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Postharvest Technology and Food Process Engineering

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PART V FOOD PROCESS ENGINEERING

Preface

This book originates from *Postharvest Technology of Cereals and Pulses* (published in 1981), which was considered to be the first of its kind. Since then, students and professionals in the field of agricultural and food engineering have felt the need for a consolidated book on postharvest technology and food process engineering.

This comprehensive book deals with grain properties, engineering principles, numerical problems, designs, and testing and provides illustrations and descriptions of the operations of various commercial grain dryers, milling machines, and furnaces, as well as utilization of by-products/biomass for producing energy, chemicals, food, feed, and other value-added products. Adequate emphasis has been placed on postharvest management, food chemistry, preservation and processing of fruits and vegetables, and relevant food engineering operations, namely, fluid mechanics, heat transfer, drying, and associated machines.

The major aim of this book is to serve as a text or as a reference book for students, professionals, and others engaged in agricultural science and food engineering, food science, and technology in the field of primary processing of cereals, pulses, fruits, and vegetables.

I would like to acknowledge my coauthor, Dr. R. Paul Singh, for contributing Chapter 17 entitled "Postharvest Management of Fruits and Vegetables." I am also indebted to my wife, Sushmita Chakraverty, and my sons, Krishnendu and Soumendu, for their painstaking assistance in the preparation of the manuscript.

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Introduction

Cereals, legumes, oilseeds, fruits, and vegetables are the most important food crops in the world. The need to increase food production and supply an adequate quantity of grains and other food in order to meet the energy and nutritional requirements of the growing world population is widely recognized. Cereals include edible grains such as rice, wheat, corn, barley, rye, oats, or sorghum. Cereal grains contribute the bulk of food calories and proteins worldwide and are consumed in various forms. They are also fed to livestock and are thereby converted into meat, milk, or eggs.

Rice and wheat are two of the most important types of staple food. Corn is mainly used as an ingredient of feed in the United States, though it has numerous uses in food items as well. Generally, cereals are composed of about 10%–15% moisture, 55%–71% carbohydrate, 8%–11% protein, 2%–5% fat, and 2%–9% fiber; while milling hull, bran and germ of cereal grains are separated, removing indigestible fiber as well as fat. The removal of fatty bran is necessary to avoid rancidity and to improve shelf life as well as the functional properties of starchy endosperm of food products.

Legumes are characterized by their high protein and low fat contents. Soybean contains a high percentage of both protein and fat, though it is mainly considered as oilseed.

Fruits and vegetables are clubbed together because of their many similarities with respect to their compositions and methods of harvest as well as postharvest operations. Fruits are the mature ovaries of plants with their seeds. Usually, fruits and vegetables contain a very high percentage of water and low percentage of protein and fat. Their water content normally varies from 70% to 85%. Fruits and vegetables are common sources of digestible starches, sugars, certain minerals, vitamins A and C, and indigestible fibers, which are important constituents of a diet. Citrus fruits, some green leafy vegetables, and tomatoes are good sources of vitamin C.

Generally, the supply of grains and other food can be enhanced in two ways: by increasing production and by reducing postharvest losses. Food production has increased significantly during the last few decades with the use of improved high-yielding cultivars, suitable fertilizers, water, as well as crop management practices.

Wheat and paddy production has increased spectacularly in many countries since the mid-1960s. Table 1 shows the production of these two grains in 1996. The production of pulses and fruits and vegetables in 1996 is presented in Tables 2 and 3, respectively.

It is recognized that hunger and malnutrition can exist despite adequate food production owing to uneven distribution, losses, and deterioration of available food resources during traditional postharvest operations. Therefore, maximum utilization of available food and minimization of postharvest losses are essential. Postharvest losses of cereals and fruits and vegetables are generally estimated to be 5%–20% and 20%–50%, respectively. A country can become self-sufficient in food if it minimizes colossal postharvest losses.

Commercial food preservation methods, as a whole, include drying/dehydration, refrigeration/cold storage or freezing, canning/pasteurization, chemical addition, and other special methods such as use of microwave, infrared rays, radiations, etc. The grain PHT, in particular, may involve drying, storage, parboiling/conditioning, milling operations, and by-product utilization. Apart from these, various other conversion technologies, namely, thermal, thermochemical, chemical, and biochemical processing, are also employed to convert biomass/by-products into energy, food, feed, and chemicals. Hence, PHT covers a wide range of diversified subjects.

Table 1 Wheat and Paddy Production (1000 Tons) in Some Countries

Country	*Wheat Production, 1996*	*Paddy Production, 1996*
India	62,620.0	120,012.0
China	109,005.0	190,100.0
Russia	87,000.0	2,100.0
United States	62,099.0	7,771.0
Canada	30,495.0	—
France	35,946.0	116.0
Australia	23,497.0	951.0
Pakistan	16,907.0	5,551.0
Argentina	5,200.0	974.0
World	584,870.0	562,260.0

Source: FAO Production Year Book, Vol. 50, FAO, Rome, Italy, 1996.

Table 2 Pulses Production (1000 Tons) in Some Continents/Countries

Continent/Country	*Production, 1996*
Asia	28,222
Africa	7,651
Europe	9,380
N. America	5,541
S. America	3,770
Australia	2,186
India	14,820[a]
China	4,979
Brazil	2,862
France	2,636
World	56,774

Source: FAO Production Year Book, Vol. 50, FAO, Rome, Italy, 1996.

[a] *Food and Agricultural Organisation (FAO) Production Year Book* (1995).

