Drying/Dehydration

Drying is one of the most ancient methods of food preservation known to mankind. Preservation of meat, fish and food plants by drying in the sun or in the naturally dry air of the deserts and mountains has been practiced since prehistoric times and is still a vital operation in the life of many rural communities.

The main purpose of dehydration is to extend the shelf-life of foods by a reduction in water activity. This inhibits microbial growth and enzyme activity, but the processing temperature is usually insufficient to cause their inactivation. Therefore any increase in moisture content during storage can result in rapid spoilage. Similarly, any pathogenic spores in the food are not destroyed by processing and can present a hazard when the food is consumed, especially if it is not cooked before consumption. Drying also causes deterioration of both the eating quality and the nutritional value of the food. The design and operation of dehydration equipment aim to minimise these changes by selection of appropriate drying conditions for individual foods.

The reduction in weight and bulk of dried foods reduces transport and storage costs. Dehydration also provides convenient products that have a long shelf-life at ambient temperature for the consumer, or ingredients that are more easily handled by food processors

Theory of drying

Dehydration involves the simultaneous application of heat and removal of moisture by evaporation from foods. There are a large number of factors that control the rate at which foods dry, which can be grouped into categories related to the processing conditions, the nature of the food and the design of dryers. Drying processes are based on either the use of hot air or heated surfaces.

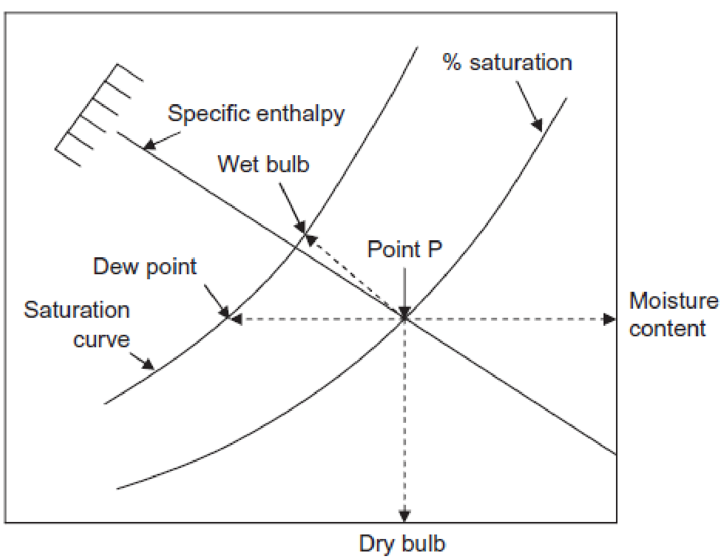

Fig.1. The psychrometric state of air at point P on a psychrometric chart.

Drying using heated air

i. Psychrometrics

Psychrometry is the study of interrelated properties of air-water vapour systems that control the capacity of air to remove moisture from a food. These are:

- The amount of water vapour already carried by the air
- The air temperature
- The amount of air that passes over the food.

The interrelationship of moisture carried by the air and the air temperature is shown in Fig.1. The amount of water vapour in air is expressed as either absolute humidity (W) (termed 'moisture content' in Fig. 1 and also known as the 'humidity ratio'), which equals the mass of water vapour per unit mass of dry air in kg per kg (Eq. 1), or as relative humidity (% RH) (Eq.2).

$$W = m_w/m_a \qquad \text{---(Eq. 1)}$$

where m_w (kg)=mass of water and m_a (kg)=mass of dry air.
RH is defined as 'the ratio of the partial pressure of water vapour in the air to the pressure of saturated water vapour at the same temperature, multiplied by 100'.

$$RH = (\rho_w/\rho_{ws}) \times 100 \qquad \text{---(Eq. 2)}$$

where ρ_w (kPa)=partial pressure of water vapour in the air and ρ_{ws} (kPa)=saturated water vapour pressure at the same temperature.

The amount of heat needed to raise the temperature of an air-water vapour mixture is known as the 'humid heat' and corresponds to the sensible heat used to heat solids or liquids. The temperature of the air is termed the 'dry-bulb' temperature. Heat absorbed from the air by the food both raises the temperature of the food and provides the latent heat needed to evaporate moisture from the surface. Heat is then lost due to evaporation and the temperature falls (known as 'evaporative cooling'). A steady state is achieved when the heat flow from air to the food equals the latent heat of vaporisation required to evaporate the moisture. This lower temperature is known as the 'wet-bulb' temperature (from original measurements made using a thermometer bulb surrounded by a wet cloth). The difference between the wet and dry bulb temperatures is used to find the relative humidity of air on a psychrometric chart (Fig. 1). An increase in air temperature, with a reduction in RH, causes water to evaporate more rapidly from a wet surface and therefore produces a greater drying effect.

