FOOD DRYING/DEHYDRATION

Drying or Dehydration: It is defined as that unit operation which converts a liquid, solid or semi-solid feed material into a solid product of significantly lower moisture content (MC).

The terms "drying" and "dehydration" are used interchangeably in process engineering.

However, in food science and technology, the term "drying" is traditionally used for thermal removal of water to about 15-20 % moisture (dry basis), which is approximately the equilibrium moisture content of dried agricultural products (e.g., fruits and grains) at ambient air conditions.

The term "dehydration" is traditionally used for drying foods down to about 2-5 %, e.g., dehydrated vegetables, milk, coffee.

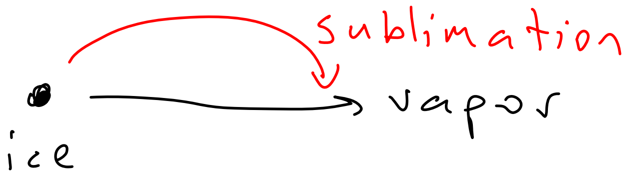
The dehydrated foods usually require special packaging to protect them from picking up moisture during storage.

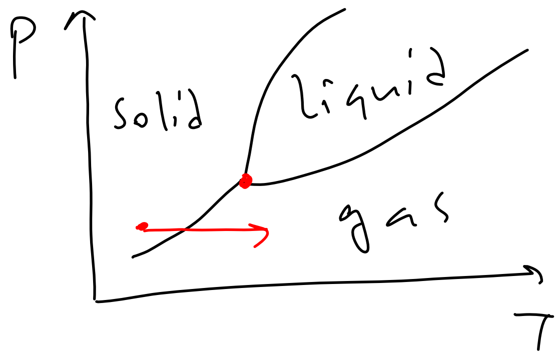
The term "intermediate moisture foods" (IMF) is used for semimoist dried foods (fruits, meat, etc.) of 20-30 % moisture content.

Drying is a complex process involving simultaneous heat, mass and momentum transfer.

In most cases, drying involves the application of thermal energy which causes to evaporate into vapor phase.

Exception: Freeze drying.





Foods are dried commercially;

- starting either from their natural state; fruits, vegetables, milk, spices, etc.

OR

- after processing; instant coffee, whey, soup mixes, etc.

REASONS FOR DRYING OF FOODS

1) preserve the product and extend its shelf-life. How ???

Microorganisms that cause food spoilage and decay cannot grow and multiply in the absence of water.

Also, many enzymes that cause chemical changes in food and other biological materials cannot function without water.

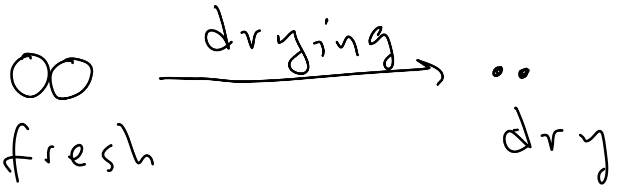
When the water content is reduced below about 10 % by weight, the m.o. are not active.

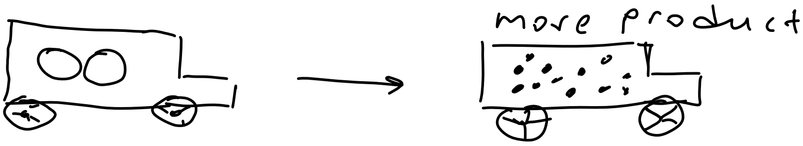
However, it is usually necessary to lower the moisture content below 5 % in foods to preserve flavor and nutrition.

2) obtain desired physical form (e.g., powder, flakes, granules, et.).

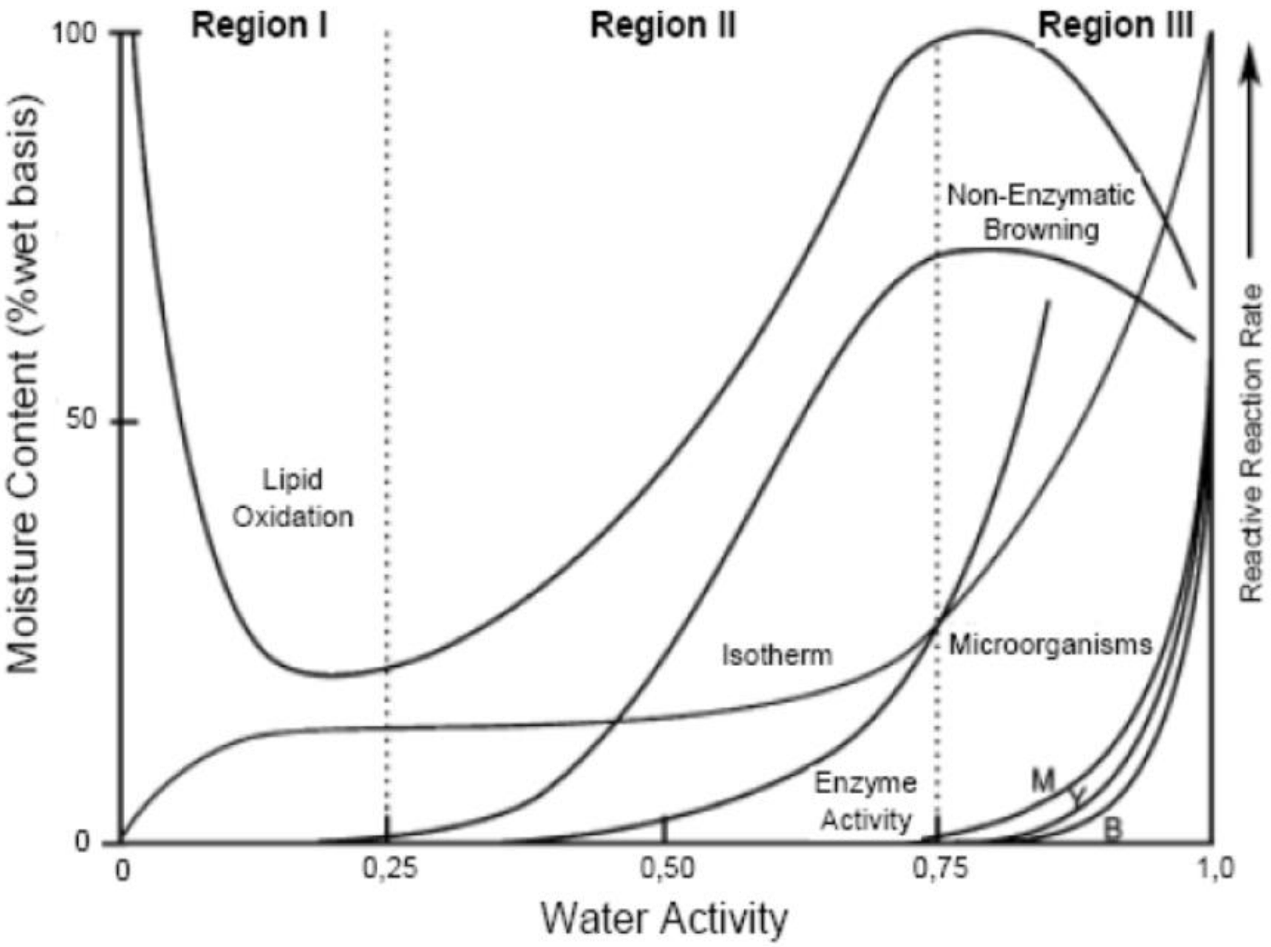
3) obtain desired color, flavor or texture.