Table 3 Fruit and Vegetable Production (Million Tons) in Some Countries

Country	*Production, 1996*			
	Apple	*Orange*	*Mango*	*Potato*
China	16.00	2.26	1.21	46.03
India	1.20	2.00	10.00	17.94
Russia	1.80	—	—	38.53
Poland	1.70	—	—	22.50
Brazil	0.65	21.81	0.44	2.70
Mexico	0.65	3.56	—	1.20
France	2.46	—	—	6.46
Germany	1.59	—	—	13.60
United States	4.73	10.64	—	22.55
World	53.67	59.56	19.22	294.83

Source: FAO Production Year Book, Vol. 50, FAO, Rome, Italy, 1996.

I

GRAIN PROPERTIES, DRYING, AND DRYERS

Chapter 1

Properties of Grains

A grain is a living biological product that germinates as well as respires. The respiration process in the grain is externally manifested by the decrease in dry weight, utilization of oxygen, evolution of carbon dioxide, and release of heat. The rate of respiration is dependent upon moisture content and temperature of the grain. The rate of respiration of paddy increases sharply (at 25°C) from 14% to 15% moisture content, which may be called the critical point. On the other hand, the rate of respiration increases with the increase of temperature up to 40°C. Above this temperature, the viability of the grain as well as the rate of respiration decreases significantly.

Structure

Wheat and rye consist mainly of pericarp, seed coat, aleurone layer, germ, and endosperm, whereas oats, barley, paddy, pulses, and some other crops consist not only of the aforementioned five parts but also an outer husk cover. The husk consists of strongly lignified floral integuments. The husk reduces the rate of drying significantly.

The embryo or germ is the principal part of the seed. All tissues of the germ consist of living cells that are very sensitive to heat. The endosperm that fills the whole inner part of the seed consists of thin-walled cells, filled with protoplasm and starch granules and serves as a kind of receptacle for reserve foodstuff for the developing embryo. The structures of a few important grains are shown in Figures 1.1 through 1.4.

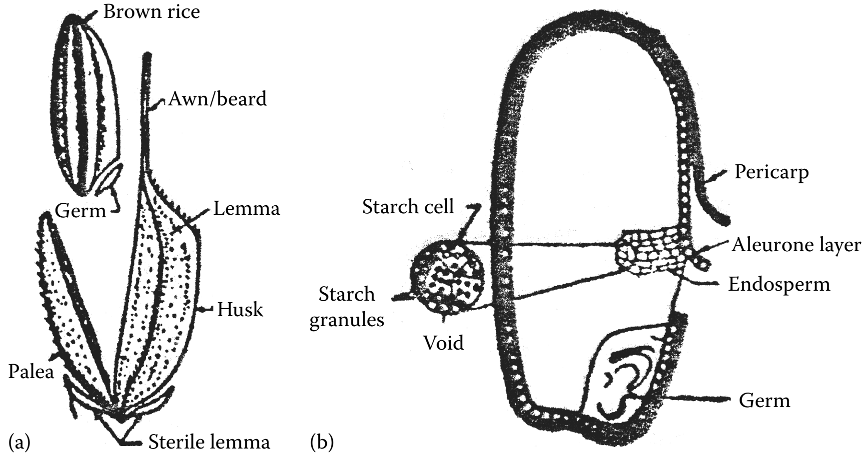


Figure 1.1 (a) Different parts of paddy. (b) Structure of brown rice kernel (longitudinal section).

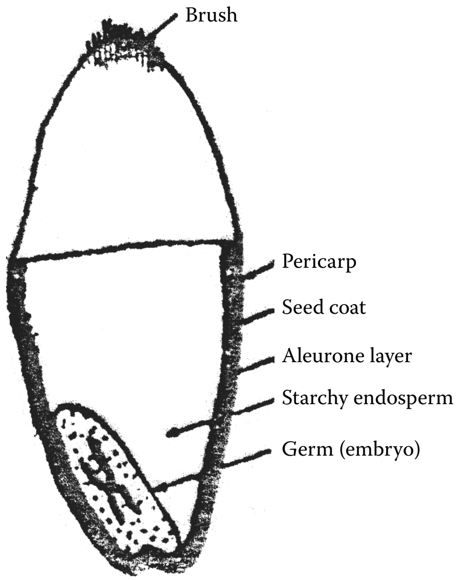


Figure 1.2 Structure of wheat.

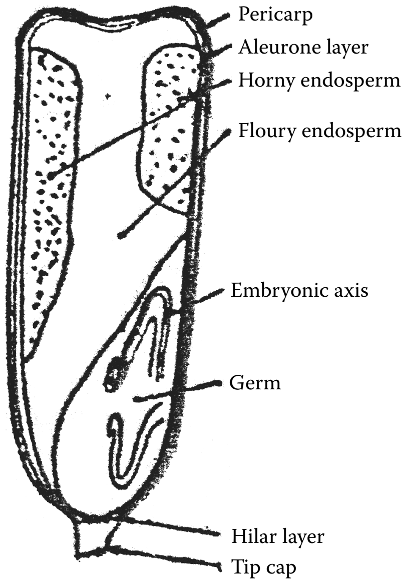


Figure 1.3 Structure of shelled corn (longitudinal section).

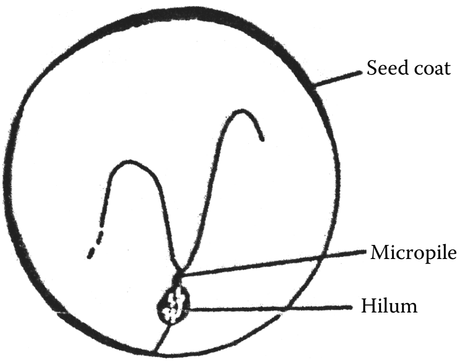


Figure 1.4 Whole arhar pulses (*Cajanus cajan*).

