CHAPTER III

THEORY OF DRYING

3.1 Preparations of Fruit Preliminary to Drying

Numerous preliminary preparations are necessary before a fruit is dried. Selection of size and maturity (ripeness) is particularly important from the standpoint of uniform driness of the finished product. Many kinds of raw fruit should be washed clean prior to dry. Certain fruits require peeling either by hand or by power-operated machinery. Some are also pitted, halved, quartered, sliced or shredded, thereby eliminating stones, cores, seeds or other tissues. Others are sometimes dipped for a few seconds in hot water or caustic solutions, such as sodium hydroxide or sodium carbonate, in order to remove the waxy bloom and check the skin. These treatments often hasten the drying process.

Some fruits, such as apricot and peach, which are not ordinarily blanched, are treated by exposure to the fumes of burning sulphur or sulphuring after cutting and pitting. This sulphuring process prevents darkening and brown discoloration during dehydration and subsequent storage. It also kills any insect present in the medium. Whole, halved or sliced fruits to be dried are exposed to fumes of burning sulphur in a sulphur house. The amount of sulphur used, time of exposure and desired of SO_2 vary, depending upon the type of fruit, its moisture content, pretreatment method and limitation by the final SO_2 content. The allowable limits of sulphur dioxide in dried fruits vary greatly from country to country (0 to 2,500 parts per million).

In sulphite dipping, whole, halved or sliced fruits (peeled or unpeeled) are dipped in a substitute of sodium bisulphite of 1 to 2 % strength. This method has been used to a very limited extent as a substitute for sulphuring in fumes of burning sulphur.

3.2 Definitions of Terms Uesed

3.2.1 Moisture Content is expressed as the amounts of moisture contained in a unit mass of dry (dry basis) or wet solid (Wet basis).

$$W_d \text{ (dry basis)} = (m-m_d)/m_d$$

$$W_w \text{ (wet basis)} = (m-m_d)/m$$

Unless specified otherwise, dry basis moisture content is assumed throughout.

3.3.2. Bone Dry Solid is a solid obtained by drying in a vacuum dryer at about 85°c for a long time.

3.2.3 Free Moisture Content is the moisture content which is removable at a given temperature and humidity.

3.3.4 Critical Moisture Content is the average moisture content at which the constant-rate period ends.

3.3.5 Equilibrium Moisture Content is the lowest moisture content to which a given material can be dried under constant specific conditions of air temperature and humidity.

3.3.6 Relative Humidity is the ratio of the mole fraction (or vapor pressure) of water vapor in the air to the mole fraction (or vapor pressure) of water vapor in saturated air at the same temperature and (atmospheric) pressure.

3.3.7 Humidity is the water vapor contained in moist air per unit mass of dry air.

3.3.8 <u>Dry-bulb Temperature</u> is the temperature of moist air indicated by an ordinary thermometer.

3.3.9 <u>Wet-bulb Temperature</u> is the temperature of moist air indicated by a thermometer whose bulb is covered with a wet wick.

3.3.10 <u>Drying Rate</u> is expressed as the mass of evaporate water per time-mass of dry material

$$R_w = \frac{-d\ W}{d\theta}$$

$$R = R_w(m_d/A)$$

R_w is assumed throughout.

3.3.11 <u>Bound Liquid</u> in a solid is that liquid which exerts a vapor pressure less than that of the pure liquid at the given temperature. Liquid may become bound by solution in cell or fiber walls, by homogenous solution throughout the solid, and by chemical or physical adsorption on solid surface.

3.3.12 <u>Unbound Liquid</u> in a hygroscopic material is the moisture in the excess of the equilibrium moisture content corresponding to saturation humidity. All water in a non-hygroscopic material is unbound liquid.

