27) PRESERVATION OF FRUITS AND VEGETABLES BY DRYING

I PURPOSES OF DRYING

Drying, in general, usually means removal of relatively small amounts of water from material. The purpose of drying food products is to allow longer periods of storage with minimised packaging requirements and reduced shipping weights. Evaporation refers to removal of relatively large amounts of water from material. In evaporation the water is removed as vapour at its boiling point. In drying the water is usually removed as a vapour by air.

Drying processes can also be categorised according to the physical conditions used to add heat and remove water vapour: (1) in the first category, heat is added by direct contact with heated air at atmospheric pressure, and the water vapour formed is removed by the air; (2) in vacuum drying, the evaporation of water proceeds more rapidly at low pressures, and the heat is added indirectly by contact with a metal wall or by radiation (low temperatures can also be used under vacuum for certain materials that may discolour or decompose at higher temperatures); and (3) in freeze drying, water is sublimed from the frozen material.

The quality of the product and its cost are greatly influenced by the drying operation. The quality of a food product is judged by the amount of physical and biochemical degradation occurring during the dehydration process. The drying time, temperature, and water activity influence the final product quality .Low temperatures generally have a positive influence on the quality but require longer processing times. Low water activity retards or eliminates the growth of micro- organisms, but results in higher lipid oxidation rates. Maillard (non-enzymatic) browning reactions peak at intermediate water activities (0.6 to 0. 7), indicating the need for a rapid transition from medium to high water activities.

Many dried foods are rehydrated before consumption. The structure, density, and particle size of the food plays an important role in reconstitution. Ease of rehydration is increased with decreasing particle size and the addition of emulsifiers such as lecithin or surfactants. Factors that affect structure, density, and rehydration include puffing, vacuum, foaming, surface temperature, low-temperature processing, agglomeration, and surface coating.
Storage stability of a food product increases as the water activity decreases, and the products that have been dried at lower temperatures exhibit good storage stability. Since lipid-containing foods are susceptible to lipid oxidation at low water activities, these foods must be stored in oxygen-impermeable packages. Poor colour retention has been a problem in the freeze-drying of coffee because the number of light-reflecting surfaces is decreased during rapid drying. This problem has been improved by slow freezing, partial melting, and re-freezing to ensure large ice crystal formation. Other food materials have different drying problems and specific solutions must be developed.

Drying or dehydration of foods is used as a preservation technique. Micro organisms that cause food spoilage and decay cannot grow and multiply in the absence of water. Also, many enzymes that cause chemical changes n food and other biological materials cannot function without water. When he water content is reduced below about 10-wt %, the micro-organisms are not active. However, it is usually necessary to lower the moisture content below 5-wt % n foods to preserve flavour and nutrition. Dried foods can be stored for extended periods of time.

Drying methods and processes can be classified in several different ways. Drying processes can be classified as *batch*, where the material so inserted into the drying equipment and drying proceeds for a given period of time, or as *continuous*, where the material is continuously added to the dryer and dried material continuously removed.

The following goals for drying foods have been summarised

1. Product quality

a. Minimal chemical and biochemical degradation reactions
b. Selective removal of water over other salts and volatile flavour and aroma substances Maintenance of product structure (for a structured food) Control of density
c. Rapid and simple rehydration or re-dispersion
d. Storage stability: less refrigeration and packaging requirements
e. Desired colour
f. Lack of contamination or adulteration

2. Process economics

a. Minimal product loss
b. Rapid rate of water removal (high capacity per unit amount of drying equipment)
c. Inexpensive energy source (if phase change is involved) Inexpensive regeneration of mass separating agents
d. Minimal solids handling problems
e. Facility of continuous operation
f. Noncomplex apparatus (reliable and minimal labour requirement).

3. *OTHER:* Minimal environmental impact.

PRETREATING FRUITS &VEGETABLES FOR DRYING

PRETREATING FRUITS

Pre-treatments prevent fruits from darkening. Many light-coloured fruits, such as apples, darken rapidly when cut and exposed to air. If not pre-treated, these fruits will continue to darken after they're dried. Suitability of some fruits are listed in Table 1.

For long-term storage of dried fruit, sulphuring or using a sulphite dip are the best pre-treatment. However, sulphites found in the food after either of these treatments have been found to cause asthmatic reactions in a small portion of the asthmatic population. Thus, some people may want to use the alternative shorter-term pre-treatment.

SULFURING

Sulphuring is an old method of retreating fruits. Sublimed sulphur is ignited and burned in an enclosed box with the fruit. The sulphur fumes penetrate the fruit and act as a pre-treatment by retarding spoilage and darkening of the fruit. The sulphur fumes also reduce the loss of vitamins A and C.

SULFITE DIP

Sulphite dips can achieve the same long-term anti-darkening effect as sulfuring, but more quickly and easily. Either sodium bisulfite, sodium sulfite or sodium meta-bisulfite that are USP (food grade) or Reagent grade (pure) can be used.

