PROC 5071:
Process Equipment Design I

Dryers

Salim Ahmed

1 Drying Fundamentals

1.1 A day-to-day example: How do they make potato chips?

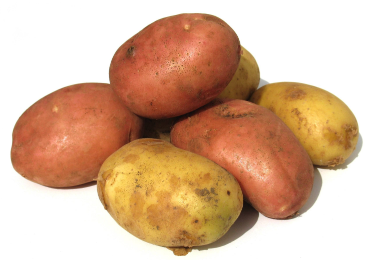


Figure 1: From potato to chips.

- Potatoes are peeled, boiled, smashed and mixed with other ingredients, then pressed into paste of particular shapes.
- The strips are then boiled or steamed and cut into slices.
- The slices are then dried.
- Dried chips are fried for consumption.

1.2 What is the role of drying in producing chips?

- The sliced paste contains water in an amount not suitable for frying.

- Through drying the water content is reduced to acceptable level.
- Remember that sliced are in solid form both before and after drying.

1.3 So what is drying?

- Drying refers to the removal of relatively small amount of a liquid from a solid material.
- In general, drying is concerned with the removal of water.
- However, the term also refers to removal of other organic liquids such as benzene, from solids.
- Drying is different from evaporation in that evaporation involves the removal of relatively large amount of water.
- The purpose of drying is to reduce the residual liquid to an acceptable level.

1.4 Mechanical vs. thermal removal

- Liquid may be removed from solid
  - mechanically - pressing, centrifugation
  - thermally - vaporization
- Mechanical removal is cheaper than thermal
- Liquid is removed mechanically to a feasible level before sending to a heated dryer.
- Generally drying refers to the thermal drying process.
- More specifically, we will refer to the thermal removal of water.
- Water is usually removed as a vapor by air.

1.5 An industrial example: Paper making

- Papermaking involves a series of drying operation.
- A fibre-water suspension with initial consistency[1] 0.2 to 1% is subjected to screening.

[1] consistency=gram of fibre per gram of fibre-water suspension

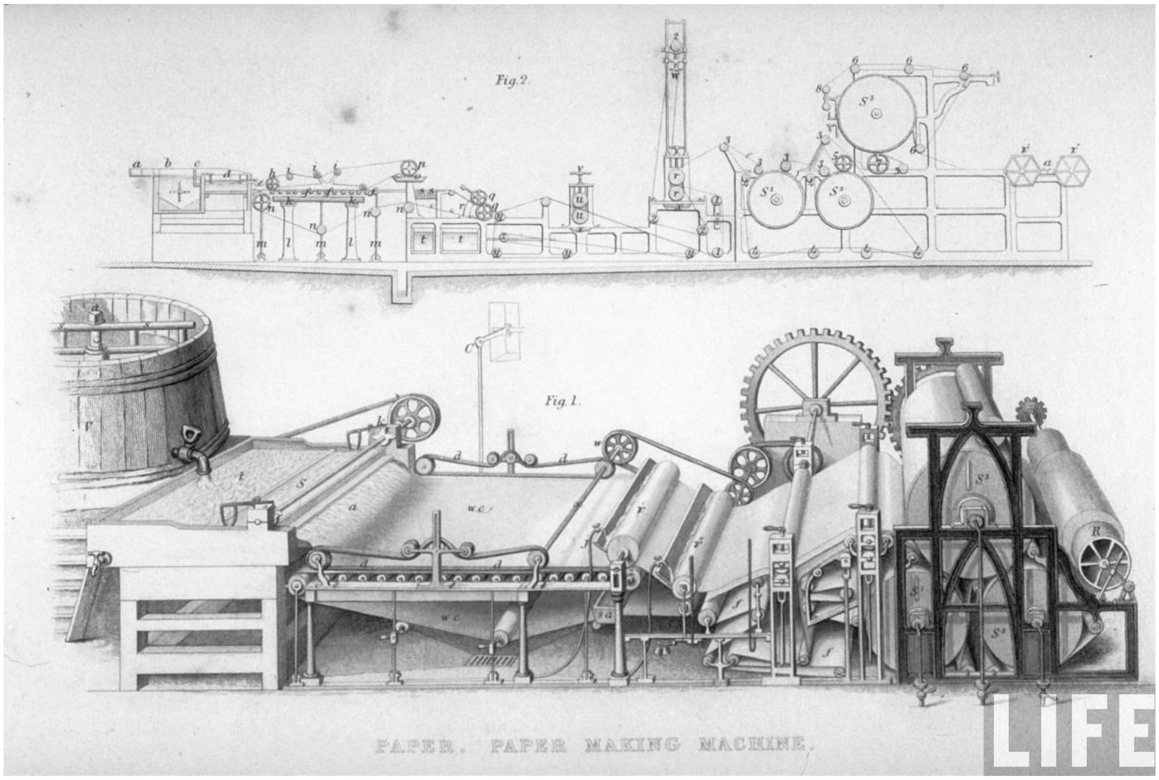


Figure 2: Artistic representation of the paper making process.

- With application of vacuum, much of the free water is removed to achieve a consistency of $18 - 23\%$.
- Next using a press, water is removed to increase the consistency to $33 - 55\%$.
- Then thermal drying is applied to reduce the moisture level to $6 - 9\%$.

1.6 Purpose of drying

- Easy-to handle free-flowing solids

- Preservation and storage
- Reduction in cost of transportation
- Achieving desired quality of product

2 Classification of dryers

Dryers can be classified based on a number of criteria.

- Mode of operation
  - Batch
  - Continuous
- Pressure
  - Vacuum
  - Pressurized
- Solid handling
  - Steady
  - Fluidized bed
- Means of heat addition

2.1 Categorization based on heat addition

1. Direct or adiabatic - solid is directly exposed to hot gas (usually air).
2. Indirect or nonadiabatic - heat is transferred to the solid from an external source such as condensing steam, usually through a metal surface
3. Heat is added by dielectric, radiant or microwave energy

2.2 Direct heating - pros and cons

- in general, less costly - because of the absence of tubes or jackets.
- Better control of temperature of the gas. Relatively simple to ensure that the material is not heated beyond a specified temperature. This is especially important with heat-sensitive materials.
- Overall thermal efficiency is generally low due to the loss of energy in the exhaust gas and
- For an expensive solvent evaporated from the

solid, the operation is often difficult and costly.

