UNIT 5 GRAIN DRYING PRINCIPLES AND TECHNOLOGY

Structure

5.0 OBJECTIVES

After reading this unit you should be able to:

- explain the principles of grain drying applicable to paddy;
- know the principle behind thin layer and deep bed drying;
- compute thermal and mechanical energy requirement for drying;
- understand the drying characteristics of raw and parboiled paddy;
- explain the principle of various types of grain dryers; and
- understand the basis of selection of air blowers for drying.

5.1 INTRODUCTION

Paddy is usually harvested at a moisture content higher than that at which it can be safely stored/processed and therefore must be subjected to some type of conditioning. Drying is the principal method of conditioning paddy for storage. Drying of paddy starts in the field after the grain has reached maturity. At maturity and the beginning of the drying, the grain gradually decreases its dependence on the plant environment. The moisture content of the grain becomes subject to the ambient environment in which it exists. The temperature and moisture of the ambient air as well as the maturity of the grain largely determine the rate at which a grain will dry. Drying takes place when the vapour pressure in a rice grain is greater than that in the surrounding air. Since moisture is removed at the surface of grain, a moisture gradient develops within the grain, with the centre having a higher moisture content than the surface. The rate of internal moisture movement can be increased by increasing the vapour pressure difference between the grain and the ambient air. Ordinarily this is accomplished by heating the ambient air which in turn heats the grain. Since the grain is hygroscopic it is dynamic and physically responds to moisture and temperature changes to which it is exposed.

5.2 APPLICATIONS OF PSYCHROMETRIC CHART IN DRYING OPERATION

Psychrometric chart is a graphical representation of thermodynamic properties of air. In this chart the absolute humidity, percent humidity, humid volume, enthalpy, and adiabatic saturation lines are drawn against air temperatures. Various applications of psychrometric chart in drying operation are enumerated below.

5.2.1 Sensible Heating and Cooling

This occurs when either hot or cold flows over a surface. During the process humidity remains constant and a horizontal line on psychrometric chart expresses it. The directions of sensible heating and cooling are opposite to each other (Fig 5.1).

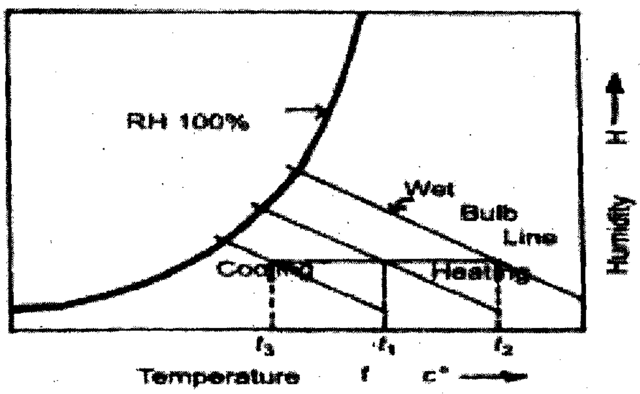


Fig. 5.1 : Heating and cooling (*Courtesy:* Chakraverty A)

5.2.2 Adiabatic Cooling or Drying

The cooling of air, without any heat transfer, by evaporation of water is adiabatic cooling. This generally occurs during the food drying process. It is also expressed by line slanted vertically (Fig.5.2).

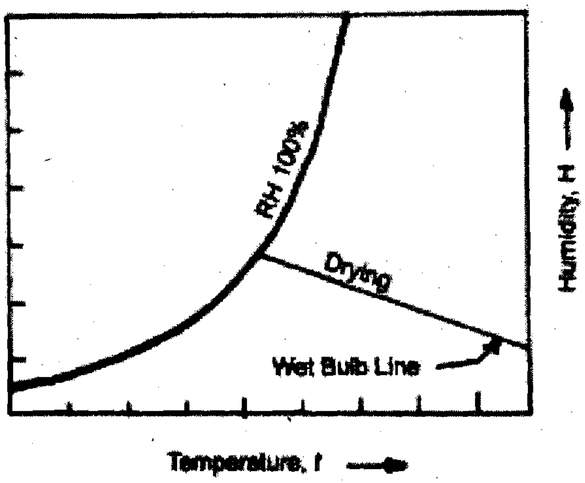


Fig. 5.2 : Adiabatic cooling/drying (*Courtesy:* Chakraverty A)

5.2.3 Heating and Humidification

It occurs in cooling tower, where air picks up heat and moisture from the spraying water. A slanted line going upward shows the heating and humidification process. Actual drying process can be shown in psychrometric chart as given in Fig 5.3.

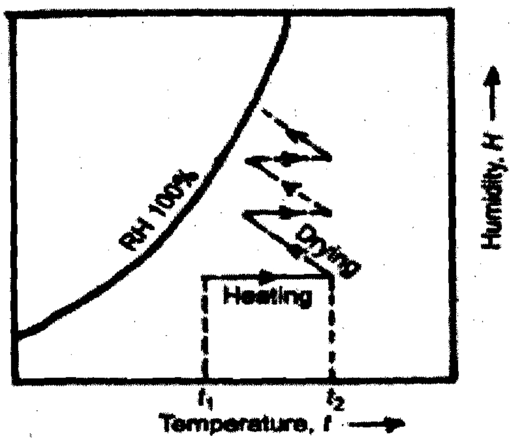


Fig. 5.3. Heating, drying, reheating and recycling (*Courtesy:* Chakraverty A)

5.2.4 Cooling and Dehumidification

It occurs when the air is cooled below its dew point. A slanted line going downwards shows it (Fig.5.4).

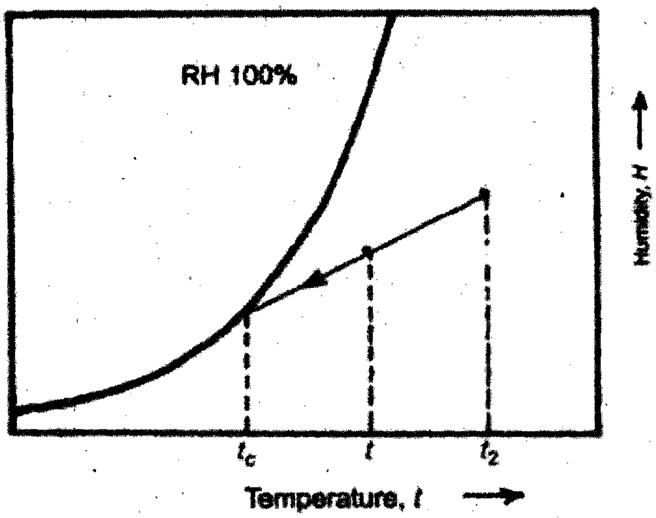


Fig. 5.4 : Cooling and dehumidifying (*Courtesy:* Chakraverty A)

5.2.5 Mixing of Two Air Streams

When two streams of air with different mass flow rates, temperature, and humidity ratios are mixed, the conditions of resulting mixture can be determined directly on the psychrometric chart.

Consider two air streams with mass flow rates m_1 and m_2, temperature T_1 and T_2, enthalpies h_1 and h_2 and humidity ratios H_1 and H_2. They are mixed and the mixture has a mass flow rate m_3, temperature T_3, enthalpy h_3 and humidity ratio H_3.

The overall mass balance for these air streams can be written as

$$m_1 + m_2 = m_3 \quad ...(5.1)$$

Also component mass balance for water vapour can be given as

$$m_1 H_1 + m_2 H_2 = m_3 H_3 \quad ...(5.2)$$

and enthalpy balance for the two streams can be expressed as

$$m_1 h_1 + m_2 h_2 = m_3 H_3 \quad ...(5.3)$$

Substituting value of m_3 from equation (1) in equation (2) and (3)

$$m_1 H_1 + m_2 H_2 = (m_1 + m_2) H_3$$

or $$m_1(H_1 - H_3) = (H_3 - H_2) m_2 \quad ...(5.4)$$

and $$m_1 h_1 + m_2 h_2 = (m_1 + m_2) h_3$$

$$m_1 (h_1 - h_3) = (h_3 - h_2) m_2 \quad ...(5.5)$$

rearranging equation (4) and (5) gives

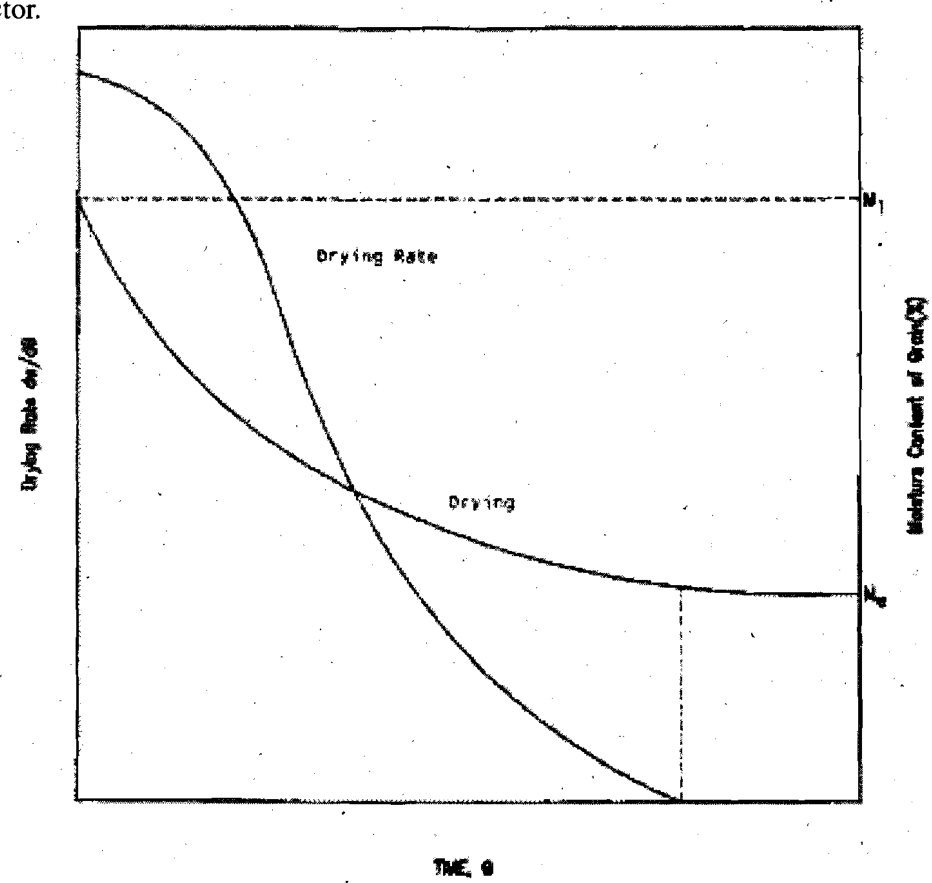
$$\frac{m_1}{m_2} = \frac{h_3 - h_2}{h_1 - h_3} = \frac{H_3 - H_2}{H_1 - H_3} \quad .....(5.6)$$

The condition of the mixture of the two air stream lies on a straight line joining (h_1 and H_1) and (h_2 and H_2) on h-H psychrometric chart. The point (h_3, H_3) can be found algebraically or by applying the rule of congruent directly on the psychrometric chart.

5.3 THEORY OF GRAIN DRYING

In the process of drying heat is necessary to evaporate moisture from the grain and a flow of air is needed to carry away the evaporated moisture. There are two basic mechanisms involved in the drying process; the migration of moisture from the interior of an individual grain to the surface, and the evaporation of moisture from the surface to the surrounding air. The rate of drying is determined by the moisture content and the temperature of the grain and the temperature, the (relative) humidity and the velocity of the air in contact with the grain.

Figure 5.5 demonstrates the drying of a single layer of grain exposed to a constant flow of air. The moisture content falls rapidly at first but as the grain loses moisture the rate of drying slows down. In general the drying rate decreases with moisture content, increases with increase in air temperature or decreases with increase in air humidity. At very low air flows rates, increasing the velocity causes faster drying but at greater velocities the effect is minimal indicating that moisture diffusion within the grain is the controlling factor.