ASCORBIC ACID

Ascorbic acid (vitamin C) mixed with water is a safe way to prevent fruit browning. However, its protection does not last as long as sulphuring of sulphating. Ascorbic acid reacts easily with oxygen and diminish oxygen that will be used by phenolase. Ascorbic acid also reduces the o-quinones formed by phenolase to the original o-dihydroxyphenolic compounds. Protection against browning last as long as any ascorbic acid remains. Ascorbic acid (vitamin C) is not satisfactory for apples since internal atmosphere of the slices contains oxygen.

Table 1. Suitability of fruits for drying

Fruit	**Suitability For Drying**	**Suitability For Fruit Leather**	**Fruit**	**Suitability For Drying**	**Suitability For Fruit Leather**
Apples	Excellent	Excellent	Guavas	Not recommended Grainy flesh full of seeds	Only in combination
Apricots	Excellent	Excellent	Melons	Poor	Not recommended
Avocados	Not recommended High fat content	Not recommended	Nectarines	Excellent	Excellent
Bananas	Good	Fair to good	Olives	Not recommended High oil content and bitter flavour	Not recommended
Berries with seeds	Not recommended High seed content	Excellent	Papayas	Good	Better in combination
Blueberries	Fair	Poor unless in combination	Peaches	Excellent	Excellent
Cherries	Excellent	Excellent	Pears	Excellent	Excellent
Citrus fruits	Not recommended Too juicy and pulp lacks firm texture	Only in combination	Persimmons	Fair	Not recommended
Citrus peel	Excellent	Only in combination	Pineapples	Excellent	Excellent
Coconuts	Excellent	Only in combination	Plums	Good	Good
Crab-apples	Not recommended Too small and tart	Only in combination	Pomegranates	Not recommended Full of seeds	Not recommended
Cranberries	Poor	Only in combination	Prune plums	Excellent	Excellent
Currants	Good	Not recommended	Quince	Not recommended Hard flesh and strongly acidic flavour	Not recommended
Dates	Excellent	Only in combination	Rhubarb	Good[9]	Fair
Figs	Excellent	Only in combination	Strawberries	Fair to good	Excellent
Grapes	Excellent	Fair to good			

FRUIT JUICE DIP

A fruit juice that is high in vitamin C can also be used as a pretreatment, though it is not as effective as pure ascorbic acid. Juices high in vitamin C include orange, lemon, pineapple, grape and cranberry. Each juice adds it own colour and flavour to the fruit.

ETHYL OLEATE DIP

Ethyl oleate increase the evaporation rate of water in the initial stages of drying, acts as surfactant by increasing the spreading of free water within the sample and remove the skin wax / cell wall of certain products such as grapes, maize grains, starch pastes.

HONEY DIP

Many store-bought dried fruits have been dipped in a honey solution. A similar dip can be made at home. Honey dipped fruit is much higher in calories.

SYRUP BLANCHING

Blanching fruit in syrup helps it retain colour fairly well during drying and storage. The resulting product is similar to candied fruit. Fruits that can be syrup blanched include: apples, apricots, figs, nectarines, peaches, pears, plums, and prunes.

STEAM BLANCHING

Steam blanching also helps retain colour and slow oxidation. However, the flavour and texture of the fruit is changed.

Pretreatment applications for some fruits are given in Table 2.

CONDITIONING FRUITS

The moisture content of dried fruit should be about 20 percent. When the fruit is taken from the dehydrator, the remaining moisture may not be distributed equally among the pieces because of their size or their location in the dehydrator. Conditioning is the process used to equalise the moisture. It reduces the risk of mould growth.

DRYING VEGETABLES

For vegetables, drying time is crucial to tenderness. The longer the drying time is, the less flavourful and poorer the product. Drying time can be hastened by drying small, uniformly cut pieces. Because they contain less acid than fruits, vegetables are dried until they are brittle. At this stage, only 10 percent moisture remains and no micro-organisms can grow.

Vegetables should be dried immediately after harvesting. To prepare them, wash in cool water to remove soil and chemical residues. Trim, peel, cut, slice or shred vegetables according to the directions for each vegetable (see Table 3). Remove any fibrous or woody portions and core when necessary removing all decayed and bruised areas. Keep pieces uniform in size so they will dry at the same rate. After washing and preparation for drying will result in loss of quality and nutrients.