- Losses also occur in the case of fluffy and powdery materials
- Further problems are encountered where either the product or the solvent reacts with oxygen in the air.

3 Industrial dryers

As categorization of dryers involves a large number factors we will discuss a number of industrial dryers without properly categorizing those into any type.

3.1 Tray dryers

- Also know as shelf, cabinet and compartment dryers
- Batch operation
- Contains removable shallow trays on which the solid is spread

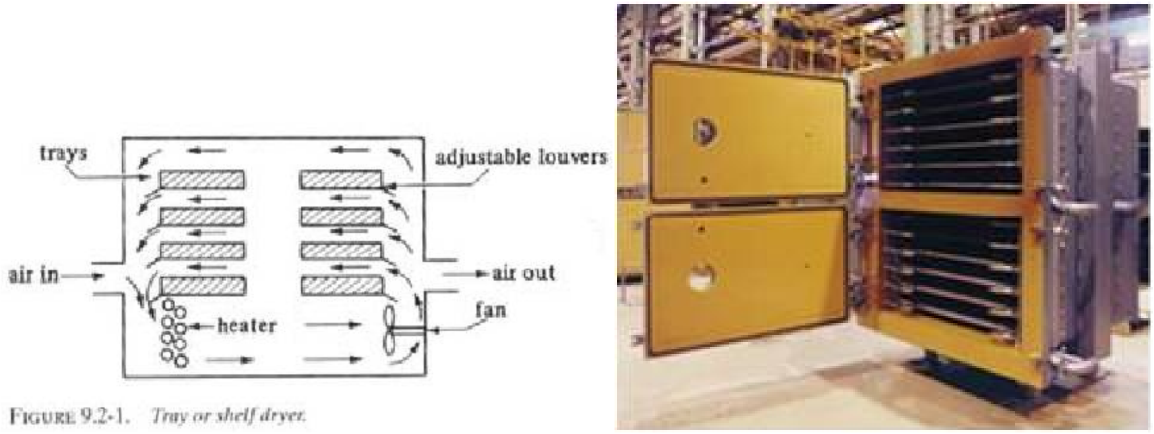


Figure 3: Schematic and photograph of a tray dryer.

- Hot air is circulated by a fan over and parallel to the surface of the trays
- Some moist air is continuously vented and fresh make up air is added
- Useful for low production rate e.g. pharmaceutical products
- May be operated under vacuum, often with indirect heating

3.2 Continuous tunnel dryers

- A series of trays or trolleys is moved slowly through a long tunnel, which may or may not be heated, and drying takes place in a current of warm air.

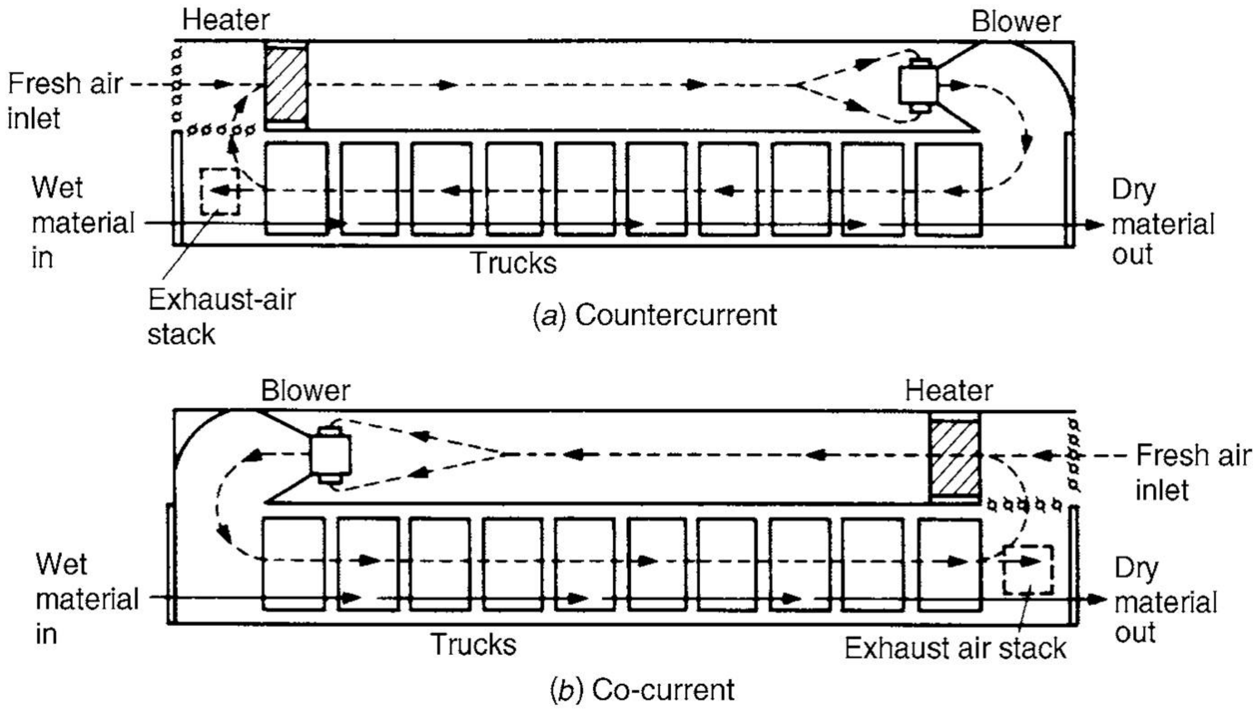


Figure 4: Co and countercurrent continuous tunnel dryer.

- Used for drying paraffin wax, gelatin, soap, pottery ware, and wherever the throughput is so large that individual cabinet dryers would involve too much handling.
- Alternatively, material is placed on a belt conveyor passing through the tunnel, an arrangement which is well suited to vacuum operation.

3.3 Rotary Dryers

- Consists of a revolving hollow cylindrical shell, horizontal or slightly inclined towards the outlet.

Figure 5: Photograph of a rotary dryer.