4) reduce volume or weight for transportation.





5) produce new products which would not otherwise be feasible.


Region I
Region II
Region III
100
50
0
Moisture Content (%wet basis)
Lipid Oxidation
Non-Enzymatic Browning
Isotherm
Microorganisms
Enzyme Activity
M
Y
B
Reactive Reaction Rate
0
0,25
0,50
0,75
1,0
Water Activity

BASIC DRYER TYPES

(based on the mode of heat input)

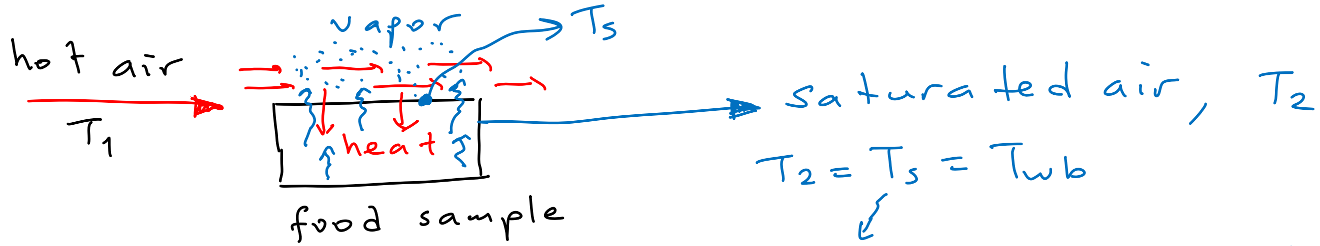
1) **Convection (direct): this accounts 90 % of dehydrated foods**
2) **Conduction (contact)**
3) **Radiative (infrared)**
4) **Dielectric (e.g., microwave) heating**
5) **Combinations of one or more of these modes.**

- **The dryers may be batch or continuous (Spray, rotary and drum dryers can only be operated in the continuous mode. However, the other dryers can operate as batch or continuous).**
- **The size of dryers can be small (up to 50 kg/h), medium (50-1000 kg/h) and large (above 1000 kg/h)**

HUMIDITY AND HUMIDITY CHART

A majority of dryers in the food industry are of the direct (or convective) type.

i.e., hot air is used both to supply the heat for evaporation and to carry away the evaporated moisture from the product.



