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Subject: Food Technology

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Paper No. : 04 Unit Operations in Food Processing

Module : 16 Drying-2: Drying Rate

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Description of Module	
Subject Name	Food Technology
Paper Name	04 Unit Operations in Food Processing
Module Name/Title	Drying rate
Module Id	FT/UOFP/16
Pre-requisites	Basic of Heat Transfer & mass transfer
Objectives	To understand the basic principle of drying in food products and apply the knowledge in solving critical problems in drying.
Keywords	Drying rate, constant rate period, conduction drying

16.1 Introduction

The separation operation of drying converts a solid, semi-solid or liquid feedstock into a solid product by evaporation of the liquid into a vapor phase via application of heat. In the special case of freeze drying, which takes place below the triple point of the liquid being removed, drying occurs by sublimation of the solid phase directly into the vapor phase. This definition thus excludes conversion of a liquid phase into a concentrated liquid phase (evaporation), mechanical dewatering operations such as Filtration, centrifugation sedimentation, supercritical extraction of water from gels to produce extremely high porosity aerogels (extraction) or so-called drying of liquids and gases by use of molecular sieves (adsorption). Phase change and production of a solid phase as end product are essential features of the drying process. Drying is an essential operation in the chemical, agricultural, biotechnology, food, polymer, ceramics, pharmaceutical, pulp and paper, mineral processing, and wood processing industries.

> "*Simply Drying is a mass transfer process consisting of the removal of water or another solvent by evaporation from a solid, semi-solid or liquid. This process is often used as a final production step before selling or packaging products*"

16.2 Mechanisms of Drying:

Drying of solids takes place in three stages:

1) Transport of the liquid from the interior of the solid to the surface
2) Evaporation of the liquid at the surface
3) Transport of the vapor away from the surface

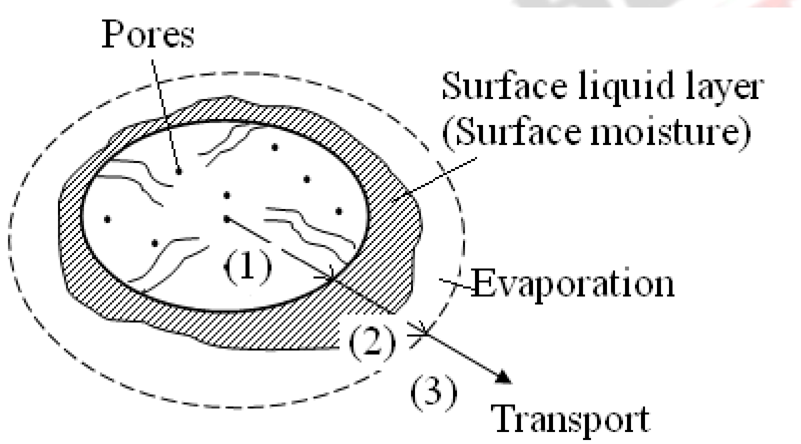


Figure 16.1: Drying steps for a particle

Materials that are surface-wet will exhibit three distinct drying regimes which is shown in fig. 16.2.

AB – material is warming (to an equilibrium temperature)
BC – constant drying rate: "Constant Drying Rate Period"
CD – rate of drying decreases: "Falling Rate Period"

