# CHAPTER 3

## BASICS OF DRYING

### 3.1 Basic Principle of Drying

When a wet solid is subjected to thermal drying, two processes coincide [Mujumdar, 2014]

1. Transfer of energy from the surrounding environment to the solid to evaporate the surface moisture. This depends on external conditions, i.e., air temperature, humidity, velocity, pressure, and the exposed surface area.

2. Transfer of internal moisture to the surface of the solid and its subsequent evaporation due to the above-mentioned process. This is a function of the physical properties of the material, temperature, and moisture content. During the drying process, the moisture evaporates at the solid surface and/or in the pores and leaves the solid due to the partial vapor pressure difference between the material and the surrounding air. Drying is a process of simultaneous heat and mass transfer.

The rate at which drying is complete is governed by the rate at which the two processes proceed. In a drying operation, either one of these steps might be the limiting factor, determining the drying rate. Despite the fact that they both happen at the same time throughout the evaporation process. Measurement of sample temperature during drying can help to identify whether a process is controlled by energy (external) or mass (internal) transfer.

A sample temperature equal to the wet-bulb temperature of the surrounding medium is characteristic of energy transfer control. If the sample reaches the dry bulb temperature of the drying medium, mass transfer control is suggested. Usually, when the first process is the limiting factor, namely the transfer of energy from the surrounding environment to the solid, drying takes place at a constant rate and is known as constant rate drying. If the second process is the limiting factor, namely the transfer of internal moisture to the surface of the solid, drying takes place at a logarithmically decreasing rate and is known as falling rate. The existence of any of these two processes depends on many parameters such as type of material, moisture content, sorption isotherm, diffusion coefficient, and other transport coefficients. The moisture content at which the drying rate of a product changes from a constant rate to a falling rate is called the critical moisture content of the product [Brooker et al., 1992]. The critical moisture content is the minimum moisture content of the grain that will sustain a rate of flow of free water to the surface of the grain equal to the maximum rate of removal of water vapor from the grain under the drying conditions. The critical moisture content can vary with air temperature and the properties of the material. [Sun et al., 1995.]

## 3.2. Drying Processes

### 3.2.1. Constant rate drying:

During the constant rate period, the material's surface is moist enough to saturate the layer of air close to it. As a result, the rate at which vaporized moisture may be transferred across the boundary layer around a substance determines the drying rate. During this time, the particle surface temperature remains constant at the air's wet-bulb temperature. Because the particle temperature does not rise during this time, all heat transfer from gas to particle across the boundary layer must be used for evaporation. The wet-bulb temperature of the air in the air-water system is nearly identical to the adiabatic saturation temperature, which may be easily calculated using psychometric charts

### 3.2.2. Falling Rate Drying

The rate of water transfer to the surface of a particle is inadequate during the falling rate period to maintain the layer of air next to the particle surface wet. As a result, the drying rate is no longer primarily dictated by boundary layer conditions. It is also affected by the substance's pore structure and the method of moisture transport. There might be numerous mechanisms operating at the same time. As the moisture content of a product falls below the critical point, the potential driving $\Delta P_v$ (difference in vapor pressure) decreases because the vapor pressure at the product surface falls below $P_{vwb}$ (vapour pressure at wet bulb temperature). Also, a moisture content gradient appears within the drying product, and the product temperature rises above wet-bulb temperature. A number of physical and thermal mechanisms have been proposed for describing the transfer of moisture in hygroscopic products.

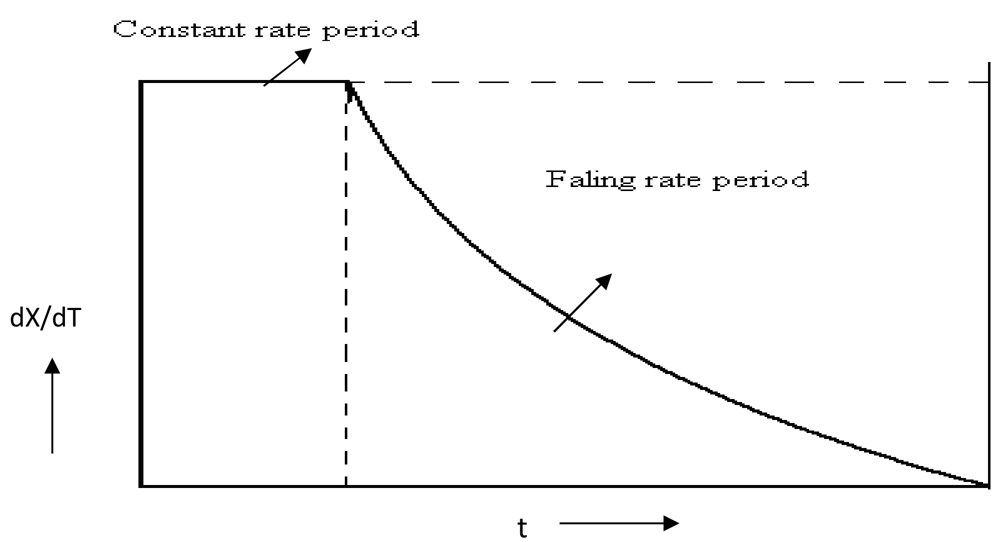


Figure 3.1 constant rate drying falling rate drying

Generally, non-hygroscopic materials dry primarily at a constant rate period and have a short time of falling rate period at the end of the drying process. Moisture in this type of material is not bonded (i.e., it is free moisture) and exists inside the relatively large size pores inside the particles. Therefore, the vapor pressure of the moisture is identical to the saturated vapor pressure of water.