M_i — Initial Moisture content, and M_e — Equilibrium Moisture content

Fig. 5.5 : Drying of a single layer of grain exposed to a constant flow of air (*Courtesy:* FAO, Rome)

Grains are hygroscopic and will lose or gain moisture until equilibrium is reached with the surrounding air. The equilibrium moisture content (EMC) is dependent on the relative humidity and the temperature of the air; EMCs for a range of grains are shown in Table 1.

Table 5.1: Equilibrium moisture content of grains with respect to relative humidity

Grain	Relative Humidity (%) 30	40	50	60	70	80	90	100
	Equilibrium Moisture Content (%wb*) at 25°C							
Barley	8.5	9.7	10.8	12.1	13.5	15.8	19.5	26.8
Shelled Maize	8.3	9.8	11.2	12.9	14.0	15.6	19.6	23.8
Paddy	7.9	9.4	10.8	12.2	13.4	14.8	16.7	-
Milled Rice	9.0	10.3	11.5	12.6	12.8	15.4	18.1	23.6
Sorghum	8.6	9.8	11.0	12.0	13.8	15.8	18.8	21.9
Wheat	8.6	9.7	10.9	11.9	13.6	15.7	19.7	25.6

* wet basis

Source: Brooker *et al.* (1974)

The relationship between EMC, relative humidity and temperature for many grains has been modelled by numerous researchers; the results of which have been summarized by Brooker *et al.* (1974).

It is very important to appreciate the practical significance of the EMC. Under no circumstances is it possible to dry to a moisture content lower than the EMC associated with the temperature and humidity of the drying air; for example, the data in Table 5.1 show that paddy can only dry to a moisture content of 16.7% when exposed to air at 25 °C and 90% relative humidity. If paddy at moisture content less than 16.7% is required then either the temperature of the drying air has to be increased or its humidity reduced.

The drying of grains in thin layers where each and every kernel is fully exposed to the drying air can be represented in the form:

$$MR = f(T, h, t) \qquad \ldots(5.7)$$

$$MR = \frac{MC - MC_e}{MC_o - MC_e} \qquad \ldots(5.8)$$

Where,

MR is moisture ratio

MC is the moisture content of the grain at any level and time, % dry basis (%db)

MC_e is the equilibrium moisture content (%db)

MC_o is the initial moisture content of the wet grain (%db);

T is the air temperature (°C)

h is the air relative humidity

t is the drying time(min)

Empirical data have been used to determine mathematical approximations of the relationship between drying rate and air conditions. Relationships for many grains have been summarized by Brook & Foster (1981). For example, a thin layer equation for paddy

$$MR = \exp.(-X * t^Y) \qquad \ldots(5.9)$$

Where $X = 0.026 - 0.0045h + 0.01215T$; and

$Y = 0.013362 + 0.194h - 0.000177h^2 + 0.009468T$,

with h expressed as a percentage, and T in °C.

In the drying of grain in a deep bed, whilst individual kernels may all be losing moisture at different rates, the overall drying rate will remain constant for a long period. The air absorbs moisture as it moves through the bed until it becomes effectively saturated and moves through the remaining layers of grain without effecting further drying. Figure 5.6A shows the three zones present within a thick drying bed at an intermediate time within the drying operation. Drying takes place within a discrete zone, the size of which depends on the moisture content of the grain and the temperature, humidity and velocity of the air. Below the drying zone is the dried zone where the grain is in equilibrium with the air. Above the drying zone is the un-dried zone wherein the grain remains unchanged from its initial condition.

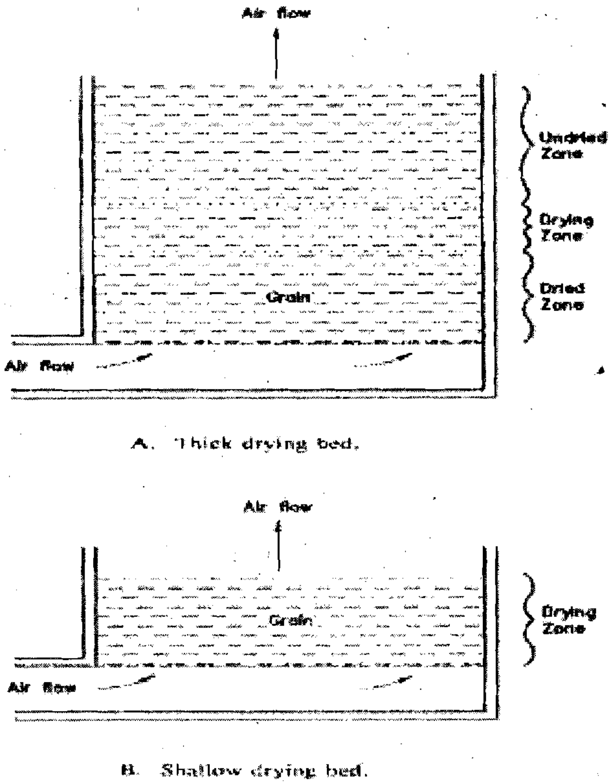


Fig. 5.6: Drying zones in thick and thin layer Drying (*Courtesy:* FAO, Rome)

In a shallow bed as in Figure 5.6B the drying zone is thicker than the bed depth and drying would occur initially throughout the bed.

The change in temperature and humidity of air as it moves through a bed of grain depends on the rate at which moisture is being evaporated from each kernel as an individually exposed element. Knowledge of the effect of grain moisture content, other grain properties, the temperature, humidity and flow rate of the air upon fully exposed kernels is essential for an understanding of how drying would proceed within a bed.

Accurate prediction of drying time is further inhibited by the variability of key factors encountered in practice, particularly so for the simple drying systems that are the most appropriate for use in developing countries. For example the moisture content of individual grains is likely to vary considerably within a batch and in the case of drying with a heater of constant heat output the temperature of the drying air will vary with changes in ambient air temperature.

5.3.1 Air Properties

The properties of the air flowing around the drying grain are a major factor in determining the rate of removal of moisture. The capacity of air to remove moisture is principally dependent upon its initial temperature and humidity; the greater the temperature and lower the humidity the greater the moisture removal capacity of the air.

The relationship between temperature, humidity and other thermodynamic properties is represented by a psychrometric chart as shown in figure 5.7. It is important to appreciate the difference between the absolute humidity and relative humidity of air. The absolute humidity is the moisture content of the air (mass of water per unit mass of air) whereas the relative humidity is the ratio, expressed as a percentage, of the moisture content of the air at a specified temperature to the moisture content of air if it were saturated at that temperature.

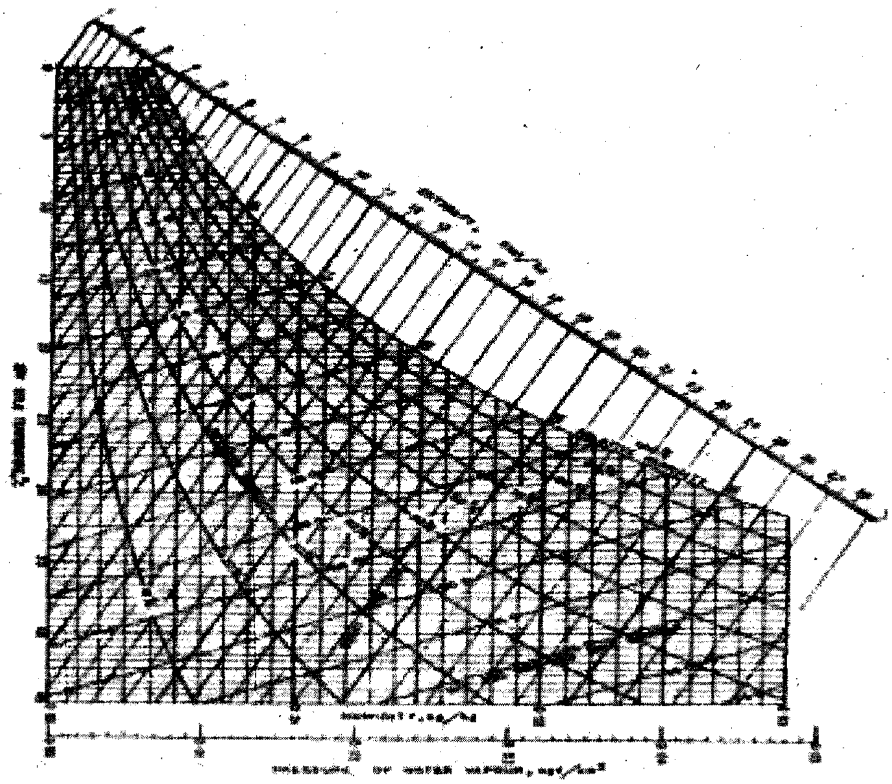


Fig. 5.7 : Psychrometric chart (*Courtesy:* Chakraverty A)

The changes in air conditions when air is heated and then passed through a bed of moist grain are shown in Figure 5.8. The heating of air from temperature TA to TB is represented by the line AB. During heating the absolute humidity remains constant at HA whereas the relative humidity falls from hA to hB. As air moves through the grain bed it absorbs moisture. Under (hypothetical) adiabatic drying sensible heat in the air is converted to latent heat and the change in air conditions is represented along a line of constant enthalpy, BC. The air will have increased in both absolute humidity, Hc, and relative humidity, hc, but fallen in temperature, Tc. The absorption of moisture by the air would be the difference between the absolute humidities at C and B. (H_C-H_A).

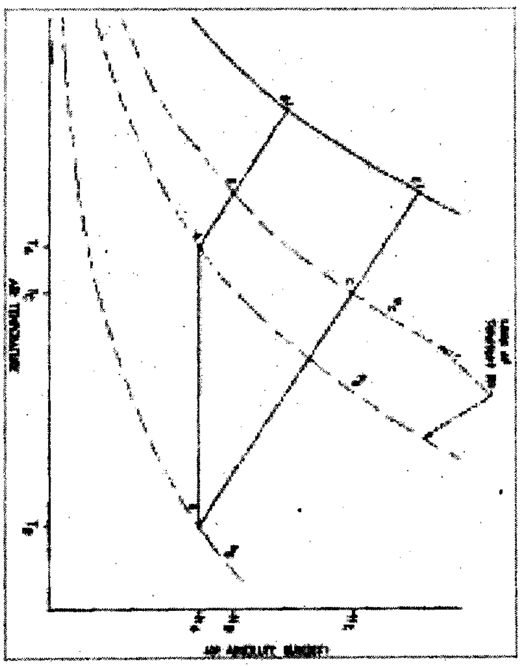


Fig. 5.8 Changes in air conditions when air is heated and then passed through a bed of moist grain (*Courtesy:* FAO, Rome)

If unheated air was passed through the bed the drying process would be represented along the line AD. Assuming that the air at D was at the same relative humidity, hc, as the heated air at C then the absorbed moisture would be (H_D-H_A), considerably less than that absorbed by the heated air (H_C-H_A).

5.3.2 Physical Properties of Grain

a) **Moisture Content:** The moisture content of the food grains and other agricultural products plays an important role in marinating the desirable quality of the product.

Changes in moisture content of agricultural material occur during harvesting, processing and marketing. The change in moisture content during successive post harvest stages is dependent upon the initial moisture content of the product and atmospheric conditions. The information of moisture content is necessary because it tells us whether the product is suitable for safe storage or for any other processing job. For some period, if the moisture content of food grains increases beyond a fixed critical value, under such conditions chances of metabolic reactions inside the grain become higher. Due to such reactions, viability of seed reduces. Drying of agricultural products become necessary at higher moisture contents.

Moisture content representation: The amount of moisture in a product is given on the basis of the weight of water present in the product and is usually expressed in percent. Moisture content is designated by two methods, (1) Wet basis (wb) and (2) dry basis (db).