Chemical Composition

The grain is composed of both organic and inorganic substances, such as carbohydrates, proteins, vitamins, fats, ash, water, mineral salts, and enzymes. Paddy, corn, wheat, and buckwheat seeds are especially rich in carbohydrates, whereas legumes are rich in proteins and oilseeds in oils.

Generally, pericarp and husk contain cellulose, pentosan, and ash. The aleurone layer contains mainly albumin and fat. The endosperm contains the highest amount of carbohydrate in the form of starch, a small amount of reserve protein, and a very little amount of ash and cellulose, whereas the germ contains the highest amount of fat, protein, and a small amount of carbohydrate in the form of sugars and a large amount of enzyme.

Effects of Temperature on the Quality of Grain

Proteins

The proteins present in cereal grains and flour are hydrophilic colloids. The capacity of flour proteins to swell plays an important role in the preparation of dough. At temperatures above 50°C, denaturation and even coagulation of proteins take place. As a result, the water-absorbing capacity of the proteins and their capacity for swelling decrease.

Starch

Starch is insoluble in cold water but swells in hot water. Up to a temperature of 60°C, the quality of starch does not change appreciably. With a further increase in temperature, particularly above 70°C, and especially in the presence of high moisture in the grain, gelatinization and partial conversion of starch to dextrin take place. In addition, a partial caramelization of sugars with the formation of caramel may take place, which causes deterioration in color of the product. These effects will be discussed in detail in Part III on Parboiling and Milling.

Fats

Fats are insoluble in water. Compared to albumins and starch, fats are more heat-resistant. But at temperatures above 70°C, fats may also undergo a partial decomposition resulting in an increase of acid numbers.

In the range of temperatures from 40°C to 45°C, the rate of enzymatic activity on fats increases with the increase of moisture and temperature. With a further rise of temperature, the enzymatic activity begins to decrease, and at temperatures between 80°C and 100°C the enzymes are completely inactivated.

Vitamins

The heat-sensitive B vitamins present in the germ and aleurone layer are destroyed at high temperature.

The details of the structures and compositions of wheat, rice, corn, and pulses/legumes can be found in Pomeranz (1971), Potter (1986), and Kadam et al. (1982).

Physical Properties

The knowledge of important physical properties such as shape, size, volume, surface area, density, porosity, color, etc., of different grains is necessary for the design of various separating and handling, storing, and drying systems. The density and specific gravity values are also used for the calculation of thermal diffusivity and Reynolds number. A few important physical properties have been discussed here.

Sphericity

Sphericity is defined as the ratio of surface area of a sphere having same volume as that of the particle to the surface area of the particle. Sphericity is also defined as

$$\text{Sphericity} = \frac{d_i}{d_c}$$

where
d_i is the diameter of largest inscribed circle
d_c is the diameter of smallest circumscribed circle of the particle

The sphericity of different grains varies widely.

Bulk Density

The bulk density of a grain can be determined by weighing a known volume of grain filled uniformly in a measuring cylinder. Bulk densities can then be found at different moisture contents for various biomaterials. The following equation is used to calculate the bulk density of the material:

$$\rho_B = \frac{W}{V}$$

where
ρ_B is the bulk density, g/cc or kg/m^3
W is the weight of the material, kg or g
V is the volume of the material, cc or m^3

True Density

The mass per unit volume of a material excluding the void space is termed as its true density.

The simplest technique of measuring true density is by liquid displacement method, where tube is commonly used. The expressions used for calculation of true volume are given as follows:

$$\text{Volume (cc)} = \frac{\text{Weight of displaced water, g}}{\text{Weight density of water, g/cc}} \quad \text{and}$$

$$\text{Volume (cc)} = \frac{\text{(Weight in air} - \text{weight in water), g}}{\text{Weight density of water, g/cc}}$$

However, the only limitation of this method is to use the materials impervious to the liquid used. Hence, the use of toluene has also been in practice for a long time. The expression used for calculating true density is

$$\text{True density, } \rho_t\text{, g/cc} = \left(- \frac{\text{Weight of the grain, g}}{\begin{matrix}\text{Weight of toluene}\\ \text{displaced by grain, g}\end{matrix}} \right) \times \left(\begin{matrix}\text{Weight density}\\ \text{of toluene, g/cc}\end{matrix} \right)$$

Air comparison pycnometer is an instrument that can be conveniently used to measure the true volume of a sample of any shape and size without wetting the sample. Thus, the true density is determined from the measurement of true volume of a sample of known weight with this instrument.

Porosity

It is defined as the percentage of volume of inter-grain space to the total volume of grain bulk. The percent void of different grains in bulk is often needed in drying, airflow, and heat flow studies of grains. Porosity depends on (a) shape, (b) dimensions, and (c) roughness of the grain surface.

Porosity of some crops is tabulated as follows:

Grain	*Porosity, %*
Corn	40–45
Wheat	50–55
Paddy	48–50
Oats	65–70

The grain porosity can be measured by using an air comparison pycnometer or by the mercury displacement method (Thompson and Issas, 1967).

Coefficient of Friction and Angle of Repose

Angle of repose and frictional properties of grains play an important role in selection of design features of hoppers, chutes, dryers, storage bins, and other equipment for grain flow.

The additional details on the method of determination of frictional coefficients are available in Chakraverty et al. (2003) and Dutta et al. (1988).

Coefficient of Friction

The coefficient of friction between granular materials is equal to the tangent of the angle of internal friction for the material. The frictional coefficient depends on (a) grain shape, (b) surface characteristics, and (c) moisture content.

