

**24AG301- APPLIED THERMODYNAMICS AND THERMAL
SYSTEMS IN AGRICULTURAL ENGINEERING**

UNIT 5 CROP DRYING AND HEATING SYSTEMS

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Grain drying

UNIT V: CROP DRYING AND HEATING SYSTEMS

5.1 crop dryer

Crop dryers are mechanical systems that use controlled heat and airflow to reduce the moisture content of harvested grains and other produce to safe levels for storage, preventing spoilage, mold growth, and pest infestation. These systems are crucial for extending the shelf life of crops, reducing postharvest losses, and ensuring the quality and marketability of agricultural products by removing excess moisture that encourages microbial activity and respiration. Crop dryers can operate as batch or continuous systems, employing various configurations like bin, recirculating, or mixed-flow types to achieve efficient and uniform drying while minimizing damage to the crop.

Why are crop dryers needed?

- **Preventing Spoilage:**

High moisture content in stored crops fosters microbial growth (molds and bacteria), leading to spoilage and reduced quality.

- **Reducing Postharvest Losses:**

Drying helps preserve crops and prevent losses that occur during storage.

- **Extending Shelf Life:**

Lowering moisture content significantly increases the time crops can be stored before they deteriorate.

- **Improving Marketability:**

Properly dried crops are higher quality, command better prices, and are more appealing to buyers.

- **Addressing Modern Farming Challenges:**

Increased production, high-yielding varieties, and irrigation often lead to wet harvests that cannot rely solely on traditional sun drying.

How do crop dryers work?

Crop dryers use controlled heat and air to remove moisture. The process involves several factors:

- **Controlled Temperature:** A balance must be struck between using enough heat to speed up drying and using low temperatures for long periods to prevent heat damage to the grain.
- **Airflow:** Sufficient airflow is necessary to carry the moisture away from the crop.
- **Time:** The duration of the drying process depends on the crop's initial moisture, air temperature, and airflow rate.

Types of Crop Dryers

- **Batch Dryers:**

These are less expensive, suit smaller quantities, and dry grain in discrete loads.

- **Floor dryers:** Suitable for all grains, often used in small and medium-scale operations.
- **Bag dryers:** Ideal for small batches of varied grain types, handled in sacks.
- **Box dryers:** Used for larger quantities of grain when slow drying is required.

- **Continuous Dryers:**

These operate continuously and are often used for large-scale operations.

- **Recirculating Dryers:** These dryers mix and recirculate the grain while exposing it to hot air.

- **Mixed-Flow Dryers:** Engineered for gentle treatment and uniform drying, often using inverted V-shaped channels for air and grain flow.

- **Solar Crop Dryers:**

Utilize solar energy as the heat source, sometimes with thermal energy storage (TES) for consistency.

Key Components of a Dryer System

- **Heat Source:**

Provides the heat to raise the temperature of the drying air, often by burning fuel or using electric heaters.

- **Air Delivery System:**

Includes blowers or fans that move large volumes of air into the drying chamber.

- **Drying Chamber:**

The core area where the grain is exposed to the hot air, designed to ensure good contact between air and grain.

- **Grain Handling Mechanism:**

Systems like bucket elevators, augers, or special discharge rollers move grain in and out of the dryer.

Basic Drying Concepts

Moisture Content

Drying reduces the amount of water contained in the crop after harvest to an acceptable level for marketing, storage, or processing. Lowering the moisture content is necessary to prevent grain spoilage, which is primarily caused by molds and insect infestation. Both grain temperature and moisture content are critical in maintaining quality. Mold and insect activity is greatly reduced below 60°F (15°C). Safe moisture levels for storage depend on grain variety, length of storage, storage structure, and geographical location. Table 1 summarizes typical recommendations for grains and oilseeds stored in aerated structures in various regions of the United States.