Wet basis: The moisture content in this method is represented by the following expression,

$$\text{Per cent moisture content} = \frac{\text{Weight of water in product}}{\text{Weight of product in sample}} \text{ X } 100$$

Dry basis: In this method of representing moisture content; it is given on the basis of dry weight of product. The dry basis moisture content is determined by the following expression

$$\text{Per cent moisture content} = \frac{\text{Weight of water in product}}{\text{Weight of dry matter of product sample}} \text{ X } 100$$

The value of dry basis moisture content is more than the wet basis moisture content. The relationship between dry basis and wet basis moisture content is given by the following expression.

$$\text{Moisturecontent (dry basis),\%} = \frac{\text{Moisturecontent (wet basis in decimals)}}{\text{1-Moisturecontent (wet basis in decimals)}} \text{ X } 100$$

b) **Bulk Density:** The bulk density of grain is the weight per unit volume. Moisture content has an appreciable effect on the bulk density.

c) **Resistance to air flow:** The energy required to force air through a bed of grain is dependent on the air flow, the grain depth and physical properties of the grain such as surface and shape factors, the kernel size distribution, moisture content, and the quantity and nature of contamination, stones, straw, weeds etc. The relation between air flow and the pressure drop generated across the bed for selected grains is illustrated in Figure 5.10. The data generally refer to clean and dry grain and correction factors of up to 1.4 are used for very wet and dirty grain.

d) **Latent Heat of Vaporization:** Energy in the form of heat must be supplied to evaporate moisture from the grain. The latent heat of vaporization, Lh, for a grain depends on its moisture content and temperature and is appreciably greater than the latent heat of evaporation of water. Data for different grains have been reported by Brooker *et al.* (1974).

5.3.3 Drying Operations

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

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

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

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

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

Teter (1987) noted that seed paddy can be sun dried at depths of up to 30 mm but that the final stages of drying to 12% moisture should be conducted in the shade to avoid overheating and kernel cracking. Flat-bed dryers can be used with bed depths of up to 0.3 m, air temperatures not exceeding 40°C, and airflows of 1.3-1.7 m^3/s per tonne of grain.

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

f) **Air Movement :** The selection and sizing of a fan to move air through a dryer is very important. The major resistance to the flow of air comes from the grain bed; the pressure drop through the bed support and ducting is of lesser effect, particularly for deep beds. The pressure drop across a grain bed is a function of the depth, the air velocity and the grain itself. Data such as those in Figure 5.10 should be used to evaluate the pressure drop across the grain bed for a given application. It is important to note the major effect of dockage upon the pressure drop generated.

For most situations either axial-flow or centrifugal fans are used. The axial-flow fan moves air parallel to its axis and at right angles to the field of rotation of its blades. With the centrifugal fan the air enters parallel to the drive shaft, moves radially through the blades and is discharged tangentially from the housing surrounding the impeller. Axial-flow fans can be easily mounted in-line in the ducting and are relatively inexpensive but are only capable of operation against pressure drops of less than 1,500 Pa. Compared with axial-flow fans centrifugal fans can operate against higher pressure drops and are quieter in use but are more expensive.

Brooker *et al.* (1974) provide comprehensive information on the selection and operation of fans. It should be noted, particularly for large-scale dryers containing perhaps hundreds of tonnes of grain, that the risks of mechanical or electrical failure of the fan is likely to result in considerable losses if the fan cannot be repaired within a day or two. Consideration should be given therefore to installation of a back-up fan, particularly in locations where repair facilities are limited.

g) **Air Heating:** Heaters can be divided into two types, direct and indirect. In direct heaters the fuel is burnt in situ with the drying air so that the products of combustion pass through the drying bed with the air. Heaters of this type are less expensive and more energy efficient; however, the quality of the grain may be lowered due to contamination with combustion products, particularly if the heater is poorly maintained. In indirect heaters the combustion air does not come into contact with the drying air and a heat exchanger is used to raise the temperature of the latter. Depending on the type of heat exchanger as much as 25 % of the heat may be lost; however, there is no danger of contamination of the grain.

Air for drying can be heated by gas and oil and also solid fuels such as coal, wood and biomass residues. Oil-fired heaters are the most common for use with small on-farm dryers. Oil-fired and gas-fired heaters for all sizes of dryers are commercially available as described by Araullo *et al.* (1976), Brookeret *et al.* (1974) and Wimberly (1983). Small heaters are usually transportable and are easily positioned on the suction side of the fan so that the hot air from the heater is drawn into the plenum chamber by the fan together with ambient air.

5.4 DRYING RATE AND DRYING TIME COMPUTATION

A basic design procedure for the field worker is best illustrated for the design of a batch type dryer although the principles can be applied to a certain extent in the design of continuous multi-stage systems.

Assumed ambient air conditions are a dry bulb temperature of Ta and a relative humidity of RHa; from the psychrometric chart the wet bulb temperature, Twa, the enthalpy, Ha, and the absolute humidity ha can be derived. The air is heated to a selected safe drying temperature, Tb, thereby raising the enthalpy of the air to Hb.

The wet grain of equivalent bone-dry mass G has a moisture content of MCw% (db) and is to be dried to a moisture content of MCd%. A mass air flow of V is available.

The moisture, M, to be removed

$$M = G * (MC_w - MC_d) \qquad \text{...(5.11)}$$

It is assumed that throughout the drying period the air will exhaust from the bed at a constant wet bulb temperature and in equilibrium with the uppermost layers of grain. Initially the exhaust air will be in equilibrium with grain at MCw moisture and finally in equilibrium with grain at MCd moisture. By superimposing equilibrium moisture content data on to the psychrometric chart for the initial and final moisture contents the humidity of the exhaust air at the beginning and end of drying can be found. An average of the initial and final exhaust air relative humidities, h_{ea} is taken for calculation of drying time, t_d.

$$t_d = \frac{M}{V \times (h_a - h_{ea})} \qquad \text{...(5.12)}$$

An alternative, more complex but more accurate method for the estimation of drying performance is the technique based on dimensionless drying curves as initially developed by Hukill (1947). The methodology permits the estimation of the moisture content of grain at any level within the bed at any time after initiation of drying. It can be used for any grain for which EMC and thin layer drying data are available as is the case for most cereal grains.

The methodology involves the use of bulk drying curves as depicted in figure 5.9 and calculation of three parameters, moisture ratio, time unit and depth factor.

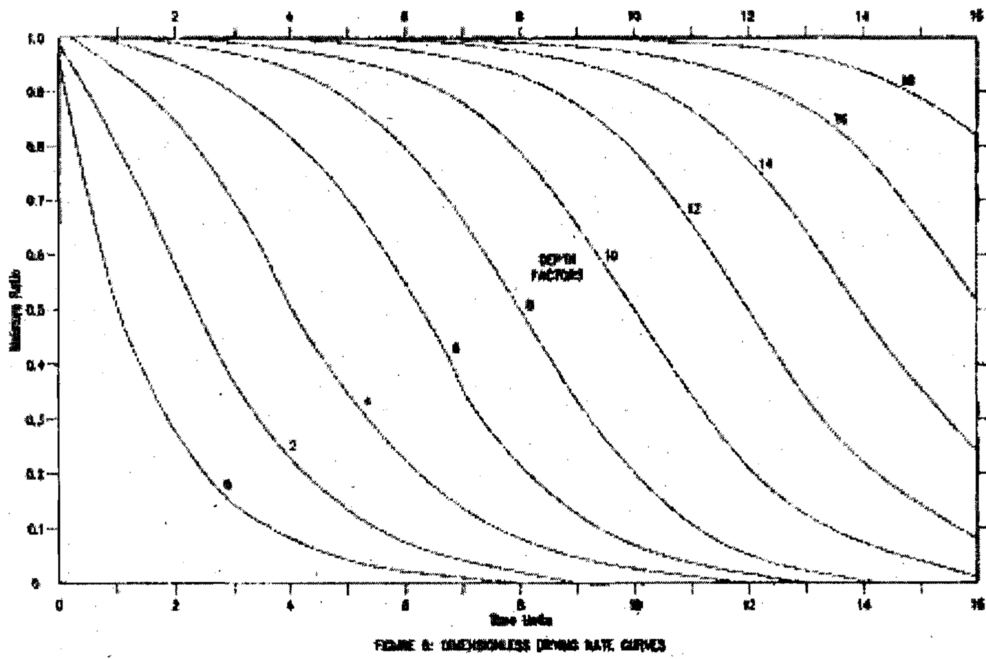


Fig. 5.9: Bulk drying curves (*Courtesy:* FAO, Rome)

The moisture ratio, MR is calculated from equation

$$MR = \frac{MC - MC_e}{MC_o - MC_e} \qquad \text{...(5. 13)}$$

The time unit, Y, is calculated using the equation:

$$Y = \frac{t_d}{t_{0.5}} \qquad \text{...(5.14)}$$

Where $t_{0.5}$ is the half-response time, the time required for fully exposed grain to reach a moisture ratio of 0.5 under the drying air conditions employed. It can be calculated from the thin layer drying equations as in Equation 5.9 with MR assigned a value of 0.5.

The depth factor, D, is defined as the depth of the bed that contains the mass of grain, DM, that can be dried from the initial moisture ratio MR = 1 to a final moisture ratio MR = 0 with the sensible heat available over the period of one half-response time as the air cools to its wet bulb temperature. DM is calculated thus

$$DM = \frac{V \times C_p \times t_{0.5} \times (T_{dh} - T_{wa})}{L_h \times (MC_o - MC_e)} \quad \ldots(5.15)$$

where C_p is the specific heat of air. The number of depth factors within the bed is found from the expression:

$$D = d \times \frac{G}{DM} \quad \ldots(5.16)$$

Where d is the bed depth.

The curves in Figure 5.9 are represented by the equation:

$$\mathrm{MR} = \frac{2^{\mathrm{D}}}{2^{\mathrm{D}} + 2^{Y} - 1} \quad \ldots(5.17)$$

By transposing the drying conditions to these units and using Figure 5.9, it is possible to predict when any layer within the bed reaches desired moisture content.

The drying conditions for specific grains and situations are many and varied. Drying will take place under any conditions where grain is exposed to a flow of unsaturated air. Very fast drying can be accomplished using large volumes of high temperature air but, if carried through to completion, is likely to be inefficient in energy use and liable to damage the grain by over-heating and/or over-drying. Conversely slow drying, as in sun drying in inclement weather, provides conditions for continued respiration and deterioration of the grain leading to both quantitative and qualitative losses and the growth of moulds.

5.4.1 Evaluation of Grain Dryers

After purchase or installation of a grain dryer it is important to evaluate its performance. This is usually done by conducting a drying test. Drying tests are important because actual performance data is often different from rated performance that is provided by the manufacturer. The following is a general procedure for evaluation of a grain dryer.

5.4.2 Drying Test

Paddy/rice of a known source should be selected with grain MC of 20% to 25%. The paddy should be cleaned so there are very few impurities (straws, etc) in it.

Before loading the material, mix the paddy and take at least 10 samples of the paddy of 10g each to determine variance in moisture content. In addition, sample 500g of wet paddy for laboratory analysis. If possible, take the entire weight of the paddy before loading.

Load the paddy and start the dryer. Measure the time that it took to load the dryer. Note the time that it takes to dry the paddy down to 14% MC. If possible, measure power consumption with a watt hour meter and measure fuel consumption with a flow meter. Alternatively, fuel consumption can be estimated by taking the initial weight or volume of the fuel and the final fuel weight after drying is completed.

During the drying process, measure drying air temperature with a thermometer at different locations in the dryer. After drying is completed, take the weight of the entire batch of dried grain. Also, take at least 10 samples of 10g for moisture content and one 500g sample for laboratory analysis.

5.4.3 Laboratory Analysis

Conduct a milling analysis of the pre-dried and post-dried sample that includes at least crack detection, milling yield, head rice recovery and discoloration.

5.4.4 Reporting

Calculate the following data to characterize the performance of the dryer:

- Average and standard deviation of the moisture content before and after drying.
- Total weight loss of paddy
- Drying rate (%/h)
- Increment in broken grain (i.e. percentage of broken grains before drying minus percentage of broken grains after drying)
- Increment in cracked grain (i.e. percentage of cracked grains before drying minus percentage of cracked grains after drying)
- Electric power consumption
- Fuel consumption

5.4.5 Drying Efficiency

The efficiency of the drying operation is an important factor in the assessment and selection of the optimum dryer for a particular task. There are three groups of factors affecting drying efficiency:

➢ those related to the environment, in particular, ambient air conditions;

➢ those specific to the crop;

➢ those specific to the design and operation of the dryer.