On the other hand, hygroscopic materials dry mostly in the falling rate period and have only a very short time of constant rate period initially. Moisture for this type of material is bonded inside the material (bound moisture), and therefore, its migration to the surface cannot take place easily. If the moisture content is lower than a specified value, the vapor pressure of moisture is not identical to the saturated vapor pressure, and should be specified through the sorption isotherm.

Different mechanisms have been proposed for moisture migration inside the particle in the falling rate period, such as [Brooker et al., 1992]:

1. Liquid movement due to surface forces (capillary flow)

2. Liquid movement due to moisture concentration differences (liquid diffusion)

3. Liquid movement due to diffusion of moisture on the pore surface (surface diffusion)

4. Vapor movement due to moisture concentration differences (vapor diffusion)

Modeling of the drying process is complicated because more than one mechanism may contribute to the total process, and the contribution of different mechanisms may change as the drying process proceeds. The development of a generally applicable drying model requires the identification and inclusion of al1 contributing mechanisms. Most models apply the liquid diffusion mechanism with sufficient accuracy.

### 3.3. Equilibrium Moisture Content (EMC)

The idea of equilibrium moisture content (EMC) is essential in grain drying research because it defines the least moisture content at which grain may be dried under a particular set of drying circumstances. The EMC of grain is defined as the moisture content of the particle after an indefinitely long duration of exposure to a certain environment. Alternately, the EMC can be defined as the moisture content at which the internal product vapor pressure is in equilibrium with the vapor pressure of the environment. The EMC is dependent on three things: air temperature and relative humidity around the material and material type. EMC values for material decrease as air humidity decreases or air temperature increases. Thus, material drying will occur as long as the EMC is less than the current material moisture content. If the EMC is greater than the current material moisture content, drying will not occur. Instead, additional moisture will be added to the material

Several theoretical and empirical models have been proposed for calculating the moisture equilibrium of grains and other materials. The theoretical EMC models are based on capillary condensation (Kelvin model), kinetic adsorption (Langmuir, BET, GAB), are field strength potential. A thorough understanding of the connection between the equilibrium moisture content (EMC) and equilibrium relative humidity (ERH) is essential for completely describing the drying process and the influence of water activity for safe storage or subsequent processing. To characterise the EMC isotherms, a number of equations have been constructed theoretically, semi-theoretically, or experimentally. However, no single equation has been discovered that adequately describes the EMC/ERH relationships for diverse types of biological or ceramic materials over a wide range of relative humidity and temperatures. A wide range of research papers demonstrates the importance of selecting the best suited equation for a given product.

## 3.4. Moisture Content Determination

The methods for determining the moisture content of cereal grains can be divided into two broad classifications: direct and indirect measurements

Direct measurement:

1. Chemical reaction
2. Heating(oven)
3. Distillation
4. Microwave radiation
5. Infrared radiation

Indirect measurement:

1. Resistance
2. Capacitance
3. Relative humidity

Direct methods determine the amount of water in the grain by removing the moisture: Oven methods evaporate the moisture from the grain and determine moisture content by the amount of weight loss; distillation methods collect the evaporated moisture and determine the water volume. Indirect methods require the measurement of an electrical property of the grain, either conductance or capacitance. In general, in a laboratory, the moisture content is determined by a direct method; moisture determinations for purchasing and selling grain are usually made by indirect techniques.

The moisture content of seed or inorganic material is defined by the International Seed Testing Association (ISTA) according to the following formula: [Project, 2007]

$$Seed\ moisture\ content(\%) = \frac{fresh\ sample\ weight - dry\ sample\ weight}{dry\ sample\ weight} \times 100$$

### 3.5. Points to remember while finding moisture content:

- The reading is most likely incorrect when measured during or immediately after drying.
- Determine the moisture content of multiple samples from the batch of material for consideration.
- Do not handle the sample with your hands (this adds moisture) or expose it to air in an open container (this causes some drying or wetting to occur)
- Weigh or measure the sample accurately.
- Use the proper procedure for temperature correction.

## 3.5. CLASSIFICATION OF DRYERS

There are numerous schemes used to classify dryers [A S Mujumdar, 2000]. Table 3.1 lists the criteria and typical dryer types. Types marked with an asterisk (*) are the most common in practice.