The amount of water, or moisture, in a grain kernel is expressed as a percentage value. Moisture content on the wet basis expresses the amount of water in the grain as a percent of the total grain weight. The difference between the wet and total weight is the amount of dry weight, or dry matter of the grain. Wet-basis moisture content is usually measured in the commercial grain industry with a calibrated moisture meter. However, it can also be calculated if the wet and dry weights are known:

$M_w = 100 \times (\text{wet weight} - \text{dry weight}) / (\text{wet weight})$
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Where, M_w is the wet basis moisture content in percent. The limitation of using wet-basis moisture content is that during drying the wet weight changes. Thus, the wet basis moisture content values cannot be directly added or subtracted to find the weight change, or moisture shrink, due to drying. For example, 10,000 bushels (250 MT) of shelled corn dried from 25% to 15% moisture do NOT experience a moisture shrink of 10% of the initial weight, or 1,000 bushels (25 MT)!

Moisture Shrink

During the drying process both the wet and total weights of grain change. This is expressed as the water, or moisture shrink loss. Moisture shrink is the amount of water lost as the grain dries to a standard moisture content – typically 15% for corn and 14% for wheat. Moisture shrink is calculated as:

$\text{Moisture Shrink} = 100 \times (M_o - M_f) / (100 - M_f)$

Where, moisture shrink is a percentage value, M_o is the original and M_f the final moisture content in percent.

Forced Airflow

Airflow is created with fans that force air to move through the grain mass, absorb moisture from the grain, and carry that moisture away from the grain mass. Airflow rates for drying and cooling typically range from 75 – 125 ft³ of air per minute per bushel (cfm/bu^c) of grain being dried or cooled (75 – 125 m³/min/t), or 50 – 100 cfm per ft² of perforated screen area (0.25-0.51 m³/s m²). These airflow rates create relatively low static pressures of 1 – 5 inches water column (0.249-1.25 kPa) in crossflow and mixed-flow dryers. [Static pressure is the resistive force the fans work against while trying to push the air through the grain columns.]

Fans

Airflow has to be provided by a fan with sufficient capacity. Fans are classified as axial-flow (air is moved by rotating blades parallel to the shaft) and centrifugal (air enters the fan parallel to the shaft, is moved radially through the blades, and discharged tangentially from the scroll housing). Proper selection of fan size is critical to assure efficient operation, which lies in the 55 to 75% range for axial-flow and in the 50 to 65% range for centrifugal fans.

Fan Power

The power requirement from a fan for supplying a given level of airflow can be calculated as:

$\text{Fan Power} = (AV \times SP) / (63.56 \times E_{ff})$

Where, fan power is in HP, AV is the total airflow rate in ft³/min (cfm), SP is the static pressure caused by the airflow in the grain column in inches of water column, E_{ff} is the fan power efficiency in percent and depends on the fan manufacturer and type.

Heat Energy

Heat is added to the drying air across a burner to raise the temperature of the air and the grain. Increasing the air temperature increases the amount of water that can be absorbed by the air and carried away from the grain. Increasing the temperature of the grain increases the rate of moisture removal from the grain. Energy for heating the air has to be provided by a burner with sufficient capacity.

Burner Capacity

The amount of energy needed from a burner to raise the air temperature to a certain level can be calculated as:

$\text{Burner Capacity} = 1.1 \times AV \times (T_f - T_o)$

Where, energy for the burner capacity is measured in Btu/h, AV is the total airflow rate in cfm, T_f is the final air temperature after the burner ($^{\circ}\text{F}$), and T_o is the initial air temperature before the burner ($^{\circ}\text{F}$). [One Btu raises the temperature of 1 lb of water by 1°F .] For example, heating air from 40°F to 220°F (from 4°C to 104°C) for a crossflow dryer with a total airflow rate of 300,000 cfm ($141.58 \text{ m}^3/\text{s}$) would require a burner with a capacity of about $(1.1 \times 300,000 \text{ cfm} \times (220^{\circ}\text{F} - 40^{\circ}\text{F})) = 59,400,000 \text{ Btu/h}$, or 59.4 million Btu/h ($62,615 \text{ MJ/h}$).