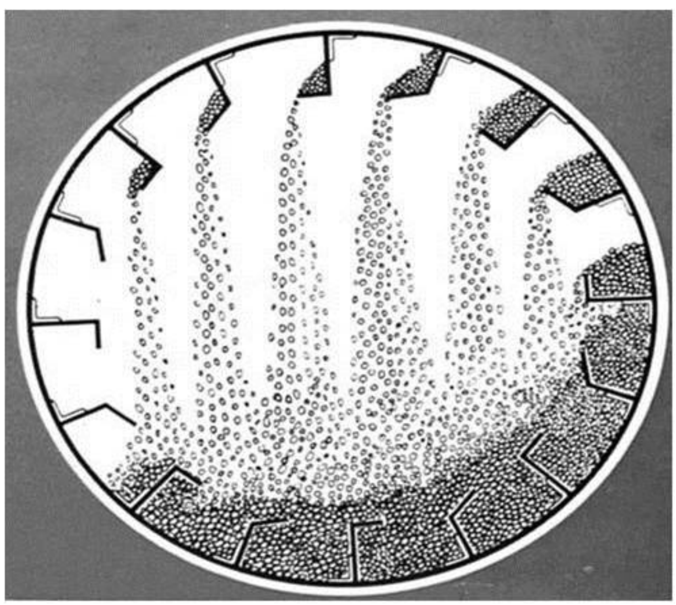


Figure 6: Inner structure of a rotary dryer showing solid flow.

- As the shell rotates, internal flights lift the solids and shower them down through the interior of the shell.

- May be direct or indirect contact or a combination of both.
- Suitable for large scale continuous operation

3.4 Drum dryers

- Consists of a slowly revolving heated metal roll.

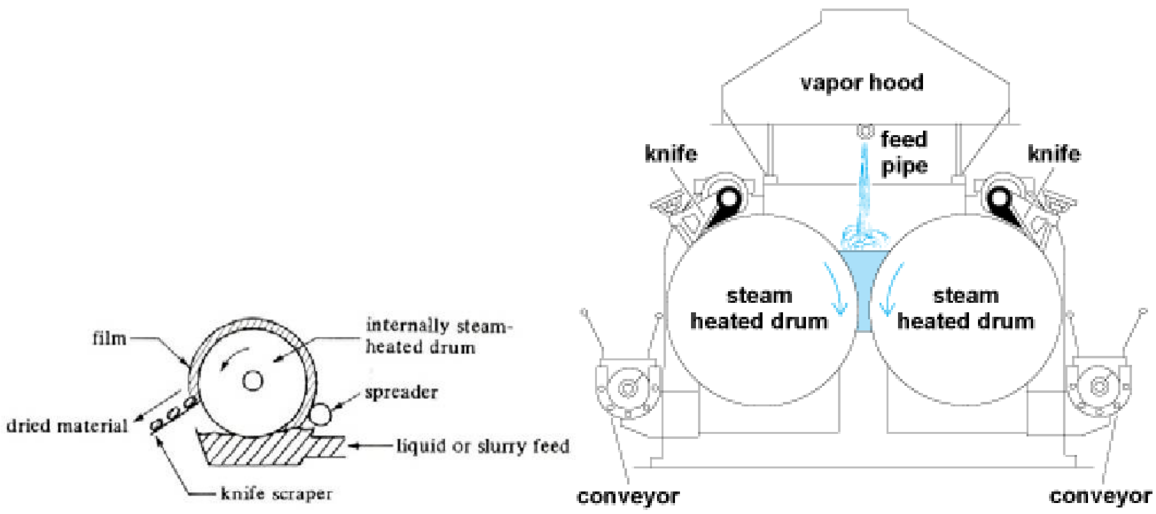


Figure 7: Schematic of a drum dryer.

- Outside the roll, a thin layer of liquid or slurry is evaporated to dryness. The final dry solid is scraped of the roll.
- Suitable for handling slurries or pastes of solids.

3.5 Spray dryers

- A suspension of solid particles is sprayed into a vessel through which a current of hot gases is passed.

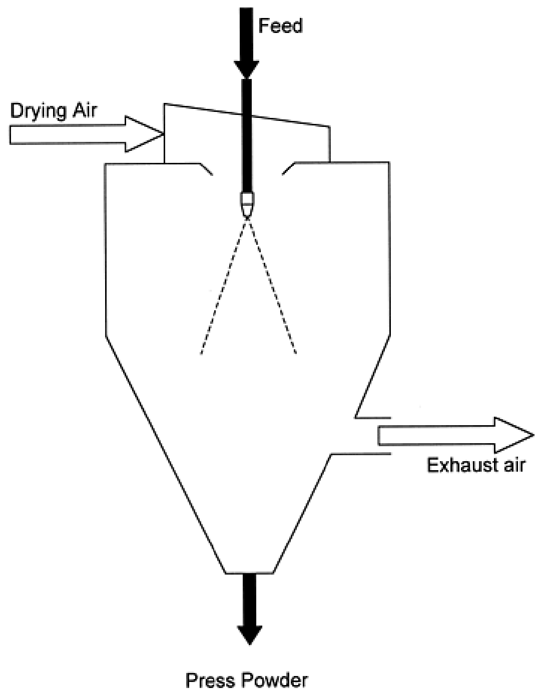


Figure 8: Schematic of a spray dryer.

- A large interfacial area is produced and consequently a high rate of evaporation is obtained.
- Examples are dried milk powder and urea pellets.
- The flow of gas an liquid may be counter or co-current or a combination.