Angle of Repose

The angle of repose of grain can be determined by the following method. Grain is poured slowly and uniformly onto a circular platform of 6.5 cm diameter to form a cone. The height of this cone is measured using a traveling microscope. The angle of repose of grain at different moisture contents is determined from the geometry of the cone formed (Dutta et al., 1988). It is the angle made by the surface of the cone with horizontal. It is calculated using the following equation:

$$\varphi_{AR} = \tan^{-1}\left\{\frac{2(H_c - H_p)}{D_p}\right\}$$

where

φ_{AR} is the angle of repose, degrees
H_c is the height of the cone, cm or m
D_p is the diameter of the platform, cm or m

Thermal Properties

Raw foods are subjected to various types of thermal treatment, namely, heating, cooling, drying, freezing, etc., for processing. The change of temperature depends on the thermal properties of the product. Therefore, knowledge of thermal properties, namely, specific heat, thermal conductivity, and thermal diffusivity, is essential to design different thermal equipment and solve various problems on heat transfer operation.

Specific Heat

The specific heat of a substance is defined as the amount of heat required to raise the temperature of unit mass through 1°C. The specific heat of wet grain may be considered as the sum of specific heat of bone dry grain and its moisture content. It can be expressed as follows:

$$c = \left(\frac{m}{100}\right)c_w + \left(\frac{100-m}{100}\right)c_d$$

$$\text{or} \quad c = \left(\frac{m}{100}\right) + \left(\frac{100-m}{100}\right)c_d, \text{ kcal/(kg °C) or kJ/(kg °C)}$$

where
c_d is the specific heat of the bone dry grain
c_w is the specific heat of water
m is the moisture content of the grain, percent (wet bulb temperature)

The specific heat of bone dry grain varies from 0.35 to 0.45 kcal/kg or 1.46 to 1.88 kJ/kg °C.

The aforementioned linear relationship between c and m exists above m = 8% moisture content only (Gerzhoi and Samochetov, 1958).

Specific Heat Measurement

The specific heat of grain can be determined by the method of mixture for which the experimental setup and the procedure are explained later.

A thermos flask of required capacity is used as a calorimeter. It is further insulated by centrally placing it in a thermocole container and filling the gap between the flask and the container with glass wool. A glass beaker of required capacity is also insulated all around by placing it in a thermocole box and used as an ice bath. A long precision mercury thermometer can be used to measure the temperature. Any balance with an accuracy of at least 0.1 mg can be used for weight measurements during the experiments.

The water equivalent of the calorimeter is first determined and it is calculated using the following heat balance equation:

$$W_e = W_{cw}\left\{\frac{t_e - t_c}{t_f - t_e}\right\}$$

where

W_e is the water equivalent of the flask calorimeter, g or kg
W_{cw} is the weight of cold distilled water, g or kg
t_f is the temperature of flask calorimeter (ambient), °C
t_c is the temperature of cold distilled water, °C
t_e is the equilibrium temperature of water, °C

The specific heat can be determined by taking about 15–25 g of grain in the calorimeter and then rapidly pouring 200 g of ice-cooled distilled water at a low temperature into it. It is then shaken thoroughly for 5 min and the equilibrium mixture temperature is recorded. The heat balance equation is used to calculate the specific heat of grain as

$$C_p = \frac{W_{cw}(t_e - t_c) - W_e(t_g - t_e)}{W_g(t_g - t_e)}$$

where

C_p is the specific heat of grain, cal/(g °C) or kcal/(kg °C) or kJ/(kg °C)
W_g is the weight of grain, g or kg
t_g is the temperature of grain and calorimeter, °C
t_c is the temperature of cold distilled water, °C
t_e is the equilibrium temperature of the mixture, °C
W_e is the water equivalent of the flask calorimeter, g or kg

The various other methods of specific heat measurement are discussed by Rahaman (1995).

Thermal Conductivity

The thermal conductivity is defined as the amount of heat flow through unit thickness of material over a unit area per unit time for unit temperature difference. The thermal conductivity of the single grain varies from 0.3 to 0.6 kcal/(m·h °C), whereas the thermal conductivity of grains in bulk is about 0.10 to 0.15 kcal/(m·h °C), which is due to the presence of air space in it. The thermal conductivity of air is 0.02 kcal/(m·h °C) only.

Thermal conductivity of the single grain is three to four times greater than that of the grain bulk. In the case of wheat bulk, the moisture content ranging from 10% to 20% (dry bulb temperature) can be expressed as follows (Gerzhoi and Samochetov, 1958):

$$K = 0.060 + 0.002M \text{ kcal/(m} \cdot \text{h °C)}$$

where

K is the thermal conductivity
M is the moisture content (dry bulb temperature)

Thermal Conductivity Measurement

The thermal conductivity of a grain can be determined by the transient heat flow method using a thermal conductivity probe. The experimental setup and the procedure are explained next.

A thermal conductivity probe is placed in a sample holder equipped with a digital multimeter, a rheostat, a d.c. ammeter, and a 12 V storage battery. The thermal conductivity probe shown in Figure 1.5 consists of a 24 gauge iron–constantan wire of 300 mm length covered with teflon, which is used as a heater and housed in a hollow brass tube of 6.35 mm (1/4″) o.d. and a wall thickness of 1.59 mm (1/16″). The heater wire with a brass tube is centrally located in a cylindrical sample holder of 200 mm diameter and 300 mm height. The cylinder is made of 0.79 mm (1/32″) thick aluminum sheet. The ends of the sample holder are closed by 12.7 mm (1/2″) thick bakelite covers. The iron–constantan thermocouples are fixed; one at the middle point of the heater and the other