The following categorization is a little sloppy. Depending on additional criteria, the fluidized bed dryer can be subcategorized into over thirty different varieties. Each type of dryer has its own set of qualities that determine whether it is acceptable for a certain use or not. Some are naturally more expensive than others (for example, freeze dryers), whereas others are fundamentally more efficient (e.g. indirect or conductive dryers). As a result, it's critical to understand the large range of dryers on the market, as well as their unique benefits and drawbacks.

Table 3.0.1 Classification of dryers

| **Criterion** | **Types** |
|---|---|
| Mode of operation | Batch<br>Continuous* |
| Heat input-type | Convection*, conduction, radiation, electromagnetic fields, combination of heat transfer modes<br>· Intermittent or continuous*<br>· Adiabatic or non-adiabatic |
| State of material in dryer | Stationary<br>Moving, agitated, dispersed |
| Operating pressure | *Vacuum**<br>· Atmospheric |
| Drying medium (convection) | Air*<br>· Superheated steam<br>· Flue gases |
| Drying temperature | Below boiling temperature*<br>· Above boiling temperature<br>· Below freezing point |
| Relative motion between drying medium and drying solids | Co-current<br>· Counter-current<br>· Mixed flow |
| Number of stages | Single*<br>· Multi-stage |
| Residence time | Short (< 1 minute)<br>· Medium (1 – 60 minutes)<br>· Long (> 60 minutes) |

It should be emphasized that the preceding classification excludes the majority of modern drying methods, which are only appropriate for extremely particular purposes. For further information on innovative drying technologies, see [Arun S. Mujumdar, 2014]. Baker (1997) presented a broad approach for classifying batch and continuous dryers, which is shown below.

It should be noted that the selection of batch dryers is more restricted, with just a few kinds capable of operating in both batch and continuous modes.

- **Because we focused primarily on deep bed dryers and fluidized bed dryers in this thesis, a quick overview of deep bed dyers and fluidized bed dryers is provided below.**

## 3.6. Deep Bed Drying

Deep Bed Grain drying refers to the drying of grains in thick layers and not individually or in thin layers. In this drying, the grains are kept as bed though which hot air is passed from below the bed. The air moves through the bed extracting moisture from the grains, thereby decreasing the moisture content of grains and increasing their humidity.

Deep bed grain drying can be done in the following ways:

### 3.6.1. Batch drying

- Batch-in bin drying
- Recalculating batch dryers

### 3.6.2. Continuous drying

- cross flow
- concurrent flow or parallel flow
- counter flow
- Mixed flow.

In fixed bed drying process, the air moves from bottom to top of bed. Moisture transfer from grains to air occurs. The temperatures of the grain and the humidity and moisture content of the grain depend upon the position of bed and drying time. As time passes, the bed of grains tends to equilibrium. The lower part of the bed attains equilibrium.

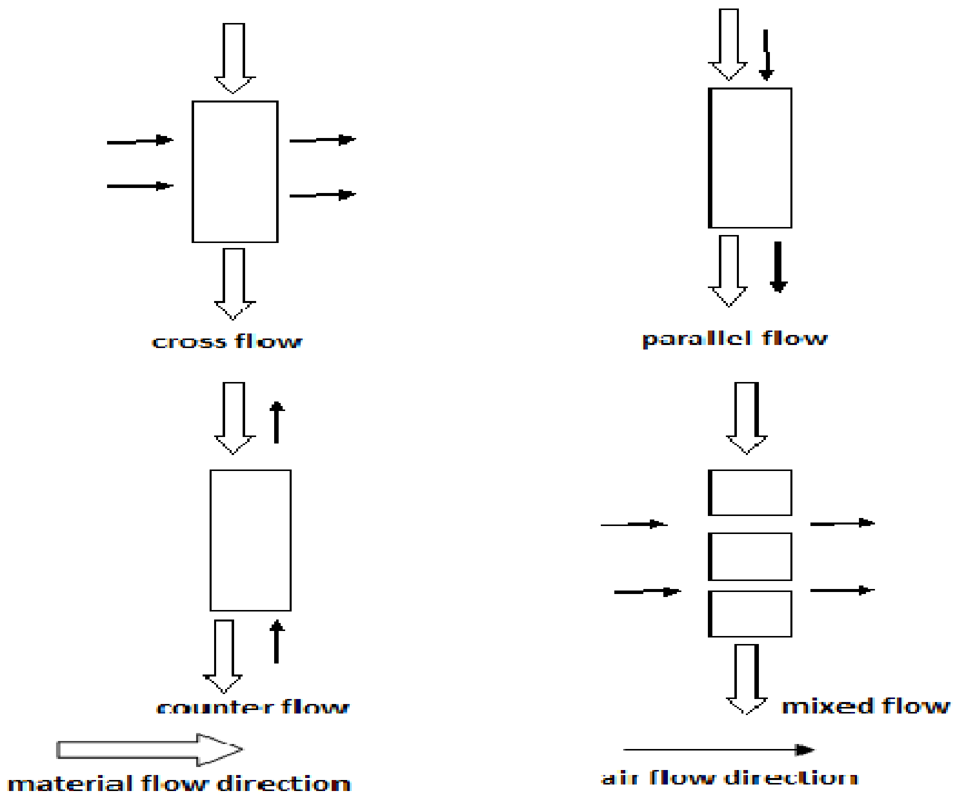


Figure 3.2 Different flow direction of air in the dryer [Bakker-Arkema et al., 1996]