$T_2 = T_s = T_{wb}$

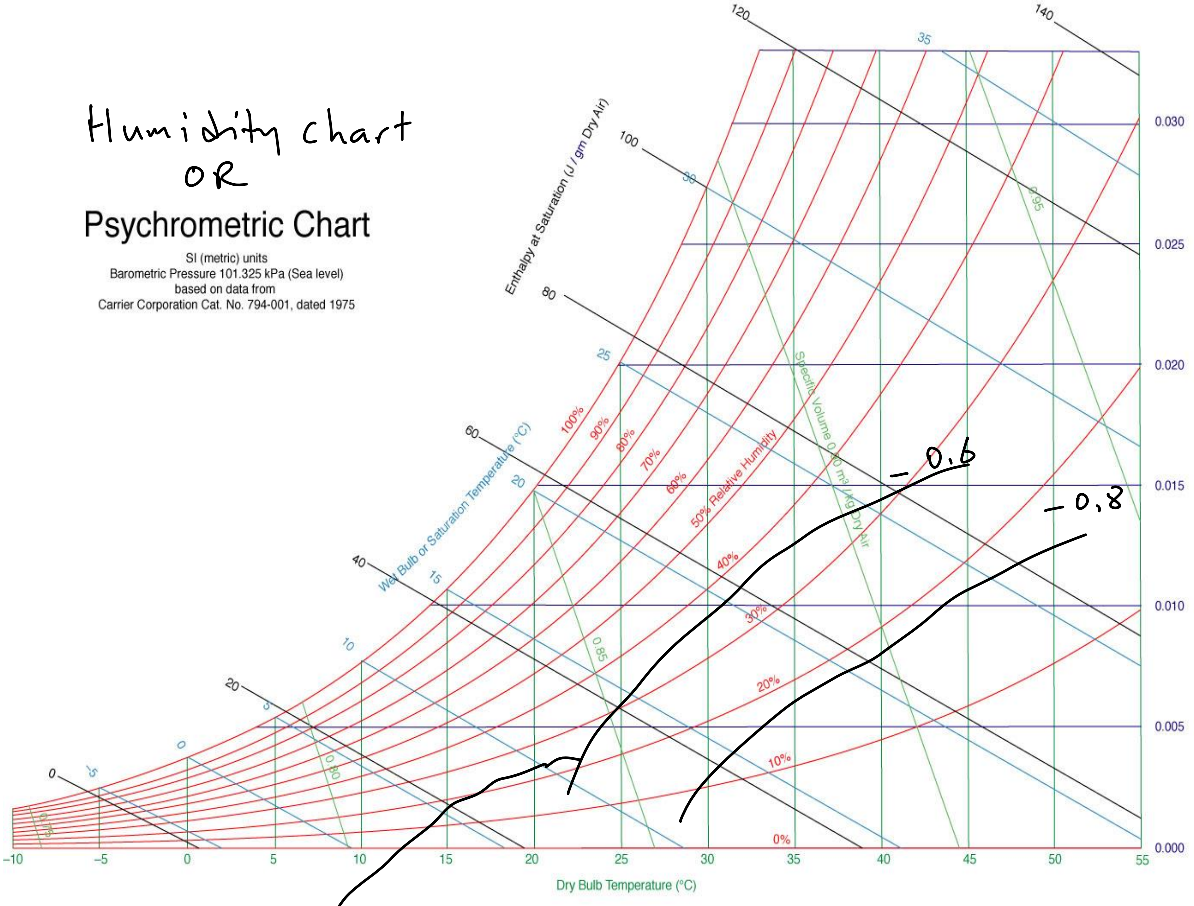
surface temperature is equal to saturation temp.

here; - air is humidified } in a well
- " " cooled; $T_1 > T_2$ } insulated dryer.

So, the hygrothermal properties of humid air are required for the design calculations of dryers. These properties are provided by humidity charts.

Humidity charts show the relationships between the T and absolute humidity of humid air at 1 atm total pressure.

Humidity chart
OR



Psychrometric Chart

SI (metric) units
Barometric Pressure 101.325 kPa (Sea level)
based on data from
Carrier Corporation Cat. No. 794-001, dated 1975

H: absolute humidity.

$H = \frac{kg\ H_2O}{kg\ DA}$

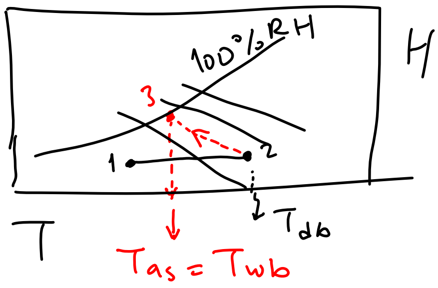
Temperature

enthalpy deviations (kJ/kg DA)

Definition of Terms Employed in Psychrometry and Drying:

Adiabatic saturation temperature (Tas):

It is the equilibrium gas T reached by unsaturated gas and vaporizing liquid under adiabatic conditions (for the air-water system only, it is equal to the wet bulb temperature, Twb).



$H \neq f(T)$

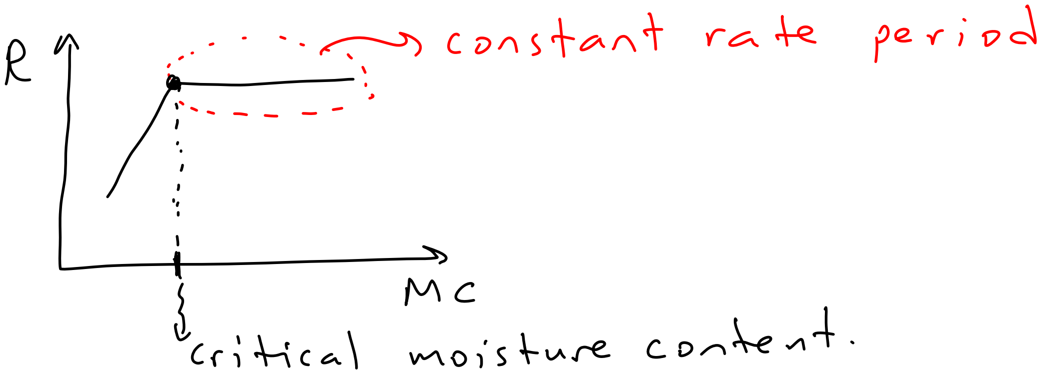
Bound moisture:

It is the liquid physically and/or chemically bound to a solid matrix so as to exert a vapor pressure lower than that of pure liquid at the same temperature.

Constant rate drying period (Rc):

Under constant drying conditions, it is the drying period when evaporation rate per unit drying area is constant (when the surface moisture is removed).

R: drying rate, Mc: moisture content =)

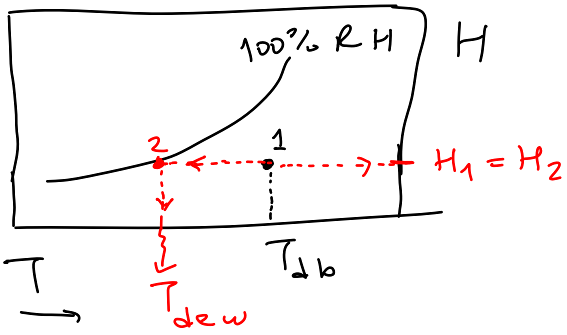


Critical moisture content (Xc):

It is moisture content at which the constant drying rate first begins to drop.

Dew point (T_{dew}):

It is the the temperature at which a given unsaturated air-vapor mixture becomes saturated.