The dew point is the temperature at which air becomes saturated with moisture (100% RH) and any further cooling from this point causes condensation of moisture from the air. These properties are conveniently represented on a psychrometric chart. Adiabatic cooling lines are the parallel straight lines sloping across the psychrometric chart, which show how absolute humidity decreases as the air temperature increases.

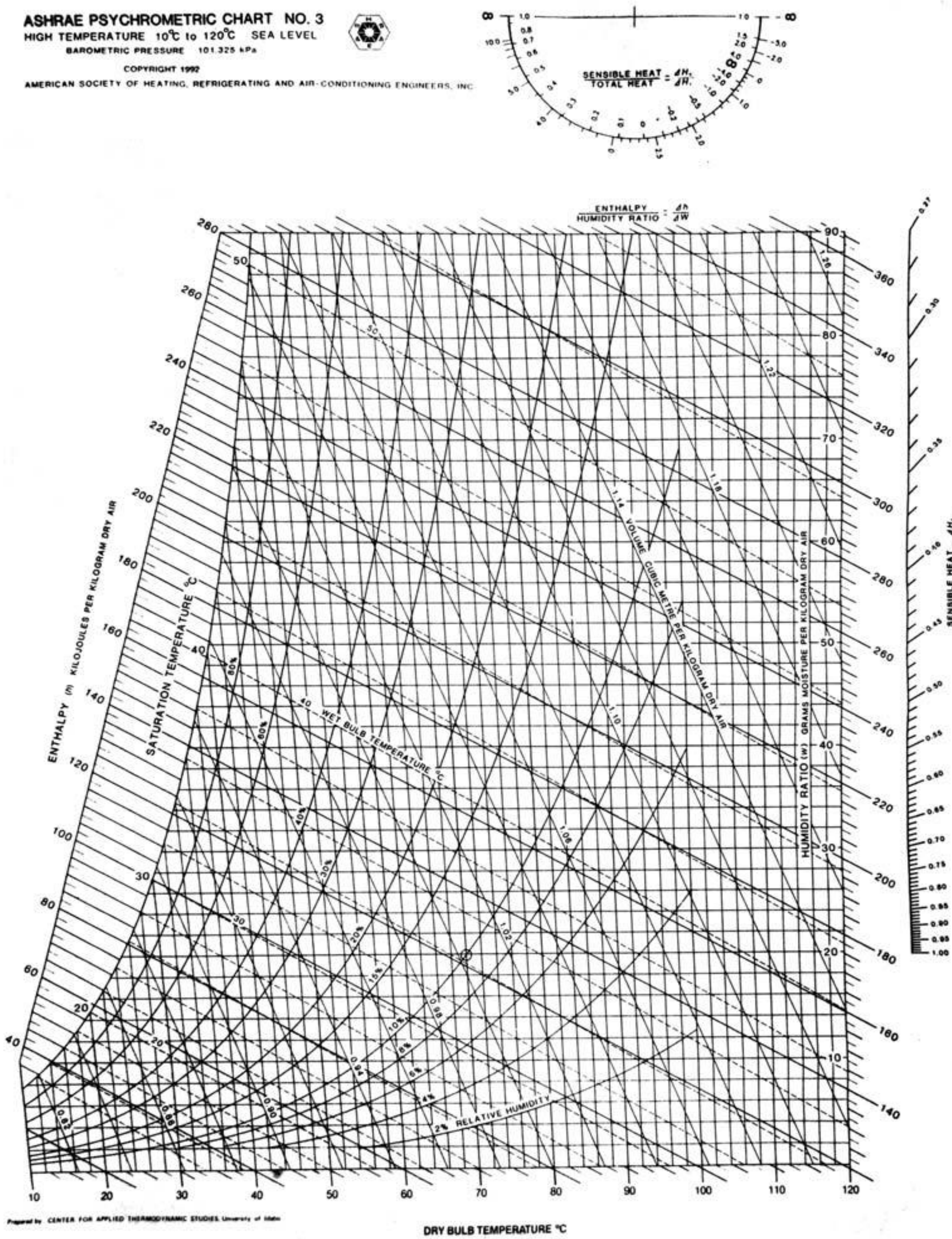

Fig. 2. Psychrometric chart based on barometric pressure of 101.3 kPa. Courtesy of ASHRAE Inc.