3.3 <u>Principle of Drying</u>

3.3.1 <u>General Drying Behavior</u>

In drying a wet solid with a gas of fixed temperature and humidity, the drying rate curve can be roughly divided into two sections; namely constant-rate period and falling rate period. Figures 3.1 and 3.2 respectively show typical drying curves, on the basis of moisture content versus time and of drying rate versus moisture content.
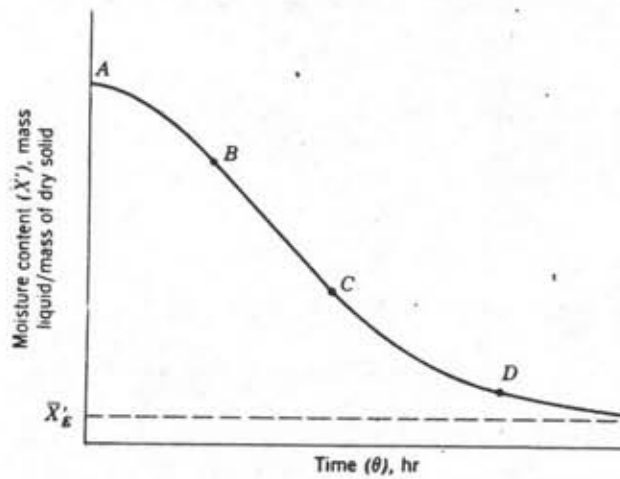
3.1 TYPICAL MOISTURE CONTENT VS. TIME FOR CONSTANT DRYING CONDITIONS
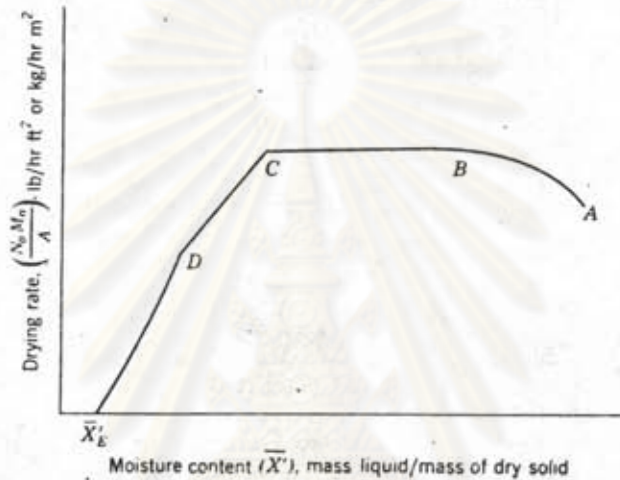
3.2 TYPICAL DRYING RATE VS. TIME FOR CONSTANT DRYING CONDITIONS

Immediately after contact between the sample and drying medium, the solid temperature adjusts itself until it reaches a steady state. The drying period represented by segment AB of the curves in Figure 3.1 and 3.2 is the unsteady state period during which the solid temperature and the rate of drying may increase or decrease to reach the steady state condition. At steady state, a temperature probe would find the temperature of the wet-solid surface to be the wet-bulb temperature of the drying medium.

The temperatures within the drying solid would also tend to equal the wet-bulb temperature of the gas. They are found to be quite stable and the drying rate also remains constant. This is the so-called constant-rate drying period represented by segment BC of the drying

curves in Figure 3.1 and 3.2. The constant rate drying regime continues as long as the mass that is evaporated from the surface is continuously replaced by the movement of liquid from the interior of the stock. The period ends when the solid reaches the critical moisture content. If the initial moisture content of the solid is below the critical moisture content, the constant-rate period does not occur. Beyond this point, the surface temperature rises and the drying rate falls off. This is the so-called first falling-rate drying period, represented by segment CD in Figure 3.1 and Figure 3.2. Subsequently the surface becomes more and more depleted in liquid because the rate of liquid movement to the surface is slower than the rate of mass transfer from the surface, until point D is reached, at which there is no significant area of liquid-saturated surface. Portion of the surface that is saturated dries by convective transfer of heat from and mass to the drying gas stream. Vapor the inner core of the sample first diffuses to the part of the surface that is not saturated and then continues its diffusion to the gas stream. At moisture contents lower than point D in Figure 3.2, all evaporation occurs from the interior of the solid. The moisture content continues to fall and the path for diffusion of heat and mass grows longer, while the concentration (moisture) gradient eventually decreases until there is no further drying at equilibrium moisture content. This period is called the second the second falling rate period.

3.3.2 Batch Drying Time and Production Rate

In the design of dryers, and important quantity is the time required for drying the material under the constant conditions.

1. Constant-rate period

$$R_c = G_o(H_2 - H_1) = G_o C_H \frac{(t_1 - t_2)}{\gamma_w} \qquad (3.1)$$

$$R_w = R_c (A/m_d) \qquad (3.2)$$

$$\theta_c = \frac{\rho_b L(W_1 - W_c)}{R_c} \qquad (3.3)$$

2. Falling-rate period

$$\theta_d = \int_{W_c}^{W_2} \frac{-d\theta}{dW} \, dW \qquad (3.4)$$

Then the drying time (θ_2) is given by integral
the area under the curve.

