

CHAPTER 1

Physico-Chemical Properties of Grains

A grain is a living biological product which germinates and respire also. The respiration process in the grain is externally manifested by the decrease in dry weight, utilisation 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) at 14 to 15 per cent moisture content which is called the critical point. On the other hand the rate of respiration increases with the increase of temperature 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 above five parts but an outer husk cover also. 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 which are very sensitive to heat. The endosperm, which 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 Figs. 1.1 to 1.4.

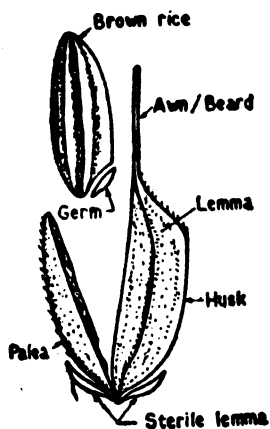


FIG. 1.1. Different Parts of Paddy.

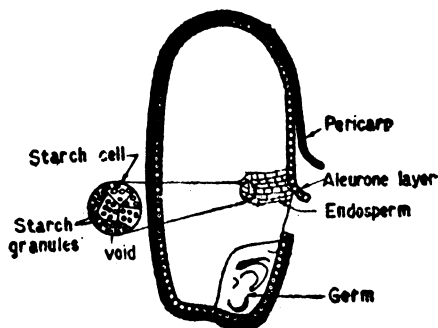


FIG. 1.1a. Structure of Brown Rice Kernel (Longitudinal Section).

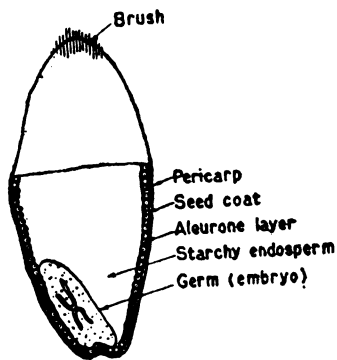


FIG. 1.2. Structure of wheat.

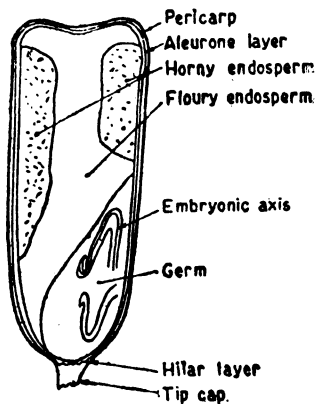


FIG. 1.3. Structure of shelled corn (Longitudinal section).

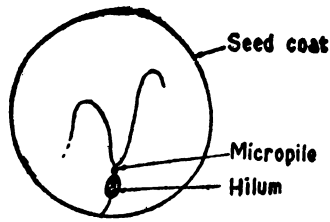


FIG. 1.4. Whole arhar pulses
(*Cajanus-Cajan*).

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, buck wheat seeds are specially rich in carbohydrates whereas legumes are rich in proteins and oil seeds rich in oils.

Generally, pericarp (and floral integuments also) contains 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, 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. The chemical compositions of different grains are given in Table 7 (Appendix).

Effects of temperature on the quality of grain

Proteins

The proteins present in cereal grains and in 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 decreases.

Starch

Starch is insoluble in cold water. It 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, gelatinisation and partial conversion of starch to dextrin take place. In addition, a partial caramelisation of sugars with the formation of caramel may take place which causes deterioration in colour of the product. These effects have been discussed in detail in Section II on Parboiling.

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 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 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.

Physical Properties

The knowledge of important physical properties such as shape, size, volume, surface area, density, porosity, colour, 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 sphere having same volume as that of the particle to the surface area of the particle. Sphericity is also defined as :

$$\text{sphericity} = \frac{d_i}{d_o}$$

where d_i = diameter of largest inscribed circle and d_o = diameter

of smallest circumscribed circle of the particle. The sphericity of different grains vary widely.

Porosity

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

Porosity of some crops are tabulated as follows :

Grain	Porosity per cent
Corn	40—45
Wheat	50—55
Paddy	48—50
Oats	65—70

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.

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 flowing capacities of different grains are different. It is characterised by the angle of natural slope (angle of repose).

The angle of repose is the angle between the base and the slope of the cone formed on a free vertical fall of the grain mass to a horizontal plane.

The angle of repose for a few important grains are tabulated as follows :

Grain	Angle of repose (degrees)
Wheat	23—28
Corn	30—40
Millet	20—25
Rye	23—28
Oats	31—44
Barley	28—40
Paddy	30—45

Thermal Properties

The 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, thermal diffusivity, is essential for the design of different thermal equipments and for solving 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 of its moisture content. It can be expressed as follows :

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

$$\text{or } c = \left(\frac{m}{100}\right) + \left(\frac{100-m}{100}\right) cd, \text{ kcal/(kg } ^\circ\text{C)}$$

where cd = specific heat of the bone dry grain ; c_w = specific heat of water ; and m = moisture content of the grain, per cent (w.b).

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

The above linear relationship between C and m exists above $m = 8$ per cent moisture content only (Gerzhoi, A.P., 1958).

The thermal conductivity is defined as the amount of heat flow through unit thickness of material over an 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.hr°C) whereas the thermal conductivity of grains in bulk is about 0.10 to 0.15 kcal/(m.hr°C) which is due to the presence of air space in it. The thermal conductivity of air is 0.02 kcal/(m. hr °C) only.

Thermal conductivity of the single grain is three to four times greater than that of the grain bulk. The thermal conductivity of the wheat bulk with moisture contents ranging from 10 to 20 per cent (d.b) can be expressed as follows (Gerzhoi, A. P., 1958).

$$K = 0.060 + 0.002 M \text{ kcal/(m. hr } ^\circ\text{C)}$$

where K = thermal conductivity

M = Moisture content (d.b).

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 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 in a suspended state 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, Fg becomes equal to the resisting upward drag force Fr .

Hence, $Fg = Fr$ when $V = V_t$

$$\text{or } W \left[\frac{\rho_p - \rho_t}{\rho_p} \right] = \frac{1}{2} C a_p \rho_t V_t^2$$

$$V_t = \left[\frac{2W(\rho_p - \rho_t)}{\rho_p \rho_t a_p C} \right]^{1/2}$$

V_t = terminal velocity, m/sec

W = weight of the particle, kg

ρ_p, ρ_t = mass density of the particles and fluids,

($\text{kg-sec}^2/\text{m}^4$)

a_p = projected area of the particle perpendicular to the direction of motion, m^2

C = overall drag coefficient (dimensionless).

Grains	Terminal velocity, m/sec
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 AIR FLOW

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) orientation of the grains, and (d) type of grain.

Symbols

a_p	Projected area, m^2
c	Specific heat, $\text{kcal}/(\text{kg}^\circ\text{C})$
C	Drag coefficient, dimension less
m	Moisture content, per cent (w.b.)
M	Moisture content, per cent (d.b.)
ρ_p, ρ_t	Mass density of particle and fluid, ($\text{kg} - \text{sec}^2$)/ m^4
V_t	Terminal velocity, m/sec
W	Weight of particle, kg
K	Thermal conductivity, $\text{kcal}/(\text{m hr}^\circ\text{C})$

CHAPTER 2

Psychrometry

Introduction

Ambient air is a mixture of dry air and water vapour. In many unit operations moist air is necessary. To work out such problems it is essential to have a knowledge of the amount of water vapour 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 vapour in air is small, it has a profound effect on the drying process.

Problems in air-water vapour mixture which include 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 and other thermodynamic properties of air-water vapour mixture are defined and discussed here.

Humidity

The absolute humidity, H is defined as kilogrammes of water vapour present in one kilogramme of dry air under a given set of conditions.

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

Therefore, H can be expressed mathematically as follows :

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

when $P = 1 \text{ atm}$ (for psychrometry).

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

As p_w is small,

$$H = \frac{18 p_w}{29} \quad (2.3)$$

Again from equation (2.1)

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

Rearranging, equation (2.4)

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

Saturated air is the air in which water vapour 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 vapour at the same temperature and pressure.

$$\text{Percentage humidity} = (H / H_s) \times 100 \quad (2.6)$$

Relative humidity

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

$$RH = (p_w / p_s) \times 100$$

The relation between percentage humidity and RH :

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

Humid heat

Humid heat is the number of kcal necessary to raise the

temperature of 1 kg dry air and its accompanying water vapour through 1° C.

$$S = 0.24 + 0.45H, \text{ kcal/kg/}^{\circ}\text{C} \quad (2.8)$$

Enthalpy

Enthalpy h' of an air and water vapour mixture is the total heat content of 1 kg of dry air plus its accompanying water vapour. If the datum temperature and pressure are 0° C and 1 atm respectively, then the enthalpy at $t^{\circ}\text{C}$ for air and water vapour mixture :

$$\begin{aligned} h' &= 0.24 (t-0) + H [\lambda + 0.45 (t-0)] \\ &= (0.24 + 0.45H)t + \lambda H \text{ kcal/kg} \end{aligned} \quad (2.9)$$

Humid volume

Humid volume, v is the total volume in cubic metre of 1 kg dry air and its accompanying water vapour.

$$\begin{aligned} v &= \frac{22.4}{29} \left(\frac{t+273}{273} \right) + \frac{22.4}{18} H \left(\frac{t+273}{273} \right) \\ &= (22.4/273)(t+273) \left[\frac{1}{29} + \frac{H}{18} \right] \\ &= (0.00283 + 0.00456 H)(t+273) \text{ m}^3/\text{kg} \end{aligned} \quad (2.10)$$

Saturated volume

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

Dew point

Dew point is the temperature to which a mixture of air and water vapour 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 a 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 = sensible heat flowing from air to the wetted surface
 = latent heat of water vapour diffusing from the wetted surface to the air, kcal/hr.

$$q = (h_g + h_r) A (t_g - t_w) = \lambda_w 18 K_G A (p_w - p_g) \quad (2.11)$$

where h_g = heat-transfer coefficient by convection from the air to the wetted surface, kcal/(hr m² °C),

h_r = heat-transfer coefficient corresponding to radiation from the surroundings, kcal/(hr m² °C),

t_g, t_w = temperatures of air and interface, °C,

p_g, p_w = partial pressure of water vapour in air and interface, atm,

A = area of the wetted surface, m²,

K_G = mass transfer coefficient, kg mole/hr m² atm,

λ_w = latent heat of water at t_w , kcal/kg

Therefore,

$$p_w - p_g = \frac{h_g + h_r}{18 \lambda_w K_G} (t_g - t_w) \quad (2.12)$$

If $h_r = 0$, $p_w = \frac{29H_w}{18}$ and $p_g = 29H_g/18$

Then

$$H_w - H_g = \frac{h_g}{29 \lambda_w K_G} (t_g - t_w) \quad (2.13)$$

The ratio h_g/K_G may be considered as constant. If the ratio h_g/K_G is constant, then the equation (2.13) can be used to determine the composition of the air-water vapour 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 (Fig. 2.2b) :

$$H_S - H_G = \frac{s}{\lambda_s} (t_G - t_S) \quad (2.14)$$

where t_S = temperature of water

H_S = saturated humidity

λ_s = latent heat of evaporation at t_S and

s = humid heat

If $h_g/K_g = s$, equations (2.13) and (2.14) become identical. Fortuitously for air-water vapour, $h_g/29 K_g = s = 0.26$ 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. In this chart 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 extreme left-hand curve representing humidities of saturated air (100 per cent RH) and the horizontal x -axis giving various dry bulb temperatures (0 per cent RH). The family of curved lines below the 100 per cent RH line represents various per cent RH. These are shown in Fig. 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 vapour pressure of water in air for different humidities is calculated by the equation (2.5) and is added to the plot in the position shown in Fig. 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 out from these lines. The humid volumes corresponding to these lines can be computed by the equation (2.10). The humid heat can be calculated by the equation (2.8) and is sometimes plotted against humidity. 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.

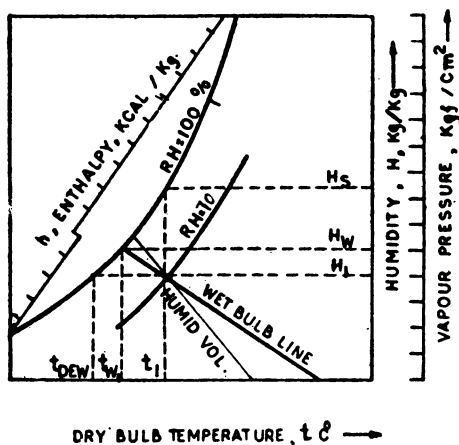


FIG. 2.1. Introduction of Psychrometric Chart (1 atm) pressure.

Use of psychrometric chart

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

- (a) dry bulb temperature,
- (b) wet bulb temperature,
- (c) dew point temperature,
- (d) absolute humidity,
- (e) relative humidity,
- (f) humid volume, and
- (g) enthalpy.

Any one of the above physical properties of air and water vapour 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 :

(a) The t_d , t_w and dew point temperatures are equal when RH is 100 per cent.

(b) The pressure of water vapour nearly doubles for each 10°C rise in temperature.

(c) The rate of heat transfer from air to the water (grain moisture) is proportional to $(t_a - t_w)$.

Psychrometric representation of several operations, namely, heating & cooling, drying, mixing, cooling and dehumidification of moist air are given in Figs 2.2a to 2.2e.

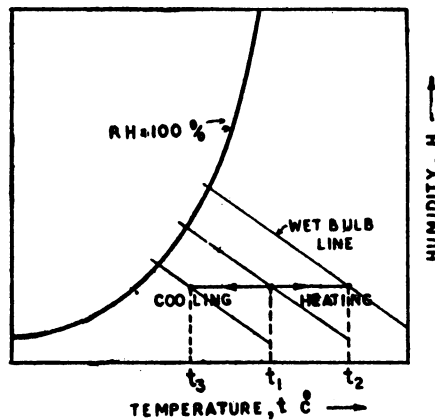


FIG. 2.2a. Heating and Cooling.

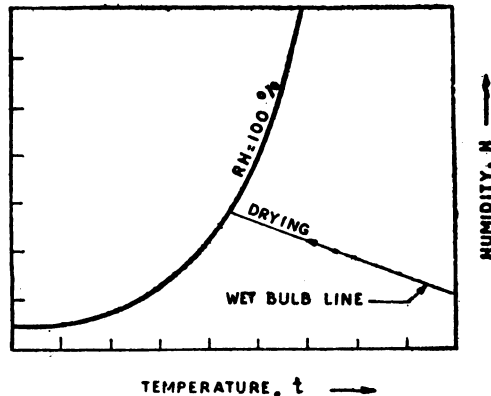


FIG. 2.2b. Adiabatic Cooling/Drying.

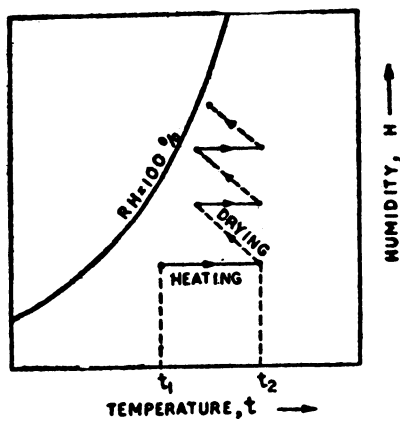


FIG. 2.2c. Heating, drying, reheating and recycling.

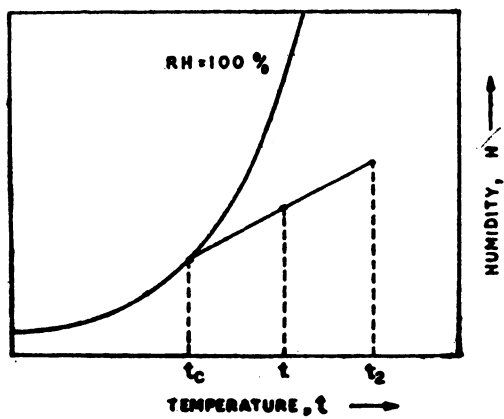


FIG. 2.2d. Cooling and dehumidifying.

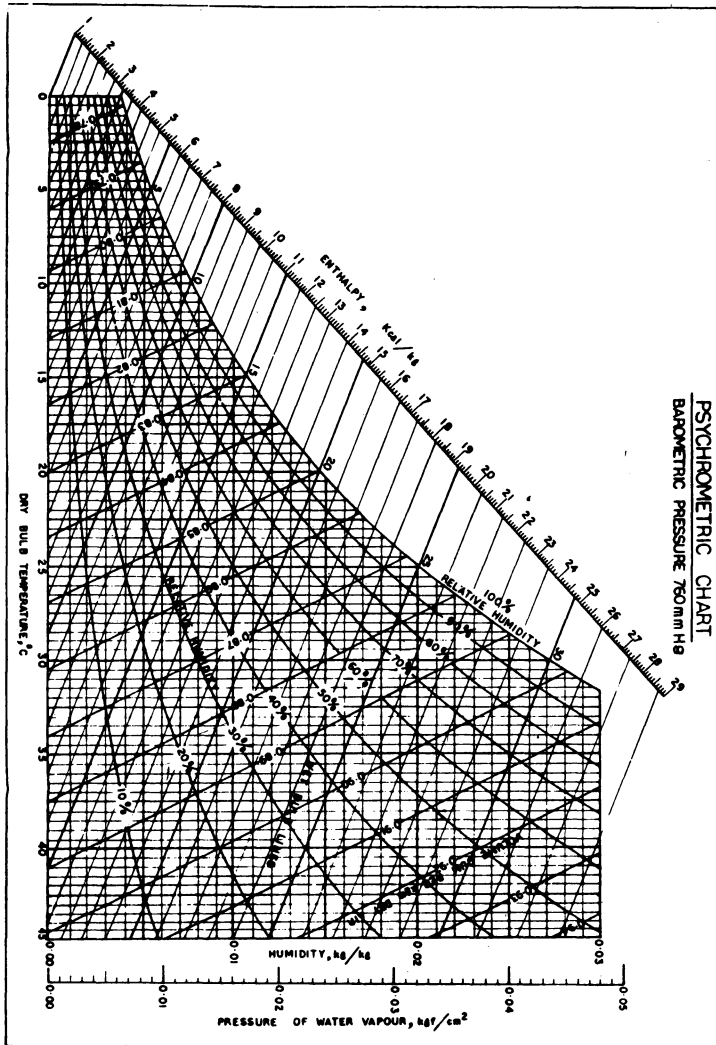


FIG. 2.3. Humidity—temperature diagram (psychrometric chart).

Problems on Psychrometry

SOLVED PROBLEMS

(1) Moist air at 25° C dry bulb and 45 per cent relative humidity 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 psychrometric chart

Humid heat = 0.244 kcal/kg° C

Humid volume = 0.856 m³/kg

Humidity = 0.009 kg/kg

Saturated humidity = 0.02 kg/kg

Per cent humidity = $\frac{0.009}{0.02} \times 100 = 45$ per cent

Enthalpy = 11.5 kcal/kg

Final Condition

Humid volume = 1.015 m³/kg

Relative humidity = 3 per cent

Enthalpy = 25.5 kcal/kg

By calculation

Humid heat = $0.24 + 0.45 H$
 $= 0.24 + 0.45 \times 0.009 = 0.24405$

Humid Volume

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

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

When $t = 25^\circ \text{C}$ and $H = 0.009 \text{ kg/kg}$

Humid volume = $(0.00283 + 0.00455 \times 0.009) \times 298$
 $= (0.00283 + 0.000041) \times 298$
 $= 0.856 \text{ m}^3/\text{kg}$

Enthalpy = $(0.24 + 0.45H)t + \lambda H$
 $= 0.24405 \times 25 + 580 \times 0.009$

$$[\because \lambda = 580 \text{ kcal/kg}]$$

$$\text{Therefore } h = 11.4 \text{ kcal/kg}$$

(2) In a grain dryer, one stream of air at $50 \text{ m}^3/\text{min}$ at 25° C and 23° C W.B. , is mixed with another air stream at $50 \text{ m}^3/\text{min}$ at 60° C and 52° C W.B. temperatures.

Determine the D.B. and W.B. temperatures of the mixture.

Solution

Stream = 1

Rate of flow = $50 \text{ m}^3/\text{min}$

Dry bulb temperature = 25° C

Wet bulb temperature = 23° C

From the psychrometric chart

Enthalpy = 16.5 kcal/kg

Humid volume = $0.866 \text{ m}^3/\text{kg}$

$$\text{Therefore, } m_1 = \frac{50}{0.866} = 57.7 \text{ kg/min.}$$

Stream = 2

Rate of flow = $50 \text{ m}^3/\text{min}$

D.B. temperature = 60° C

W.B. temperature = 52° C

From the chart

Enthalpy = 72.5 kcal/kg

Humid volume = $1.084 \text{ m}^3/\text{kg}$

$$\text{Therefore, } m_2 = \frac{50}{1.084} = 46.12 \text{ kg/min}$$

We know that

$$\frac{m_1}{m_2} = \frac{h_2 - h_3}{h_3 - h_1}$$

$$\frac{57.7}{46.12} = \frac{72.5 - h_3}{h_3 - 16.5}$$

Therefore, enthalpy of the final mixture state :

$$h_3 = 41.38 \text{ kcal/kg.}$$

From the psychrometric chart

Dry bulb temperature = 41° C

Wet bulb temperature = 40.75° C

(3) The air to be used in a dryer at a dry bulb temperature of 26.66°C and wet bulb temperature 21.1°C is heated to 71.1°C and blown into the dryer. In the dryer it cools along an adiabatic cooling line and leaves the dryer fully saturated. Find the dew point temperature at the initial condition, absolute humidity of initial air, percentage humidity of initial air, amount of heat needed to heat $2.8\text{ m}^3/\text{min}$ of entering air and temperature of the air leaving the dryer.