ii. Mechanism of drying

The third factor that controls the rate of drying, in addition to air temperature and humidity, is the air velocity. When hot air is blown over a wet food, water vapour diffuses through a boundary film of air surrounding the food and is carried away by the moving air (Fig.3). A water vapour pressure gradient is established from the moist interior of the food to the dry air. This gradient provides the 'driving force' for water removal from the food. The boundary film acts as a barrier to both heat transfer and the removal of water vapour. The thickness of the film is determined mostly by the air velocity; low-velocity air produces thicker boundary films that reduce the heat transfer coefficient and slow removal of moisture. When water vapour leaves the surface of the food, it increases the humidity of the air in the boundary film. This reduces the water vapour pressure gradient and hence slows the rate of drying. Conversely, fast-moving air removes humid air more quickly, reduces the thickness of boundary film and increases the water vapour pressure gradient - hence increasing the rate of drying. In summary, the three characteristics of air that are necessary for successful drying when the food is moist are:

1. A moderately high dry-bulb temperature
2. A low RH
3. A high air velocity.

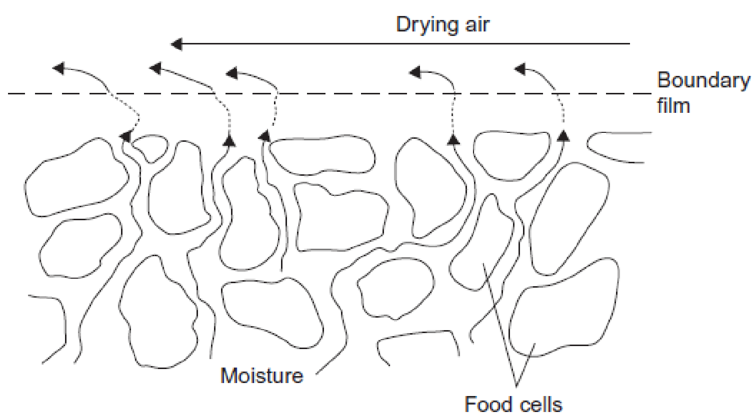

Fig. 3. Movement of moisture during drying.

Constant rate period

When food is placed in a dryer, there is a short initial settling down period as the surface heats up to the wet-bulb temperature (A-B in Fig. 4A). Drying then commences and, provided that water moves from the interior of the food at the same rate as it evaporates from the surface, the surface remains wet. This is known as the constant-rate period and continues until a certain critical moisture content is reached (B-C in Fig. 4A and B). The surface temperature of the food remains close to the wet-bulb temperature of the drying air until the end of the constant-rate period, due to the cooling effect of the evaporating water. In practice, different areas of the food surface dry out at different rates and, overall, the rate of drying declines gradually towards the end of the 'constant'-rate period.

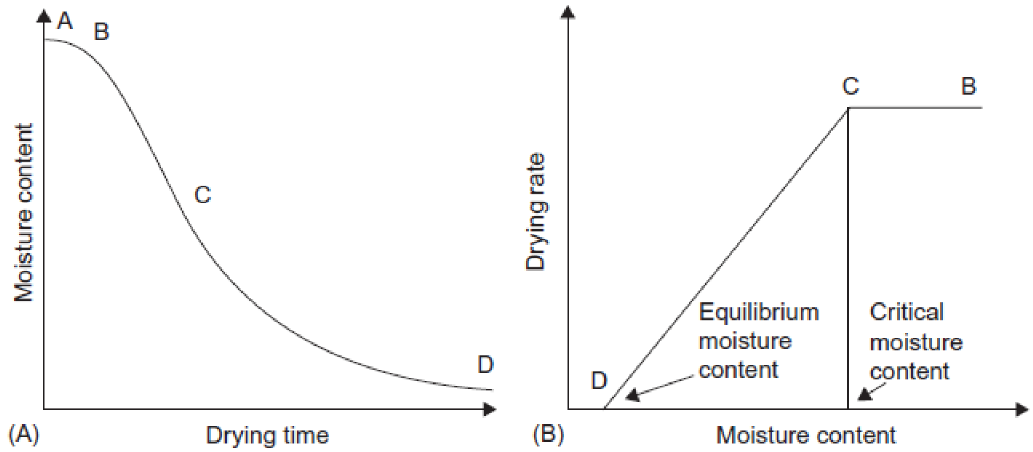

Fig. 4. Drying curves. The temperature and humidity of the drying air are constant and all heat is supplied to the food surface by convection.

The moisture content of a food may be expressed on a wet weight basis (mass of water per unit mass of wet food) or a dry weight basis (mass of water per unit mass of dry solids in the food). In the calculations described below, a dry weight basis is used throughout. The moisture content of foods in other sections is given as wet weight basis.

- ***Free moisture*** is the moisture in excess of the equilibrium moisture content at a particular temperature and humidity, and so free to be removed.
- ***Critical moisture content*** is the amount of moisture in a food at the end of the constant-rate period of drying.
- ***Equilibrium moisture content*** is the moisture content of a food at which it neither gains nor loses moisture to its surroundings (at a given temperature and pressure, the food is in equilibrium with the air vapour mixture surrounding it).