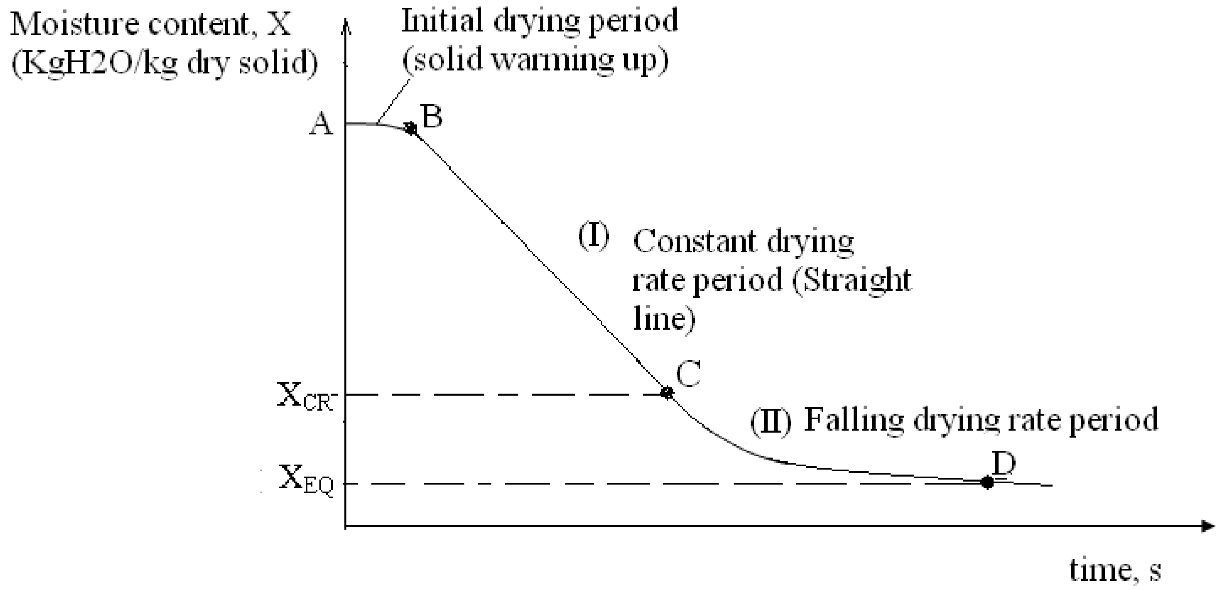


Fig. 16.2 Moisture content vs. time

Amount of moisture removed from the dried material in unit time per unit of drying surface:

$$W_D = -\frac{m_s}{A}\frac{dX}{dt}$$

Where, m_s=mass of **DRY** solid (kg)

WD =drying rate (kg/m^{2}s)

X =moisture content, dry basis (kg [MOISTURE]/kg [BONE DRY MATERIAL]) i.e. m.dX is the mass of total moisture, on a dry basis

A =surface area (m^2)

t =time (s)

We can integrate this expression to:

$$\int_0^t dt = -\frac{m_s}{A}\int_{X_1}^{X_2}\frac{dX}{W_d}$$

NB: Negative sign is because moisture content decreases with time.

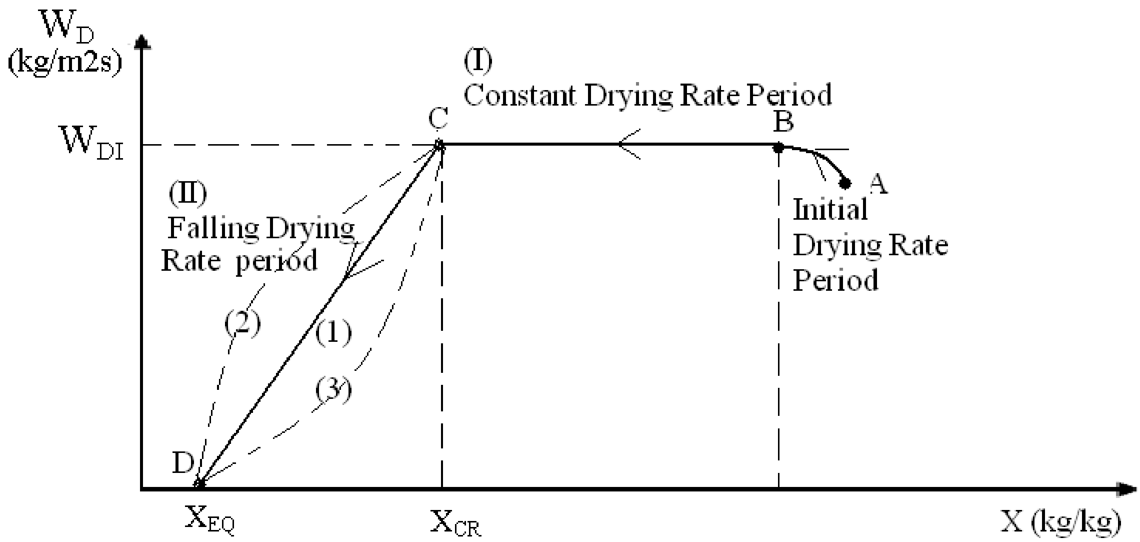


Fig 16.3: typical WD vs. X

16.3 Drying rate curves or drying periods:

The drying characteristic of wet solids are usually described by the drying rate curves .Generally, a drying rate curve can be divided into the following drying rate period.