Solution

Data supplied:

Dry bulb temperature = 26.66°C

Wet bulb temperature = 21.10°C

Heated to = 71.10°C

Volume of air entering = $2.8\text{ m}^3/\text{min}$

From Psychrometric chart

(1) Dew point temperature = 18°C

(2) Humidity Ratio, $H = 0.0132\text{ kg/kg}$

(3) Saturated humidity, $H_s = 0.022\text{ kg/kg}$

(4) Percent $H = \frac{H}{H_s} \times 100 = \frac{0.0132}{0.022} \times 100 = 60\text{ per cent}$

(5) Relative humidity at initial condition = $RH = 64\%$

(6) Initial humid volume, $v = 0.867\text{ m}^3/\text{kg dry air}$ (at $H = 0.0132$)

(7) Temperature of air leaving dryer = 31.8°C

(8) Amount of heat needed to heat = $2.8\text{ m}^3/\text{min}$

$$\frac{\text{Volume of air}}{\text{Humid volume}} \times \Delta t \times \text{humid heat}$$

Humid heat

$$\begin{aligned} s &= 0.24 + 0.45 H \\ &= 0.24 + 0.45 \times 0.0132 \\ &= 0.24 + 0.0058 \\ &= 0.246\text{ kcal/kg}^{\circ}\text{C} \end{aligned}$$

$$\begin{aligned} \text{Hence, heat required} &= \frac{2.8}{0.867} \times (71.11 - 26.66) \times 0.246 \\ &= 35.3\text{ kcal/min} \end{aligned}$$

Exercises

(1) The air supply for a dryer has a dry bulb temperature of 27°C and wet bulb temperature of 21°C . It is heated to 94°C and blown it through the dryer and in the dryer it cools along adiabatic line and leaves the dryer saturated. Find the following :

Dew point temperature of the initial air

Absolute humidity of the initial air

Percentage humidity.

Amount of heat needed to heat $100\text{ m}^3/\text{min}$ entering air.

Temperature of the air leaving the dryer.

(2) Temperature and dew point of the air entering a dryer are 70°C and 26°C . What additional data can be obtained from the psychrometric chart ?

(3) Air is heated by a heating system from 30°C , 80 per cent RH to 60°C . Find out the relative humidity wet bulb temperature, dew point temperature of the heated air. Determine the quantity of heat added per kg. of dry air.

(4) The dry bulb and wet bulb temperatures of an air supply are 60°C and 40°C respectively. Calculate the Relative humidity, Humid volume, dew point temperature, and enthalpy at 60°C and check the answers by psychrometric chart.

(5) A grain dryer requires $300\text{ m}^3/\text{min}$ of heated air at 45°C . The atmospheric air is at 24°C and 80 per cent relative humidity. Calculate the amount of heat required per hour to raise the air temperature from 24°C to 45°C . Check the answer with the help of the psychrometric chart.

SYMBOLS

A	Area, m^2
H, H_g, H_w, H_s	Humidity, humidity at dry bulb temperature, humidity at wet bulb temperature, and saturation humidity respectively, kg/kg
h_o	Heat transfer coefficient, $\text{kcal}/(\text{hr m}^2\text{ }^{\circ}\text{C})$
h_r	Heat transfer coefficient equivalent to radiation, $\text{kcal}/(\text{hr m}^2\text{ }^{\circ}\text{C})$
h_i	Enthalpy, kcal/kg
K_o	Mass transfer coeff. $\text{kg mole}/(\text{hr m}^2\text{ atm})$

P	Total pressure, atm
p_q	Partial pressure of water vapour in air, atm
p_w	Partial pressure of water vapour in air at the interface, atm
q	Rate of heat transfer, kcal/hr
s	Humid heat, kcal/(kg °C)
RH	Relative humidity, per cent
t_a, t_w, t_d	Dry bulb, wet bulb and dew point temperatures respectively, °C
t_s	Temperature of water, °C
v	Humid volume, m ³ /kg.
λ	Latent heat of evaporation of water, kcal/kg.

CHAPTER 3

Theory of Grain Drying

Generally the term drying refers to the removal of relatively small amount of moisture from a solid or nearly solid material by evaporation. Therefore, drying involves both heat and mass transfer operations simultaneously. In convective drying the heat required for evaporating moisture from the drying product is supplied by the external drying medium, usually air. Because of the basic differences in drying characteristics of grains in thin layer and deep bed, the whole grain drying process is divided into thin layer drying and deep bed drying.

THIN LAYER DRYING

Thin layer drying refers to the grain drying process in which all grains are fully exposed to the drying air under constant drying conditions, i.e., at constant air temperature, and humidity. Generally, up to 20 cm thickness of grain bed (with a recommended air-grain ratio) is taken as thin layer. All commercial flow dryers are designed on thin layer drying principles.

The process of drying should be approached from two points of view : the equilibrium relationship and the drying rate relationship.

For convenience, a few terms used in describing the drying process are defined and discussed.

Moisture content

Usually the moisture content of a substance is expressed in percentage by weight on wet basis. But the moisture content on dry basis is more simple to use in calculation as the quantity

of moisture present at any time is directly proportional to the moisture content on dry basis.

The moisture content, m , per cent, wet basis is :

$$m = \frac{W_m}{W_m + W_d} \times 100 \quad (3.1)$$

where W_m = weight of moisture and W_d = weight of bone dry material.

The moisture content, M , dry basis, per cent is :

$$M = \frac{W_m}{W_d} \times 100 = \frac{m}{100 - m} \times 100 \quad (3.2)$$

The moisture content, X , dry basis is sometimes expressed in decimal also :

$$X = \frac{M}{100} \quad (3.3)$$

Two additional useful equations for moisture content are given below for the calculation of the following :

$$\frac{W'_m}{W_1} = \frac{m_1 - m_2}{100 - m_2} = \frac{M_1 - M_2}{100 + M_1} \quad (3.3a)$$

$$\frac{W'_m}{W_2} = \frac{m_1 - m_2}{100 - m_1} = \frac{M_1 - M_2}{100 + M_2} \quad (3.3b)$$

Where W_1 = Initial weight of wet material = $(W_m + W_d)$ kg

W_2 = Final weight of dried product, kg

W'_m = Weight of moisture evaporated, kg

m_1, m_2 = Initial and final moisture contents respectively,
per cent, wet basis

M_1, M_2 = Initial and final moisture contents respectively,
per cent, dry basis.

Moisture measurement

Moisture content can be determined by direct and indirect methods. Direct method includes air-oven drying method ($130^\circ \pm 2^\circ$ C) and distillation method. Direct methods are simple and accurate but time consuming whereas indirect methods are convenient and quick but less accurate.

DIRECT METHODS

The air-oven drying method can be accomplished in a single stage or double stage in accordance with the grain samples

containing less than 13 per cent or more than 13 per cent moisture content (Hall, 1957).

Single stage method

Single stage method consists of the following steps :

- (a) Grind 2-3 gm sample.
- (b) Keep the sample in the oven for about 1 hour at $130^{\circ} \pm 2^{\circ}$ C.
- (c) Place the sample in a dessicator and then weigh. The samples should check within 0.1 per cent.

Double stage method

(a) In this method keep 25-30 gm whole grain sample in the air oven at $130^{\circ} \pm 2^{\circ}$ C for 14-16 hours so that its moisture content is reduced to about 13 per cent.

(b) Then follow the same procedure as in single stage method.

Other methods

Place the whole grain sample in the air-oven at $100^{\circ} \pm 2^{\circ}$ C for 24 to 36 hours depending on the type of grain and then weigh.

The vacuum oven drying method is also used for the determination of moisture content.

However, moisture determination should be made according to the standard procedure for each grain which is laid down by the Government or by the Association of Agricultural Chemists.

Brown-Duvel distillation method

The distillation method directly measures the volume of moisture, in cc condensed in a measuring cylinder by heating a mixture of 100 gm grain and 150 cc oil in a flask at 200° C for 30 to 40 minutes.

Moisture content can be measured by the toluene distillation method also.

INDIRECT METHODS

Indirect methods are based on the measurement of a property of the grain that depends upon moisture content.

Two indirect methods are described as follows :

Electrical resistance method

Resistance type moisture meter measures the electrical resistance of a measured amount of grain sample at a given compaction (bulk density) and temperature. The electrical resistance varies with moisture, temperature and degree of compaction.

The universal moisture meter (U.S.A.), Tag-Happenstall moisture meter (U.S.A) and Kett moisture meter (Japan) are some of the resistance type moisture meters. They take only 30 seconds for the moisture measurement.

Dielectric method

The dielectric properties of grain depend on its moisture content. In this type of moisture meter, 200 gm grain sample is placed between the condenser plates and the capacitance is measured. The measured capacitance varies with moisture, temperature and degree of compaction.

The Motomco moisture meter (U.S.A) and Burrows moisture recorder (U.S.A.) are some of the capacitance type of moisture meters. They take about 1 minute for the measurement of moisture. These are also known as safe crop moisture testers as they do not damage the grain sample.

Equilibrium moisture content

When a solid is exposed to a continual supply of air at constant temperature and humidity, having a fixed partial pressure of the vapour, p the solid will either lose moisture by evaporation or gain moisture from the air until the vapour pressure of the moisture of the solid equals p . The solid and the gas are then in equilibrium, and the moisture content of the solid in equilibrium with the surrounding conditions is known as equilibrium moisture content E.M.C. (Fig. 3.1). The E.M.C. is useful to determine whether a product will gain or lose moisture under a given set of temperature and relative humidity conditions. Thus E.M.C. is directly related to drying and storage. Different materials have different equilibrium moisture contents. The E.M.C. is dependent upon the temperature and relative humidity of the environment and on the variety and maturity of the grain. The E.M.C. of different grains at different temperatures and humidity-

tics are given in Table I (Appendix). A plot of the equilibrium relative humidity and moisture content of a particular material

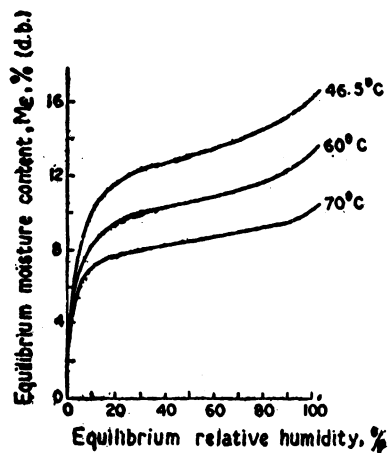


FIG. 3.1. Desorption isotherms for
Patnai-23 variety of paddy.
(Kachrew, R. P. *et al.*, 1971)

at a particular temperature (usually 25° C) is known as equilibrium moisture curve or isotherm. Grain isotherms are generally S-shaped and attributed to multi-molecular adsorption.

DETERMINATION OF EQUILIBRIUM MOISTURE CONTENT

Generally E.M.C. is determined by two methods : (a) the static method, and (b) the dynamic method. In the static method, the grain is allowed to come to equilibrium with the surrounding still air without any agitation, whereas in the dynamic method, the air is generally mechanically moved. As the static method is time consuming, at high relative humidities mould growth in the grain may take place before equilibrium is reached. The dynamic method is faster and is thus preferred. The E.M.C. is to be determined under constant relative humidity and temperature conditions of air. Generally a thermostat is used to control the temperature and aqueous acid or salt solutions of different concentrations are used to control the relative humidity of air.

E.M.C. Models

A number of E.M.C. equations namely BET equation (1938), Harkin and Jura equation (1944), Smith equation (1947), Henderson equation (1952), Chung and Fost equation (1967), etc., have been developed for different ranges of relative humidities. A few purely empirical E.M.C. equations namely Haynes equation (1961), Baker and Arkema equation (1974), etc., have also been proposed for different ranges of relative humidities for different cereal grains. Of them Henderson's equation is well known and discussed here :

Using Gibb's adsorption equation, Henderson (1952) developed the following equation to express the equilibrium moisture curve mathematically :

$$1 - RH = \exp [-cTM_e^n] \quad (3.4)$$

Where RH = equilibrium relative humidity, decimal

M_e = E.M.C., dry basis, per cent

T = temperature, °K and

c and n = product constants, varying with materials.

Values of c and n for some grains are given in Table 'II (Appendix).

But Henderson's equation has been found to be inadequate for many cereal grains. A few useful empirical modified forms of Henderson equation for different cereal grains are given as follows :

Day and Nelson (1965) proposed the following equation for wheat :

$$1 - (p'_g/p'_s) = \exp [-J'M_e^{K'}] \quad (3.5)$$

where $J' = 4.1605 \times 10^{-9}(t+17.78)^{5.3718}$

$$K' = 11.6300(t+17.78)^{-0.41783}$$

Thompson (1965) proposed the following E.M.C. equation for corn :

$$\begin{aligned} 1 - (p'_g/p'_s) &= \exp [-3.8195 \times 10^{-5}(1.8t+82)M^2] \\ &= \exp [-6.875 \times 10^{-5}(t+45.55)M^2] \end{aligned} \quad (3.6)$$

Hysteresis

Many solid materials including cereal grains exhibit different equilibrium moisture characteristics depending upon whether the equilibrium is reached by adsorption/sorption or desorption of

the moisture. This phenomenon is known as hysteresis which is shown in Fig. 3.2.

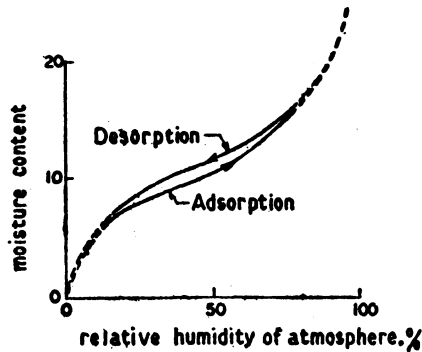


FIG. 3.2. Relation between equilibrium moisture content of paddy and relative humidity showing hysteresis.

Bound moisture

This refers to the moisture contained by a substance which exerts equilibrium vapour pressure, less than that of the pure liquid at the same temperature (Fig. 3.3). The bound moisture may be contained inside the cell walls of the plant structure, moisture in loose chemical combination with the cellulosic material, moisture held in small capillaries and crevasses throughout the solid.

Unbound moisture

This refers to the moisture contained by a substance which exerts equilibrium vapour pressure equal to that of the pure liquid at the same temperature (Fig. 3.3).

Free moisture

Free moisture is the moisture contained by a substance in excess of the equilibrium moisture, $X - X_e$ (Fig. 3.3). Only free moisture can be evaporated and the free water content of a solid depends upon the vapour concentration in the air.

The above relations are shown in Fig. 3.3 for a solid of moisture content X exposed to air of relative humidity RH .

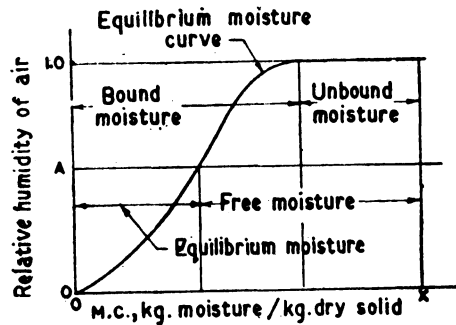


FIG. 3.3. Types of moisture.

A typical drying curve is shown in Fig. 3.4. The figure clearly shows that there are two major periods of drying, namely, the constant-rate period and the falling-rate period.

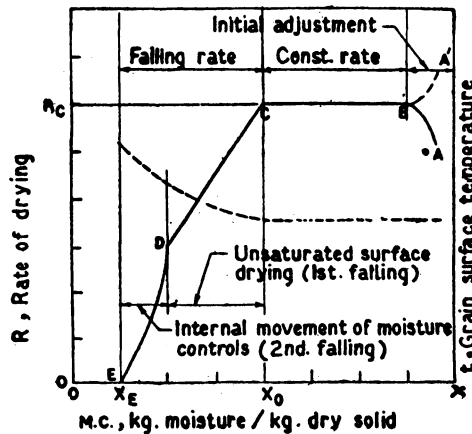


FIG. 3.4. Typical drying rate curve, constant drying condition.

The plots of moisture content versus drying time or drying rate versus drying time or drying rate versus moisture content are known as drying curves (Figs. 3.4 to 3.8)

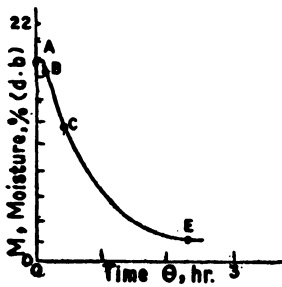


FIG. 3.5. Moisture content versus drying time.

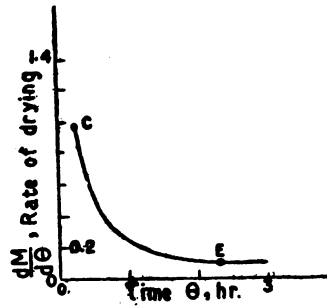


FIG. 3.6. Drying rate versus drying time.

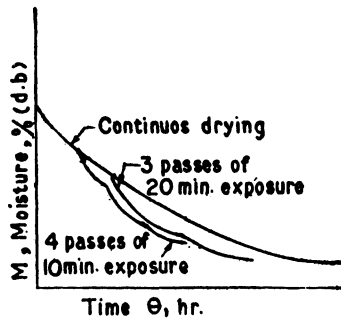


FIG. 3.7. Effects of tempering on intermittent drying.

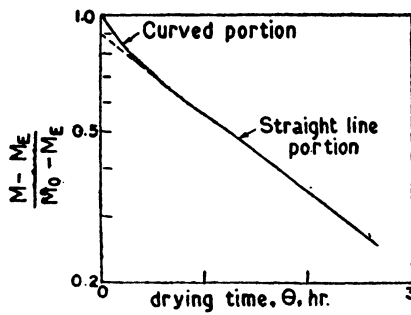


FIG. 3.8. Relation between moisture ratio and drying time.

Constant-rate period

Some crops including cereal grains at high moisture content are dried under constant-rate period at the initial period of drying. Falling-rate period follows subsequently. As for example, wheat is dried under constant-rate period when its moisture content exceeds 72%.

In the constant-rate period the rate of evaporation under any given set of air conditions is independent of the solid and is essentially the same as the rate of evaporation from a free liquid surface under the same condition. The rate of drying during this period is dependent upon : (a) difference between the temperature of air and temperature of the wetted surface at constant air velocity and relative humidity, (b) difference in humidity between air stream and wet surface at constant air velocity and temperature, and (c) air velocity at constant air temperature and humidity.

Under adiabatic and controlled drying air conditions, the temperature of the wetted surface attains the wet bulb temperature. In the constant-rate period drying takes place by surface evaporation and moisture moves by vapour pressure difference. The moisture content at which the drying rate ceases to be constant is known as the critical moisture content of the solid. The average critical moisture content, X_c for a given type of material depends upon the surface moisture concentration, bed thickness of the material and rate of drying. The critical moisture content of a product also depends upon the characteristics of the solid such as shape, size and the drying conditions.

If the drying takes place entirely within the constant-rate period so that $X_1, X_2 > X_c$.

Then by definition, $R = -\frac{W_d}{A} \frac{dX}{d\theta}$.

Separating the variables and integrating the equation within proper limits, we get :

$$\text{time of drying, } \theta_c = \frac{W_d}{A} \left(\frac{X_1 - X_2}{R_c} \right), \quad (3.7)$$

where W_d = Weight of dry solid kg, *

A = Wet surface, m^2

X_1 = Initial moisture content, kg moisture/kg dry solid

X_2 = Final moisture content, kg/kg

X_c = Critical moisture content, kg/kg

R_c = Rate of drying in the constant rate period,
kg moisture evaporated/(hr m²)

θ_c = drying time, hr.

The constant drying rate of a crop can also be expressed as follows by use of wet bulb temperature theory :

$$\frac{dw}{d\theta} = 18 k A (p_s - p_a) = h_{fa} A (t_a - t_s) / \lambda_s \quad (3.8)$$

where

$\frac{dw}{d\theta}$ = constant rate of drying, kg/hr,

p_a, p_s = Water vapour pressures at t_a and t_s respectively,
atm

t_a, t_s = air and water temperature respectively, ° C,

h_{fa} = film heat transfer coefficient of air at air-water
interface, kcal/hr m² ° C,

λ_s = latent heat of water at t_s , kcal/kg,

A = water surface area, m²

k = water vapour transfer coefficient at the water-air
interface, kgmole/(hr m² atm)

Falling-rate period

Cereal grains are usually dried entirely under falling-rate period.

The falling-rate period enters after the constant drying rate period and corresponds to the drying cycle where all surface is no longer wetted and the wetted surface continually decreases, until at the end of this period the surface is dry. The cause of falling off in the rate of drying is due to the inability of the moisture to be conveyed from the centre of the body to the surface at a rate comparable with the moisture evaporation from its surface to the surroundings.