Falling rate period

When the moisture content of the food falls below the critical moisture content, the rate of drying slowly decreases until it approaches zero at the equilibrium moisture content (that is the food comes into equilibrium with the drying air). This is known as the falling-rate period. Non-hygroscopic foods have a single falling-rate period (CD in Fig. 4A and B), whereas hygroscopic foods have two or more periods. In the first period, the plane of evaporation moves from the surface to inside the food, and water diffuses through the dry solids to the drying air. The second period occurs when the partial pressure of water vapour is below the saturated vapour pressure, and drying is by desorption.

During the falling-rate period(s), the rate of water movement from the interior to the surface falls below the rate at which water evaporates to the surrounding air, and the surface therefore dries out (assuming that the temperature, humidity and air velocity are unchanged). If the same amount of heat is supplied by the air, the surface temperature rises until it reaches the dry-bulb temperature of the drying air. Most heat damage to food can therefore occur in the falling rate period. To minimise this, the air temperature is controlled to match the rate of moisture movement and reduce the extent of surface heating.

The falling-rate period is usually the longest part of a drying operation and, in some foods (e.g. grain drying), the initial moisture content is below the critical moisture content and the falling-rate period is the only part of the drying curve to be observed. During the falling-rate period, the factors that control the rate of drying change. Initially the important factors are similar to those in the constant rate period and liquid diffusion from the interior to the surface may be the main mechanism. In later stages, vapour diffusion may be more important. In summary, water moves from the interior of the food to the surface by the following mechanisms:

- Liquid movement by capillary forces, particularly in porous foods
- Diffusion of liquids, caused by differences in the concentration of solutes at the surface and in the interior of the food
- Diffusion of liquids that are adsorbed in layers at the surfaces of solid components of the food
- Water vapour diffusion in air spaces within the food caused by vapour pressure gradients.

The mechanisms that operate in the falling rate period depend mostly on the temperature of the air and the size of the food pieces. They are unaffected by the RH of the air (except in determining the equilibrium moisture content) and the velocity of the air. In the later stages of the falling rate period, the temperature of the air determines the rate of heat transfer to the plane of evaporation within the food. Heat is transferred by conduction through the food and the rate is limited by the thermal conductivity of the food. The amount of heat reaching the liquid within the food controls the amount of evaporation that takes place and hence the vapour pressure above this liquid surface. The vapour pressure gradient between the internal liquid surface and the food surface controls the rate at which moisture is removed from the product.

The size of food pieces has an important effect on the drying rate in both the constant rate and falling rate periods. In the constant rate period, smaller pieces have a larger surface area available for evaporation, whereas in the falling-rate period, smaller pieces have a shorter distance for heat and moisture to travel through the food.

Other factors that influence the rate of drying include:

- The composition and structure of the food, which influence the mechanism of moisture removal. For example, the orientation of fibres in vegetables and protein filaments in meat allow more rapid moisture movement along their length than across their structure.
- Moisture is removed more easily from intercellular spaces than from within cells.
- Rupturing cells by blanching or size reduction increases the rate of drying.
- As food dries, increased concentrations of solutes such as sugars, salts, gums, starches, etc., increase the viscosity of liquid within a food and reduce the rate of moisture movement.

- The amount of food placed into a dryer in relation to its capacity influences the drying rate (in a given dryer, faster drying is achieved with smaller quantities of food).

For these reasons the rate at which foods dry may differ in practice from the idealised drying curves described above. Calculation of heat transfer rates in drying systems is often very complex and calculation of drying rates is further complicated if foods shrink during the falling rate period. Mathematical modeling of dehydration systems is used to address these complexities.

Heat and mass transfer in drying

The removal of moisture from a food product involves simultaneous heat and mass transfer. Heat transfer occurs within the product structure and is related to the temperature gradient between the product surface and the water surface at some location within the product. As sufficient thermal energy is added to the water to cause evaporation, the vapors are transported from the water surface within the product to the product surface. The gradient causing moisture-vapor diffusion is vapor pressure at the liquid water surface, as compared with the vapor pressure of air at the product surface. The heat and the mass transfer within the product structure occurs at the molecular level, with heat transfer being limited by thermal conductivity of the product structure, whereas mass transfer is proportional to the molecular diffusion of water vapor in air.

At the product surface, simultaneous heat and mass transfer occurs but is controlled by convective processes. The transport of vapor from the product surface to the air and the transfer of heat from the air to the product surface is a function of the existing vapor pressure and temperature gradients, respectively, and the magnitude of the convective coefficients at the product surface.

Since the drying rate is directly proportional to the slowest of the four processes, it is important to account for all processes. In most products, the heat and mass transfer within the product structure will be rate-limiting processes.