Table 2. Pretreatment applications for some fruits

Fruit	**Preparation**	**Pretreatment (Choose One)**			**Other**	**Drying Times Dehydrator (hours)***
		Sulfur (hours)	Blanching			
			Steam (minutes)	Syrup (minutes)		
Apples	Peel and core, cut into slices or rings about 1/8-inch thick.		3-5 (depending on texture)	10	-ascorbic acid solution-ascorbic acid mixture -fruit juice dip -sulfite dip	6-12
Apricots	Pit and halve. May slice if desired.	2	3-4	10	-ascorbic acid solution-ascorbic acid mixture -fruit juice dip -sulfite dip	24-36**
Bananas	Use solid yellow or slightly brown-flecked bananas. Avoid bruised or overripe bananas. Peel and slice â-inch to 1/8-inch thick, crosswise or lengthwise.				-honey dip-ascorbic acid solution -ascorbic acid mixture -fruit juice dip -sulfite dip	8-10
Berries	Wash and drain berries. With waxy coating - blueberries, cranberries, currants, gooseberries, huckleberries. Boysenberries and strawberries				-For firm berries Plunge into boiling water 15-30 seconds to "check" skins. Stop cooking action by placing fruit in ice water. -No treatment necessary for soft ones.	24-36
Cherries	Stem, wash, drain, and pit fully ripe cherries. Cut in half, chop or leave whole.			10 (for sour cherries)	-Whole: dip in boiling water 30 seconds or more to "check" skins. -Cut and pitted: no treatment necessary.	24-36
Figs	Select fully ripe fruit. Immature fruit may sour before drying. Wash or clean whole fruit with damp cloth. Leave small fruit whole, otherwise cut in half.	1 (whole)			-Whole: Dip in boiling water 30 seconds or more to "check" skins. Plunge in ice water to stop further cooking. Drain on paper towels.	6-12**
Grapes Seedless: With Seeds:	Leave whole -Cut in half and remove seeds				-Whole: Dip in boiling water 30 seconds or more to "check" skins. Plunge in ice water to stop further cooking. Drain on paper towels. -Halves: No treatment necessary.	12-20
Nectarines and Peaches	When sulfuring, pit and halve; if desired, remove skins. For steam and syrup blanching, leave whole, then pit and halve. May also be sliced or quartered.	2-3 (halves) 1 (slices)	8	10	-ascorbic acid solution-ascorbic acid mixture -fruit juice dip -sulfiting	36-48**
Pears	Cut in half and core. Peeling preferred. May also slice or quarter.	5 (halves) 2 (slices)	6 (halves)	10	-ascorbic acid solution-ascorbic acid mixture -fruit juice dip -sulfiting	24-36**
Persimmons	Use firm fruit of long, soft varieties or fully ripe fruit of round drier varieties. Peel and slice using stainless steel knife.				-may syrup blanch	12-15**
Pineapple	Use fully ripe, fresh pineapple. Wash, peel and remove thorny eyes. Slice lengthwise and remove core. Cut in à-inch slices, crosswise.				-No treatment necessary	24-36
Plums (Prunes)	Leave whole or if sulphuring, halve the fruit.	1			-Sun drying:(whole) dip in boiling water 30 seconds or more to "check" skins. -Oven or dehydrator drying: rinse in hot tap water.	24-36**

*Because of variations in air circulation, drying times in conventional ovens could be up to twice as long. Drying times for sun drying could range from 2 to 6 days, depending on temperature and humidity.
**Drying times are shorter for slices and other cuts of fruit.

Table 3. Suitability of Vegetables For Drying

Suitability of Vegetables For Drying			
Vegetable	**Suitability For Drying**	**Vegetable**	**Suitability For Drying**
Artichokes	Fair	Okra	Fair to good
Asparagus	Poor to fair	Onions	Good to excellent
Beans, green	Fair to good	Parsley	Good
Beans, lima	Fair	Parsnips	Good
Beets	Fair to good	Peas	Fair to good
Broccoli	Not recommended small size and layered leaves; strong flavour	Peppers, green or red	Good
Brussels sprouts	Poor	Peppers, chilli	Excellent
Cabbage	Fair absorbs moisture from the air	Popcorn	Good
Carrots	Good	Potatoes	Good
Cauliflower	Poor	Pumpkins	Fair to good
Celery	Poor	Radishes	Not recommended low quality.
Collard greens	Poor	Rutabagas	Fair to good
Corn, sweet	Good	Spinach	Poor
Cucumbers	Poor	Squash, summer	Poor to fair
Eggplant	Poor to fair	Squash, winter	Not recommended
Garlic	Good	Sweet potatoes	Fair
Horseradish	Good Odour extremely strong during processing;	Swiss chard	Poor
Kale	Poor	Tomatoes	Fair to good absorb moisture which causes undesirable colour and flavour changes
Kohlrabi	Fair	Turnips	Fair to good
Lettuce	Not recommended High water content	Turnip greens	Poor
Mushrooms	Good	Yams	Fair
Mustard greens	Poor	Zucchini	Poor to fair

PRETREATING VEGETABLES

Blanching is a necessary step in preparing vegetables for drying. By definition, blanching is the process of heating vegetables to a temperature high enough to destroy enzymes (catalase and peroxidase) present in the tissue. It stops the enzyme action, which causes loss of colour and flavour during drying and storage. It also sets the colour and shortens the drying and rehydration time by relaxing the tissue walls so moisture can escape or re-enter more rapidly

In water blanching, the vegetables are submerged in boiling water. In steam blanching, the vegetables are suspended above the boiling water and heated only by the steam. Water blanching usually results in a greater loss of nutrients, but it takes less time than steam blanching. (See Table 4). Steam blanching may prevent leakage of nutritive compounds such as water-soluble vitamins. Not all vegetables require blanching. Onions, green peppers and mushrooms can be dried without blanching.

COOLING AND DRYING PREPARED VEGETABLES

After blanching, dip the vegetables briefly in cold water, only long enough to stop the cooking action. However they should not cooled to room temperature. When they feel only slightly hot to the touch, they will be cooled to about 120°F. The heat left in the vegetables from blanching will cause the drying process to begin more quickly.