The falling-rate period is characterised by increasing temperatures both at the surface and within the solid. Furthermore,

changes in air velocity have a much smaller effect than during the constant-rate period. The falling-rate period of drying is controlled largely by the product and is dependent upon the movement of moisture within the material from the centre to the surface by liquid diffusion and the removal of moisture from the surface of the product.

The falling-rate period of drying often can be divided into two stages : (a) unsaturated surface drying, and (b) drying where the rate of water diffusion within the product is slow and is the controlling factor. Practically all cereal grains are dried under falling-rate period if their moisture contents are not very high.

Many theories have been proposed to describe the moisture movement phenomena in cereal grains. Of them, the following are most popular :

- (1) Liquid movement due to moisture concentration differences (liquid diffusion surface) ;
- (2) Liquid movement due to surface forces (capillary flow) ;
- (3) Liquid movement due to moisture diffusion in the pores (surface diffusion) ;
- (4) Vapour movement due to differences in vapour pressures (vapour diffusion) ;
- (5) Vapour movement due to temperature differences (thermal diffusion) ; and
- (6) Liquid and vapour movement due to total pressure differences (hydrodynamic flow).

DRYING EQUATIONS

(A) On the basis of the above mechanisms Luikov et al. (1966) developed mathematical models to describe the drying of capillary porous products as follows :

$$\frac{\delta M}{\delta \theta} = \nabla^2 K_{11}M + \nabla^2 K_{12}t + \nabla^2 K_{13}P \quad (3.9)$$

$$\frac{\delta t}{\delta \theta} = \nabla^2 K_{21}M + \nabla^2 K_{22}t + \nabla^2 K_{23}P \quad (3.10)$$

$$\frac{\delta P}{\delta \theta} = \nabla^2 K_{31}M + \nabla^2 K_{32}t + \nabla^2 K_{33}P \quad (3.11)$$

where K_{11} , K_{22} , K_{33} are the phenomenological coefficients and the other K terms are the coupling coefficients which resulted from the combined effects of moisture, temperature and pressure.

In grain drying analyses the effects of total pressure and temperature gradients need not be considered. Therefore, the final simplified Luikov's equation will be of the form :

$$\frac{\delta M}{\delta \theta} = \nabla^2 K_{11} M \quad (3.12)$$

If it is accepted that the movement of moisture takes place by liquid or vapour diffusion, then the transfer coefficient K_{11} may be replaced by the diffusion coefficient D_v .

If D_v is taken as constant, then the equation (3.12) can be written as :

$$\frac{\delta M}{\delta \theta} = D_v \left[\frac{\delta^2 M}{\delta r'^2} + \frac{c'}{r'} \frac{\delta M}{\delta r'} \right] \quad (3.13)$$

where $c' = 0$ for planar symmetry, $c' = 1$ for cylindrical body and $c' = 2$ for sphere.

Under the following boundary conditions :

$$M(r', 0) = M_o \text{ (IMC)}, \text{ and } M(r_o', \theta) = M_e \text{ (EMC)},$$

the solutions of equation (3.13) are as follows :

$$\frac{M - M_e}{M_o - M_e} = \frac{8}{\pi^2} \sum_{n'=0}^{\infty} \frac{1}{(2n'+1)^2} \exp \left[-\frac{(2n'+1)^2 \pi^2}{4} X'^2 \right] \quad (3.14)$$

for infinite plane

$$\frac{M - M_e}{M_o - M_e} = \frac{6}{\pi^2} \sum_{n'=1}^{\infty} \frac{1}{n'^2} \exp \left[-\frac{n'^2 \pi^2}{9} X'^2 \right] \quad (3.15)$$

for sphere

$$\frac{M - M_e}{M_o - M_e} = \sum_{n'=1}^{\infty} \frac{4}{\lambda_n'^2} \exp \left[-\frac{\lambda_n'^2}{4} X'^2 \right] \quad (3.16)$$

for infinite cylinder

where λ_n' are the roots of the Bessel function of zero order,

$$X' = \frac{A}{V} (D_v \theta)^{1/2},$$

A = surface area,

V = Volume of the body,

$$\frac{A}{V} = \frac{1}{\text{half thickness}} \text{ for plane,}$$

$$\frac{A}{V} = \frac{3}{\text{radius}} \text{ for sphere and}$$

$$\frac{A}{V} = \frac{2}{\text{radius}} \text{ for cylinder.}$$

(B) If the moisture contents X_1 and X_2 are both less than X_c so that drying occurs under conditions changing R , (i.e., under falling-rate period) the drying time in this period may be expressed as follows :

The rate of drying is by definition :

$$R = -\frac{W_a}{A} \int \frac{dX}{d\theta}$$

Rearranging and integrating over the time interval while the moisture content changes from its initial value X_1 to its final value X_2 :

$$\theta_f = \int_0^{\theta_f} d\theta = \frac{W_a}{A} \int_{X_1}^{X_2} \frac{dX}{R} \quad (3.17)$$

General case : For any shape of falling-rate curve equation (3.17) may be integrated graphically by determining the area under a curve of $1/R$ as ordinate, X as abscissa, the data for which may be obtained from the rate of drying curve.

(C) Based on Newton's equation for heating or cooling of solids, a simple drying equation can be derived as follows :

$$\text{The Newton's equation is } \frac{dt}{d\theta} = -K(t - t_e).$$

If the temperature term t is replaced by the moisture term M ,

$$\text{then } \frac{dM}{d\theta} = -K(M - M_e) \quad (3.18)$$

where M = Moisture content (d.b.), %

θ = time, hr,

M_e = EMC, (d.b.), %

K = drying constant, 1/hr.

Rearranging the equation (3.18) :

$$\frac{dM}{M - M_e} = -K d\theta$$

Integrating the above equation within proper limits, we get :

$$\frac{M - M_e}{M_o - M_e} = \exp [-K\theta] \quad (3.19)$$

$$\text{or } \theta = \frac{1}{K} \ln \frac{M_o - M_e}{M - M_e} \quad (3.20)$$

$\frac{M - M_e}{M_o - M_e}$ is known as the moisture ratio, M.R.

(D) The similar form of the equations (3.14) and (3.15) can be derived assuming concentration difference as the driving force in diffusion of liquid through solid :

$$\frac{\partial C}{\partial \theta} = D_v \frac{\partial^2 C}{\partial x^2} \quad (3.21)$$

where D_v = Diffusivity, m^2/hr

C = Concentration, θ = time, hr

x = Distance from the Centre of the material, m

If the concentration term be replaced by the moisture content term, M , the above equation will be of the form :

$$\frac{\partial M}{\partial \theta} = D_v \frac{\partial^2 M}{\partial x^2} \quad (3.22)$$

The solutions of the equation are as follows :

$$\begin{aligned} \frac{M - M_s}{M_o - M_s} = \frac{8}{\pi^2} \left[\exp \left(-D_v \theta \frac{\pi^2}{4a^2} \right) + \frac{1}{9} \exp \left(-9D_v \theta \frac{\pi^2}{4a^2} \right) \right. \\ \left. + \frac{1}{25} \exp \left(-25 D_v \theta \frac{\pi^2}{4a^2} \right) + \dots \right] \end{aligned} \quad (3.23)$$

for a slab of infinite length.

where a = half of the thickness of the slab.

$$\begin{aligned} \frac{M - M_s}{M_o - M_s} = \frac{6}{\pi^2} \left[\exp \left(-D_v \theta \frac{\pi^2}{r^2} \right) \right. \\ \left. + \frac{1}{4} \exp \left(-4D_v \theta \frac{\pi^2}{r^2} \right) + \dots \right] \end{aligned} \quad (3.24)$$

for a sphere.

where r = radius of the sphere

If MR is plotted against θ on a semilog graph paper, a curve of the type shown in Fig. 3.8 is obtained. The curvature portion of the Fig. 3.8 results from the effects of second, third and following terms in the series.

The equation of the straight line portion of the curve can be expressed as follows :

As θ increases, the terms other than first approach zero.

Neglecting higher terms of the equation,

$$\frac{M - M_s}{M_o - M_s} = \frac{6}{\pi^2} \left[\exp \left(-D_v \theta \frac{\pi^2}{r^2} \right) \right] = \frac{6}{\pi^2} e^{-K\theta}$$

$$\text{i.e., } \frac{M - M_s}{M_o - M_s} = B \exp [-K\theta] \quad (3.25)$$

where $K = D_v \frac{\pi^2}{r^2}$ for a sphere

and $B = 6/\pi^2$, B is the shape factor.

Determination of Drying Constant

(1) Graphical method

For straight portion of the curve shown in Fig. 3:8, the drying constant, K can be worked out easily by finding out the slope of the straight line. This method is illustrated in example 2 (page 59).

(2) Half-life period method

If the time of one-half response in a drying process be defined as the number of hours necessary to obtain a moisture content ratio of one-half, then the drying equation

$$\frac{M - M_e}{M_o - M_e} = \exp [-K\theta] \text{ can be written as}$$

$$\frac{1}{2} = \exp [-K\theta_{1/2}] \text{ or } \theta_{1/2} = \frac{\ln 2}{K}$$

$$\text{and } \frac{1}{4} = \exp [-K\theta_{1/4}] \text{ or } \theta_{1/4} = \frac{\ln 4}{K}$$

Therefore, by knowing the values of $\theta_{1/2}$ or $\theta_{1/4}$ K can be found out.

Remarks on thin layer drying equations

None of the theoretical equations presented in this chapter represents the drying characteristics of grains accurately over a wide range of moisture and temperature, on account of the following limitations :

(1) The theoretical drying equations are based on the concept that all grains in thin layer are fully exposed to the drying air under constant drying conditions (at constant drying air temperature and humidity) and dried uniformly. Therefore, there is no gradient in thin layer of grain which is not true for finite mass depths.

(2) The grain drying equations developed from diffusion equation are based on the incorrect assumptions that D_v and K are independent of moisture and temperature.

(3) It is not possible to choose accurate boundary condition and shape factors for drying of biological materials.

(4) Drying equation developed from Newton's equation for heating or cooling does not take into account of the shape of the material.

Therefore, the uses of the theoretical drying equations are limited. However, if accurate results are not desired and the values of D_v and K are known then the theoretical drying equations can be used and give fairly good results within a limited range of moisture.

Many empirical drying equations for different cereal grains are found to be useful and frequently used as they give more accurate results in predicting drying characteristics of a particular grain for a certain range of moisture, temperature, air flow rate and relative humidity. A few empirical drying equations are presented below.

Becker (1959) proposed the following equations for wheat :

$$MR = 1 - 8.78 (D_v \theta)^{\frac{1}{2}} + 13.22 (D_v \theta) \quad (3.26)$$

$$\text{for } (D_v \theta)^{\frac{1}{2}} < 0.0104$$

$$MR = 0.509 \times \exp [-58.4 D_v \theta] \quad (3.27)$$

$$\text{for } (D_v \theta)^{\frac{1}{2}} \geq 0.0104$$

$$\text{where } D_v = 7.135 e^{-19944/T}, \quad (3.28)$$

$$D_v = m^2/hr, \theta = hr \text{ and } T = ^\circ K.$$

Based on drying equation for planar symmetry Pabis and Henderson (1961) developed the following expression for diffusivity for thin layer drying of corn :

$$D_{v \text{ corn}} = 5.853 \times 10^{-10} \exp [-12502/T] \quad (3.29)$$

On the basis of drying equation for sphere the following expression for drying constant, K corn has been developed :

$$K_{\text{corn}} = 5.4 \times 10^{-1} \exp [-9041/T] \quad (3.30)$$

$$\text{where } K = 1/\text{sec}, T = ^\circ K.$$

Effects of different factors on the drying process

The drying rate is dependent upon many factors, namely air temperature, air flow rate, relative humidity, exposure time, types, variety and size of the grain, initial moisture content, grain depth,

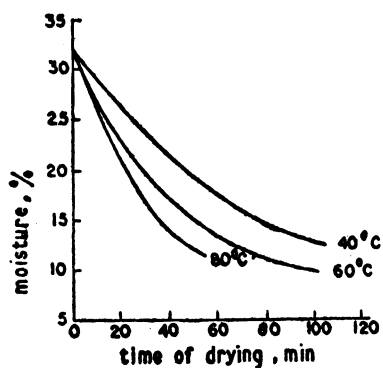


FIG. 3.9. Effects of air temperatures on drying characteristics of parboiled paddy (Bhattacharya et al, 1967).

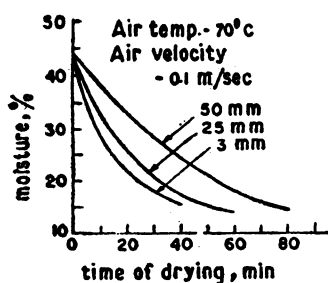


FIG. 3.10. Effects of grain thickness on thin layer drying of wheat (Gerzhoi, 1958).

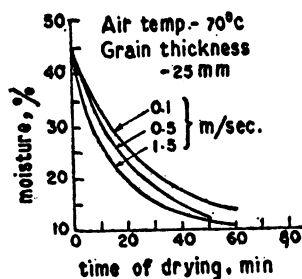


FIG. 3.11. Effects of Air velocity on thin layer of drying of wet corn (Gerzhoi, 1958).

etc. Of them first four factors are important drying process variables which have been discussed below. The effects of some of the factors are shown in Figs. 3.9 through 3.11.

EFFECT OF AIR TEMPERATURE

Simmonds et al. (1953a) showed that the rate of drying of wheat was sharply dependent upon the temperature of air varying from 21 to 77° C. The rate of drying increases with the rise of air temperature. But the equilibrium moisture content falls as air temperature increases. These observations are true for other cereal grains also.

The effects of air temperature on the quality of grains have been discussed in Chapter 1.

EFFECT OF AIR VELOCITY

It is generally assumed that the internal resistance to moisture movement of agricultural materials is so great when compared to the surface mass transfer resistance that the air rate past the particles has no significant effect on the time of drying or on the drying coefficient. Henderson and Pabis found that air rate had no observable effect on thin layer drying of wheat when air flow was turbulent. According to them air flow rate varying from 10 cm³/sec/cm² to 68 cm³/sec/cm² had no significant effect on the drying rate of wheat. But in cases of paddy and corn it has been found that air rate has some effect on rate of drying.

However, the recommended air flow rates per unit mass of different grains are given in Table 8.

EFFECT OF AIR HUMIDITY

When the humidity of the air increases the rate of drying decreases slightly. The effect, however, is much smaller in comparison to the effect of temperature changes.

EFFECT OF AIR EXPOSURE TIME

In the case of intermittent drying, drying rate of grain depends on its exposure time to the drying air in each pass. Total drying time which is the sum of all exposure times, is dependent upon exposure time. Total drying time reduces as exposure time decreases (Chakraverty, 1975).

DEEP BED DRYING

In deep bed drying all the grains in the dryer are not fully exposed to the same condition of drying air. The condition of drying air at any point in the grain mass changes with time and at any times it also changes with the depth of the grain bed. Over and above the rate of air flow per unit mass of grain is small compared to the thin layer drying of grain. All onfarm static bed batch dryers are designed on deep bed drying principle. The condition of drying in deep bed is shown in Fig. 3.12.

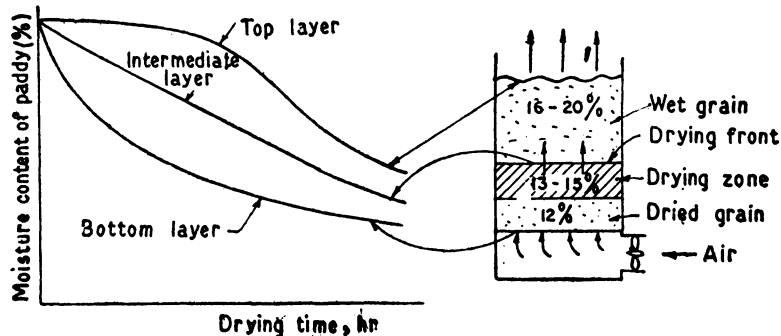


FIG. 3.12. Deep bed drying characteristics at different depths.

The drying of grain in a deep bin can be taken as the sum of several thin layers. The humidity and temperature of air entering and leaving each layer vary with time depending upon the stage of drying, moisture removed from the dry layer until the equilibrium moisture content is reached. Little moisture is removed, rather a small amount may be added to the wet zone until the drying zone reaches it. The volume of drying zone varies with the temperature and humidity of entering air, the moisture content of grain and velocity of air movement. Drying will cease as soon as the product comes in equilibrium with the air.

Time of advance of drying front

The time period taken by the drying front to reach the top of the bin is called the maximum drying rate period.

The time taken by the drying front to reach the top of the bed can be calculated by the following equation :

$$\frac{W_a(M_1 - M_x)}{100} = AG(H_s - H_1)\theta_1$$

or $\theta_1 = \frac{W_a(M_1 - M_x)}{AG(H_s - H_1) \times 100}$ (3.31)

where

M_1 = initial moisture content of grain (d.b.), %

M_x = average moisture content, (d.b.), % at the end of drying front advance at the top.

θ_1 = time of advance, hr

A = cross-sectional area of the dryer, through which air passes, m^2

G = mass flow rate of dry air, $kg/hr m^2$

H_s = humidity of the saturated air leaving the dryer kg/kg

H_1 = humidity of the air entering into the dryer, kg/kg

W_a = weight of dry grain in the bin, kg

Decreasing rate period

As soon as the drying front reaches the top of the bin, the rate of drying starts decreasing and is termed as decreasing rate period. The time of drying for this decreasing rate period can be expressed by the following equation :

$$\theta_2 = (1/K) \ln \left(\frac{M_x - M_e}{M - M_e} \right) \quad (3.32)$$

where

θ_2 = time of drying during decreasing rate period, hr

M_e = equilibrium moisture content of the grain (d.b.)

K = drying constant, $1/hr$

M = average moisture content (d.b.) at the end of decreasing rate period.

M_x = average initial moisture content (d.b.), at the beginning of decreasing period.

The total drying time for grains in the bin is the sum of the time required for the maximum drying rate and decreasing rate periods.

Total drying time, $\theta = \theta_1 + \theta_2$

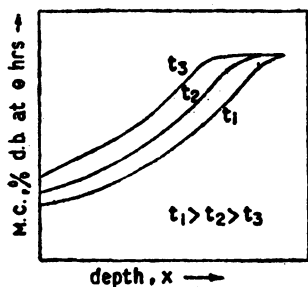


FIG. 3.13. Effect of drying air temperature ' t ' on the moisture content distribution within a fixed bed of grain after a drying period θ .

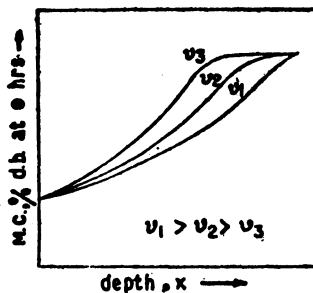


FIG. 3.14. Effects of air flow rate ' v ' on the moisture content distribution within a fixed bed of grain after a drying period θ .

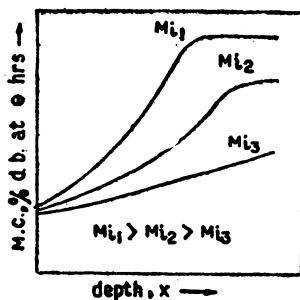


FIG. 3.15. Effect of initial moisture content. M_i on the moisture content distribution within a fixed bed of grain after a drying period θ .

Deep bed drying problems can be solved by Hukill's analysis also (Hukill, 1947). The effects of air temperature, air velocity, bed depth and initial moisture content of grain on deep bed drying characteristics of grain are shown in Figs. 3.14 through 3.18.

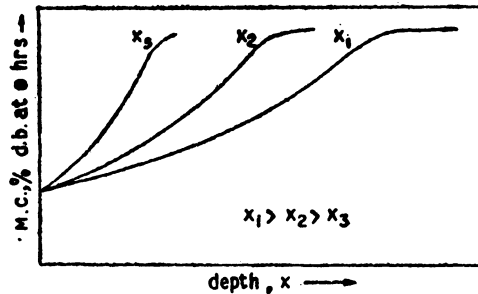


FIG. 3.16. Effect of bed depth X on the moisture content distribution within a fixed bed of grain after a drying period θ .

From these figures, the following general observations can be made in regard to deep bed drying :

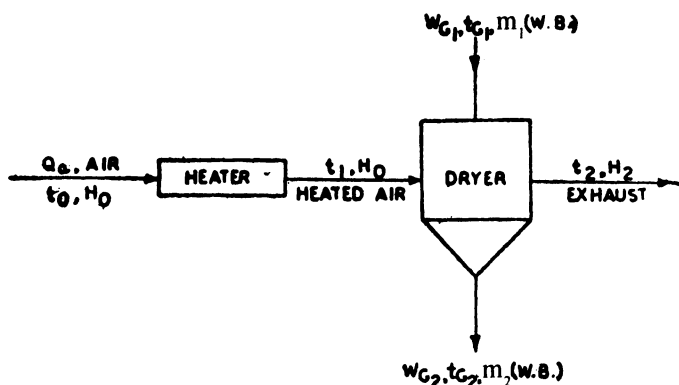
- (1) The rate of drying of a grain bed increases with an increase in drying air temperature (Fig. 3.13).
- (2) The bottom layer of a static grain bed is dried more than the top layer. The moisture gradient across the grain bed increases as the inlet drying air temperature increases (Fig. 3.13).
- (3) The rate of drying of a grain bed is increased with an increase in air flow rate (Fig. 3.14).
- (4) The drying zone passes more quickly through a grain bed if the initial moisture content of grain is low (Fig. 3.15).
- (5) Moisture gradient across the grain bed increases with an increase in bed depth (Fig. 3.16).