1) Settle down period
2) Constant drying rate period
3) First falling drying rate period
4) Second falling rate period

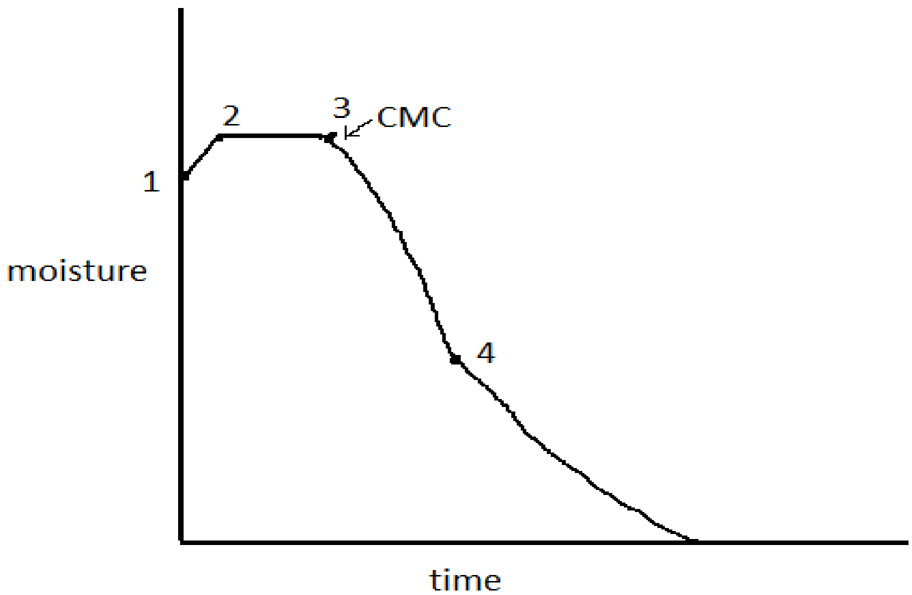


Figure 16.4: Typical Drying Curve

Here, Point 1-2 > Settle down period

Point 2-3 > Constant rate period

Point 3-4 > First falling rate period

Point 4-5 > Second falling rate period

- <u>Settle down period</u> :

The stage 1-2 (in fig.16.4) represents the settle down period where the solid surface comes to equilibrium with dry air. At time 0, point 1 represents the initial moisture content .This stage is usually very short and may be ignored from the drying time calculation.

- <u>Constant rate period :</u>

The stage 2-3 represents the constant rate period.This period has the following characteristics:

- It occurs with the product at the WBT of the air.
- A continuous film of water exists on drying surface and evaporation of water occurs from this film of water.
- The duration of constant rate period depends on three external factors.
  1) Heat or mass transfer coefficient
  2) Exposed area
  3) Temperature and humidity difference between the air stream and wet surface of food material

- <u>Critical moisture content(CMC) :</u>

Point 3 in the figure represents the Critical moisture content.It is the end point of constant rate period (CRP)and starting point of falling rate periods(FRP).From this point onwards the surface temperature begins to rise ,the moisture content decreases ,rate of diffusion drops and rate of drying becomes slow as drying proceeds.

- <u>First falling rate period(FFRP):</u>

In FFRP, the food surface is no longer capable of supplying sufficient moisture from within the food mass to the surface .This is the period of unsaturated surface drying.

- <u>Second falling rate period(SFRP):</u>

It begins at point 4 when the surface is completely dried.This period have some characteristics.

1) In this period, the drying rate is mainly limited by the diffusion of moisture from within the product to surface.
2) Heat for evaporation is transferred through the solid to the zone of evaporation and vaporized water comes into the air stream through the solid .Most of the drying is generally takes place in secondfalling rateperiod.

The time of falling rate period is longer than constant period, though the amount of water evaporation is smaller .The entire drying process occurs in falling rate period when initial moisture content (IMC) is less than Critical moisture content (CMC).