Table 4. Pretreatments for vegetables

Vegetable	Preparation	Blanching Time		Drying Time Dehydrator *(hours)
		Steam (minutes)	Water (minutes)	
Artichokes, globe	Cut hearts into 1/8-inch strips. Heat in boiling solution of ä cups water and 1 tablespoon lemon juice.		6-8	4-6
Asparagus	Wash thoroughly. Cut large tips in half.	4-5	3à-4à	4-6
Beans, green	Wash thoroughly. Cut in short pieces or lengthwise. (May freeze for 30 to 40 minutes after blanching for better texture.)	2-2à	2	8-14
Beets	Cook as usual. Cool; peel. Cut into shoestring strips 1/8-inch thick.	Already cooked no further blanching required.		10-12
Broccoli	Trim, cut as for serving. Wash thoroughly. Quarter stalks lengthwise.	3-3à	2	12-15
Brussels sprouts	Cut in half lengthwise through stem.	6-7	4à-5à	12-18
Cabbage	Remove outer leaves, quarter and core. Cut into strips 1/8-inch thick.	2½-3^{**}	1à-2	10-12
Carrots	Use only crisp, tender carrots. Wash thoroughly. Cut off roots and tops; preferably peel, cut in slices or strips 1/8-inch thick.	3-3à	3à	110-12
Cauliflower	Prepare as for serving.	4-5	3-4	12-15
Celery	Trim stalks. Wash stalks and leaves thoroughly. Slice stalks.	2	2	10-16
Corn, cut	Select tender, mature sweet corn. Husk and trim. Cut the kernels from the cob after blanching.	5-6	4-5	6-10
Eggplant	Use the directions for summer squash.	3à	3	12-14
Garlic (chard, kale, turnips, spinach)	Peel and finely chop garlic bulbs. No other pretreatment is needed. Odour is pungent.	No blanching needed.		6-8

Greens (chard, kale, turnips, spinach)	Use only young tender leaves. Wash and trim very thoroughly	2-2à	1à	8-10
Horseradish	Wash; remove small rootlets and stubs. Peel or scrape roots. Grate.	None		4-10
Mushrooms (WARNING, see footnote[***])	Scrub thoroughly. Discard any tough, woody stalks. Cut tender stalks into short sections. Do not peel small mushrooms. Peel large mushrooms, slice.	None		8-10
Okra	Wash, trim, slice crosswise in 1/8 to â-inch disks.	None		8-10
Onions	Wash, remove outer "paper shell." Remove tops and root ends, slice 1/8-to â-inch thick.	None		3-9
Parsley	Wash thoroughly. Separate cluster. Discard long or tough stems.	None		1-2
Peas, green	Shell.	3	2	8-10
Peppers and Pimientos	Wash, stem, core. Remove "partitions." Cut into disks about 3/8- by 3/8-inch.	None		8-12
Potatoes	Wash, peel. Cut into shoestring strips â-inch thick, or cut in slices 1/8-inch thick.	6-8	5-6	8-12
Pumpkin and hubbard squash	Cut or break into pieces. Remove seeds and cavity pulp. Cut into 1-inch strips. Peel rind. Cut strips crosswise into pieces about 1/8-inch thick.	2à-3	1	10-16
Squash, summer	Wash, trim, cut into â-inch slices.	2à-3	1à	10-12
Tomatoes, for stewing	Steam or dip in boiling water to loosen skins. Chill in cold water. Peel. Cut into sections about ä-inch wide, or slice. Cut small pear or plum tomatoes in half.	3	1	10-18

[*] Drying times in a conventional oven could be up to twice as long, depending on air circulation.

[**] Steam until wilted.

[***] WARNING: The toxins of poisonous varieties of mushrooms are **not** destroyed by drying or by cooking. Only an expert can differentiate between poisonous and edible varieties.

DRYING PRINCIPLES OF FOODS

Drying is the removal of majority of water from food material and provides maximum concentration and microbial safety, lowers water activity for preservation, minimises rate of biochemical reactions, stabilises nutritional quality and increase shelf life of the food.

Drying is defined as a process of moisture removal due to simultaneous heat and mass transfer. Heat transfer from the surrounding environment evaporates the surface moisture. The moisture can be either transported to the surface of the product and then evaporated, or evaporated internally at a liquid vapour interface and then transported as vapour to the surface.

The transfer of energy (heat) depends on the air temperature, air humidity, airflow rate, exposed area of food material and pressure. The physical nature of the food, including temperature, composition, and in particular moisture content, governs the rate of moisture transfer. The dehydration equipment generally utilises conduction, convection, or radiation to transfer energy from a heat source to the food material. The heat is transferred directly from a hot gas or indirectly through a metal surface.

The model equations for dryers cannot be discussed without a thorough understanding of the basic heat and mass transfer concepts. The typical drying cycle consists of three stages: heating the food to the drying temperature, evaporation of the moisture from the product surface occurring at a rate proportional to the moisture content, and once the critical moisture point is reached, the falling of the drying rate. The critical moisture point depends greatly on the drying rate since high drying rates will raise the critical point and low drying rates will decrease them. Terminology and basic concepts associated with drying will be discussed to facilitate proper selection of dryers.

