Drying and Storage Engineering

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Lesson 1. Moisture content

1.1 Food and Moisture

Food is any substance consumed to provide nutritional support for the body. It is usually of plant or animal origin, and contains essential nutrients, such as carbohydrates, fats, proteins, vitamins, or minerals. All foods content solids, water and other chemicals. The moisture contained in a material comprises all those substances which vaporize on heating and lead to weight loss of the sample. The weight is determined by a balance and interpreted as the moisture content. According to this definition, moisture content includes not only water but also other mass losses such as evaporating organic solvents, alcohols, greases, oils, aromatic components, as well as decomposition and combustion products. The moisture content also called as moisture assays is one of the most important analyses performed on most of the food products. Table 1 gives the general idea about the moisture content of different foods. Water activity measurements parallel to the moisture content is also an important parameter for quality and stability of food.

Table 1: Water Contents of Various Foods

Food	*Water Content (%)*
Meat	
Pork, raw, composite of lean cuts	53–60
Beef, raw, retail cuts	50–70
Chicken, all classes, raw meat without skin	74
Fish, muscle proteins	65–81
Fruit	
Berries, cherries, pears	80–85
Apples, peaches, oranges, grapefruit	90–90
Rhubarb, strawberries, tomatoes	90–95
Vegetables	
Avocado, bananas, peas (green)	74–80
Beets, broccoli, carrots, potatoes	85–90
Asparagus, beans (green), cabbage, cauliflower, lettuce	90–95

Source: Fennema, O.R. in *Food Chemistry*, Marcel Dekker, New York, 1996, 17–94.

1.2 Types of bonding of moisture in the product

The moisture in food can be present in different forms which are decided by type of bonding with solids (Fig 1). It is available in following forms:

Free water: water on the surface of the test substance and it retains its physical form

Absorbed water: water in large pores, cavities or capillaries of the test substance

Water of hydration: Occluded in lattice ions or water of crystallization coordinately bonded to ions.

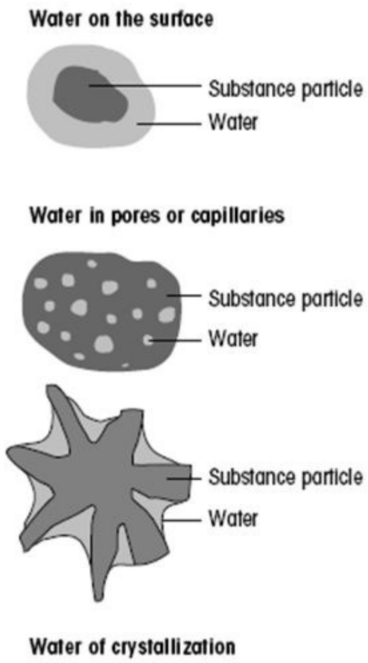

Fig 1.1 Types of bonding of moisture in food products

1.3 Esimation of Moisture Content

Moisture content is the quantity of water contained in a food material. Moisture content is used in a wide range of scientific and technical areas, and is expressed as a ratio, which can range from 0 (completely dry) to the value of the materials' porosity at saturation. It can be given on a volumetric or mass (gravimetric) basis. Moisture content is expressed as a percentage of moisture based on total weight (wet basis) or dry matter (dry basis). Wet basis moisture content is generally used. Dry basis is used primarily in research. The moisture content is expressed by following formulae.

$$M_w(\text{wet basis}) = \frac{w - d}{w} \times 100$$

$$M_d(\text{dry basis}) = \frac{w - d}{d} \times 100$$

where, M is moisture content on a percent basis, w is total weight (also called as wet weight) and d is dry weight.
Based on the different forms of moisture present in the food the method used for measurement of moisture may estimate more or less moisture

1.4 Importance of Moisture Content in Foods

Proper moisture content is essential for maintaining fresh, healthy foods. If a food is too moist or too dry, it may not be suitable to eat and will not taste as good as it would if it had the correct moisture content. Most of the food products contain moisture. The moisture content per cent is seldom of interest. Rather, it shows whether a product intended for trade and production has standard characteristics such as:

1. Storability
2. Agglomeration in the case of powders
3. Microbiological stability
4. Flow properties, viscosity
5. Dry substance content
6. Concentration or purity
7. Commercial grade (compliance with quality agreements)
8. Nutritional value of the product
9. Legal conformity (statutory regulations governing food)

In addition to above characteristics, the determination of moisture content plays important role commercially with respect to following aspects:

1. Freshness

Fresh, ripe fruits and vegetables are moist to the touch. As they age and begin to rot, some dry out and some pick up excess moisture and begin to mold.

2. Labeling

Food industries require a minimum or maximum percentage of moisture on certain foods in order for them to be packaged and labeled. If they don't fit to these standards, the foods cannot be sold.

3. Cost

In processed foods, the percentage of water in a product can determine its final price. Generally, a product with more water will cost less.

4. Processing

Biologists and manufacturers need to know the moisture content of food to ensure that it's processed and packaged in a safe, stable way.

5. Quality

Moisture content determines the way most foods taste, feel and look. It is one of the important ways to measure food quality.

6. Shelf life

Shelf life of product depends on its moisture content at the time of packaging and rate of moisture gain during storage which is also called as sorption isotherm study.

Lesson 2. Determination Of Moisture Content

The moisture content is determined by several direct and indirect methods. These can be classified in different sections as shown in Figure 1.

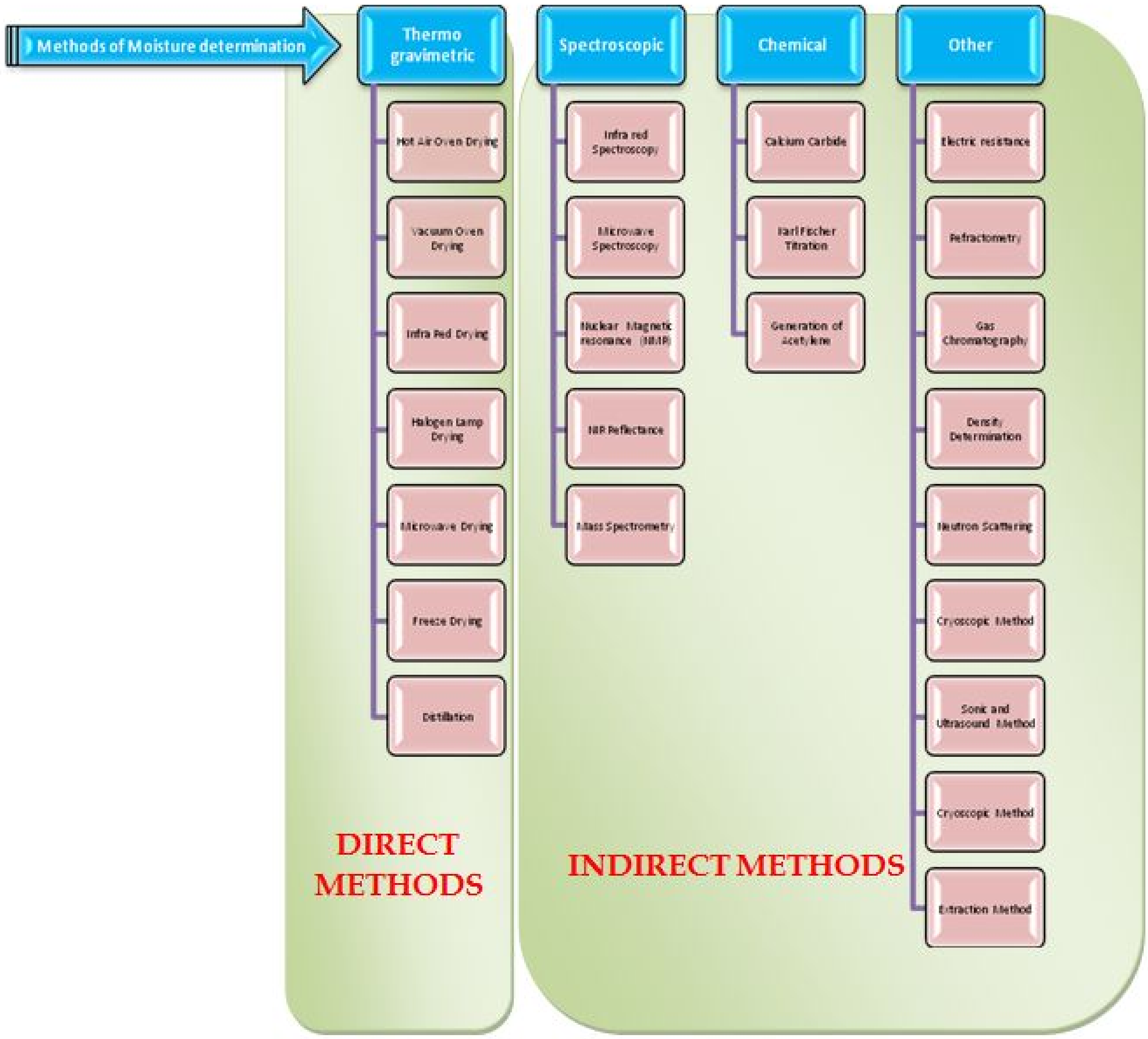

Figure 2.1: Classification of methods of moisture determination

2.1 Direct Methods

The direct methods include mainly thermo gravimetric methods. The moisture content can be determined by an oven method directly. The food is weighed and dried, then weighed again according to standardized procedures. In the Thermogravimetric method, moisture is always separated. Thus, there is no distinction made between water and other readily volatile product components. A representative sample must be obtained to provide a useful moisture content evaluation. Also, the moisture content of the product must be maintained from the time the sample is obtained until the determination is made by storing in a sealed container. Thermogravimetric techniques can be used to continuously measure the mass of a sample as it is heated at a controlled rate. The temperature at which water evaporates depends on its molecular environment: free water normally evaporates at a lower temperature than bound water. Thus by measuring the change in the mass of a sample as it loses water during heating it is often possible to obtain an indication of the amounts of water present in different molecular environments. The figure 2 shows the process of measuring moisture content thermo gravimetrically. For many food samples this method is mandatory particularly for grains. For grains the moisture content is measured by heating the grain in hot air oven at 100-110 °C for 24 hours or until constant weight comes. For fruits and vegetables where heat sensitivity is problem, vacuum is applied in the oven to decrease the boiling point of moisture. The product temperature generally varies in vacuum oven between 60-70°C and vacuum is maintained at <450 mm Hg. The advantages and disadvantages of direct methods are given in Table 1 which can be used for selection of particular method for moisture content determination.

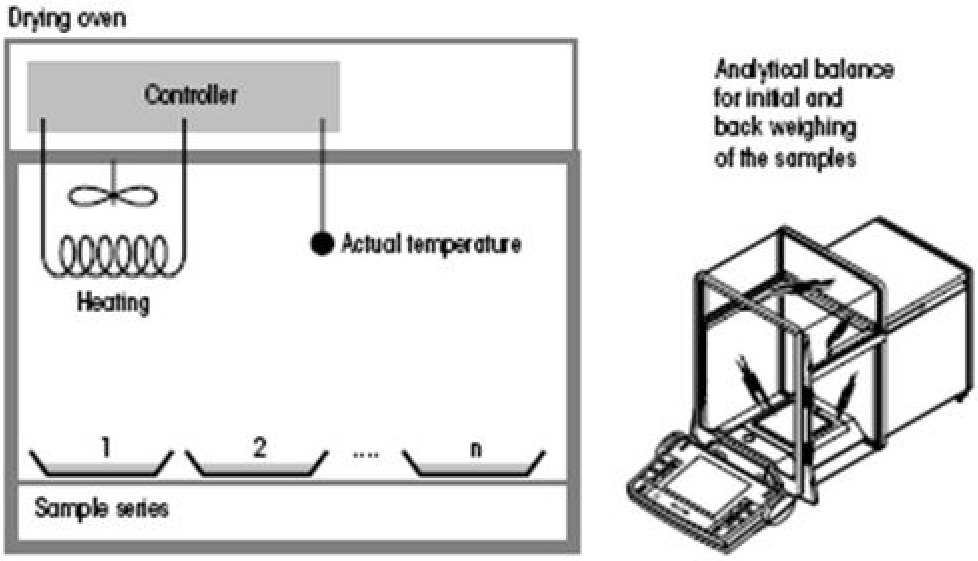

fig. 2.1 determination of moisture content by oven drying

Table 1: Advantages and Disadvantages of direct Methods for Moisture

Method	*Advantages*	*Disadvantages*
Oven drying	Standard conventional method	Variations of temperature due to particle size, sample weight, position in the oven, etc.
	Convenient	Difficult to remove all water
	Relative speed and precision	Loss of volatile substances during drying
	Accommodates large number of samples	Decomposition of sample (i.e., sugar)
	Attain the desired temperature more rapidly	
Vacuum-oven drying	Lower heating temperatures possible	Possible volatile loss
	Prevents sample decomposition	Lower number of samples than drying oven
	Uniform heating and constant evaporation	Drying efficiency reduced for high-moisture foods
Freeze-drying	Excellent for sensitive, high-value liquid foods	Expensive
	Preserves texture and appearance	Long drying time
	No foaming	Sample must be initially frozen
	No case-hardening	Most applicable to high moisture foods
	No oxidation	
	No bacterial changes during drying	
Distillation methods	Determines water directly rather than weight loss	Low precision of measuring device
	Apparatus is simple to handle	Organic solvents such as toluene pose a fire hazard
	Accuracy may be greater than oven-drying method	Organic solvents may be toxic
	Takes relatively short time (30 min to 1 h) to determine	Can have higher results due to distillation of water-soluble components (e.g., glycerol and alcohol)
	Prevents oxidation of sample	Water droplets may adhere to internal surface of the apparatus, causing erroneous results
	Not affected by environmental humidity	Emulsions may form
	Suitable for samples containing volatile substances	
Karl Fischer method	A standard method for moisture analysis	Chemicals of the highest purity must be used for preparing the reagent
	The accuracy and precision are higher than with other methods	Titration endpoint may be difficult to determine visually

Method	Advantages	Disadvantages
	Useful for determining water in fats and oils by preventing oxidation	The reagent is unstable and needs standardization before use
	Once the apparatus is set up, determination takes a few minutes	Titration apparatus must be protected from atmospheric moisture due to extreme sensitivity of reagent to moisture
	Automated equipment available	Ascorbic acid and other carbonyls can react with reagents, causing over-estimation of the moisture content
Chemical desiccation	Can serve as a reference standard for other methods	Requires a long time to achieve constant dry weight
	Can be done at room temperature	Moisture equilibrium depends on strength of desiccant
	Good for measuring moisture in substances containing volatile compounds	
Thermogravimetric analysis	More automated method than standard oven drying	Excellent for research, but not practical
	Weighing error is minimal because sample is not removed from oven	Small sample may not be representative
	Sample size is small	Sample may decompose or oxidize
GC	Analysis is rapid (takes 5–10 min per sample)	Unit cost per sample may be higher than drying oven
	Results similar to conventional methods	Sample extraction required
		Requires expensive equipment

Source: Park, Y.W. in *Handbook of Food Analysis*, Marcel Dekker, New York, 1996, 59–92; Park, Y.W. and L.N. Bell in *Handbook of Food Analysis*, Marcel Dekker, New York, 2002, 55–82.

2.2 Indirect Methods

There are several methods developed to determine the moisture content rapidly. These include use of modern heating, measurement methods like infrared, microwaves, ultra sound, and spectroscopy. These methods are developed due to requirements of rapid, nondestructive and precise moisture content determination. The indirect methods are generally faster than the direct methods for moisture determination. When done properly, the indirect methods can be as accurate and precise. However, the accuracy and precision of the indirect methods depend on careful preparation and analysis of known standards to establish reliable calibration curves. Although most indirect methods require a large capital investment in equipment, the potential application for rapid on-line quality control might make the investment worthwhile. Nevertheless, preparation of the standards and accurate calibration curves must be verified by a specific direct method to establish a reliable indirect method of instrumentation that can achieve accurate and precise predicted values. One of the most important indirect methods in foods is use of moisture meters for grains. Most moisture meters measure the electrical properties of grain, which change with the moisture content. This is considered an indirect method and must be calibrated by a direct method. It is important to follow moisture meter directions carefully to achieve an accurate moisture test. A moisture meter should be periodically checked to see if it is accurate. One method of checking the meter is to compare it to at least two other meters. There are several factors that control use of each method. The advantages and disadvantages of indirect methods are given in Table 2.

Table 2: Advantages and Disadvantages of indirect Methods for Moisture Determination

Method	Advantages	Disadvantages
Refractometry	Determination takes only 5–10 min (rapid)	Temperature sensitive
	Does not require complex or expensive instrumentation	Requires uniformity of fluid samples
	Simple method	Solid samples (e.g., meat) require homogenization in an anhydrous solvent
	Reasonable accuracy	
	Excellent method for high-sugar products	
IR Absorption	Can perform multicomponent analysis	Accuracy depends on calibration against reference standard
	Most versatile and selective	Temperature-dependent
	Nondestructive analysis	Dependent on homogenization efficiency of sample
		Absorption band of water is not specific
NIR reflectance spectroscopy	Rapid	Reflectance data are affected by sample particle size, shape, packing density, and homogeneity
	Precise	Interference between chemical groups (e.g., hydroxyl and amine)
	Nondestructive	Temperature-dependent
	No extraction required	Accuracy depends on calibration of standard samples
	Minimum sample preparation	Equipment is expensive
Microwave absorption	Nondestructive	Possible leakage of microwave energy during measurement
	No extraction required	Has relatively low sensitivity and limited range for moisture determinations
	More accurate than low-frequency resistance or capacitance meters	Depends on the fluctuation of the material density in the volume measured
		Results affected by factors such as particle size, temperature, soluble salt contents, polarization, and frequency of sample
Dielectric Capacitance	Has high sensitivity due to large dielectric constant of water	Affected by texture of sample, packing, electrolytes, temperature, and moisture distribution
	Convenient to industrial operations with the continuous measurement system	Potential calibration difficulty beyond pH 2.7–6.7
	System can be modified to have universal applicability	Difficult to measure bound water at high frequencies
Conductivity	Measurement is instantaneous	Measures only free water
	Nondestructive	Conversion charts are needed to obtain total moisture values

2.3 Problem:

1. Suppose, for example, that you weigh 10 g of grains (W_w) into a 4 g container and that after drying the container plus grains weighs 6.3 g. Subtracting out the 4-g. container weight leaves 2.3 g as the dry weight (W_d) of your sample. Percent moisture would be:

$M_n = ((W_w\text{-}W_d)/W_w) \times 100$
$= ((10 - 2.3) / 10) \times 100$
$= 77\%$

Lesson 3. Equilibrium Moisture Content (Emc) And Its Importance

3.1 Equilibrium Moisture Content (EMC)

Every food exerts a characteristic vapor pressure at a certain temperature and moisture content. All porous food materials, when in contact with moist air, adsorb or desorb water molecules to attain equilibrium moisture content. This equilibrium moisture content depends very strongly on the partial pressure of the water vapor in the surrounding air and rather weakly on the air temperature that are commonly experienced in drying and storage of foods. If the moisture content of the food material does not vary with time for a given combination of water vapor pressure and air temperature, it is then said that it has reached the equilibrium moisture content (EMC) of the material at that water vapor pressure and temperature. When left undisturbed, the natural end of any adsorption or desorption process is the attainment of EMC. This, though a natural process, is often very slow. Food materials may take several days or weeks to reach equilibrium.

When the water vapor pressure of the air approaches the saturation water vapor pressure at the temperature of the air, the EMC of food materials rapidly increases. At these stages, the process undergone by the food material is not only adsorption. Water vapor begins to condense within the pore structures of the building materials. Theoretically, if the food material is in contact with air that is 100 % saturated for a very long period, all pores of the material should be filled with the condensed moisture. The EMC that corresponds to that hypothetical state is called the saturation moisture content of the material. But in practice the rate of this process becomes infinitesimally small at an EMC that is known as the capillary saturation moisture content and is often substantially less than the saturation moisture content referred to above.

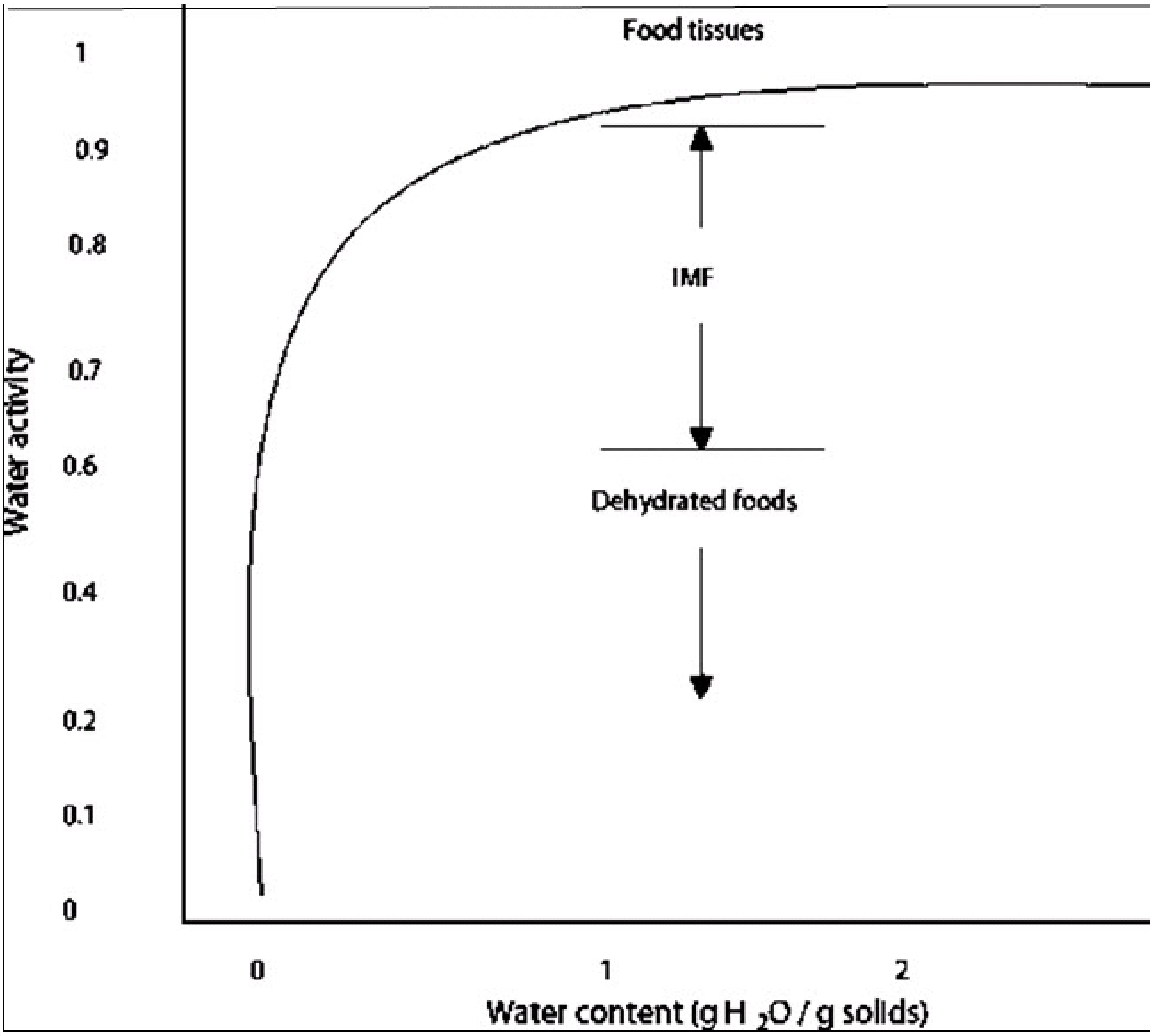

Fig 1. Relationship between equilibrium moisture content and water activity

Drying of grain involves exposing grain to ambient air with low relative humidity or to heated air. This will evaporate the moisture from the grain and then the drying air will remove the moisture from the grain bulk. Since drying practices can have a big impact on grain quality or seed quality, it is important to understand some fundamentals of grain drying.

3.2 **Importance of Equilibrium Moisture Content**

The concept of equilibrium moisture content (EMC) is important in the study of drying and storage of fruits, vegetables and grains. The EMC helps to decide the stability of food at particular moisture content in the given environment. The EMC values of several grains and foods have been determined by several research workers and reported in literature. If exposed to air, high moisture foods, loose moisture whereas low moisture foods gain moisture in humid air. EMC determines the minimum moisture content to which food can be dried under a given set of conditions. Also, it determines the maximum amount of moisture the dehydrated food can absorb during storage.

The EMC can be elaborated by an example given by Hall (1980). If wheat and oats having 16 % moisture content are kept in the environment of 86°C and 75% relative humidity, wheat will absorb moisture and oat will lose. This is because of the different vapor pressures of the moisture in wheat and oat. At above air temperature and humidity the vapor pressure of wheat is 0.444 psi and oat is 0.477 psi where as vapor pressure of moisture in air at 86°C and 75% relative humidity is 0.461 psi. Therefore, wheat will gain moisture from air as vapor pressure of air is more than wheat. At the same time oat will lose moisture as its vapor pressure is higher than air. There is always tendency of movement of moisture from higher vapor pressure to lower vapor pressure. The Figure 2 shows the movement of moisture from and to food.