## 3.7 Batch drying

### 3.7.1 Batch in bin drying

A bin is used as a batch drier in the batch-in-bin drying process. The fan and heating are turned on after a 3 to 4-foot layer of grain are deposited in the bin. The normal drying air temperature ranges from 120 to 160 degrees Fahrenheit. The drying process starts at the bottom and gradually moves up. The grain on the bin's bottom gets abnormally dry, while the top layer of the batch remains moist. After drying, the grain is cooled in the bin. Some batch-in-bin dryers keep the grain in a layer towards the roof while drying. The grain is dropped to the bin bottom to cool after it has been dried. The grain is mixed as it is transferred from the bin, and the average moisture level going into final storage should be low enough to prevent fungus development. The primary premise of a batch-in-bin dryer's function is to drive relatively large amounts of air through a deep grain depth to achieve a quick-drying rate, allowing the producers to tolerate higher harvest rates than with other forms of in-bin drying.

### 3.7.2 Recalculating Batch drying

A tapered sweep auger is used in the recalculating bin dryer to extract grain from the bottom of the bin as it dries. Temperature and moisture sensors regulate the sweep auger. Sensors activate the sweep auger, which sweeps a layer of cereal when the necessary condition is met. The sweep auger stops after one complete round around the bin, or when the sensor indicates that another layer is dry. The dried seed is re-distributed over the grain surface. The damp air passing through the grain will partially rewet the dried grain, lowering drying efficiency. The grain is cooled in the bin after it has been dried. The grain is then dried and chilled before being transferred to storage or left in the bin. It is common to dry the last bin full of grain using a continuous flow bin dryer as a recalculating bin dryer.

Because of its unique structure and shorter length of exposure to hot air, a recirculating batch type dryer is excellent for efficient drying, with a low cracking ratio, optimum airflow, even drying, and comparatively higher air temperature that can be employed without impacting seed quality. Grains are fed from the feeding hopper then conveyed by bucket elevator to upper screw conveyer; in turn, grains are distributed evenly in tempering bin by the distributor.

Gradually grains flow downward to the drying column formed by vertically erected perforated sheeting. With heat source generated by burner, hot air is introduced and passing through the drying column where grains are flowing through, and grain moisture is taken away by heated air; in turn, moisture absorbed air is exhausted by Exhausters.

Below each drying column, a rotary valve is constantly rolling, which determines the speed of grain flow as well as the duration of grain exposed to heated air. Constantly, grain is discharged to the lower hopper, which gathers grain to lower screw conveyer then conveyed to the inlet of the elevator and starting another drying cycle.

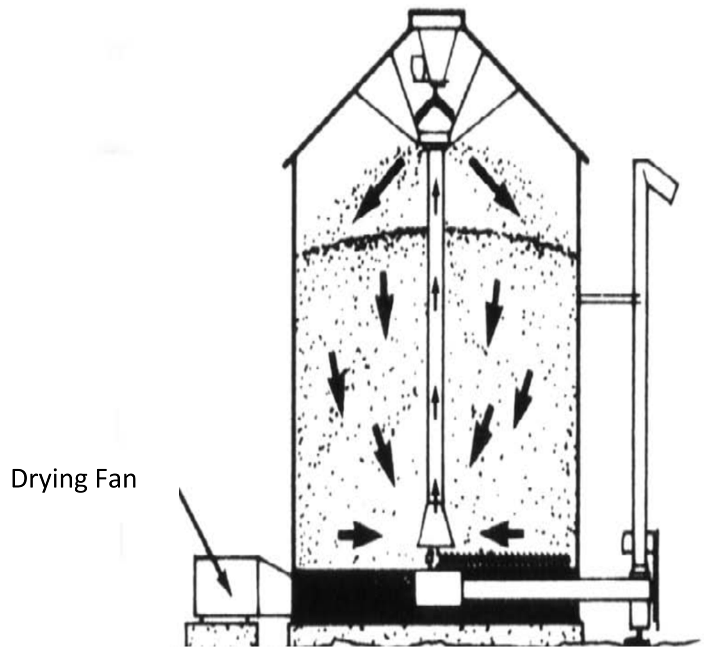


Figure 3.3 Recalculating Batch Dryer [Brooker et al., 1992]

## 3.8 Continuous drying:

Wet grain is continuously fed into the top of the dryer, where it is dried and cooled in a continuous flow dryer. The base of the bin is emptied of dry grain, which is then stored. The layout of these dryers is similar to that of batch dryers, except they contain a split plenum chamber. The upper chamber receives hot drying air, while the lower chamber receives unheated cooling air. Continuous flow dryer column diameters vary depending on our needs. The discharge rate, and hence the moisture levels of the dried seed, is controlled by a sensor. High temperatures and high airflow rates are used in continuous flow dryers. Airflow rates ranging from 0.5 to 1 m/sec Continuous flow dryers come in a wide variety of sizes. Portable units and stationary units of larger capacity are also available. The first grain through a continuous-flow dryer generally will need to be cycled through the dryer again for drying to be completed.   Continuous flow dryers can be considered as an extension of recalculating batch dryers.