Drying theory

- Convection process in which moisture from a product is removed
- The water content of agricultural product is given in terms of moisture content
- They gain or loose moisture as per the atmospheric conditions
- Moisture migration into or from a product is dependent on the difference of vapour pressure between atmosphere and product
- If the vapour pressure of grain is greater than atmospheric vapour pressure, transfer of moisture from grain to atmosphere takes place
- If the atmospheric vapour pressure is greater than grain vapour pressure, grain absorbs moisture from atmosphere

Drying rate periods**Divided into 3 periods**

- Constant rate period
- First Falling rate period
- Second falling rate period

Constant rate period

- Moisture migration rate from inside of product to its surface is equal to the rate of evaporation of water from surface
- This period continues till critical moisture content is reached
- Critical moisture content: Moisture content of a product where constant rate drying ceases and falling rate starts
- This period is very short for agricultural products
- Drying of sand and washed seeds takes place in constant rate period

Falling rate period

- Most of the agricultural products are dried in falling rate drying period
- Movement and diffusion of moisture in interior of grains controls the entire drying process

Controlled by

- Migration of moisture from interior of grains to upper surface due to water vapour diffusion
 - Removal of moisture from the surface
- Divided into two periods
 - First falling rate period
 - Second falling rate period

First falling rate

- Unsaturated surface drying
- Drying rate decreases because of the decrease in wet surface area
- Fraction of wet surface decreases to zero, where first falling rate ends

Second falling rate

- Sub surface evaporation takes place & it continues until the equilibrium moisture content is reached

Mechanism of drying process

- Movement of moisture takes place due to
 - Capillary flow – Liquid movement due to surface forces
 - Liquid diffusion – Liquid movement due to difference in moisture concentration
 - Surface diffusion - Liquid movement due to moisture diffusion of the pore spaces
 - Vapour diffusion – vapour movement due to moisture concentration difference
 - Thermal diffusion - vapour movement due to temperature difference
 - Hydro dynamic flow – water and vapour movement due to total pressure difference

Moisture Evaporation in Grains

The moisture content of food grains and other agricultural products plays an important role in maintaining the desirable quality of the product. The change in moisture content during successive post harvest stages is dependent upon the initial moisture content of product and atmospheric conditions. 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.

Moisture content is designated by two methods. (1) Wet basis (wb) (2) Dry basis (db)

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

$$\text{Percent moisture content} = \frac{\text{weight of water in product}}{\text{weight of product sample}} \times 100$$

• Dry basis: The dry basis moisture content is determined by the following expression.

$$\text{Percent moisture content} = \frac{\text{weight of water in product}}{\text{weight of dry matter of product sample}} \times 100$$

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

$$\text{Moisture content (db), \%} = \frac{\text{moisture content (wb) in decimals}}{1 - \text{moisture content (wb) in decimals}} \times 100$$

$$M = \frac{m}{1 - m} \quad \text{or} \quad m = \frac{M}{1 + M}$$

where: m = decimal moisture content wet basis (wb)

M = decimal moisture content dry basis (db)

m_d = mass of dry matter in the product

m_w = mass of water in the product

m_t = total mass of the product, water plus dry matter

$$m = \frac{m_w}{m_w + m_d} = \frac{m_w}{m_t}$$

$$M = \frac{m_w}{m_d}$$

Problem : 500 kg of paddy at 22% moisture content (wb) is dried to 14% moisture content (wb) for milling. Calculate the amount of moisture removed in drying.

Solution:

1st method, using wet basis moisture content data

$$\begin{aligned} \text{Amount of initial water content} &= 0.22 \times 500 \\ &= 110 \text{ kg} \end{aligned}$$

$$\text{Dry matter in paddy} = 500 - 110 = 390 \text{ kg}$$

Final moisture content in 14% or 0.14

$$0.14 = \frac{\text{weight of water } (W_w)}{\text{weight of water + dry matter}} = \frac{W_w}{W_w + 390}$$

or

$$W_w = \frac{0.14 \times 390}{0.86}$$

$$= 63.488 \text{ kg}$$

Thus amount of water removed = 110 – 63.49

$$= 46.51 \text{ kg}$$

Moisture content determination methods

There are several methods for determination of Moisture content of agricultural products. For determination of Moisture content of a particular product, the choice of method depends on many factors, they are:

- 1) The form in which water is present in the product
- 2) The relative amount of water present
- 3) The rapidity of determination
- 4) Accuracy of method
- 5) Products nature whether easily oxidised or decomposed
- 6) The cost of equipment used.