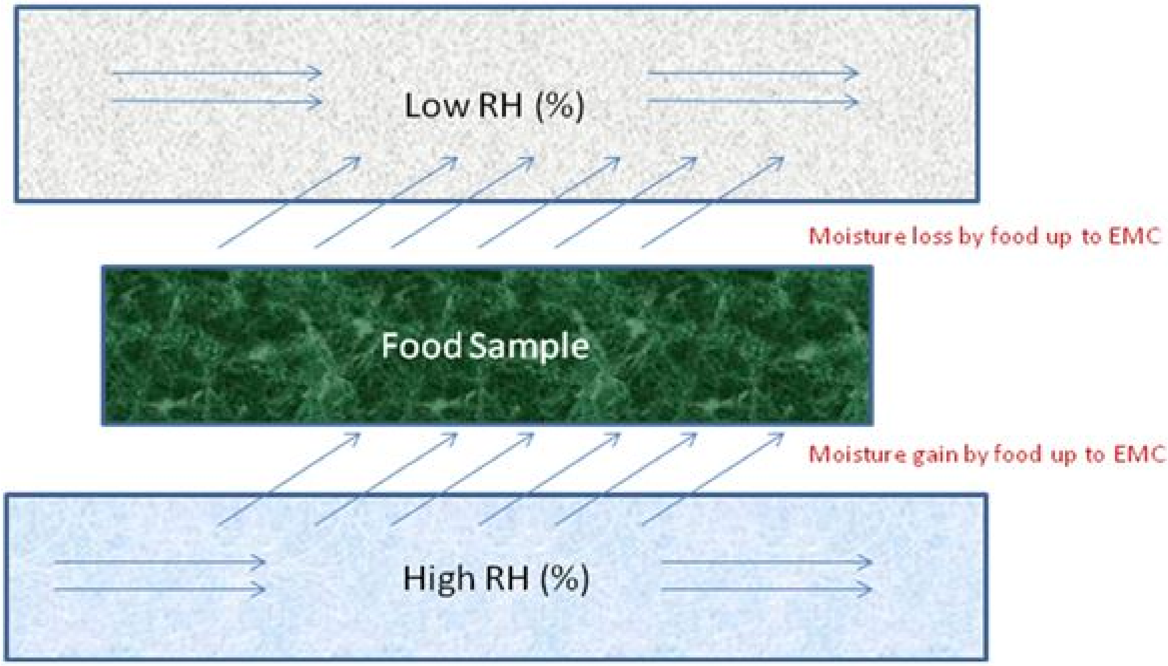

Figure 2. Movement of moisture from and to food.

When the vapor pressure of the water held by food particles becomes equal to the water vapor pressure of the surrounding air the movement of moisture stops and comes to equilibrium. At this moment the food product remains at the same moisture content in the same air temperature and humidity. This moisture is called as equilibrium moisture content. The relative humidity of air surrounding the food particles at the same conditions is called as equilibrium relative humidity (ERH) which is also known as water activity (a_w).

3.3 Factors affecting the EMC

The EMC is dependent mainly on:

1. Air temperature

2. Relative humidity.

If a food sample of same initial moisture content and vapor pressure is exposed to air having different vapor pressures, it will come to equilibrium at different moisture content values (EMCs). Therefore, it can be understood that EMC is dependent on the air vapor pressure which in turn depends on the temperature and relative humidity of air. Figure 3 shows the graphical representation of change of EMC with different vapor pressures (V_1 to V_4). For example a shelled corn at air having 70% relative humidity and 40 °F, EMC is 15.7% whereas it is 10.3% at 140°F. A change in the chemical composition can affect the EMC of food products. Foods with high oil content adsorb less moisture from the surrounding air. Also, previous moisture adoption desorption history of food affects EMC values. Plotting different EMC values with relative humidity at constant temperature results in sigmoid type (S-shaped) curve.

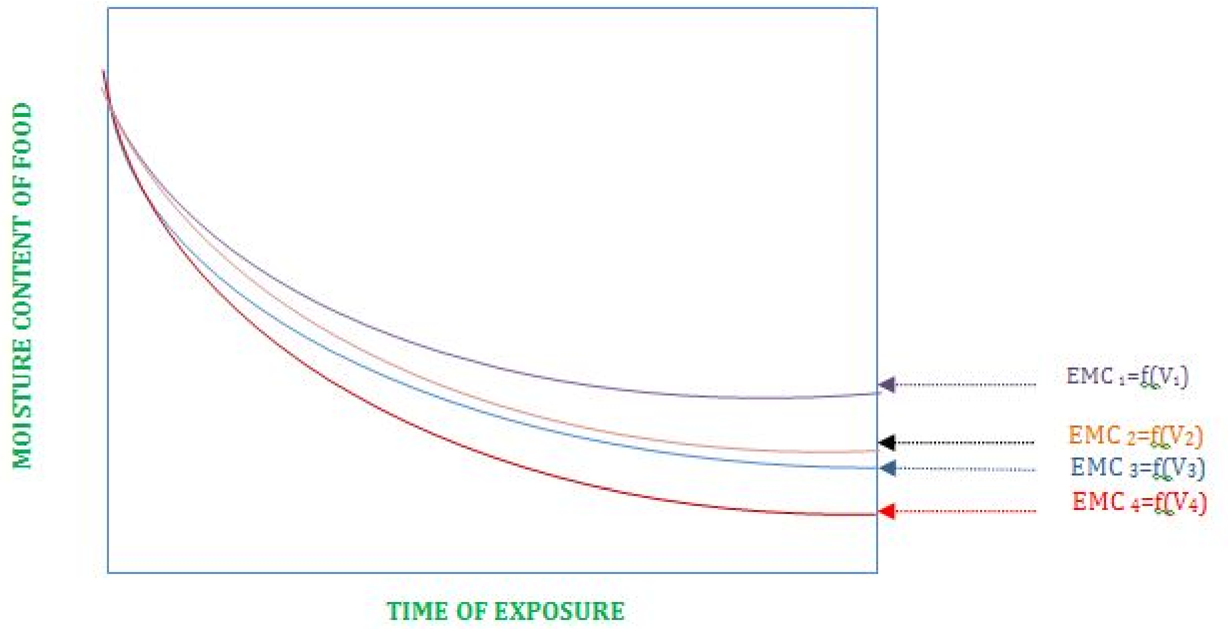

Figure 3. Graphical representation of change of EMC with different vapor pressures (V_1 to V_4)

Lesson 4. EMC Curve and EMC Models

4.1 Sorption Theory

EMC data for dry food which is generally hygroscopic material, describe the material's moisture content originating from an interaction with the moisture and temperature of the surrounding air. If a dry food is placed in environment with a constant humidity and temperature, it will take up moisture by adsorption until it reaches its equilibrium moisture content (where the net moisture exchange is zero) which is called as adsorption EMC. If, however, a wet food with the same properties is placed in the same environment, it will loose moisture by desorption and reach to equilibrium moisture content which is called as desorption EMC. For each product the relative humidity of environment can be changed and different adsorption and desorption EMC values can be obtained. If these values are plotted on a graph a loop is obtained which is called hysteresis (Figure 1). The hysteresis effect is observed due to shrinkage effect during desorption which changes the water binding properties of the food product. Therefore, during adsorption same path of EMC is not observed.

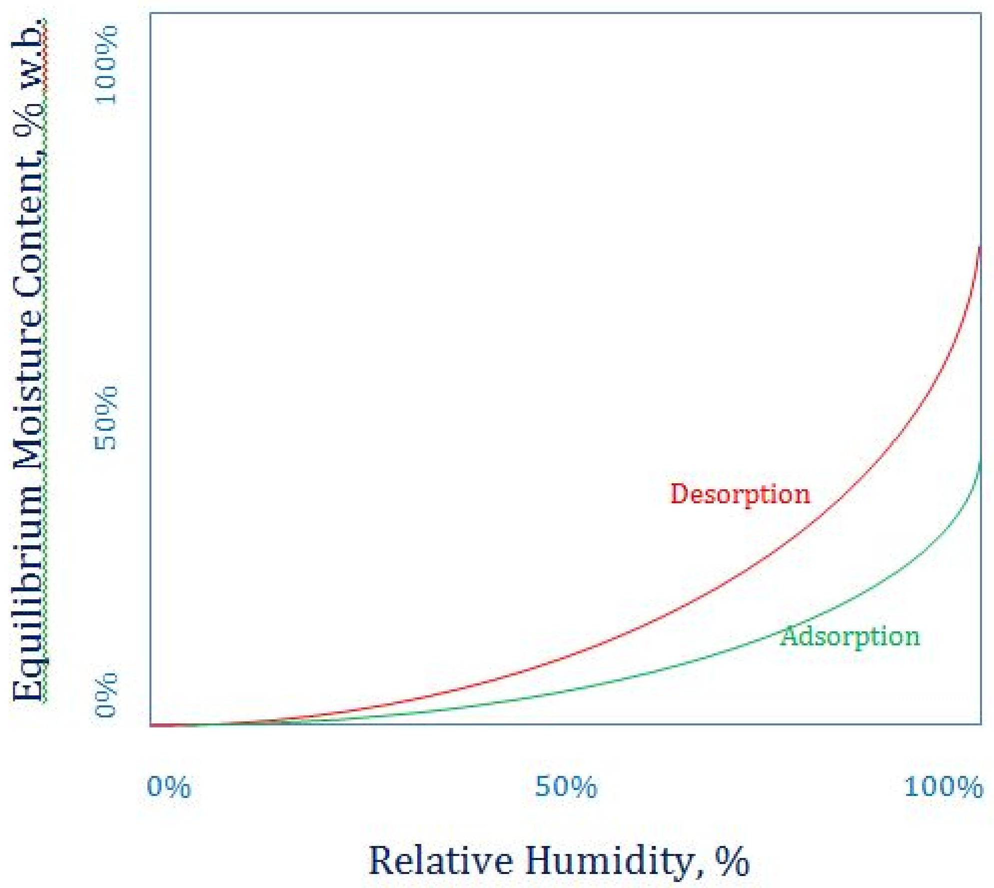

Figure 4.1. Sorption isotherm for porous food materials

4.2 EMC Models

Equilibrium moisture content (EMC) relationships are required to achieve target moisture contents (MC) during the grain conditioning process. ASAE Standard D245.5 provides EMC models for popcorn grains along with the parameter values for the desorption process. However, the accuracy of these values have been found to be inadequate to tightly control fans and heaters during automatic grain conditioning, which can result in huge losses especially in high value crops such as popcorn.

A presentation of EMC at a given temperature versus the equilibrium relative humidity of the surrounding is expressed as a sorption isotherm. With the help of water activity meter, instead of using different humidity levels, only one high humidity (90%) can be used to find equilibrium relative humidity values. The following formula was used to calculate equilibrium relative humidity at particular equilibrium moisture content.

There are several models available for different foods to predict the EMC. They are as given Table 1.

Table 1. Sorption Models and Their Linear Forms.

Author	Model	Linear Forms
Bradley (1936)	$\ln a_w = A(B)^M$	$\ln(-\ln a_w) = -\ln A - M \ln B$
BET (1938)	$M = \dfrac{M_O A a_w}{1-a_w} + \dfrac{M_O A}{(A-1)(1-a_w)}$	$\ln M = \ln(M_O A)(1 + a_w(A-1)) - \ln(A-1)(1-a_w)$
Smith (1947)	$M = A - \ln(1-a_w)^B$	$M = A - B\ln(1-a_w)$
Henderson (1952)	$M = -\dfrac{1}{AT}\ln(1-a_w)^{\frac{1}{B}}$	$\ln M = \dfrac{1}{B}\ln(-\ln(1-a_w)) + \dfrac{1}{B}\ln\dfrac{1}{AT}$
GAB (1966)	$M = \dfrac{M_O ABa_w}{(1-Aa_w)(1-Aa_w+ABa_w)}$	$\ln M = \ln M_O ABa_w - \ln((1-Aa_w)(1-Aa_w + AB$

Note: M = Equilibrium moisture content (decimal, dry basis); M_o = monolayer moisture content (decimal, dry basis); a_w = water activity or relative humidity (decimal); A, B = parameters pertinent to each equation; T = absolute temperature (K); BET is an acronym formed from the surnames of the three authors (Brunauer, Emmet and Teller) that developed the model; GAB is an acronym formed from the surnames of the three authors (Guggenheim, Anderson, and de Boer) that developed the model. The models are therefore referred to as BET or GAB model in literature. The above definitions apply to all tables and figures where they appear.

4.3 Kelvin Model

Kelvin in 1871 developed EMC model based on the condensation in capillary. He developed relationship between vapour pressure over liquid in capillary (Pv) and the saturated vapour pressure at the same temperature (Pvs), the relationship is as follows:

$$\ln\left(\frac{P_v}{P_{vs}}\right) = -\frac{2\sigma V \cos\alpha}{r R_o T_{abs}}$$

Where Pv is the water vapor pressure of the product, Pvs is the saturated water vapour pressure at the equilibrium temperature of the system, σ is the surface tension of the moisture, V is the volume of the moisture in liquid form, r is the cylindrical capillary radius and α is contact angle between moisture and capillary wall.

4.4 GAB Model

The GAB model was used to describe relationship between the water activity (a_w) - equilibrium moisture content (X) and storage life was predicted. The model is given below:

$$X = \frac{MCKa_w}{(1 - Ka_w) \times (1 - Ka_w + CKa_w)}$$

Where, X is the moisture content (kg water.kg dry solid^{-1}); a_w is water activity; C, K and M are the GAB constants. M is monolayer moisture content (g g^{-1} dry solids), C is the Guggenheim constant and K is a molecule multilayer factor.

Water sorption isotherms are determined by exposing product to air. Saturated salt solution is prepared by using different salts. These salts solutions exert different RH in the desiccators. The relative humidity of the solutions and temperature of the environment inside the desiccators can be verified with the help of data logger.

For rapid determination of EMC and shelf life prediction the sample is kept in the desiccators containing saturated Potassium nitrate solution to maintain the relative humidity at 90 % at 40°C temperature. Approximately, 20 g of sample is kept in the desiccators for the study. The desiccators are placed inside temperature-controlled chamber. Moisture content and water activity of each sample can be measured periodically using hot air oven and water activity meter, respectively. The water activity meter is shown in Plate 1.

Plate 1. Water Activity Meter

The equilibrium was judged to have been attained when less than 1% change in both the parameters was found after two measurements. Very few days were required for foods to reach equilibrium with the surrounding air. The shelf life of the product can be calculated using following equation.

$$\theta_{ps} = \frac{W_p}{2k_g b_p l_p P_p^*} \int_{X_i}^{X_F} \frac{dX}{R_{hp} - a_w}$$

Where, θ_{ps} is the shelf life, (s); W_p is weight of the product, (kg); k_g is the permeability of packaging material, (kg water $m^{-2}s^{-1}Pa^{-1}$); b_p is width of the package, (m); l_p is length of the package, (m); P_p^* is saturation vapor pressure of water at Tp, (Pa); X_i is the initial moisture content of the product, (kg water kg^{-1} dry solids); X_{pc} is the critical moisture content of the product, (kg water kg^{-1} dry solids); R_{hp} is relative humidity of the storage environment (fraction) and a_w is the water activity of the product at X_{pc}.

Lesson 5. Emc Curve And Emc Models

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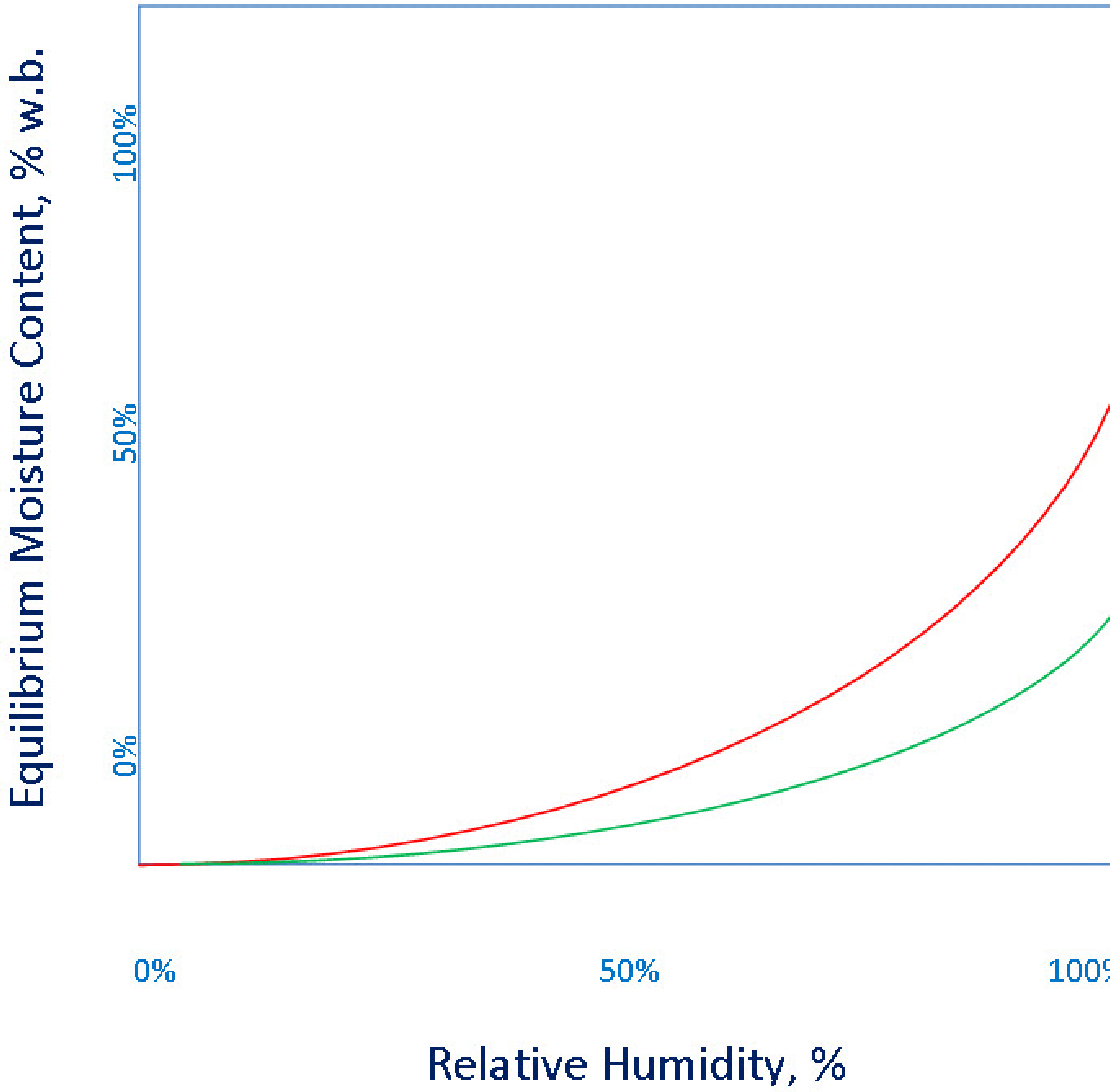

Figure 1. Sorption isotherm for porous food materials

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GAB (1966)	$M = \frac{M_O A B a_w}{(1-Aa_w)(1-Aa_w+ABa_w)}$	$\ln M = \ln M_O A.$

Note: M = Equilibrium moisture content (decimal, dry basis); M_o = (decimal, dry basis); a_w = water activity or relative humidity (decimal) to each equation; T = absolute temperature (K); BET is an acronym the three authors (Brunauer, Emmet and Teller) that developed the formed from the surnames of the three authors (Guggenheim, A developed the model. The models are therefore referred to as BET o above definitions apply to all tables and figures where they appear.

2. Langmuir model
3. BET equation
4. Harkins-Jura equation
5. GAB equation

Lesson 6. Principle of drying

6.1 Introduction

Drying is one of the oldest methods of fruits and vegetables preservation. It is currently a versatile and widespread technique in the food industry as well as a subject of continuous interest in food research. Drying is a critical step in the processing of dehydrated products because of the high energy requirement of the process (due to low thermal efficiency of dryers). The main aim of drying fruits and vegetables is the removal of moisture up to certain level at which microbial spoilage and deterioration chemical reactions are greatly minimized. In addition to preservation, the reduced weight and bulk of dehydrated products decreases packaging, handling, and transportation costs. Furthermore, most food products are dried for improved milling or mixing characteristics in further processing. In contrast, with literally hundreds of variants actually used in drying of particulates, solids, pastes, slurries, or solutions, it provides the most diversity among food engineering unit operations.

Currently, dehydrated fruits, vegetables, grains and spices command considerable importance in the Indian and international market. These dehydrated products are the single largest import item in Europe and United States both in quantity and value items, as these products are used by every home, canteen, cafeteria, restaurant and other institutional food establishment. At present, instant beverage powders, dry soup mixes, spices, coffee, and ingredients used in food transformation are the major food products that are dehydrated. Also in India, dehydrated products are required for armed forces. In India, generally the agricultural production exceeds the requirement. Due to lack of proper post harvest management and storage facility for agricultural products, a considerable percentage of it produced goes as waste. Therefore, India needs processing of agro produce to convert them into stable products so as to minimize losses due to waste during the post harvest phase.

Fresh agricultural product is a perishable commodity in tropical countries as higher temperature causes it to wilt and gives a poor appearance. Therefore, the refrigeration and controlled atmosphere storage have been used to increase their storability. The shelf life of agricultural products can also be enhanced by drying. These products are generally dried by hot air. Sun drying is the most common method to preserve the agricultural products in most of tropical countries. However, this technique is extremely weather dependent and has the problems of contamination with dust, soil, sand particles and insects. Also, the required drying time can be quite long. Therefore, mechanical dryers, which are rapid, providing uniformity in drying and hygiene, are inevitable for industrial food drying processes. Agricultural material are dried by several methods like sun drying, hot air drying, fluidized bed drying, heat pump drying, freeze-drying, microwave hot air/vacuum drying, vacuum drying and hybrid drying. For improving quality of dehydrated products the pretreatments like osmotic dehydration, blanching, dipping in chemical solutions and microwave heating are common.

In short the main objectives of drying are:

– Extended Storage Life

– Quality Enhancement

– Ease of Handling

– Further Processing

The drying requires different pr processing operations of the product. These are operations are based on the product requirement. The Figure 1 shows steps to be carried in drying operation.

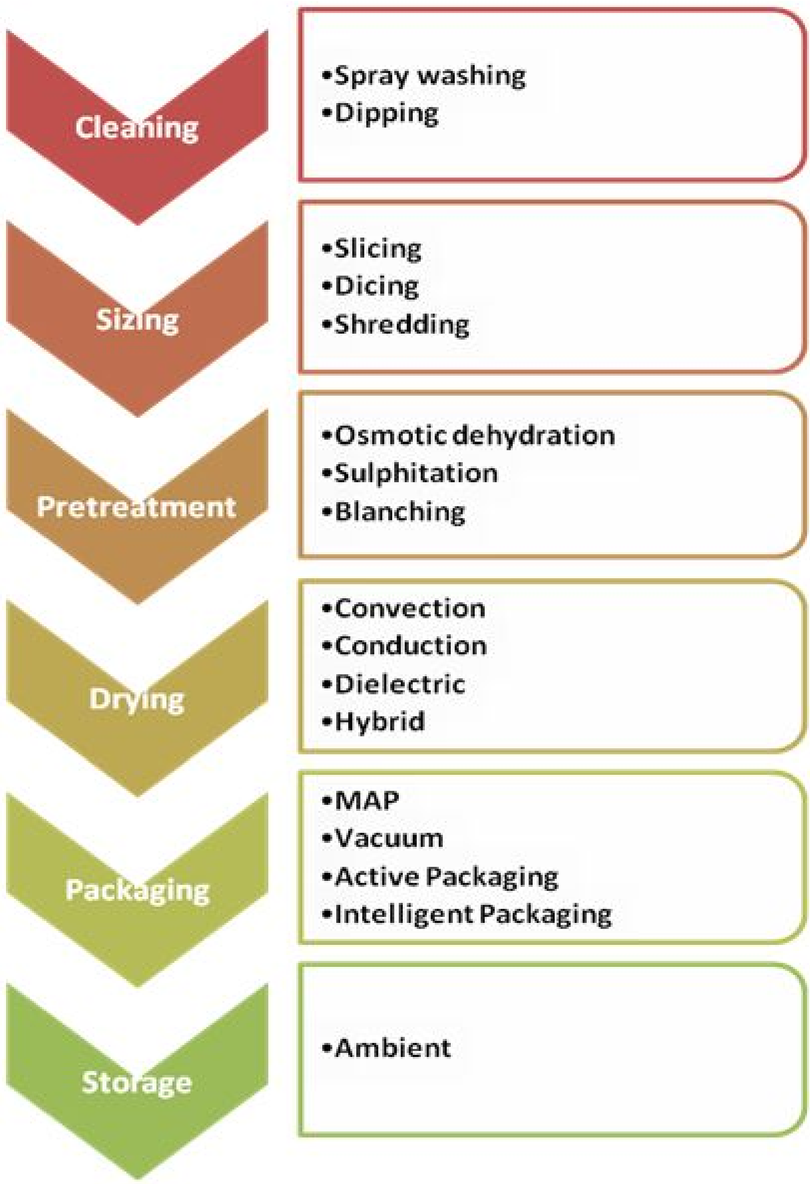


Figure 6.1. Steps to be carried in drying operation

6.2 Theory of Drying

As most of drying operations require air to remove moisture from the product, it is necessary to know the some important properties of air related to drying. These properties are used to estimate the drying rate of the product. The properties of air water vapor mixture are also known as psychrometric properties of air.

There are three inter-related factors that control the capacity of air to remove moisture from a food:

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

6.3 Fundamental properties of water vapor and air mixtures related to drying

The most important psychrometric properties of air are as follows:

Humidity (H) and relative humidity (RH) are calculated according to the following equation:

$$H = \frac{P_w}{P - P_w} \frac{M_w}{M_g}$$

where M_w is the molecular weight of the moisture vapor, M_g is the molecular weight of dry air (gas), P is the total pressure, and P_w is the partial pressure of water vapor.

When the partial pressure of the vapor in the gas phase equals the vapor pressure of the liquid at the temperature of the system (T), the gas is saturated. The relative humidity is a measure of moisture saturation. It is defined as the ratio of the partial pressure of water vapor in a gaseous mixture with air to the saturated vapor pressure of water at a given temperature. The relative humidity is expressed as a percentage and is calculated in the following manner:

$$\mathrm{RH} = \frac{P_w}{P_w^0} \times 100$$

where P_w^0 is the saturated vapor pressure.

The *dry bulb temperature* (T_{db}) is the temperature of the air as measured by a thermometer freely exposed to the air but shielded from radiation and moisture.