16.4 Calculation of constant rate period / prediction of drying time in Constant Rate Period (CRP):

For calculation or prediction of constant drying rate period the following relation can be used:

16.4.1 Moisture removal rate in constant rate period

$$R_c = \frac{dm}{dt} = \frac{X_i - X_c}{T_c} = K_g.A.(P_w - P_a) = \frac{hA(T_a - T_w)}{h_{fg}} \qquad \text{.......(1)}$$

Where

Rc=Rate of constant drying period

Xi=Initial moisture content, kg water/kg dry solids

Xc=Critical moisture content, kg water/kg dry solids

Tc=Time for constant drying

dm/dt= moisture removal rate

Kg=overall mass transfer coefficient

Pw=Vapor pressure at surface temperature (i.e; WBT Tw)

Pa=Vapor pressure in the air

H=Heat transfer coefficient

Ta=Heated air temperature

Tw=Wet bulb temperature

A=Area over drying takes place

h_{fg}=Enthalpy of evaporation

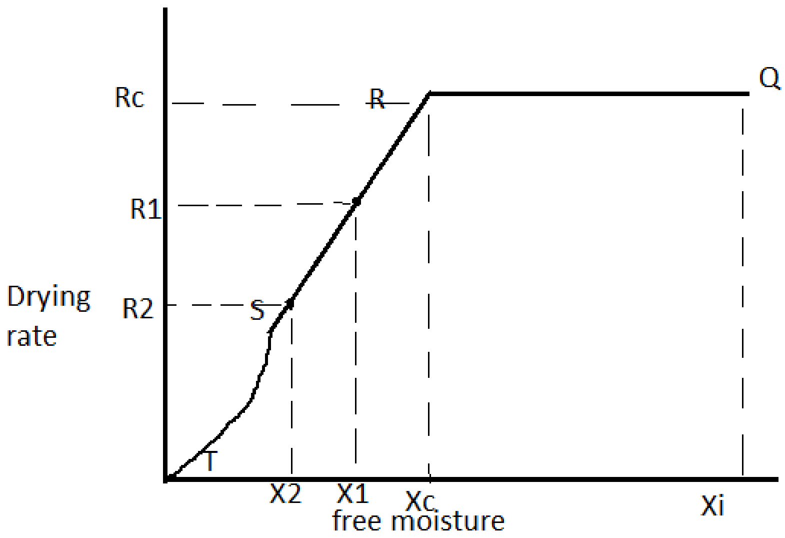


Fig 16.5: Prediction of drying time

16.4.2 CRP in terms of heat transfer coefficient:

$$T_c = \frac{h_{fg}(X_i - X_c)}{hA(T_a - T_w)} \qquad \text{.................. (2)}$$

16.4.3 CRP in terms of mass transfer coefficient:

$$T_c = \frac{0.622RT(X_i - X_c)}{K_g A M_w (H_w - H_a)} \qquad \text{.................. (3)}$$

Where,

Hw-Ha= Gradient of humidity ratio at the product surface and in the heated air

T= Absulate temperature

16.4.4 CRP in terms of rate of drying:

$$T_c = Moisture\ removed\ during\ constant\ rate\ period/Rate\ of drying$$

$$T_c = \frac{M_d(X_i - X_c)}{AR_c} \qquad \text{............... (4)}$$

Where,

M_d =Mass of dry solids

Example: 16.1

A batch drying process of 100 kg food powder whose drying curve represented by Figure 6.9 is dried from 28% moisture (w_b) to 16% moisture (w_b) at a constant rate of 0.006 kg/m^2s . The critical moisture content is 15%. Estimate the batch drying time if drying surface is 0.03 m^2 per kg of dry weight.

Solution: Since initial and final moisture content are greater than the critical moisture content, then the drying take place in constant rate period and drying time calculated by equation. Referring to figure 16.6 convert the moisture content to dry basis gives

x_1= 0.389 and x2=0.190.the available surface area for drying is 0.03Md m2.