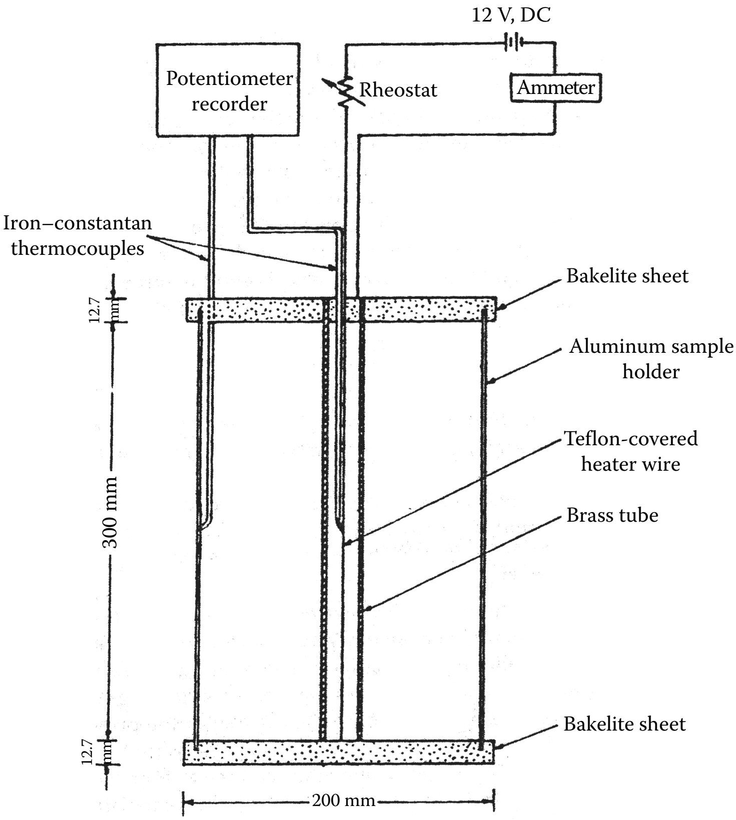


Figure 1.5 Schematic representation of a thermal conductivity probe.

to the inner wall of the sample holder to measure the temperatures at the said points. The heater is connected to the battery for the necessary power supply. The required strength of the current is adjusted with the help of a rheostat. An ammeter measures the current. The temperatures at the heater and the inside wall of the sample holder are recorded in terms of millivolts with a digital multimeter. The cold junction of the thermocouples is kept in an ice bath.

The moisture content of a grain sample is determined prior to the experiment by the standard oven drying method (105°C ± 2°C for 24 h). The resistance of the heating wire per unit length can be predetermined to be 2.0866 Ω/m (approximately). Similarly, a current of 1.25 A can be determined in preliminary trials to achieve a rise in temperature of the heater by 10°C–15°C in 10 min.

The sample holder is completely filled with the sample in an identical manner during each test to maintain the same bulk density.

A current of 1.25 A indicated by an ammeter is passed through the heater by adjusting the rheostat. The temperature of grain is recorded in terms of millivolts at every 30 s interval from the digital multimeter.

Thermal conductivity of a grain at a moisture content is calculated using the following equation:

$$K = \left\{ \frac{0.86\ I^2 R}{4\pi(t_2 - t_1)} \right\} \text{In} \left[\frac{\theta_2 - \theta_0}{\theta_1 - \theta_0} \right]$$

where

K is the thermal conductivity, kcal/h m °C
I is the current flow, A
R is the resistance of the line heater, Ω/m
θ_0 is the time correction factor, min
t_2 and t_1 are temperatures at θ_2 and θ_1 times, °C
θ_2 and θ_1 are times, min
0.86 is conversion factor from W to kcal

The thermal conductivity probe and an analysis of the method are detailed in Rao and Rizvi (1986).

Aerodynamic Properties

For designing air and water conveying and separating systems (i.e., pneumatic or hydrodynamic systems), the knowledge of aerodynamic and hydrodynamic properties of the agricultural products is necessary. In this connection, the knowledge of terminal velocities of different crops in a fluid is necessary.

The air velocity at which an object remains suspended in a vertical pipe under the action of the air current is called terminal velocity of the object.

Thus, in free fall, the object attains a constant terminal velocity, V_t, when the gravitational accelerating force, F_g, becomes equal to the resisting upward drag force F_r.

Hence, $F_g = F_r$ when $V = V_t$

$$\text{or} \quad W\left[\frac{\rho_v - \rho_f}{\rho_v}\right] = \frac{1}{2} c a_v \rho_f V_t^2$$

$$V_t = \left[\frac{2W(\rho_v - \rho_f)}{\rho_v \rho_f a_v c}\right]^{1/2}$$

where

V_t is the terminal velocity, m/s
W is the weight of the particle, kg
ρ_v and ρ_f are mass densities of the particles and fluids, (kg s^2)/m^4
a_v is the projected area of the particle perpendicular to the direction of motion, m^2
c is the overall drag coefficient (dimensionless)

Grains	*Terminal Velocity, m/s*
Wheat	9–11.5
Barley	8.5–10.5
Small oats	19.3
Corn	34.9
Soybeans	44.3
Rye	8.5–10.0
Oats	8.0–9.0

Resistance of Grain Bed to Airflow

In the design of blowers for grain dryers, it is necessary to know the resistance exerted by the grain bed to the air current blown through it. The resistance is dependent upon (a) the bed thickness, (b) the air velocity, (c) the orientation of the grains, and (d) the type of grains.

Additional details of all physical properties of agricultural products biomaterials are available in Mohsenin (1980) and Rahaman (1995).