The *wet bulb temperature* (T_{wb}) is measured by a gas passing rapidly over a wet thermometer bulb. It is used along with dry bulb temperature to measure the relative humidity of a gas.

The *dewpoint* is the temperature at which air becomes saturated with moisture (100% RH) and

any further cooling from this point results in condensation of the water from the air.

The relationships between air and water vapor and the psychrometric properties of moist air are commonly found in the form of psychrometric tables and chart which is shown in Figure 5.2.

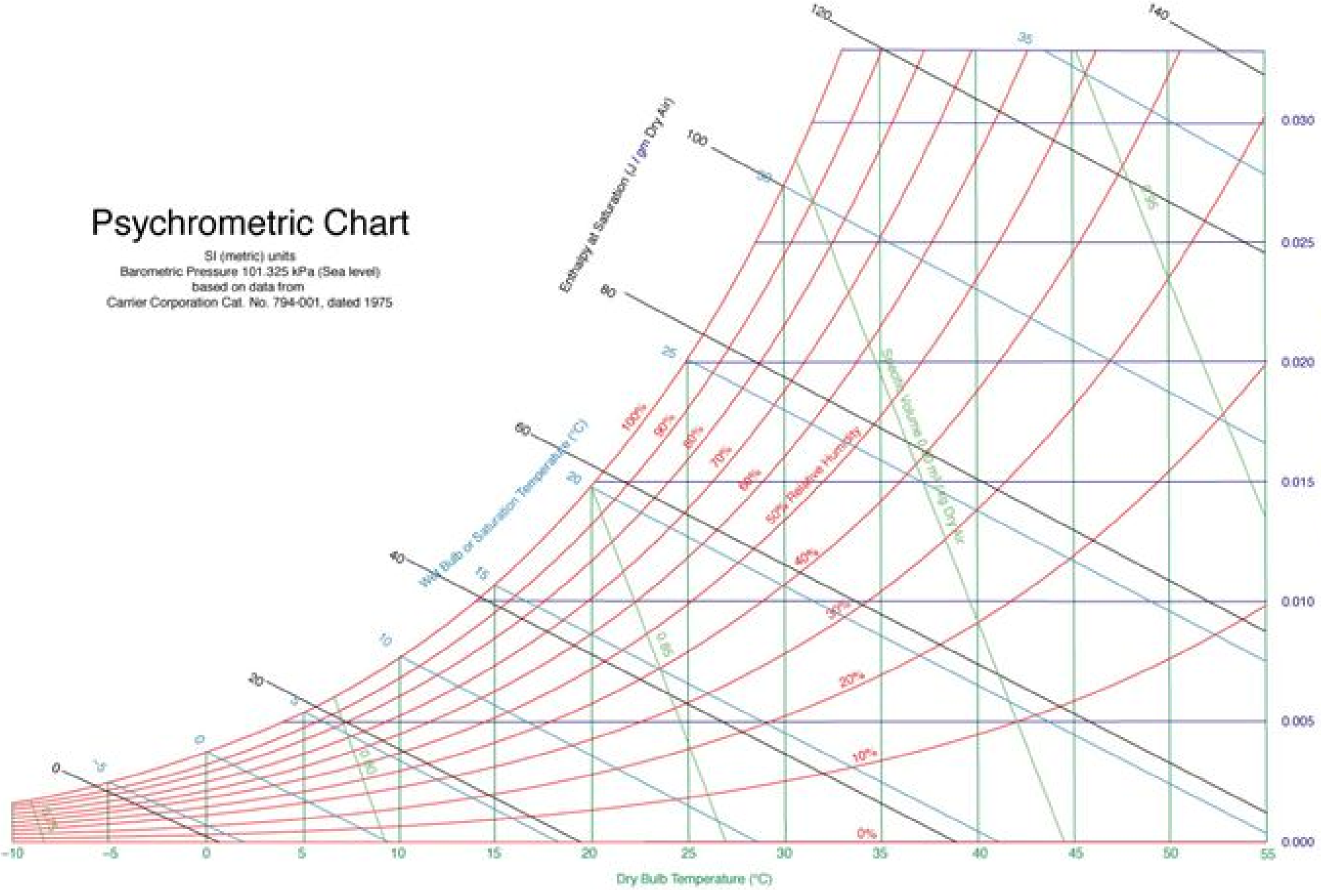


Figure 6.3: Graphical representation of psychrometric properties of air water vapour mixture

6.4 Fundamental Properties of food product related to drying

In addition to air properties there are some properties of food which play important role in drying. These are:

The *moisture content* of a material is the weight of water per unit weight of wet solid (wet basis, X_w) or the weight of water per unit weight of dry solid (dry basis, X). They are related in the following manner:

$$X_w = \frac{X}{X+1} \quad \text{and} \quad X = \frac{X_w}{1-X_w}$$

The *moisture ratio* (MR) is the moisture content of a material during drying. It is usually expressed in a dimensionless form as:

$$\mathrm{MR} = \frac{X - X_e}{X_0 - X_e}$$

where X is the moisture content at any time t, X_e is the equilibrium moisture content, and X_0 is the initial moisture content of the product.

Water activity (a_w) is an index of the availability of water for chemical reactions and microbial growth. It can be defined by the following equation:

$$a_w = \frac{P_w}{P_w^0} = \frac{RH}{100}$$

Moisture content can be classified according to its availability in the food matrix in following types:

1. Bound moisture: Bound moisture is the amount of water tightly bound to the food matrix, mainly by physical adsorption on active sites of hydrophilic macromolecular materials such as proteins and polysaccharides, with properties significantly different from those of bulk water.

2. Free moisture content: Free moisture content is the amount of water mechanically entrapped in the void spaces of the system. Free water is not in the same thermodynamic state as liquid water because energy is required to overcome the capillary forces. Furthermore, free water may contain chemicals, especially dissolved sugars, acids, and salts, altering the drying characteristics.

An important term in drying is the equilibrium moisture content, which is the moisture content of a product in equilibrium with the surrounding air at given temperature and humidity conditions. Theoretically, it is the minimum moisture content to which a material can be dried under these conditions. A plot of the equilibrium moisture content versus the relative humidity or water activity at constant temperature, which is called sorption isotherm, is used to illustrate the degree of water interactions with foods. The value of the equilibrium moisture content for some solids depends on the direction from which equilibrium is approached, and the desorption equilibrium is of particular interest for drying calculations. The equilibrium moisture content for biological materials generally increases rapidly with a relative humidity above 60 to 80% because of capillary and dissolution effects.

6.5 Moisture migration during drying

Water migration in foods is an important phenomenon in drying. During drying heat flows over the product and goes in to the product. This heat increases the temperature of product and moisture which converts the moisture in to water vapor which results in to increase in the vapour pressure that moves moisture towards the surface (Figure 6.5).

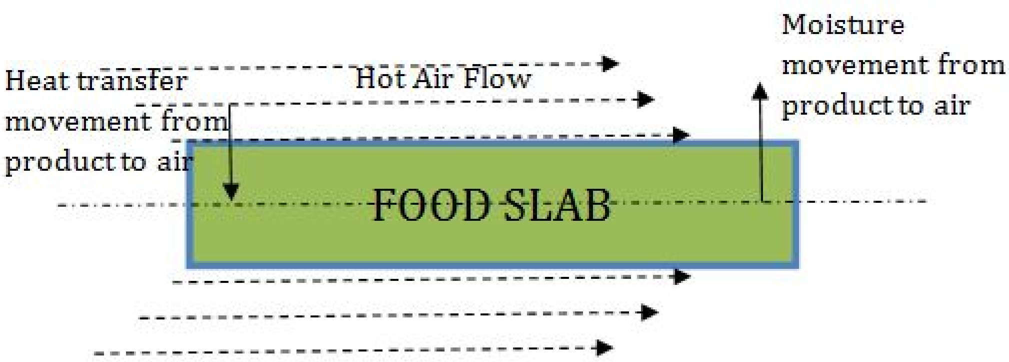


Figure 6.5. Heat and moisture flow during hot air drying of food slab.

From the surface the moisture moves in to the environment. To make easy movement of moisture from product surface to environment there should not be any resistance. The resistance is generally arrived if there is more moisture in the air (which is related to relative humidity of air). Therefore, it is always necessary to use the drying air having low relative humidity. For this purpose, most commonly used convection drying method uses the hot air having temperature in the range 50° to 90°C. Due to increase in the air temperature relative humidity decreases which helps to remove the moisture from the product rapidly and high temperature of air transfers heat to product to evaporate the moisture within the product Also, it can be understood as a driving force for drying. It is defined as the difference in partial pressure of water vapor in the air and the pressure of the moisture in the product. This is a simple theory of moisture movement during drying.

Actually the drying is very complicated phenomenon. Moisture in foods is subdivided in to ionic groups, such as carboxyl and amino acids; hydrogen groups, such as hydroxyl and amides and unbound free moisture in interstitial pores and intercellular spaces (Figure 4). Therefore, the moisture movement within product (internal mass transfer) takes place by combination of several phenomenon like vapor diffusion, liquid diffusion, pressure diffusion, capillary movement, flow by evaporation – condensation sequence and gravity flow. Internal mass transfer is generally recognized to be the principal rate-limiting step during drying. After the moisture reaches the surface of the product it can be removed by convection and diffusion in to the atmosphere (external mass transfer). Therefore diffusion is one of the most important transport phenomenons in the drying and dehydration. While drying takes, the heat transfer also takes place in the product either by conduction, convection or radiation as shown in the figure 5.4.

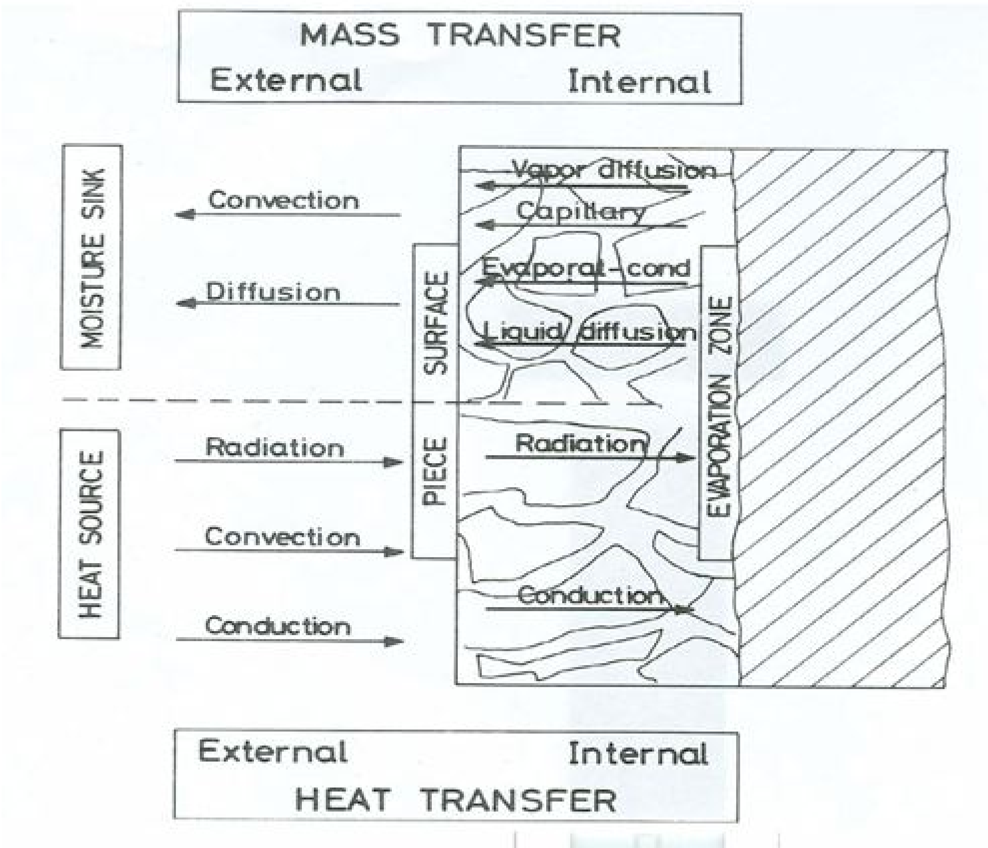


Figure 6.5.1. Internal and external heat and mass transfer during drying

Lesson-4_1:Methods of EMC Determination

However, in storage the moisture content controlled by circulation of air and control of the relative humidity. Hall (1980) mentioned two different methods for determining the EMC:

1. Static method, in which atmosphere surrounding the product comes to equilibrium with the product without mechanical agitation of air or product.

2. The dynamic method, in which the atmosphere surrounding the product itself is mechanically moved.

He preferred the static method than the dynamic one. Although, the dynamic method is quicker but represents problems in design and instrumentations. Therefore, the static method has been used extensively. Several weeks may be required using static method, whereas, with dynamic method the data may be obtained in couple of days or less. He also stated that when using static method for determining the EMC, saturated salt solutions or acids may be used for maintaining the desired relative humidity at the temperature of storage.

1. Steps for equilibrium moisture content determination

For the determination of EMC curves, the following basic steps are necessary regardless of the method used:

1. Sample collection

2. Exposure of the samples to different relative humidities (Rh) at a given temperature T (until equilibrium is reached, respectively)

3. Determination of moisture content

2. Principle of the dynamic method

- Equilibrium moisture content is an important moisture characteristic of porous materials, but its determination has required considerable time and care and the judgement of equilibrium may eventually be arbitrary.
- Dynamic method that can predict the equilibrium moisture content by curve fitting to

- Dynamic method that can predict the equilibrium moisture content by curve-fitting to sorption kinetics experiments was proposed in the absence of accuracy consideration.
- In the equation of continuity of water in porous media, water diffusivity is normally a function of the moisture content.
- Relationship between the concentration of a mass in a porous material isothermally in equilibrium with that in the environment is called sorption isotherm.
- When the mass is water, the relation between atmospheric relative humidity and equilibrium moisture content of materials is the water vapor sorption isotherm, which is an indispensable material property when studying moisture behavior of porous hydrophilic materials such as cement-based materials.
- Especially in moisture transport analysis, moisture capacity that can convert the chemical potential gradient or relative humidity gradient into moisture content gradient, can be obtained from the water vapor sorption isotherm.
- As the name implies, it takes so long time to obtain "equilibrium" values that difficulties of changes in material properties may arise.

3. Conventional methods

Correct equilibrium moisture content can be obtained when a relative humidity is accurately generated and the adsorbed mass is continuously weighed.

Standard methods of relative humidity generation include the saturated salt solution method, flow-division method that mixes dry and saturated air and the method altering temperature or pressure or both. The volumetric method that isothermally changes the vapor pressure in a vacuum system has been widely used in the chemical engineering laboratory.

- The saturated salt solution method can produce a relative humidity with a precision of 1 percent when the container of the salt solution is stirred and the temperature is controlled carefully.
- Haggymassy combined weighing bottle with saturated salt solutions under vacuum and determined isotherms of hardened cement pastes. The mean free path of water vapor decreases under vacuum leading to an increase in its diffusivity in air. This reduces the time to reach equilibrium and is effective in preventing carbonation of cement based specimens. Yuasa and co-workers ground specimens into powder and introduced stirring mechanism in a saturated salt solution container. With all these means, the saturated salt solution method has an disadvantage of generating limited number of relative humidities. This method, as well as the volumetric method, is a standard with its simplicity, and is placed as the reference method of this study.

4. Principle of the dynamic method

- In the equation of continuity of water in porous media, water diffusivity *D*q is normally a function of the moisture content q. In this experiment, the equation is taken as linear because an adsorption experiment will be executed under a constant relative humidity. For a sphere with a radius *r*, the water balance equation may be given by:

$$\frac{\partial \theta}{\partial t} = D_{\theta v}\left(\frac{\partial^2 \theta}{\partial r^2} + \frac{2}{r}\frac{\partial \theta}{\partial r}\right)$$

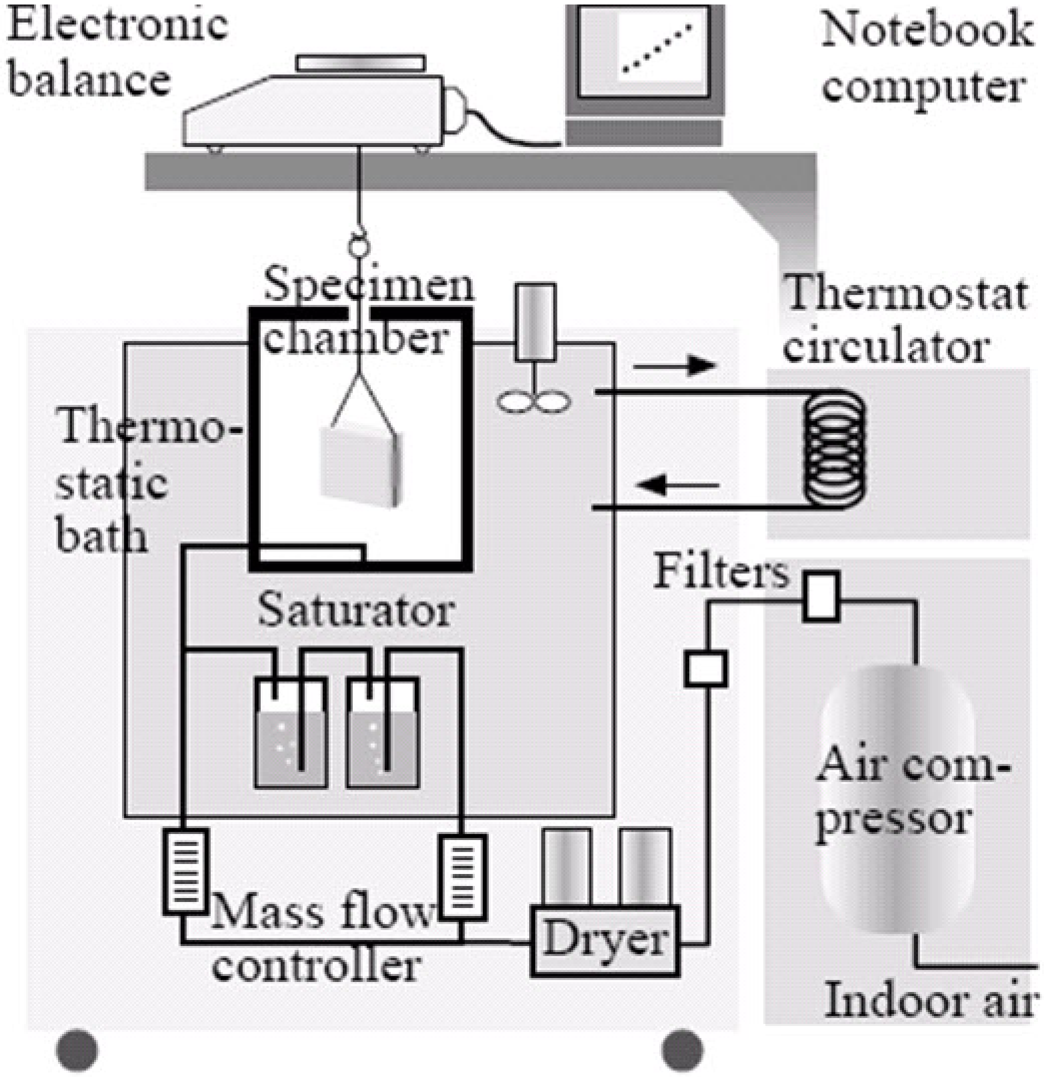
Which can be converted to the one dimensional linear equation by substituting q with*u*/*r*. The initial and the boundary conditions are that the surface moisture content of a sphere with a radius *R*, or relative humidity in equilibrium with the moisture content, is always constant and that the initial moisture content of the sphere in the beginning of adsorption is zero,

$$u=0,\ r=0,\ t>0$$
$$u=R\theta_0,\ r=R,\ t>0$$
$$u=0,\ 0<r<R,\ t=0.$$

With variables separation method, the following formula is obtained

$$m(t) = m_e\left[1 - \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-n^2 kt\right)\right]$$

where $m(t)$ is the total mass passed from the surface of a sphere in a finite time, *me* is the total mass passed after the infinitely long time and k is Dq$\pi^2/R2$.



System of the sorption isotherm apparatus

Lesson 8. Theory of Diffusion

8.1 During drying and dehydration the mass transfer takes by different mechanisms. The diffusion of moisture is most important phenomenon in drying. The drying is mainly

- A multiphase process –phase change,
- evaporation happens under non –equilibrium conditions,
- thermodynamically difficult to define interfacial properties (thermodynamics equilibrium) and
- Continuum assumptions cannot be made immediately. First, the physics needs to be understood .

Temperature, through its effect on the saturation vapor density of air and the vapor pressure of water, determines the concentration of water molecules in the subsurface of food. Changing temperatures may create a positive, negative, or identically zero concentration gradient with respect to the vapor density in the atmosphere. If a gradient of concentration exists, there will be a net flux of water molecules down the gradient, resulting in a net growth or depletion of the subsurface water with time, even under isobaric conditions. The magnitude of this flux depends both on the magnitude of the concentration gradient and on the diffusive properties of the food product, as represented by the diffusion coefficient, D.

In the analysis of falling rate drying period, a simple diffusion model based on Fick's second law of diffusion was considered for the evaluation of moisture transport, which is given by the following equation.

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial M}{\partial x}\right) \qquad \ldots(1)$$

where, M is the free moisture content (kg water/kg dry matter), t is time (s), x is diffusion path or length (m) and D is moisture dependent diffusivity (m^2/s).

The diffusivity varies considerably with moisture content of the food and was estimated by analyzing the drying data using the "method of slopes" technique (Karathanos et al., 1990).

For an infinite slab being dried from both sides and with the assumptions of (i) uniform initial moisture distribution throughout the mass of the sample and (ii) negligible external resistance to mass transfer, the following initial and boundary conditions were fixed for a solution of Eqn. 1

$M = M_0$ at $t = 0$ for all L

$M = M_s = M_e$ at $t > 0$, $x = \pm L/2$ at the surface where, M_0 is the initial moisture content; M_s is the moisture content at the surface; $M_e$is the equilibrium moisture content and L is the thickness of the slab.

The solution of Eqn. 3.12 for constant moisture diffusivity (D) in an infinite slab is given by Eqn. 3.13

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-(2n+1)^2\frac{\pi^2 Dt}{4l^2}\right] \quad \ldots(2)$$

where, l is half thickness of slab.

When the drying time becomes large and n > 1, Eqn. 2 can be reduced to the following form after neglecting all other terms of right hand side except the first one.

For infinite slab

$$\frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\exp\left(-\frac{D\pi^2 t}{4l^2}\right) \quad \ldots(3)$$

The equation 3 is evaluated numerically for Fourier number ($F_0 = D.t / l^2$).

It is noted here that the diffusivity calculated would be a lumped value called apparent moisture diffusivity (D_a) incorporating factors that were not considered separately but would affect the drying characteristics. During microwave vacuum drying, moisture transport takes place by one or more combinations of the liquid diffusion, vapor diffusion, internal evaporation by microwaves and surface diffusion. Since the exact mechanism of moisture transport is not known, an apparent diffusivity, D_a, instead of the true diffusivity, is considered in equation 3 Therefore, the above equation is simply a model with empirical values for apparent diffusivity and not true diffusivity.

Even though the process in each test is assumed to be isothermal, experiments were conducted at four temperature levels to determine temperature dependence, which is usually assumed to follow the Arrhenius relationship which is given below:

$$D = D_0 e^{\left(-\frac{E_0}{RT}\right)} \quad \ldots(4)$$

In this expression D_0 is the Arrhenius factor (m^2/s), E_0 is the activation energy for moisture diffusion (kJ/mol), R is the ideal gas constant (kJ mol^{-1} K^{-1}) and T is the sample temperature (K).

8.2 Modeling water and solid diffusion using transient solution of Fick's law of diffusion

The mathematical models used to describe mass transfer during osmotic dehydration are usually based upon various solutions to Fick's Law of Diffusion. The solution applies to unsteady one dimensional transfer between a plane sheet and a well stirred solution with a constant surface concentration, that is, infinite or semi-infinite medium. The following Fick's unsteady state diffusion model (Eqn. 3.5) can be applied to describe the osmosis mechanism:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial Z^2} \qquad \ldots(5)$$

The effective diffusivity can be determined by solving the above Fick's diffusion model using Newton Raphson method and Crank–Nicholson method (Singh et al., 2006). There are some analytical solutions of Eqn. 5 and are given by Crank (1975) for several geometries and boundary conditions. With the uniform initial water and solute concentration, the boundary conditions for a negligible external resistance and varying bulk solution concentration with the time, analytical solution of Fick's equation for infinite slab geometry being placed in a stirred solution of limited volume is given below by Eqns. 6 and 7 for moisture loss and solute gain, respectively.

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \sum_{n-1}^{\infty} \frac{2\alpha(1+\alpha)}{1+\alpha+\alpha^2 q_n^2} \exp\left[\frac{-D_{ew} q_n^2\, t}{1^2}\right] \qquad \ldots(6)$$

$$SR = \frac{S_t - S_e}{S_0 - S_e} = \sum_{n-1}^{\infty} \frac{2\alpha(1+\alpha)}{1+\alpha+\alpha^2 q_n^2} \exp\left[\frac{-D_{es} q_n^2\, t}{1^2}\right] \qquad \ldots(7)$$

where, MR is the moisture ratio, SR is solid ratio, M_t is moisture in product at any time t (g), S_t is solids in the product at any time t (g), M_e is the equilibrium moisture in the product (g), S_e is the equilibrium solid in product (g), M_0 is the initial moisture in the product (g), S_0 is the initial solid in the product (g), D_{ew} is the effective water diffusivity in the product, D_{es} is effective solid diffusivity in the product, t is the time of osmosis (min), *l* is the half thickness of the slab (m) and q_n are the non-zero positive foods of the equation:

$$\tan q_n = -\alpha q_n \quad \ldots$$

and

$$\alpha = m\frac{V_L}{V_s} \quad \ldots$$

where, m is the partition coefficient and is defined as:

$$m = \frac{C_\infty^L}{C_\infty^S} \quad \ldots$$

where, is volumetric solute concentration (kg of solute/m^3) in solution at infinite time and is volumetric solute concentration (kg of solute/ m^3) in the product at infinite time.