Total drying time $= \theta_c + \theta_d$ (see Figure 3.3)
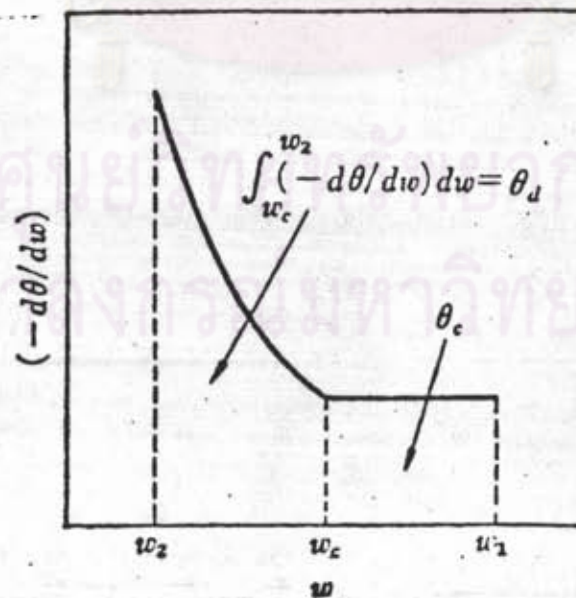

FIGURE 3.3 THE DETERMINATION OF DRYING RATE

The dry-materials production rate P often provides a more informative guide to the performance of a dryer.

$$P = \frac{AL \rho_s (1-\varepsilon)}{\theta} \qquad (3.5)$$

3.3.3 Classification of Types of Materials and Corresponding to Drying Characteristic Curves

Generally drying characteristics vary from one material to another, even if they are of the same shape. The drying characteristics depend primarily on the properties of the water contained within a material, Such factors as the hydrophilicity or hydrophobicity of the material and its pore structures play an important role in determining the drying characteristics. On the other hand, even for the same material, the drying characteristics may vary remarkable according to its shapes. The classification of types of materials is as follows.

A. Non-Hygroscopic Capillary-Porous Media

Some examples are packings of sand, crushed minerals, nonhygroscopic crystals, polymer particles, some ceramics. The defining criterial are:

1. There is a recognizable pore space. The pore space is filled with liquid when the capillary-porous medium is completely saturated, and filled with air when the medium is completely dry.

2. The amount of physically bound water is negligible, i.e., the equilibrium moisture content is usually very close to zero.

3. The medium does not shrink during drying.

Figure 3.5 (a) depicts the probable moisture-content profiles, initially uniform but soon adopting the parabolic form characteristic of the regular regime. The critical point occurs when the moisture content at the exposed surface becomes zero.

B. Hygroscopic Porous Media

Some example are clay, molecular sieves, wood and textiles. This category might be furthur classified into:

a. hygroscopic capillary-porous materials (micropores and macropores) including bidisperse media, for example, wood, clay and textiles.

b. strictly hygroscopic media (only micropores: silica gel, alumina, zeolites)
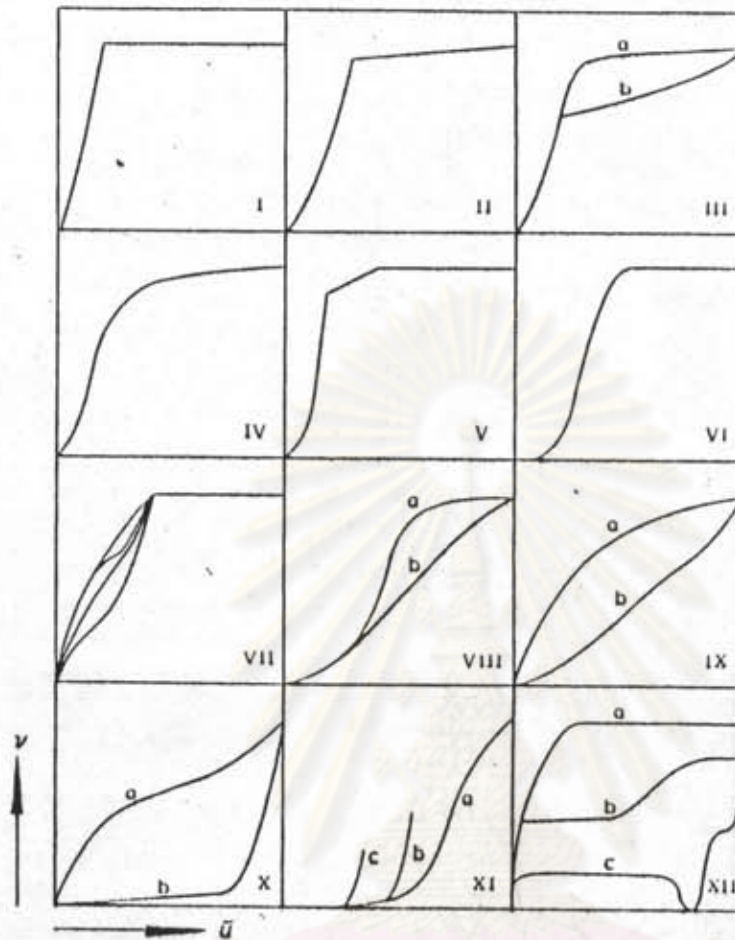
Figure 3.4 NORMALIZED DRYING RATE CURVE $\nu(\bar{\nu})$ FOR DIFFERENT TYPES OF MEDIA.