Remarks on deep bed drying

- (1) If drying air at high relative humidity and relatively low temperature is used, then the total drying time will be very long due to slow rate of drying which may cause spoilage of grains.
- (2) The correct choice of air flow rate is very important.

(3). Drying air at high temperature cannot be used due to development of moisture gradients within the grain bed. It leads to non-uniform drying of grain. In general an air temperature of 40°C (15°C rise) is recommended for deep bed drying.

MASS AND HEAT BALANCE IN GRAIN DRYING



Mass balance

$$\text{Let } W = W_{G_1} - W_{G_2} \quad (3.33)$$

$$\text{or } W_{G_1} = W_{G_2} + W$$

Amount of dry material entering into the dryer

$$= \frac{100 - m_1}{100} W_{G_1} \text{ kg/hr.}$$

Amount of dry material leaving the dryer = $\frac{100 - m_2}{100} W_{G_2}$ kg/hr

$$\text{But } \frac{100 - m_1}{100} W_{G_1} = \frac{100 - m_2}{100} \times W_{G_2}$$

$$W_{G_1} = W_{G_2} \frac{100 - m_1}{100 - m_2} \quad (3.34)$$

Put the equation (34) in equation (33)

$$W = W_{G_1} - W_{G_2} \frac{100 - m_1}{100 - m_2} = W_{G_2} \left(\frac{m_1 - m_2}{100 - m_2} \right)$$

Similarly,

$$W = W_{G_2} \frac{m_1 - m_2}{100 - m_1}, \quad W_{G_2} \left(\frac{m_1 - m_2}{100 - m_1} \right) = W_{G_2} \frac{m_1 - m_2}{100 - m_1} \quad (3.35)$$

If f_d , the dryer factor be defined as follows :

$$f_d = \frac{W}{W_{G_1}} \times 100 = \frac{W_{G_1} - W_{G_2}}{W_{G_1}} \times 100 = \left(\frac{m_1 - m_2}{100 - m_2} \right) \times 100 \quad (3.36)$$

Heat Balance

$$\begin{aligned} W_d \times C p_d \times (t_{G_1} - t_{G_2}) + W_d \times (X_1) \times C p_w (t_{G_1} - t_{G_2}) + W_d (X_1 - X_2) \lambda \\ \text{Sensible heat} \qquad \qquad \qquad \text{Latent heat} \\ = Q_a \times (0.24 + 0.45 H_o) \times (t_1 - t_2) \times \theta \end{aligned} \quad (3.37)$$

where, W_d = B.D. mat., kg ; Q_a = air rate kg/hr ;

θ = time, hr ;

X_1, X_2 = moisture content, (d.b), decimal

Dryer performance

Dryer performance can be expressed in terms of various efficiency factors which are given below :

Thermal efficiency

Thermal efficiency can be defined as the ratio of the latent heat of evaporation credited to the heat energy of the fuel charged. Thermal efficiency can be expressed mathematically as follows :

$$\frac{\left(\frac{dM}{d\theta} \right) W_d \lambda}{q} \quad (3.38)$$

$$\text{where } q = \frac{60 V A}{v} (h_1 - h_o) \quad (3.39)$$

$\frac{dM}{d\theta}$ = drying rate, kg/(hr kg)

W_d = weight of dry material, kg.

λ = latent heat of evaporation, kcal/kg.

q = rate of heat flow, kcal/hr

V = air rate, $m^3/(\text{min } m^2)$

A = area, m^2

v = humid volume of air (at the point of rate measurement) m^3/kg

h_1 and h_0 = enthalpy of drying and ambient air, kcal/kg.

Heat Utilisation Factor

H.U.F. may be defined as the ratio of temperature decrease due to cooling of the air during drying and the temperature increase due to heating of air.

Heat utilisation factor

$$\begin{aligned} &= \frac{\text{Air temperature decrease during drying}}{\text{Air temperature increase during heating}} \\ \text{H.U.F.} &= \frac{\text{Heat utilised}}{\text{Heat supplied}} = \frac{t_1 - t_2}{t_1 - t_0} \end{aligned} \quad (3.40)$$

H.U.F. may be more than unity under certain drying conditions.

The Coefficient of Performance

The coefficient of performance (C.O.P.) of a grain dryer is expressed mathematically as follows :

$$\text{C.O.P.} = \frac{t_2 - t_0}{t_1 - t_0} \quad (3.41)$$

where t_2 = dry bulb temperature of exhaust air, °C

t_0 = dry bulb temperature of ambient air, °C

t_1 = dry bulb temperature of drying air, °C

The relationship between H.U.F. and C.O.P.

$$\text{H.U.F.} = 1 - \text{C.O.P.} \quad (3.42)$$

The Effective Heat Efficiency (E.H.E.)

The E.H.E. is mathematically defined as follows :

$$\text{E.H.E.} = \frac{t_1 - t_2}{t_1 - t_{w1}} \quad (3.43)$$

where t_{w1} = wet bulb temperature of drying air, °C.

Effective heat efficiency considers the sensible heat in drying air as being the effective heat for drying.

**PROBLEMS ON MOISTURE CONTENT, HENDERSON'S
EQUATION AND DRYING**

Solved problems on Moisture Content

(1) Two tonnes of paddy with 22 per cent moisture content on wet basis are to be dried to 13 per cent moisture content on dry basis. Calculate the weight of bone dry products and water evaporated.

Solution

Weight of bone dried sample

$$= 2000 - \frac{2000 \times 22}{100}$$

$$= 1560 \text{ kg.}$$

Moisture content on dry basis for 22 per cent moisture on wet basis :

$$= \frac{22}{100 - 22} \times 100$$

$$= 28.2 \text{ per cent (d.b.)}$$

Therefore, water evaporated

$$= 1560 \times (0.282 - 0.13)$$

$$= 237.2 \text{ kg.}$$

Amount of dried product

$$= 2000 - 237.2$$

$$= 1762.8 \text{ kg.}$$

(2) Determine the quantity of parboiled paddy with 40 per cent moisture content on wet basis required to produce 1 tonne of product with 12 per cent moisture content on wet basis. Work out the problem on wet basis and check the answer using dry basis.

Solution

On wet basis : Weight of paddy with 12 per cent moisture on wet basis = 1 tonne.

Weight of bone dry paddy

$$= 1 - \frac{12 \times 1}{100}$$

$$= 0.88 \text{ tonne}$$

Let x be the amount of water present in the paddy with 40 per cent moisture content.

Therefore,

$$\frac{x}{0.88+x} \times 100 = 40$$

$$x = \frac{40 \times 0.88}{60} = 0.587 \text{ tonne}$$

Therefore, quantity of paddy with 40 per cent moisture content on wet basis :

$$= 0.587 + 0.88$$

$$= 1.467 \text{ tonne}$$

On dry basis :

40 per cent m.c. (w.b) = 66.66 per cent (d.b.)

Similarly 12 per cent m.c. (w.b) = 13.65 per cent (d.b.)

Amount of moisture evaporated

$$= 0.88 \left(\frac{66.66 - 13.65}{100} \right)$$

$$= 0.467 \text{ tonne}$$

Total weight of paddy should be $1 + 0.467 = 1.467$ tonne

(3) Determine the values of c and n from the Henderson's equation for the following data obtained from thin layer paddy drying studies :

$$RH = 30 \text{ per cent, } t = 50^\circ \text{ C, } M_e = 10.5 \text{ per cent} \quad (i)$$

$$RH = 55 \text{ per cent, } t = 50^\circ \text{ C, } M_e = 15.5 \text{ per cent} \quad (ii)$$

Solution

Henderson's equation is expressed as,

$$1 - RH = \exp [-cTM_e^n]$$

Putting condition (i) in Henderson's equation we get

$$1 - 0.3 = \exp [-c(50 + 273)(10.5)^n]$$

$$0.7 = \exp [-c \times 323 \times (10.5)^n]$$

$$e^{-0.357} = \exp [-c \times 323 \times (10.5)^n]$$

$$0.357 = c \times 323 \times (10.5)^n \quad (1)$$

Substituting condition (ii) in Henderson's equation we get

$$1 - 0.55 = \exp [-c(50 + 273) \times (15.5)^n]$$

$$\text{or } 0.45 = \exp [-c \times 323 \times (15.5)^n]$$

$$\text{or } e^{-0.796} = \exp [-c \times 323 \times (15.5)^n]$$

$$\text{or } 0.796 = c \times 323 (15.5)^n \quad (2)$$

Dividing equation (2) by equation (1),

$$\frac{0.796}{0.357} = \frac{c \times 323 \times (15.5)^n}{c \times 323 \times (10.5)^n}$$

$$\text{or } 2.23 = \left(\frac{15.5}{10.5}\right)^n$$

$$\text{or } (1.475)^n = 2.23$$

Therefore $n = 2.07$.

Substituting the value of n in equation (1),

$$0.357 = c \times 323 (10.5)^{2.07}$$

$$\text{or } c = \frac{0.357}{323 \times 130}$$

Therefore $c = 8.5 \times 10^{-6}$

EXERCISES

(1) Calculate the amount of moisture evaporated from 100 kg of grain for drying it from an initial moisture content of 25 per cent to a final moisture content of 13 per cent on wet basis.

(2) Draw a graph showing moisture content of grain on wet basis versus moisture content on dry basis. Take moisture content of grain on wet basis from 10 to 60 per cent at equal intervals of 5 per cent.

(3) 1000 kg of parboiled paddy is to be dried from 32 to 13 per cent moisture content (w.b). Calculate the amount of moisture to be evaporated.

(4) Determine the equilibrium moisture content of Sorghum at $RH = 10$ per cent and $t = 60^\circ \text{C}$ using Henderson's equation, where $c = 6.12 \times 10^{-6}$ and $n = 2.31$.

(5) Determine the values of c and n from Henderson's equation for the following data :

(a) $RH = 40$ per cent, $t = 60^\circ \text{C}$, $M_e = 8.65$ per cent.

(b) $RH = 80$ per cent, $t = 60^\circ \text{C}$, $M_e = 14.62$ per cent.

Solved problems on Drying

(1) In an experiment on drying of raw paddy at an air temperature of 55°C , the following data were obtained. Initial weight of the sample = 1000 gm.

Initial moisture content = 30.8 per cent (d.b.)

Sl. No	Drying time in min	Moisture removed in gm
1	0	0.0
2	10	22.9
3	20	38.2
4	40	57.4
5	60	68.8
6	80	78.0
7	100	84.0
8	140	101.0
9	180	112.5
10	220	121.0
11	260	128.4
12	300	131.8

Prepare a drying rate curve for the experiment.

Solution

I.M.C. = 30.8 per cent (d.b.)

Therefore, the amount of bone dry material in the sample

$$= \frac{100}{130.8} \times 1000 = 764.5 \text{ gm.}$$

The amount of moisture present in the sample

$$= 235.5 \text{ gm.}$$

After 10 minutes, 22.9 gm of water was removed.

Therefore, moisture content of the sample after 10 min.

$$= \frac{235.5 - 22.9}{764.5} \times 100$$

$$= 27.8 \text{ per cent (d.b.)}$$

Drying rate, R in gm of water per minute per 100 gm of bone dry material is expressed as follows :

$$R = \frac{\text{Amount of moisture removed}}{\text{Time taken} \times \left(\frac{\text{Total bone dry weight of sample in gm}}{100} \right)}$$

For example, for the second reading,

$$R = \frac{22.9}{10 \times \left(\frac{764.5}{100} \right)}$$

$$= 0.300 \frac{\text{gm of water}}{\text{min } 100 \text{ gm. of b.d. material}}$$

Similar calculations are made for all readings and the following table is prepared.

S. No.	Drying time min	Moisture removed gm	Moisture present in the sample gm	Moisture content (d.b) per cent	Average moisture content (d.b) per cent	Drying rate, R (<i>gm of water/min 100 gm. of b.d. materials</i>)
1	0	0.0	235.5	30.8	29.30	0.299
2	10	22.9	212.6	27.8	26.80	0.249
3	20	38.2	197.3	25.80	24.545	0.189
4	40	57.8	178.10	23.29	22.545	0.150
5	60	68.8	166.70	21.80	11.20	0.128
6	80	78.0	157.5	20.60	20.205	0.110
7	100	84.0	151.5	19.81	18.70	0.944
8	140	101.0	134.5	17.59	16.835	0.081
9	180	112.5	123.0	16.08	15.525	0.072
10	220	121.0	114.5	14.97	14.485	0.065
11	260	128.4	107.1	14.0	13.79	0.054
12	300	131.8	103.7	13.58		

The drying rate curve is obtained by plotting the rate of drying against the average moisture content.

(2) The drying curve for a batch of solid dried from 25 to 6 per cent moisture (w.b.) is shown in Fig. 3.17. The initial weight of solid is 159 kg and drying surface is 1 m²/39 kg dry material. Determine the time for drying.

Solution

The time required for drying upto 'C' or time for constant-rate period :

$$\theta_o = \frac{W_d}{A} \left(\frac{X_1 - X_o}{R_o} \right)$$

$$\begin{aligned} \frac{W_d}{A} &= \frac{1}{1/39} \text{ kg/m}^2 \\ &= 39 \text{ kg/m}^2 \end{aligned}$$

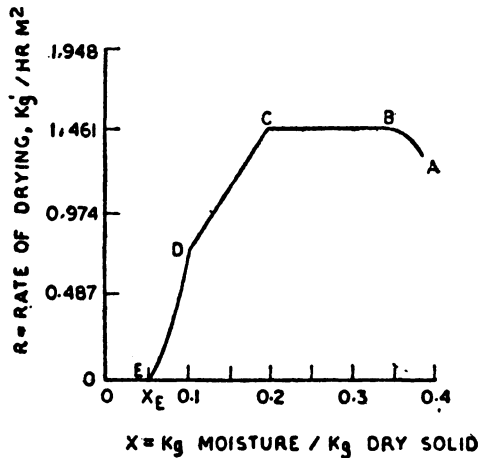


FIG. 3.17 Drying curve (for Problem 2).

$$X_1 = \frac{25}{100-25} = \frac{25}{75} = 0.333 \text{ kg/kg dry material}$$

$$X_o = 0.2 \text{ (from fig. 3.17)}$$

$$R_o = 1.461 \text{ kg/(m}^2\text{)(hr) (from fig. 3.17)}$$

$$\theta_o = 39 \times \frac{0.333 - 0.2}{1.461} = 3.55 \text{ hrs}$$

$$\therefore \theta_o = 3.55 \text{ hours} \quad (1)$$

For falling-rate period

Time required for drying can be calculated by two methods :

- (a) approximate method by assuming straight line, and
- (b) graphical method.

(a) By assuming straight line

$$\theta_f = \frac{W_d}{A} \cdot \frac{X_o - X_a}{R_m}$$

where $R_m = \frac{R_o - R_a}{\ln (R_o/R_a)}$,

$$R_o = 1.461 \text{ kg/(m}^2\text{) (hr) (from fig. 3.17)}$$

$$X_a = \frac{6}{94} = 0.0637 \text{ kg/kg of dry material}$$

$$R_a = 0.075 \text{ kg/m}^2 \text{ hr (from fig. 3.17)}$$

$$R_m = \frac{1.461 - 0.075}{2.3 \log \frac{1.461}{0.075}} = \frac{1.386}{2.3 \log 19.5} = \frac{1.386}{2.3 \times 1.29}$$

$$= 0.466 \text{ kg/hr m}^2$$

$$\theta_f = 39 \frac{0.200 - 0.0637}{0.466}$$

$$= 39 \times \frac{0.1363}{0.466} = 11.4 \text{ hours}$$

$$\theta_f = 11.4 \text{ hr.}$$

(b) In graphical solution divide the falling-rate curve in two parts :

(i) Unsaturated surface drying and

(ii) Drying under control of internal movement of moisture.

In unsaturated surface drying the falling-rate curve is a straight line, therefore, above method can be used up to the point 'D'

$$\theta_{f1} = \frac{W_d}{A} \cdot \frac{X_o - X_d}{R_{md}}$$

where $R_{md} = \frac{R_o - R_d}{\ln \frac{R_o}{R_d}}$

From the curve :

$$X_d = 0.1 \text{ kg/kg}$$

$$X_o = 0.2 \text{ kg/kg}$$

$$R_o = 1.461 \text{ kg/hr m}^2$$

$$R_d = 0.73 \text{ kg/hr m}^2$$

$$R_{md} = \frac{1.461 - 0.73}{2.3 \log_{10} \frac{1.461}{0.73}} = \frac{0.731}{2.3 \log_{10} 2} = \frac{0.731}{2.3 \times 0.3010}$$

$$= 1.056 \text{ kg/hr m}^2$$

$$\theta_{f1} = 39 \times \frac{0.2 - 0.1}{1.056} = 3.693 \text{ hrs.}$$

θ_{f1} , time for falling rate period for unsaturated surface drying
= 3.69 hours.

For the second part in which internal movement of moisture controls, a curve is plotted relating $1/R$ and X .

The area under that curve = $\int \frac{dX}{R}$.

X	0.1000	0.0950	0.0870	0.0785	0.0700	0.0637
R	0.73	0.568	0.460	0.290	0.180	0.075
$1/R$	1.37	1.76	2.195	3.450	5.55	13.35

$$\text{Area under the curve} = 1 \times 60 + \frac{1}{100} \times 1371$$

$$= 73.71$$

$$\text{Area of each square} = 0.001667 \text{ m}^2 \text{ hr/kg}$$

$$\text{Total area, } \int \frac{dX}{R} = 0.001667 \times 73.71$$

$$= 0.1228 \text{ m}^2 \text{ hr/kg}$$

Therefore, time required for drying for the second part

$$\theta_{f2} = \frac{W_d}{A} \int \frac{dX}{R} = 39 \times 0.1228$$

$$= 4.78 \text{ hours.}$$

Total time required for drying in the falling rate period

$$\theta_f = \theta_{f1} + \theta_{f2} = 3.69 + 4.78 = 8.47 \text{ hrs.}$$

Therefore, total time required for the entire period of drying
= time for constant rate period + time for falling rate period

$$\theta = \theta_c + \theta_f = 3.55 + 8.47$$

$$= 12.02 \text{ hours.}$$

(3) In an experiment on thin layer drying of parboiled wheat at

a drying air temperature of 75° C, the following drying data were obtained :

Drying time, min	0	10	20	30	40	50	70	90	110	130	150	180	210
M. C.(d.b.)	88.0	59.66	45.02	33.59	28.85	19.86	12.54	8.42	6.59	5.45	4.996	4.99	4.86

The EMC of parboiled wheat at 75° C was found to be 4.75 per cent (d.b.). Find out drying constant, K by graphical method.

Solution

Using above drying data the following table is prepared :

Drying time, min	0	10	20	30	40	50	70	90	110	130	150	180	210
$\frac{(M-M_e)}{(M_o-M_e)}$	1.0	0.702	0.515	0.369	0.263	0.193	0.0996	0.046	0.024	.00895	.00575	.00807	.0014

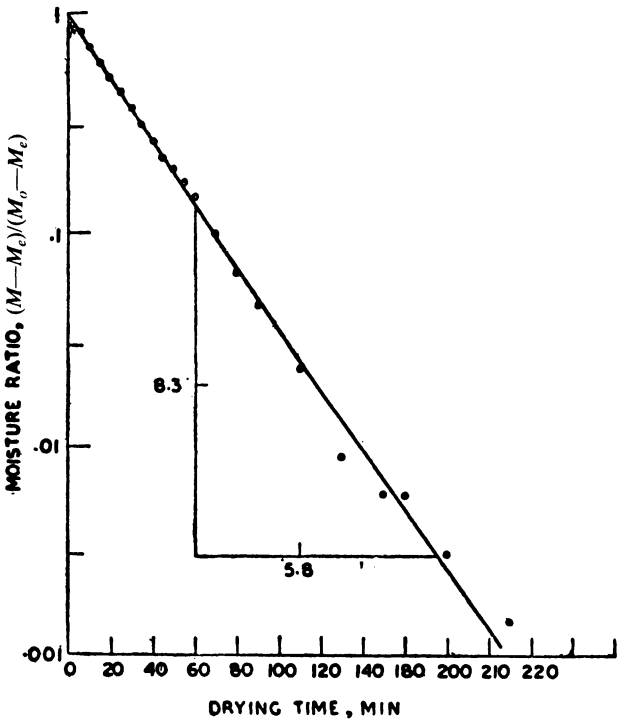


FIG. 3.18 Graph to calculate drying constant.

The moisture ratio, $(M-M_e)/(M_o-M_e)$ is plotted against drying time on a semilog graph paper (Fig. 3.18). From the graph, the slope of straight line, K is calculated below.

$$K = -\left(\frac{8.3}{5.8} \times \frac{1}{0.432 \times 100}\right) = -0.03313 \text{ (min)}^{-1}$$

EXERCISES

(1) The following data were obtained on the tray drying of sand. Obtain the drying rate curve for the test :

- (1) Area of the tray = 0.20 m²
- (2) Thickness of bed = 2.54 cm
- (3) Weight of dry sand = 10.0 kg

S. No.	Drying time hr	Total moisture present in the sample, kg
1	0.00	0.050
2	0.50	1.835
3	1.50	1.410
4	2.00	1.215
5	2.50	1.015
6	3.00	0.811
7	4.00	0.430
8	4.50	0.272
9	5.00	0.163
10	7.00	0.009
11	7.50	0.000

(2) In an experiment on thin layer drying of parboiled wheat with drying air at 85°C, the following data were obtained :

The initial and equilibrium moisture contents were found to be 83 per cent (d.b.) and 4.50 per cent (d.b.) respectively :

Time, min	Weight of the sample during drying, gm
0	200.0
15	159.0
30	138.0
45	128.0
60	122.0
90	117.0
130	114.5
210	114.25

Determine the drying constant, K by graphical method.