Based on the model given by Crank (1975), Azuara et al. (1992) presented an expression from which the diffusion coefficient (D) can be calculated at different times during the osmotic process:

$$D = \frac{\pi L^2}{4t}\left[\left(\frac{St}{1+St}\right)\left(\frac{X_{\infty th}}{X_{\infty ex}}\right)\right]^2 \quad \ldots(11)$$

where, S is the constant related to the rate of ML or SG, $X_{\infty th}$ is theoretical equilibrium value for ML or SG and $X_{\infty ex}$ is experimental equilibrium value for ML or SG.

8.3 modeling moisture diffusivity during microwave vacuum drying

In the analysis of falling rate drying period, a simple diffusion model based on Fick's second law of diffusion was considered for the evaluation of moisture transport, which is given by the following equation (Karathanos et al., 1990).

\[\frac{{\partial M}}{{\partial t}}=\frac{\partial}{{\partial x}}\left({D\frac{{\partial M}}{{\partial x}}}\right)\]........ (12)

where, M is the free moisture content (kg water/kg dry matter), t is time (s), x is diffusion path or length (m) and D is moisture dependent diffusivity (m^2/s).

The diffusivity varies considerably with moisture content of the food and was estimated by analyzing the drying data using the "method of slopes" technique (Karathanos et al., 1990).

For an infinite slab being dried from both sides and with the assumptions of (i) uniform initial moisture distribution throughout the mass of the sample and (ii) negligible external resistance to mass transfer, the following initial and boundary conditions were fixed for a solution of Eqn. 12

$M = M_0$ at $t = 0$ for all L

$M = M_s = M_e$ at $t > 0$, $x = \pm L/2$ at the surface

where, M_0 is the initial moisture content; M_s is the moisture content at the surface; M_e is the equilibrium moisture content and L is the thickness of the slab.

The solution of Eqn. 12 for constant moisture diffusivity (D) in an infinite slab is given by Eqn. 13

$$MR=\frac{{M-{M_e}}}{{{M_0}-{M_e}}}=\frac{8}{{{\pi^2}}}\sum\limits_{n=0}^\infty{\frac{1}{{{{\left({2n+1}\right)}^2}}}\exp \left[{-{{\left({2n+1}\right)}^2}\frac{{{\pi ^2}Dt}}{{4{l^2}}}}\right]} \quad ....(13)$$

where, l is half thickness of slab.

When the drying time becomes large and $n > 1$, Eqn. 13 can be reduced to the following form after neglecting all other terms of right hand side except the first one.

<u>For infinite slab</u>

$$\frac{{M-{M_e}}}{{{M_0}-{M_e}}}=\frac{8}{{{\pi^2}}}\exp \left({ -\frac{{D{\pi^2}t}}{{4{l^2}}}}\right) \quad ....(14)$$

The equation 3.13 is evaluated numerically for Fourier number ($F_0 = D.t / l^2$).

It is noted here that the diffusivity calculated would be a lumped value called apparent moisture diffusivity (D_a) incorporating factors that were not considered separately but would affect the drying characteristics.

During microwave vacuum drying, moisture transport takes place by one or more combinations of the liquid diffusion, vapor diffusion, internal evaporation by microwaves and surface diffusion. Since the exact mechanism of moisture transport is not known, an apparent diffusivity, D_a, instead of the true diffusivity, is considered in equation 14. Therefore, the above equation is simply a model with empirical values for apparent diffusivity and not true diffusivity.

Lesson 9. Modeling And Simulation Of Drying Process

- Every product shows a typical behavior during drying operation under the different processing conditions like air temperature, product temperature, air velocity, product shape and size and product loading.
- Therefore, any drying process is required to be studied for its repeated applications. This helps in deciding the energy and time requirement for the drying of product in advance. By using such a data, design of efficient dryer is possible.
- In literature, several approaches on prediction of drying rate and moisture content with variation in air temperature, air velocity, product thickness, air humidity and product density are available.
- Mathematical modeling is required for describing mass transfer in the osmotic dehydration process. Literature shows the two basic approaches to model osmotic dehydration processes: macroscopic approach and microscopic approach.

9.1 Macroscopic approach

The macroscopic approach assumes the tissue is homogeneous and the modelling is carried out on the lumped properties of cell wall, cell membrane and cell vacuole (Yao and Le Maguer, 1996; Azuara et al., 1992). The models available in literature can be classified under the following approaches:

1. Estimation of diffusion coefficients for water loss and solid gain by using Fick's second law of diffusion.
2. Estimation of water loss and solid gain as a function of time, temperature and initial concentration of the medium (Empirical models).
3. Based on cellular structure according to non-reversible thermodynamic principles.
4. Prediction of equilibrium moisture loss.
5. Pressure gradient dependent modeling accounting the capillary and external pressure effects (Hydrodynamic mechanism).
6. Artificial Neural Network (ANN) modeling
7. Statistical modeling like stochastic approach, Weibull probabilistic distribution and multiple regression.

9.2 Microscopic approach

The microscopic approach recognizes the heterogeneous properties of the tissue and the complex cellular structure is represented by a simplified conceptual model. The modeling of the cellular structural is attempted by very few researchers.

9.3 Modeling and simulation of temperature and moisture distribution in foods during drying

Table 9.3 Mathematical models used to test the drying kinetics

Model Name	Model	Reference
Newton	MR = exp(-kt)	Liu and Bal Nellist (198
Page	MR = exp(-kt^n)	Agrawal an Bruce (198:
Henderson and Pebis	MR = a exp(-kt)	Pal and Cha Rahman an
Two-Term	MR = a exp(bt) + c exp(dt)	Henderson
Asymptotic Logarithmic	MR = a exp(-kt)+b	Yaldız and
Wang and Singh	MR =1+at+bt^2	Wang and S
Diffusion approximation	MR = a exp(-kt)+(1-a) exp(-kat)	Yaldız and
Two term Exponential	MR = a exp(-kt) + (1-a) exp(-kat)	Wang and S
Verma et. al.	MR = a exp(-kx)+(1-a) exp(-gt)	Verma et. a
Modified Henderson and Pabis	MR = a exp(-kx)+b exp(-gx) +c exp(-gx)	Karathanos Belessiotis

The non-uniformity in temperature and moisture distributions is the main reason for unacceptable food quality of microwaved products. Some of the key factors that influence the uniformity of temperature distribution are the dielectric and thermo-physical properties of the product, frequency and power of the incident microwave energy, and the geometry and dimensions of the product (Jun and Puri, 2004). The successful design of industrial microwave application can be done with the aid of modeling techniques which relate electrical and physical properties of foods (Van Remmen et al., 1996). The literature shows the two approaches of modeling of power deposition patterns: (1) making use of Maxwell's equations for electromagnetic field, and (2) using Lambert's law in which power is attenuated exponentially as a function of distance of one dimensional penetration into the material. However, the Lambert's law can be used for samples thicker than about three times the characteristics penetration depth of microwaves, but the law fails for thinner samples. It turns out that Lambert's law is inapplicable for most foods prepared in home microwave ovens. Therefore, Maxwell's equation must be used to accurately describe the propagation and absorption of radiation (Ayappa et al., 1991). Generally, finite difference, finite element and boundary element methods are used to solve the Maxwell's equations to obtain power deposition patterns in slabs, cylinders and spheres (Van Remmen et al., 1996).

Finite difference approximations have been used to obtain reasonable estimation of internal temperature and moisture profiles during microwave heating. However, most of these models were for microwave-convective heating. Very few literatures focus on modeling of microwave-vacuum drying of sliced and individual food particles. Lian et al. (1997) described the coupled heat and moisture transfer during microwave vacuum drying of a soluble food concentrate. They considered the moisture transfer as a combination of simultaneous water (liquid) and vapour transfer. Pandit and Prasad (2003) have developed simplified heat and mass transfer model to predict moisture and temperature changes during microwave drying of various shaped food materials. Kiranoudis et al. (1997) studied the mathematical model of the microwave vacuum drying kinetics of some fruits. An empirical mass transfer model, involving a basic parameter of phenomenological nature, was used and the influence of process variables was examined by embodying them to the drying constant.

9.4 Mass transfer kinetics during osmotic dehydration

The osmotic dehydration process different than other drying processes as mass transfer takes place in liquid form (water comes out of product without phase change). Therefore, different models are available for the process. During osmotic dehydration, two resistances oppose mass transfer, one internal and the other external. The fluid dynamics of the solid fluid interface governs the external resistance whereas, the much more complex internal resistance is influenced by cell tissue structure, cellular membrane permeability, deformation of vegetable/fruit pieces and the interaction between the different mass fluxes. Under the usual treatment conditions, the external resistance is negligible compared to the internal one. Variability in biological product characteristics produces major difficulties regarding process modeling and optimization. Mass transfer is affected by variety, maturity level and composition of product. The complex non-homogenous structure of natural tissues complicates any effort to study and understand the mass transport mechanisms of several interacting counter current flows (water, osmotic solute, soluble product solids).

A mathematical model developed by Azuara et al. (1992) was used to study the mass transfer in osmotic dehydration of carrot slices. The various parameters considered for the model were moisture loss at any time (ML_t), moisture loss at equilibrium ( ), solid gained at any time (SG_t), solids gained at equilibrium ( ) and the time of osmotic dehydration (t). The models are as follows:

For moisture loss:

$$ML_t = \frac{S_1 t (ML_\infty)}{1 + S_1 t} = \frac{(ML_\infty) t}{\dfrac{1}{S_1} + t} \quad \text{...(1)}$$

$$\frac{t}{ML_t} = \frac{1}{S_1 (ML_\infty)} + \frac{t}{ML_\infty} \quad \text{...(2)}$$

For solid gain:

$$SG_t = \frac{S_2 t (SG_\infty)}{1 + S_2 t} = \frac{(SG_\infty) t}{\dfrac{1}{S_2} + t} \quad \text{...(3)}$$

$$\frac{t}{SG_t} = \frac{1}{S_2 (SG_\infty)} + \frac{t}{SG_\infty} \quad \text{...(4)}$$

The plots of t/ML_t vs. t and t/SG_t vs. t would be linear, the parameters could be determined from the intercept and slope. The Eqns. 3.1 and 3.3 could then be used to predict the mass transfer kinetics. S_1 and S_2 are the constants related to the rates of water and solid diffusion, respectively. The terms indicate that 1/S1 or 1/S2 represent the time required for half of the diffusible matter (water or solids) to diffuse out or enter in the product, respectively. Further, as the time t becomes much longer (that is, t ® ¥) than the values of that 1/S1 or 1/S2, the water loss or the solid gain, ML_t or SG_t, approaches equilibrium value, $ML_{¥}$ or $SG_{¥}$, asymptotically.

In above equations, the values of parameters S_1, $ML_{¥}$, S_2 and $SG_{¥}$ can be estimated from short duration osmotic kinetic data by performing linear regression or graphical plotting of the above equations in the linearized form.

9.5 Mathematical Modeling of Heat and Mass Transfer in Product by Microwave Assisted Drying

For proper equipment design, process optimization and improvement of final product quality, accurate prediction of the heat and moisture transfer in the product is vital. Many researchers have modeled the heat and moisture transfer in the food products during microwave heating and drying. They used numerical techniques based on the finite difference method, finite element method and transmission line matrix method to simulate the microwave heating with varying degree of accuracy.

9.6 Heat transfer and temperature profile within the product

In microwave heating, the governing energy balance equation includes a heat generation term Q by dielectric heating. Temperature changes at any location within a food during microwave drying are affected by thermal diffusion, generation of heat by microwaves and evaporation of moisture. Mathematically, it is represented as:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{Q}{\rho c_p} + \left(\frac{1}{\rho c_p}\right)\frac{\partial (M * H)}{\partial t} \qquad ...(5)$$

where, T is the product temperature, t is the time, Q is the conversion of microwave energy to heat per unit volume, M is the moisture concentration and H is enthalpy of moisture. The parameters a, r and c_p are the thermal diffusivity, density and specific heat of the material, respectively.

The heat generated per unit volume of material (Q) is the conversion of electromagnetic energy in to heat energy. Its relationship with the average electric field intensity (E_{rms}) at that location can be derived from Maxwell's equations of electromagnetic waves as shown by Metaxax and Meredith (1983):

$$Q = 2\pi f \epsilon_0 \epsilon'' E^2_{rms} \qquad ...(6)$$

where, f is the frequency of microwaves, $\hat{I}_0$ is the dielectric constant of free space and Î² is the loss factor of food being heated. At a given frequency, the dielectric loss factor is a function of the composition of food materials and its temperature.

9.7 Mass transfer and moisture profiles

Assuming the food material as a capillary porous body, the governing equation for the internal moisture transport process can be written as:

$$\frac{\partial M}{\partial t} = \alpha_m \nabla^2 M + \alpha_m \delta_p \nabla^2 P + \alpha_m \delta_t \nabla^2 T \qquad ...(7)$$

where, M is the total moisture content (liquid and vapour phase); a_m is the moisture diffusivity; d_p and d_t are the pressure and thermal gradient coefficients, respectively. The three terms in the right hand side of Eqn. 3.17 represent moisture movement due to concentration, pressure and temperature gradients, respectively. Flow due to thermal gradient is generally ignored during microwave drying of solid moist foods and the moisture movement is considered due to the pressure and concentration gradients.

9.8 Boundary and initial conditions

The generalized boundary conditions for microwave heating can be written as:

$$-k_t \frac{\partial T}{\partial x} = h\,(T - T_\infty) + \in\sigma\,(T^4 - T^4_s) + m_w\lambda_w \qquad \ldots(8)$$

where, 'x' represents the direction normal to the boundary and 'k_t' is the thermal conductivity of the food material. The first term of the right hand side is for convective heat transfer at the surface with 'h', the convective heat transfer coefficient and '$T_¥$', the air temperature. Convective heat loss for a food under vacuum would be much lower due to low temperature gradient. The second term of the above equation involves radiative heat loss by the food material and T_s is the temperature of the surface facing the food material. The quantities Î and s are the surface emissivity and Stefan-Boltzman constant, respectively. Radiative heat transfer is important when the surfaces of the material act as susceptors. Evaporation (m_w) at the surface is more important in microwave heating than in conventional heating because more moisture moves from the interior (Datta, 1990).

The boundary conditions for food samples in drying are featured by convective cooling and surface moisture loss. That is:

$$\text{At } x = \pm 1/2, \quad -k_t \frac{\partial T}{\partial x} = h(T - T_\infty) \qquad \ldots(9)$$

$$-D_v \frac{\partial M}{\partial x} = K_m(M_v - M_{v\infty}) \qquad \ldots(10)$$

$$\text{at } x = 0, \qquad \frac{\partial T}{\partial x} = 0; \qquad \frac{\partial M}{\partial x} = 0$$

The initial sample temperature and moisture content are considered to be uniform

i.e. $T = T_0$; $M_v = M_{v0}$; $M = M_0$

where, l is the thickness of slices, M_{v0} is the saturated vapour concentration at T_0 and M_0 is the initial moisture concentration of the food material.

Lesson 10. Mass Transfer Kinetics During Osmotic Dehydration

- The osmotic dehydration process different than other drying processes as mass transfer takes place in liquid form (water comes out of product without phase change). Therefore, different models are available for the process.
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- The fluid dynamics of the solid fluid interface governs the external resistance whereas, the much more complex internal resistance is influenced by cell tissue structure, cellular membrane permeability, deformation of vegetable/fruit pieces and the interaction between the different mass fluxes.
- Under the usual treatment conditions, the external resistance is negligible compared to the internal one. Variability in biological product characteristics produces major difficulties regarding process modeling and optimization.

  Mass transfer is affected by variety, maturity level and composition of product.
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  (ML_∞), solid gained at any time (SG_t), solids gained at equilibrium (SG_∞) and the time of osmotic dehydration (t). The models are as follows:

For moisture loss:

$$ML_t=\frac{S_1 t\,(ML_\infty)}{1+S_1 t}=\frac{(ML_\infty)t}{\frac{1}{S_1}+t} \qquad \text{.................(1)}$$

$$\frac{t}{ML_t}=\frac{1}{S_1(ML_\infty)}+\frac{t}{ML_\infty} \qquad \text{..................(2)}$$

For solid gain:

$$SGt=\frac{S_2 t\,(SG_\infty)}{1+S_2 t}=\frac{(SG_\infty)t}{\frac{1}{S_2}+t} \qquad \text{..........(3)}$$

$$\frac{t}{SG_t} = \frac{1}{S_2(SG_\infty)} + \frac{t}{SG_\infty} \qquad \text{....................(4)}$$

- The plots of $\frac{t}{{M{L_t}}}$ vs. t and $\frac{t}{{S{G_t}}}$ vs. t would be linear, the parameters could be determined from the intercept and slope. The Eqns. 1 and 3 could then be used to predict the mass transfer kinetics. S_1 and S_2 are the constants related to the rates of water and solid diffusion, respectively.
- The terms indicate that $\frac{1}{{{S_1}}}$ or $\frac{1}{{{S_2}}}$ represent the time required for half of the diffusible matter (water or solids) to diffuse out or enter in the product, respectively. Further, as the time t becomes much longer (that is, $t \to \infty$) than the values of $\frac{1}{{{S_1}}}$ or $\frac{1}{{{S_2}}}$, the water loss or the solid gain, ML_t or SG_t, approaches equilibrium value, ML_∞ or SG_∞, asymptotically.
- In above equations, the values of parameters S_1, ML_∞, S_2 and SG_∞ can be estimated from short duration osmotic kinetic data by performing linear regression or graphical plotting of the above equations in the linearized form.

Lesson.11 Mathematical Modeling of heat and Mass Transfer in Product

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Heat transfer and temperature profile within the product

In microwave heating, the governing energy balance equation includes a heat generation term Q by dielectric heating. Temperature changes at any location within a food during microwave drying are affected by thermal diffusion, generation of heat by microwaves and evaporation of moisture. Mathematically, it is represented as:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{Q}{\rho c_p} + \left(\frac{1}{\rho c_p}\right)\frac{\partial (M*H)}{\partial t} \quad \ldots(15)$$

where, T is the product temperature, t is the time, Q is the conversion of microwave energy to heat per unit volume, M is the moisture concentration and H is enthalpy of moisture. The parameters a, r and c_p are the thermal diffusivity, density and specific heat of the material, respectively.

The heat generated per unit volume of material (Q) is the conversion of electromagnetic energy in to heat energy. Its relationship with the average electric field intensity (E_{rms}) at that location can be derived from Maxwell's equations of electromagnetic waves as shown by Metaxax and Meredith (1983):

$$Q = 2\pi f \epsilon_0 \epsilon'' E^2_{rms} \quad \ldots(16)$$

where, f is the frequency of microwaves, Î$_0$ is the dielectric constant of free space and Î^2 is the loss factor of food being heated. At a given frequency, the dielectric loss factor is a function of the composition of food materials and its temperature.

Mass transfer and moisture profiles

Assuming the food material as a capillary porous body, the governing equation for the internal moisture transport process can be written as:

$$\frac{\partial M}{\partial t} = \alpha_m \nabla^2 M + \alpha_m \delta_p \nabla^2 P + \alpha_m \delta_t \nabla^2 T \quad \ldots(17)$$

where, M is the total moisture content (liquid and vapour phase); a_m is the moisture diffusivity; d_p and d_t are the pressure and thermal gradient coefficients, respectively. The three terms in the right hand side of Eqn. 17 represent moisture movement due to concentration, pressure and temperature gradients, respectively. Flow due to thermal gradient is generally ignored during microwave drying of solid moist foods and the moisture movement is considered due to the pressure and concentration gradients.

Boundary and initial conditions

$$-k_t \frac{\partial T}{\quad} = h\,(T-T_\infty) + \epsilon\sigma\,(T^4-T^4_s) + n \qquad \ldots(18)$$

The generalized boundary conditions for microwave heating can be written as:

where, ‘x’ represents the direction normal to the boundary and ‘k_t’ is the thermal conductivity of the food material. The first term of the right hand side is for convective heat transfer at the surface with ‘h’, the convective heat transfer coefficient and ‘$T_¥$’, the air temperature. Convective heat loss for a food under vacuum would be much lower due to low temperature gradient. The second term of the above equation involves radiative heat loss by the food material and T_s is the temperature of the surface facing the food material. The quantities Î and s are the surface emissivity and Stefan-Boltzman constant, respectively. Radiative heat transfer is important when the surfaces of the material act as susceptors. Evaporation (m_w) at the surface is more important in microwave heating than in conventional heating because more moisture moves from the interior (Datta, 1990).

The boundary conditions for food samples in drying are featured by convective cooling and surface moisture loss. That is:

At $x = \pm l/2$, $-k_t = \frac{\partial T}{\partial x} = h(T-T_\infty)$ $\qquad \ldots(19)$

$$-D_v \frac{\partial M}{\partial x} = K_m(M_v - M_{v\infty}) \qquad \ldots(20)$$

at $x = 0$, $\frac{\partial T}{\partial x} = 0;\qquad \frac{\partial M}{\partial x} = 0$

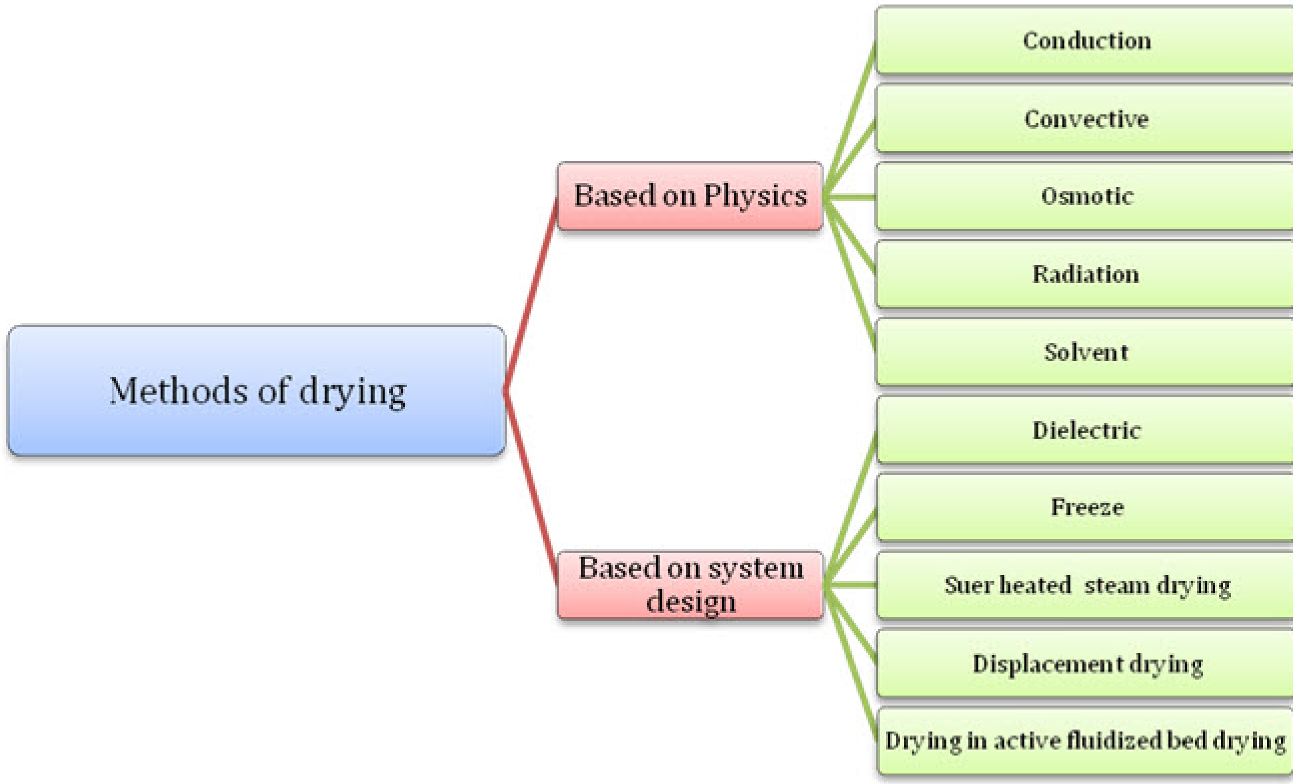
The initial sample temperature and moisture content are considered to be uniform

i.e. $T = T_0$; $\quad M_v = M_{v0}$; $\qquad M = M_0$

where, l is the thickness of slices, M_{v0} is the saturated vapour concentration at T_0 and M_0 is the initial moisture concentration of the food material.

Lesson.12 Methods of Drying

Foods are dried using several methods falling into various categories. The drying methods being used for foods



along with the process parameters are given in Table 3. It can be observed from the table that sun/solar drying, hot air, osmotic dehydration, microwave assisted drying, infra-red, freeze, vacuum and hybrid drying are most commonly used methods for majority of the foods. The foregoing sections illustrate these methods of food drying.