Symbols

a_v	Projected area, m^2
C, C_p	Specific heat, kcal/(kg °C), or cal/(g °C) or kJ/(kg °C)
c	Drag coefficient, dimensionless
K	Thermal conductivity, kcal/(m h °C) or kW/(m °C)
m	Moisture content, percent (wet bulb temperature)
M	Moisture content, percent (dry bulb temperature)
φ_{AR}	Angle of repose, degree
ρ_v and ρ_f	Mass densities of particles and fluid, $(kg\ s^2)/m^4$
ρ_B	Bulk density, kg/m^3 or g/cc
ρ_t	True density, kg/m^3 or g/cc
V_t	Terminal velocity, m/s
W_t	Weight of particle, kg or g

Chapter 2

Psychrometry

Ambient air is a mixture of dry air and water vapor. Moist air is necessary in many unit operations. To work out such problems, it is essential to have knowledge of the amount of water vapor present in air under various conditions, the thermal properties of such a mixture, and changes in the heat and moisture contents as it is brought in contact with water or wet solid. Particularly in grain drying, the natural or heated air is used as a drying medium. Although the proportion of water vapor in air is small, it has a profound effect on the drying process.

Problems in air–water vapor mixture including heating, cooling, humidification, dehumidification, and mixing can be solved with the help of mathematical formulae. As these calculations are time-consuming, special charts containing the most common physical and thermal properties of moist air have been prepared and are known as psychrometric charts. The psychrometric chart is, therefore, a graphical representation of the physical and thermal properties of atmospheric air.

The different terms used to express the physical as well as other thermodynamic properties of air–water vapor mixture are defined and discussed here.

Humidity

The absolute humidity, H, is defined as kilograms of water vapor present in 1 kg of dry air under a given set of conditions.

H depends upon partial pressure of water vapor, p_w, in air and total pressure, P.

Therefore, H can be expressed mathematically as follows:

$$H = \frac{18 p_w}{29(P - p_w)} \tag{2.1}$$

When P = 1 atm (for psychrometry),

$$H = \frac{18 p_w}{29(1 - p_w)} \text{ kg/kg} \tag{2.2}$$

As per p_w is small,

$$H = \frac{18 p_w}{29} \tag{2.3}$$

Again, from Equation 2.1

$$H = \frac{p_w}{\frac{29}{18}(P - p_w)} = \frac{p_w}{1.611(P - p_w)} \tag{2.4}$$

Rearranging Equation 2.4

$$p_w = \left(\frac{1.611H}{1 + 1.611H}\right)P \tag{2.5}$$

Saturated air is the air in which water vapor is in equilibrium with the liquid water at a given set of temperature and pressure.

Percentage Humidity

It is the ratio of the weight of water present in 1 kg of dry air at any temperature and pressure and the weight of water present in 1 kg of dry air, which is saturated with water vapor at the same temperature and pressure:

$$\text{Percentage humidity} = \left(\frac{H}{H_s}\right) \times 100 \tag{2.6}$$

Relative Humidity

Relative humidity (RH) is defined as the ratio of the partial pressure of water vapor in the air to the partial pressure of water vapor in saturated air at the same temperature:

$$\text{RH} = \left(\frac{p_w}{p_s}\right) \times 100$$

The relation between percentage humidity and RH

$$\text{Percentage humidity} = \text{RH}\left(\frac{1-p_s}{1-p_w}\right) \tag{2.7}$$

Humid Heat

Humid heat is the number of kilocalories necessary to raise the temperature of 1 kg dry air and its accompanying water vapor through 1°C:

$$S = 0.24 + 0.45H,\ \text{kcal/(kg°C)}$$

$$= 1.005 + 1.88H,\ \text{kJ/(kg°C)} \tag{2.8}$$

Enthalpy

Enthalpy h' of an air and water vapor mixture is the total heat content of 1 kg of dry air plus its accompanying water vapor. If the datum temperature and pressure are 0°C and 1 atm, respectively, then the enthalpy at t°C for air and water vapor mixture is

$$h' = 0.24(t-0) + H[\lambda + 0.45\,(t-0)] = (0.24 + 0.45H)t + \lambda H\ \text{kcal/kg}$$

$$= (1.005 + 1.88H)t + \lambda H\ \text{kJ/kg} \tag{2.9}$$

Humid Volume

Humid volume, v, is the total volume in cubic meter of 1 kg dry air and its accompanying water vapor:

$$v = \frac{22.4}{29}\left(\frac{t+273}{273}\right) + \frac{22.4}{18}H\left(\frac{t+273}{273}\right)$$

$$= (22.4/273)\ (t+273)\left[\frac{1}{29} + \frac{H}{18}\right]$$

$$= (0.00283 + 0.00456H)\ (t+273)\ \text{m}^3/\text{kg} \tag{2.10}$$

Saturated Volume

Saturated volume is the volume of 1 kg of dry air plus that of the water vapor necessary to saturate it.

Dew Point

Dew point is the temperature at which a mixture of air and water vapor has to be cooled (at constant humidity) to make it saturated.

Wet Bulb Temperature

Under adiabatic condition, if a stream of unsaturated air, at constant initial temperature and humidity, is passed over wetted surface (which is approximately at the same temperature as that of air), then the evaporation of water from the wetted surface tends to lower the temperature of the liquid water. When the water becomes cooler than the air, sensible heat will be transferred from the air to the water. Ultimately, a steady state will be reached at such a temperature that the loss of heat from the water by evaporation is exactly balanced by the sensible heat passing from the air into the water. Under such conditions, the temperature of the water will remain constant and this constant temperature is called wet bulb temperature.