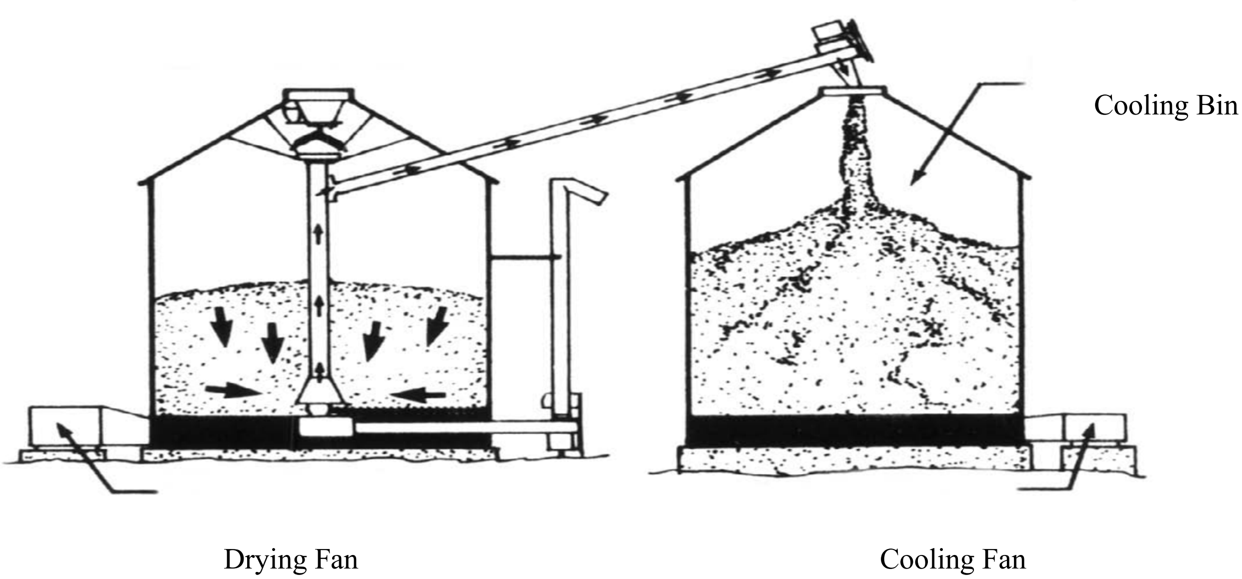


Figure 3.4.Continuous flow dryer [Brooker et al., 1992]

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

### 3.9. Cross Flow Grain Drying System:

In North America, cross-flow dryers are perhaps the most prevalent. They contain a plenum enclosed by a thin grain column, and hot air passes through the grain perpendicular to the grain's downward movement. The lowest portion of the grain column is where the grain is cooled. Tower or column dryers are common names for cross-flow dryers. Grain does not dry evenly in cross-flow dryers. When the drying process is stopped, significant moisture and temperature gradients persist across the grain column. Although the degree of non-uniformity reduces during the cooling cycle, there is still a significant moisture difference among the kernels as the grain leaves the drier, despite the fact that the average moisture content may have achieved the appropriate level. The grain-quality properties of cross-flow dryers have improved as a result of recent design developments. In order to verify the moisture and temperature differentials in the grain column, several cross-flow dryers have included airflow reversal. Grain inverters move hot grain from the air inflow side of the column to the air exhaust side, reducing over-drying and overheating. Tempering, a recently added element to the basic cross-flow design, increases the quality of cross-flow-dried cereal. Modern cross-flow dryers with air recycling, grain tempering, and grain inverting can dry wet grain at high throughput and reasonable energy efficiency, as well as produce dried grain with modest moisture differentials between kernels. The cross-flow drier is an excellent alternative for feed grain.

### 3.10. Concurrent-flow dryers

The grain and drying air move in the same direction in a concurrent flow drier, but in the opposite direction in a counterblow cooler. Concurrent-flow dryers have two or three concurrent-flow drying regions, with the exception of a modest, one-stage on-farm concurrent-flow type. This dryer type has the benefit of being able to use varied air temperatures in different phases.