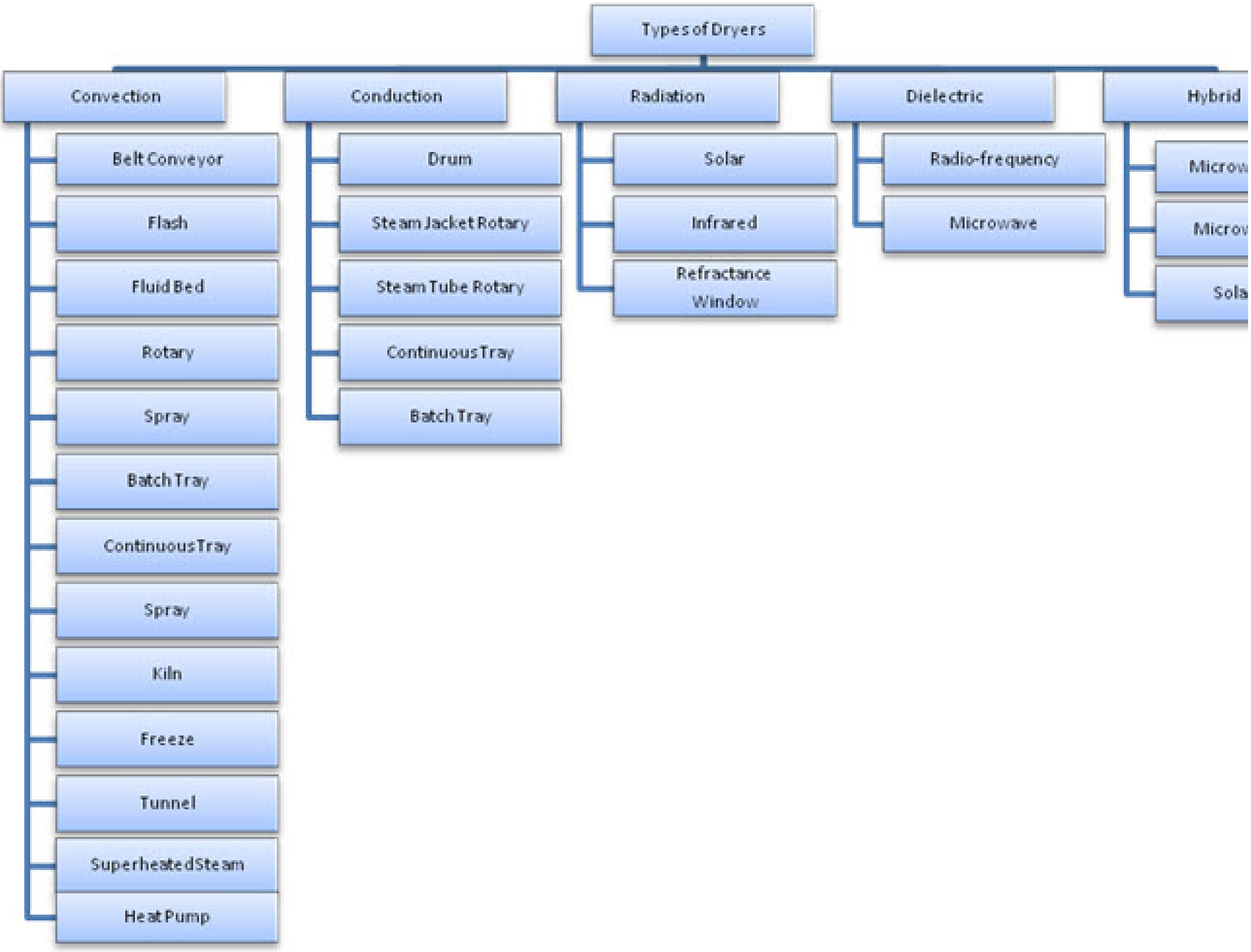


Figure 2: Chart showing the classification of dryers based on methods of drying

Hot air drying

The hot air dryer is used to dry several fruits and vegetables and biomaterials. Heating ambient air to use for drying, a simple cost-effective procedure. Increase in the air temperature decreases the humidity of air which makes favourable conditions to increase the surface mass transfer during drying. A typical hot air dryer consists of a cabinet with fitted blower, speed regulator, temperature controller, heaters and humidity sensing device. The product is generally   The relative humidity and temperature of the ambient air were in the range 60–65% and 30°C, respectively. The typical setup of HAD is shown in Fig. 1.

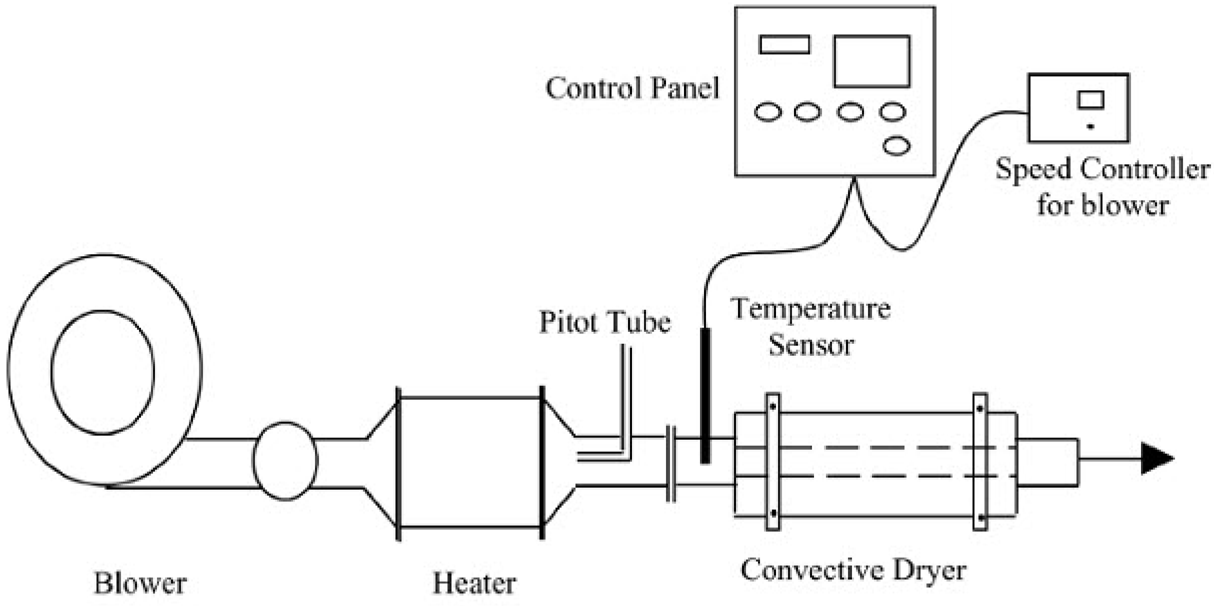


FIG. 1. Hot air dryer (HAD) set up for dehydration.

Heat Pump Dryer

High temperature drying deteriorates the material structure and can render it unsuitable for further use. Low temperature drying of specialty crops reduces the risk of loss in nutrient content and damage to physical properties. Drying system incorporating a dehumidification cycle have been developed that both conserve energy and handle the material gently. The dryer operates using a heat pump where both sensible and latent heats are recovered from the exhaust air. The heat is then recycled back through the dryer by heating the air entering the dryer. The heat pump drying system is a combination of two sub-systems: a heat pump and a dryer.

The heat pump operates according to a basic air conditioning cycle involving four main components: the evaporator, the compressor, the condenser and the expansion valve.

The working fluid (refrigerant) at low pressure is vaporized in the evaporator by heat drawn from the dryer exhaust air. The compressor raises the enthalpy of the working fluid of the heat pump and discharges it as superheated vapor at high-pressure. Heat is removed from the working fluid and returned to the process air at the condenser. The working fluid is then throttled to the low-pressure line (using an expansion valve) and enters the evaporator to complete the cycle.

In the dryer system, hot and dry air at the exit of condenser is allowed to pass through the drying chamber where it gains latent heat from the material. The humid air at dryer exit then passes through the evaporator where condensation of moisture occurs as the air goes below dew point temperature.

A performance study of a heat pump dryer system is required to fully understand its operating characteristics based on different materials to be dried. To accomplish this objective, the project was divided into three tasks (steps). Task A is concerned with the design and construction of a prototype heat pump dryer system. Task B involves field-testing of a prototype system using specialty crops or material with similar characteristics. Finally, task C is to develop a comprehensive computer model using the fundamentals of thermodynamics for a heat pump dryer system and to determine its accuracy compared to experimental results.

Sun/Solar drying

Sun drying is common method to preserve the root products in tropical countries. Sun drying consists of direct and indirect drying. Open sun drying is considered as direct sun drying process. It is generally used in the developing and undeveloped countries and carried out by spreading foods either on the floor or on supporting structures made from locally available material like wood, bamboo etc. However, this technique is extremely weather dependent and has the problems of contamination with dust, wind-blown debris, sand particles and environmental pollution, insect infestation, damage to the product by rodents, birds and animals, growth of microorganisms and additional losses during storage due to insufficient or non-uniform drying. Also, degradation through exposure to direct irradiation of the sun and to rain, storm and dew takes place as well as the required drying time can be quite long. Losses during open sun drying can be estimated at more than 30% and could be reduced to a great extent by improved methods of solar drying. Therefore, indirect method of sun drying that is use of solar assisted mechanical dryers, which are far more rapid, providing uniformity and hygiene, are inevitable for root drying processes. The literature shows that most of the fruit and vegetables can be dried using indirect type of solar drying with drying time from few hours to 5 days depending upon the product to be dried.

Disadvantages of Open Sun Drying

- Damage to the product by rodents, birds and animals
- Degradation through exposure
- Contamination
- Insect infestation
- Growth of microorganisms
- Insufficient or non-uniform drying
- Losses > 30%

Main Parts of Solar Dryers

- Drying cabinet, where the material to be dried is placed and where the drying takes place
- Collector to convert solar radiation into heat
- Means for keeping the drying air in flow
- Ducts, pipes, and other appliances
- Measuring and control equipment
- Auxiliary energy source (optional)

- Heat transfer equipment for transferring heat to the drying air or to the material (optional)
- Heat storage unit (optional).

Classification of Solar Dryers

- solar dryers can be classified on the basis of energy sources used in to following types:

1. Solar natural dryers using ambient energy sources only.
2. Semiartificial solar dryers with a fan driven by an electric motor for keeping a continuous air flow through the drying space.
3. Solar-assisted artificial dryers able to operate by using a conventional (auxiliary) energy source if needed.

FIG. 1. Schematic diagram and photograph of a solar cabinet dryer.

1. Inlet from atmosphere; 2. control valve for inlet air; 3. duct carrying atmospheric air to the collector panels; 4. solar collector panel; 5. duct carrying heated air from collector panels to the blower; 6. blower; 7. drying cabinet; 8. control valve for hot air dryer outlet.

Lesson.13 Hot Air Assisted Drying

Inroduction

Hot Air Drying

Hot air drying is one of the most common methods of drying in which air is circulated by natural or forced convection though or over the bed of product. The product may be spread on the screened trays or in a controlled room or platform. The drying medium is air which is heated generally in the temperature range from ambient to 110°C during root drying depending upon the nature of foods. The most common methods of hot air drying include tray drying/cabinet drying and fluidized bed drying. There are several sizes of trays depending on type of product. The root products are generally spread on perforated trays in a single layer or multiple layers depending upon the required tray loading density in kg product/m^2 of the tray area. Air having temperature in the range ambient to 100°C is blown either in cross flow or parallel flow mode in the dryer in the velocity range 0.1 to 1.9 m/s. Foods like carrots, sweet potato, potato and onion are sensitive to temperature, the problem of darkening in colour, loss of flavour and decrease in rehydration ability of the dried product occur during hot air drying that can be solved by some pre-treatments like blanching, chemical dipping and osmotic dehydration. The range of air temperature and velocity used during hot air drying of various foods is given in Table 3. It can be observed the table that hot air drying is most common method of root drying as compared to other methods.

Hot air drying of foods can be carried out in single and multiple stages. Literature shows that multistage drying of root like onion is more effective than the single stage. Munde et al. [18] developed a process for multistage dehydration of onion flakes. They dried 4 mm thick onion slices at 50°, 60°, 70°, 80°, 90° and 100°C temperatures up to 30, 40, 50 and 60 per cent cut-off moisture levels and the remaining moisture was removed at the control temperature 50°C. On the basis of quality factors and production time, they recommended the two stage dehydration process for onions and also stated that the four stage dehydration process saves 24% drying time at the cost of very marginal sacrifice in quality from the possible best two stage dehydration process.

Fluidized Bed Drying

Fluidized bed drying is carried out by passing the air at fluidization velocity through a bed of product so as to fluidize the material. In **fluid bed drying**, heat is supplied by the fluidization air, but the air flow need not be the only source. Heat may be effectively introduced by heating surfaces (panels or tubes) immersed in the fluidized layer. Uniform processing conditions are achieved by passing a gas (usually air) through a product layer under controlled velocity conditions to create a fluidized state. Some foods like green peas, onions rings, garlic, carrot pieces can be dried using fluidized bed. Generally fluidized bed drier can be used with air temperatures in the range 40° to 80 °C and air velocity equivalent to minimum fluidization to dry the products. In case of fluidized bed drying, after the initial falling rate period, temperature no longer controls the drying rate. The fluidized bed dried products show better colour, rehydration properties, greater retention of chemical compounds and better overall sensory quality than those dried by solar and hot air thin layer drying methods. Due to the high air velocities required to fluidize the material, power requirements for the fan are high and the thermal efficiency is low compared to conventional (fixed bed) drying. But re-cycling of the exhaust air can be done to improve the thermal efficiency.

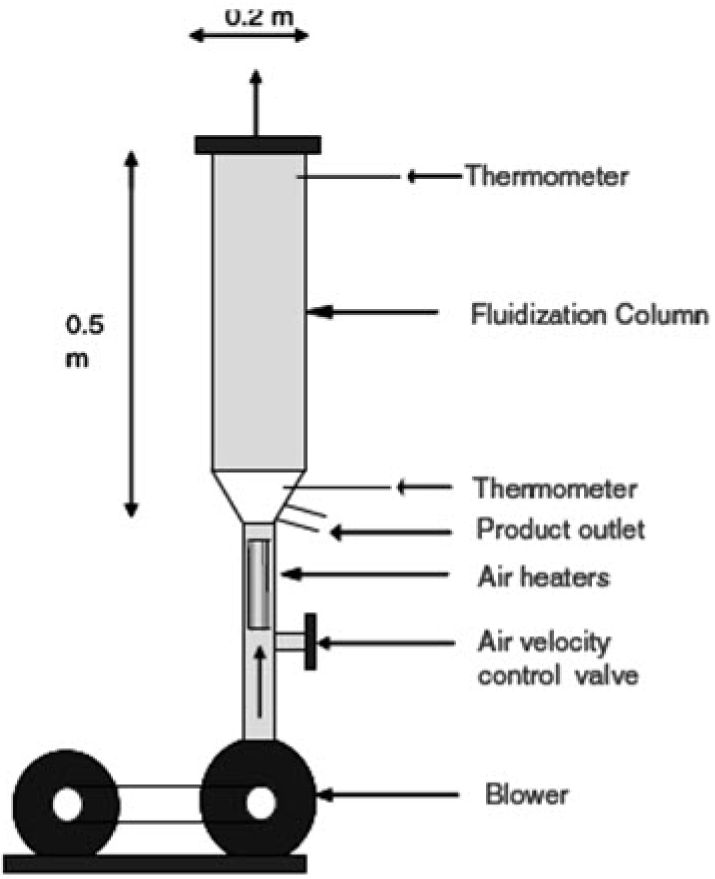


Figure . Schematic Diagram of experimental setup of Fluidized Bed drying

This type of dryer in which individual grains are suspended and sometimes transported by air moving at high velocity, 2-3 m/s, can produce very evenly dried grain. Recent research in the Philippines (Sutherland & Ghaly 1990; Tumambing & Driscoll 1991) has indicated that the fluid bed dryer has promising potential for the rapid first-stage drying of paddy to 18% moisture in two-stage drying (see above). Paddy at a bed depth of 100 mm can be dried from 24% to 18% moisture in 15 minutes with air at 100°C and a velocity of 2 m/s, with no adverse effects on quality. However, due to the high air velocities required to fluidise the paddy, power requirements for the fan are high and the thermal efficiency is low compared to conventional (fixed bed) drying.

Types of Fluidized bed dryers

Well mixed fluidized bed dryers

Vibrated fluidized bed dryers

Plug flow fluidized bed dryers

Heat pump drying (room temperature drying)

- Low temperature drying method

- Use of refrigeration system to remove the moisture from the air
- Humidity of air is reduced at evaporator and heat rejected at condenser is used to heat the dry air
- Increases the drying rate at low air temperature
- Results in high quality dehydrated food product
- Time and energy saving as compared to other methods of drying

Lesson.15 Osmotic Dehydration

Mechanism

In osmotic dehydration, the fruit or vegetable pieces are immersed in concentrated aqueous solution of high osmotic pressure (hypertonic media) for a specified time and temperature. The driving force for water removal is the concentration gradient between the solution and the intracellular fluid. If the membrane is perfectly semi permeable, solute is unable to diffuse through the membrane into the cells. Selective properties of cell membranes make it possible for water and low-molecular cell sap components diffuse into the surrounding solution of higher osmotic pressure. However, it is difficult to obtain a perfect semi permeable membrane in food systems due to their complex internal structure, and there is always some solid diffusion into the food, which means that osmotic dehydration, is actually combination of simultaneous water and solute diffusion process (Chaudhari et al., 1993;Ghosh et al., 2004).

In general, during osmotic pre-concentration, two major counter current flow take place simultaneously across the semi permeable cell membrane,(i) water diffusion out of the food into the solution, at a faster rate initially and slowly afterwards and, (ii) solute penetration in the opposite direction, at a slower rate initially but increasing with time (Chaudhari et al., 1993). A third transfer process, leaching of product solutes (sugars, acids, minerals, vitamins) into the medium, although recognized as affecting the organoleptic and nutritional characteristics of the product, is considered quantitatively negligible (Lazarides et al., 1995). Fig.1 shows the different flows, in and out of the fruit/vegetable tissue.

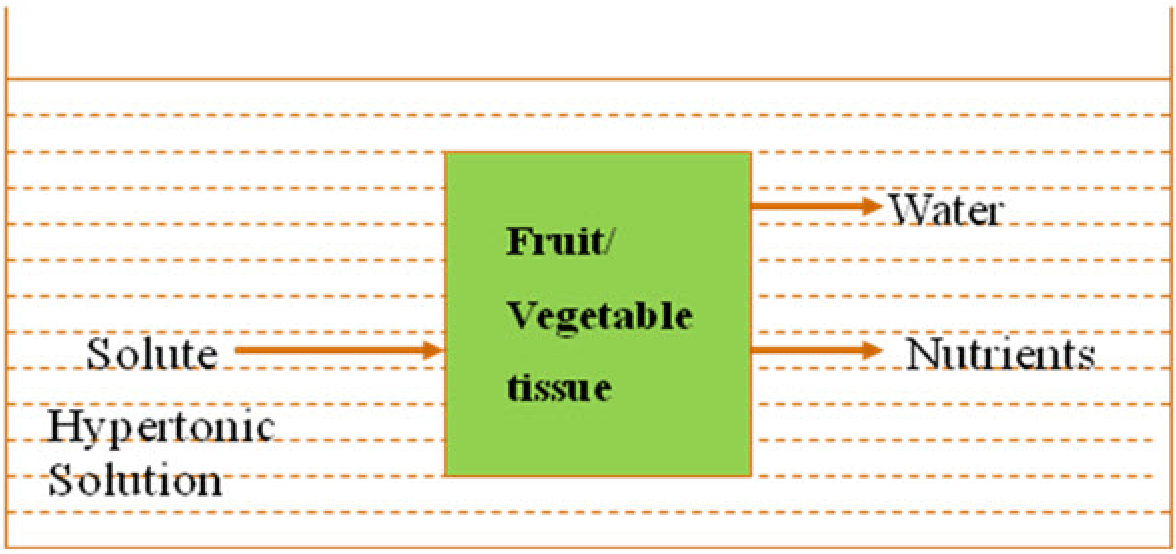


Fig.1. Mass transfer across a fruit/vegetable tissue during osmotic dehydration

Advantages:

The advantages of osmotic dehydration are as follows (Islam and Flink, 1982; Chaudhari

The advantages of osmotic dehydration are as follows (Islam and Flink, 1982; Chaudhari et al., 1993; Ghosh et al., 2004).

1. Mild heat treatment favours less heat damage to colour and flavour of the product with superior sensory attributes.
2. The use of sugar or syrup as osmotic agent prevents much of the loss of flavour commonly found with ordinary air or vacuum drying.
3. Enzymatic and oxidative browning is prevented as the fruit pieces are surrounded by sugar, thus making it possible to retain good colour with little or no use of sulpher dioxide.
4. Energy consumption is much less as no phase change of moisture is involved during dehydration. Osmotic dehydration with syrup re-concentration demands two to three times less energy compared to convection hot air drying.
5. Acid removal and sugar uptake by the fruit pieces modify the composition (sugar to acid ratio) and improve the taste and acceptability of the final product.
6. It partially removes water and thus reduces water removal load at the dryer.
7. It increases solid density due to solid uptake and helps in getting quality product in freeze-drying.
8. If salt is used as an osmotic agent, higher moisture content is allowed at the end of the drying as salt uptake influences the water sorption behaviour of the product.
9. The final product shows much lower rehydration rate, lower hygroscopicity and better textural quality after rehydration in comparison to other dehydration techniques.
10. The storage life of the product is greatly enhanced.
11. Simple equipment is required for the process.

Disadvantages*:*

It also has some disadvantages (Chaudhari et al., 1993;Ghosh et al., 2004).

1. The reduction in acidity level reduces the characteristic taste of some products. This can be overcome by adding fruit acid in the solution.
2. Solute uptake and leaching of valuable product constituents often lead to substantial modification of the original product composition with a negative impact on sensory characteristics and nutritional profile.
3. Sugar coating is not desirable in certain products and quick rinsing may be necessary after the treatment.
4. Sugar uptake results in the development of a concentrated solids layer under the

4. Sugar uptake results in the development of a concentrated solids layer under the surface of the fruit, upsetting the osmotic pressure gradient across the fruit interface and decreasing the driving force for water flow.

5. In terms of final product characteristics, sugar uptake affects both rehydration and flavour retention due to lower rehydration of sugar in the fruit, compared with fruit tissue itself.

Osmotic dehydration process

Since osmotic dehydration generally will not give a product of low enough moisture content to be considered self-stable, it has to be coupled with other methods of drying, viz., hot air drying, vacuum drying, freeze drying etc (Ponting, 1973; Sagar, 2001). The schematic diagram of osmotic dehydration process is shown in Fig. 2. All the steps given in Fig. 2 may not be followed as such and are subjected to change considering the types of material being processed (Chaudhary et al., 1993). It is usually not worthwhile to use osmotic dehydration technique for more than 50% weight reduction because of the decrease in the osmosis rate with time (Chaudhary et al., 1993; Ghosh et al., 2004).

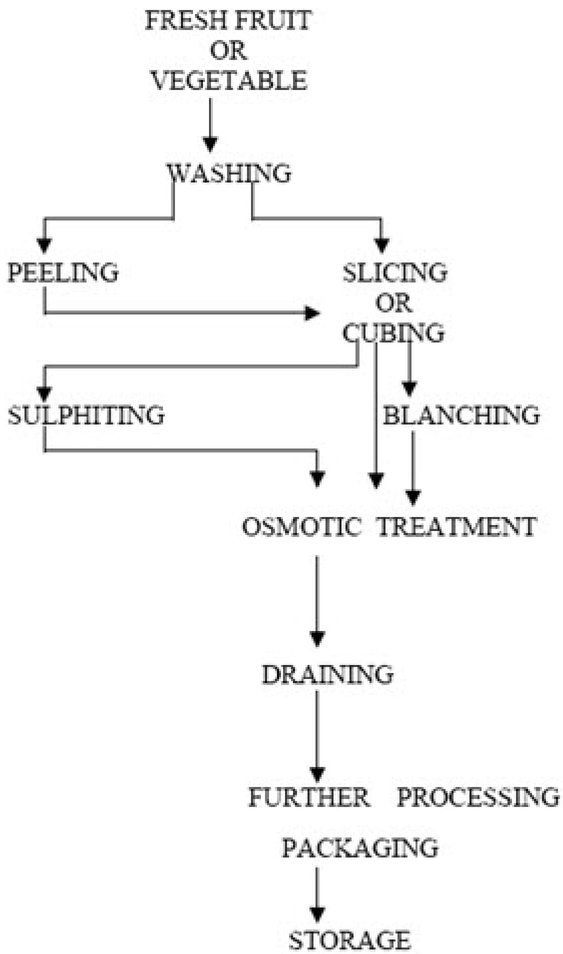


Fig.2.Osmotic dehydration process

Factors affecting osmotic dehydration process

Product characteristics

Species, Variety and Maturity Level

Not only different species, but also different varieties of the same species, even

Not only different species, but also different varieties of the same species, even different maturity levels of the same variety have been found to give substantially different response to osmotic dehydration. Under identical conditions five varieties of apricots showed different mass reduction during osmotic dehydration.

Tissue Location

The tissue at different locations in the same fruit or vegetable responds differently to osmotic dehydration. The inner and outer parenchyma tissue of Grany Smith variety of apple showed different water loss and solid gain at same osmotic dehydration conditions (Marvroudis et al., 1998). The interconnectivity and pore spaces of two kinds of tissues show different mass transfer due to different pathways of transport.

Size and shape

The kinetics of osmotic dehydration is affected by the size and shape of the samples, due to different specific surface area or surface to thickness ratio. Also different forms of samples are selected on the basis of end-use of product after further processing (Islam and Flink, 1982; Lerici et al., 1985; Sankat et al., 1996;Ghosh et al., 2004).

Concentration of osmotic solution

The choice of the solute and its concentration depends upon several factors. The organoleptic evaluation of the final product is the most important consideration besides the cost of the solute. The solubility of the substance in water is crucial for its effect on maximum possible concentration in the osmotic solution. The capacity of the compound to lower the water activity will also affect the driving force responsible for the mass transport. It is also not desirable to have a solute that reacts with the final product. During osmosis, the kinetics of water removal, the solid gain and the equilibrium moisture content are strongly affected by the kind of osmotic agent, its molecular weight and ionic behaviour. Sucrose and sodium chloride are most commonly used osmotic agents. Sodium chloride is found to be an excellent agent for vegetables as it changes cell permeability but has limited use in fruits dehydration due to salty taste (Hawkes and Flink, 1978; Lerici et al., 1985 Pawar et al., 1988; Yang and Le Maguer, 1992; Erketin and Cakaloz, 1996; Sagar, 2001;Pokharkar, 2001).