Moisture content is determined only by two methods: 1) Direct or primary 2) Indirect or secondary

Direct methods

Air oven method:

In this method the temperature of the oven is set at 130°C and the samples are kept in oven for 1-2 hours. Afterwards, the samples are taken out and placed in a desiccator to cool down. The drop in the weight of grain is measured based on its initial weight.

Vacuum-oven method:

In this method, 2-3 grams of representative sample of ground material is placed in vacuum-oven (25 mm vacuum) and dried at 100°C for 72-96 hours. Afterwards, the samples are taken out and placed in a desiccator to cool down. The drop in the weight of grain is measured based on its initial weight.

Moisture from the sample is thus evaporated, collected and condensed in a graduated cylinder. The millilitre of moisture collected shows the percentage moisture content. The determined moisture content is on wet basis. In this method the temperature of mineral oil in flask should reach to 200°C within 26 minutes. The time required for moisture determination is about 30 minutes. If the temperature of the mineral oil reaches to desired temperature within time, the moisture content determination is found to be fairly accurate, when samples of grains are the tune of 1 to 1.5%.

Infra-red method:

In this method, grain moisture content is directly measured by evaporation of the water from a sample of grain with an infrared heating lamp. The instrument consists of a balance, a pan counter balanced by a fixed weight and a variable length of weighing chain. A scale calibrated

in percentage moisture content is incorporated in the stem of the instrument. The sample of grains may be unground, but when ground sample is used, the time needed to evaporate the water is reduced.

The salt-jar method

It is a simple field method for determining whether maize is dry enough for storage in bags. A teaspoon full of dry non-iodized salt is placed in a thoroughly dry jar (or bottle) with a tight cover. The salt should not stick to the sides of the jar when it is rolled. Then a cob of maize is shelled, the kernels placed in the jar and the cover sealed tightly. The jar is then shaken and rolled gently for 2–3 minutes. If the salt does not lump or adhere to the sides of the jar, the moisture is usually below 15 percent.

Moisture meters measure one or more electrical properties of the grain that are closely related to moisture content. Although acetylene and hair hygrometer measurement techniques have been used in the past, electrical moisture meters are now the most commonly used type of moisture meter. Developments in electronics have led to the manufacture of cheap and easy-to-use electronic meters that are also quite accurate. These are sold under different brand names.

Relative humidity

Relative humidity (RH) as a measure of air moisture is defined in Chapter 12. It is a useful factor for grain drying. The relative humidity of ventilating air indicates how much, if any, moisture can be removed from the grain with unheated air, and is a basis for deciding on ventilation rates and air temperatures. Relative humidity measurement Of the devices available for measuring relative humidity, one of the simplest and most accurate is a psychrometer. The temperatures of the wet-bulb and dry-bulb thermometers mounted on the instrument are noted and the values are used with a psychrometric chart. In fan systems, the psychrometer may simply be held in the airstream to obtain a reading

Indirect methods

Electrical resistance method:

The electrical conductivity or resistance of a product depends upon its moisture content. The universal moisture meter measures the electrical resistance of the grain at a given compaction. It gives fairly accurate readings of moisture content on wet basis.

Equilibrium Moisture Content (EMC)

The moisture content attained by a grain with respect to a set of atmospheric temperature and relative humidity is called the **Equilibrium moisture content (EMC)** of the grain. It is the moisture content at which the product will neither lose nor gain moisture with the atmospheric condition. It is in equilibrium with atmospheric moisture i.e., RH. The relative humidity of the air surrounding cereal grain in equilibrium with the environment is called the Equilibrium relative humidity (ERH). This property of gaining or losing of moisture as per the atmospheric conditions is known as Hygroscopicity

Importance of EMC

- It gives an idea whether the material gain or lose moisture

- It gives an idea about the rate of moisture removal
- It helps to determine drying characteristics
- It can be used to predict to which moisture level the product can be dried
- Essential for preservation, drying, storing, packaging and mixing