The consistency of the drying is the concurrent flow dryer's most distinguishing attribute. Unlike cross-flow and mixed-flow dryers, each kernel receives the identical heating, drying, tempering, and chilling treatment. Because the wet material is exposed to the hot drying air for seconds rather than hours (cross-flow dryers) or minutes (mixed-flow dryers), the temperature of the drying air is substantially higher than in other dryers. As a result, unlike in the other dryer, the grain does not reach the temperature of the drying air. Concurrent-flow dryers provide superior-quality dried grain because of the homogeneous, pretty smooth drying and cooling operations, as well as the built-in tempering treatment. Concurrent-flow dryers had a lower percentage of stress-cracked kernels than mixed-flow and cross-flow dryers. In terms of grain quality and fuel economy, dryer experts believe that concurrent-flow grain dryers are preferable to cross-flow and mixed-flow dryers. However, this dryer type has a number of drawbacks, including high-tech elements, widespread misunderstanding, and a somewhat high starting cost.

## 3.11. Mixed-flow dryers

Grain is dried in mixed-flow dryers by a mixture of cross-flow, concurrent-flow, and counter-flow processes. This results in fairly uniform drying, and therefore in relatively uniform grain moisture content and quality. The drying temperature in mixed-flow dryers is higher than in cross-flow dryers because the grain is not subjected to the high temperature for as long. During the mixed-flow drying process, the grain kernels are subjected to a continuously-changing pattern of repeated cross flow concurrent-flow and counterblow drying treatments. Therefore, a mixed-flow dryer simulation model consists of a combination of all three dryers.

## 3.12. Counter Current Grain Drying:

In this process, the relative motions of grains and the drying air are in opposite directions. The grain in this type of dryer moves downwards, and the air moves upward. Dry grain is extracted from the bottom and stored. Hot drying air is pumped into the upper chamber, while unheated air is sent into the bottom chamber for cooling. Column widths on counterflow dryers vary depending on our needs. A sensor regulates the flow rates and, as a result, the moisture content of the dried grain. And the auger is regulated by sensors, and its operation is intermittent in the sense that it will halt the grain going into the drier if the grain is not dry enough to be removed.

## 3.13. Advantages:

1. Heat is not wasted in drying grain below the desired moisture content.
2. The grain is exposed to the hottest air while it is still losing moisture at a significant rate, and it is exposed to a high temperature for a shorter time than in a conventional batch in process, thus reducing heat damage. Thus relatively high temperatures can be used.
3. Ability to dry particles of varying size.

4. It can even dry, moist, sticky kernels if specific measures like recirculation are incorporated, which is not much expensive.

5. Lesser electric power requirement.

6. The filling schedule is entirely flexible; however, the deeper the grain, the lower the drying rate.

7. The installation cost and operation cost are low.

### 3.14. Disadvantages

1. The quality of drying is not as good as in fluidized bed drying

2. Food shrinkage and possible heat damage.

3. Risk of spoilage from warm moist air.

4. Requires more grain handling.

### 3.15. Fluidized Bed Drying

Fluidization is an operation by which solid particles are transformed into a fluid-like state through suspension in gas [12]. When a gas is passed through a layer of particles supported by a grid at a low flow rate, the fluid percolates through void spaces between stationary particles, and the bed remains in a fixed state shown in fig.4.1. As the fluid velocity increases, the voidage increases, thus resulting in a pressure drop on the particle. The pressure drop across the particle layer will continue to increase in proportion to the gas velocity till the pressure drop reaches a constant value that equivalent to the weight of the particles in the bed divided by the area of bed; at this point the upward drag force on the particle is exactly equal to the weight of the particle. At this stage, the bed is to be incipiently fluidized shown in fig.3.5. Fluid velocity at this point is known as minimum fluidization velocity. By further increasing gas velocity, the bulk density of the bed will continue to decrease, and its fluidization becomes more violent until the particles no longer form a bed and are "conveyed" upwards by the gas flow.

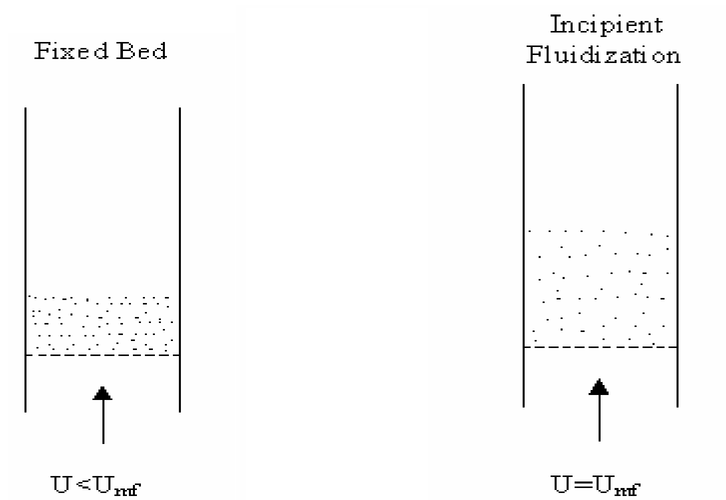


Figure 3.5  Region of Fluidization [Husain et al., 2007]