The use of sucrose salt mixture as osmotic reagent also have beneficial effects as it develops high osmotic potential thereby causing higher water loss, retarding oxidative and non-enzymatic browning, and gives product with better quality (Islam and Flink; 1982).

Process temperature

Temperature of osmotic solution plays an important role in osmotic dehydration process. The effect of temperature is more pronounced between 30 to 60°C for fruits and vegetables on the kinetic rate of moisture loss without affecting solid gain (Ponting, 1973; Rastogi and Raghavarao, 1995; Pokharkar, 2001).

Sample to solution ratio

The sample weight to solution ratio is an important consideration during the osmosis

The sample weight to solution ratio is an important consideration during the osmosis. The change in ratio affects the mass transfer during osmosis up to a certain limit. Most of research workers used the sample to solution ratio ranging from 1:1 to 1:5 in order to study the mass transfer kinetics by following changes in concentration of solution and other factors (Islam and Flink, 1982; Lenart and Flink, 1984; Grabowski et al., 1994; Welti et al., 1995; Erketin et al., 1996; Pokharkar, 2001). Higher ratio (1:10 to 1: 60) can also be used in order to avoid significant dilution of the medium due to uptake of water from sample and loss of solute to the sample, and subsequent decrease in the osmotic driving force during the osmotic dehydration (Karthanos et al., 1995; Lazarides et al., 1995).

Method/system to enhance the mass transfer

Agitation during the osmotic dehydration reduces the mass transfer resistance at the surface of the fruit/vegetable sample and provides a uniform distribution of osmotic solution around the product. But gentle agitation has little effect on the osmosis rate (Erketin et al., 1996; Pokharkar and Prasad, 1997; Ghosh et al., 2004). Agitation may cause damage to the sample and may be difficult to apply.

Several methods and systems can be used to enhance the mass transfer during osmotic dehydration process. These methods include high electric field pulse treatment, centrifugal force, high hydrostatic pressure and application of vacuum. Some pretreatments like freezing, microwave treatment and blanching before osmotic dehydration can increase the rate of moisture loss and solid gain. The systems available for accelerating the mass transfer during osmotic dehydration are cylindrical vessel and impeller rotating at center, pipe holding food with flow of osmotic solution, horizontal cylindrical tank with a helical tube with blades at regular intervals, ultrasound, fixed percolated blade, mobile percolated blade, immersion with combined food/solution displacement, single layer drenching with conveyor, recurrent action multilevel drenching, massaging/tumbling, injection of solution into the food and application of solid solute on the food (Ade-Omowaye et al.,2001; Ade-Omowaye et al.,2002).

Process duration

In general, as the time of osmotic treatment increases, the weight loss increases with a decreasing rate (Yang and Le Maguer, 1992;Chaudhary et al., 1993) Different data on osmotic dehydration of different foods show that, water loss, solid gain and weight loss of foods during osmotic dehydration are related to time and come to equilibrium with respect to time. (Azuara et al., 1992; Lazarides et al., 1995)

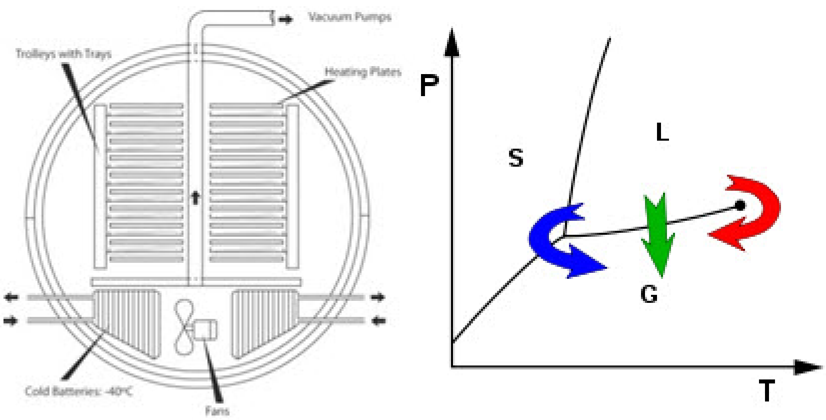
Process pressure

The pressure gradient in the osmotic dehydration process changes the rates of water loss and solid gain. The hydrodynamic mechanism describes the change in the mass transfer by expansion or compression of internal pore gas of tissue.

The brief review of osmotic dehydration of several fruits and vegetables has been given in Table 1 and 2. The tables show the variables and their ranges taken for osmotic dehydration of fruits and vegetables.

Lesson.16 Low Temperature Drying

Freeze drying is a process by which a solvent is removed from frozen foodstuff or a frozen solution by sublimation of the solvent by desorption of the sorbed solvent, generally under reduced pressure.



The freeze drying involves freezing stage and sublimation stage. The foods like ginger, carrots, and ginseng are dried using freeze drying. The freeze drying parameters of the selected foods are given in Table 3. The freezing temperature ranges from -50° to -80°C and for sublimation the frozen foods are kept on heating plates having temperature 10° to 55°C with pressure less than 1 mbar. Freeze drying produces a high quality product, but being an expensive process, its application for root drying is limited. Literature shows several studies on freeze drying of carrots. Freeze dried root possess a preferable appearance, due to the excellent structural retention. Litvin et al. dried 7-10 mm thick carrot slices by combining the freeze drying with a short microwave treatment and air and vacuum drying. They first dried carrot slices by freeze drying at heating plate temperatures 30°, 45° and 55°C at 10^{-1} mbar to 50 % moisture content, then treated by microwaves at 637 W for 30, 40, 50, 60 and 70 s and finally dried to 5% moisture content by two drying methods namely, vacuum (45 ^{o}C for 5 h) and air (50 ^{o}C for 5 h). They concluded that during freeze drying, the rate of drying was temperature dependent and drying at lower temperature should be preferred. The sublimation process ceases at moisture content 45-50%.

Freeze-drying also known as lyophilisation, lyophilization, or cryodesiccation, is a dehydration process typically used to preserve a perishable material or make the material more convenient for transport. Freeze-drying works by freezing the material and then reducing the surrounding pressure to allow the frozen water in the material to sublimate directly from the solid phase to the gas phase.

Foam Mat Freeze Drying

The high cost of operation associated with freeze drying can restricts its usage to functional foods. Foam-mat drying can be used for the functional products that can be foamed to increase the surface area to improve the mass transfer rate. Foam-mat freeze drying is one of the promising methods of drying of, which tries to utilize the advantages of both freeze drying and foam-mat drying to produce better quality functional food products like egg white powder. Muthukumaran (2007) used foam mat drying technique to prepare egg white powder. He used different stabilizers (Methyl cellulose, Propylene glycol alginate and Xanthan gum) to optimize foam stability and determined the bubble size distribution using microscopy to understand foam structure. His results showed that Xanthan gum at 0.125% provide sufficient stability for freeze drying. Also, he conducted experiments to study foam-mat freeze drying of egg white, in an effort to determine the suitability of their method. His results indicated that the addition of Xanthan Gum during foaming had a positive impact in reducing the total drying time producing excellent quality egg white powder. The addition of stabilizer also plays an important role in improving drying.

Vacuum Drying

Vacuum drying is an effective way to dry heat-sensitive foods having oxidative properties. Foods are dried in vacuum chamber having pressure less than 100 kPa at different temperatures. The heat is transferred by radiation or conduction to the product in vacuum. The lower pressure allows the moisture removal from foods at low temperature by preserving the quality. The vacuum dying parameters of carrot and ginger are given in Table 3. Madamba and Bekki [48] studied the effect of vacuum level, slice thickness and drying air temperature on final product quality and drying rate for carrots. They used slices of 1, 2 and 3 mm and drying air temperatures of 65°, 70° and 75 °C at 5, 10 and 15 kPa vacuum pressures. They found that final moisture content is affected by all the variables, average drying rate is affected by thickness while overall acceptability of product by pressure and thickness. The optimum drying conditions of 68 °C and 10 kPa for drying 1.6 mm strips were established by them.

Lesson.17 Microwave Assisted Drying

The application of microwave energy to dry foods is becoming more popular as it is a good approach for coping with certain drawbacks of conventional drying.

Mechanism of Heating

In microwave heating or drying, microwave-emitted radiation is confined within the cavity and there is hardly heat loss by conduction or convection so that energy is mainly absorbed by a wet material placed in the cavity. Furthermore, this energy is principally absorbed by water in the material, causing temperature to raise, some water to be evaporated, and moisture level to be reduced. A domestic microwave oven works by passing microwave radiation, usually at a frequency of 2450 MHz (a wavelength of 12.24 cm), through the food. Water, fat, and sugar molecules in the food absorb energy from the microwave beam in a process called dielectric heating. Many molecules (such as water) are electric dipoles, meaning that they have a positive charge at one end and a negative charge at the other, and therefore rotate as they try to align themselves with the alternating electric field induced by the microwave beam. This molecular movement creates heat by friction as the rotating molecules hit other molecules and put them into motion.

Microwave heating is most efficient on liquid water, and much less so on fats and sugars (which have less molecular dipole moment), and frozen water (where the molecules are not free to rotate). Large industrial/commercial microwave ovens operating in the 900 MHz range also heat water and food perfectly well. The power generated in a material is proportional to the frequency of the source, the dielectric loss of the material, and the square of the field strength within it. The microwave heating rates and potential non-uniformity are functions of oven factors and load characteristics (size, shape, dielectric properties, etc.).

In conventional heating, heat is transferred to the surface of the material to be heated by conduction, convection, and/or radiation, and into the interior by thermal conduction. In contrast, in dielectric heating, heat is generated directly inside the material, making possible higher heat fluxes and thus a much faster temperature rise than in conventional heating. However, heat conduction still plays an important role when heating thick samples by dielectric heating and for equilibrating temperatures when heat generation is uneven.Depending on water content the depth of initial heat deposition may be several centimeters or more with microwave ovens, in contrast to grilling, which relies on infrared radiation, or the thermal convection of a convection oven, which deposit heat shallowly at the food surface. Depth of penetration of microwaves is dependent on food composition and the frequency, with lower microwave frequencies being more penetrating. The heat generated per unit volume of material (Q) is the conversion of electromagnetic energy in to heat energy. Its relationship with the average electric field intensity (Erms) at that location can be derived from Maxwell’s equations of electromagnetic waves as shown by Metaxax and Meredith (1983):

…(1)

Where, f is the frequency of microwaves, Î0 is the dielectric constant of the free space

Where, f is the frequency of microwaves, ε_0 is the dielectric constant of the free space (8.854×10^{-12} A^2 s^4/kg m^3), and is the loss factor of the food being heated. At a given frequency, the dielectric loss factor is a function of the composition of the food materials and its temperature. Penetration depth (Dp) is another important factor in microwave heating. It is defined as the depth below the surface of the material where the power density of a plane electromagnetic wave decays by 1/e (37%) from the original value at the surface. The D_p is calculated as follows:

$$D_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\left[\sqrt{1+(\varepsilon''/\varepsilon')^2}-1\right]}} \quad \ldots(2)$$

Where, c is speed of light in free space (3×10^8 m/s), is the frequency (Hz), is the loss factor of the food and is dielectric constant.

Microwaves

Microwaves are electromagnetic waves having wavelength (peak to peak distance) varying from 1millimeter to 1 meter. Frequency of these microwaves lies between 0.3 GHz and 3 GHz. Microwaves have greater frequency than radio waves so they can be more tightly concentrated. Microwaves propagate through air and space at about the speed of light. Microwaves can also be considered as electromagnetic force fields for better understanding of working of microwave oven. Microwaves interfere inside the microwave oven to produce high and low energy pockets. This can be explained by the phenomenon of resonance.

Mechanism of heating

In microwave heating or drying, the microwave-emitted radiation is confined within the cavity and there is hardly heat loss by conduction or convection so that the energy is mainly absorbed by a wet material placed in the cavity. Furthermore, this energy is principally absorbed by the water in the material, causing the temperature to rise, some water to be evaporated, and the moisture level to be reduced.

Microwave Oven

A microwave oven consists primarily of a magnetron, a magnetron control circuit (usually with a microcontroller), a waveguide and a cooking chamber (cavity). A cavity magnetron is a high-powered vacuum tube that generates coherent microwaves, and its theory of operation is based on the motion of electrons under the influence of combined electric and magnetic fields. A waveguide is a structure which guides waves, such as electromagnetic waves, light, or sound waves.

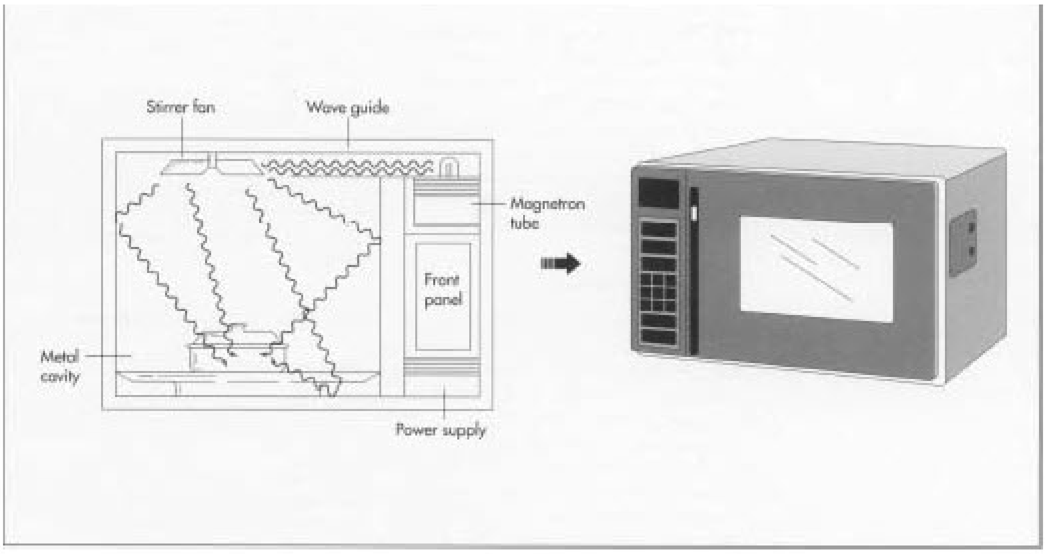


Fig 2. Schematic diagram of a microwave oven

A microwave oven works by passing microwave radiation, usually at a frequency of 2450 MHz (a wavelength of 12.24 cm), through the food. Water, fat, and sugar molecules in the food absorb energy from the microwave beam in a process called dielectric heating. Many molecules (such as those of water) are electric dipoles, meaning that they have a positive charge at one end and a negative charge at the other, and therefore rotate as they try to align themselves with the alternating electric field induced by the microwave beam. This molecular movement creates heat as the rotating molecules hit other molecules and put them into motion. Microwave heating is most efficient on liquid water, and much less so on fats and sugars (which have less molecular dipole moment), and frozen water (where the molecules are not free to rotate). Microwave heating is sometimes incorrectly explained as a rotational resonance of water molecules: such resonance only occurs at much higher frequencies, in the tens of gigahertz. Moreover, large industrial/commercial microwave ovens operating in the 900 MHz range also heat water and food perfectly well. The power generated in a material is proportional to the frequency of the source, the dielectric loss of the material, and the square of the field strength within it. The microwave heating rates and potential non-uniformity are functions of oven factors and load characteristics (size, shape, dielectric properties, etc.). Heat is also generated by another mechanism. Food material also contains ions (charged molecules) which accelerate in electric fields. Force on such ion is given by

$$\vec{F} = q.\vec{E} \quad \dots (1)$$

where, is the force vector acting on the ion,q is the charge on the ion and is the electric field applied

A common misconception is that microwave ovens cook food from the "inside out". In reality, microwaves are absorbed in the outer layers of food in a manner somewhat similar to heat from other methods. The rays from a microwave electrically manipulate water particles to cook food. It is actually the friction caused by the movement that creates heat and warms the food. The misconception arises because microwaves penetrate dry nonconductive substances at the surfaces of many common foods, and thus often deposit initial heat more deeply than other methods. Depending on water content the depth of initial heat deposition may be several centimeters or more with microwave ovens, in

contrast to grilling, which relies on infrared radiation, or the thermal convection of a contrast to grilling, which relies on infrared radiation, or the thermal convection of a convection oven, which deposit heat shallowly at the food surface. Depth of penetration of microwaves is dependent on food composition and the frequency, with lower microwave frequencies being more penetrating.

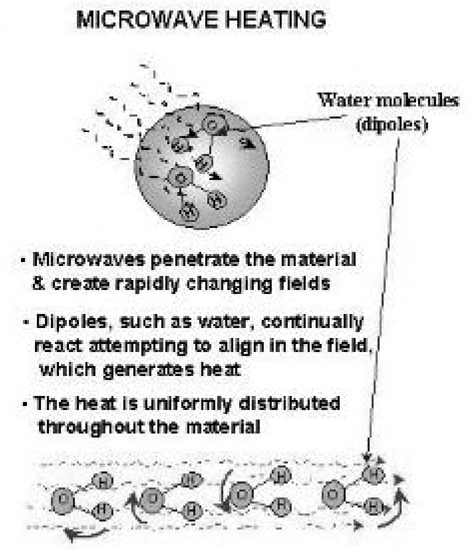
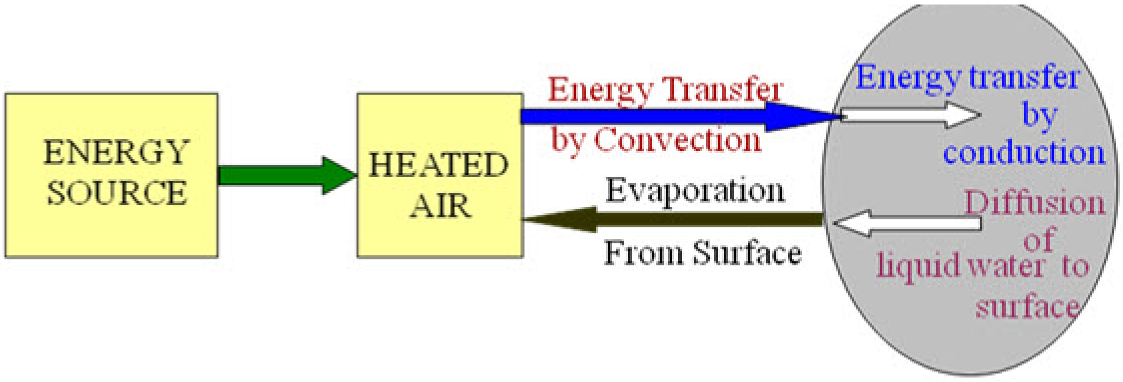
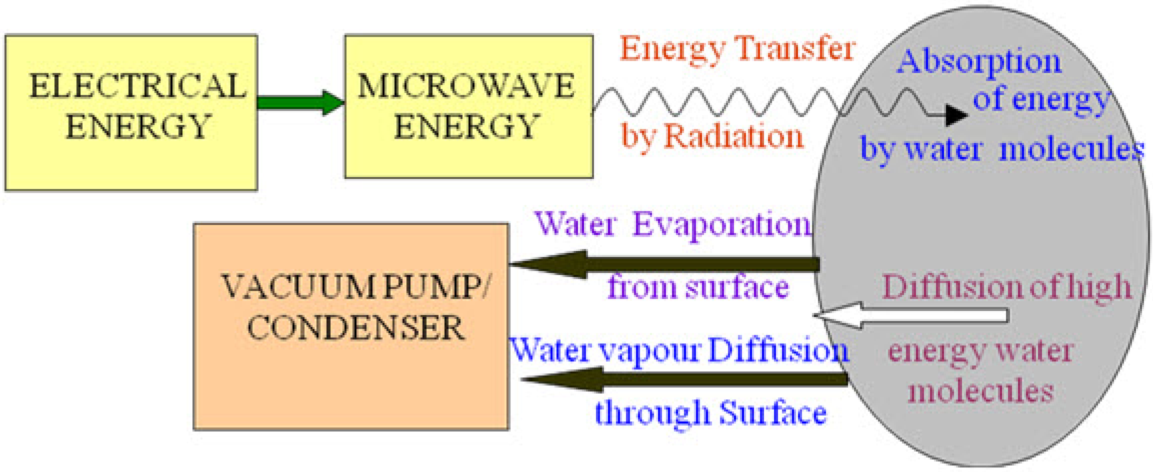


Fig. 3. Heating effect of microwaves

In microwave heating, microwaves penetrate to the interior of food and heat is generated by absorption of electromagnetic radiation by dipolar molecules like water and fat present in foods to be heated. The microwave radiation is transformed into kinetic energy, which makes water molecules vibrate intensively causing friction and leading to rapid increase in temperature and consequently efficient water evaporation. This results in a greatly increased vapor pressure differential between the center and surface of the product, allowing fast transfer of moisture out of the food. Hence, microwave drying is rapid, more uniform and energy efficient compared to conventional hot air drying. The problems in microwave drying, however, include product damage caused by excessive heating due to poorly controlled heat and mass transfer [29,30]. Gunasekaran [31] proposed two strategies to apply microwaves effectively for drying and they are by creating a vacuum in the dryer to lower the drying temperature and applying microwave in a pulsed manner to maximize drying efficiency. In recent years, microwave-vacuum drying (MVD) has been investigated as a potential method for obtaining high quality dried food products. Microwave-vacuum drying combines the advantages of both vacuum drying and microwave heating. The low temperature and fast mass transfer conferred by vacuum combined with rapid energy transfer by microwave heating leads to rapid and low temperature drying and thus it has the potential to improve energy efficiency and product quality. Some foods have been successfully dried by microwave-vacuum drying techniques. The effect of vacuum in microwave drying operation is system specific and for successful design and operation of an industrial microwave-vacuum drying system, knowledge of the drying characteristics of the material under different conditions is important [32,33,34]. This reduces the time required for complete drying by more than 30% as compared to conventional methods [35]. Some researchers have reported the microwave vacuum drying studies of foods like garlic, carrots, potato, and parsley root and showed that microwave vacuum drying can be used to dry the foods for better product quality [21, 36,37,38,39,40].





Another approach to use microwaves is combining them with conventional hot air drying. Microwaves help to enhance the rate of moisture removal during hot air drying by evaporating moisture within product that generates additional pressure gradient for moisture movement. Researchers have attempted microwave convective drying of carrots, potatoes, garlic and onions. Bouraoui et al. [42] dried potato slices using combined microwave and convective drying and concluded that microwave drying had a potential for producing better quality dried product than convective drying alone. The drying time was reduced considerably that is 10 min with microwave-convective drying as compared to 10 h in convective drying. No case hardening was observed and shrinkage was less than that found in convective drying. Pravanjan et al. [43] evaluated the drying characteristics of carrot cubes by microwave hot air drying and reported that the microwave drying results in a substantial decrease (25-90%) in the drying time and better product quality than conventional hot air drying. Sharma and Prasad [44]dried garlic cloves by combined microwave convective drying technique. They reported that the microwave convective drying results in saving to an extent of about 91% of total drying time. Good quality dried garlic cloves were also obtained by the microwave convective drying technique. The details of microwave drying of various foods are given in Table 3.

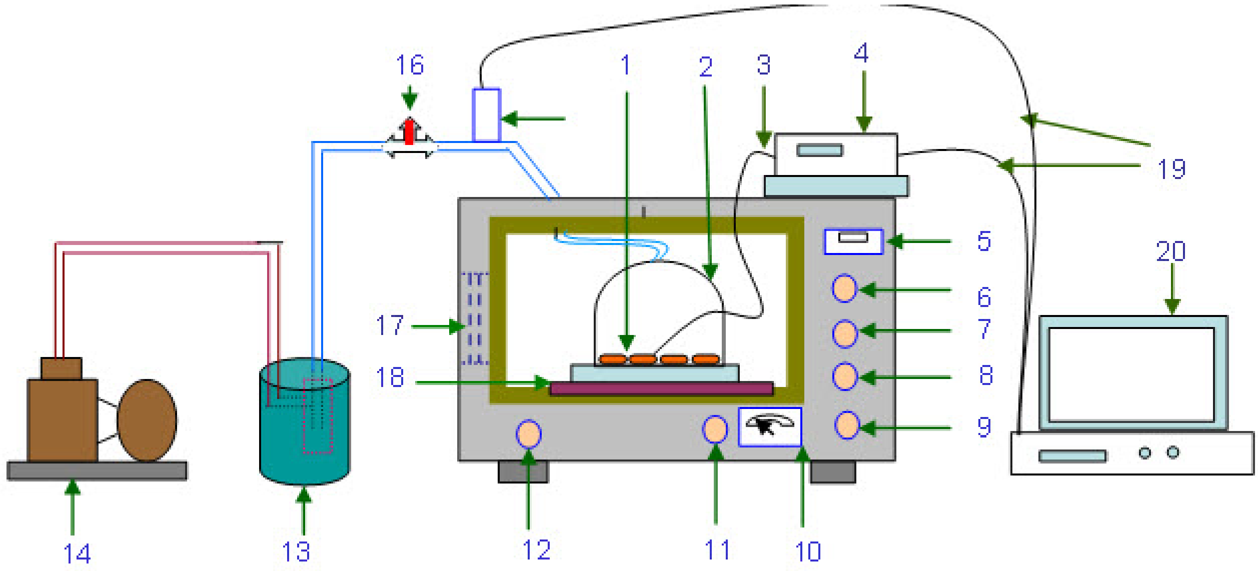


Figure 14 Experimental setup for microwave vacuum drying of carrot slices

Types of Microwave Dryers

Microwaves can be combined with different types of dryers to accelerate the drying rate. Following combinations are available with microwaves:

- Microwave vacuum dryer
- Microwave convective dryer
- Microwave freeze dryers

Several researchers in the developed and developing countries have done studies on microwave assisted drying of various fruits and vegetable and reported that the drying by microwave assisted convective and microwave vacuum methods is more efficient than conventional drying techniques. Some researchers (Shivhare et al., 1992; Sharma and Prasad, 2001) have reported microwave assisted hot air drying of foodstuffs and found considerable improvements in the drying process and quality of dehydrated products. The simple laboratory microwave convective dryer for foodstuffs is shown in Fig.1.