There are several different ways of expressing the efficiency of drying, of which the 'Sensible Heat Utilization Efficiency' (SHUE), the fuel efficiency, and the drying efficiency are the most useful.

The SHUE takes into account the sensible heat attributable to the condition of the ambient air and any heat added to the air by the fan as well as the heat supplied by combustion of the fuel. It is defined as:

$$\text{SHUE} = \frac{\text{Heat utilized for moisture removal}}{\text{Total sensible heat in the drying air}}$$

The fuel efficiency is based only on the heat available from the fuel:

$$\text{Fuel efficiency} = \frac{\text{Heat utilized for moisture removal}}{\text{Heat supplied for fuel}}$$

It can be appreciated that the fuel efficiency would be significantly different for the operation of the same dryer at two locations with widely different ambient conditions.

With low temperature drying, particularly in dry climates, the heat supplied from the fuel may be less than half of the total sensible heat and the fuel efficiency may exceed 100%. Direct comparison of the performance of dryers at separate locations is not possible using the fuel efficiency.

The drying efficiency, defined as

$$\text{Drying efficiency} = \frac{\text{Heat utilized for moisture removal}}{\text{Heat available for moisture removal}}$$

It is the expression to be used for evaluation of dryer designs or comparison between dryers, since it is a measurement of the degree of utilization of the sensible heat in the drying air.

Foster (1973) evaluated the fuel and drying efficiencies of several types of dryers used with maize. Over a wide range of conditions, continuous-flow dryers were found to have a fuel efficiency of 38% and a drying efficiency of 51%, batch dryers 42% and 58%, dryeration 61% and 78%, and two-stage drying, 60% and 79%, respectively.

5.4.6 Effect of Drying on Grain Quality

The drying operation must not be considered as merely the removal of moisture since there are many quality factors that can be adversely affected by incorrect selection of drying conditions and equipment. The desirable properties of high-quality grains include:

- low and uniform moisture content;
- minimal proportion of broken and damaged grains;
- low susceptibility to subsequent breakage;
- high viability;
- low mould counts;
- high nutritive value;
- consumer acceptability of appearance and organoleptic properties.

5.4.7 Appearance and Organoleptic Properties

The colour and appearance as perceived by the customer and/or consumer. For example, the colour of milled rice can be adversely affected if the paddy is dried with direct heated dryers with poorly maintained or operated burners or furnaces.

5.5 THERMAL AND MECHANICAL ENERGY REQUIREMENTS FOR DRYING

Drying of wet solids is by definition a thermal process, while it is often complicated by diffusion in the solid or through a gas, it is possible to dry many materials merely by heating them above the boiling point of the liquid-perhaps well above, to free the last traces of absorbed material. Wet solids, for example, can be dried by exposure to highly superheated steam. Here there are no diffusion limitations; the problem is solely one of heat transfer. In most adiabatic drying of course, diffusion may occur in the solid or gas phase, but often drying rates are more dependent on heat transfer coefficients than on mass-transfer coefficients.

5.5.1 Calculation of Heat Duty

Heat must be applied to a dryer to accomplish the following:

1) Heat the feed (solids and liquid) to the vapourization temperature
2) Vapourize the liquid
3) Heat the solid to their final temperature
4) Heat the vapour to its final temperature

Item 1, 3 and 4 are often negligible compared with item 2. In the general case the total rate of heat transfer may be calculated as follows, If ms is the mass of bone-dry solids to be dried per unit time and X_a and X_b are the initial and final liquid contents in mass of liquid per unit mass of bone-dry solid, then the quantity of heat transfer per unit mass of solid q_r/m_s is

$$\frac{q_T}{m_s} = C_{ps}(T_{sb} - T_{sa}) + X_a C_{pL}(T_v - T_{sa}) + (X_a - X_b)\lambda + X_b C_{pL}(T_{sb} - T_v) + (X_a - X_b)C_{pv}(T_{va} - T_v)$$

...(5.18)

Where, T_{sa} = feed temperature

T_v = vapourization temperature

T_{sb} =final solid temperature

T_{va}= final vapour temperature

λ = heat of vapourization

C_{ps}, C_{pL}, C_{pv} = specific heats of solid, liquid and vapour, respectively

The equation is based on average specific heats for the temperature range from inlet to outlet and on the heat of vapourization at Tv.

5.5.2 Air Heating System for Dryers

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-cum husk fired grain drying system.

5.6 THIN LAYER AND DEEP BED DRYING

5.6.1 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.

5.6.1.1 Remarks on thin layer drying equations

None of the theoretical equations represents the drying characteristics of grains accurately over a wide range of moisture and temperature, on account of the4 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 equations are based on the incorrect assumptions that the drying constants are independent of moisture and temperature.

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

4) Drying equations developed from Newton's equations are limited. However, if accurate results are not desired and the values of drying constants are known then the theoretical drying equations can be used and give fairly good results within a limited range of moisture.

5.6.1.2 Deep Bed Drying

In deep bed drying all 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 time it also changes with the depth of the grain bed. Over and above the rate of air flow per unit mass of the grain is small compared to the thin layer drying of grain. All of farm static bed batch dryers are designed on deep bed drying principle.

The drying of grain in a deep bin can be taken as the sum of several thin layers. The humidity and temperature of the air entering and leaving each 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.

5.6.1.2.1 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 the air flow rate is very important.

3) Drying 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.

5.7 INTERMITTENT DRYING

Intermittent drying is a process in which the heated air-drying periods are followed by periods of rest (no airflow). The intermittent drying usually requires shorter drying times (excluding rest periods) than continuous drying. Oxley"' explained that the shorter drying times are due to the influence of the rate of moisture diffusion to the kernel surface on the overall drying rate. The rest periods can otherwise be termed as tempering times. The effect of tempering times on improved grain quality and energy utilization has been well established.

5.8 TEMPERING

The tempering of grains prior to milling is essential since the milling yield is highly dependent on the moisture content of the grain going into the first break of the mill. An accurate moisture analysis is important to make sure that the grain has absorbed the correct moisture content for milling. To temper the grain is to add water in order to strengthen the bran and soften the endosperm prior to milling. The desired moisture content is around 16% for soft grains and around 18% for hard grains. After water has been added, the grain must have time to equilibrate, i.e. the moisture has to penetrate through the entire kernel.

5.9 DRYING CHARACTERISTICS OF RAW AND PARBOILED PADDY

5.9.1 Drying Characteristics of Raw Paddy

An increase in the moisture removal rate beyond 3-5 per cent per pass in the continuous-flow dryers adversely affect the milling yield. Multiple drying of wet paddy (with limited moisture per pass, and a period of tempering between each pass) greatly improved head yield (Table 5.2). However tempering is beneficial only below 20 to 21 per cent (d.b.) moisture level.

Table 5.2: Mean head yield of raw paddy

Sl. No.	Number of passes	Tempering period		
		B_1 10 min	B_2 5 hours	B_3 10 hours
1	A_1 2 passes	31.64	43.79	53.07
2	A_2 3 passes	44.57	48.04	47.75
3	A_3 4 passes	36.09	52.96	53.20

A temperature of 60°C with air flow rate of 5cm³/min per 1.25 tonne of raw paddy will be optimum for drying in re-circulatory batch dryer and the milling breakage was found below 13 per cent (Table 5.3)

Table 5.3: Drying of raw paddy with re-circulatory dryer

Sl. No.	Variety of paddy	Initial moisture content (% wet basis)	Final moisture content (% wetbasis)	Drying timie(hr)	Total yielf(%)	Head yielf(%)
1	Adt 27	24.11	13.88	3.40	72.85	65.91
2	Adt 27	22.33	14.05	3.16	72.96	64.90
3	Adt 27	20.00	13.94	2.16	72.56	63.16
4	Co 33	23.66	13.95	3.50	72.42	64.70
5	Co 33	21.95	13.80	2.50	72.59	59.16
6	Co 33	20.05	14.08	2.08	71.80	58.00

5.9.2 Drying of Parboiled Paddy

The parboiled paddy is required to be dried to moisture of 14-16 per cent to obtain the desirable milling and storing properties. In India, drying is generally carried out on large paved yards in the rice mills. The paddy is dried to a moisture of about 18-20 per cent and then heaped and tempered for few hours and then again dried for 1-2 hours to bring down the moisture to 14-16 per cent.

The drying is also carried out in mechanical driers in some mills with hot air. The most important aspect in drying is that the process should be carried in two stages. If the drying is continued in one stage below a moisture of 18 per cent there is considerable amount of breakage. But if it is conditioned at that level and again dried to 14-16 per cent moisture, the breakage is considerably reduced.

Slow drying of wet parboiled paddy in the shade will give excellent results (0.4-1 per cent breakage); which further improved (up to 3 per cent) when the paddy is spread thinly on a very dry day. Rapid drying with hot air, however, leads to heavy breakage. The milling quality of parboiled paddy will not affect until a moisture content of about 15 per cent is reached, damage will start at that point and increases sharply with further drying. In fact damage to the grain will occur only after its removal from the dryer.

Conditioning the hot dried paddy for about 2 hours will prevent cracks in the rice. For best results, conditioning is to be done at a temperature close to that of drying, although under-dried paddy can be protected at lower temperature.

The most convenient practice of parboiled paddy drying will be to dry in two passes with a tempering in the moisture range of 15-19 per cent followed by conditioning after final drying. When parboiled paddy is dried in this way, even when it is produced under very mild conditions of processing, breakage in milling need not exceed 1-2 per cent including the broken part lost in the bran.

Working at relatively lower temperature does not appear to offer any advantage; drying at 60-80°C is equally satisfactory and faster. Similarly, drying with multiple tempering is of no additional benefit to the milling quality, although it may not be useful in increasing the drying rate.

5.10 PRESSURE DROP IN FLOW THROUGH GRANULAR BEDS

When air is forced through a layer of grain, resistance to the flow, the so-called pressure drop, develops as a result of the energy lost through friction and turbulence. The resistance is overcome either by providing a pressure buildup on the air entrance side of the grain mass or by providing a vacuum on the air exit side. The pressure drop of air flow thorough any product depends on the rate of the airflow; the surface and shape characteristics of the product; the number, size and configuration of the voids; the viability of the particle size and the depth of the grain bed. Pressure drop data for airflow through agricultural products are usually presented as curves shown as a logarithmic plot. One set of such data is shown in figure 5.10, in which the air flow is plotted versus the pressure drop per unit depth of product on log-log paper. These curves with the exception of sunflower and rapeseed are from the data of Shedd.

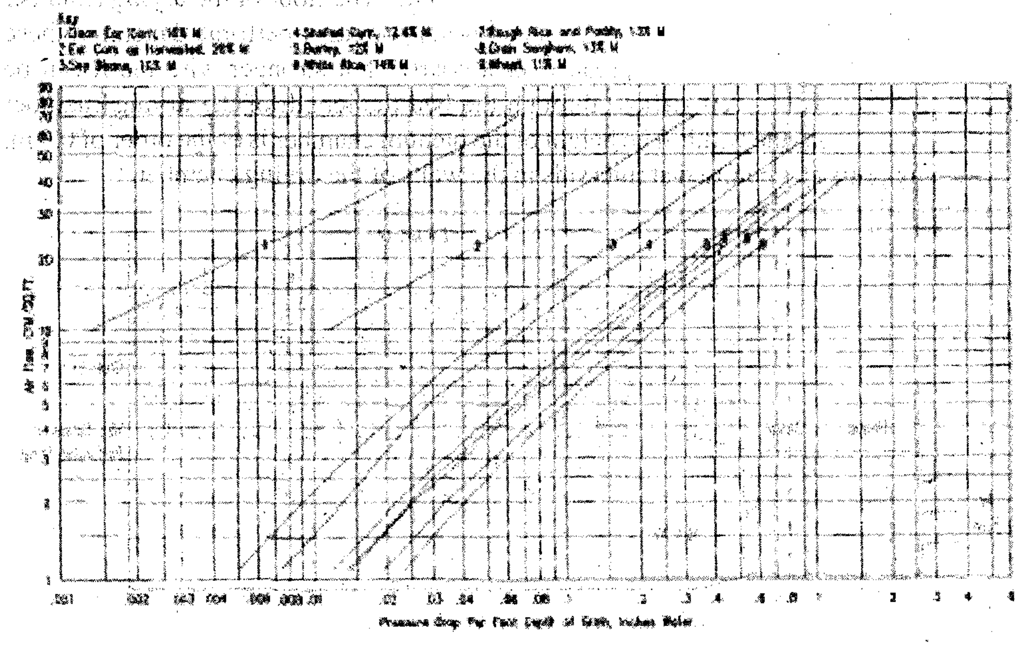


Fig. 5.10: Air flow resistanc e of selected grains (*Courtesy* Shedds)

These data imply that the pressure drop per foot of grain is independent of the depth of the grain. This assumption is not correct for deep masses of grain. Because of the effect of other variables, such as method of filling and size of foreign material, cannot be accurately assessed, and because the change in pressure drop per unit depth as related to depth is small.