Where, M_d=total dry weight of solids

From equation 6.15, drying time t_c for constant rate period is

$$t_c = \frac{M_d(0.389-0.190)}{0.03*M_d*6*10^{-3}}$$

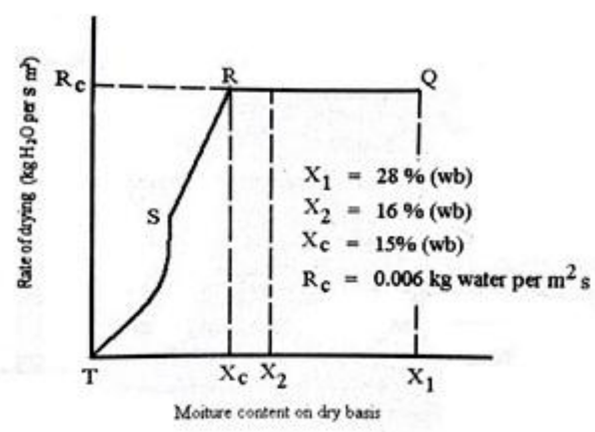
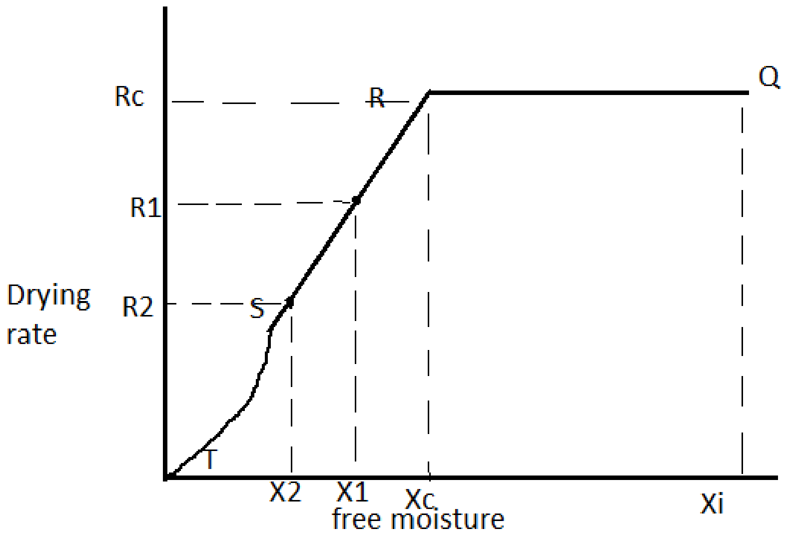


Figure 16.6 on Constant Rate drying

16.5: Calculation of falling rate period/Prediction of drying time in falling rate period:



Fig; 16.7: Prediction of drying time

For first falling rate period (R to S), the drying time can be calculated if moisture removal rate(R) is represented by R=m.X+k, where m is the slope of the line and k is the intercept. Thus, R1= m.X1 +k and R2=m.X2 +k

$$t_{F1} = \frac{M_d(X_1 - X_2)}{A(R_1 - R_2)} \ln\left(\frac{R_1}{R_2}\right) \quad \text{......... (5)}$$

Similarly, drying time for second falling rate can be calculated.

However, drying time in the falling rate period can also be determined, if rate of drying at constant period is known, by following expression

$$t_F = \frac{M_d(X_c - X_e)}{AR_c} * \ln\left(\frac{X_1 - X_e}{X_2 - X_e}\right) \quad \text{..........(6)}$$

Often for lack of more detailed data an assumption is made that there is only one falling rate period and this would be straight line RO(as shown in the fig;2)from Critical moisture content (Xc) passing through origin .Then drying rate R at any moisture content X is directly proportional to free moisture content.

Thus in that case R=Mx

$$X_1 \quad = \quad X_c \qquad = CMC$$

$$R_1 \;=\; R_c = mX_1 = mX_c$$

$$R_2 = mX_2$$

Or $\frac{R_1}{R_2} = \frac{X_c}{X_2}$ ………….. (7)

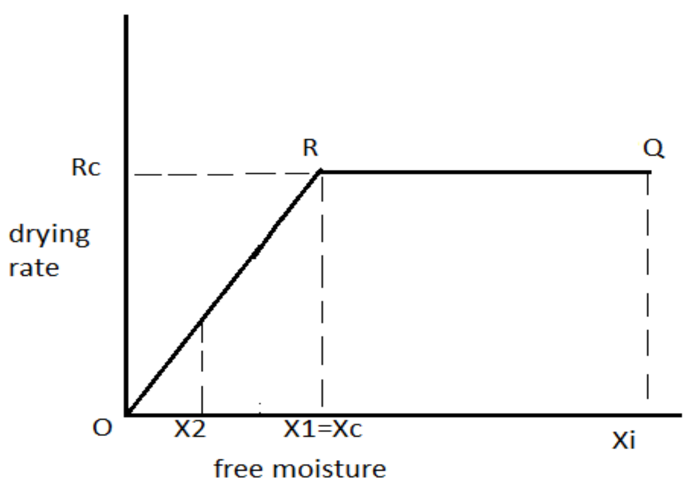


Fig. 16.8: Drying curve for falling rate period

Now, rewriting the equation (5)

$$t_{F1} = \frac{M_d X_1 \left(1 - \frac{X_2}{X_1}\right)}{AR_1 \left(1 - \frac{R_2}{R_1}\right)} * \ln\left(\frac{R_1}{R_2}\right)$$