Wet Bulb Theory

By definition of wet bulb temperature,

$$q = (h_G + h_r)A\ (t_G - t_w) = \lambda_w 18\ K_G A(p_w - p_G) \tag{2.11}$$

where

- q is the sensible heat flowing from air to the wetted surface
- h_G is the heat transfer coefficient by convection from the air to the wetted surface, kcal/(h m^2 °C) or kW/(m^2 °C)
- h_r is the heat transfer coefficient corresponding to radiation from the surroundings, kcal/(h m^2 °C) or kW/(m^2 °C)
- t_G and t_w are the temperatures of air and interface, °C
- p_G and p_w are the partial pressures of water vapor in air and interface, atm
- A is the area of the wetted surface, m^2
- K_G is the mass transfer coefficient, kgmol/(h m^2 atm)
- λ_w is the latent heat of water vapor diffusing from the wetted surface to the air, kcal/kg or kJ/kg

Therefore,

$$p_w - p_G = \frac{h_G + h_r}{18\lambda_w K_G}(t_G - t_w)$$

$$\text{If } h_r = 0, \quad p_w = \frac{29H_w}{18} \quad \text{and} \quad p_G = \frac{29H_G}{18} \tag{2.12}$$

Then

$$H_w - H_G = \frac{h_G}{29\lambda_w K_G}(t_G - t_w) \tag{2.13}$$

The ratio h_G/K_G may be considered as constant. If the ratio h_G/K_G is constant, then Equation 2.13 can be used to determine the composition of the air–water vapor mixture from the observed values of t_G, the dry bulb temperature and t_w, the wet bulb temperature.

It is apparent from Equation 2.13 that the wet bulb temperature depends only upon the temperature and humidity of the air, provided h_r is negligible and h_G/K_G is constant.

It may be noted that the equation for the adiabatic cooling line is (Figure 2.2b)

$$H_s - H_G = \frac{s}{\lambda_s}(t_G - t_s) \tag{2.14}$$

where

t_s is the temperature of water
H_s is the saturated humidity
λ_s is the latent heat of evaporation at t_s
s is the humid heat

If $h_G/(29\ K_G) = s$, Equations 2.13 and 2.14 become identical. Fortuitously, for air–water vapor, $h_G/(29\ K_G) = s = 0.26$ at a humidity of 0.047. Therefore, under ordinary conditions the adiabatic cooling line can be used for wet bulb problems.

Introduction of Psychrometric Chart

Usually a psychrometric chart is prepared for 1 atm pressure, where humidities are plotted as ordinates against temperatures as abscissa. Any point on this chart represents the humidity and temperature of a given sample of air. The psychrometric chart is bound by an extreme left-hand curve representing humidities of saturated air (100% RH) and the horizontal *x*-axis giving various dry bulb temperatures (0% RH). The family of curved lines below the 100% RH line represents various percent RH as shown in Figure 2.1. Values of *H* for the saturation curve can be calculated by putting saturated pressure values from a steam table for different temperatures in Equation 2.4. The vapor pressure of water in air for different humidities is calculated by Equation 2.5 and added to the plot in the position shown in Figure 2.1. The oblique isovolume straight lines (humid volume lines) are plotted in the chart with steeper slopes than those of wet bulb lines. They are not exactly parallel. The humid volume at any temperature and humidity can be found from these lines. The humid volumes corresponding to these lines can be computed by Equation 2.10. The humid heat sometimes plotted

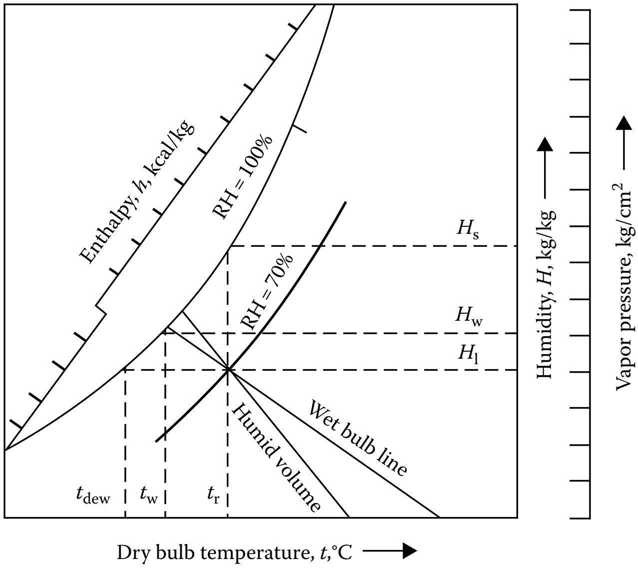


Figure 2.1 Introduction of psychrometric chart (1 atm) pressure.

against humidity can be calculated by Equation 2.8. The values of the enthalpy lines are usually indicated on a scale on the upper left-hand side of the chart. The wet bulb lines presented in the chart for different temperatures and humidities are actually adiabatic cooling lines. The straight wet bulb lines are inclined at angles of slightly unequal magnitudes.

Use of Psychrometric Chart

The psychrometric chart can be used to find out the following:

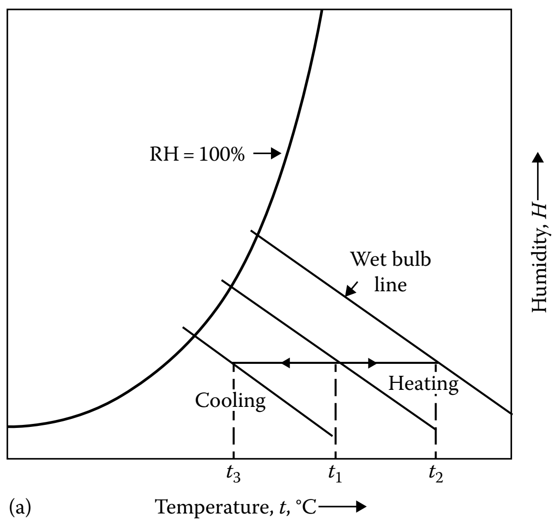
1. Dry bulb temperature
2. Wet bulb temperature
3. Dew point temperature
4. Absolute humidity
5. Relative humidity
6. Humid volume
7. Enthalpy

Any one of the aforementioned physical properties of air and water vapor mixture can be obtained from the psychrometric chart, provided two other values are known. Figure 2.1 shows that the meeting point of any two property lines represent the state point from which all other values can be obtained.