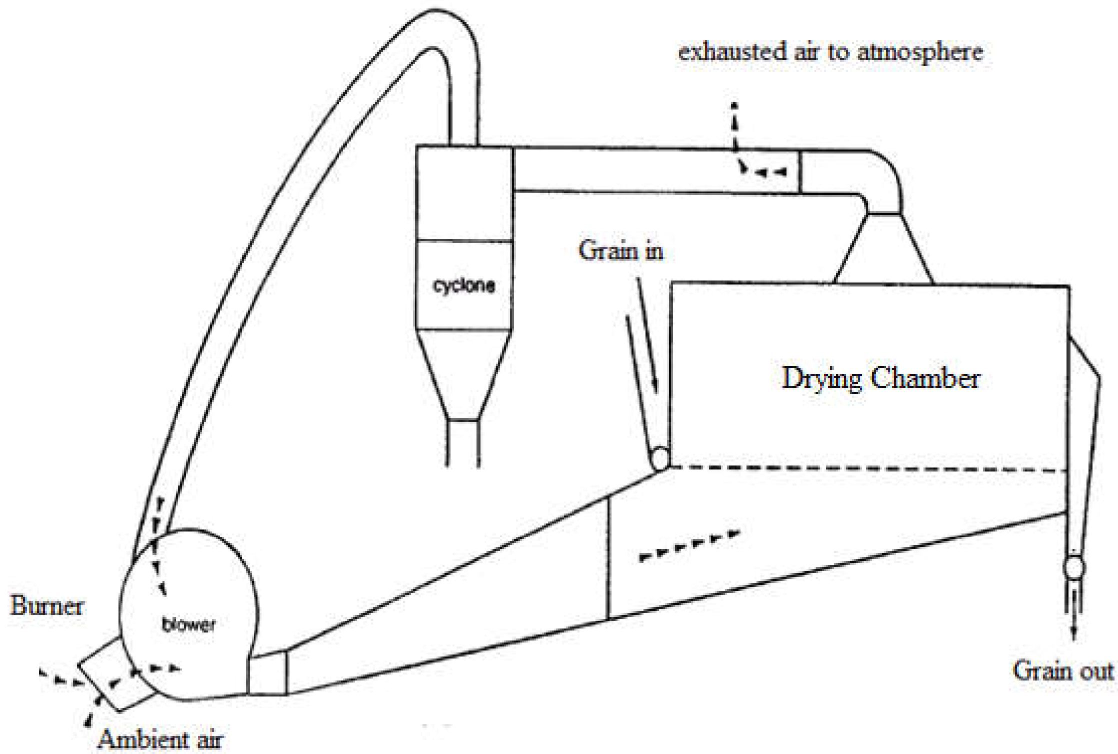


Figure 3.6. Fluidized Bed Dryer [Wiriyaumpaiwong et al., 2001]

A drying chamber, a fan, a heater, and a cyclone separator are all part of a fluidized bed dryer. A weir regulates the height of the bed rotary feeders transport grain in and out of the machine. In operation, hot air (regulated by a thermostat) is forced into the drying compartment via a perforated steel sheet bottom. The grain and air fluxes are perpendicular to one another. A tiny percentage of the air exiting the drying chamber is vented to the environment, whilst the remainder is returned to the dryer after cleaning in a cyclone, mixed with ambient air, and reheated to the correct temperature, respectively. [Wiriyaumpaiwong et al., 2001]

## 3.16. Advantages of Fluidized Bed Drying

The popularity of fluidized bed dryers is increasing because of the following factors:

1. The drying rate is very fast as compared to conventional grain dryers.
2. Rapid exchange of heat and mass between the fluidizing gas and particles because of high heat and mass transfer coefficient.
3. Rapid mixing of solid leads to nearly uniform moisture content and temperature of solids throughout the bed.
4. The lack of moving part results in low maintenance cost and low equipment cost.
5. Possibility of applying additional heat transfer modes (i.e., immersed heating panels)
6. Maximum area of contact between air and solids.
7. The fluidity of particles provides an excellent condition for handling and moving the particles under automatic or manual control.
8. The lack of moving parts, other than feeding and discharge mechanisms, keeps reliability highs.
9. Excellent temperature control and operation up to the highest temperature.
10. High drying capacity due to high ratio of mass of air to mass of product.
11. Grain quality maintained.

## 3.17. Limitations of Fluidized-Bed Drying

The main limitations of fluid bed dryers include

1. There is an excessive loss of kinetic energy due to high gas velocity.
2. High electric power requirement because of increased air velocity.
3. High specific energy consumption due to the low relative humidity of the exhaust air.

4. The material being dried must be fluidizable.
5. Limited allowable size distribution of the kernels.
6. Inability to dry very moist sticky kernels.
7. At high temperatures, the melting and fusion of the material on the grid plate can become a problem.