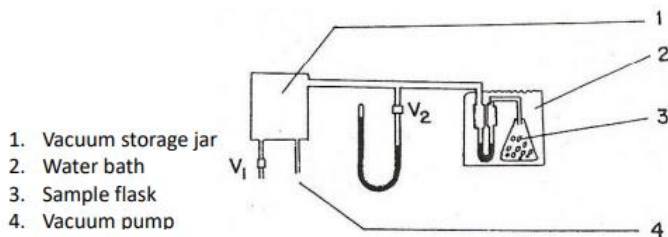
METHODS OF FINDING EMC

1. Static method Grains left in humid & still air until they attain equilibrium H_2SO_4 , HCl used to achieve desired RH levels Time consuming (3-4 weeks), mold attack, decomposition of grain structure

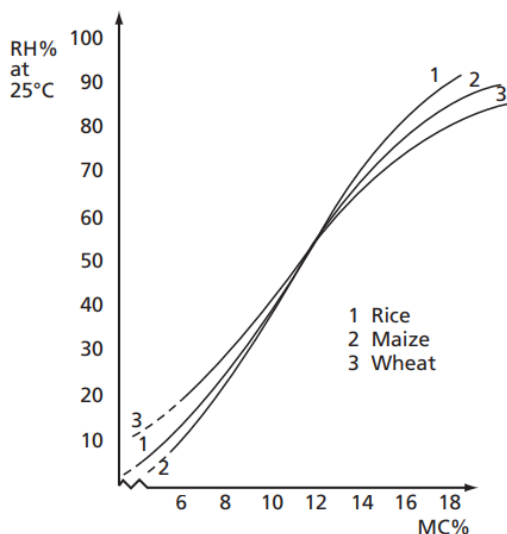
2. Dynamic method Humid air is agitated or moved by mechanical means & grains attain equilibrium condition Desorption, Isotenscopic method .

Desorption method : Property of dry air to absorb moisture from moist grain is used Moist grains are put in an air tight container RH measured by electric or hair hygrometer

Isotenscopic method: Equipment with U tube filled with liquid of negligible vapor pressure & conical flask Grain sample kept in a conical flask Vapor pressure exerted by moist grain is measured

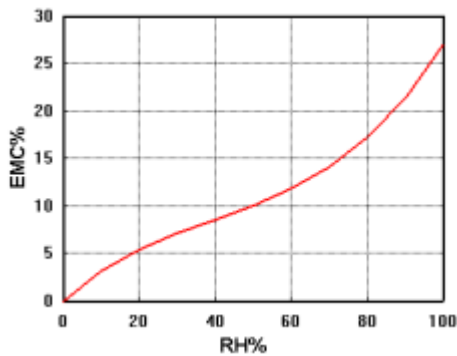


The EMC will also vary slightly with temperature. For most cereals, it will drop by approximately 0.5 percent for every 10 °C temperature rise at the same percentage relative humidity of the air.



EMC Curve

- Plotting the EMC versus relative humidity (holding temperature constant)
- Results in a sigmoid –type (S-shaped) curve that rises sharply above 85% relative humidity.
- The S-shaped curve is characteristic for biological products, including grains.
- EMC curves also called moisture equilibrium isotherms.

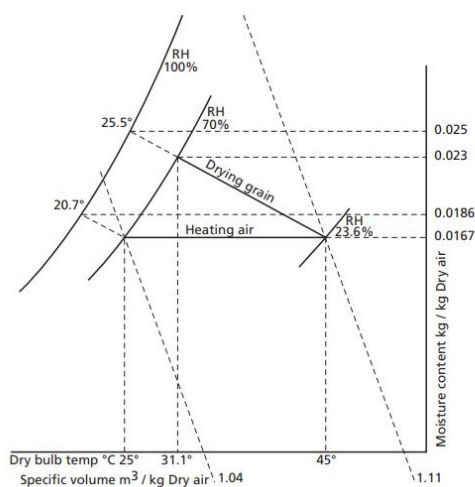


Desorption Isotherm: When some agricultural products in the process of losing moisture attains equilibrium moisture content with the surroundings, the EMC is known as desorption EMC.