Pressure drop from air flow through rice depends on whether the rice is rough, brown, or milled and whether it is long grain or medium grain.

The various parameters which affect the resistance to flow through granular beds are

1. Effect of Fines
2. Effect of moisture content
3. Combination of fines and moisture content
4. Effect of method of filling bin
5. Effect of air flow direction

a) **Resistance of perforated metal to airflow:** When air is introduced into a grain mass through a perforated metal floor, a pressure drop develops across the metal. If the floor area is 10% or more of the total surface area, the pressure drop through the perforations is small compared with the drop through the grain mass and can be neglected.

b) **Pressure loss in ducts:** Loss of pressure in ducts supplying air to grain conditioning systems results from friction, restriction to air flow, change in direction, and enlargement or contraction of the cross-sectional area of the flow stream. The total pressure at any point in a duct system is the sum of the static pressure and velocity pressure.

5.11 BATCH-IN-BIN DRYERS

The small capacity version of the batch-in-bin dryer, otherwise known as the flat-bed dryer, has been developed for farm- or village-level use. Its capacity is of the order of 1-3 tonnes/day with drying times of 6-12 hours.

As represented in Figure 5.11 the flat-bed dryer is simple to construct using easily available and inexpensive materials and easy to operate with unskilled labour. The walls of the drying bin can be constructed of wood, brick or metal. The floor of the drying chamber is preferably made from fine wire mesh, suitably supported, or perforated metal. If these are not available then sacking spread over a coarser but stronger wire mesh can be used. To facilitate an even airflow through the bed the length of the drying chamber should be 2-3 times the width. The height of the plenum chamber is of the order of 0.3 m. Unloading ports can be fitted at intervals in the walls of the drying chamber.

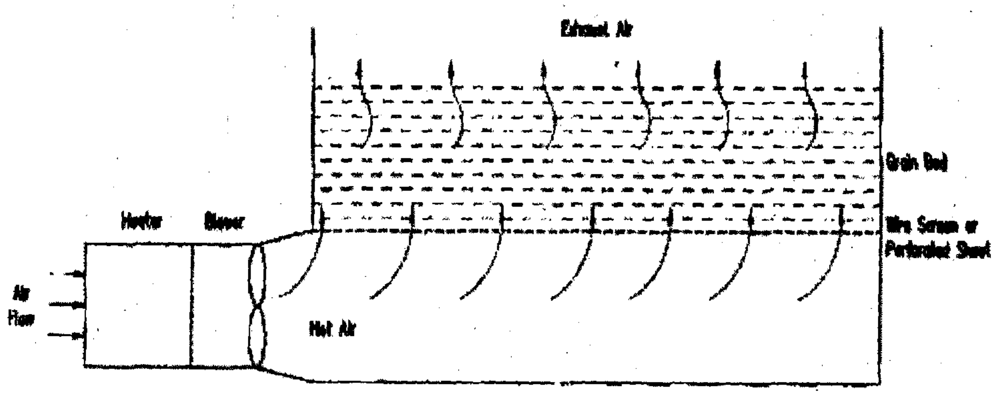


Fig.5.11 : Flat bed dryer (*Courtesy* FAO, Rome)

In order to prevent excessive moisture gradients through the bed, the depth of grain in the bin is relatively shallow, 0.4-0.7 m. and the air velocity is usually of the order of 0.08-0.15 m/s for maize and 0.15-0.25 m/s for paddy. The temperature of the air is selected according to the desired safe storage moisture content of the grain. For the drying of paddy in tropical areas an air temperature of 40-45 °C is usually used, with a heater capable of raising the air temperature by 10-15°C. With such bed depths and air velocities the pressure drop over the bed is relatively low, 250-500 Pa, and therefore simple and inexpensive axial-flow fans can be used. Typically power requirements are 1.5-2.5 kW per tonne of grain for a belt-driven fan powered by a petrol or diesel engine.

Operation of flat-bed dryers invariably results in a moisture gradient between the lower layers and the higher layers of the bed (Soemangat *et al.* 1973). This problem can be reduced by careful selection of drying temperature and airflow conditions but, even so, gradients of 34% moisture are to be expected. Turning of the grain in flat-bed dryers at intervals can alleviate the problem but this extends the drying time and requires additional labour.

The flat-bed dryer is easily loaded from sacks by hand. However, unloading the dried grain into sacks can be time - and labour-consuming; placement of the drying bin on a tilting frame has been investigated (Wimberly 1983) but this incurs additional costs.

IRRI have also developed a vertical batch-in-bin dryer which operates more efficiently than the flat-bed dryer. It differs from the latter in that the airflows horizontally through the bed on either side of the plenum chamber and exhausts through slatted sides. The bin is easily unloaded by removing the slats. Details are available from IRRI (International Rice Research Institute).

Both direct and indirect heaters can be used with the flat-bed dryer (see below). Solar air heating (see above) can also be an option. The waste heat from the engine used to power the fan can be used (Esmay & Hall 1973; Soemangat *et al.* 1973; Teter 1987). Heating of the air by 5-10°C using waste engine heat is possible but the engine exhaust gases should not be drawn through the grain; the exhaust gases should be ducted outside the housing around the engine. A development of this principle is the moisture extraction unit (MEU) in which the fan is directly driven by the engine and the air is drawn over and around the engine block and exhaust pipe.

Large capacity batch-in-bin (or in-store) dryers can be used in cooler dryer areas. The advantage of this technique is that the bin is used for both drying and storage with savings in both capital and operating costs. With heated air at a temperature of 40-45°C, bed depths of 2-3 m can be used with air velocities through the bed not exceeding 0.08 m/s. Since drying times to achieve reductions in moisture content of 5-10% can be of the order of 20-40 days, this method should not be used in humid areas with grain of moisture contents greater than 18% because of the risks of sprouting and mould growth in the upper layers of the bed.

Large batch-in-bin dryers are usually round or rectangular and range in capacity from ten to several hundred tonnes. With large bins, air distribution ducts at the base of the bin are used rather than a plenum chamber. The ducts can be semi-circular, rectangular or triangular as shown in Figure 5.12. To ensure good air distribution through the bed, ducts should be spaced from each other at a distance of half the depth of grain and one quarter the depth from the end and side walls. Air velocity through the ducts should not exceed 5 m/s because of pressure drop factors. More than one fan can be used to provide the airflow required. Detailed information on duct design and airflow distribution is presented by Brooker *et al.* (1974).

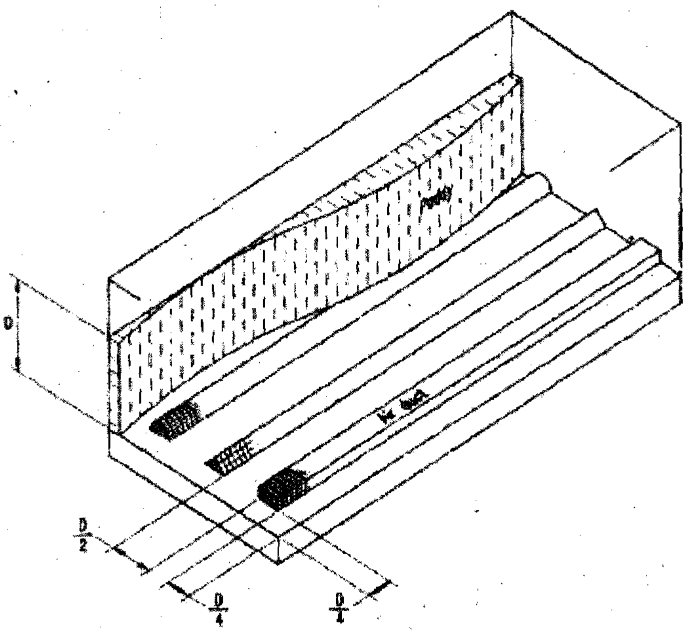


Fig. 5.12 :Air ducts for large batch in-bin dryers (*Courtesy* FAO, Rome)

5.12 IN-BIN LAYERED DRYING

In-Bin layered drying with ambient air can be performed with confidence in locations where the relative humidity of the air is less than about 70%. An initial layer of grain, 0.6-0.9 m deep, is loaded into a storage bin, 5-10 m deep, and further layers are added as drying proceeds. Over-drying of the grain is minimized because of the low air temperature. In the USA an airflow of 0.025-0.06 m^3/s per tonne was used to dry paddy from 20% moisture to 16% moisture within 14 days when ambient temperature ranged from 18-24°C (Houston 1972). Careful and skilled management is required to ensure that each layer is dried before the succeeding layer is loaded into the bin.

View showing three different forms of Air Duct: Rectangular, Triangular, and Semi Circular. Dimensions are in relationship to grain depth D.

Some success has been reported in Indonesia for the drying of paddy from 18% moisture to 13% moisture (Gracey 1978; Renwick & Zubaidy 1983). The latter also demonstrated that field-wet paddy (24% moisture) could be dried safely in bulk to 18 % moisture by continuous aeration (24 in/day) with ambient air, regardless of the humidity of the air. Subsequent drying to 14% moisture or less was accomplished by drying at times of lesser humidity and with the addition of waste engine heat.

There can be a need to dry grain in sacks in certain instances: for example, at central drying facilities where farmers wish to retain access to their own grain. Stacks of sacks are laid over air distribution ducts with no need for a conventional drying bin. Drying proceeds in much the same manner as for bin drying. After use, the air distribution ducts can be dismantled easily to allow use of the building for other purposes.

5.13 RE-CIRCULATING BATCH DRYERS

This type of dryer avoids the problems of moisture gradients experienced with bin dryers by re-circulating the grain during drying. One version of a re-circulating batch dryer is shown in Figure 5.13. The dryer is a self-contained unit with an annular drying chamber, 500 mm thick, around a central plenum chamber, a fan and heater, and a central auger for transporting the grain from the bottom to the top. When drying is complete the grain is discharged from the top. Most dryers of this type are portable and can be moved relatively easily from farm to farm.

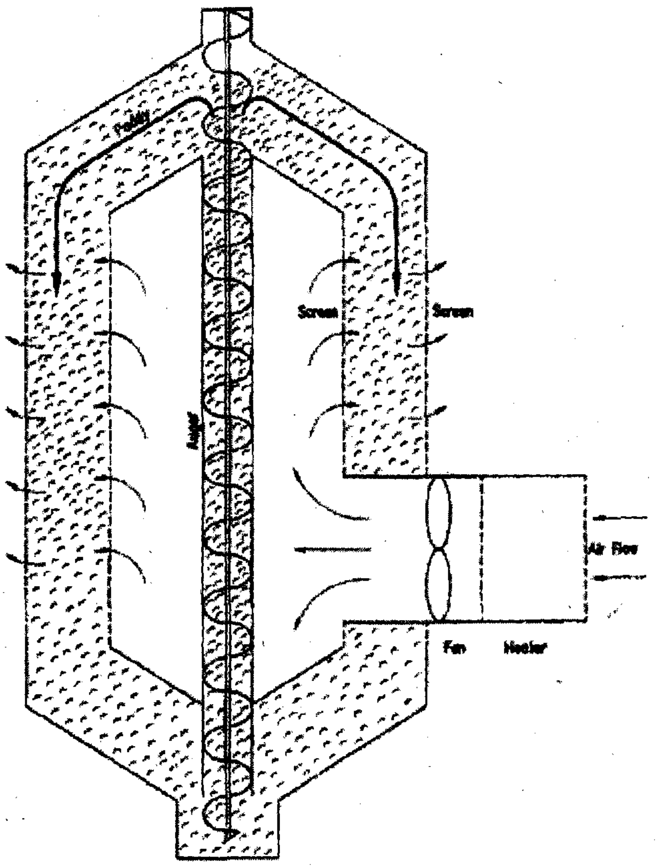


Fig. 5.13: Recirculatory batch dryer (Courtesy FAO, Rome)

Air temperatures of 60-80°C are employed with air flow rates of 0.9-1.6 m^3/s per tonne of grain twice that used in flat-bed dryers (Wimberly 1983). However, since the grain is only exposed to the flow of hot air for relatively short times within each cycle, too rapid drying rates are avoided and moisture distribution within individual grains is equalised during the period the grain remains in the non-drying sections at the top and bottom of the dryer. Control of the drying rate can be effected by adjusting the auger speed to regulate the flow of grain through the dryer.