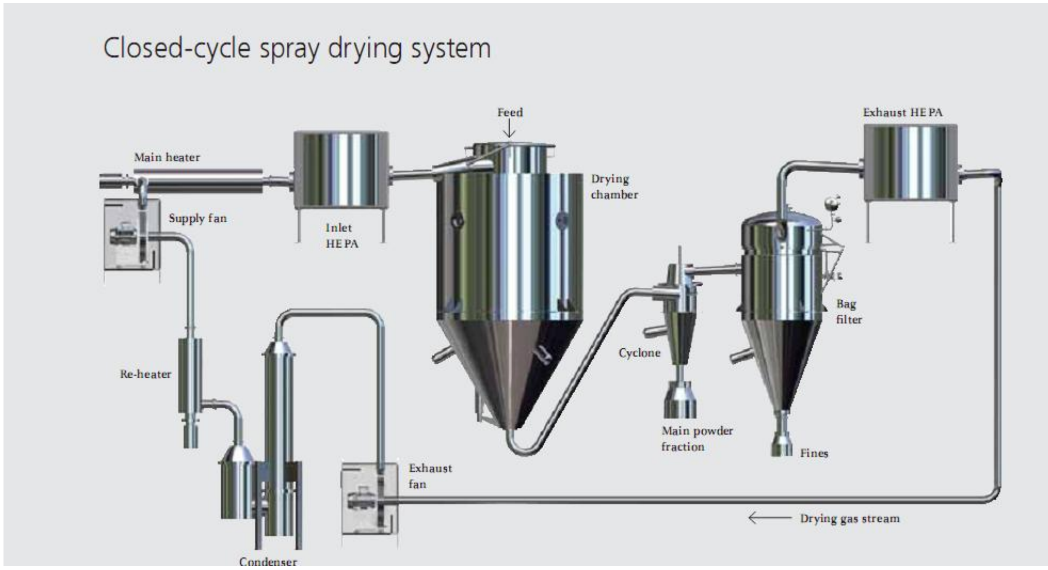
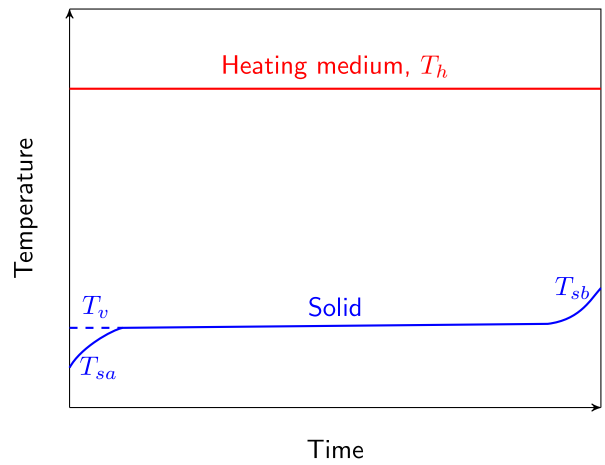


Figure 9: Schematic of a closed cycle spray drying system.

4 Principles of drying

4.1 Temperature pattern

- The way temperature vary in a dryer depends on
  - the nature and liquid content of the feedstock
  - the temperature of the heating medium
  - the drying time
  - allowable final temperature of the dry solid
- The pattern of variation, however, is similar.
- The drying time may range from a few seconds to many hours.



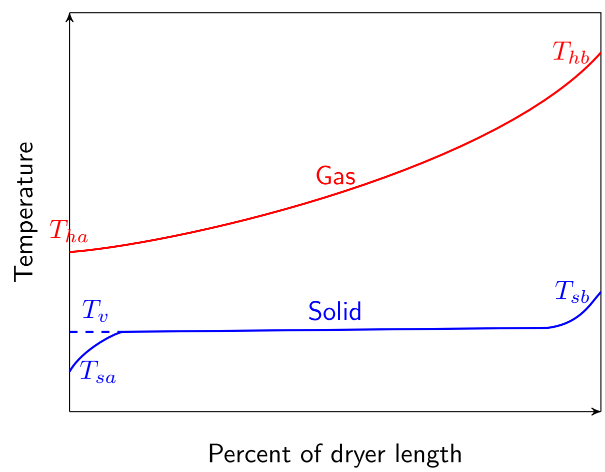


Figure 10: Temperature pattern in batch (above) and continuous countercurrent (below) dryer.

4.2 Heat duty

Heat is required for the followings:

1. Heat the feed (solid + liquid) to the vaporization temperature
2. Vaporize the liquid
3. Heat the product (solid + liquid) to their final temperature

4. Heat the vapor to its final temperature

Using the following notations: T_{sa} = feed temperature
T_v = vaporization temperature
T_{sb} = final product temperature
T_{va} = final vapor temperature
λ = heat of vaporization
c_{ps}, c_{pL}, c_{pv} = specific heat of solid, liquid and vapor, respectively

$$(1)\frac{q_1}{\dot{m}_s} = c_{ps}(T_v - T_{sa}) + X_a c_{pL}(T_v - T_{sa})$$
$$(2)\frac{q_2}{\dot{m}_s} = (X_a - X_b)\lambda$$
$$(3)\frac{q_3}{\dot{m}_s} = c_{ps}(T_{sb} - T_v) + X_b c_{pL}(T_{sb} - T_v)$$
$$(4)\frac{q_4}{\dot{m}_s} = (X_a - X_b)c_{pv}(T_{va} - T_v)$$

So the total heat required is

$$\begin{aligned}\frac{q_T}{\dot{m}_s} = & \; c_{ps}(T_{sb} - T_{sa}) + X_a c_{pL}(T_v - T_{sa}) \\ & + (X_a - X_b)\lambda + X_b c_{pL}(T_{sb} - T_v) \\ & + (X_a - X_b) c_{pv}(T_{va} - T_v)\end{aligned}$$

4.3 Heat transfer coefficients

The basic heat transfer equation is applicable

$$q = UA\overline{\Delta T}$$

$A =$ heat transfer area
$\overline{\Delta T} =$ average temperature difference
Figure shows the patterns of gas solid interaction in a dryer.

- (a) gas flow across a static bed of solids
- (b) gas passing through a bed of preformed solid
- (c) showering action in a rotary dryer
- (d) fluidized bed