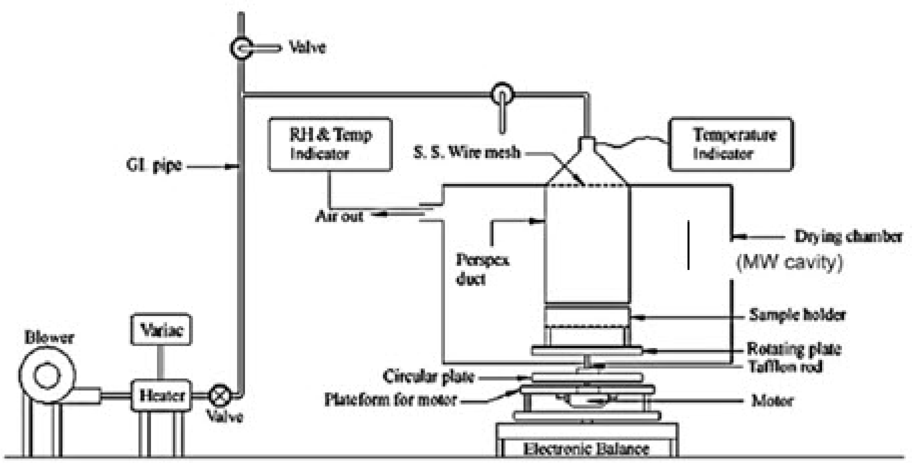


Fig. 1 Schematic diagram of microwave convective dryer (Sharma and Prasad, 2001)

Lesson.18 High Temperature Drying

One of the ways to shorten the drying time is to supply heat by infrared radiation. This method of heating is especially suitable to dry thin layers of material with large surface exposed to radiation. Infrared radiation is transmitted through water at short wavelength, while at long wavelength; it is absorbed on the surface [45]. Hence, drying of thin layers seems to be more efficient at far-infrared radiation-FIR (25–100 Am), while drying of thicker bodies should give better results at near-infrared radiation-NIR (0.75–3.00 Am) [46]. Sharma et al.[46] dried onion slices at infrared power levels 300, 400 and 500 W, drying air temperatures of 35°, 40° and 45 °C and inlet drying air velocities 1.0, 1.25 and 1.5 m/s. They reported that drying time reduced by about 2.25 times on increasing infrared power from 300 to 500 W, air temperature 35° to 45 °C and air velocity from 1.0 to 1.5 m/s. Effective moisture diffusivity was significantly influenced by infrared power and air temperature. Baysal et al. [47] dehydrated carrots in a tray drier at 70 °C with 0.86 m/s air velocity, in microwave oven at power density of 6 W/g (60 s power on and power off for 15 s) and by infrared drying at different time temperature combinations of 105°C for 15 min, 100°C for 30 min and 95°C for 40 min. The Infrared dehydrated carrot had the best rehydration capacity.

Spray Drying

Spray drying has important application in functional food formulation. The spray drying process consists of the conversion of a spray of pumpable liquid (i.e., juices, slurries, and purees) into a dry particulate (i.e., powder, granules, or agglomerate) by exposure to a hot (150 to 200°C) medium (Sunjka et al., 2008). Operating and dryer components that influence the final product include the feed rate, temperature of the inlet drying air, pressure of compressed air at the nozzle, air flow (i.e., cocurrent, counter current, or mixed flow), atomizer design, and air heating method. Spray dryers are the most widely used drying systems for the formation of powdered food additives and flavors in the dairy, beverage, and pharmaceutical industries. This technique enables the transformation of feed from a fluid state into dried particulate form by spraying the feed into a hot drying medium. It is a continuous particle processing drying operation. The feed can be a solution, suspension, dispersion or emulsion. The dried product can be in the form of powders, granules or agglomerates depending upon the physical and chemical properties of the feed, the dryer design and final powder properties desired (Michael, 1993).

Spray drying process mainly involves five steps:

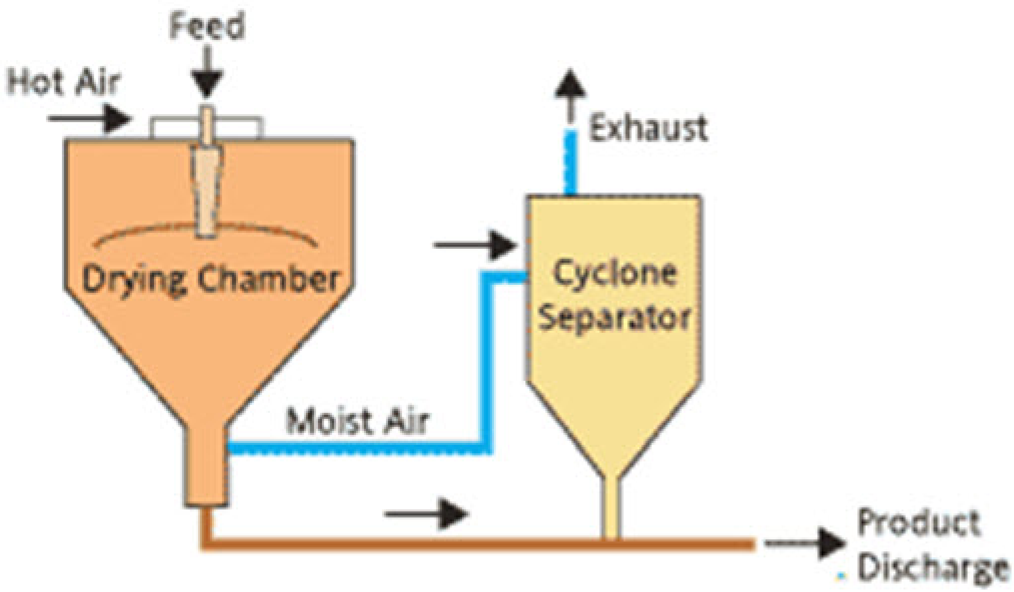
1. Concentration: feedstock is normally concentrated prior to introduction into the spray dryer.
2. Atomization: the atomization stage creates the optimum condition for evaporation to a dried product having the desired characteristics.
3. Droplet-air contact: in the chamber, atomized liquid is brought into contact with hot gas

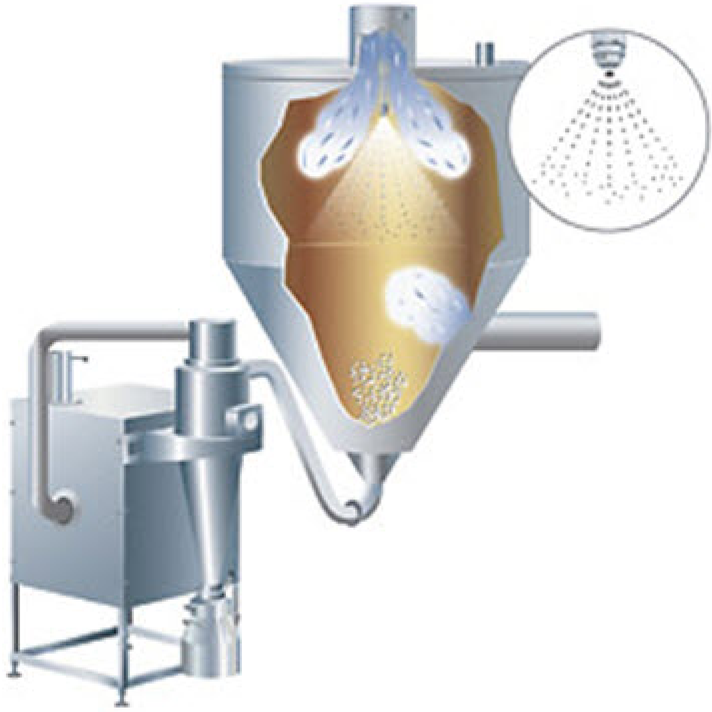
3. Droplet-air contact: in the chamber, atomized liquid is brought into contact with hot gas, resulting in the evaporation of 95%+ of the water contained in the droplets in a matter of a few seconds.

4. Droplet drying: moisture evaporation takes place in two stages- 1) during the first stage, there is sufficient moisture in the drop to replace the liquid evaporated at the surface and evaporation takes place at a relatively constant rate (Keey & Pham, 1976), and 2) the second stage begins when there is no longer enough moisture to maintain saturated conditions at the droplet surface, causing a

5. dried shell to form at the surface. Evaporation then depends on the diffusion of moisture through the shell, which is increasing in thickness.

6. Separation: cyclones, bag filters, and electrostatic precipitators may be used for the final separation stage. Wet Scrubbers are often used to purify and cool the air so that it can be released to atmosphere.





Lesson.19 Dryeration

Originally developed for use with maize, dryeration is a combination of heated air drying and aeration cooling. In this process a tempering period is employed between a high temperature drying phase and a cooling phase. Whereas less than 1% moisture is removed if cooling is carried out immediately after drying, as much as 2% moisture can be removed if the grain is cooled slowly after tempering. Damage to the grain is reduced and drying efficiency is improved through better utilization of the residual heat in the grain for moisture removal during cooling. Higher air temperatures can be used in the drying phase since the grain is not dried to such a low moisture content.

Two-Stage Drying

Two-stage or combination drying can be used to relieve pressure on drying facilities during peak periods. For example, paddy at moisture contents of less than 18% can be stored for up to 20 days without significant losses either in quantity or quality. In two-stage drying, grain is dried to an intermediate moisture content, 20% moisture for maize, 18% moisture for paddy, as soon as possible using any of the methods described above and then dried instore to the desired final moisture content over several days or weeks with intermittent use of ambient air or air heated by 3-5°C. Research with paddy in the Philippines (Tumambing & Bulaong 1986; Adamczak et al. 1986) has shown that, in addition to increasing throughput of the first stage dryers, there were substantial overall energy savings and no loss of quality compared to drying to 14% moisture in the conventional manner.

Pre-drying Aeration

Work in the Philippines has shown that wet paddy can be maintained in reasonable condition for 3-7 days when aerated with ambient air (Raspusas et al. 1978; de Castro et al. 1980). By aerating stacks of sacked paddy at a rate of 0.5 m3/s per tonne for eight hours a day, quality could be maintained for nine days during the dry season and two days during the wet season. Aerating in bulk with similar airflows maintained quality for 14 days and three days respectively (Raspusas et al. 1978). The length of time that paddy can remain in aerated storage without deterioration is dependent on the moisture content of the grain and ambient air conditions.

Drying of Parboiled Paddy

After parboiling, paddy contains about 35% moisture. During the parboiling process the starch is gelatinized which confers quite different drying properties to that of field paddy. It has been shown (Bhattacharya & Indudhara Swamy 1967) that in the drying of parboiled paddy, significant damage (ie kernel cracking) does not occur until the moisture content falls to 16%, regardless of the drying method or the rate of drying,. Cracking then occurs some time after the grain has cooled. The recommended drying procedure is to dry the parboiled paddy to 16-18% moisture as fast as facilities permit, temper it for four hours if warm or eight hours if cooled, and then dry in a second operation to 14% moisture. Air temperatures of 100-120°C can be used for parboiled paddy in continuous-flow dryers.

Drying of Seed Grain

If grain is destined for use as seed then it must be dried in a manner that preserves the viability of the seed. Seed embryos are killed by temperatures greater than 40-42°C and therefore low temperature drying regimes must be used. Seed grain may be dried in any type of dryer provided that it is operated at a low temperature and preferably with greater air flowrates than generally used. It is essential that batches of grain of different varieties are not mixed in any way and therefore the dryers and associated equipment used must be designed for easy cleaning. In this respect simple flat-bed dryers are more suitable than continuous-flow dryers.

Teter (1987) noted that seed paddy can be sun dried at depths of up to 30 mm but that the final stages of drying to 12% moisture should be conducted in the shade to avoid overheating and kernel cracking. Flat-bed dryers can be used with bed depths of up to 0.3 m, air temperatures not exceeding 40°C, and airflows of 1.3-1.7 m3/s per tonne of grain.

Cross-mixing between batches of different varieties can be avoided by drying in sacks in a flat-bed dryer although care must be taken in packing the loaded sacks in the dryer to ensure reasonably even distribution of airflow. Specialised tunnel dryers in which sacks or portable bins are individually placed over openings in the top of the tunnel have been developed (Teter 1987).

Lesson.20 Miscellaneous Drying

20.1 DRUM Drying

Drum drying consists of indirect moisture removal from a thin film of product on the surface of internally heated twin (or single drum) hollow metal cylinders that rotate on a horizontal axis (Orsat and Raghavan, 2007; Vega-Mercado et al., 2001). Dried product is fl aked off using a scraper. This system is applicable to viscous foods and purees that can withstand high temperatures for a short period. Drum dried powdered and flaked products are used in bakery goods, beverages, cereal, granola, and dairy foods (Vega-Mercado et al., 2001). This method was also investigated as a texturizing method for wheat, rice, and fababean mixed breakfast cereals or puffed baked snacks (Abdel-Aal et al., 1996) and for the processing of apple pomace (Constenla et al., 2002). The effectiveness of the drying system relies on the uniform thickness of the film applied to the drum surface, the speed of rotation, and the heating temperature. The main advantages of this system are the high drying rate and energy efficiency.

20.2 REFRACTANCE WINDOW® DRYERS

Refractance Window drying is a relatively new indirect drying technology that is used to evaporate moisture from foods (Nindo and Tang, 2007; Nindo et al., 2007; Vega-Mercado et al., 2001). This approach uses a plastic fi lm to facilitate thermal energy transfer between a heating medium (i.e., water below the film) and a suspension (on the surface of the film). The thin plastic film, fabricated from Mylar, allows the transmission of infrared radiation in a wavelength that matches the absorption spectrum of water in the product. Refractance Window was developed to provide an alternative to long drying times and/or the use of high temperatures. Although the water is maintained at temperatures just below boiling at 95 to 98°C, product temperatures do not exceed 70°C. Shorter drying times are demonstrated by a reduction from hours (tray and freeze-drying) to 5 min (Refractance Window) for strawberry puree (Nindo and Tang, 2007). This system is applicable to the drying or preconcentration of liquid foods. It is also being pursued for its potential to process fruits, vegetables, and herbs into value-added powders, flakes, and concentrates.

20.3 Hybrid Drying

The use of hybrid drying technologies is another approach to combine the advantages of different drying methods which are in practice.

The combination of the osmotic dehydration and hot air drying is one of the important hybrid drying techniques.

The osmotic dehydration of foods prior to hot air drying partially removes water and thus reduces water removal load at the dryer. Also, solute gain creates elevated temperature during hot air drying resulting in faster drying rates as well as solid uptake by the root pieces modify the composition (sugar to acid ratio), prevent the enzymatic and oxidative browning, and improves the sensory attributes (colour, flavour, texture, taste and overall acceptability) of the final product.

Foods like onions can be dried using combination of osmotic dehydration and fluidized bed drying to get the better quality dehydrated onions with less energy consumption [19]. Recently, osmotic dehydration is combined with microwave drying.

Microwave vacuum drying of osmotically pre-treated foods combines the benefits of both the operations and high quality product can be obtained. The combined osmotic and microwave drying results in more homogeneous heating of the product by modification of its dielectric properties due to the solute uptake, slightly reduced drying time, reduced shrinkage, high porosity and improved rehydration characteristics[49,50] .

Literature shows some studies on the combined osmotic microwave vacuum dehydration of carrots and potatoes [19,51].

The value addition in the orange coloured carrots can be done by increasing its sweetness using osmotic pre-concentration and further it can be dried by microwave vacuum drying.

The probable benefit of the osmotic pre-treatment using sucrose solution is simultaneous sugar gain and osmotic dehydration which reduces the water removal load during finish drying by microwave vacuum drying.

The hybrid drying techniques of foods involve low energy unit operations and result into high quality product [52].

Lesson 22. Types of spoilage in storage

22.1 Introduction

Post-harvest spoilage may occur in the following areas:

- during harvesting
- during transportation
- during drying
- during threshing
- during processing
- during storage

This chapter is concerned primarily with spoilage which occur during storage. Such losses do not only result from the effects of moisture, heat and pests. The following factors are also of importance:

- The previous history of the stored produce as well as the growing conditions before harvesting, any field infestation with pests or fungi or any heat damage which may have occurred during the drying process.
- Genetic differences, i.e. differences specific to certain varieties and species with regard to tolerance against storage pest

22.2 Types of Spoilage

22.2.1 Losses in quantity

Losses in quantity of the stored produce result from grain being spoilt or running out from damaged bags, from theft or from the grain being damaged by pest organisms. Losses in weight may also result from changes in the grain moisture content during the storage period. Due to the following reasons, it is generally difficult to evaluate the exact extent of losses in quantity:

- There is no method of calculating losses which is simple, quick, reliable and generally applicable at the same time.
- The exact amount of harvested produce is often not known, particularly in small farm storage, so that losses may be registered at a later date but not quantified.
- in the case of infestation with insects, the loss in weight in no way corresponds to the difference in weight before and after infestation. When weighing the produce, leftovers, grass, webbing, pest carcasses and rodent droppings are also weighed. Assuming that this filth cannot be separated from the produce, the actual losses are higher than those calculated.

Estimating Losses

The most simple method of establishing losses in the store is to record the amounts

The most simple method of establishing losses in the store is to record the amounts entering and leaving the store (weigh-in, weigh-out method), even though the results achieved using this method are not always satisfactory for the reasons and shortcomings mentioned above.

It is also possible to make use of other methods of estimating losses, out of which the **count and weigh method** (C&W) is fairly easy to apply in small farm storage.

By establishing the number and weight of damaged and undamaged grains of a composite sample (e.g. 1000 grains) at monthly intervals, changes in the weight of stored produce can be determined over a period of storage.

The loss in weight in per cent is calculated using the following equation:

$$\frac{(W_u \times N_d) - (W_d \times N_u)}{W_u \times (N_d + N_u)} \times 100 = \%\ Weight\ loss$$

W_u=weight of undamaged grains, g
N_u=number of undamaged grains, g
W_d=weight of damaged grains, g
N_d = number of damaged grains, g

Shortcomings in this count and weigh method become apparent particularly:

- when there are large variations in grain size
- when grain is so heavily infested, that kernels cannot be counted any more because of complete destruction
- When infestation inside the grains occurs this cannot be detected so that attacked grains are classified as "undamaged".

Other applicable methods for the estimation of storage losses are the Thousand Grain Mass Method (TGM) and the Standard Volume Weight Method (SVM).

The Thousand grain mass (TOM) method

Basic Principle

When an entire lot of grain is weighed before and after being attacked by insect pests, microorganisms or some other causing agent, the percentage loss of mass is easily calculated by using the formula:

$$\frac{M_1 - M_2}{M_1} \times 100 = \%\ \text{Weight Loss}$$

where:
M_1 = Grain mass before attack

M_2 = Grain mass after attack

M_2 = Grain mass after attack

"Mass" in this context refers to the dry matter weight.

A sample taken from the lot in strict accordance with representative sampling principles should possess all the characteristics of the grain in proportion to their ccurrence in the lot at the time of sampling. Therefore, if the lot consists of 40% large grains, 50% medium size grains and 20% small grains, these proportions should be found in representative samples. Likewise if 7% of the grains in the lot are damaged, this percentage of damaged grains should also be found in the representative sample.

It is important that the mass per standard unit of a representative sample should be the same as the mass per standard unit of the entire lot of grain at the time of sampling. A reduction in the value of this unit between two sampling occasins should be proportional to a dry weight loss in the grain lot and should therefore provide a means of estimating the loss.

22.2.2 Losses in quality

Losses in occur in various forms:

- changes in colour (e.g. yellowing of rice)
- changes in smell
- changes in taste
- loss in nutritional value (degradation of proteins and vitamins)
- loss in cooking, milling or baking quality
- contamination of stored produce with mycotoxins or pathogenic agents
- loss of germination power in seeds

Often several qualitative changes occur at the same time, usually also in connection with weight losses. Losses in quality are much more difficult to assess than losses in quantity, as they cannot always be easily recognized (e.g. loss in nutritional value). Additionally in many countries there is a lack of quality standards and quality changes may be assessed differently by individual consumers.

22.2.3 Longevity

The viability period of a grain during storage can be short or long. The grain dies owing

The viability-period of a grain during storage can be short or long. The grain dies owing to the degeneration of protein which, in turn, is influenced by decay of components in the cell nucleus. Generally, the life of a stored grain regulated by the grain-type, the seed-borne micro flora, and by the interaction between temperature and moisture.

22.2.4 Sprouting

Sprouting of the grain during storage occurs mainly owing to generation of heat as a result of infestation. A grain sprouts only when its moisture content exceeds certain limit of moisture content of 30-35%.

References:

- Anonymous (1985), Prevention of Post-Harvest Food Losses, FAO, Rome, 121 pp.
- Boxall, R.A. (1986), A critical review of the methodology for assessing farm-level grain losses after harvest, TDRI, Slough, 139 pp.
- Hall, D.W. (1970), Handling and Storage of Food Grains in Tropical and Subtropical Areas.

Lesson 23. Causes of spoilage in storage

Following are the various sources causing spoilage in the stored food and corrective measures are required to be exercised to minimize the effect to alleviate the effects.

23.1 Mechanical Damage

Causes

- incorrect harvesting methods
- Poor handling, threshing, shelling, cleaning, sorting or drying
- Bad transport and loading practices (e.g. use of hooks)

Effects

- Losses in weight
- Losses in quality (germination power, nutritional value)
- increased vulnerability to infestation from insect pests, fungi and rodents

Countermeasures

- Pay attention to maximum temperatures when drying
- Use safe techniques in harvesting, transport, processing and storage
- Take care when handling bags
- Repair or replace damaged bags
- Do not use hooks to carry bags
- Repair pallets (e.g. protruding nails!)

23.2 Heat

Causes

- Unsuitable storage structures (false location, insufficient shade and ventilation facilities, lack of heat insulation)
- Mass reproduction of storage pests and fungi
- Lack of aeration of store
- High moisture content of the grain

Effects

- Losses in weight
- Losses in quality (nutritional value, germination power)
- Good conditions for pest development

- Good conditions for pest development
- Condensation with subsequent development of fungi

Countermeasures

- Build suitable storage structures
- Provide shade for stores or silos (e.g. by means of wide eaves or shading trees)
- Keep temperatures as low as possible (aerate storage facility)
- Conduct treatments for pest control
- Store bags on pallets in order to improve aeration
- Maintain spaces of 1 m around all bag stacks

23.3 Moisture

Causes

- insufficient drying before storage
- High relative humidity
- Constructional faults and damage to the store (unsuitable materials, unsealed floor, walls and roof, holes, gaps, etc.)
- imbalances in temperature (e.g. day/night) in storage facility with subsequent condensation
- Produce stored on the floor or touching the walls
- Mass reproduction of pests

Effects

- Losses in quality
- Losses in weight
- Development of fungi and formation of mycotoxins
- improved conditions for the development of pests
- Swelling and germination of seeds
- Damage to storage structures

Countermeasures

- Dry produce sufficiently before storage
- Repair and seal storage facility
- Keep relative humidity as low as possible in storage facility (perform controlled ventilation)
- Store bags on pallets
- Maintain spaces of 1 m around all bag stacks

- Maintain spaces of 1 m around all bag stacks
- Conduct pest control treatments
- Avoid temperature fluctuations (day/night) in store by means of shade and ventilation

23.4 Insect Pests

Causes of infestation

- introduction of infested lots
- Cross infestation from neighboring lots or stores
- Migration from waste or rubbish
- Hiding places in stores (cracks, fissures)
- Use of infested bags

Effects

- Losses in weight
- Losses in quality (impurities such as droppings, cocoons and parts of insects, reduction of nutritional value, reduction in germination power)
- increase of temperature and moisture

Countermeasures

- Harvest at the right time
- Choose tolerant varieties
- Keep means of transportation clean
- Remove infested cobs, panicles or pods before storage
- Ensure that produce is dry before storing
- Prevent pest introduction by checking for infestation before storing
- Clean the store daily
- Keep the temperature and relative humidity as low as possible (perform controlled ventilation)
- Prevent any pest infiltration by sealing the store (windows, doors, ventilation facilities; e.g. with the use of insect gauze)
- Repair any damage to the store immediately
- Store old and new lots separately
- Clean empty bags thoroughly and treat them against insects if necessary
- Perform pest control treatments
- Rotate stocks: 'first in first out'

23.5 Microorganisms

Causes of infestation

Causes of infestation

- High moisture content of stored produce
- High relative humidity in store
- Condensation
- Humidity and moisture produced by insects

Effects

- Loss of quality (smell, taste, colour, nutritional value, germination power)
- Formation of mycotoxins
- Slight loss of weight (mould)
- Further increase in temperature and moisture
- Further condensation

Countermeasures

- Dry produce sufficiently before storage
- Keep relative humidity as low as possible in storage facility (perform controlled ventilation)
- Store bags on pallets
- Maintain spaces of 1 m around all stacks
- Conduct pest control treatments

23.6 Rodents

Causes of infestation

- Penetration through badly closing doors, windows, ventilation openings, holes
- Lack of barriers
- Lack of hygiene in store and surrounding area (possible hiding and breeding places)

Effects

- Loss of weight
- High losses in quality due to contamination of produce with faeces and urine
- Contamination of produce with pathogenic agents (typhoid, rabies, hepatitis, plague, etc.)
- Damage of material and facilities (bags, doors, electric cables)

Countermeasures

- Prevent entry of rodents by sealing store rat-proof
- Keep store and surrounding area clean

- Keep store and surrounding area clean
- Place traps
- Carry out rodent control measures

23.7 Birds

Causes of infestation

- Open or broken doors, windows, ventilation openings or roofs

Effects

- Losses in weight
- Damage to bags
- Contamination of stored produce with droppings and pathogenic agents

Countermeasures

- Bird-proof stores (carry out repair work, fit grilles or nets)
- Remove any nests of granivore birds from the store and surrounding area