RATE OF DRYING

During drying, water (liquid or vapour) must make it's way to the surface and is limited by internal resistance based on physical resistance to water migration. Once at the surface, water (liquid or vapour) must be transferred to the drying air and is limited by external resistance based on difference between water vapour pressure in air and at the surface. Drying cases when vapour pressure at the surface equals vapour pressure in the air (See Fig 1.)

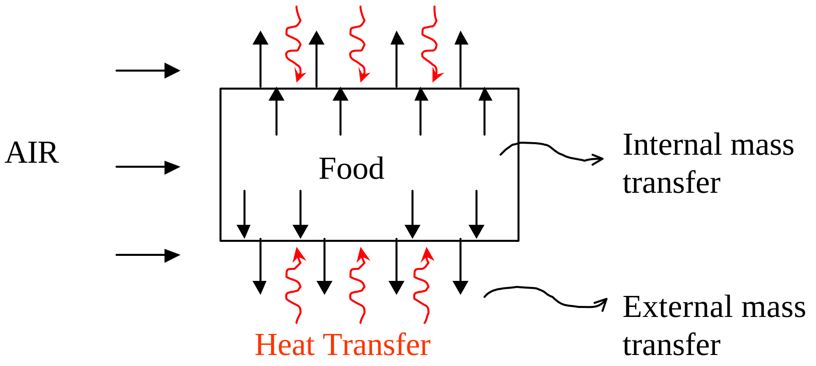

Figure 1. Drying of a food material

To select a dryer, it is necessary to determine the drying rate at a specific air temperature and humidity. These data are scarce for food materials and must be obtained experimentally by plotting the free moisture content versus drying time. This plot is converted to a drying rate curve by calculating the derivative of the curve over the time. Typical curves are shown in

Fig. 2 and 3. At time zero, the moisture content of a solid is given by point A if the solid is at a cold temperature and by A 1 if hot. The drying curve is divided into two distinct portions. The first is the constant-rate period, in which unbound water is removed (line *BC* in Fig.2). Water evaporates as if there is no solid present, and its rate of evaporation is not dependent on the solid. This continues until water from the interior is no longer available at the surface of the

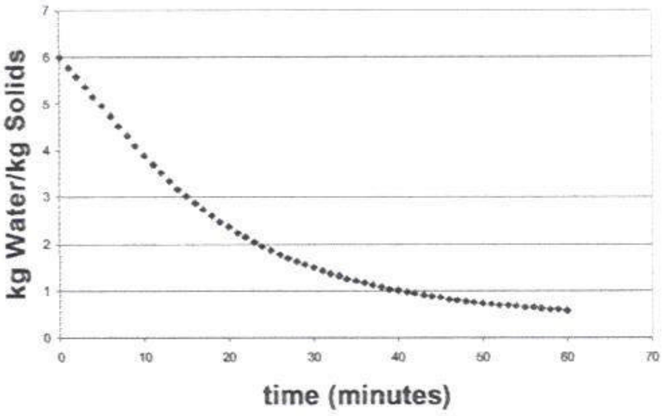

Figure 2. Drying Curve.

food material. Point C distinguishes the constant-rate period from the falling-rate period and is called the *critical moisture content* .The surface of the solid is no longer wet. The falling-rate period has two sections as seen in Fig. 3. From C to *D*, the wet areas on the surface become completely dry. When the surface is dry (point *D)*, the evaporation will continue moving toward the centre of the solid. This is shown by the curve in from *D* to *E* .The water that is removed from the centre of the solid moves to the surface as a vapour. Although the amount of water removed in the falling-rate period is relatively small, it can take considerably longer than in the constant-rate period. In general, increased air velocity and air temperature increase the drying rate, while increased humidity and solid thickness decrease it.

The drying rate in the constant-rate period is determined by conditions external to the material being dried, including temperature, gas velocity, total pressure and partial vapour pressure. Mass transfer during the constant-rate period involves diffusion of water vapour from the material surface through a boundary layer into the drying medium. During the falling-rate period, the drying rate decreases with time, and the rate of internal mass transfer to the material surface typically controls the process. A falling drying rate may be observed when internal mass transfer resistance is controlling and the surface vapour pressure of the solid is decreasing as moisture content drops.

The importance of internal versus external mass transfer resistance can be inferred from drying studies on samples of different size [i.e., varying slab thickness *(1)* or sphere and cylinder radii *(r)]*. The drying time required to reach a given moisture content will be proportional to *1* or r for external mass transfer control and proportional to l^2 or r^2 for control by internal diffusion.