## 3.18. Kinds of Fluidized-Bed Dryers

The different types of fluidized bed dryers are briefly described below.

### 3.18.1. Batch dryers [Geldart, 1986]

When the production scale is modest and multiple types of products are to be produced on the same manufacturing line; batch fluidized bed dryers are typically employed. The filter sock module loads the moist feed into the cabinet. After that, the cabinet doors are locked, and the blower is turned on. The amount of air circulation is controlled by an adjustable damper. A heater might be used to heat the flowing air (shown in fig.3.7). Batch fluid bed dryers are widely used in the pharmaceutical and dyestuff industries.

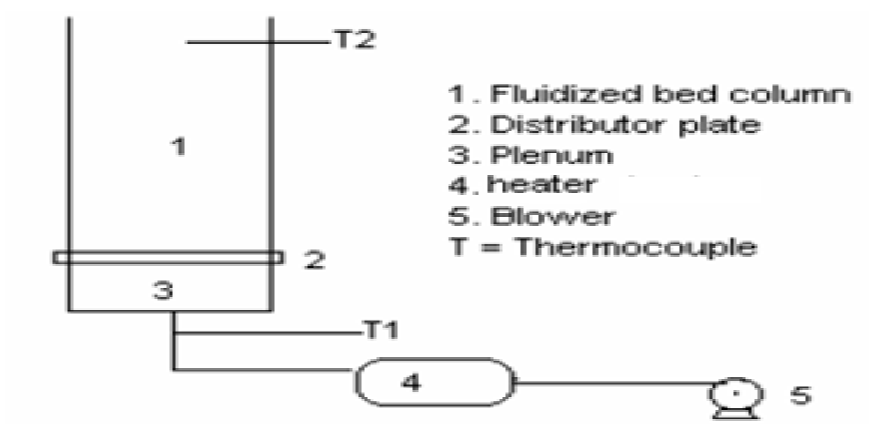


Figure 3.7. Schematic Diagram of Batch Fluidized Bed Dryer [Husain et al., 2007]

### 3.18.2. Continuous Well-mixed Dryers [Geldart, 1986]

The first continuous fluid bed dryer was the 'well-mixed' type, which was introduced in the United States in 1948. It is usually of circular cross-section and takes its name from the fact that the particle residence time distribution approaches the perfect mixing law:

$$E(t) = \frac{1}{t_R} \exp\left( -\frac{t}{t_R} \right) \tag{4.1}$$

in this expression, E(t) is the fraction of particles with residence times between t and

(t + dt), and $t_R$ is the mean residence time. Because of the near-perfect mixing, the bed has a nearly uniform composition and temperature equal to the composition and temperature of the outlet product stream. Hence, the moist feed falls into a bed of almost dry particles. For this reason, this type of continuous fluid bed dryer can handle wet feedstocks than can other types of dryers.

### 3.18.3. Continuous Plug Flow Dryers [Geldart, 1986]

Plug flow design having a large aspect ratio (typically in the range 4:1 to 30:1) for a cross-sectional area with shallow depth (typically 0.1m) operation at velocities slightly higher than the minimum fluidization velocity is required for keeping the residence time variation, over its mean value, to desirable lower limits. This leads to a smaller deviation of the moisture content in the final product and is directly linked with the quality of the dried product. It is a continuous operation; wet material is fed from one side, and dried material comes out from another side in a flow pattern (as shown in fig.3.8), and it is used for high-scale production.

This type of dryer will dry down to low final moisture contents but is not well suited to handling wet, sticky feedstocks unless special measures, such as mechanical stirring of the bed at the feed end, are taken. The temperature of the drying solids progressively increases from the inlet value at the feed end of the dryer to a value approaching the air inlet temperature at the discharge end.

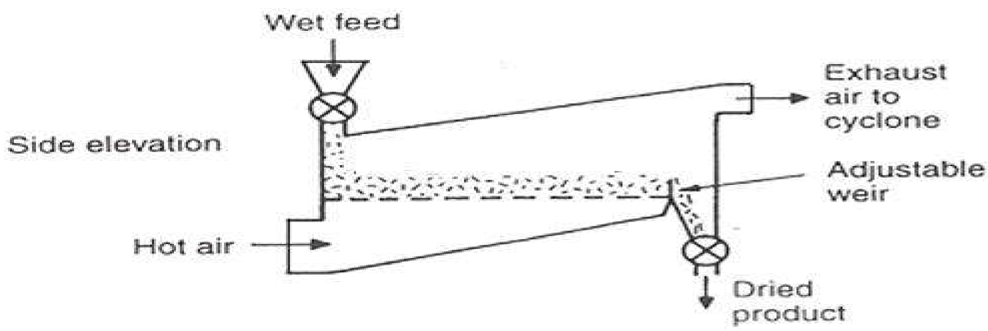


Figure 3.8. Continues Plug Flow Fluidized Bed Dryer [Geldart, 1986]