Another version of a re-circulating batch dryer is rectangular with drying chambers on either side of the heater, fan and plenum chamber. Under each drying chamber are horizontal screw conveyors that collect the grain and return it to a screw auger at one end that lifts the grain to a holding section at the top. A screw conveyor in the holding section distributes the grain evenly along each drying chamber.

The capital cost of re-circulating batch dryers is considerably greater than batch-in-bin dryers because of their greater complexity and incorporation of handling and conveying devices. However, throughput is greater due to the shorter drying times and the quality of the dried grain is likely to be higher. Re-circulating batch dryers require specialist skills for construction and trained operators for successful operation and therefore are not generally suitable for operation by small-scale farmers or enterprises.

5.14 CONTINUOUS-FLOW LARGE CAPACITY DRYERS

Continuous-flow dryers can be considered as an extension of re-circulating batch dryers. However, rather than the grain re-circulating from bottom to top, as in the latter, the grain is removed from the bottom, in some systems, cooled, and then conveyed to tempering or storage bins. In their simplest form continuous-flow dryers have a garner (or holding) bin on top of a tall drying compartment. With some dryers a cooling section is employed below the drying compartment in which ambient air is blown through the grain. At the bottom of the dryer is the flow control section that regulates both the circulation of grain through the dryer and its discharge.

There are three categories of continuous-flow dryers based on the way in which grain is exposed to the drying air:

- crossflow, in which the grain moves downward in a column between two perforated metal sheets while the air is forced through the grain horizontally. Dryers of this type are relatively simple and inexpensive, but, unless mixing systems are incorporated, moisture gradients are set up across the bed;

- counterflow, which employs a round bin with an unloading system at the base and an upward air flow. These dryers are relatively efficient since the air exhausts through the wettest grain. Bed depths of up to 3-4 m can be used;

- concurrent flow, which is the reverse of counterflow drying in that the air moves down through the bed. High air temperatures can be used since the air first comes into contact with wet, and sometimes cold, grain. Drying is rapid in the upper layers but slower at the bottom with some tempering action. Bed depths of at least a metre are used;

Probably the most commonly used continuous-flow dryer is the crossflow columnar dryer, which can be classified as non-mixing and mixing types.

In one version of a non-mixing dryer (Figure 5.14), drying takes place between two parallel screens, 150-250 mm apart on either side of the plenum chamber. The air escapes from the dryer through louvres on either side of the dryer. The flow rate of grain through the dryer is controlled by a regulator gate at the base of the drying column. Since the grain flows plug-like through the drying section the layer of grain closer to the plenum chamber is dried by hotter and drier air than is the grain on the outside. However, mixing is effected to a fair degree when the grain is discharged and conveyed to tempering and storage bins. Air temperatures of 45-55°C and airflows of 2-4 m^3/s per tonne of grain are used. Flow problems can be encountered with very wet and dirty grain as the grain may clog. Teter (1987) notes that if very wet paddy is to be dried then the grain should be cleaned and also pre-dried to at least 22% moisture before a non-mixing dryer can be used.

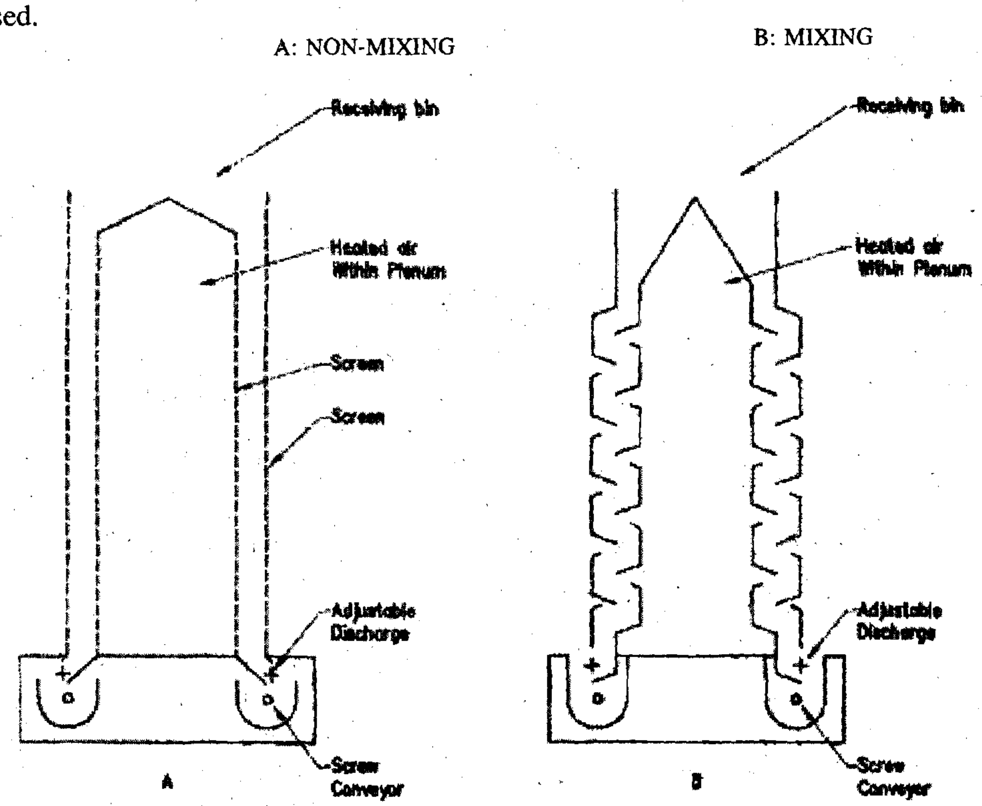


Fig. 5.14 : Continuous flow type dryer (*Courtesy* FAO, Rome)

In one design of the mixing type of continuous-flow dryer, as also shown in Figure 5.14, a baffle system facilitates the mixing of grain and avoids the development of moisture gradients across the drying bed. Higher air temperatures, 60-70°C, can therefore be used without damaging the grain. Unless screens are fitted on the outside of the drying section lower airflows, 1-1.5 m^3/s per tonne of grain, have to be used to avoid grain being blown out of the dryer.

Another design of this type is the LSU (Louisiana State University) dryer (Figure 5.15). In this version the drying section consists of a vertical compartment across which rows of air channels are installed. One end of each channel is open and the other closed. Alternative rows are open to the plenum chamber and intervening rows to the exhaust section. Alternate rows are also offset such that the channel tops divide the moving stream of grain as it descends providing considerable mixing.

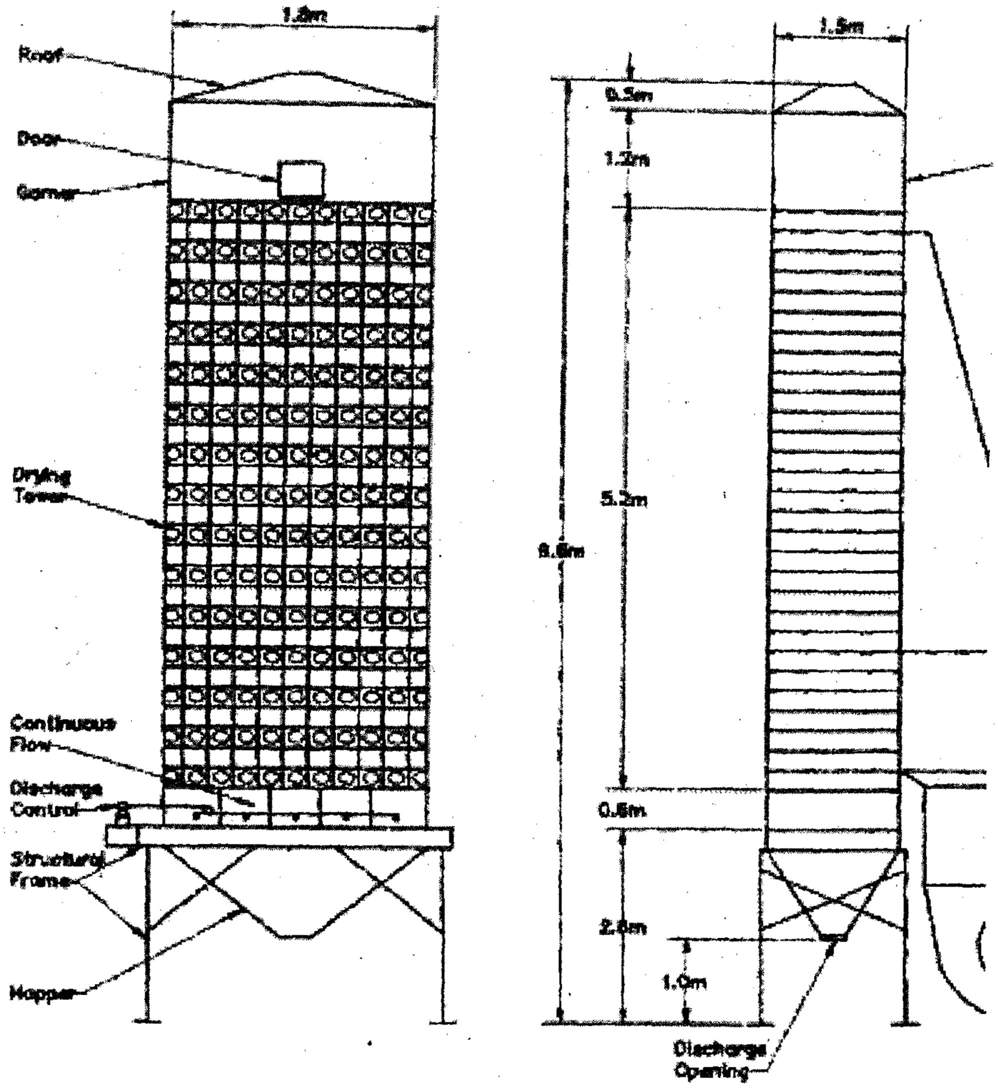
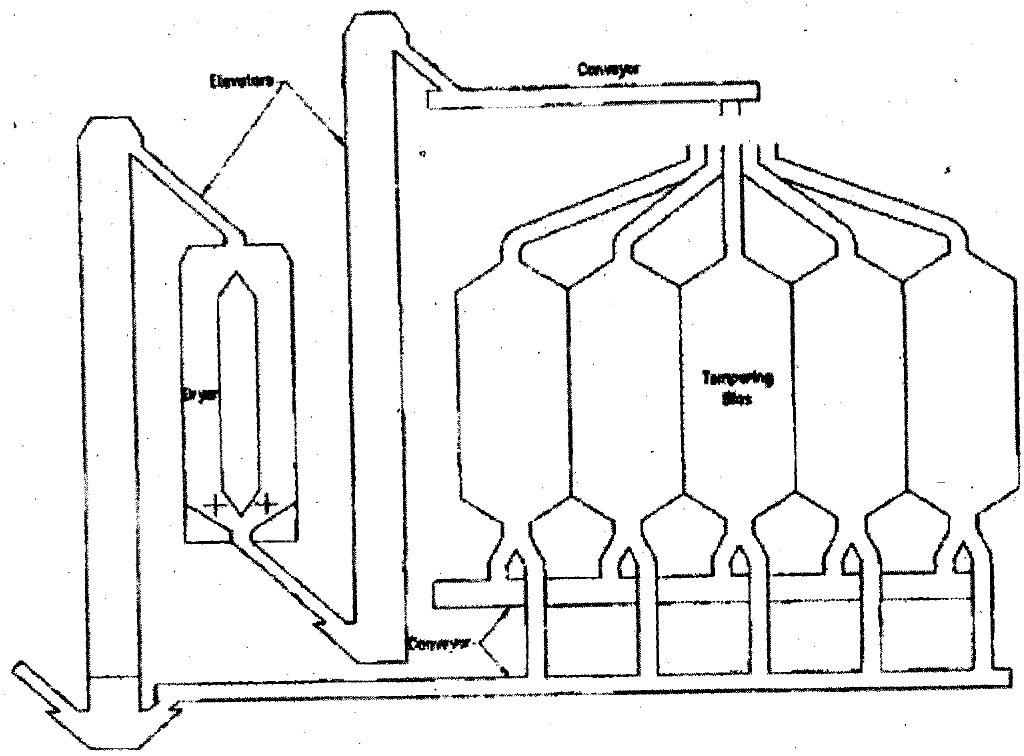


Fig. 5.15 : Louisiana State University (LSU) continuous dryer (*Courtesy:* Chakraverty A)

Further information on continuous-flow dryers has been presented by Bakker-Arkema *et al.* (1982), Fontana et al. (1982) and Houston (1972). As can be appreciated from Fig 5.15 many of these dryers are large and complex structures and are usually designed and constructed by specialist firms.