Putting $X_1 = X_c, R_1 = R_c\ and\ \frac{R_1}{R_2} = \frac{X_c}{X_2}$

$$t_{F1} = \frac{M_d X_c\left(1-\frac{X_2}{X_C}\right)}{AR_c\left(1-\frac{X_2}{x_C}\right)} * \ln\left(\frac{X_c}{X_2}\right) \qquad \ldots\ldots\ldots (8)$$

$$t_F = \frac{M_d X_c}{AR_c} * \ln\left(\frac{X_c}{X_2}\right) \qquad \ldots\ldots (9)$$

The above expression can also be obtained in equation (6), if the value of X_e in that equation takes as zero.

Example: 16.2

A batch of wet solid whose drying rate curve is represented by figure 16.7 is to be dried from 0.40 kg water per kg dry solid to 0.10 kg water per kg dry solids in two hours with constant air condition .If the EMC=2% (dry basis).Calculate the total time required from 40% to 4% moisture content (dry basis).

Solution: Referring to figure 16.9, constant rate period only from 40% to 15% and therefore, using equation, we get drying time for constant rate period

$$t_1 = \frac{(0.40-0.15)M_d}{R_c A} = \frac{(0.25)M_d}{R_c A}$$

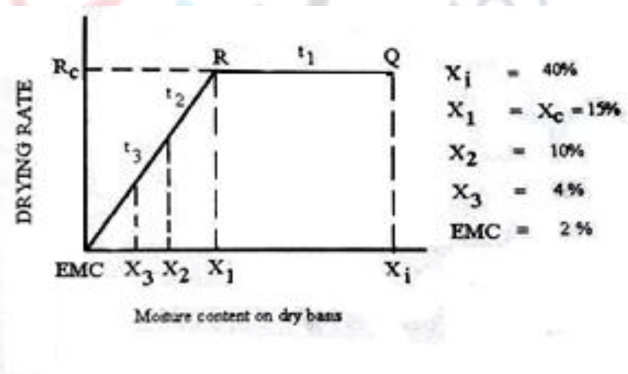


Figure 16.9 on Falling rate period

Where, M_d, R_c and A are all unknown.

For falling rate period between 15 % to 10 % the values of X_1 abd X_2 become 0.15 and 0.10 respectively. From equation, drying time over this range of moisture content is given by

$$t_1 = \frac{M_d}{R_c A}(0.15 - 0.02) ln \frac{(0.15 - 0.02)}{0.10 - 0.02}$$

$$= \frac{(0.0631) M_d}{R_c A}$$

However, Total drying time from moisture conetnt of 40 % to 10 % is 2 hour.

Thus

$$t_1 + t_2 = (0.25 - 0.0631) \frac{M_d}{R_c A} = 2$$

$$\frac{M_d}{R_c A} = 6.39\ h$$

For falling rate period between Moisture conent of 10 % and 4 % respectively the drying time is

$$t_3 = 6.39(0.15 - 0.02) ln \frac{(0.10 - 0.02)}{(0.04 - 0.02)}$$

=1.15

Hence total drying time required to down the mositure conetnt from 40 % to 4% is

= 2+1.15= 3.15 h

16.6 METHODS OF DRYING

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

16.6.1 Convection Drying

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

1. Drying is dependent upon the heat transfer from the drying agent to the wet material, the former being the carrier of vaporized moisture
2. Steam heated air, direct flue gases of agricultural waste, etc., can be used as drying agents
3. Drying temperature varies widely.
4. At gas temperatures below the boiling point, the vapor content of the gas affects the drying rate and the final moisture content of the solid.
5. If the atmospheric humidities are high, natural air drying needs dehumidification.
6. Fuel consumption per kilogram of moisture evaporated is always higher than that of conduction drying.