Adsorption/Sorption isotherm: When a dry product gains moisture from the surroundings and attains EMC, that value of EMC is said to be adsorption EMC.

Temperature and psychrometrics of drying

Grain to be stored in bins or sacks may have too high a temperature or too high a moisture content, or both. If ambient temperatures are low, then air alone may cool the stored grain enough to prevent mould and insect damage while the moisture content is being slowly reduced to a safe level. If the air temperature is too high (over 10 °C), drying may be hastened by heating, as heating the air further increases its capacity to absorb moisture. Figure 16.3 shows the effect of heating the air, increasing its capacity to absorb moisture.



Loss of moisture As grain dries, it releases its moisture into the drying air and consequently loses weight. The weight of grain after drying may be found using the following equation:

$$W_2 = W_1 - \frac{W_1 (M_1 - M_2)}{100 - M_2}$$

where:

W_1 = Weight of undried grain (kg)

W_2 = Weight of dried grain (kg)

M_1 = Moisture content of undried grain (percent)

M_2 = Moisture content of dried grain (percent).

For example, if 200 kg of peas at 32 percent moisture content are dried to 19 percent moisture content, what is the weight of the dried peas?

$$W_2 = 200 - \frac{200 (32 - 19)}{100 - 19} = 200 - 32.1 = 167.9 \text{ kg}$$

Classification of grain drying

Grain drying can be broadly classified based on **source of energy**, **method of heat supply**, and **mode of operation**.

Based on Source of Energy

- **Natural Drying**
 - Uses sun and ambient air.
 - Examples: Open sun drying, solar cabinet drying.
 - Low cost but weather dependent.
- **Artificial (Mechanical) Drying**
 - Uses external energy (electricity, biomass, LPG, diesel, etc.) to heat air.
 - Examples: Batch dryers, continuous flow dryers, fluidized bed dryers.
 - Fast and controlled drying.

Based on surface of contact

- **Thin layer drying**
- Process in which all grains are fully exposed to the drying air under constant drying conditions i.e. at constant air temp. & humidity.
- Up to 20 cm thickness of grain bed is taken as thin layer
- All commercial dryers are designed based on thin layer drying principles
- Represented by Newton's law by replacing moisture content in place of temperature

Represented by Newton's law

$$\frac{M - M_e}{M_o - M_e} = e^{-K\theta}$$

Where, M = Moisture content at any time θ , % db

M_e = EMC, % db

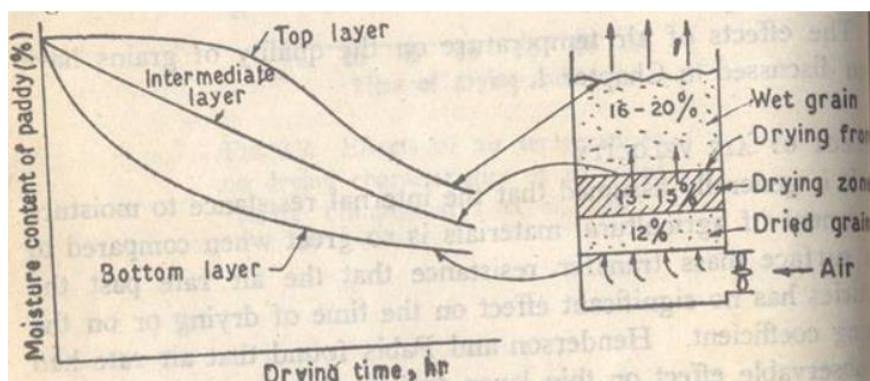
M_o = Initial moisture content, % db

K = drying constant

θ = time, hour

Deep bed drying

- All grains are not fully exposed to the same condition of drying air
- Condition of drying air changes with time and depth of grain bed
- Rate of airflow per unit mass of grain is small
- Drying of grain in deep bin can be taken as sum of several thin layers
- Humidity & temperature of air entering & leaving each layer vary with time
- Volume of drying zone varies with temp & humidity of entering air, moisture content of grain & velocity of air



Deep bed drying is a process used for drying agricultural products such as grains, seeds, nuts, fruits, vegetables, and many others. The method is characterized by the use of an airtight chamber or container where the product is placed in a deep bed or layer. It involves the application of heat and controlled airflow to remove moisture from the product without destroying its quality.