Compared with batch-in-bin dryers and re-circulating batch dryers, continuous-flow dryers offer the largest drying capacity. When large volumes of wet grain are to be dried in a single site these are the types to be considered first. They are most commonly used in a multi-pass drying operation as shown in Figure 5.16. Investment costs are high but because of the large throughputs operating costs per tonne can be lower than the larger batch-in-
... ing dryers.



Source: Wimberley (1983).

Fig. 5.16 : Large drying system using continuous flow dryer conveying equipment and tempering bins (*Courtesy* Wimberly)

In a multi-pass drying system, continuous-flow dryers are used in association with tempering bins. During each pass through the dryer the grain is dried for 15-30 minutes with a reduction in moisture content of 1-3%. Drying at this rate sets up moisture gradients within the individual grains. After each pass the grain is held in a tempering bin where the moisture within the kernel equalises as moisture diffuses from the interior of each kernel to the surface. The combination of rapid drying and tempering is repeated until the desired moisture content is attained. Using this procedure the actual residence time of the grain within the continuous-flow dryer is of the order of 2-3 hours to effect a 10% reduction in moisture. Selection of the number of passes is a compromise between the dryer efficiency, i.e; fewer passes, and grain quality, i.e; longer drying time. Tempering periods are usually 424 hours in duration. The tempering bins may be aerated with ambient air to cool the grain with some slight moisture removal.

It is vital that the operation of drying with tempering is carefully planned and managed to ensure maximum throughput and efficiency. This usually means that the plant is operated 24 hours a day with two or more batches of grain being dried at a time. Well trained management and staff are essential.

5.15 AIR BLOWERS

Types of air blowers used in dryers are as under ·

1) Centrifugal blower
2) Forward curved blower
3) Backward curved blower

5.15.1 Centrifugal Blower

A centrifugal blower consists of blower wheel, housing or scroll and a motor. The air inlet of the centrifugal blower casing is located at 90° to the air outlet. Air enters the centre of the centre of the rotating blower impeller parallel to the impeller shaft and is turned through 90° by impeller before being discharged. Most of the velocity pressure is converted into static pressure by the time the air is discharged from the outlet. Energy is required to change the direction of air flow; therefore, slightly lower efficiency is achieved as compared to axial flow fans. Air is thrown from the blades due to centrifugal forces generated by the rotor (Figure 5.17)

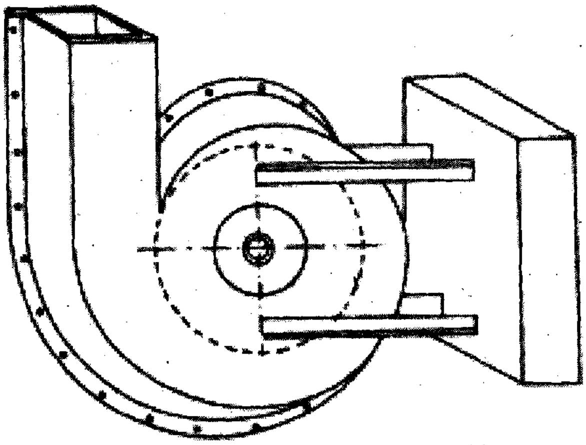


Fig. 5.17 : Centrifugal blower (*Courtesy:* K M Sahay and K. K. Singh).

Performance of a centrifugal blower depend on the configuration of the blower housing, the size of the inlet opening relative to the impeller, the location and shape of the cutoff, the shape and dimension of the scroll and the shape of the outlet into the air system.

The centrifugal blower can be divided into three broad types on the basis of shape of impeller. These are forward curved, backward curved and radial or straight bladed (Figure 5.18.).

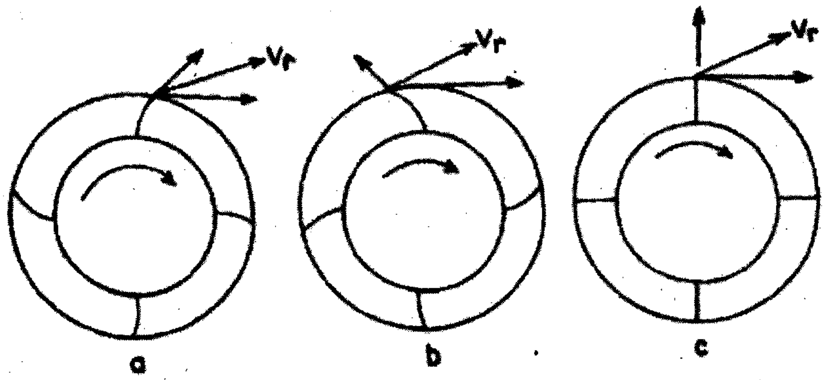


Fig. 5.18 : Types of centrifugal blower impellers a. forward curved b. backward curved c. straight curved (*Courtesy:* K M Sahay and K. K. Singh)

5.15.1.1 Forward Curved Blades

A centrifugal blower with forward curved blade is basically an impulse device. The impeller carries a large number of shallow blades with curved surfaces, the concave side facing the direction of rotation. It accelerates the air to a high velocity, while rotating at a speed that is usually low in comparison to a backward curved blower. A forward curved blower requires high power for generating large volume of air. A forward curved blower requires high power for generating large volume of air. Hence care must be taken to ensure that sufficient power is available to drive the blower while it is delivering large than the normal volume of air.

5.15.1.2 Backward Curved Blower

The blades of the impeller of backward curved blower are curved backwards. The convex side of the blade faces the direction of rotation. The backward curved centrifugal blowers are the most efficient blowers which make them suitable for drying grains in bulk. The characteristic curves of backward blower are shown in figure 5.19.

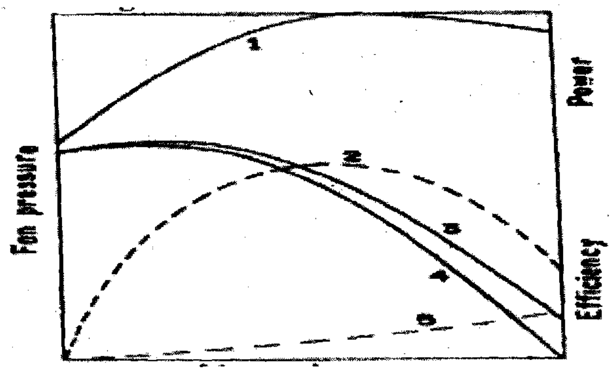


Fig. 5.19 : Characteristics of a back-ward curved centrifugal blower 1. fan power 2. fan efficiency 3. fan pressure 4. static pressure of fan 5.dynmic pressure of fan((*Courtesy:* K M Sahay and K. K. Singh)

5.15.1.3 Selection/Design of a Centrifugal Blower

For a given set of airflow rate and static pressure, the impeller diameter and width of blower may be calculated as follows

1. Calculate the specific speed (N_s) for the specific static pressure, air flow rate and designed motor speed.

$$N_s = \frac{N\sqrt{Q}}{p_s^{0.75}} rpm \qquad ....(5.18)$$

Where, N= speed of motor, rpm

Q= air flow rate, cfm

P_s = static pressure, in inches of water

2. From figure 6.20 determine the type of air moving unit which would operate at high efficiency, at or near peak efficiency at the calculated specific speed. If more than one type of air moving unit has good efficiency, make the final selection on the other factors involved in the application such as relative cost, size and shape of space available and the characteristics of the flow path.

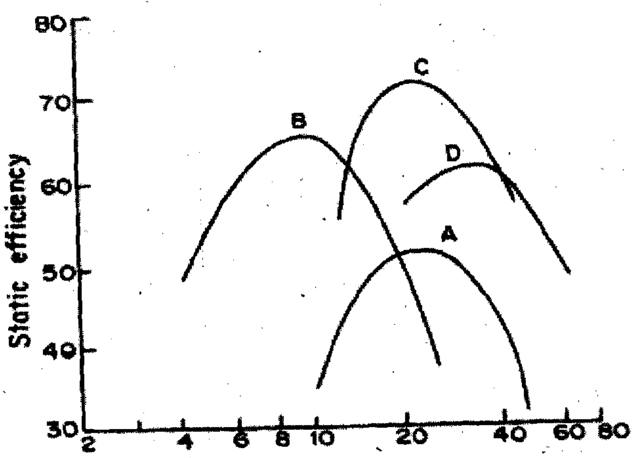
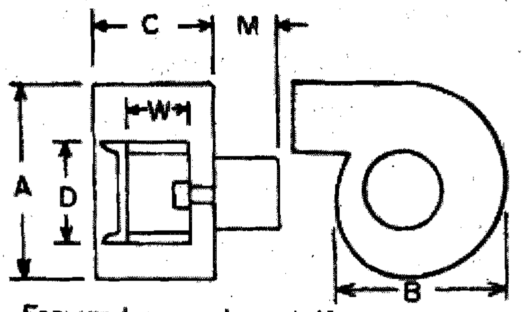


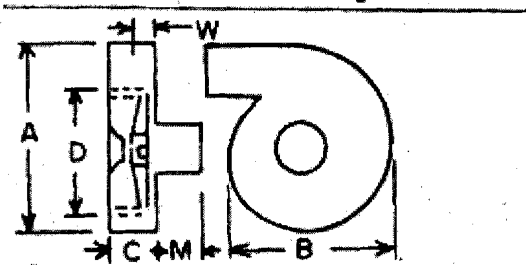
Fig. 5.20 : Specific speed vs. static efficiency of various impellers (*Courtesy:* K M Sahay and K. K. Singh)

3. From Table 4 find the typical value of pressure coefficient ψ by interpolation, for the type of fan or blower selected and the value of N_s .