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

Convection drying can be further classified as follows:

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

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

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

16.6.2: Conduction Drying

When the heat for drying is transferred to the wet solids mainly by conduction through a solid surfaces the phenomenon is known as conduction or contact drying. In this method, conduction is the principal mode of heat transfer and the vaporized moisture is removed independently of the heating media. Conduction drying is characterized by:

- Heat transfer to the wet solid takes place by conduction through a solid surface, usually metallic. The source of heat may be hot water, steam, flue gases, hot oil etc.
- Surface temperatures may vary widely
- Contact dryers can be operated under low pressure and inert atmosphere.
- Dust and dusty materials can be removed very effectively.

Conduction drying can be carried out either continuously or batch wise. Cylinder dryers, drum dryers, steam tube rotary dryers are some of the continuous conduction dryers.

Vacuum tray dryers, Freeze dryers and agitated pan dryers are the examples of batch conduction dryers.

16.6.2.1 Drum Dryers

Drum drying is unique drying process in which both cooking and drying takes place. Gelatinization of starch is also takes place during drying. Here, the food is coated as a thin paste over the surface of a slowly revolving heated horizontal cylinder (Fig. 16.8). In such a case, the food dries for as much of one revolution of the cylinder as is mechanically feasible, after which it is scraped off and replaced by fresh wet material .The amount of drying is substantially controlled by the rate of heat transfer and estimates of the heat transfer rate can be used for calculation of the extent of drying.

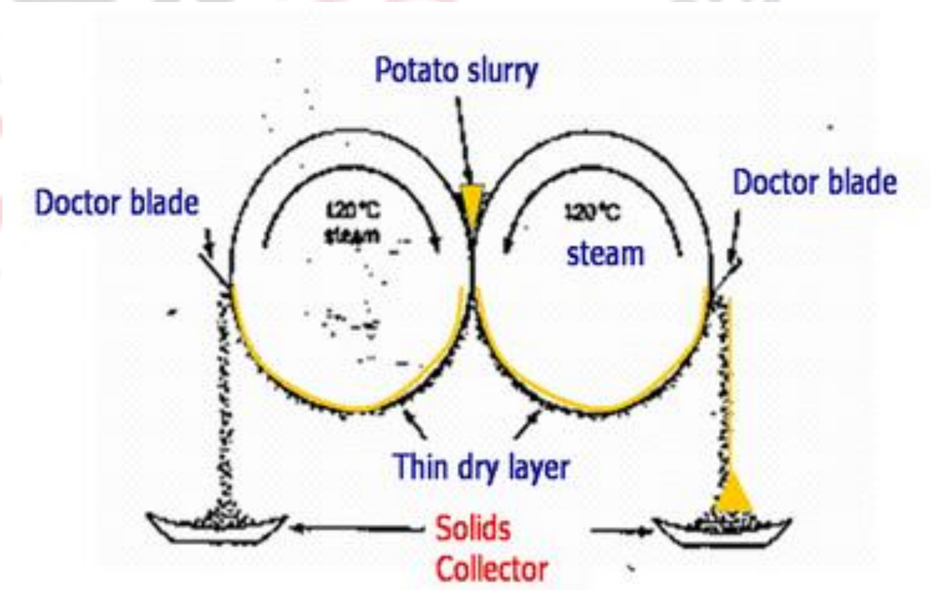


Fig 16.8 Double Drum Dryer

16.6.2.1.1 Working principle:

- This is an example of conduction drying because conduction is taking place here.
- It consist of two drums or cylinder separated by a little distance according to the feed size.The two drums are standed by two rod stand and they are rotated by the help of pulley,bearing and a shaft in a direction opposite to each other.
- The feed is fed at the joint of the two drums and the drum is filled with hot steam of 120 degree centigrade.The hot steam give heat to the surface of the drum which is generally high conductive in nature (eg; nickel surface) .So, the surface gets heated and it gives heat to the feed and rotates and then the feed are get evaporated and the moisture from the food get removed and the dried feed are scraped off by the doctor blades and they are collected to the collectionplates.
- Generally, sticky and sugar or salt type foods can not dry using this dryer because the hot surface of the drum attract hardly the particles if they are sticky and in this case the separation or scrapping off of the product may not occur.

The drum dryer is generally used for making baby foods and weaning foods from slurries of cereals, pulses and oil cakes taken in powder form.