SYMBOLS

A	= area, m^2
a	= half of the thickness of the slab, cm
B	= shape factor, dimensionless
C	= concentration
c	= a constant, dimensionless
c'	= 0 or 1 or 2
Cp_g	= specific heat of grain, kcal/kg °C
Cp_w	= specific heat of water, kcal/kg °C
$D.B$	= dry bulb temperature, °C
D_v	= diffusivity, m^2/hr
d.b.	= dry basis
d_c	= diameter, mm
G	= mass flow rate of base dry air, kg/hr m^2
H	= humidity, kg/kg
H_o	= humidity of atmospheric air, kg/kg
H_1	= humidity of drying air, kg/kg
H_2	= humidity of exhaust air, kg/kg
H_s	= humidity of saturated air, kg/kg
H_a	= humidity at t_a °C
h_{f_a}	= film heat transfer coefficient kcal/(m^2 hr °C)
h	= enthalpy, kcal/kg
h_o	= enthalpy of atmospheric air, kcal/kg
h_1	= enthalpy of drying air, kcal/kg
J'	= a constant in modified Henderson's equation
K	= drying constant, 1/hr
K'	= a constant in modified Henderson's equation
k	= water vapour transfer coefficient, kg/hr m^2 atm
k_{11}, k_{22}, k_{33}	= phenomenological coefficients in Luikov's equation
$k_{12}, k_{13}, k_{21},$ k_{23}, k_{31}, k_{32}	= coupling coefficients in Luikov's equation
M	= moisture content, dry basis, per cent
M_E	= equilibrium moisture content, EMC, dry basis, per cent
M_1	= initial moisture content of grain, I.M.C., dry basis, per cent
M_2	= final moisture content of grain, F.M.C., dry basis, per cent
MR	= moisture ratio, $(M-M_c)/(M_o-M_c)$

M_x	= average moisture content at the end of maximum period of drying
n	= a constant, dimensionless
n'	= whole numbers
p_a	= partial pressure of water vapour at t_a , atm.
p_s	= partial pressure of water vapour at t_s , atm
p'_g	= water vapour pressure of the grain, kg/cm ²
p'_s	= saturated water vapour pressure at equilibrium temperature of the system, kg/cm ²
Q_a	= rate of air supply, kg/hr
q	= heat flow rate, kcal/hr
R	= rate of drying kg/(hr m ²)
R_c	= constant rate period drying, kg/(hr m ²)
r	= radius of the sphere, m
r'_o	= radius of a body, m
r'	= coordinate of a body, m
RH	= relative humidity, decimal
T	= temperature, ° K
t_o	= temperature of the inlet or ambient air, ° C
t_1	= temperature of the drying air (heated air), ° C
t_2	= temperature of the exhaust air ° C
t_a	= temperature of the air, ° C
t_s	= temperature of the saturated air, ° C
t_{w_o}	= wet bulb temperature of the ambient air, ° C
t_{w_1}	= wet bulb temperature of drying air, ° C
V	= Volumetric air flow rate, m ³ /(min m ²)
v	= humid volume, m ³ /kg
W_d	= weight of bone dry material, kg
W_m	= weight of moisture, kg
W	= grain flow rate at the inlet condition, kg/hr
W_{G_s}	= grain flow rate at the outlet condition, kg/hr
w	= moisture removed, kg
$W.B.$	= wet bulb temperature, ° C
X	= moisture content, dry basis, decimal
X_1	= initial moisture content, dry basis, decimal
X_2	= final moisture content, dry basis, decimal
X_o	= critical moisture content, dry basis, decimal
X_s	= equilibrium moisture content, dry basis, decimal
X'	= dimensionless quantity

z	= distance from the centre, mm
θ	= time, hr
θ_1	= drying time for maximum rate period in deep bed drying, hr
θ_2	= drying time for decreasing rate period in deep bed drying, hr
θ_c	= drying time for constant-rate period, hr
θ_f	= drying time for falling-rate period, hr
λ	= latent heat of vaporisation, kcal/kg
λ_n'	= roots of Bessel function
λ_s	= latent heat at t_s , kcal/kg

Methods of Grain Drying

So far, drying systems have not been classified systematically. However, drying methods can be broadly classified on the basis of either the mode of heat transfer to the wet solid or the handling characteristics and physical properties of the wet material. The first method of classification reveals differences in dryer design and operation, while the second method is most useful in the selection of a group of dryers for preliminary consideration in a given drying problem.

According to the mode of heat transfer, drying methods can be divided into : (a) conduction drying, (b) convection drying, and (c) radiation drying. There are other methods of drying also, namely, dielectric drying, chemical or sorption drying, vacuum drying, freeze drying, etc.

Of them, convection drying is commonly used for drying of all types of grain and conduction drying can be employed for drying of parboiled grain.

Conduction drying

When the heat for drying is transferred to the wet solid mainly by conduction through a solid surface (usually metallic) the phenomenon is known as conduction or contact drying. In this method, conduction is the principal mode of heat transfer and the vaporised moisture is removed independently of the heating media. Conduction drying is characterised by :

(a) Heat transfer to the wet solid takes place by conduction through a solid surface, usually metallic. The source of heat may be hot water, steam, flue gases, hot oil, etc. ;

(b) Surface temperatures may vary widely ;

(c) Contact dryers can be operated under low pressure and in inert atmosphere ;

(d) Dust and dusty materials can be removed very effectively ; and

(e) When agitation is done, more uniform dried product and increased drying rate are achieved by using conduction drying. Conduction drying can be carried out either continuously or batch-wise. Cylinder dryers, drum dryers, steam tube rotary dryers are some of the continuous conduction dryers. Vacuum tray dryers, freeze dryers, agitated pan dryers are the examples of batch conduction dryers.

Convection drying

In convection drying, the drying agent (hot gases) in contact with the wet solid is used to supply heat and carry away the vaporised moisture and the heat is transferred to the wet solid mainly by convection. The characteristics of convection drying are :

(a) Drying is dependent upon the heat transfer from the drying agent to the wet material, the former being the carrier of vaporised moisture ;

(b) Steam heated air, direct flue gases of agricultural waste, etc., can be used as drying agents ;

(c) Drying temperature varies widely ;

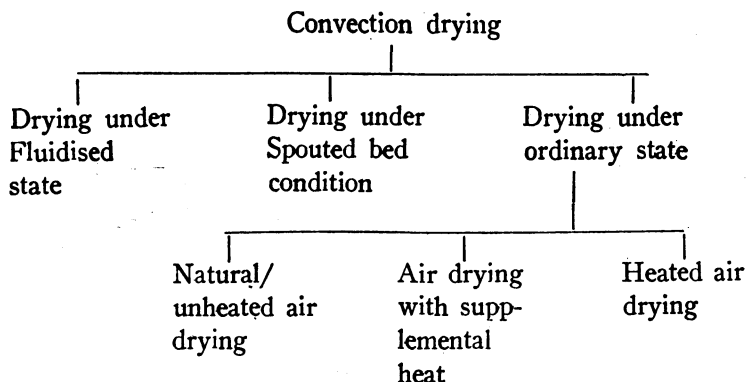
(d) At gas temperatures below the boiling point, the vapour content of the gas affects the drying rate and the final moisture content of the solid ;

(e) If the atmospheric humidities are high, natural air drying needs dehumidification ; and

(f) Fuel consumption per kg of moisture evaporated is always higher than that of conduction drying.

Convection drying is most popular in grain drying. It can be carried out either continuously or batch-wise. Continuous tray dryers, continuous sheeting dryers, pneumatic conveying dryers, rotary dryers, tunnel dryers come under the continuous system, whereas tray and compartment dryers, batch through circulation dryers are the batch dryers.

Convection drying can be further classified as follows :



Pneumatic or fluidised bed drying : When the hot gas (drying agent) is supplied at a velocity higher than the terminal velocity of the wet solid, the drying of the wet solid occurs in a suspended or fluidised state. This phenomenon is known as *fluidised bed drying*.

Drying may be carried out in a semi-suspended state or *spouted bed condition* also.

Generally, the convection drying is conducted under ordinary state, i.e., drying agent is supplied at a velocity much lower than the terminal velocity of the wet material.

In *natural air drying*, the unheated air as supplied by the nature is utilised. In *drying with supplemental heat* just sufficient amount of heat (temperature rise within 5 to 10° C) only, is supplied to the drying air to reduce its relative humidity so that drying can take place.

In *heated air drying*, the drying air is heated to a considerable extent.

The natural air drying and drying with supplemental heat methods which may require one to four weeks or even more to reduce the grain moisture content to safe levels, are generally used to dry grain for short term storage in the farm. Heated air drying is most useful when large quantity of grain is to be dried within a short time and marketed at once. It is used for both short and long term storage.

Comparative advantages and disadvantages of the three convective drying methods are given as follows :

NATURAL AIR DRYING

Advantages

- (1) Lowest initial investment and maintenance cost.
- (2) No fuel cost.
- (3) No fire hazard.
- (4) Least supervision.
- (5) Least mould growth compared to supplemental heat.

Disadvantages

- (1) Very slow drying rate, drying period may be extended to several weeks.
- (2) Weather dependent.
- (3) More drying space necessary in comparison to heated air drying.
- (4) Useful particularly for short-term storage in the farm.
- (5) Not useful for humid tropics.

SUPPLEMENTAL HEAT DRYING

Advantages

- (1) Lower cost of equipment and maintenance.
- (2) Independent of weather.
- (3) Requires less supervision.
- (4) Most efficient use of bin capacity.

Disadvantages

- (1) Fire hazard to a certain extent.
- (2) Danger of accelerated mould growth.
- (3) Rate of drying is still low.
- (4) Useful particularly for short-term storage in the farm.

HEATED AIR DRYING

Advantages

- (1) Independent of weather.
- (2) Fast drying.

- (3) High drying capacity per fan horse-power.
- (4) Used for both long and short-term storage of grains.

Disadvantages

- (1) Higher initial investment and maintenance cost.
- (2) Considerable fuel expenditure.
- (3) Danger of fire hazard.
- (4) Requires skilled manpower for control of drying condition.
- (5) By direct firing with liquid fuel, the products may be contaminated with the flue gases.

Radiation drying

Radiation drying is based on the absorption of radiant energy of the sun and its transformation into heat energy by the grain. Sun drying is an example of radiation drying. Radiation drying can also be accomplished with the aid of special infra-red radiation generators, namely, infra-red lamps. Moisture movement and evaporation is caused by the difference in temperature and partial pressure of water vapour between grain and surrounding air. The effectiveness of sun drying depends upon temperature and relative humidity of the atmospheric air, speed of the wind, type and condition of the grain, etc.

SUN DRYING

Sun drying is the most popular traditional method of drying. A major quantity of grain is still dried by the sun in most of the developing countries.

Advantages

- (1) No fuel or mechanical energy is required.
- (2) Operation is very simple.
- (3) Viability, germination, baking qualities are fully preserved.
- (4) Microbial activity and insect/pest infestation are reduced.
- (5) Labour oriented.
- (6) No pollution.

Disadvantages

- (1) Completely dependent on weather.
- (2) Not possible round the clock and round the year.
- (3) Excessive losses occur due to shattering, birds, rodents, etc.
- (4) Requires specially constructed large floor area, restricting the capacity of mill to a certain limit.
- (5) The entire process is unhygienic.
- (6) Unsuitable for handling of large quantity of grain within a short period of harvest.

INFRA-RED DRYING

Infra-red rays can penetrate into the irradiated body to a certain depth and transformed into heat energy. Special infra-red lamps, or metallic and ceramic surfaces heated to a specified temperature by an open flame, may be used as generators of infra-red radiation.

Advantages

- (1) Small thermal inertia.
- (2) Simplicity and safety in operation of lamp radiation dryers.

Disadvantages

- (1) High expenditure of electric power.
- (2) Low utilisation factor.

Radiation dryers have been used in many countries for drying the painted surfaces of machinery, and in the timber processing, textile industry and cereal grain and other food industries.

Dielectric drying

In dielectric drying, heat is generated within the solid by placing it in a fixed high frequency current. In this method, the substance is heated at the expense of the dielectric loss factor. The molecules of the substance, placed in a field of high frequency current are polarised and begin to oscillate in accordance with the frequency. The oscillations are accompanied by friction, and thus a part of the electrical energy is trans-

formed into heat. The main advantage of this method is that the substance is heated with extraordinary rapidity.

The dielectric drying has now been in use in different industries such as timber, plastics and cereal grain processing.

Chemical drying

Various chemicals such as sodium chloride, calcium propionate, copper sulphate, ferrous sulphate, urea, etc., have been tried for the preservation of wet paddy. Of these, common salt has been proved to be effective and convenient for arresting deteriorative changes during storage. When wet paddy is treated with common salt, water is removed from the rice kernel by osmosis. The common salt absorbs moisture from paddy but it cannot penetrate into the endosperm through the husk layer. This is an unique property of the paddy which has rendered the application of common salt preservation possible.

Advantages

- (1) It not only dries paddy but also reduces the damage due to fungal, microbial and enzymatic activities and heat of respiration.
- (2) It does not affect the viability of the grain.
- (3) The milling quality of paddy is satisfactory.
- (4) Loss of dry matter is negligible.
- (5) It does not affect the quality of rice bran.

Disadvantages

- (1) The moisture may be retained on the husk due to the presence of sodium chloride.
- (2) The useful life of gunny will be shortened.
- (3) The colour of husk changes to dark yellow.
- (4) The common salt treated paddy requires an additional drying subsequently.
- (5) Economy of the process has yet to be established.

Sack drying

This method is particularly suitable for drying of small quantity of seed to prevent mixing of varieties and conserve strain purity and viability.

The grain bags are laid flat over holes cut on the floor of a tunnel system so that heated air can be forced up through the grain from an air chamber underneath.

Usually an air temperature of 45° C with an air flow rate of 4 m³/min at 3-4 cm static pressure per bag of 60 kg is used for fastest drying rate. The sacks are turned once during the drying operation. The sack drying process involves higher labour cost.

Grain Dryers

Grain dryers can be divided into two broad categories, unheated air dryers and heated air dryers. Different types of grain dryers of both groups have been discussed in this chapter.

UNHEATED AIR DRYERS

Unheated or natural air drying is usually performed in the grain storage bin. That is why unheated air drying is also known as in-bin or in-storage drying.

Natural air drying is commonly used for on-farm drying for a relatively small volume of grains. Either full bin or layer-drying system is employed in natural air drying. The period of drying for either system may be as long as several weeks depending on the weather. In layer drying, the bin is filled with a layer of grain at a time and drying, is begun. After the layer is partially dried, other layers of grain are added periodically, perhaps daily with the continuation of drying until the bin is full and the whole grain mass is dried. In full-bin drying, a full bin of grain is dried as a single batch. Then the drying bin is used for storage purposes. The air flow rate provided is relatively low. Though natural air is supposed to be used, an air heating system should be kept so that supplemental heat may be supplied to the natural air during rainy seasons and during periods of high humidity weather and for highly moist grains. Natural air drying cannot be used if the ambient relative humidity exceeds 70 per cent. So also grains containing moisture higher than 20 per cent should not be dried with natural air.

Various types of unheated air dryers with different constructions, shapes, grain feeding and discharging mechanisms and aeration systems are available. Some of the common types of dryers are described here.

As in natural air drying the grain is aerated (for drying) and stored in the same unit, the complete installation simply consists of a storage unit equipped with ducts for air distribution and devices for air exhaustion and a blower.

Storage unit

Any shape of grain holding bin such as semi-circular, circular, square or rectangular and of any material like metal, wood, concrete, asbestos or mineral agglomeration can be used provided the bin is made moisture proof. Different types of units are shown in Figs. 5.1 to 5.7.

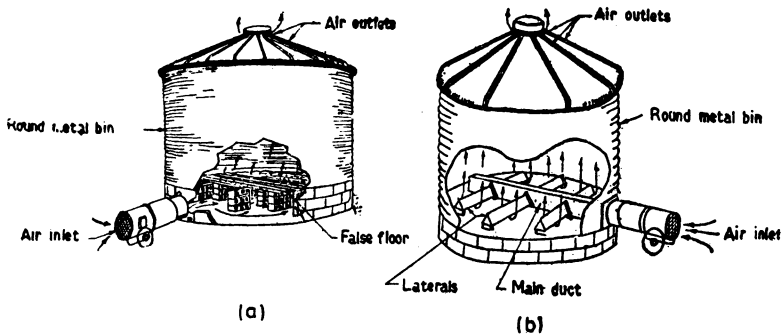


FIG. 5.1. Types of air distribution systems used in bin drying

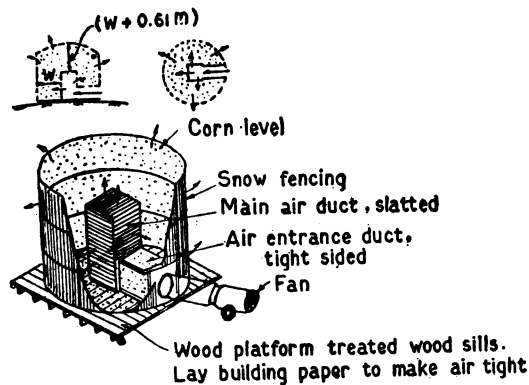


FIG. 5.2. An inexpensive, easily built crib for the mechanical drying of ear corn.

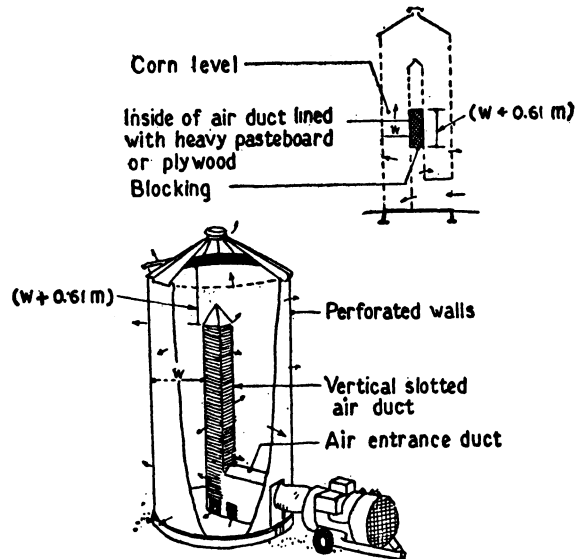


FIG. 5.3. High round crib with perforated walls (permanent structure) for drying of ear corn.

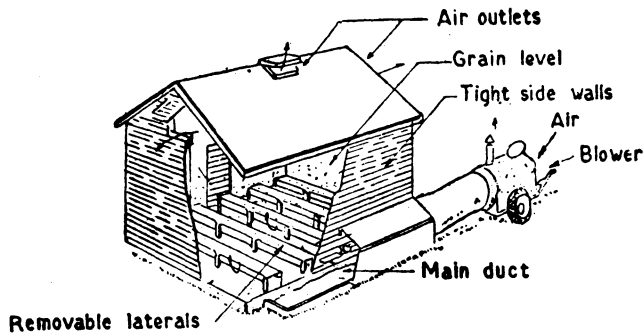


FIG. 5.4. Rectangular metal bin dryer with cross-wise air ducts—permanent construction.

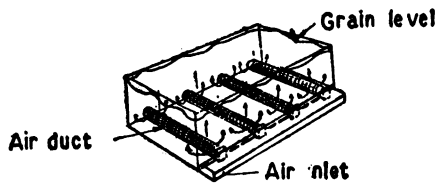


FIG. 5.5a. Rectangular metal bin dryer with cross-wise air ducts—Temporary construction.

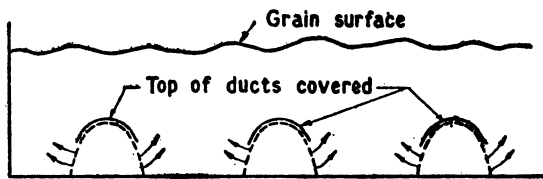


FIG. 5.5b. Most desirable ducting system.

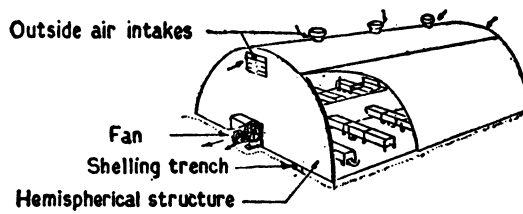
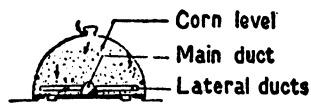


FIG. 5.6. General purpose building for drying and storing of grain (Permanent structure).