The following points may be noted from the psychrometric chart:

1. The t_G, t_w, and dew point temperatures are equal when RH is 100%.
2. The pressure of water vapor nearly doubles for each 10°C rise in temperature.
3. The rate of heat transfer from air to water (grain moisture) is proportional to $(t_G - t_w)$.

Psychrometric representation of several operations, namely, heating and cooling, drying, mixing, cooling, and dehumidification of moist air, is given in Figure 2.2a–d.



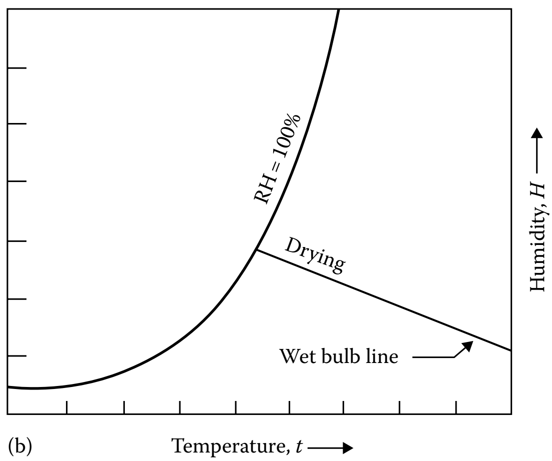


Figure 2.2 (a) Heating and cooling. (b) Adiabatic cooling/drying.

(*continued*)

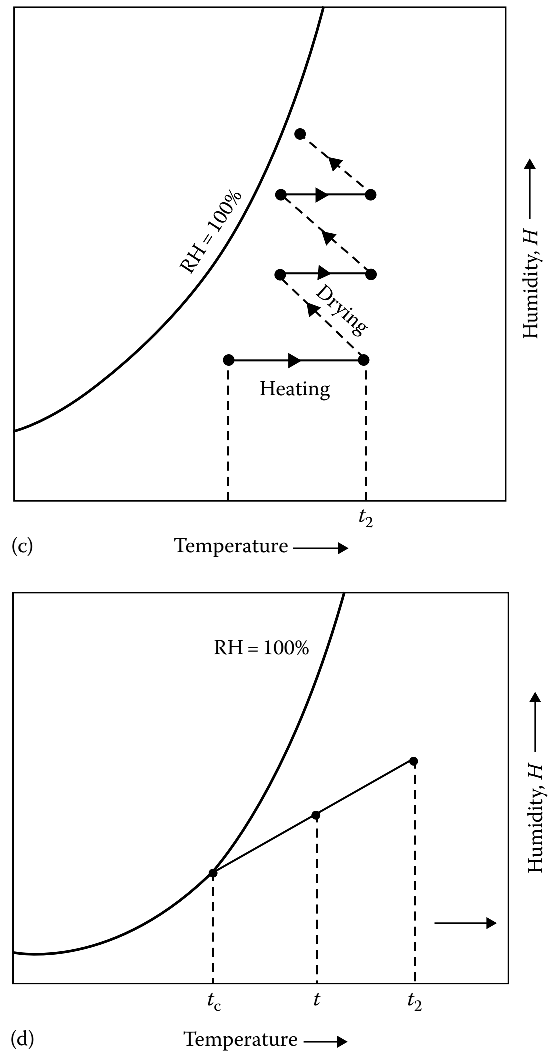


Figure 2.2 (continued) (c) Heating, drying, reheating, and recycling. (d) Cooling and dehumidifying.

Problems on Psychrometry

Solved Problems

1. Moist air at 25°C dry bulb and 45% RH is heated to 80°C. Calculate the humid volume, percentage humidity, and humid heat at the initial condition and check the results from chart. Find also the final condition of the air.

Data given

Initial condition: Dry bulb temperature = 25°C RH = 45%

Final condition = 80°C

From the psychrometric chart

Humid heat = 0.244 kcal/kg °C
Humid volume = 0.856 m^3/kg
Humidity = 0.009 kg/kg
Saturated humidity = 0.02 kg/kg

Percent humidity = $\frac{0.009}{0.02} \times 100 = 45\%$

Enthalpy = 11.5 kcal/kg = 11.5 × 4.184 = 48.12 kJ/kg

Final condition

Humid volume = 1.015 m^3/kg
Relative humidity = 3%
Enthalpy = 25.5 kcal/kg = 25.5 × 4.184

By calculation

$$\text{Humid heat} = 0.24 + 0.45H$$

$$= 0.24 + 0.45 \times 0.009 = 0.24405 \text{ kcal / kg}$$

$$\text{Humid volume} = (1.005 + 1.88 \times 0.009) = 0.022 \text{ kJ / kg}$$

$$= \frac{22.4}{273 \times 29}(t + 273) + \frac{22.44H}{273 \times 18}(t + 273)$$

$$= (0.00283 + 0.00455H)(t + 273)$$

When t = 25°C and H = 0.009 kg/kg

$$\text{Humid volume} = (0.00283 + 0.00455 \times 0.009) \times 298$$

$$= (0.00283 + 0.000041) \times 298$$

$$= 0.856 \text{ m}^3\text{/kg}$$

$$\text{Enthalpy} = (0.24 + 0.45H)t + \lambda H = (1.005 + 1.88H)t + \lambda H$$

$$= 0.24405 \times 25 + 598 \times 0.009 = 1.02 \times 25 + 2501.4 \times 0.009$$

[therefore, λ = 598 kcal/kg = 2501.4 kJ/kg]

Therefore, h = 11.48 kcal/kg = 48.06 kJ/kg.