapor pressure at product surface (Pa), and P_a is the vapor pressure at ambient temperature (Pa). As soon as the surface moisture dries up, vapor bubbles generated by boiling within the sheet then flash through the sheet. In gelatinized starch sheets, this drying regime tends to form pores within the sheet and craters at the surface.[8,28]

9.3.4.3 Slow Drying Zone

The sheet becomes quite dry very quickly and the temperature of the drum surface as well as that of the sheet start to rise since the thermal capacitance of the drum wall is larger than that of the thin sheet and there is little moisture left to lower the temperature further by boiling. Tang et al.[7] suggests that at this point, the evaporation rate can be estimated by

$$E_1 = 3.6 \times 10^3 h (T_o - T_e)/\Delta H_v \qquad (9.5)$$

where h is a coefficient having a value of between 200 and 2000 W/m^2 °C, depending on the product and its thickness, T_o is the temperature of outer drum surface in °C, and T_e is the temperature of evaporating product surface in °C.

9.3.4.4 Vacuum Drying

The principle of operation of the vacuum drum drying is similar to that of the atmospheric drum drying process as described in the previous section except that both the pressure and temperature of operation are lower.[1–3,29] A heat-sensitive material dried on a vacuum drum dryer suffers less damage and retains most of its structure and functionality than that dried in ordinary atmospheric drum dryer.[30]

9.4 DRY PRODUCT HANDLING

The dry sheet is then scrapped off by a doctor's blade or knife located at about three quadrants away from the feed point. After the sheet is removed by the knife, the temperature of the bare metal rises slightly further until the feed point is reached. The sheet falls into a product trough below the knife and a screw conveyor in the trough transport the dry products away to a milling process where the sheet is crushed to form a powder product.

9.5 CONTROL OF DRUM DRYERS

The control strategy of the drum dryer in the past has always been the basic control for steady operation only without any on-line quality control. The set points for the control variables are developed by trial and error for each product. The temperature of the drum can be controlled independently for the required drying task by setting the steam pressure. In vacuum drum dryers, the pressure of the enclosure and thus the temperature of drying can also be controlled by setting the vacuum pressure. In most cases, the sheet thickness is controlled by setting the nip width and the feed flow rate for asymptotic sheet thickness. The final moisture content is then controlled by varying the drum speed. In cases where the sugar content is high enough for the final sheet to be in a glassy state and sticky, the final temperature and drying rate of the sheet just before the doctor's blade is controlled by blowing cool dry air.

This strategy is adopted because of the sheer complexity of the process and the unavailability in the past of suitable sensors for on-line quality moisture content measurement. The quality of the product such as final moisture content, thickness, porosity, wetting, and rehydration capability (for pregelatinized starch) as well as the right crystal structure (the right therapeutic form for pharmaceuticals) are complex functions of drum speed, temperature, nip width, feed material, feed concentration, and feed-spreading technique. In addition, the final moisture content and thickness of the sheet may not be uniform across the width of the drum dryer that can lead to problems in shelf life and packaging of the product, respectively.

Dynamic drum dryer models that have been developed so far can only predict the final temperature and moisture content.[31–34] These models cannot predict other important quality parameters and are only useful for steady process operation. With the advent of improved infrared technology, the moisture content can be measured by inference using infrared temperature sensors.[35,36]

9.6 DRUM-DRIED PRODUCTS

Products that are suitable for drying on a drum dryer are viscous liquids, slurries, suspensions, and pastes. The final dry products are typically in the form of porous flakes or powders. The drum dryer has been used extensively to dry chemicals and food products. Chemicals that have been successfully dried on a drum dryer are polyacrylamides, and various salts such as silicate, benzoate, propionate, and acetate salts.[1,2] Drum dryers have been successfully used in drying sludge.[37]

The drum dryer is also extensively used to dry and gelatinize or "cook" starch slurries, such as potato,[38] rice,[5,39] wheat,[40–42] maize,[43,44] corn,[45] soybean-banana,[46] and cowpea[47] slurries to produce pregelatinized starch for instant foods. Nonstarch, low-sugar foods, such as tomato puree, milk, skim milk, whey,[4] beef broth, yeast,[48] coffee, and malt extract, have also been successfully dried on a drum dryer.[1,2] Heat-sensitive products such as pharmaceuticals[30] and vitamin-containing products[3] can be dried in a vacuum drum dryer.

Sugar-containing slurries, such as apple puree,[49] apple sauce, citrus pulps,[50] and other fruit juice, have also been successfully dried on drum dryers. However if the sugar content is high, some of the sugar does not crystallize properly as drying proceeds but becomes molten instead at well above the glass transition temperature.[7] The uneven scrapping of the doctor's blade at the rubbery and glassy parts of the sheet forms wrinkles in the sheet which eventually become "sticks" in the final product. The "sticks" reduce the quality of the product by making it very hard to disperse and physically unsatisfactory in appearance. The formation of sticks can be controlled by enhanced cooling and drying of the sheet at the doctor blades by a stream of dry, cool air, and by controlling the sheet thickness using takeoff rolls.[7]

NOMENCLATURE

LATIN SYMBOLS

T_D	sheet thickness on the drum m
T_R	sheet thickness on the roller m
N_D	rotational speed of drum, rpm
N_R	rotational speed of roller, rpm
D_D	diameters of drum, m
D_R	diameters of roller, m
n	the index of power law fluid
g	gravitational constant, m/s
D_i	inner diameter of drum, m
T_s	steam temperature, °C
T_i	inner drum wall temperature, °C
ΔH_v	latent heat of vaporization of steam, J/kg
u_a	velocity of air over the surface of sheet, m/s
P_p	vapor pressure at product surface, Pa
P_a	vapor pressure at ambient temperature, Pa
h	heat transfer coefficient, W/m^2 °C
T_o	temperature of outer drum surface, °C
T_e	temperature of evaporating product surface, °C

GREEK SYMBOLS

λ_l	thermal conductivity of water, W/m °C
ρ_v	density of steam, kg/m^3
ρ_l	density of water, kg/m^3
σ	surface tension of water, N/m
μ_l	viscosity of liquid, Ns/m^2

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