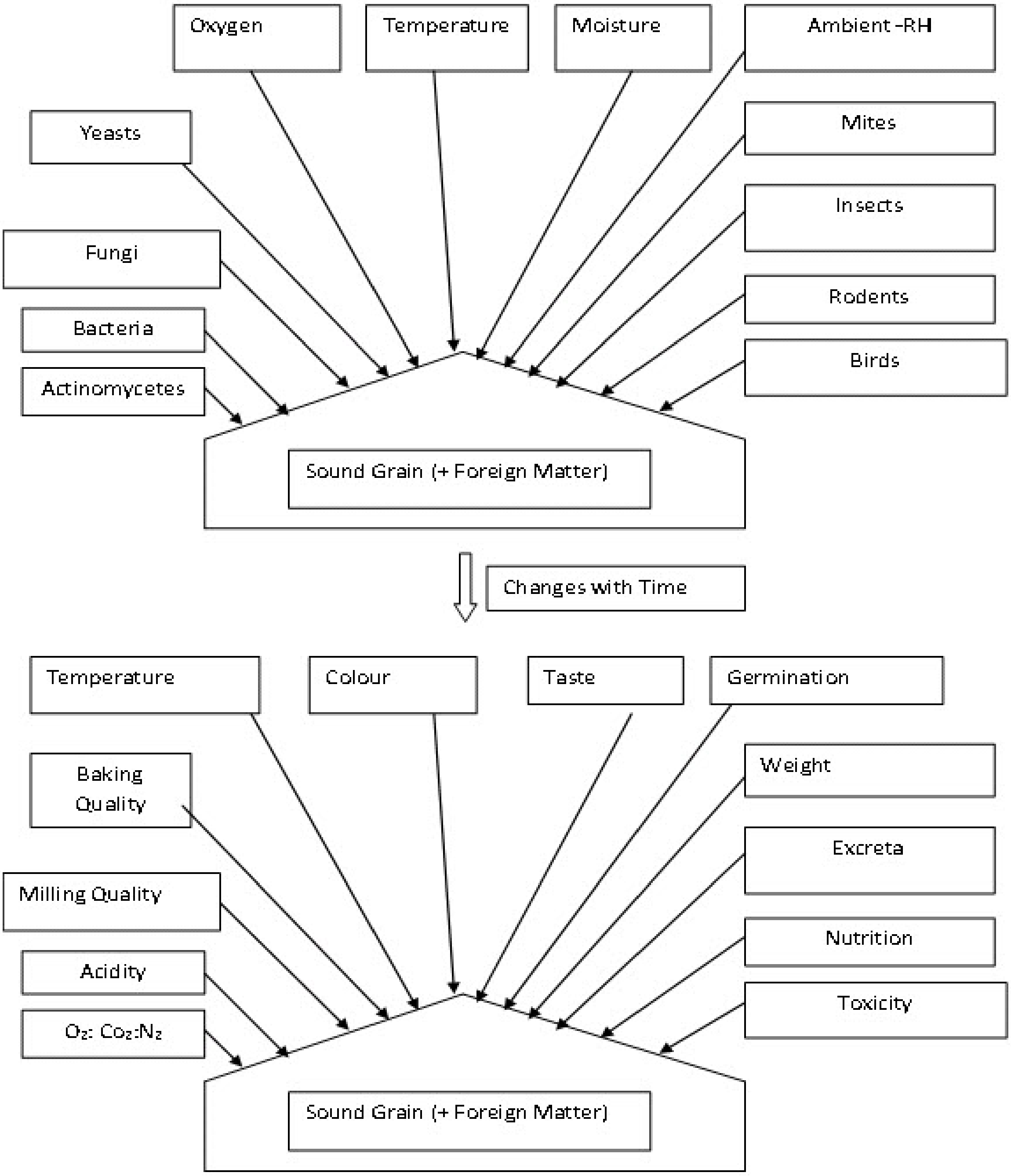


Fig. 23.1 Causes of spoilage in storage

23.8 References

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Lesson-24 Storage of perishable products

24.1 Introduction

Perishable food includes fruits and vegetables, fresh meat, foods purchased from chill cabinets, freshly cooked food stored to be used later. It is usually stored in a refrigerator. Some fresh fruits and vegetables, however, will store quite well out of the refrigerator as long as they are stored in a cool place.

24.2 Why storage?

Storage is an important marketing function involving holding and preserving foods from the time they are produced until they are needed for consumption.

- The storage of foods, therefore, from the time of production to the time of consumption, ensures a continuous flow of foods in the market.
- Storage protects the quality of perishable and semi-perishable products from deterioration.
- Some of the farm products, have a seasonal demand. To cope with this demand, production on a continuous basis and storage become necessary.
- It helps in the stabilization of prices by adjusting demand and supply.
- Storage is necessary for some period for performance of other marketing functions.
- Storage provides employment and income through price advantages.

24.3 How to store?

1) Refrigeration:

Refrigeration can substantially reduce the rate at which food will deteriorate. Low temperatures slow down the growth of microorganisms and the rate of chemical (including enzymatic) changes in food. These are two of the main causes of food spoilage.

2) Cartons:

When sending perishable goods, small Thermochron data loggers can be put into strategically chosen boxes clearly marked with Alert Tape. The Thermochrons are easy to return to shipper if they are put in fobs tied to tags with return address. And they are not so expensive that it would be a disaster to lose one.

3) Cold Storage:

Availability of proper cold storages are important for preserving perishable commodities like milk, meat, eggs, vegetables, fruits, ornamental flowers and other floricultural goods. These cold storages give perishable food items a longer shelf life by preventing them from rotting due to humidity, high temperature and micro-organisms. This results in a substantial decrease in loss due to spoilage.

4) Warehouse:

Three public sector agencies are involved in building large-scale storage and warehousing capacities in the country. These are as follows

a. Food Corporation of India (FCI)

The FCI has the largest agricultural warehousing systems with over 30.52 million tonnes of storage capacity in over 1820 godowns located all over India. This includes owned as well as hired warehouses.

b. Central Warehousing Corporation (CWC)

The CWC was founded in 1957 to provide logistics support to the agricultural sector. Currently, it operates around 465 warehouses across the country with a storage capacity of 10.80 million tonnes. Other than storage and handling, CWC also offers services such as disinfestations, pest control, fumigation, clearing and forwarding, handling and transportation, procurement and distribution.

c. State Warehousing Corporations (SWCs)

State Warehousing Corporations exist in 17 States to provide storage facilities and pest control services for various agricultural commodities belonging to farmers of that State. These warehouses work under different Warehousing Acts enacted by the respective State Governments.

While the FCI uses its warehouses mainly for storing food grains, the storage capacities with CWC and SWCs are used for the storage of food grains as well as other items.

Uses of Warehouses:

- Scientific storage of produce from the vagaries of weather, rodents, insects and pests. They prevent quality and quantity losses.
- Meeting the financial needs of people who store the produce by providing value for the goods stored.
- Regulating price levels by regulating the supply of goods in the markets. More goods from the buffer are released when supplies are less and less is released when supplies are more in the markets.
- Offering market intelligence in the form of price, supply and demand information so that market users may develop selling and buying strategies.

References:

- McFarlane JA. Storage methods in relation to post-harvest losses in cereals. Insect Sci Appl 1988; 9:747–754.
- K.M Sahay and K.K.Singh. Unit Operations of Agricultural Processing, Vikas Publishing House Pvt Ltd.

Lesson 25. Functional Requirements Of Storage

25.1 INTRODUCTION

In the post green revolution era, there is a significant growth in the production and productivity in the Indian agriculture. The country has become self sufficient in food grains and achieved a remarkable growth in the production of pulses, oil seeds and fibres to meet the requirements of the country. Although our farming community toiled hard, they could not get real benefit of the growth in the economy in the absence of a suitable mechanism to ensure a reasonable rate of return to their hard labour and investments. Only a handful of influential farmers, who have the infrastructure to overcome the market fluctuations, could derive the benefits.

Our farming community depends heavily on the borrowed money for the agricultural operations. The borrowings are at an unreasonably high rate of interest, mostly from the money lenders. As a result, they are forced to sell their produce immediately after the harvest although price is very low. Thus, the farmers lose heavily on their investments. This vicious cycle is recurring year after year making the farmers poorer. Today, the country is not having a reasonable infrastructure for providing relief to these farmers. The facility for storage of agricultural produce is inadequate in rural areas. The farmers therefore have to dispose of their produce at an unremunerative price, immediately after the harvest. The creation of storage facilities, through construction of grain godowns in villages will remedy the above situation. The farmers can store their produce in godowns by paying rents, and release the produce to market when the price is reasonable. Meanwhile, the farmers can borrow from a financial institution, in case of need, by pledge of godown receipt. This will help modernization of rural economy, development of banking habit of the farmers and teach the bankers the lesson of development through credit. This facility will not only enable the farmers to break the vicious cycle by generating money from their own produce to pay back a part of the loan and meet some of their day-to-day urgent needs; but also reduce the subsidy burden on the government on procurement of excess produce.

A reasonable spread of agricultural storage godowns linked to financial organizations to provide pledge loan will go a long way in meeting the needs of the farmers as it will not only provide the basic infrastructure for making arrangements for the pledge loan but also preserve the quality and quantity of their produce over a longer period to enable them to sell it when rates are higher for the quality produce to ensure a decent return on their labour and investments. Scientifically designed storage structures reduce the losses and its existence provides confidence to the farmers for raising crops with quality/ costly inputs.

25.2 REQUIREMENTS OF AN IDEAL GRAIN STORAGE STRUCTURE

The object of an ideal grain storage structure is to control and reduce the storage loses from rodents, insects and micro-organisms, birds, moisture and heat to a minimum.

A good storage structure is the one, which can provide protection against all possible causes of damage. A food storage structure, for storing food grains on a large scale, should have the following essential features:

1. It should be easy to clean.
2. It should provide protection from rodents, birds and other animals.
3. It should be waterproof and moisture proof.
4. It should protect the food grains against variations of temperature and humidity.
5. It should have provision for periodical inspection.
6. It should have provision for application of pesticides through spraying or fumigation.
7. It should be located far away from possible sources of infection such as kilns, flour mills, and bone crushing mills, garbage rumps, tanneries, slaughter houses and chemical industries.
8. It should be located at a convenient place from where it is easy to receive issue and transport the food gains. This explains why most of the storage structures are located near railway stations or on highways.

Therefore in designing and constructing storage structure following points shall be borne in mind:

1. All holes, pipes and ducts and other openings shall be guarded by suitable means, such as gratings, etc., in order to prevent the entry of rats and other vermin.
2. The structure shall have smooth, crack free internal surfaces and shall have no unnecessary cavities and projections to prevent the lodgement from insects and vermin. Periodical fumigation and other treatments should be done to eliminate infestation of grains by insects, fungus etc. The structure shall be designed so as to facilitate its sealing for fumigation or have facility to seal a portion where fumigation has to be carried out, or it may be made completely airtight if required.
3. Godowns should have good ventilation arrangement to prevent moisture accumulation in pockets.
4. The structure shall be designed to make it possible to control moisture. Moisture may be controlled by adopting methods of construction using non-hygroscopic material, by sound wall, roof and floor construction, by the use of vapour barriers, and by the use of aeration.
5. The structure shall be so oriented that it will receive the minimum solar radiation. Reflective external surfaces, insulating materials, sun shades, a minimum of glass surfaces, controlled ventilation and aeration, to reduce the internal temperature may be used.

Lesson 26. Control Of Environment Inside Storage

The environment, in regard to temperature and relative humidity, inside a storage structure plays and significant role as far as stability of the commodity is concerned which is of paramount importance for a processor.

26.1 Aeration

Aeration preserves the quality of stored grain by keeping an even and cool temperature, and is a valuable tool for managing grain quality at harvest and in storage. Grain stored under aeration can be held safely at a higher moisture content and retain its viability and vigour longer.

26.2 The advantages of aeration

- Extends the harvesting window of grain and seed crops reducing delays from rain at harvest and the downgrading of premium grain due to weather damage.
- Minimizes colour deterioration from delayed harvest of premium products that are paid on the basis of colour , such as shochu barley or pulses.
- Equalises the silo temperature to minimise hot spots, which directly affect grain quality and provide favourable conditions for insect and mould contamination.
- Protects high moisture grain from developing moulds in storage.
- Cools the grain and reduces damage from insect populations in high throughput storage, typically lot feed operations, where the grain is fed to stock and there are limited opportunities for fumigation.
- Provides opportunities to supply wheat to millers or manufacturers throughout the year. Wheat milled for Flour retains its baking qualities longer when stored cool.

26.3 The aeration process

Aeration passes ambient (unheated) air through bulk grain. If the air passing through has a relative humidity (RH) that is different to the air surrounding the grain, then moisture moves either from the grain or to the grain until equilibrium is reached.

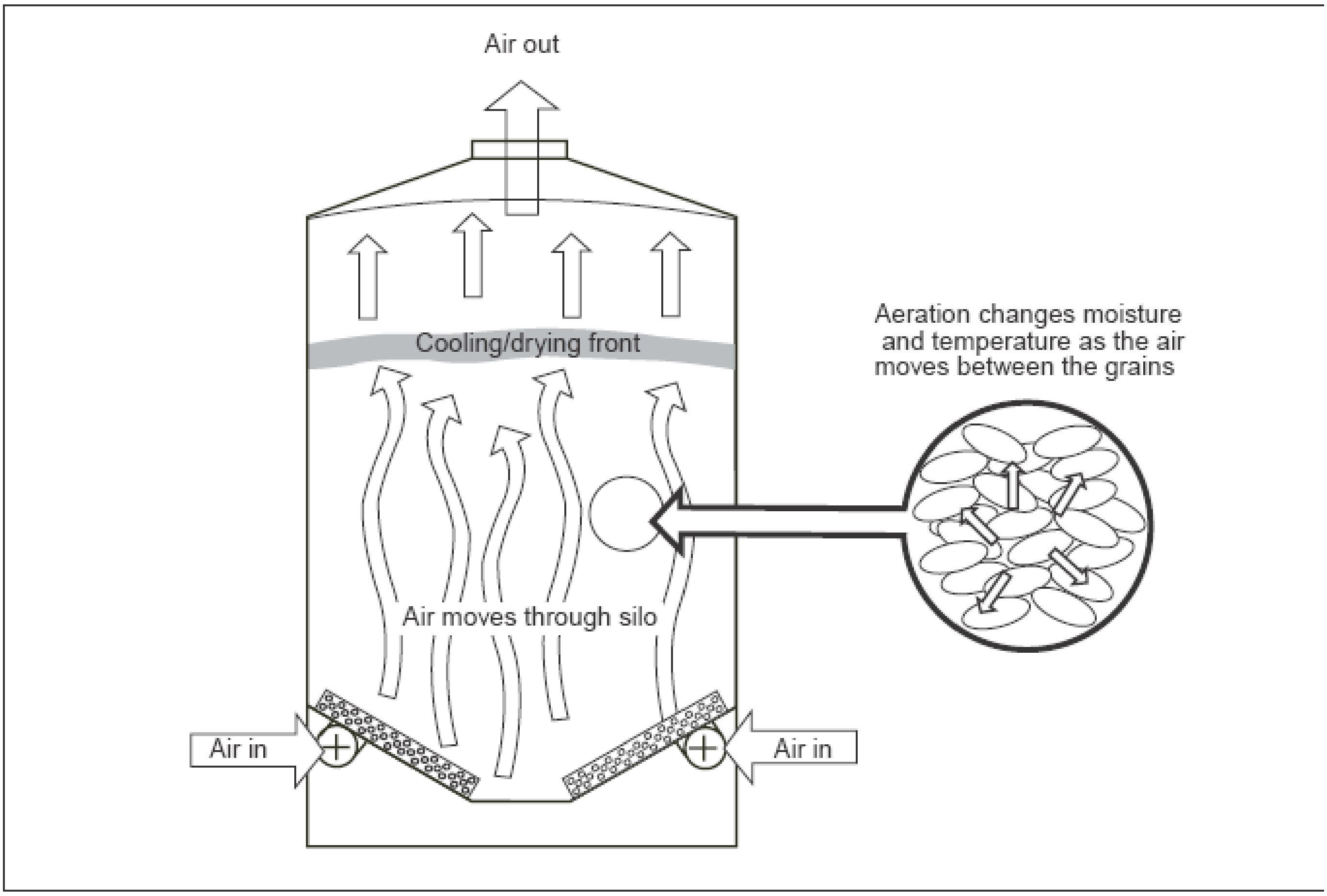

Fig. 26.1 Aeration Process

26.3.1 Long term storage of low moisture grain

Low airflow aeration

Low flow aeration protects the quality of low moisture grain for many months in storage and has the added advantage of slowing the development of insect populations. To hold low moisture grain in a safe condition for long storage, a fan capacity of about two liters per second per tonne (l/s/t) is usually adequate. Exhaust air must be able to escape freely from the top of the storage. It is recommended for an opening of at least 0.1 m^2 for each 500 liters per second of air delivered to the storage. (As a guide, a hole 30 cm by 30 cm is approximately 0.1 m^2). Exhaust vents must be designed to prevent water entering the silo. Temperature monitoring and automatic fan control systems are recommended for long-term storage. The controllers select the best quantity and quality of air for use in the system and some controller models prevent high humidity air entering the grain bulk.

26.3.2 Short-term storage of high moisture grain

Medium airflow aeration

Harvesting barley and other grains at high moisture levels, above those suitable for delivery and storage, optimizes quality and minimizes the risk of fungal staining and sprouting and losses due to wet harvest conditions. Medium airflow aeration is needed to preserve the quality of high moisture grain before it is dried in a heated air dryer. Under aeration, the moisture content and temperature of the grain is equalized in the stack. This has the advantage of providing a consistent feedstock for the dryer and reduces the need for frequent changes to the dryer speed and heat settings. The airflow rate depends on the grain moisture content but is typically in the 4 to 10 l/s/t range. To hold the grain in a safe condition, aim for a temperature of 20^{o}C at a maximum moisture content of 15 per cent. When harvesting in the early morning or late evenings the moisture content of each grain may be raised by moisture on or close to the grain surface. Airflow of 4 to 10 l/s/t will remove moisture from the surface region of each grain.

26.4 Equipment for Monitoring, Management

To properly manage stored grain the operator must be able to obtain samples from the stored grain, determine moisture content, monitor grain temperatures, and keep a simple record of both grain and ambient temperatures.

A deep bin probe should be used to obtain samples at different locations to determine the moisture content, the level of fine material, and general grain conditions. A reasonably accurate moisture tester is needed. The operator must know the accuracy of the moisture tester under all conditions. Inexpensive electrical testers can give inaccurate readings under many conditions. Readings on freshly dried grain, warm or hot grain, and excessively cold grain can be inaccurate. The operator can calibrate the tester under these conditions by checking readings with the local elevator or other more accurate testers.

Thermocouple cables installed in larger bins are valuable in monitoring temperatures in storage to determine the progress of aeration. In bins without cables, thermometer probes should be used to check the temperature at different locations within the bin. This helps in monitoring the progress of the aeration and in locating trouble spots. A thermometer to measure the exhaust air temperature and one to read ambient air temperature is necessary for proper fan management. Maximum-minimum thermometers are especially helpful because they provide the operator an indication of changes in temperature with time. This equipment not only helps the operator manage the stored grain but provides information on how the aeration system works and how stored grain responds to treatment.

Lesson.27 Types of Cooling Load

INTRODUCTION

The total amount of heat required to be removed from the space in order to bring it at the desired temperature by the air conditioning and refrigeration equipment is known as cooling load. The purpose of load estimation is to determine the size of the equipment. Cooling loas on refrigeration equipment is the summation of heat given up by different sources.

27.1 COMMON SOURCES OF HEAT

1. Heat that leaks into the refrigerated space from the outside by conduction through the insulated walls.
2. Heat that enters the space by direct radiation through glass or other transparent material
3. Heat that is brought into the space by warm outside air entering the space through open doors or through cracks around window and doors.
4. Heat given off by a warm product
5. Heat given off by a people occupying the refrigerated space
6. Heat given off by any heat-producing equipment located inside the space eg. Motors, lights, electronic equipment, material handling equipments etc.

27.2 TOTAL COOLING LOAD

The total cooling load is divided into four separate loads;

1. The wall gain load
2. The air change load,
3. The product load,
4. The miscellaneous or supplementary load.

27.2.1 Wall gain load

Wall gain load or wall leakage load is a measure of heat flow rate by conduction through the walls of refrigerated space from the outside to the inside. There is no perfect insulation i.e. there is always a certain amount of heat passing from the outside to the inside. The heat gain through walls, floor & ceiling vary with

- The types of insulation
- Thickness of insulation
- Construction material
- Outside wall area

- Temperature difference between refrigerated space and ambient air

27.2.2 Air change load

When the door of a refrigerated space is opened, warm outside air enters the space to replace the more dense cold air that is lost from the refrigerated space through the open door. The heat which must be removed from this warm outside air to reduce its temperature and moisture content to the space design conditions, becomes a part of the total cooling load. This is called the air change load.

Air change load, $Q_a = m\ (h_o\text{-}h_i)$ ………… (27.1)

Where, m= mass of air entering, kg /h

h_o = Enthalpy of outside air, kJ/kg dry air

h_i = Enthalpy of inside air, kJ/kg dry air

Fruits and vegetables respire even at low temperature storage Heat produced due to respiration of the fruits and vegetables, is required to be considered for cold storages. It can be calculated as

$Q_r = m_p$ (kg/h) x Respirate rate (kJ/kg) ……….. (27.2)

Where, Q_r = Respiration load

m_p = mass

27.2.3 The product load

Product load is the heat that must be removed from the refrigerated product in order to reduce the temperature of the product to the desired level. The term product means any material whose temperature is to be reduced. When, the product is to be frozen, in this the latent heat removed is also a part of the product load.

27.2.4 Miscellaneous load

This load takes into account all miscellaneous sources of heat. Chief among them are people working in or otherwise occupying the refrigerated space, along with lights or other electrical equipment operating inside the space.

Lesson 28: Cooling Load Calculation

Introduction:

To simplify the cooling load calculations, the total cooling load is divided into a number of individual loads i.e. according to the sources of heat supplying the load.

The total cooling load is divided into four separate loads;

1. The wall gain load
2. The air change load,
3. The product load,
4. The miscellaneous or supplementary load.

28.1 WALL GAIN LOAD

The quantity of heat transmitted through the walls, ceiling & floor of a refrigerated space per unit time is calculated as follows;

Wall gain load,

Where, U= Overall heat transfer co-efficient, W/m K

A= Area of the wall, m^2

= Temperature difference across the wall, K

The value of U depends on the materials used in construction and insulation used in the construction of wall as well as on the thickness of these materials. If either U or are different for different walls, then it is necessary to calculate Q_w of each wall/ceiling/floor separately taking corresponding values of U and .

The overall heat transfer co-efficient is given by

Where, h_o = Convection heat transfer Co-efficient on the outer surface

h_i = Convection heat transfer Co-efficient on the inner surface

x_1, x_2…..= thickness of different layers of wall including insulation

k_1, k_2,….= conductivities of different layers of wall including insulation

28.2 AIR CHANGE LOAD

This is the quantity of outside air entering a space through door openings in a 24hrs periods depends on the number, size & location of the door openings and the densities of the outside and inside air. The measurement of amount of air changed due to door opening is difficult and hence air change factor is used to estimate the amount of air changed.

Air change load, $Q_a = m\,(h_o - h_i)$

Where, m= mass of air entering, kg /h

h_o = Enthalpy of outside air, kJ/kg dry air

h_i = Enthalpy of inside air, kJ/kg dry air

Mass of air can be estimated by multiplying inside volume of space with air change factor. The volume of the air is converted into amount of dry air in the volume taking specific volume of the outside air.

28.3 PRODUCT LOAD

It is necessary to cool the product from initial temperature to the storage temperature. The amount of heat given off by the product in cooling to the space temperature depends upon temperature of the space and upon the mass, specific heat, and entering temperature of the product. It is also necessary to estimate the heat load for cooling of the packaging material along with the product as specific heat of product and material is different.

Product load, $Q_p = m_p \times C_1 \times (t_1 - t_2)$

Where m_p = Mass of the product, kg/h

C_1 = Specific heat of the product kJ/kg K

t_1 = Initial temperature of the product

t_2 = Final storage temperature of the product.

Similarly, heat load of packaging materials transferred in the cold store along with the product is estimated as above taking the mass of packaging material, its specific heat and temperature difference. This load is added in the actual product load.

For product freezing and storage: When a product is to be frozen and stored at some temperature below its freezing temperature, the product load is calculated in three parts; heat given off by the product(entering temperature to its freezing temperature), heat given off by the product in solidifying or freezing(heat removal to freeze the product) & heat given off by the product in cooling from its freezing temperature to the final storage temperature. This is calculated as below;

$$Q_p = m_p \text{ x } C_1\,(t_1 + t_f) + m_p\,h_{fg} + m_p \text{ x } C_2\,(t_f - t_2)$$

Where t_f = Freezing temperature, ^oC

h_{fg} = Latent heat of freezing, J/kg

Heat produced due to respiration of the fruits and vegetables are required to be considered for such types of cold storages.

$Q_r = m_p$ (kg/h) x Respirate rate (kJ/kg)

28.4 MISCELLANEOUS LOAD

The miscellaneous load consists of primarily of heat given off by light and electric motors present in the cold storage.

Cooling load for electric appliances in terms of kJ is given by

$$Q_c = kW \times 3600 \text{ kJ/h}$$

Heat Load from occupants is calculated based on the data available for heat loss from human body. It is necessary to refer standard data if heat loss from human body under different temperature conditions. For example, a person at rest at 20 ^{o}C, total heat loss from the body is about 400 kJ/h (Q_l= 160 kJ/h and Qs = 240 kJ/h)

TOTAL HEAT LOAD

The total cooling load is the summation of individual loads

$$\text{Total load, } Q_t = Q_w + Qa + Q_p + Q_m$$

It is common practice to add 10-15% of total load as safety factor. After adding safety factor, the cooling load is multiplied by 24 hours and divided by the desired operating time in hours to find capacity of the plant required for the cold storage.