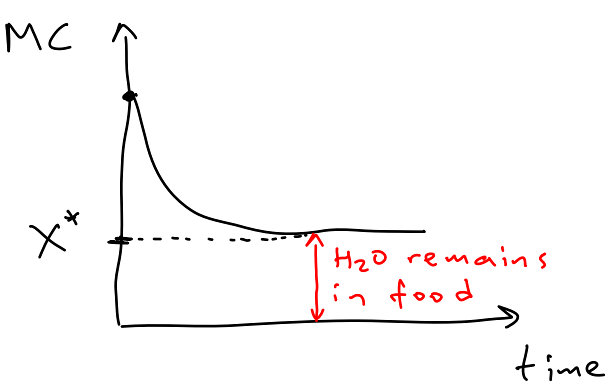


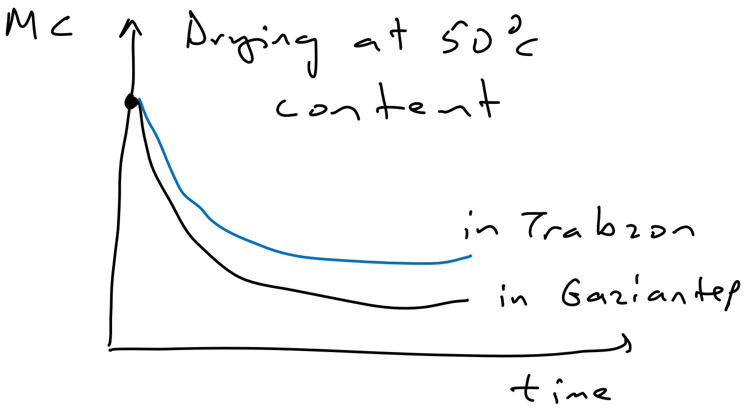
Dry bulb temperature (T_{db}):

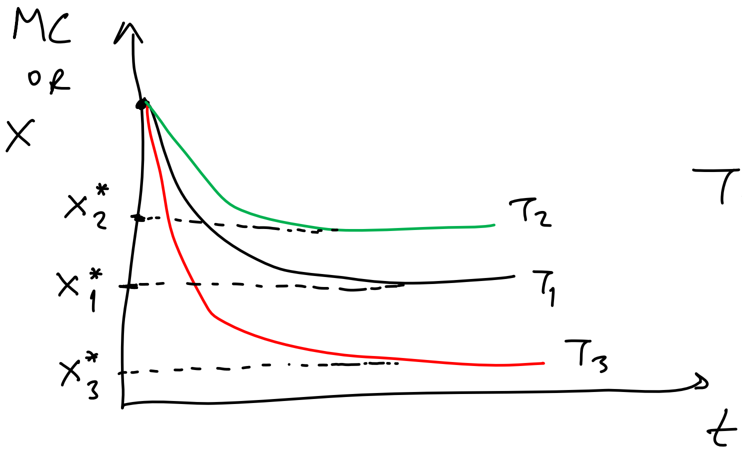
It is the temperature measured by a dry thermometer immersed in vapor-gas (air) mixture. It is the T of heated air to be used in drying operation.

Equilibrium moisture content (X*):

At a given T and P, it is the moisture content of a moist solid in equilibrium with the gas-vapor mixture.







$T_3 > T_1 > T_2$

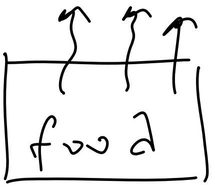
⊛ If %RH (i.e., a_w) of surrounding air = a_w of food that we are drying ⇒ no further drying occurs.

i.e., $\frac{dX}{dt} \cong 0$ at X^*

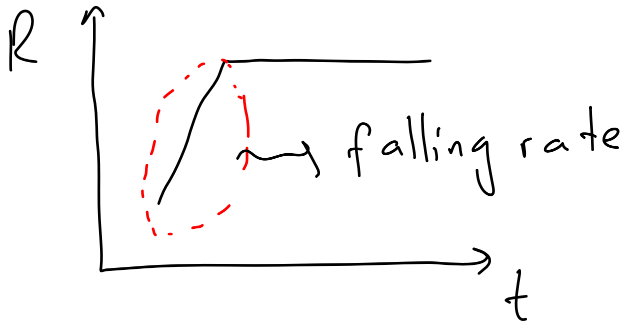
Note that: $a_w = \frac{\%RH}{100}$

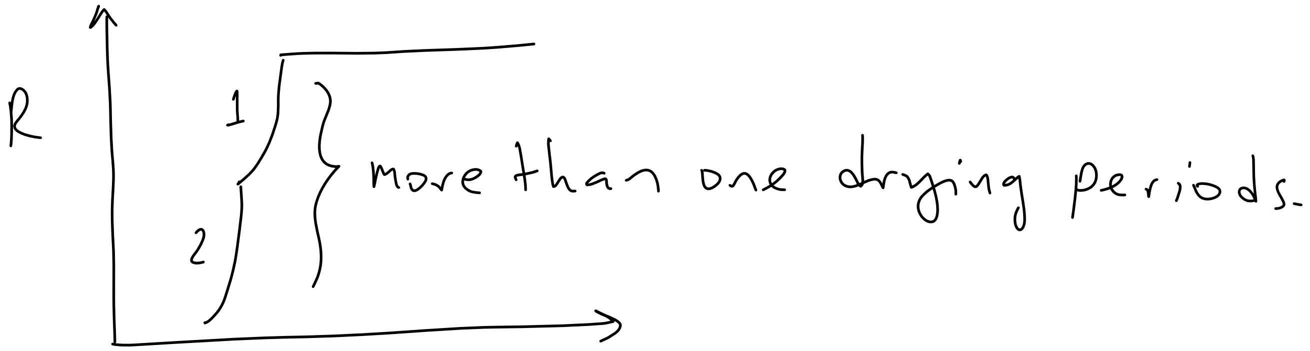
Falling-rate period:

It is the drying period during which the rate falls continuously.