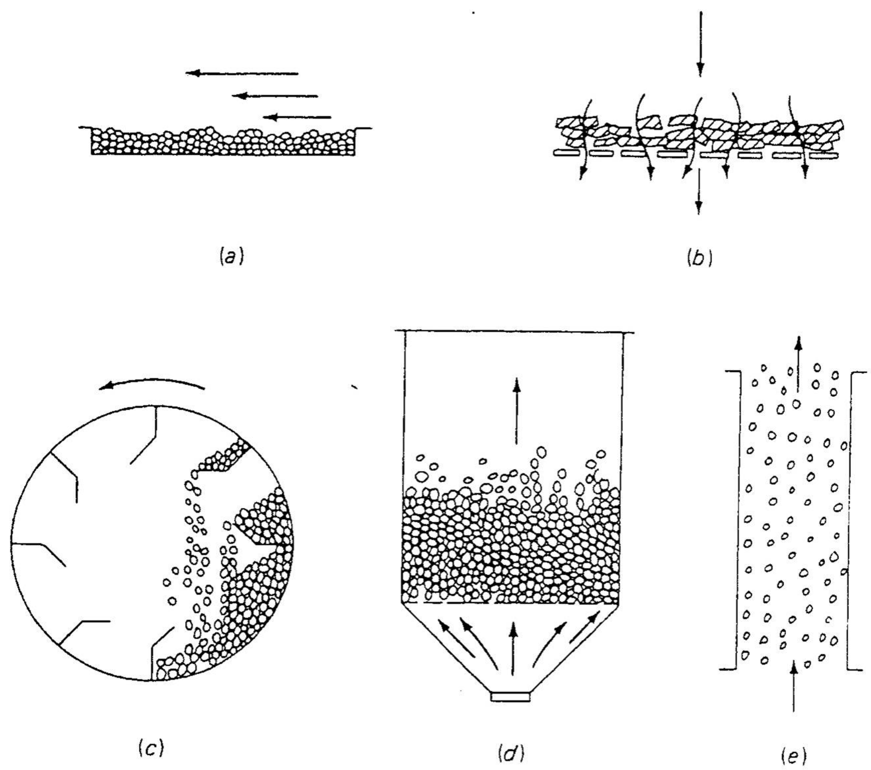


Figure 11: Pattern of gas solid interaction in a dryer.

- (e) cocurrent flow in a pneumatic conveyor flash dryer

What is A

- Tray dryers and moving belt dryers- horizontal surface carrying the wet solids
- Drum dryers - active surface area of the drum
- Through circulation dryers - total surface area of particles
- For some dryers e.g. screw conveyor or rotary

dryers - effective area is hard to determine.

- For unknown A, a volumetric heat transfer coefficient is defined

$$q_T = U_a V \overline{\Delta T}$$

$U_a =$ volumetric heat transfer coefficient, $W/m^3.^oC$
$V =$ volume of dryer

- Heat transfer coefficients can be predicted only approximately from empirical correlations
- Experimental data are needed for accurate design

4.4 Equilibrium moisture content

When a wet solid is brought in contact with a stream of air having a constant humidity and temperature, after a sufficiently long time the solid attain a definite moisture content beyond which moisture cannot be removed from it. This is known as the equilibrium moisture content of the solid under the specified humidity and temperature of the air.

- The equilibrium moisture content varies greatly with the type of material

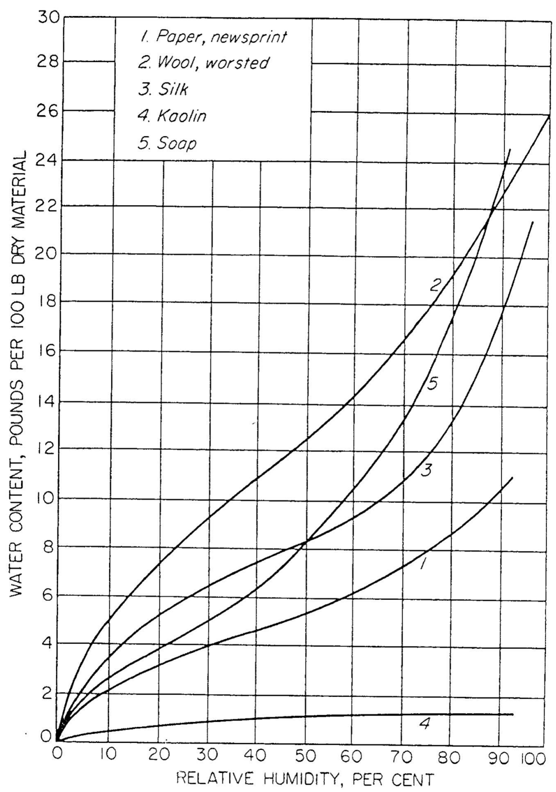


Figure 12: Equilibrium moisture curve at 25^oC.

- Nonporous insoluble solids e.g. glass wool and kaolin, tend to have low equilibrium moisture content
- Certain spongy, cellular materials of organic and biological origin e.g. wool, leather and wood, show large equilibrium moisture content.

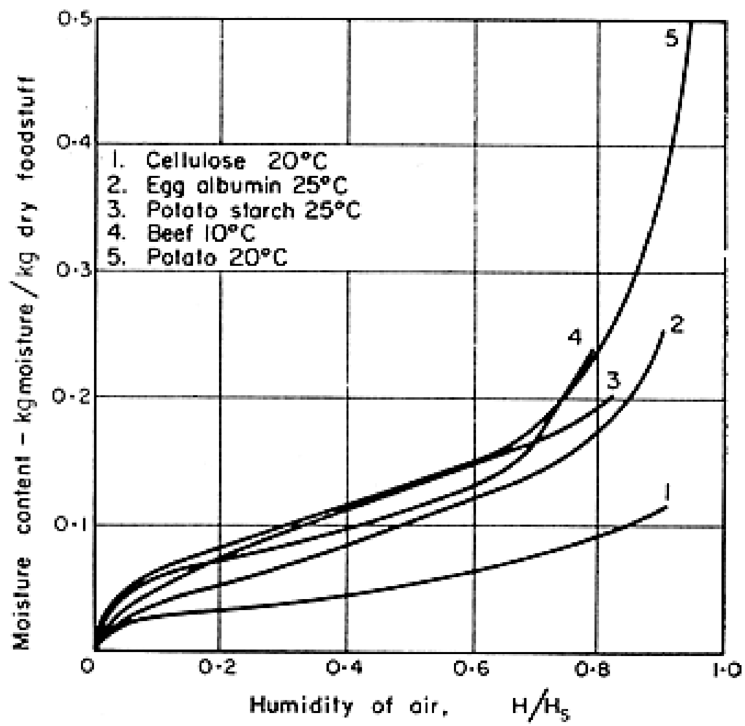


Figure 13: Equilibrium moisture content of different organic substances.

- Typical food materials show large equilibrium moisture content.
- Equilibrium moisture content somewhat decreases with an increase in temperature.

4.5 Free moisture

- The air entering a dryer contains some moisture
- A wet solid cannot reach a moisture content below its equilibrium moisture content corresponding to the air.

- Free moisture in a solid is the moisture above the equilibrium moisture content.
- Only the free moisture can be removed under the given condition of the air.
- If X_T is the total moisture content of a solid and X^* is the equilibrium moisture, then the free moisture is given by

$$X = X_T - X^*$$

- From the figure, if you want to dry paper (curve 1) using air with a relative humidity of 57% and the paper has $17\ lb$ water per $100\ lb$ dry materials
  - The equilibrium moisture content of paper is $6\ lb$ water per $100\ lb$ dry materials
  - So the free moisture is $11\ lb$ water per $100\ lb$ dry materials
  - If you want to dry the paper below $4\ lb$ water per $100\ lb$ dry materials, the air should have a relative humidity $< 30\%$.