The process of deep bed drying generally involves three stages: Heating, Drying, and Cooling. During the heating stage, the chamber or container is preheated to a specific temperature. Then, the product is carefully loaded into the container, ensuring that it is evenly distributed in the deep bed. At this point, the container is sealed to prevent moisture from entering.

Next, the drying stage begins, and hot air is circulated through the container to remove moisture from the product. The temperature and airflow rate are maintained at specific levels depending on the type of product being dried. Humidity sensors are installed to monitor the moisture content in the deep bed to avoid over-drying or under-drying. As the moisture is removed, it is transported away from the product in the surrounding air.

Once the desired moisture content is reached, the cooling stage commences. The temperature of the airflow is gradually decreased to prevent thermal shock to the product. The cooler airflow also prevents the re-absorption of moisture by the product.

The design of a deep bed drying system varies depending on the product to be dried and the intended application. Most systems consist of a chamber, a heat source, a fan to circulate hot air, and a moisture removal system.

One of the advantages of deep bed drying is that it maintains the quality and nutritional value of the product. Unlike other drying methods that can result in the loss of nutrients and product quality, deep bed drying uses low temperatures and controlled airflow to remove moisture. As a result, the product retains its original color, texture, flavor, and nutritional value.

Based on Method of Heat Supply

- **Convection Drying**
 - Hot air passes over the grain → heat transfer by convection → moisture evaporates.
 - Common method in grain dryers.
- **Conduction Drying**
 - Heat supplied by direct contact of grain with hot surfaces.
 - Example: Rotary drum dryers with heated walls.
- **Radiation Drying**
 - Uses **solar or infrared radiation** for heating grains.
 - Example: Solar tunnel dryer, infrared dryers.
- **Dielectric / Microwave Drying**
 - Uses electromagnetic waves to excite water molecules inside the grain.
 - Very fast but costly.

Based on Mode of Operation

- **Batch Drying**
- **Continuous drying**

Based on Air Flow Pattern

- **Cross-Flow Drying**
 - Hot air moves perpendicular to grain flow.
 - Common in commercial dryers.
- **Counter-Flow Drying**
 - Hot air moves opposite to grain flow.
 - More efficient heat and mass transfer.
- **Concurrent Flow Drying**
 - Hot air and grains move in the same direction.
 - Reduces thermal stress on grains.

Based on Temperature of Drying

- **Low-Temperature Drying**
 - Uses slightly heated or natural air.
 - Slow but preserves seed viability.
- **High-Temperature Drying**
 - Uses hot air (40–110 °C depending on grain type).
 - Fast but risk of grain damage if not controlled.

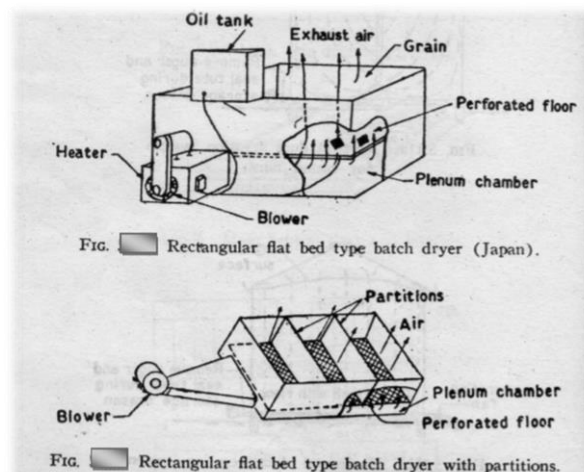
Batch type dryer

Batch dryers process a fixed amount of grain at one time. Once the batch is dried, it is emptied, and a new one is loaded. They are often more affordable and suitable for small to medium-sized operations. 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 Figure. The size of the dryer depends on the area of the 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 horse power of the motor for the blower ranges from $\frac{1}{4}$ 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 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 used for seed drying and for storage purpose also after drying
- 5) It can be manufactured locally using various types of materials like steel sheet, wood piece etc.

Disadvantages:

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