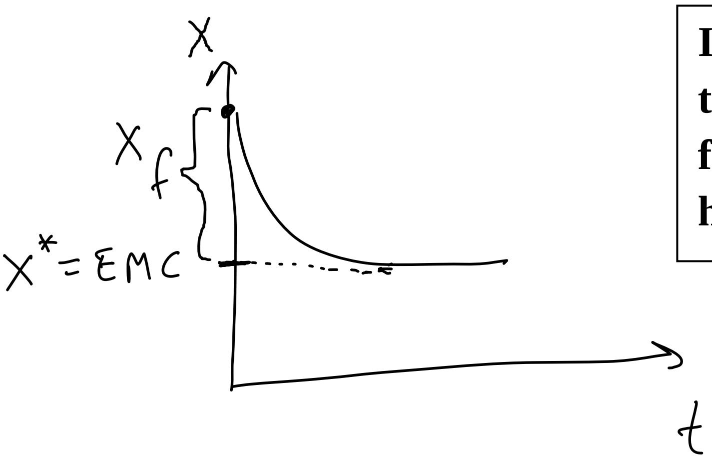


$$R = \frac{X}{\text{Area} \cdot \text{time}}$$



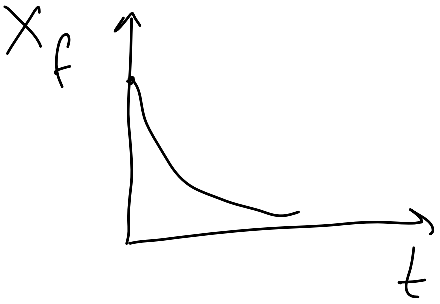


Free moisture (X_f):



It is the moisture content in excess of the equilibrium moisture content (hence free to be removed) at a given air humidity and temperature.

$$X_f = X - X^*$$



Humid heat (Cs):

Heat required to raise the T of unit mass of dry air and its associated vapor through 1°.

Absolute humidity (H):

$$H = \frac{\text{mass of } H_2O \text{ vapor}}{\text{mass of dry air}} \Rightarrow H = \frac{\text{kg } H_2O}{\text{kg DA}}$$

Relative humidity (% RH):

It is the ratio of partial P of water vapor in gas-vapor mixture to equilibrium vapor P at the same T. RH = f (T), as T ↗ RH ↘.

Moisture content (X):

It is mass of water per mass of solid (dry or wet solid).

$$X_{\text{wet basis}}(\%) = X_{wb}\% = \frac{\text{mass of } H_2O}{\text{mass of wet material}} \times 100$$

$$X_{wb}(\%) = \frac{\text{kg } H_2O}{\text{kg wet solid}} \times 100$$

$$X_{\text{dry basis}}(\%) = X_{db}(\%) = \frac{\text{mass of } H_2O}{\text{mass of dry solids}} \times 100$$

$$\% X_{db} = \frac{\text{kg } H_2O}{\text{kg DS}} = \frac{\text{kg } H_2O}{\text{kg wet solid} - \text{kg } H_2O} \times 100$$

Unbound moisture:

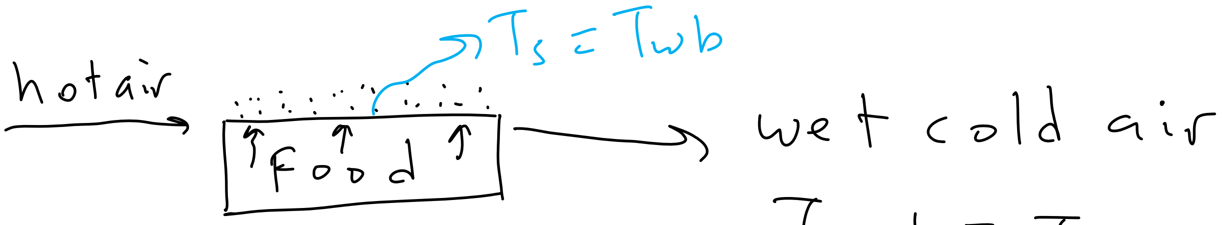
Moisture in solid which exerts vapor pressure equal to that of pure liquid at the same T

All the moisture content of a non-hygroscopic material is unbound moisture (material cannot hold water).

Wet-bulb temperature (T_{wb}):

It is the saturation T of an air-vapor mixture.

At constant drying rate period ⟹



$T_{out} = T_{wb}$

$T_{wb} < T_{db}$

Psychrometric Equations For an Air-Water Vapor System:

Absolute Humidity (H) $= \dfrac{18.02}{28.97} \times \dfrac{P}{P_a - P}$

$= \text{kg } H_2O / \text{kg DA}$

P_a: the total P of air-water vapor mixture

P: partial P of water vapor in air.

Saturation Humidity (H_s): $\dfrac{\text{kg } H_2O}{\text{kg DA}}$

$$H_s = \frac{18.02}{28.97} \times \frac{P_w}{P_a - P_w}$$

P_w: vapor P of pure water at the given T.

Percent Humidity (H_p): $H_p = \dfrac{H}{H_s} \times 100$

Relative Humidity (%RH): $\%RH = \frac{p}{p_w} \times 100$

Humid Heat (C_s):

$C_s = 1.005 + 1.88 \times H \rightsquigarrow$ SI: $\text{kJ}/\text{kg DA.K}$

$C_s = 0.24 + 0.45 \times H$ ⟶ English, Btu/lb DA.°F

Humid Volume (V_H): m^3 of mixture/kg DA

$$V_H = (2.83\times10^{-3} + 4.56\times10^{-3} \times H)\times \underbrace{T}_{\text{in K}} \rightsquigarrow \text{SI}$$

Total Enthalpy of An Air-Water Vapor Mixture:

$$H_T = (1.005 + 1.88\times H)(T - T_r) + H \times \lambda_r \rightsquigarrow \frac{\text{kJ}}{\text{kg DA}} \rightsquigarrow \text{SI}$$

T_r : reference T.