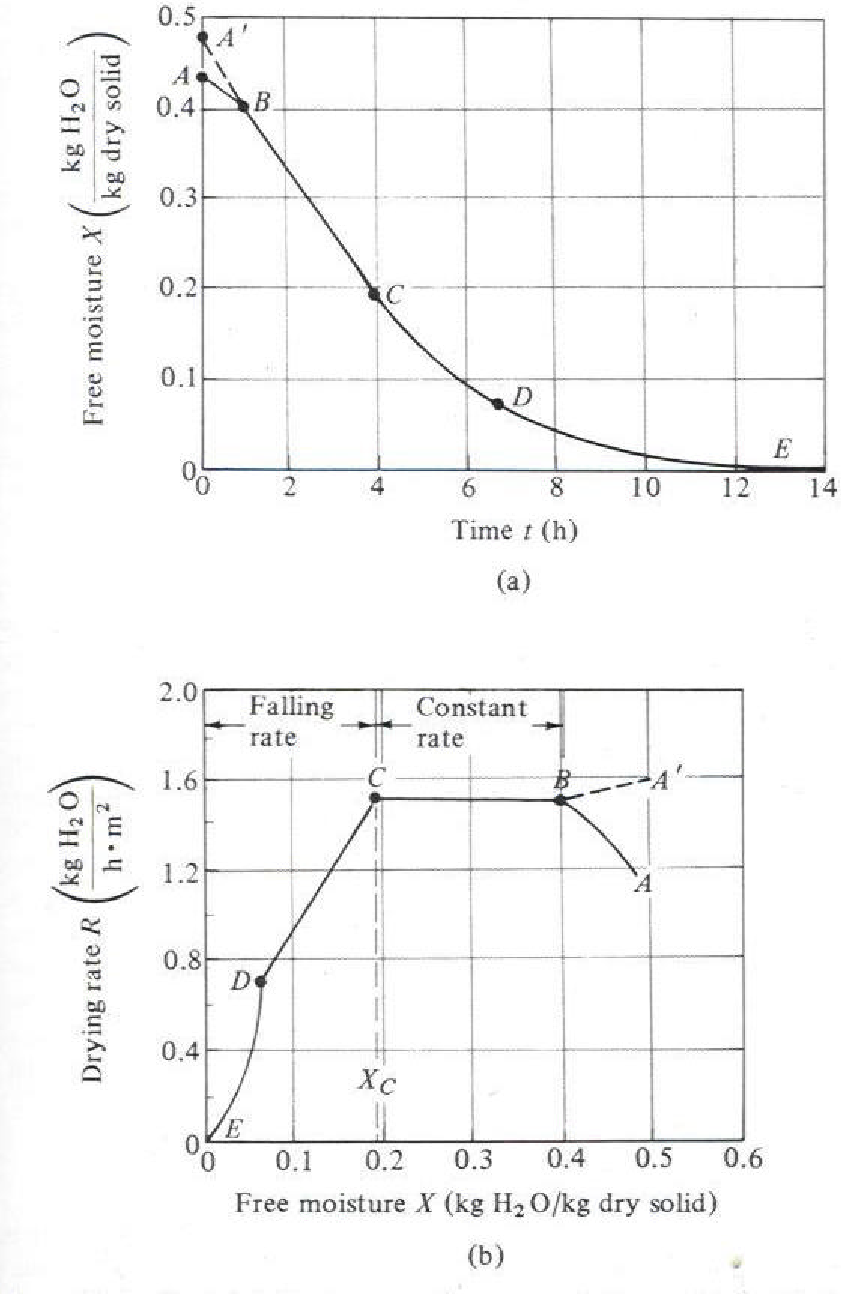

Figure 3. Typical drying –rate curve for constant drying conditions: a) plot of data as free moisture versus time, b) rate of drying curve as rate versus free moisture content.

Rate of Drying

1. Conversion of data to rate -of-drying curve. Data obtained from a batch-drying experiment are usually obtained as W total weight of the wet solid (dry solid plus moisture) at different times t hours in the drying period. These data can be converted to rate-of- drying data in the following ways. First, the data are recalculated. if W is the weight of the wet solid in kg total water plus dry solid and Ws is the weight of the dry solid in kg,

$Xt = (W - Ws)/Ws$ [kg total water/ kg dry solid) Eq. 1

For the given constant drying conditions, the equilibrium moisture content X* kg equilibrium moisture/kg dry solid is determined. Then the free moisture content X in kg free water/kg dry solid is calculated for each value of X t.

$X = Xt - X^*$ Eq. 2

Using the data calculated from Equation 2., a plot of free moisture content X versus time t in h is made as in Fig. 3a. To obtain the rate-of-drying curve from this plot, the slopes of the tangents drawn to the curve in Fig. 3a can be measured, which give values of dX/dt at given values of t. The rate R is calculated for each point by

$R = -Ls/A\,(dX/dt)$ Eq. 3

2. Plot of rate-of-drying curve. In Fig. 3b the rate-of-drying curve for constant- drying conditions is shown. At zero time the initial free moisture content is shown at point A. In the beginning the solid is usually at a colder temperature than its ultimate temperature, and the evaporation rate will increase. Eventually at point B the surface temperature rises to its equilibrium value. Alternatively, if the solid is quite hot to start with, the rate may start at point A'. This initial unsteady-state adjustment period is usually quite short and it is often ignored in the analysis of times of drying.

From point B to C in Fig. 3a the line is straight, and hence the slope and rate are constant during this period. This constant-rate-of-drying period is shown as line BC in Fig. 3b.

At point C on both plots, the drying rate starts to decrease in the falling-rate period until it reaches point D. In this first falling-rate period, the rate shown as line CD in Fig. 3b is often linear.

At point D the rate of drying falls even more rapidly, until it reaches point E, where the equilibrium moisture content is X* and $X = X^* - X^* = 0$. In some materials being dried, the region CD may be missing completely or it may constitute all of the falling-rate period.