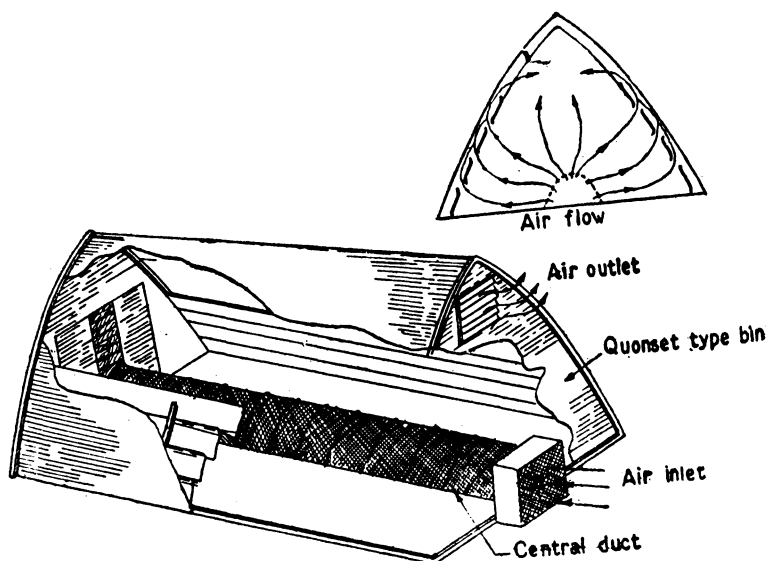


FIG. 5.7. Types of air distribution systems used in bin drying.

Of the many types of bins used in grain drying some of the common types are described as follows :

(a) *A round metal bin*

With false perforated floor, having 4.5 metres diameter and 3 metres height can hold about 25 tonnes of paddy. The bin is fitted with a cover at the top in such a way that only the exhaust air can escape through it but rain cannot enter into the bin. In some cases exhaust air is allowed to escape through the side walls of the dryer also (Fig. 5.3). The round bins can also be made of concrete or ferrocement. They are usually constructed of several rings sealed together.

Rectangular or square bins fitted with false perforated floor or main duct and laterals are also in use (Fig. 5.4).

(b) *A screen tunnel quonset type storage unit*

The unit is fitted with a central horizontal screen type duct and a special air outlet system near the top of each vertical wall (Fig. 5.7).

The bins are generally made circular to ensure uniform distribution of air and avoid stagnant pockets. The quonset type has the same advantages in this respect as the cylindrical bin.

Aeration system

Both propeller and centrifugal types of blowers are used for aeration. Centrifugal blowers may have either forward-curved or backward-curved blades.

The air flow and static pressure requirements for different types of grains and for different depths of grains are given in Table VIII (Appendix).

Air distribution system

Sufficient care should be taken in selecting and designing the air distribution system so that air is uniformly distributed throughout the grain bulk and void pockets are avoided. There are five major systems of air distribution :

- (a) Perforated floor,
- (b) Central horizontal duct,
- (c) Main duct and laterals, and
- (d) Vertical slatted duct.

(a) *Perforated floor*

The circular storage bin (Fig. 5.1) can be fitted with the perforated false floor through which unheated air is blown. Though the system is suitable for small and medium sized round bins and for small depths of grain, it is used for large rectangular bins and for higher grain depths as well.

(b) *Central horizontal duct*

This system is used in the quonset type units (Fig. 5.7). This type of duct with openings in the wall can distribute air more uniformly through the grain bulk.

(c) *Main duct and laterals*

The system of main duct and laterals is most commonly used and is adopted in round, square and even rectangular bins (Figs. 5.1b, 5.4 and 5.6). The laterals are open at the bottom

and raised off the floor of the bin so that the air can flow through the mass. The laterals are inverted V or U or rectangular in shape and are made of wood or steel or concrete or ferro-cement. The laterals are spaced in accordance with the size of the storage unit, quantity of grain to be aerated or dried and depth of the grain (Figs. 5.8 to 5.10).

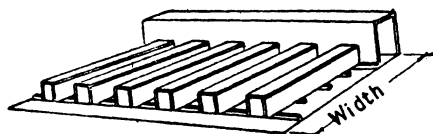


FIG. 5.8. Main side duct and laterals.

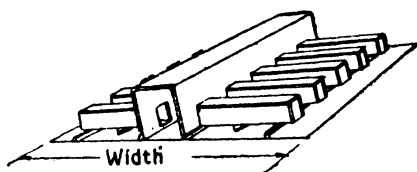


FIG. 5.9. Main central duct and laterals.

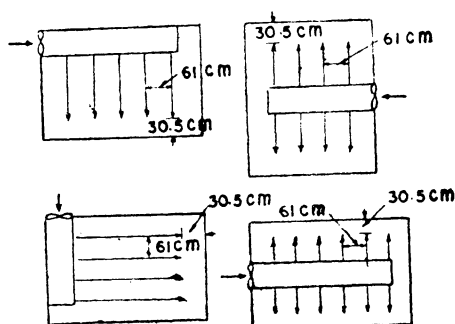


FIG. 5.10. Four common floor layouts for the main duct and laterals in bins.

In round bins the ducts can also be placed in the form of a ring on the bin floor.

(d) *Vertical ducts*

This system consists of either a vertical slatted duct (Figs. 5.2 and 5.3) or a central vertical perforated tube (Fig. 5.11a). The air is blown through the slots or perforations and is spread laterally through the grain mass.

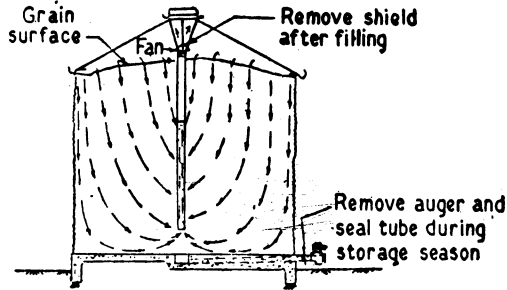


FIG. 5.11a. Vertical duct aeration system for round bins.

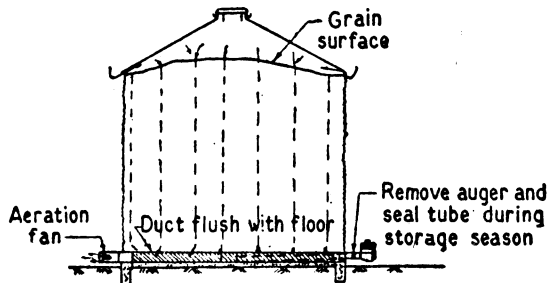


FIG. 5.11b. Horizontal duct aeration system for round bins.

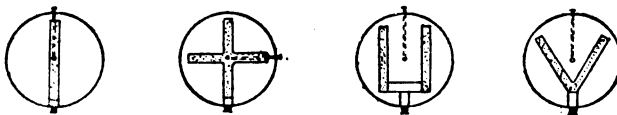


FIG. 5.11c. Different duct patterns for aeration.

HEATED AIR DRYERS

Flat Bed Type Batch Dryer

This is a static, deep bed, batch dryer. This type of batch dryer is very simple in design and is most popular for on-farm drying in many countries.

Construction

The rectangular box type batch dryers are shown in Figs. 5.12 to 5.14. The size of the dryer depends on the area of the

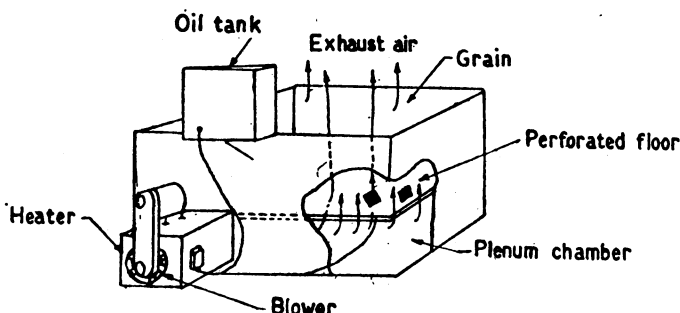


FIG. 5.12. Rectangular flat bed type batch dryer (Japan).

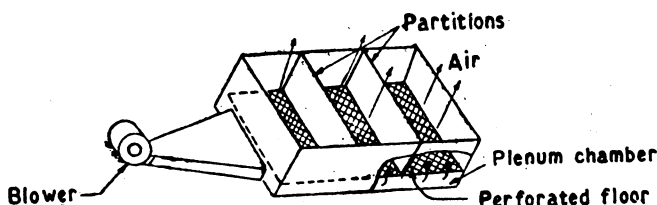


FIG. 5.13. Rectangular flat bed type batch dryer with partitions.

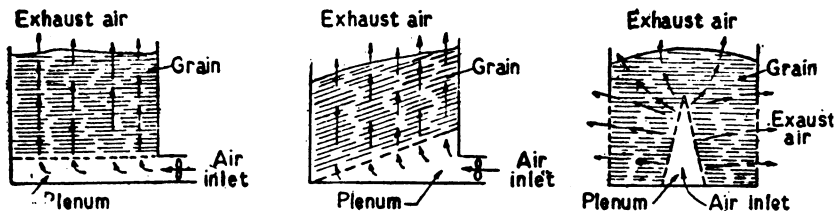


FIG. 5.14. Some aeration systems for deep bed batch dryers.

supporting perforated screen on which the grain is placed. The holding capacity of these dryers ranges from 0.25 to 1 tonne/batch only. The horsepower of the motor for the blower ranges from 1/4 to 1. For convenience an oil burner can be used but for economy a husk fired furnace should be used for the supply of heat.

Operation

The grain is placed on the supporting screen and the heated air is forced through the deep bed of grain. After drying of grains to the desired moisture level, they are discharged manually.

The temperature of the heated air should be limited to 45°C. The drying rate varies with the drying temperature.

Air flow rate varies from 20 to 40 m³/min per 1000 kg of raw paddy depending on the initial moisture content.

Advantages

- (1) Fairly reasonable price.
- (2) Intermittent drying can also be used.
- (3) Operation is very simple.
- (4) It can be manufactured locally using various types of materials like steel sheet, wood piece, etc.
- (5) It can be used for seed drying and for storage purpose also after drying.

Disadvantages

- (1) Rate of drying is slow.
- (2) Uneven drying which results in higher percentage of broken in grains.
- (3) Holding capacity is small compared to flow dryers.

Recirculatory Batch Dryer (PHTC type)

This is a continuous flow non mixing type of grain dryer.

Construction

The dryer consists of two concentric circular cylinders made of perforated (2 mm dia) mild steel sheet of 20 gauge. The

two cylinders are set 15 to 20 cm apart. These two cylinders are supported on four channel sections. The whole frame can be supported by a suitable foundation or may be bolted to a frame made of channel section. A bucket elevator of suitable capacity is used to feed and recirculate the grain into the dryer. A centrifugal blower blows the hot air into the inner cylinder which acts as a plenum. The hot air from the plenum passes through the grain moving downward by gravity and comes out of the outer perforated cylinder. A torch burner is employed to supply the necessary heat with kerosene oil as fuel. The designs of PHTC dryer for 1/2, 1 and 2 tonnes holding capacity are available. The PHTC dryer of 2 tonnes holding capacity developed at PHTC, IIT, Kharagpur, India is shown in Fig. 5.15.

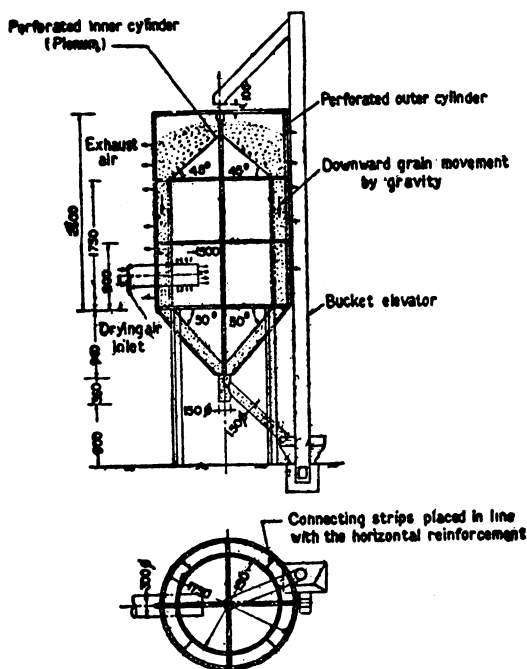


FIG. 5.15. PHTC Recirculating batch dryer (Holding capacity—2 tonnes).

Some Columnar Dryers (Non-Mixing)

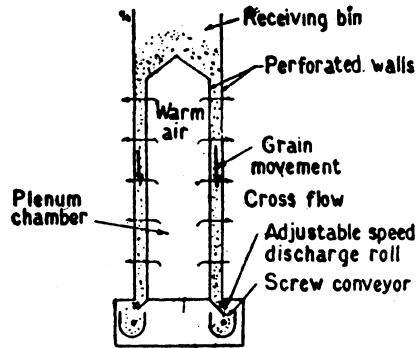


FIG. 5.16. Continuous flow type non-mixing double columnar dryer.

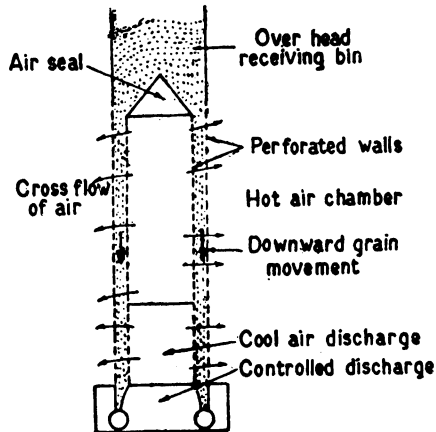


FIG. 5.17. Continuous flow type non-mixing double screen columnar dryer with grain cooling chamber.

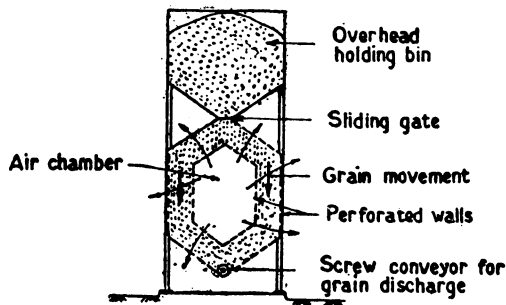


FIG. 5.18. Columnar dryer with overhead tempering bin.

Operation

The grain is fed to the top of the inside cylinder. While descending through the annular space from the feed end to the discharge end by gravity, the grain comes in contact with a cross flow of hot air. The exhaust air comes out through the perforations of the outer cylinder and the grain is discharged through the outlet of the hopper. The feed rate of grain is controlled by closing or opening the gate provided with the outlet pipe of the discharge hopper. The grain is recirculated till it is dried to the desired moisture level.

Advantages

- (1) Price is reasonable.
- (2) Simplest design amongst all flow type dryers.
- (3) Easy to operate.
- (4) It can be used on the farm and rice mill as well.
- (5) Operating cost is low with husk fired furnace.

Disadvantages

- (1) Drying is not so uniform as compared to mixing type.
- (2) Perforations of the cylinders may be clogged with the parboiled paddy after using it for a long time.

Louisiana State University Dryer

This is a continuous flow-mixing type of grain dryer which is popular in India and the U.S.A.

Construction

It consists of : (1) a rectangular drying chamber fitted with air ports and the holding bin, (2) an air blower with duct, (3) grain discharging mechanism with a hopper bottom, and (4) an air heating system.

(1) *Rectangular bin* : Usually the following top square sections of the bin are used for the design of LSU dryers :

- (i) 1.2 m×1.2 m, (ii) 1.5 m×1.5 m,
- (iii) 1.8 m×1.8 m and (iv) 2.1 m×2.1 m.

The rectangular bin can be divided into two sections, namely, top holding bin and bottom drying chamber.

(2) *Air distribution system* : Layers of inverted V-shaped channels (called inverted V-ports) are installed in the drying chamber. Heated air is introduced at many points through the descend-

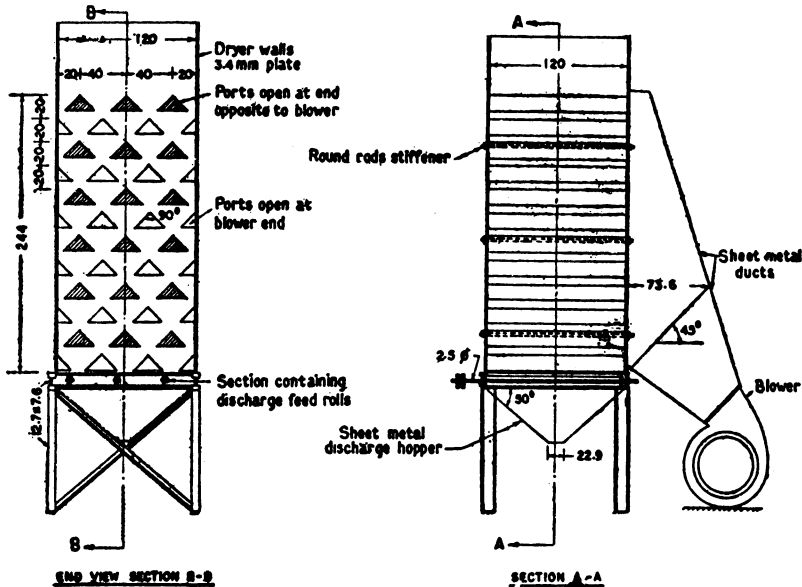


FIG. 5.19. LSU Type dryer details.

ing grain bulk through these channels. One end of each air channel has an opening and the other end is sealed. Alternate layers are air inlet and air outlet channels. In the inlet layers, the channel openings face the air inlet plenum chamber but they are sealed at the opposite wall, where as in the outlet layers, the channel openings face the exhaust but are sealed other side. The inlet and outlet ports are arranged one below the other in an offset pattern. Thus air is forced through the descending grain while moving from the feed end to the discharge end. The inlet ports consist of a few full size ports and two half size ports at two sides. All these ports of same size are arranged in equal spacing between them. The number of ports containing a dryer varies widely depending on the size of the dryer.

Each layer is offset so that the top of the inverted V ports

helps in splitting the stream of grain and flowing the grains between these ports taking a zigzag path.

In most models, the heated air is supplied by a blower.

(3) *Grain discharging mechanism* : Three or more ribbed rollers are provided at the bottom of the drying chamber which can be rotated at different low speeds for different discharge rates of grains. The grain is discharged through a hopper fixed at the bottom of the drying chamber.

Causing some mixing of grain and air the discharge system at the base of the dryer also regulates the rate of fall of the grain.

(4) *Air heating system* : The air is heated by burning gaseous fuels such as natural gas, butane gas, etc., or liquid fuels such as kerosene, furnace oil, fuel oil, etc., or solid fuels like coal, husk, etc. Heat can be supplied directly by the use of gas burner or oil burner or husk fired furnace and indirectly by the use of heat exchangers. Indirect heating is always less efficient than direct firing system. However, oil fired burner or gas burners should be immediately replaced by husk fired furnace for economy of grain drying.

The heated air is introduced at many points in the dryer so as to be distributed uniformly through the inlet ports and the descending grain bulk. It escapes through the outlet ports.

This type of dryer is sometimes equipped with a special fan to blow ambient air from the bottom cooling section in which the dried or partially dried warm grain comes in contact with the ambient air.

In general, the capacity of the dryer varies from 2 to 12 tonnes of grain, but sometimes dryers of higher capacities are also installed. Accordingly power requirement varies widely.

Recommended air flow rate is 60—70 m³/min/tonne of par-boiled paddy and optimum air temperatures are 60° C and 85° C for raw and parboiled paddy respectively. A series of dryers can also be installed.

Advantages

(1) Uniformly dried product can be obtained if the dryer is designed properly.

(2) The dryer can be used for different types of grains.

Disadvantages

- (1) High capital investment.
- (2) Cost of drying is very high if oil is used as fuel.

Baffle Dryer

This is a continuous flow mixing type of grain dryer (Figs. 5.20 and 5.21).

Construction

The baffle dryer consists of: (1) grain receiving bin, (2) drying chamber fitted with baffles, (3) plenum fitted with hot air inlet, (4) grain discharge control device, and (5) hopper bottom. A number of baffles are fitted with the drying chamber to divert the flow and effect certain degree of mixing of grain. The two baffle plates with the outer and inner sides are set 20 cm apart for the passage of the grain in the drying chamber. The dryer is made of mild steel sheet.

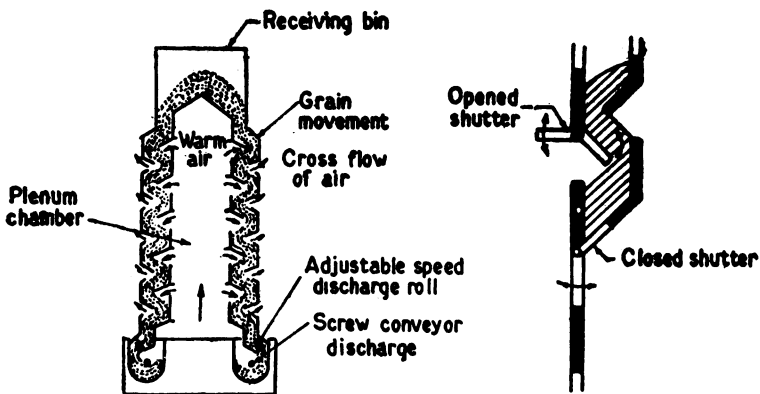


FIG. 5.20. Mixing type baffle dryer.