4.6 Rates of drying

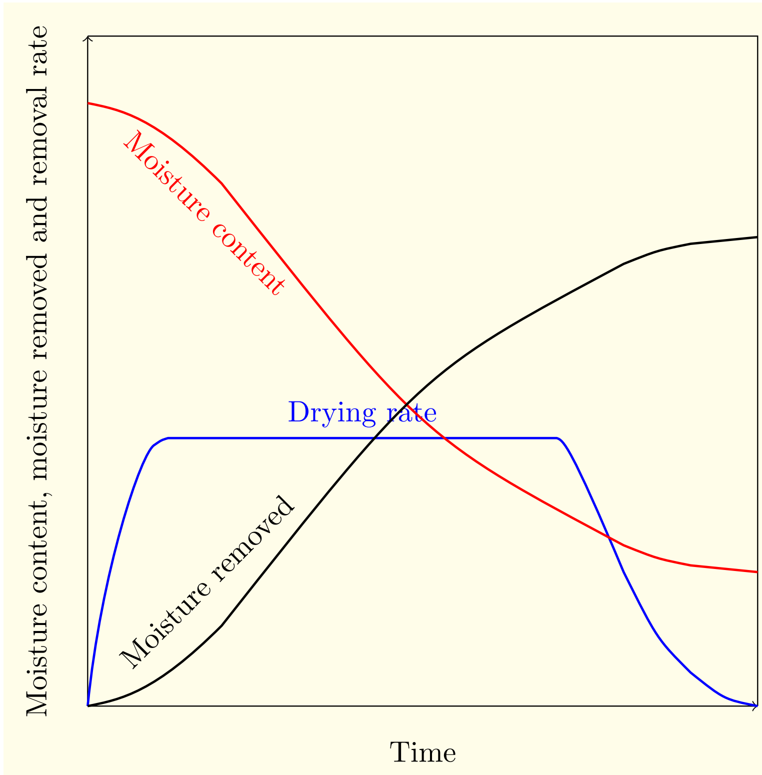


Figure 14: Drying rate, solid temperature and free moisture with time for a drying operation.

- As time passes, the moisture content typically falls.
- At the beginning, heat is used to raise the feed temperature to the vaporization temperature
- After a short period, the moisture content becomes nearly linear depicting constant rate of evaporation
- After the linear period, the graph curves towards becoming horizontal and finally levels off.

- The drying rate is the derivative of the moisture content
- AT the beginning the drying rate is low
- After the initial period, the rate becomes constant which is the constant rate period.
- After the constant rate period, the rate falls down eventually becoming zero.

4.7 Critical moisture content

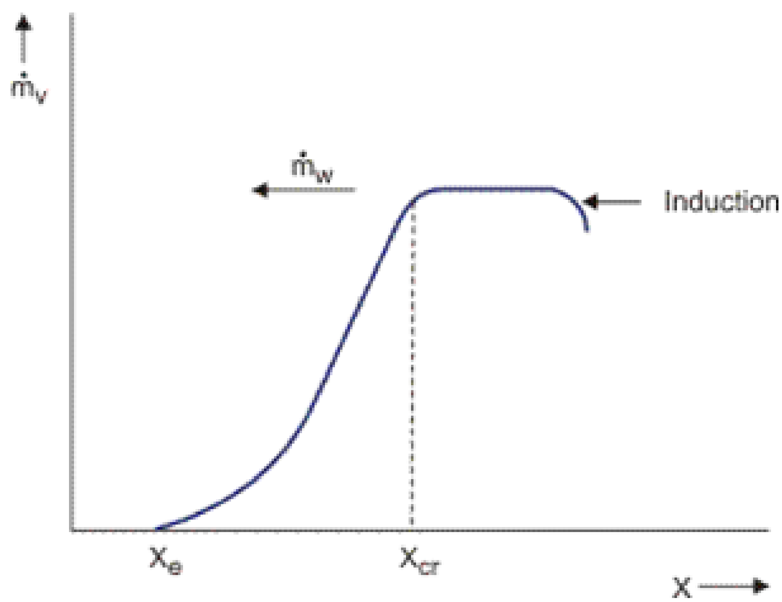


Figure 15: Drying rate with free moisture.

- The point at which the constant rate period ends is called the critical moisture content.

- It is the moisture content below which insufficient liquid is transferred from the interior of the solid to maintain continuous liquid film on the surface
- It depends on the type of the material
- It also depends on the thickness of the solid, the rate of drying and the resistance to heat and mass transfer in the solid

4.8 Calculation of rate of drying

- The rate of evaporation for the constant drying period can be based on mass or heat transfer.

$$\dot{m}_v = \frac{M_v k_y (y_i - y) A}{\overline{(1-y)}_L}$$

$$\dot{m}_v = \frac{h_y (T - T_i) A}{\lambda_i}$$

- Usually the heat transfer equation is used because there is less uncertainty in the driving force
- The heat transfer coefficient for gas in turbu-