Drying in the Constant-Rate Period

Drying of different solids under different constant conditions of drying will often give curves of different shapes in the falling-rate period, but in general the two major portions of the drying-rate curve-constant-rate period and falling-rate period-are present.

In the constant-rate drying period, the surface of the solid is initially very wet and a continuous film of water exists on the drying surface. This water is entirely unbound water and the water acts as if the solid were not present. The rate of evaporation under the given air conditions is independent of the solid and is essentially the same as the rate from a free liquid surface. Increased roughness of the solid surface, however, may lead to higher rates than from a flat surface.

If the solid is porous, most of the water evaporated in the constant-rate period is supplied from the interior of the solid. This period continues only as long as the water supplied to the surface as fast as it is evaporated. Evaporation during this period is similar to that in determining the wet bulb temperature, and in the absence of heat transfer by radiation or conduction, the surface temperature is approximately that of the wet bulb temperature. Constant rate period can be calculated by the Eq. 4.

$t_c = Ls/A.R_c(X_c - X_i)$ Eq. 4.

Drying in the Falling-Rate Period

Point C in Fig. 3b is at the *critical free moisture content Xc.* At this point there is insufficient water (in the surface to maintain a continuous film of water. The entire surface is no longer wetted, and the wetted area continually decreases in this first falling-rate period until the surface is completely dry at point *D* in Fig. 3b.

The second falling-rate period begins at point *D* when the surface is completely dry. The plane of evaporation slowly recedes from the surface. Heat for the evaporation is transferred through the solid to the zone of vaporisation. Vaporised water moves through the solid into the air stream.

In some cases no sharp discontinuity occurs at point D, and the change from partially wetted to completely dry conditions at the surface is so gradual that no sharp change is detectable.

The amount of moisture removed in the falling-rate period may be relatively small but the time required may be long. This can be seen in Fig. 3. The period BC for constant-rate drying lasts for about 3.0 h and reduces X from 0.40 to about 0.19, a reduction of 0.21 kg H_2O/kg dry solid. The falling-rate period CE lasts about 9.0 h and reduces X only from 0.19 to 0.

Moisture Movements in Solids During Drying in the Falling-Rate Period

When drying occurs by evaporation of moisture from the exposed surface of a solid, moisture must move from the depths of the solid to the surface. The mechanisms of the movement affect the drying during the constant-rate and falling-rate periods. Some of the theories advanced to explain the various types of falling-rate curves will be briefly reviewed.

1. Liquid diffusion theory: In this theory diffusion of liquid moisture occurs when there is a concentration difference between the depths of the solid and the surface. This method of transport of moisture is usually found in nonporous solids where single-phase solutions are formed with the moisture, such as n paste, soap, gelatine, and glue. This is also found in drying the last portions of moisture from clay, flour, wood, leather, paper, - starches, and textiles. In drying many food materials, the movement of water in the falling-rate period occurs by diffusion.

The moisture diffusivity D_{AB} usually decreases with decreased moisture content, so that the diffusivities are usually average values over the range of concentrations used. Materials drying in this way are usually said to be drying by diffusion, although the actual mechanisms may be quite complicated. Since the rate of evaporation from the surface is quite fast, i.e., the resistance is quite low, compared to the diffusion- rate through the solid in the falling-rate period, the moisture content at the surface is at the equilibrium value:

The shape of a diffusion-controlled curve in the falling-rate period is similar to Fig. 4. If the initial constant-rate drying is quite high, the first falling-rate period of unsaturated surface evaporation may not appear. If the constant-rate drying is quite low, the period of unsaturated surface evaporation is usually present in region CD in Fig. 3b. and the diffusion-controlled curve is in region DE.

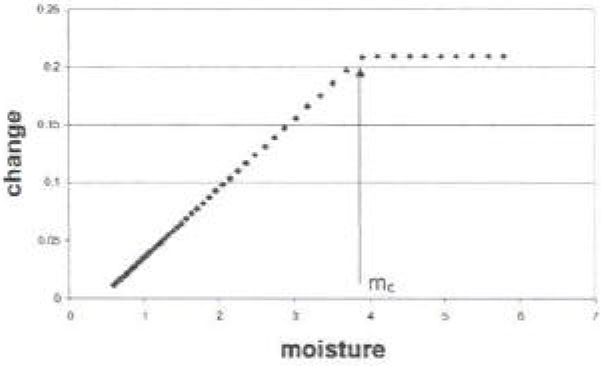

Figure 4. Drying curve: diffusion controlled falling rate period.

2. Capillary movement in porous solids. When granular and porous solids such as clays, sand, soil, plant pigments, and minerals are being dried, unbound or free moisture moves through the capillaries and voids of the solids by capillary action, not by diffusion. This mechanism, involving surface tension, is similar to the movement of oil in a lamp wick.

A porous solid contains interconnecting pores and channels of varying pore sizes. As water is evaporated, a meniscus of liquid water is formed across each pore in the depths of the solid. This sets up capillary forces by the interfacial tension between the water and solid. These capillary forces proved the driving force for moving water through the pores to the surface. Small pores develop greater forces than those developed by large pores.