Operation

Grain is fed at the top of the receiving bin and allowed to move downward in a zigzag path through the drying chamber where it encounters a cross flow of hot air. On account of zigzag movement, a certain degree of mixing of grain takes place. The partially dried grain discharged from the hopper

bottom is recirculated by a bucket elevator until it is dried to the desired moisture level.

Some of the dryers are fitted with a large overhead bin at the top which acts as an overhead tempering bin. This type of tempering dryer is shown in Fig. 5.21.

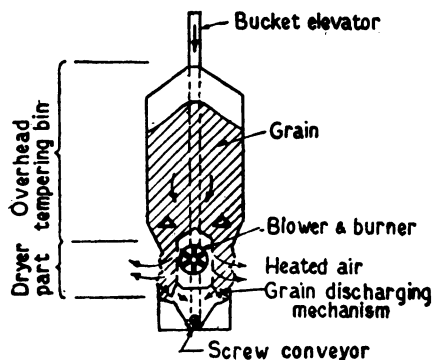


FIG. 5.21. Baffle type tempering dryer.

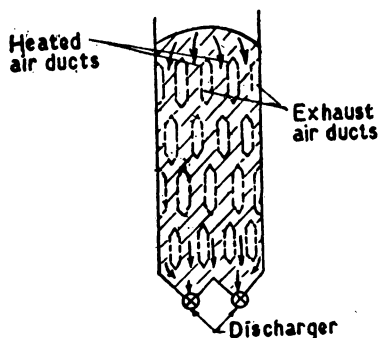


FIG. 5.22. Multiple air ducts type dryer.

Advantages

- (1) Uniformly dried product is obtained.

Disadvantages

- (1) Ratio of the volume of plenum to the total volume of the dryer is relatively high.

(2) Grains on the baffle plates move slowly than that of other sections.

Other advantages and disadvantages are same as described in LSU dryer.

Rotary Dryer

This is a continuous dryer (Fig. 5.23) as it produces the final dried product continuously. Horizontal rotary dryers of various designs have been developed by different countries for the drying of parboiled paddy. Some of them are fitted with external steam jacket and internal steam tubes as well. As parboiled paddy can stand high temperature without significant increase of cracks in grains, these dryers can be employed for rapid drying of parboiled paddy using temperatures as high as 100 to 110° C. In India, the Jadavpur University, Calcutta introduced a rotary dryer of 1 tonne/hr capacity for the drying of parboiled paddy. The construction and operation of the same dryer are described as follows.

Construction

It consists of a cylindrical shell 9.15 m long and 1.22 m in diameter, with 48 pairs of 5 cm and 3.75 cm size steam pipes

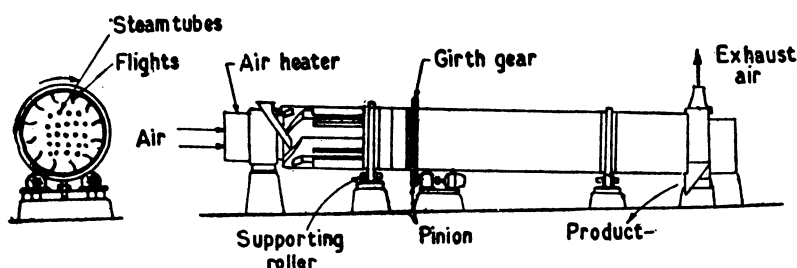


FIG. 5.23. Steam tube rotary dryer.

in two concentric rows inside the shell in combination with common steam inlet and condensate outlet fittings. The shell is equipped with six longitudinal flights of 9.15 m long and 15.24 cm wide for lifting and forward movement of the parboiled paddy towards the discharge end while it is being dried. Over the feed end breeching box there are feed hopper

and screw conveyor with an adjustable sliding gate. The dryer is equipped with an air blower and a small steam tube heat exchanger for supplying heated air at the entrance of the feed end breeching box. The cylindrical shell of the dryer is rotated at 2 to 6 rpm by a motor through speed reduction gear, pulley and belt drive system.

Operation

The soaked and steamed paddy is fed to the dryer by the screw feeder. Heated air at about 80° C is blown (from the feed end) through the dryer in the same direction as the paddy moves and exhausted through the exhaust pipe. Heated air acts here mainly as a carrier of moisture from the dryer. While travelling from the feed end to the discharge end of the dryer, the parboiled paddy comes in contact with the steam heated pipes for a very short time in each rotation and is gradually dried to about 16 per cent moisture content in a single pass. Therefore, drying is accomplished mainly by the conduction of heat from the steam pipe to the grain. The travelling time of the grain in the dryer, is adjusted to 30 to 45 min by adjusting inclination and rpm of the dryer. The hot paddy discharged from the dryer is then aerated by passing it through a cup and cone type cooler.

Advantages

- (1) Fast rate of drying.
- (2) Uniform drying of all grains.
- (3) Milling quality of parboiled paddy is high if it is dried in two passes under optimum drying conditions.

Disadvantages

- (1) Complicated design.
- (2) Needs careful attention.
- (3) Higher capital investment.
- (4) Higher power requirement.
- (5) Operating cost may be high due to higher consumption of electricity and steam.

- (6) The dryer being horizontal larger floor space is required.
- (7) Generally only 30 per cent of the dryer volume is utilised.
- (8) It cannot be used for all types of freshly harvested grains.

Selection, Design, Specifications and Testing of Grain Dryers

Selection of Dryers

Many factors have to be considered before the final selection of the most suitable type of dryer for a given application. Such a selection is further complicated by the availability of a large number of different types of dryers. Commercial dryers are not usually flexible enough to compensate for design inaccuracies or for problems associated with the handling of different types of food materials that have not been previously considered. For this reason, it is particularly important that all pertinent points be considered and that drying tests be conducted prior to the final selection of a dryer for a given problem. The following procedure is recommended for the selection of the most suitable dryer to produce the desirable product, economically.

PRELIMINARY DRYER SELECTION

The important factors to be considered in the preliminary selection of a crop dryer are as follows :

- (1) Physicochemical properties of the crop being handled.
- (2) Drying characteristics of the crop : (a) Type of moisture ; (b) Initial, final and equilibrium moisture contents ; (c) Permissible drying temperature ; and (d) Drying curves and drying times for different crops with different dryers.
- (3) Flow of the crop to and from the dryer : (a) Quantity to be handled per hour ; (b) Continuous or batch operation ; and (c) Processes during drying and subsequent to drying.
- (4) Product qualities : (a) Colour ; (b) Flavour ; (c) Shrinkage ; (d) Contamination ; (e) Uniformity of drying ; (f) Decomposition or conversion of product constituents ;

(g) Overdrying; (h) State of subdivision; (i) Product temperature; (j) Bulk density; (k) Case hardening; and (l) Cracking and other desirable qualities of the end products.

(5) Dust recovery problems.

(6) Facilities available at the site of proposed installation :

(a) Space ; (b) Temperature, humidity and cleanliness of air ; (c) Available fuels ; (d) Available electric power ; (e) Permissible noise, vibration, dust or heat losses ; (f) Source of wet feed ; and (g) Exhaust-gas outlets.

Comparison of dryers

The dryers so selected are to be evaluated on the basis of drying performance and cost data.

DRYING TEST

Drying tests described in this chapter for a given crop have to be carried out with the dryers under consideration to determine the drying performance, operating conditions and the product characteristics. An approximate cost analysis is also useful for evaluation of the dryers.

Final selection of dryer

From the results of the drying tests and cost analyses the final selection of the most suitable dryer can be made.

For successful introduction of any grain dryer at the farm level, a few additional points are to be borne in mind in the selection and design of grain drying system. They are as follows :

(1) The dryer should be of proper size matching with the demand of a farmer, miller or any organisation ;

(2) The price of the dryer should be reasonable ;

(3) The dryer should be simple in design and should be made of different cheap and locally available materials so that it can be manufactured locally ;

(4) It should be easy to operate ;

(5) It should be possible to make the dryer portable, if necessary ;

(6) The operating cost should be minimum. Solar-cum-

furnace (fired with agricultural waste like husk, shells, etc.) air heating system should be introduced in grain drying to minimise the cost of drying ;

(7) The repair and maintenance requirements should be minimum ;

(8) It should be possible to use the dryer for different grains and to be used as a storage bin later for its maximum utilisation.

Design of Grain Dryers

As indicated earlier, heated air grain dryers can be divided into three major groups :

- (1) Static deep bed batch dryers ;
- (2) Continuous-flow-batch dryer (either mixing or non-mixing type) ; and
- (3) Continuous dryer

Grain dryers mainly consist of : (a) drying chamber, (b) air distribution system, (c) direct or indirect air heating system, (d) blower, (e) control system (if any), and (f) grain conveying system (for flow dryers).

The following important factors are taken into consideration in the design of heated air grain dryers :

(1) DRYER FACTORS

- (a) Size, shape and type of dryer ;
- (b) Grain feeding rate ;
- (c) Total drying time ;
- (d) Air flow pattern and air distribution system ;
- (e) Depth of grain bed in the dryer ; and
- (f) System of cooling grain (if any).

(2) AIR FACTORS

- (a) Velocity and air flow rate per unit mass of the grain.
- (b) Temperatures and relative humidities of the heated air and exhaust air.
- (c) Static pressure of the air at which it is blown, and
- (d) Average ambient conditions.

(3) GRAIN FACTORS

- (a) Type, variety and condition of grain ;
- (b) Initial and final moisture contents of grain ;
- (c) The *usage* of dried grain ; and
- (d) Latent heat of vaporisation of grain moisture.

(4) HEATING SYSTEM

- (a) Type of fuel and rate of fuel supply
- (b) Type of burner (for liquid fuel) or type of furnace (for solid fuel) ; and
- (c) Type of heat exchanger (for indirect heating system).

Some of the important design factors have been discussed very briefly in subsequent paragraphs.

Size, shape and type of dryer

Size or capacity of a dryer is decided by the amount and variety of grain to be dried per day or for the whole season.

Sizes of the dryer are expressed either in terms of holding capacity or amount of grain to be dried per unit time or the amount of grain passing through the dryer per unit time (throughput capacity).

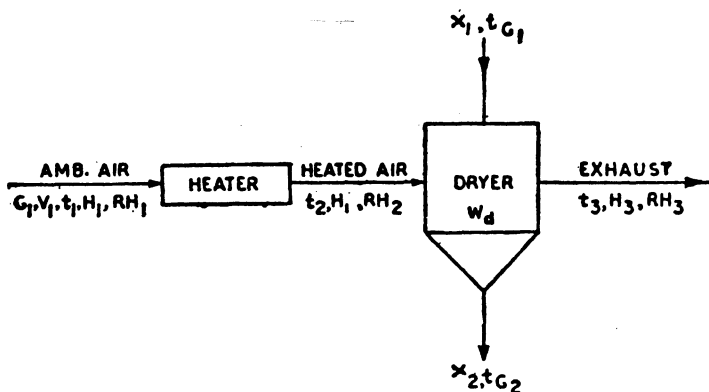
Thickness of grain layer exposed to the heated air is generally restricted to 20 cm for continuous flow dryers. The designs of the continuous flow dryers are based on thin layer drying principles whereas static batch dryers are designed on deep bed drying principles. Air flow requirements for different depths and for different grains are given in Table 8 (Appendix). Total drying time required for various air temperatures for different grains are obtained from the drying curves given in Chapter 3 on Theory of Grain Drying.

Choice of a grain dryer largely depends on the situation. Continuous flow dryers are normally used for commercial purposes whereas static deep bed batch dryers are used for on-farm drying. Constructructional features of different types of heated air dryers have been described in Chapter 5. Farm level batch dryers can be made of locally available materials, namely, wood, bamboo, etc., if necessary. But commercial big dryers are made of mild steel sheet, angle iron, channel section supports.

Calculation of air, heat and fuel requirements for heated air dryers

The air flow rate required for heated air drying systems can be calculated as follows :

The rate of air flow required for drying may be calculated by making heat balance. The heated air drying system is represented by :



where

G	= air flow rate, m ³ /min.
H_1, H_2	= humidities of ambient and heated air, kg/kg.
H_3	= humidity of exhaust air, kg/kg.
RH_1, RH_2 & RH_3	= relative humidities of ambient, heated and exhaust air, respectively, per cent.
t_1, t_2 & t_3	= dry bulb temperatures of ambient, heated and exhaust air respectively, °C.
W_d	= total weight of bone dry grain in the dryer, kg.
X_1, X_2	= initial and final moisture contents of grain, (d.b.) kg/kg.
t_{G1}, t_{G2}	= initial and final grain temperatures, °C.
v_1	= initial humid volume, m ³ /kg.

Heat supplied by drying air, q_a , kcals :

$$q_a = (0.24 + 0.45 H_1) G' (t_2 - t_3) \theta$$

Where G' = rate of air supply, kg/min.

θ = total drying time, min.

Amount of heat required :

Heat required for evaporation of moisture from the grain,
 q_1 , kials :

$$q_1 = W_d (X_1 - X_2) \lambda$$

where,

λ = average value of latent heat of vaporisation of
moisture from the grain, kials/kg.

Sensible heat required to raise the temperature of the grain
and its moisture, q , kials :

$$q = W_d C_g (t_{g_2} - t_{g_1}) + W_d C_w (t_{g_2} - t_{g_1}) X_1$$

where

C_g, C_w = specific heats of grain and water respectively,
Kcal/kg °C

Therefore

$$q_a = q_1 + q$$

$$\text{or } G' = (0.24 + 0.45 H_1) (t_2 - t_3) \theta$$

$$= W_d [(X_1 - X_2) \lambda + C_g (t_{g_2} - t_{g_1}) + C_w (t_{g_2} - t_{g_1}) X_1]$$

$$\text{or } G' = \frac{W_d [(X_1 - X_2) \lambda + C_g (t_{g_2} - t_{g_1}) + C_w (t_{g_2} - t_{g_1}) X_1]}{(0.24 + 0.45 H_1) (t_2 - t_3) \theta}$$

$$\therefore G = G' \times v_1$$

where v_1 = humid volume.

Fuel consumption :

The rate of fuel consumption can be calculated as follows :

$$f = \frac{q'_a}{\eta \cdot \eta_h \cdot \eta_{hs} \cdot C_n}$$

where f = fuel rate, kg/hr.

q'_a = total heat required to heat the drying air, kcal/hr.

C_n = Calorific value of fuel, kcal/kg of fuel.

η = efficiency of the heating system.

η_{hs} = efficiency of the heat exchanger.

η_b = efficiency of the boiler, if any.

Drying air temperature

Correct choice of drying air temperature for a given type of grain is very important as it has effects on the quality of the dried product. The highest allowable air temperature for drying of grain depends on the type and condition of grain and the usage of dried grain. The upper limit of drying air temperatures for different grains to be used for food, feed and seed purposes are different and are given in Table 8 (Appendix).

Grain parameters

The grain factors which affect the rate of drying are as follows :

- (a) Type, variety and condition of grain ;
- (b) Initial/harvest moisture content, final moisture and equilibrium moisture contents of the grain ;
- (c) Structure and chemical composition of the kernel, seed coat, husk etc., and
- (d) Foreign materials present in the grain.

The above stated factors, are, therefore, to be considered in the design of grain dryers. Over and above, data on physical properties such as bulk density, angle of repose, porosity, angle of internal friction, flow properties of grain, aerodynamic properties and thermal properties (specific heat, thermal conductivity, etc.) are required in the design of a grain dryer and are thus taken into consideration. Some of these properties are tabulated in Tables 3 to 6 (Appendix).

AIR FLOW PATTERN AND AIR DISTRIBUTION

Any one of the three systems of air flow namely cross flow, counter flow and co-current flow can be adopted in flow type grain dryers. Generally cross flow of air is preferred. Double screen (say RPEC type) and baffle types of columnar dryers have a plenum chamber and LSU dryer has inverted V shaped air channels for uniform distribution of air throughout the drying chamber. The deep bed batch dryer has the plenums at the bottom of the grain drying chamber. These systems have been shown in Chapter 5 on Grain Dryers.

CONVEYING AND HANDLING SYSTEM

Suitable conveying equipments for loading, discharging, re-circulating and shifting of grain before, during and after drying of grain are necessary for the grain drying system. Bucket elevators, vertical screw lifts for feeding, hopper bottom with proper inclination for grain discharging are commonly used. Forced discharge mechanism with slowly rotating fluted rolls are used for better control of the feed rate and drying rate. Dried grain from the dryer is usually conveyed to different places by belt conveyor or screw conveyor and bucket elevator.

AIR HEATING SYSTEM

Generally direct firing systems are used for gaseous and liquid fuels and indirect heating system using heat exchangers is employed for solid fuels. But direct flue gas from the husk fired furnace can also be efficiently used for grain drying. In view of the present energy crisis, the liquid or gaseous fuel burning system should be immediately replaced by the agricultural waste (husk, shells, bagasse, etc.) fired furnace for the supply of heated air economically. The drying cost can be further reduced by introducing solar-cum-husk fired grain drying system.

SPECIFICATIONS

Table—Specifications of dryer and its accessories.

Name of the unit/part	Sl. No.	Items
Dryer	1.	Name of the dryer
	2.	Type of the dryer
	3.	Model of dryer
	4.	Manufacturer's name and address
	5.	Holding capacity of dryer (tonnes)
	6.	Dimensions of dryer (cm)
	7.	Total height of dryer, and ground clearance (cm)
	8.	Total weight of dryer (kg)
	9.	Safety measures of dryer (if any)
	10.	H.P. required for feed rolls
	11.	Total H.P. requirement
	12.	Total power requirement (KW)
	13.	Price of the dryer (Rs.)
Drying chamber	1.	Type of drying section (screen, baffle, etc.)
	2.	Dimensions (cm)
	3.	Grain holding capacity (kg)
	4.	Dimensions of the plenum (for double screen and baffle type)
	5.	Size and number of air ports (for LSU type)
	6.	Ratio of plenum volume to the whole drying chamber volume
	7.	Thickness of grain layer (grain depth) in drying section
	8.	Mesh No. of the screen (for double screen)
	9.	Dimensions and position of hopper
	10.	Grain distribution mechanism
	11.	Grain discharging mechanism
Blower	1.	Blower type
	2.	Dimensions (cm)
	3.	Rated capacity of blower (m ³ /min)
	4.	Static pressure (mm water)
	5.	Diameter of discharge outlet (cm)
	6.	Diameter of inlet port (cm)
	7.	Rated H.P. of the blower motor
	8.	Recommended speed of blower (rpm)
	9.	No. of rotary blades/impeller vanes
	10.	Diameter of rotary blades/impeller (cm)

Name of the unit/part	Sl. No.	Items
Control System	1.	Drying air temperature range and control
	2.	Air flow rate control
	3.	Grain flow rate control
	4.	Any other control
<i>Handling Equipments</i>		
Bucket elevator	1.	Capacity (tonnes/hr)
	2.	Total height (cm)
	3.	Height from the ground level (cm)
	4.	Shape and size of bucket
	5.	Number of buckets
	6.	Position of grain inlet and outlet
	7.	Rated speed of main shaft (rpm)
	8.	Material of construction
Screw Conveyor	9.	Power requirement
	1.	Capacity (tonnes/hr)
	2.	Speed of shaft (rpm)
	3.	Outer diameter of screw (cm)
	4.	Outer diameter of shaft (cm)
	5.	Pitch (cm)
	6.	Length of the screw (cm)
	7.	Clearance between the screw tip and housing troughs (mm)
	8.	Material and thickness of flight (cm)
	9.	Power requirement
<i>Air Heating System</i>		
Oil Burner	Type of fuel used and its calorific value (kcal/kg)	
	Direct or indirect firing	
	1.	Dimensions (cm)
	2.	Built-in type or separate
	3.	Type of burner
	4.	Nozzle diameter (cm)
	5.	Burner rating (kg/min)
	6.	Fuel and air ratio (kg/kg)
	7.	Required pressure for atomising (kg/cm ²)
	8.	Fuel feeding method and control
	9.	Material of construction
	10.	Capacity of the fuel storage tank (litres)
	11.	Method of temperature control
	12.	Method of ignition and extinguishing
	13.	Safety device

Testing of Grain Dryers

No generalised test procedure can be adopted for all types of grain dryers. The testing method for static deep bed batch dryer cannot be same as that of continuous flow thin layer dryers. It is always preferable that test procedure for each type of dryer be designed separately.

However, for convenience, the dryer testing method can be broadly divided into two major heads : simple method and rigorous method. Either of these two methods can be adopted in accordance with the objectives of the test.

SIMPLE METHOD

A simple test procedure is so designed as to determine the approximate performance of the grain dryer.