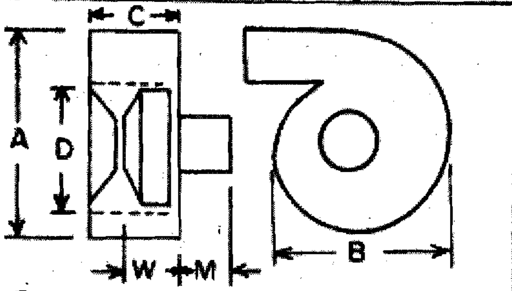
Table: 4 Values of specific speeds, typical pressure coefficient, typical flow coefficient and dimensions of centrifugal blowers



Forward curved centrifugal



Backward curved centrifugal(Narrow)



Backward curved centrifugal (Wide)

Type	Dimensions A	Dimensions B	Dimensions C	Specific speed Ns	Typical pressure coeff.	Typical flow coeff.
Forward curved centrifugal	1.7(D)	1.5(D)	1.25W+0.1D	13,000	1.0	0.15
				20,000	2.0	0.5
				40,000	1.0	0.75
Backward curved centrifugal (Narrow)	1.4(D)	1.35(D)	W+0.1D	4,000	1.4	0.002
				8,000	1.0	0.01
				20,000	0.8	0.10
Backward curved centrifugal (Wide)	2.0(D)	1.6(D)	W+0.16D	15,000	1.0	0.06
				30,000	0.75	0.3
				45,000	0.5	0.5

4. Calculate the diameter of the impeller

$$\psi = \frac{2.35\ x10^8\ p_s}{N^2 d^2} \qquad \ldots(5.19)$$

Where, ψ = pressure coefficient

d= diameter of the impeller, inch

5. Find out the typical value of flow coefficient ϕ from Table and then calculate the width

$$W = \frac{175Q}{\phi N d^2} \qquad \ldots(5.20)$$

Where, ϕ = flow coefficient

W= width of the impeller, inch

5.15.1.4 Blower Housing

The configuration of the housing considerably affects the performance of a centrifugal blower and thus is as important as the blower wheel (figure 5.21). The size of the housing must be considered keeping in view the space available. The standard housing dimension recommended by the blower manufacturers may be followed to maximize the performance of a particular blower wheel. These dimensions are generally given as proportions of wheel diameter and width and so can be determined after the selected procedure is completed.

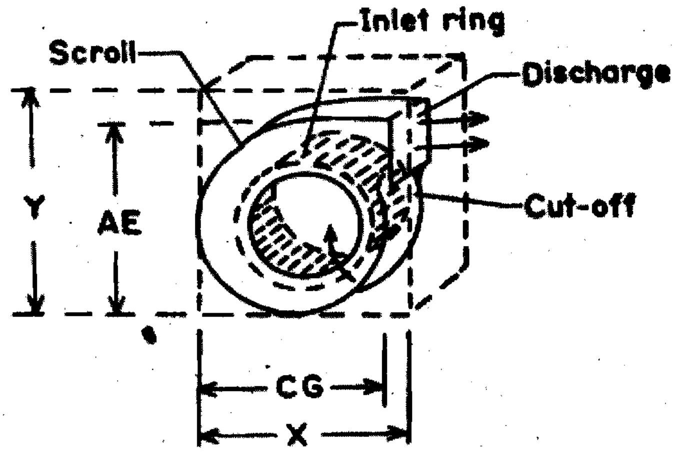


Fig. 5.21 : Housing of centrifugal blower (*Courtesy:* K M Sahay and K. K. Singh)

The purpose of centrifugal blower housing as shown in figure, is to control the air flow from intake to discharge, and in the process, to covert the velocity head into the static pressure head. Pressure conversion is accomplished as the cross-section of the air stream increases in the increasing annular space on the periphery of the blower wheel form cutoff to discharge. Since the amount of pressure conversion is determined by the scroll configuration, the shape of the housing considerably affects air performance. The cutoff eliminates almost all free circulation of air within the housing.

5.15.1.5 Diffuser angle

The increase in annular cross-section in the scroll around a blower wheel is proportional to the developed length of the wheel periphery. The angle between the developed scroll surface and blower wheel periphery is called the diffuser angle. Wheel diameter and diffuser angle determines the shape and dimensions of the scroll (figure 5.22).

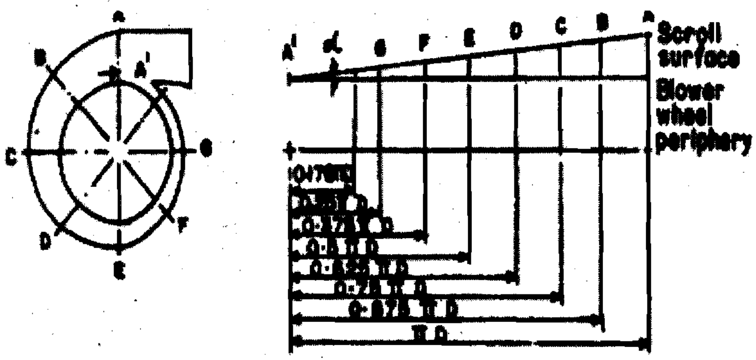


Fig. 5.22 : Scroll development of a centrifugal blower *Courtesy:* K M Sahay and K. K. Singh)

The diffuser angle can be determined graphically and expressed in terms of impeller diameter and either the maximum height or maximum width of the housing. Diffuser angle may be given as

...(5. 21)

and

$$\alpha_w = 12\left(\frac{W_M}{d} - 1\right) \qquad ...(5.22)$$

As shown by the above equation, the diffuser angle decreases if either dimensions AE and CG decreases. However, it is sensitive to change in AE.

As the diffuser angle increases, the flow rate increases significantly at any particular static pressure. Diffuser angle also affects performance of the blower in a particular system.

The diffuser angle generally uses as the basis for blower performance data is 10°. Although large diffuser angle improve performance, the relative amount of diameter of the blower wheel becomes too large.

The housing width may be determined by the following equation

$$M = 1.25W + 0.1d \qquad ...(5.23)$$

Where, M = housing width

W = impeller width

d = diameter of impeller

The optimum diameter is based on a blower wheel mounted close to the inlet ring and minimal clearance between the wheel pack plate and side of the housing. If the width of the housing recommended for standard blower wheel is too large. A narrower housing should be selected. If either dimension AE or CG of the recommended housing is too large for the space available, housing with a smaller diffuser angle should be selected. The resulting reduction in air flow rate should then be determined and compared to the original requirement.

5.16 LET US SUM UP

Drying is an important step for proper storage and processing of paddy as it affects its quality parameters. Heat is a necessary component to evaporate moisture from grain and a flow of air required to carry away the evaporated moisture from the grain. The rate of drying is determined by the moisture content and the temperature of the grain and the temperature, relative humidity and velocity of the air in contact with the grain. Equilibrium moisture content of the grain plays an important role during storage of grain. There are many types of dryers for grain viz batch and continuous type. Centrifugal type blowers are generally used for forcing heated air through the dryers. Drying efficiency plays an important role in the selection of dryers. Higher the efficiency lesser the cost of drying.

5.17 KEY WORDS

Moisture Content : It is essential that the grain after drying is at moisture content suitable for storage. As discussed the desired moisture content will depend on the type of grain, duration of storage, and the storage conditions available. It is also important that the drying operation is carried out to minimize the range of moisture levels in a batch of dried grain. Portions of under-dried grain can lead to heating and deterioration.

Stress Cracking and Broken Grains : Drying with heated air or excessive exposure to sun can raise the internal kernel temperature to such a level that the endosperm cracks. The extent of stress cracking is related to the rate of drying. Rapid cooling of grain can also contribute to stress crack development.

Nutritive Value : Grain constituents such as proteins, sugars and gluten may be adversely affected when the grain attains excessive temperatures. The feeding value of grains can be lowered if inadequately dried.

Grain Viability : Seed grain requires a high proportion of individual grains with germination properties. The viability of grain is directly linked to the temperature attained by grains during drying.

Mould Growth : Many changes in grain quality are linked to the growth of moulds and other microorganisms. The rate of development of microorganism is dependent on the grain moisture content, grain temperature, and the degree of physical damage to individual grains. Mould growth causes damage to individual grains resulting in a reduction in value. Under certain circumstances mycotoxin development can be a particular hazard.

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.

Deep bed drying : In deep bed drying all 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 time it also changes with the depth of the grain bed.

Psychrometric chart : It is a graphical representation of thermodynamic properties of air. In this chart the absolute humidity, percent humidity, humid volume, enthalpy, and adiabatic saturation lines are drawn against air temperatures.

Check Your Progress

Note: a) Use the space given below for your answers.

b) Check your answers with those given at the end of unit.

1. What are the various applications of psychrometric chart?

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2. Define equilibrium moisture content

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3. What are the factors which affects the drying efficiency?

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4. What is intermittent drying?

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5. Define drying efficiency.

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6. What are the parameters which affect the resistance to flow through granular beds?

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7. What are the various advantages of drying?

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8. Define moisture ratio.

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9. What are the various types of blowers used in dryers?

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10. Enumerate the basic and commonly used drying methods.

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11. What are the desired performance objectives of the drying system?

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12. What are the advantages of a re-circulatory batch dryer?

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13. What are the disadvantages of Louisiana State University dryer?

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14. What are the various factors to be considered in the design of heated air dryers?

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15. What is psychrometric chart?

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5.19 ANSWERS TO CHECK YOUR PROGRESS

1. The various applications of psychrometric chart in drying operation are as under;

   a) sensible heating and cooling load calculation

   b) adiabatic cooling or drying

   c) heating and humidification

   d) cooling and dehumidification

   e) mixing of two air streams

2. The moisture content of a solid in equilibrium with the surrounding condition is known as equilibrium moisture content. It can also be defined as the moisture content attained by a product for a particular set of relative humidity and ambient temperature.

3. There are three groups of factors affecting drying efficiency

   a) those related to the environment, in particular, ambient air conditions

   b) those specific to the crop

   c) those specific to the design and operation of the dryer

4. Intermittent drying is a process in which the heated air-drying periods are followed by periods of rest (no airflow). The intermittent drying usually requires shorter drying times (excluding rest periods) than continuous drying.

5. **Drying efficiency:** It is defined as the ratio of heat utilized for moisture removal to the heat available for moisture removal.

$$\text{Drying efficiency} = \frac{\text{Heat utilized for moisture removal}}{\text{Heat available for moisture removal}}$$

6. The various parameters which affect the resistance to flow through granular beds are,

   1. Effect of Fines

   2. Effect of moisture content

   3. Combination of fines and moisture content

   4. Effect of method of filling bin

   5. Effect of air flow direction

7. Various advantages of drying are,

   a) Drying permits early harvest of crops. This leads to reduction of losses by shattering.

      This also leads to permit time for preparation of land sowing of following crop.

   b) Drying helps in proper planning of harvesting season.

   c) Drying of agricultural products to optimum moisture content results in safe storage of products over a long period.

   d) Storage of products after drying makes products available during off seasons.

e) When grains are stored, due to increase in the temperature and moisture content, heat of respiration also increases. The heat of respiration can be removed by aeration and drying. Thus the temperature and moisture content of the products can be brought down and the viability of seeds could be maintained.

8. The moisture ratio is given as

$$MR = \frac{MC - MC_e}{MC_o - MC_e}$$

Where,

MR is moisture ratio

MC is the moisture content of the grain at any level and time, % dry basis (%db)

MC_e is the equilibrium moisture content (%db)

MC_o is the initial moisture content of the wet grain (%db);

9. Various types of air blowers used in dryers are as under

a) Centrifugal blower

b) Forward curved blower

c) Backward curved blower

10. The basic and commonly used drying methods are

a) Contact drying

b) Convective drying

c) Freeze drying

d) Radiation drying

e) Super heated steam drying

f) Osmotic drying

g) Fluidized bed drying

h) Desiccant air drying

11. The desired performance objectives of the drying system are

a) The grain quality must be preserved

b) The grain should be uniformly dried

c) The grain should dry fast enough to arrest molding and germination

d) The dryer should be efficient in utilization. The drying potential of the heated air should be maximized.

12. The advantages of re-circulatory batch dryer are

a) Price is reasonable

b) Simplest design amongst all flow type dryers

c) Easy to operate

d) It can be used on the farm and rice mill as well

e) Operating cost is low with husk fired furnace

13. The disadvantages of Louisiana State University dryer are its high capital investment and cost of drying is very if oil is used as fuel.

14. The following factors are taken into consideration in the design of heated air dryers.

    a) Dryer factors: Size, shape and type of dryer; grain feeding rate; total drying time; air flow pattern and air distribution system; depth of grain bed in the dryer and system of cooling grain(if any)

    b) Air factors: velocity and flow rate; temperature and relative humidity; static pressure and exhaust air

    c) Grain factors: Type, variety and condition of grain; initial and final moisture content of grain; the usage of the dried grain and latent heat of vapourization

    d) Heating system: Type of fuel and rate of fuel supply; type of burner or type of furnace; type of heat exchanger.

15. **Psychrometric chart:** It is a graphical representation of thermodynamic properties of air. In this chart the absolute humidity, percent humidity, humid volume, enthalpy, and adiabatic saturation lines are drawn against air temperatures