λ_r : latent heat of water vapor at T_r.

⊛ Latent heat of vaporization:

$$\lambda = a_1 \times (a_2 \times T)^{a_3} \rightsquigarrow \text{kJ}/\text{kgDA}$$

$a_1 = 267.155$, $a_2 = 374.2$, $a_3 = 0.38$, T in °C.

$$\frac{H - H_{as}}{T - T_{as}} = -\frac{C_s}{\lambda_{as}} = -\frac{1.005 + 1.88 \times H}{\lambda_{as}} \quad \text{and}$$

$$\frac{H - H_{wb}}{T - T_{wb}} = \frac{h/(M_B \times k_y)}{\lambda_{wb}} \cong \frac{C_s}{\lambda_{wb}}$$

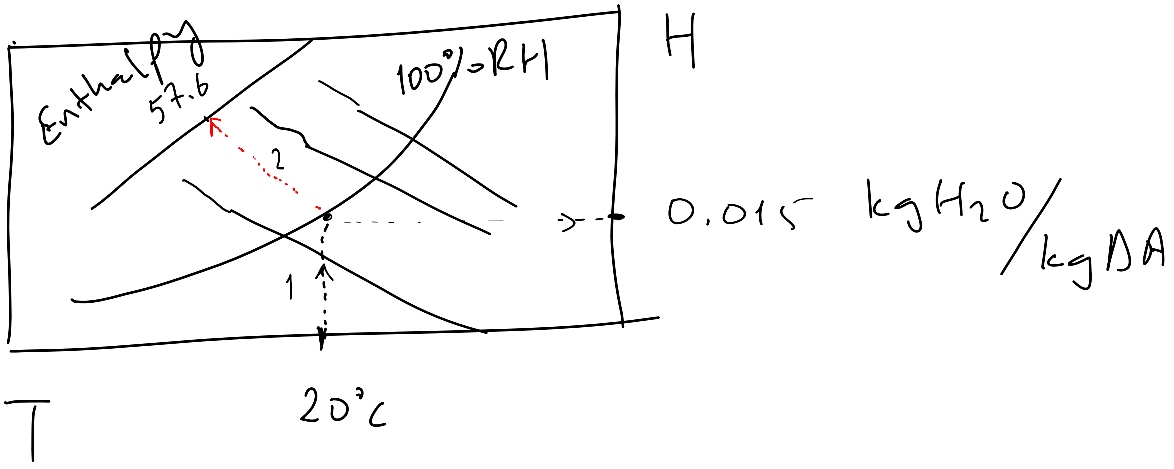
h: heat transfer coefficient, $\text{kW}/\text{m}^2 \cdot \text{K}$

M_B : M.wt of air

k_y: mass transfer coefficient: $\dfrac{\text{kg mol}}{\text{s. mol fraction}}$

Example: A tank contains 10 kg of saturated air. The dry bulb temperature is 20°C. Find the enthalpy of this system in kJ.

Solution:



Enthalpy of air at 20°C = 57.6 kJ/kg DA

X_{DA} = mass fraction of dry air ⇒

$$X_{DA} = \frac{1 \text{ kg DA}}{1 + 0{,}015} = 0{,}985$$

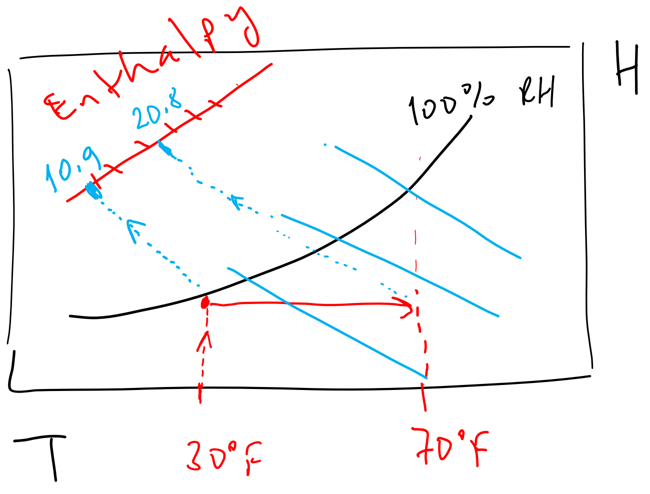
Mass of dry air = 10 kg × (0,985) = 9.85 kg DA

$$\text{Enthalpy} = m \times \hat{H}_{DA} = 9.85 \ \text{kg}\cancel{\text{DA}} \times 57.6 \ \frac{\text{kJ}}{\text{kg}\cancel{\text{DA}}} = 576 \text{ kJ}$$

Example: A saturated mixture contains 100 lb of dry air. How much heat is required (Btu) to raise the dry bulb temperature from 30°F to 70°F ?

Solution:

Using humidity chart ⇒



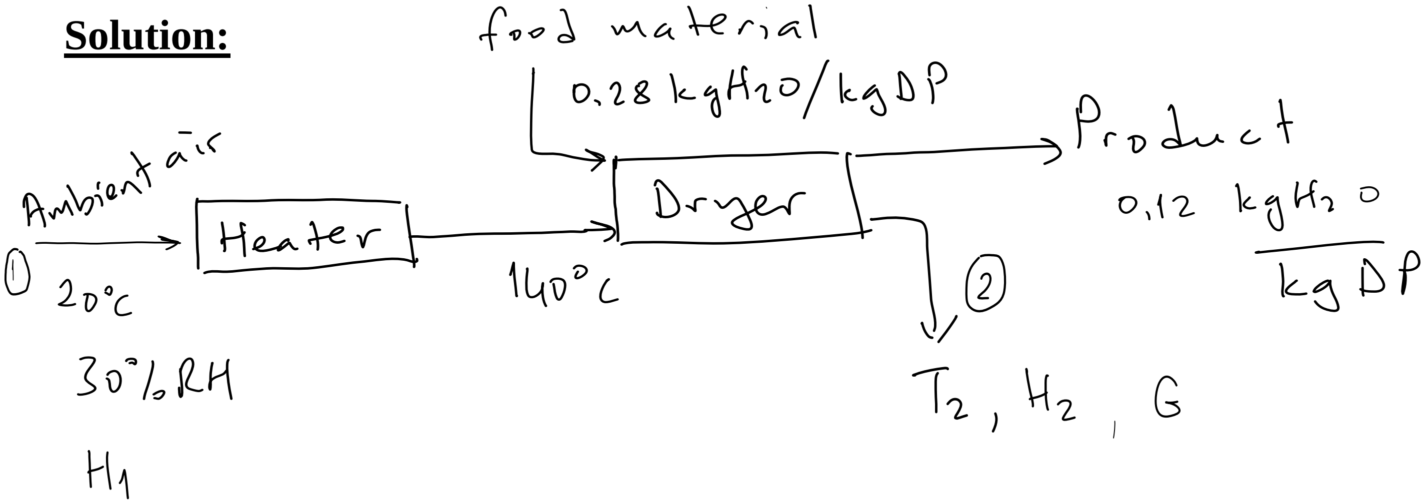
$$\text{Heat required} = (20.8 - 10.9)\ \frac{\text{Btu}}{\cancel{\text{lb}}} \times 100\ \cancel{\text{lb}}$$

$$= 990\ \text{Btu}$$

Example: A food product is to be dried in an adiabatic cocurrent dryer. The inlet and outlet moisture contents are 0.28 and 0.12 kg H_2O/kg dry product (DP), respectively. Ambient air at 20°C and 30 % RH is heated indirectly by steam to the specified dryer inlet air temperature of 140°C. The difference between the dry bulb temperature of the exhaust air and its dew point should be at least 10°C in order to avoid the possibility of condensation in the downstream ductwork and air cleaning devices.

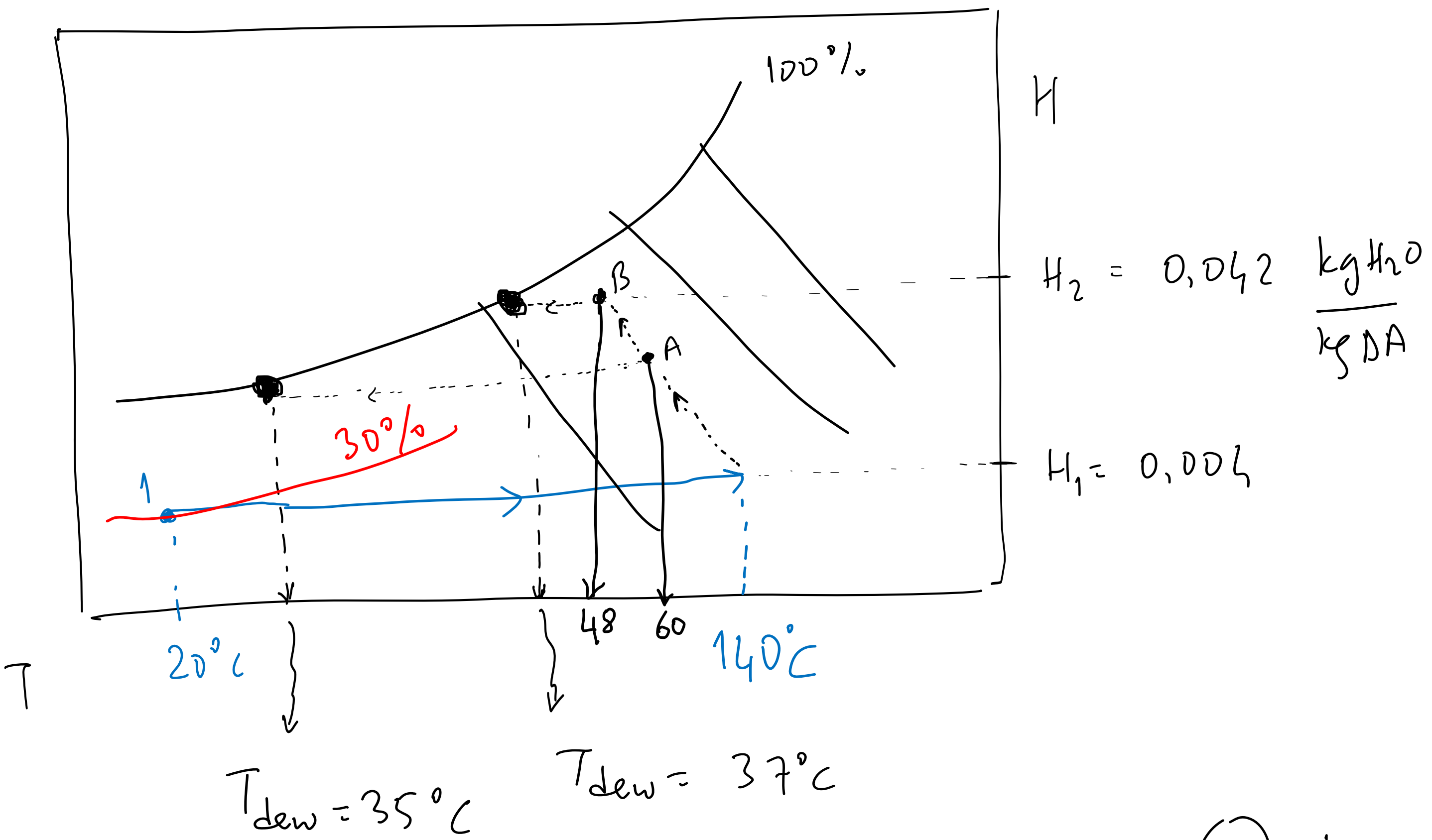
Calculate the mass flow rate of air required (kg/h).