The simple test procedure for a batch dryer is tabulated as follows :

Test Procedures for the Performance of the Static Deep Bed Batch dryer

Type and model No. of dryer : Type of grain and variety	
Grain	1. Initial weight of wet grain (kg)
	2. Final weight of dried grain (kg)
	3. Initial moisture content (per cent)
	4. Final moisture content (per cent)
	5. Dryer loading time (hr)
	6. Dryer unloading time (hr)
	7. Average drying grain temperature ($^{\circ}$ C)

Type of grain and variety	
Air	1. Air flow rate (maximum) (m ³ /min)
	2. Air flow rate (minimum) (m ³ /min)
	3. Max. static pressure (mm water)
	4. Min. static pressure (mm water)
	5. Average ambient d.b. temp. (° C)
	6. Average ambient w.b. temp. (° C)
	7. Average heated air d.b. temp. (° C)
	8. Average heated air w.b. temp. (° C)
	9. Average exhaust air d.b. temp. (° C)
	10. Average exhaust air w.b. temp (° C)
Drying capacity	1. Total drying time (hr)
	2. Cooling time (if any) (hr)
	3. Total moisture evaporation (kg)
	4. Rate of moisture evaporation (kg/hr)
	5. Rate of dried grain productions (tonnes/hr)
Heater and Fuel	1. Air heating method (oil fired burner/husk fired furnace/steam heat exchanger)
	2. Type of air heating (direct/indirect)
	3. When oil fired burner/husk fired furnace is used
	(a) type of fuel and cal. value
	(b) total fuel consumption (kg)
	(c) rate of fuel consumption (kg/hr)
	4. When steam heat exchanger is used
	(a) incoming steam pressure (kg/cm ²)
	(b) rate of condensate outflow (kg/hr)
	(c) Temp. of condensate (° C)

Type of grain and variety	
Power	1. Power consumption for blowing air to burner (KW)
	2. Power consumption for pumping oil to burner (KW)
	3. Power consumption for blowing heated air (KW)
	4. Power consumption for loading and unloading grain (KW)
	5. Power consumption for running feed rolls (KW)
Quality of dried grain	1. Germination of grain before drying (per cent)
	2. Germination after drying (per cent)
	3. Head yield before drying (per cent—for paddy)
	4. Total yield before drying (per cent)
	5. Head yield after drying (per cent)
	6. Total yield after drying (per cent)
	7. Other quality factors

The simple test procedure for continuous flow dryer

Besides the test items tabulated in the above Table, the following items are to be taken into consideration for continuous flow dryers :

- (1) Moisture content after each pass (per cent) ;
- (2) Residence time in the dryer for each circulation (hr) ;
- (3) Number of passes ;
- (4) Tempering time (hr) ;
- (5) Average rate of moisture reduction or rate of moisture evaporation in each circulation (kg/hr) ;
- (6) Rate of grain recirculation (tonnes/hr) ;
- (7) Drying air temperature at each pass ($^{\circ}\text{C}$) ;
- (8) Weight of remaining grain in the dryer, elevator, etc. (kg).

Rigorous method

Rigorous test procedures for some batch and continuous flow dryers are given as follows. The whole test procedure can be grouped into the following major heads :

- (1) Checking of construction ;
- (2) Drying performance test ;
- (3) Fan/blower performance test ;
- (4) Control system performance test ;
- (5) Handling equipments performance test ; and
- (6) Checking of different dryer-parts after disassembling (after the drying tests).

(1) CHECKING OF CONSTRUCTION

The purpose of this test is to ascertain the major dimensions, material of construction and other necessary specifications of the dryer and its accessories.

Investigation items

Specifications of : (a) dryer as a whole, (b) drying chamber with air distribution system, (c) blower, (d) heating system and (e) conveying units such as bucket elevator, grain distributor, screw conveyor, belt conveyor, etc. .

The specifications of the above items have already been discussed earlier.

(2) DRYING PERFORMANCE TEST

The objectives of this test are to determine the drying performance of a dryer on the basis of rate of drying, rate of consumption of fuel and electricity, heat utilisation, quality of the dried grain and other operating conditions.

The investigation items have already been tabulated.

(3) BLOWER PERFORMANCE TEST

The objective of this test is to determine the performance of the fan/blower attached with the dryer.

Investigation items

(a) Power input, kw, (b) air flow rate, $\text{m}^3/\text{min.}$, (3) static and total pressure, mm water, (d) static pressure efficiency, and (e) vibration, noise and other working conditions of the blower.

(4). PERFORMANCE OF THE CONTROL SYSTEM

The objective of this test is to find out the accuracy of :

(a) The control of drying air temperature and the temperature of heating unit, (b) control of air flow rate etc., and (c) other working conditions of the whole control system.

Investigation items

(a) Accuracy of the temperature control with the heating unit, (b) accuracy of the temperature control of the drying air, (c) variation of heated air temperature at different points, (d) air flow rate control and any other control system, and (e) any mechanical trouble with the system.

(5) PERFORMANCE OF THE HANDLING EQUIPMENT

The rated and actual capacities and other working conditions of the conveying and handling equipments are to be found out. This has already been discussed earlier.

(6) INVESTIGATION AFTER DISASSEMBLING

This is necessary to investigate the conditions of different parts of various units after completion of the drying test.

PROBLEMS ON DRYER DESIGN**Solved problems**

(1) Design a PHTC-recirculating batch dryer having holding capacity of 2 tonnes of paddy with 15 per cent m.c. (w.b.).

Assume the following data :

Ambient air temp. = 30° C

Relative humidity of ambient air = 70 per cent

Initial m.c. of paddy = 30 per cent (w.b.)

Final m.c. of paddy = 15 per cent (w.b.)

Grain inlet temp. = 30° C

Grain outlet temp. = 70° C

Heated air temp. = 85° C

Exhaust air temp. = 40° C

Latent heat of water vapour = 600 kcal/kg

Angle of repose = 45°

Thickness of grain bed to be dried = 20 cm
 Bulk density of paddy grain at 15 per cent m.c.
 = 575 kg/m³
 Diameter of plenum chamber = 135 cm
 Diameter of dryer = 175 cm
 Hopper angle = 50°
 Drying time = 3 hrs.

*Solution**Assumptions*

- (1) Distance between top of dryer and top of plenum chamber = 15 cm
- (2) Angle of conical portion of plenum chamber = 45°
- (3) Diameter of grain outlet = 15 cm
- (4) Specific heat of grain = 0.4 kcal/(kg) (°C)

Height of the dryer

Height, $H = H_1 + H_2$

$$H_1 = H_2 + \frac{135}{2} \tan 45^\circ + 15 = H_2 + 82.5$$

$$H_2 = \frac{175 - 15}{2} \tan 50^\circ = 95.34 = 96 \text{ cm}$$

Volume of plenum chamber

V_1 = volume of inner cylinder + volume of inner cones

$$V_1 = \frac{\pi}{4} (135)^2 H_2 + 2 \cdot \frac{1}{3} \cdot \pi \left(\frac{135}{2} \right)^2 \left(\frac{135}{2} \tan 45^\circ \right)$$

$$\text{or } V_1 = 14313.88 H_1 - 536770.53 \quad (1)$$

Suppose V_2 = Volume of outer cylinder and hopper bottom

$$\therefore V_2 = \frac{\pi}{4} \times (175)^2 \times H_1 + \frac{1}{3} \cdot \pi \cdot \tan 50^\circ \left[\left(\frac{175}{2} \right)^2 - \left(\frac{15}{2} \right)^2 \right] \quad (2)$$

$$= 24055.9 H_1 + 831557 \text{ cm}^3$$

Volume of drying chamber = $V_2 - V_1$

$$= 24055.9 H_1 + 831557 - 14313.88 H_1 + 536770$$

$$= 9742.02 H_1 + 1368327 \quad (3)$$

$$\text{Volume of the drying chamber} = \frac{2000}{575} = 3.478 \text{ m}^3$$

$$= 3478000 \text{ cm}^3 \quad (4)$$

Hence from equations (3) and (4)

$$9742.02H_1 + 1368327 = 3478000$$

$$H_1 = 216 \text{ cm}$$

$$H_1 \approx 220 \text{ cm}$$

$$H_2 = 220 - 82.5 = 137.5 \text{ cm}$$

$$\therefore H_2 \approx 140 \text{ cm}$$

$$H_3 = 96 \text{ cm}$$

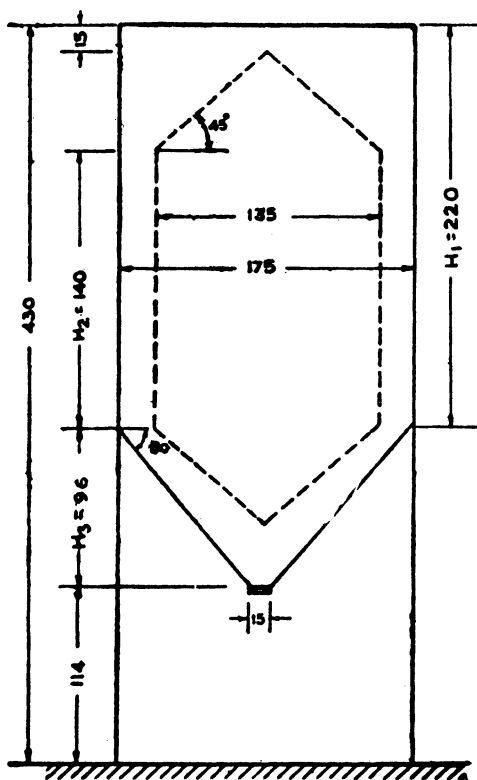


FIG. 6.1. Specifications of PHTC dryer as per solution of problem 1.

Air requirement

Bone dry paddy = $2000 (1 - 0.15) = 1700 \text{ kg.}$

Initial moisture content = 30 per cent w.b. = 42.857 per cent (d.b.)

Final moisture content = 15 per cent (w.b.) = 17.647 per cent (d.b.)

Weight of moisture evaporated

$$\begin{aligned} &= \text{Wt. of bone dry paddy} \times (X_1 - X_2) \\ &= 1700 (0.42857 - 0.17647) \\ &= 428.57 \text{ kg.} \end{aligned}$$

From psychrometric chart

Absolute humidity of ambient air = 0.019 kg/kg

Humid heat of ambient air

$$\begin{aligned} S &= 0.24 + 0.45 H \\ &= 0.24 + 0.45 \times 0.019 \\ &= 0.24855 \text{ kcal/(kg) } (^{\circ}\text{C}) \end{aligned}$$

Let G be the rate of air supply in kg/min

Heat supplied by the air in 180 min

$$\begin{aligned} &= G \cdot S \cdot (t_2 - t_1) \cdot \theta \\ &= G (0.24855) (85 - 40) \times 3 \times 60 \\ &= 2013.255 G \end{aligned} \quad (5)$$

Heat Utilised

(i) As sensible heat of grain

$$\begin{aligned} &= \text{B.D. grain} \times \text{sp. heat of grain} \times \text{temp. rise} \\ &= 1700 \times 0.4 \times (70 - 30) \\ &= 27200 \text{ kcal} \end{aligned} \quad (6)$$

(ii) As sensible heat of water

$$\begin{aligned} &= \text{total weight of water} \times \text{sp. heat of water} \times \text{temp. rise} \\ &= 1700 \times 0.42857 \times 1.0 \times (70 - 30) \\ &= 29140 \text{ kcal} \end{aligned} \quad (7)$$

(iii) As latent heat of water vapour

$$\begin{aligned} &= \text{water evaporated} \times \text{latent heat of water} \\ &= 428.57 \times 600 \\ &= 2,57,100 \text{ kcal} \end{aligned} \quad (8)$$

Total heat utilised = sum of (6), (7) and (8)

$$= 3,13,440 \text{ kcal} \quad (9)$$

Suppose, heat loss = 10 per cent

$$\text{Net heat required} = \frac{313440}{0.9} = 3,48,266.6 \text{ kcal}$$

Hence, 2013.255 $G = 3,48,266.6$

$$G = 172.987 \text{ kg/min}$$

From psychrometric chart, humid volume of the ambient air

$$= 0.88 \text{ m}^3/\text{kg}$$

$$\text{So air required} = 172.987 \times 0.884$$

$$= 152.92 \text{ m}^3/\text{min}$$

$$\text{Air requirement} = 155 \text{ m}^3/\text{min}$$

Static pressure drop

Surface area of plenum chamber

$$= \pi \times 135 \times 140 + \left[\frac{1}{2} \pi \times 135 \times \left(\frac{135}{2} \sec 45^\circ \right) \right] \times 2$$

$$= 59383.8 + 28627.76$$

$$= 88011.56 \text{ cm}^2$$

Since maximum 50 per cent of the area is perforated, area through which air passes = 44005.78 cm²

$$\text{Air requirement per m}^2 = \frac{155}{4.400578}$$

$$= 35.1 \text{ m}^3/\text{min/m}^2$$

From Shedd's curve (Agri. Engg. Handbook) static pressure drop for 32.12 m³/min/m² = 8.13 cm of water per 30.48 cm grain depth.

Depth of grain = 20 cm

$$\text{So pressure drop} = \frac{8.13}{30.48} \times 20 = 5.42 \text{ cm of water}$$

Density of air = 1.13/kg/m³

$$\begin{aligned} \text{Pressure drop in terms of air column} &= \frac{5.42}{100} \times \frac{1000}{1.13} \\ &= 47.95 \text{ m} \end{aligned}$$

H.P. required

$$= \frac{\text{Height of air column (m)} \times \text{air flow rate (kg/min)}}{4500}$$

$$= \frac{47.95}{4500} \times 172.987$$

$$= 1.868 \text{ hp}$$

$$\approx 2 \text{ hp.}$$

(2) Design a LSU Dryer of 2 tonnes holding capacity with

paddy at 15 per cent m.c. (w.b.). Data for grain and air parameters are same as in the previous problem. Additional data are given below.

Cross-section of the dryer	= $1.2 \times 1.2 \text{ m}^2$
Air velocity in the air ports	= 5 m/sec
Pitch of the air ports	= 40 cm
Row to row spacing	= 20 cm
Grain residence time	= 30 minutes

Solution

The heat and mass balance for the dryer are same as those in the previous problem.

Hence, air required = $155 \text{ m}^3/\text{min}$

Since velocity of air inside the air port or duct is 5 m/sec
total cross-sectional area of ducts required

$$= \frac{155}{5 \times 60} = 0.5167 \text{ m}^2$$

Let the height of drying chamber be $h \text{ cm}$

Therefore, volume of drying chamber

$$V = \text{Volume of the drying chamber} - \text{Volume of ducts} \\ = 1.2 \times 1.2 \times h - 0.5167 \times 1.2$$

$$V = (1.44h - 0.620) \text{ m}^3 \quad (1)$$

The holding capacity of the dryer is given as 2 tonnes of paddy at 15 per cent m.c. (w.b.) and the bulk density of paddy at 15% m.c. is $= 575 \text{ kg/m}^3$

$$\text{Hence, volume } V = \frac{2000}{575} = 3.478 \text{ m}^3 \quad (2)$$

Substituting for V in equation (1)

$$1.44h - 0.620 = 3.478$$

$$1.44h = 4.098$$

$$h = 2.846 \text{ m}$$

Height of the grain holding bin = 35 cm (assumed)

Height of the hopper bottom = 60 cm (approx.)

According to spacing, number of ducts in a row = 3

and number of rows in 2.85 m = 14

Total number of ducts = 39 (leaving 1 row for discharge rolls)

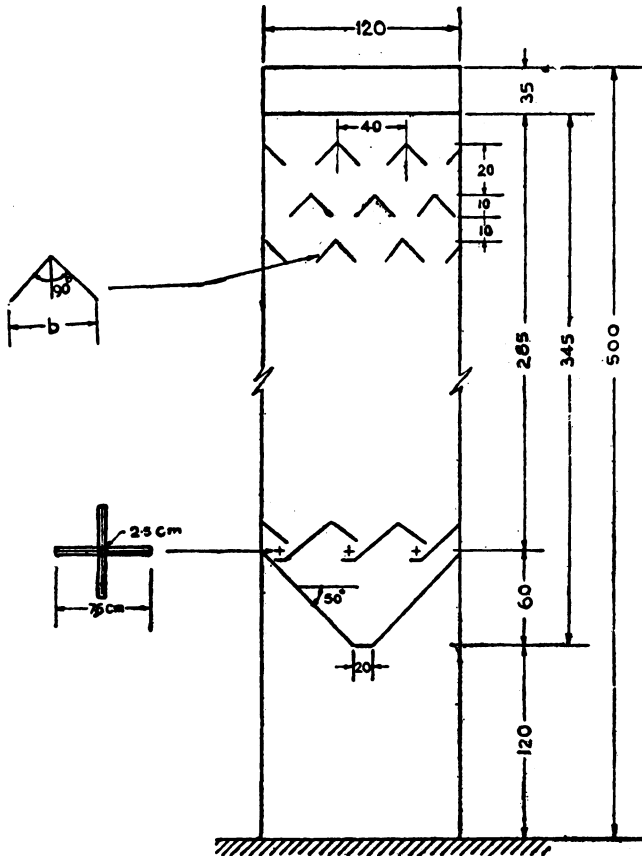
$$\begin{aligned}\text{Cross-sectional area of each duct} &= \frac{0.5167}{39} \times 10^4 \text{ cm}^2 \\ &= 132.5 \text{ cm}^2\end{aligned}$$

$$\text{Cross-sectional area of each duct} = \frac{1}{2} b \cdot \frac{b}{2}$$

$$\text{or } \frac{b^2}{4} = 132.5$$

$$\text{or } b = 23.02 = 23 \text{ cm}$$

Let there be three discharge rolls having shaft diameter 2.5 cm and flute diameter 7.5 cm



All dimensions in cm

FIG. 6.2 Specifications of LSU dryer as per solution of problem 2.

Volume discharged by each roll in one revolution

$$\begin{aligned}
 &= \frac{\pi}{4} (D_o^2 - D_i^2) L \\
 &= \frac{\pi}{4} (7.5^2 - 2.5^2) 120 \\
 &= 4712.39 \text{ cm}^3.
 \end{aligned}$$

∴ Volume discharged by 3 rolls = $0.014137 \text{ m}^3/\text{revolution}$

Wt. of paddy discharged = $0.014137 \times 575 = 8.129 \text{ kg/revolution}$

Since the grain retention time in the dryer is 30 minutes,

$$\text{grain discharge rate} = \frac{2000}{30} = 66.67 \text{ kg/min}$$

$$\therefore \text{Roller speed} = \frac{66.67}{8.129} = 8.2 \text{ rpm} \approx 8 \text{ rpm}$$

Specifications of the LSU dryer of 2 tonnes grain holding capacity :

- Total height of the dryer = 3.8 m
- Height of drying chamber = 2.85
- Height of the holding bin = 0.35 m
- Height of the hopper bottom = 0.60 m
- Number of feed rolls = 3
- Grain outlet diameter = 20 cm
- Space between inlet and outlet duct = 20 cm
- Pitch of ducts in a row = 40 cm
- Blower capacity = $155 \text{ m}^3/\text{min}$ with static pressure 5 cm (W.G)
- Blower motor hp = 2
- Duct dimensions : height = 11.5 cm, width = 23 cm
- Speed of the discharge roll = 8.0 rpm

Exercises

(1) From the following data determine the rate of air supply in a grain dryer :

- (a) Holding capacity of the dryer — 6 Tonnes
- (b) Initial m.c. of the parboiled paddy — 30 per cent (w.b.)
- (c) Final m.c. of the parboiled paddy — 15 per cent (w.b.)
- (d) Ambient air temp. — 30°C
- (e) Heated air temp. — 85°C
- (f) Exhaust air temp. — 40°C

- (g) Grain temp. (at inlet) — 30° C
- (h) Grain temp. (at outlet) — 70° C
- (i) Relative humidity of air before heating — 70 per cent
- (j) Total drying time — 3 hrs
- (k) Loss of heat to the surroundings — 20 per cent

(2) Design a recirculating RPEC dryer of 1.25 tonnes holding capacity. Diameter of the plenum chamber (inner cylinder) is 90 cm. Assuming other necessary data as in Example No. 1, determine (i) height of the inner and outer cylinders, (ii) total height of the dryer, (iii) air flow rate, and (iv) H.P. requirement of the blower.

(3) Design a L.S.U. dryer of 2 tonnes/hr capacity. The square cross section of the rectangular chamber is 2.02×2.02 m². Assume other necessary data as in Example No. 2. Calculate (i) total height of the dryer, (ii) number of air ports required, (iii) speed of the discharge roll, and (iv) H.P. of the motor for the discharge rolls.

(4) Assuming all necessary data, design a baffle type grain dryer of 1.25 tonnes holding capacity.

(5) A static deep bed rectangular batch dryer of 1 tonne holding capacity has to be designed. The temperature of the ambient and drying air are 25° C and 40° C respectively. Assuming other necessary data determine (i) the dimensions of the drying chamber and plenum chamber and (ii) capacity of the blower.

SYMBOLS

C_g	= specific heat of grain, kcal/kg° C
C_w	= specific heat of water, kcal/kg° C
C_u	= calorific value of fuel, kcal/kg
f	= rate of fuel consumption, kg/min
G	= volumetric air flow rate, m ³ /min
G'	= air flow rate, kg/min
H_1	= humidity of ambient air, kg/kg
H_2	= humidity of heated air, kg/kg
H_3	= humidity of exhaust air, kg/kg
X_1	= initial moisture content of grain, (d.b), kg/kg

X_2	= final moisture content of grain (d.b), kg/kg
q	= heat required for heating the grain and moisture, kcal
q_1	= latent heat required for evaporating grain moisture, kcal
q_a	= total heat required for drying, kcal
q'_a	= heat required to heat the drying air, kcal
RH_1	= relative humidity of ambient air, per cent
RH_2	= relative humidity of drying air, per cent
RH_3	= relative humidity of exhaust air, per cent
t_1	= temperature of the ambient air, °C
t_2	= temperature of the drying air, °C
t_3	= temperature of the exhaust air, °C
v_1	= humid volume of the ambient air, m ³ /kg
W_d	= weight of bone dry grain, kg

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