lent flow parallel with the surface of solid can be obtained from

$$Nu = \frac{h_y D_e}{k} = 0.037 Re^{0.8} Pr^{0.33}$$

4.9 Calculation of drying time

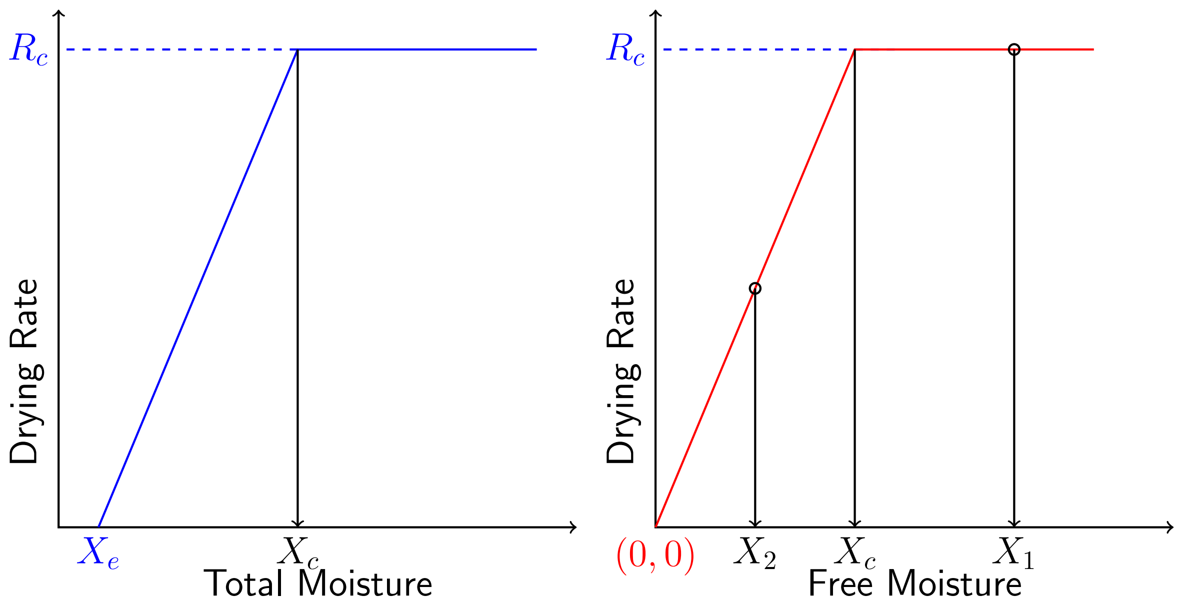


Figure 16: Ideal drying rate versus total moisture and free moisture.

The rate of drying is defined as the change of moisture content (negative of evaporation) per unit time per unit of drying area.

$$
\begin{aligned}
R &= -\frac{1}{A}\frac{dm_v}{dt} \\
&= -\frac{m_s}{A}\frac{dX}{dt} \qquad (1)
\end{aligned}
$$

To obtain the drying time we have

$$
dt = -\frac{m_s}{A}\frac{dX}{R} \qquad (2)
$$

Integrating the above equation we get

$$
\int_0^{t_T} dt = -\frac{m_s}{A}\int_{X_1}^{X_2}\frac{dX}{R} \qquad (3)
$$

The rate, R is dependent on X. Between X_2 and X_c, the rate is a constant, $R = R_c$. Between X_c and X_2, R linearly changes with X, i.e. $R = aX$.

So by performing integration by parts,

$$\begin{aligned}
\int_0^{t_T} dt &= -\frac{m_s}{AR_c}\int_{X_1}^{X_c} dX - \frac{m_s}{A}\int_{X_c}^{X_2}\frac{dX}{aX} \\
t|_0^{t_T} &= -\frac{m_s}{AR_c}X|_{X_1}^{X_c} - \frac{m_s}{Aa}\ln X|_{X_c}^{X_2} \\
t_T &= -\frac{m_s}{AR_c}(X_c - X_1) - \frac{m_s}{Aa}\ln\frac{X_2}{X_c} \\
&= \frac{m_s}{AR_c}(X_1 - X_c) + \frac{m_s}{Aa}\ln\frac{X_c}{X_2} \qquad (4)
\end{aligned}$$

The slope, a can be obtained as $a = \frac{R_c}{X_c}$. So we get,

$$\begin{aligned}
t_T &= -\frac{m_s}{AR_c}(X_1 - X_c) + \frac{m_s X_c}{AR_c}\ln\frac{X_c}{X_2} \\
&= \frac{m_s}{AR_c}\left(X_1 - X_c + X_c\ln\frac{X_c}{X_2}\right) \qquad (5)
\end{aligned}$$

Note that, for $X_2 > X_c$, i.e. if the drying is not done below the critical moisture content, then

$$t_T = \frac{m_s}{AR_c}(X_1 - X_2) \qquad (6)$$

5 Workbook: Drying below the critical moisture content

The problem

A porous solid is dried in a batch dryer under constant drying conditions. 3.2 hours are required to reduce the moisture content from 35% to 21%. The critical moisture content is 20% and equilibrium moisture content is 4%. Assuming that the rate at falling rate period is proportional to the free moisture, how long will it take to dry the sample to 5%.

Solution

Given information:

- Case 1: 3.2 hours is required to dry from 35% total moisture to 21% total moisture
- Critical moisture 20%
- Equilibrium moisture 4%

Need to calculate

1. Time required to dry from 35% total moisture

to 5% total moisture

Problem analysis

- We have

$$t_T = \frac{m_s}{AR_c}\left(X_1 - X_c + X_c \ln\frac{X_c}{X_2}\right)$$

- For the first case $X_2 > X_c$, i.e.

$$t_T = \frac{m_s}{AR_c}(X_1 - X_2) \qquad (7)$$

- However, m_s, A and R_c are unknown
- However, we can estimate the whole term $\frac{m_s}{AR_c}$ from case 1 and use it to calculate t_T for the second case.
- Always remember to convert the moisture contents into free moisture

Calculations

Step 1: Calculate $\frac{m_s}{AR_c}$

For this case

$$\begin{aligned} X_1 &= X_{1T} - X_e = \qquad - \qquad = \\ X_2 &= X_{2T} - X_e = \qquad - \qquad = \\ X_c &= X_{cT} - X_e = \qquad - \qquad = \end{aligned}$$

We get

$$\begin{aligned} t_T &= \frac{m_s}{AR_c}(X_1 - X_2) \\ &= \frac{m_s}{AR_c}(\qquad - \qquad) \end{aligned}$$

This gives,

$$\frac{m_s}{AR_c} =$$

Step 2: Calculate t_T for case 2

For this case, X_1 and X_c remain the same

$$X_2 = \qquad - \qquad =$$

So we have

$$
\begin{aligned}
t_T &= \qquad \left(\qquad - \qquad + \qquad \ln \frac{}{} \right) \\
&= 13.6h
\end{aligned}
$$

6 Workbook: Calculation of drying rate and drying time

The problem

You have been asked to dry a filter cake $1m$ by $0.5m$ and with thickness $5cm$ and dry density $1.9kg/l$. The initial total moisture content of the cake is 27%. You need to dry it to a final moisture content of 6% total moisture). The available air has a dry bulb temperature of 72^oC and wet bulb temperature of 27^oC. The critical free moisture content is 10% and the equilibrium moisture content under these conditions is 1%. If air flows parallel to the cake surface on both sides at a velocity of $3m/s$, how long will it take to dry the cake? The drying can be considered to be proportional to the moisture content for the declining rate period. The equivalent diameter can be taken as $0.25m$.