At the beginning of the falling-rate period at point C in Fig 3b, the water is being brought to the surface by capillary action, but the surface layer of water starts to recede below the surface. Air rushes in to fill the voids. As the water is continuously removed, a point is reached where there is insufficient water left to maintain continuous films across the pores, and the rate of drying suddenly decreases at the start of the second falling-rate period at point D. Then the rate of diffusion of water vapour in the pores and rate of conduction of heat in the solid may be the main factors in drying.

3. Effect of shrinkage. A factor often greatly affecting the drying rate is the shrinkage of the sold as moisture is removed. Rigid solids do not shrink appreciably, but colloidal and fibrous materials such as vegetables and other foodstuffs do undergo shrinkage. The most serious effect is that there may be developed a hard layer on the surface, which is impervious to the flow of liquid or vapour moisture and slows the drying rate; examples are clay and soap. In many foodstuffs, if drying occurs at too high a temperature, a layer of closely packed shrunken cells, which are sealed together, forms at the surface. This presents a barrier to moisture migration and is known as case hardening. Another effect of shrinkage is to cause the material to warp and change its structure. This can happen n drying wood.

Sometimes to decrease these effects of shrinkage, it is desirable to dry with moist air. This decreases the rate of drying so that the effects of shrinkage on warping or hardening at the surface are greatly reduced. Probably the most important factor in drying calculations is the Length of time required to dry a material from a given initial free moisture content X to a final moisture content X_2 .For drying in the constant-rate period, we can estimate the time.

Effects of Process variables on Constant Rate Period

a. Air velocity
b. Gas Humidity
c. Gas Temperature
d. Thickness of the solid being dried

Rate of drying can be calculated using an empirical formula;

First approximation is to use empirical model:

$dm/dt = -k.m$ Eq. 5

Integration results;

$(m-m_e) / (m_c-m_e) = \exp(-k.t)$ Eq. 6

in the following model (where m_c is the critical moisture content and m_e is the final equilibrium moisture content).

Material and Heat Balances for Continuous Dryers

Simple heat and material balances. In Fig. 5 a flow diagram is given for a continuous-type dryer where the drying gas flows counter currently to the solids flow. The solid enters at a rate of Ls kg dry solid/h. having a free moisture content X_1 and temperature T_S. It leaves at X_2 and T_{S2} .The gas enters at a rate G kg dry air/h, having a humidity H_2 kg H_2O/kg dry air and a temperature of T_{G2} .The gas leaves at T_G and H_1.

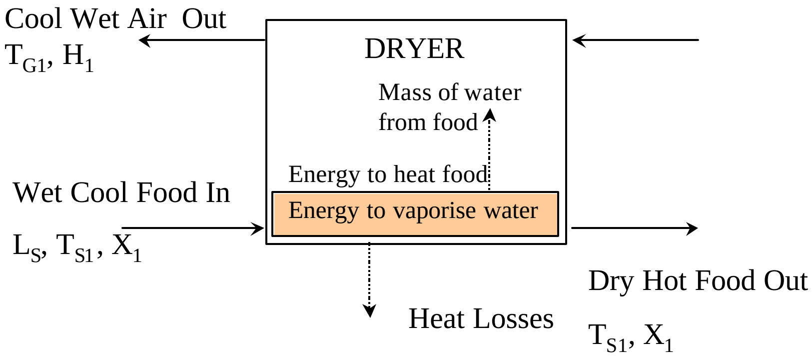

Figure 5. A flow diagram for a continuous-type dryer where the drying gas flows counter currently to the solids flow.

For a material balance on the moisture,

$G . H_2 + L_s X_t = G . H_1 + L_S . X_2$ Eq. 7

For a heat balance a datum of T_o°C is selected. A convenient temperature is 0°C (32°F). The enthalpy of the wet solid is composed of the enthalpy of the dry solid plus that of the liquid as free moisture. The heat of wetting is usually neglected. The enthalpy of the gas H_G' in kJ/kg dry air is

$H_G' = c_s(T_G - T_o) + H?_o$ Eq. 8

where ?$_{o}$ is the latent heat of water at T_o °C, 2501 kJ/kg (1075.4 btu/lb_m) at 0°C, and c_s is the humid heat, given as kJ/kg dry air. K.

$c_s = 1.005 + 1.88H$ Eq. 9

The enthalpy of the wet solid Hs in kJ/kg dry solid, where $(T_S - T_o)^oC = (T_S - T_o)$ K, is

$H_s' = c_{pS}(T_S - T_o) + X\,C_{pA}(T_S - T_o)$ Eq. 10

where c_{pS} is the heat capacity of the dry solid in kJ/kg dry solid .K and C_{pA} is the heat capacity of liquid moisture in kJ/kg H_2O .K. The heat of wetting or adsorption is neglected.

A heat balance on the dryer is

$GH'_{G2} + L_S H'_{S1} = GH'_{G1} + L_S H'_{S2} + Q$ Eq. 11

where Q is the heat loss in the dryer in kJ/h. For an adiabatic process Q = 0, and if heat is added, Q is negative.

Driving Forces for the rate considerations are

1. Differential water vapour pressure between food and atmosphere
2. Increased by raising food temperature, lowering atmospheric pressure, lowering atmospheric humidity
3. Resisting forces
4. Tortousity of the path for water and water vapour to escape from food
5. Increased by food thickness

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