Unless noted otherwise, the evaporating liquid is
water. For comparison all curves extend from (1.1)to(0.0). Class 1:
glass beads, sand, clay, ,ixtures of sand and clay, calcium carbonate,
silica gel, paper pulp, leather, pig manure, class 11: glass beads,
ceramic tiles, clay, silica gel. ClassIII: liquids in glass beads,
for example, (a)benzene and n-propanol, (b) n-pentanol, Class IV:
glass beads, polystyrene beads. Class V: sand, plastic-clay mix,
silica-brick mix, whiting slab, ceramic plate, leather, lactose
granulation. Class VI: special case of class 1; Schlunder reports
that for molecular sieves $\nu(\bar{\nu})$ is independent of T". Class VII: class
1 with diferent curvatures during the period of decreasing drying rate,

aluminum silicate particles as a function of air temperature temperature
and sand and paper pulp as a function of thickness of the dample.
Class VIII: (a) fir wood; (b) cypress wood. Class IX: (a) paper,
aluminum stearate, dough; (b) potatoes, tapioca tuber, and rice flour
(this laboratory). Class X: (a) rye bread,yeast; (b) butter and margarine.
Class XI: (a) wheat corns; (b)and (c) the same for lower X_o normalized
to the initial drying rate for (a). Class XII: limestone granules
saturated with(a) water, (b) 0.05-M NaCl, (c) 0.35-M NaCl. Similar
behavior, due to crust formation, has been observed for plaster tiles
and for clay.

The defining criteria are:

1. There is a clearly recognizable pore space.

2. There is large amount of physically bound liquid

3. shrinkage often occurs in the initial stage of drying.

The moisture profiles (see Figure 3.5) attain a parabolic
form as long as the moisture is unbound; the s-shaped nature of the
moisture isotherm results in the profiles becoming flattened sigmoids
over the hygroscopic-moisture zone.

C. Colloidal (non-porous) Medium

Some examples are soap, glue, certain polymers (e.g.
nylon) and various food products.

The defining criteria are:

1. There are no pore space (evaporation can take
place only at the surface) and no penetration of air in wet solid.
Moisture moves by diffusion under an ever-diminishing concentration
gradient, and drying rate dwindles without the apperance of any
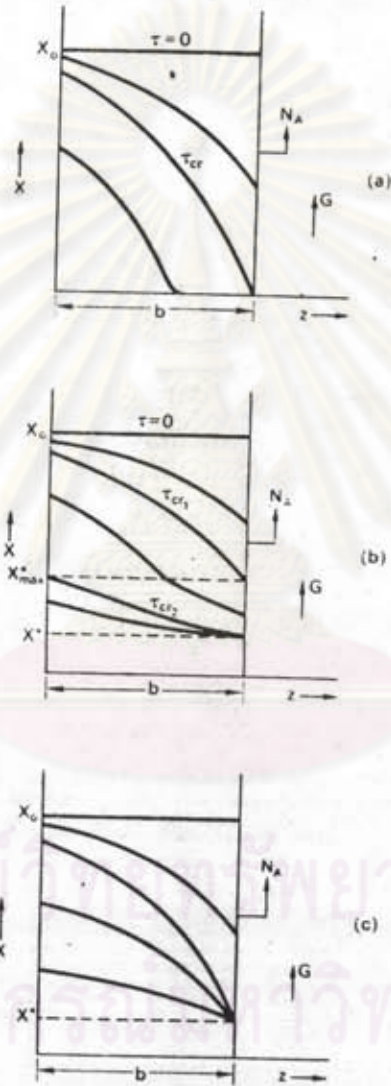critical point.

2. All liquid is physically bound.

Fig. 3.5. VARIATION OF MOISTURE-CONTENT PROFILES WITH TIME. (a) Non-hygroscopic capillary-porous materials; (b) hygroscopic capillary-porous materials; (c) hygroscopic non-porous materials.

21

The moisture-content profiles are parabolas, which flatten as the equilibrium moisture content is approached, Figure 3.5 (c).

Of course, the above classifications apply only to homogeneous media, which can be considered as continua for transport. Many practical systems do not meet this criterion.

Roughly speaking, class I-VIII in Fig 3.4 are for capillary- and hygroscopic porous media. Class IX and X are for colloid media and class XI and XII give examples of special cases.