Solution

Given information:

- Cake dimensions, $L = 1m$, $W = 0.5m$ and $H = 0.05m$
- Dry density $\rho_{cake} = 1.9kg/l$
- $X_{1T} = 0.27$, $X_{2T} = 0.06$, $X_c = 0.1$ and $X_e = 0.01$
- For air, $T_{db} = 72^oC$ and $T_{wb} = 27^oC$
- Air velocity $v = 3m/s$

Need to calculate

1. the time required for drying, t_T

Problem analysis

- For this case, we have $X_2 < X_c$; so we need to use the equation

$$t_T = \frac{m_s}{AR_c}\left(X_1 - X_c + X_c \ln \frac{X_c}{X_2}\right)$$

Note that this equation is in terms of free moisture. You need to convert the total moisture content values into free moisture contents.

- In the above equation all X values are given and A can be directly calculated from the dimensions.
- The only unknown is R_C, the rate of drying during the constant drying period which is given by

$$R_C = \frac{h_y(T - T_i)}{\lambda_i}$$

- In the above equation T and T_i are the temperatures of the dry air and the interface temperature, respectively. For this case $T = 72^oC$ and the interface temperature is the wet bulb temperature 27^oC. λ_i is the latent heat of evaporation of water at 27^oC.
- h_y, the convection heat transfer coefficient can be calculated from

$$Nu = \frac{h_y D_e}{k} = 0.037 Re^{0.8} Pr^{0.33}$$

- So the solution procedure will be
  - Calculate Re and Pr; obtain Nu and h_y
  - Calculate R_c

∘ Calculate t_T

Calculations

Step 1: Calculate Re and Pr

We can get Re using

$$Re = \frac{D_e v \rho}{\mu}$$

ρ and μ are density and viscosity, respectively, of air at 72^oC. The density can be obtained from ideal gas property that the volume of one mole of an ideal gas at $1atm$ pressure and $273K$ is $22.4l$. The molecular weight of air being $29kg/kmol$, we have the density of air as

$$\begin{aligned} \rho &= \frac{29kg/kmol}{22.4m^3/kmol} \frac{273K}{(72+273)K} \\ &= 1.02kg/m^3 \end{aligned}$$

The viscosity of air can be obtained from Appendix 8 as $\mu = 0.0204cP = 0.0204 \times 10^{-3} kg/m.s$

So we get,

$$Re = \frac{(\qquad)(\qquad)(\qquad\qquad)}{}$$

$$=$$

Pr can be obtained from tabulated value for the given conditions. From Appendix 16, $Pr = 0.69$. So we get

$$Nu = 0.037Re^{0.8}Pr^{0.33}$$
$$\frac{h_y D_e}{k} =$$

To calculate h_y, k can be obtained from tabulated value. From Appendix 12, for air at 72^oC,

$$k = 0.017Btu/h.ft.^oF \times \frac{1.73073W/m.^oC}{1Btu/h.ft.^oF}$$
$$= 0.0297W/m.^oC$$

Thus we get,

$$h_y = \frac{(N_u)(k)}{D_e}$$
$$= \frac{(\qquad)(\qquad\qquad\qquad\qquad)}{\qquad}$$
$$= \qquad W/m^2.^oC$$

Step 2: Calculate Rc

R_c can be obtained from

$$R_c = \frac{h_y(T - T_i)}{\lambda_i}$$
$$= \frac{(\qquad\qquad\qquad\qquad)(\qquad - \qquad)}{1048 \times 2.326 kJ/kg} \frac{10^{-3} kJ/s}{1W}$$
$$= 328 \times 10^{-6} kg/s.m^2$$

Step 3: Calculate t_T

To calculate t_T, we need m_s, the mass of the dry cake and drying area

$$
\begin{aligned}
m_s &= V \times \rho_{cake} \\
&= (\qquad\qquad\qquad\qquad)(1.9kg/l)\frac{10^3 l}{1m^3} \\
&= \qquad kg
\end{aligned}
$$

As the cake is dried from both sides

$$
\begin{aligned}
A &= 2 \times (\qquad\qquad) \\
&= \; m^2
\end{aligned}
$$

Also we get

$$
\begin{aligned}
X_1 &= X_{1T} - X_e = 0.27 - 0.01 = 0.26 \\
X_2 &= X_{2T} - X_e = 0.06 - 0.01 = 0.05
\end{aligned}
$$

Finally, we get

$$
\begin{aligned}
t_T &= \frac{m_s}{AR_c}\left(X_1 - X_c + X_c \ln \frac{X_c}{X_2}\right) \\
&= \frac{kg}{(\ \ m^2)(\qquad\qquad kg/s.m^2} \\
&\quad \times \left(\quad - \quad + \quad \ln \frac{}{} \right) \\
&= \qquad\qquad s \\
&= 9.22hr
\end{aligned}
$$

7 Workbook: Calculation of drying rate and drying time

The problem

A filter cake $24in.(610mm)$ square and $2in.(51mm)$ thick, supported on a screen, is dried from both side with air at a wet-bulb temperature of $80^oF(26.7^oC$ and a dry bulb temperature $160^oF(71.1^oC)$. The air flows parallel with the faces of the cake at a velocity of $8ft/s(2.44m/s)$. The dry density of the cake is $120lb/ft^3(1,922kg/m^3)$. The equilibrium moisture content is negligible. Under the conditions of drying the critical moisture is 9 percent, dry basis.

1. What is the drying rate during the constant rate period?
2. How long would it take to dry this material from an initial moisture content of 20 percent (dry basis) to a final moisture content of 10 percent?

Equivalent diameter is equal to $6in.(153mm)$.

References

1. W. L. McCabe, J. C. Smith, P. Harriott. (2005). Unit Operations of Chemical Engineering, 7th Edition, McGraw Hill, New York, USA. ISBN-13: 978-0-07-284823-6
2. D. Green and R.H. Perry. 2007. Perry's Chemical Engineers' Handbook, 8th Edition, McGraw-Hill. ISBN-13: 9780071422949
3. C. J. Geankoplis. (2003). Transport Processes and Separation Process Principles, Fourth Ed., Prentice Hall, NJ, USA. ISBN 0-13-101367-X