16.6.2.1.2 Advantages

1. The method gives rapid drying, the thin film spread over a large area resulting in rapid heat and mass transfer.
2. The equipment is compact, occupying much less space than other dryers.
3. Heating time is short, being only a few seconds.
4. The drum can be enclosed in a vacuum jacket, enabling the temperature of drying to be reduced.
5. The product is obtained in flake form, which is convenient for many purposes.

16.6.2.1.3 Dis-advantages

The only disadvantage is that operating conditions are critical and it is necessary to introduce careful control on feed rate, film thickness, speed of drum rotation and drum temperature

16. 7 Dryer Efficiencies

Energy efficiency in drying is of obvious importance as energy consumption is such a large component of drying costs. Basically it is a simple ratio of the minimum energy needed to the energy actually consumed. But because of the complex relationships of the food, the water, and the drying medium which is often air, a number of efficiency measures can be worked out, each appropriate to circumstances and therefore selectable to bring out special features important in the particular process. Efficiency calculations are useful when assessing the performance of a dryer, looking for improvements, and in making comparisons between the various classes of dryers which may be alternatives for a particular drying operation.

Heat has to be supplied to separate the water from the food. The minimum quantity of heat that will remove the required water is that needed to supply the latent heat of evaporation, so one measure of efficiency is the ratio of that minimum to the energy actually provided for the process. Sensible heat can also be added to the minimum, as this added heat in the food often cannot be economically recovered.

Yet another useful measure for air drying such as in spray dryers, is to look at a heat balance over the air, treating the dryer as adiabatic with no exchange of heat with the surroundings. Then the useful heat transferred to the food for its drying corresponds to the drop in temperature in the drying air, and the heat which has to be supplied corresponds to the rise of temperature of the air in the air heater. So this adiabatic air-drying efficiency, □, can be defined by:

□= $(T_1 - T_2) / (T_1 - T_a)$

Where T_1 is the inlet (high) air temperature into the dryer, T_2 is the outlet air temperature from the dryer, and T_a is the ambient air temperature. The numerator, the gap between T_1 and T_2, is a major factor in the efficiency.

Example 15.4

A dryer reduces the moisture content of 100 kg of a potato product from 80% to 10% moisture. 250 kg of steam at 70 kPa gauge is used to heat 49,800 m^3 of air to 80°C, and the air is cooled to 71°C in passing through the dryer. Calculate the efficiency of the dryer. The specific heat of potato is 3.43 kJ kg^{-1} $°C^{-1}$. Assume potato enters at 24°C, which is also the ambient air temperature, and leaves at the same temperature as the exit air.

Solution:

In 100 kg of raw material there is 80% moisture, that is 80 kg water and 20 kg dry material,

total weight of dry product = 20 x (10/9)

= 22.2 kg

weight of water = (22.2 - 20)

= 2.2 kg.

Water removed = (80 - 2.2)

= 77.8 kg.

Heat supplied to potato product

= sensible heat to raise potato product temperature from 24°C to 71°C + latent heat of vaporization.

Now, the latent heat of vaporization corresponding to a saturation temperature of 71°C is 2331 kJ kg^{-1}

Heat (minimum) supplied/100 kg potato

= 100 x (71 - 24) x 3.43 + 77.8 x 2331

= 16 x 10^3 + 181 x 10^3

= 1.97 x 10^5 kJ

Heat to evaporate water only = 77.8 x 2331

= 1.81 x 10^5 kJ

The specific heat of air is 1.0 J kg^{-1} $°C^{-1}$ and the density of air is 1.06 kg m^{-3}

Heat given up by air/100 kg potato

= 1.0 x (80 - 71) x 49,800 x 1.06

= 4.75 x 10^5 kJ.

The latent heat of steam at 70 kPa gauge is 2283 kJ kg^{-1}

Heat in steam = 250 x 2283

= 5.71 x 10^5 kJ.

Therefore (a) efficiency based on latent heat of vaporization only:

$$= (1.81 \times 10^5)/ (5.71 \times 10^5)$$

$$= 32\%$$

(b) efficiency assuming sensible heat remaining in food after drying is unavailable

$$= (1.97 \times 10^5)/ (5.71 \times 10^5)$$

$$= 36\%$$

(c) efficiency based heat input and output, in drying air

$$= (80 – 71)/ (80 – 24)$$

$$= \underline{16\%}$$