Solution:



G : air flow rate

$$\underbrace{T_{db_{out}}}_{T_2} - T_{dew\,point} \cong 10°C$$



The condition of exhaust air at ② has to be determined by trial and error.

1) Assume that $T_2 = 60°C$ (point A)

$60 - 35 = 25°C$ exceeds 10°C by a wide margin.

2) Assume that $T_2 = 48°C$ (point B)

$48 - 37 = 11°C \Rightarrow$ satisfies the criterion approximately

Basis: 1 kg dry solids /h

$$\text{Moisture lost (kg/h)} = (0,28-0,12)\frac{kg\,H_2O}{\cancel{kg}\,DS} \times \frac{1\,\cancel{kg}\,DS}{h}$$

$$= 0,16\ kg\,H_2O/h$$

Moisture removed from the food = Moisture gained by air.

$$(H_2-H_1)\frac{\cancel{kg\,H_2O}}{kg\,DA} \times G = 0.16\ \cancel{kg\,H_2O}/h$$

$$(0,042-0,004) \times \frac{G}{kg\,DA} = \frac{0.16}{h} \Rightarrow$$

$$G = 4.2\ kg\,DA/h$$

Example: **Ambient air at 30 ºC and 50 % RH is heated to 50ºC to dry rice. The air exits the dryer under saturated conditions. Determine**

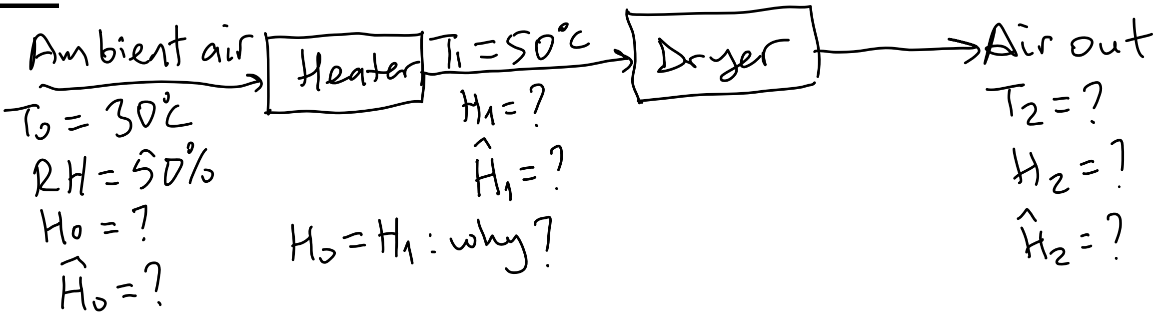
a) wet bulb temperarure of ambient air

b) amount of water removed per kg dry air

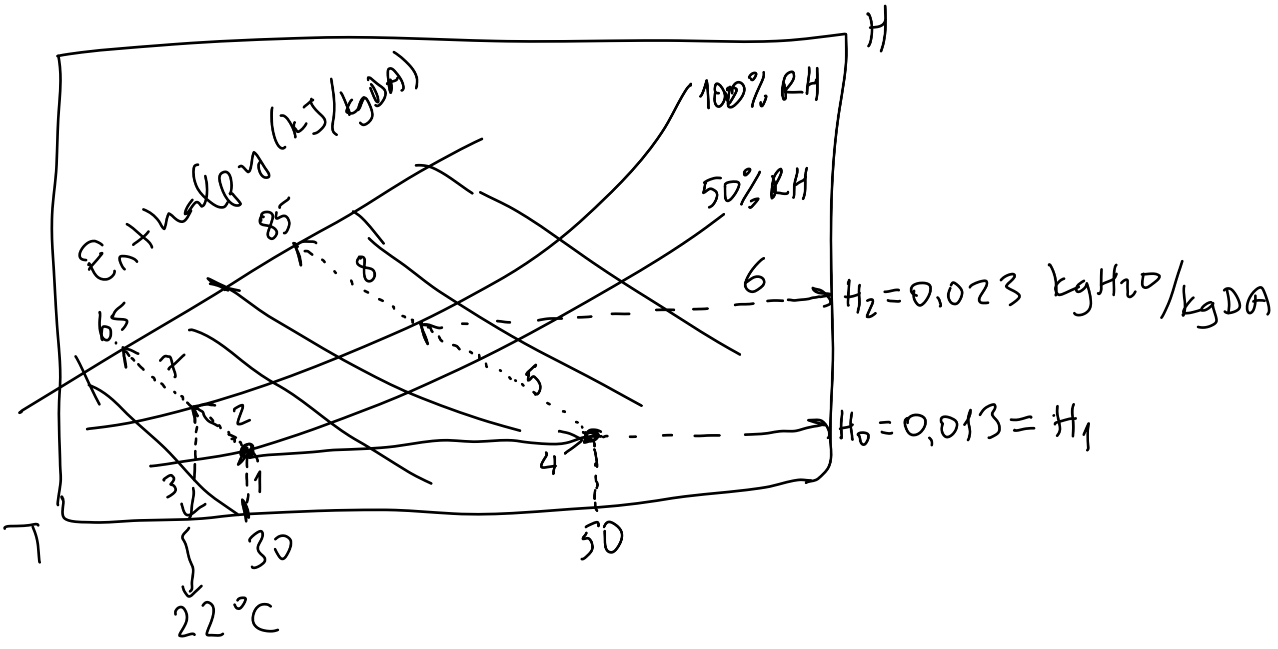
c) total mass of water removed when we use 1000 kg dry air for drying

d) total heat required (in kJ) to dry air to 50 ºC.

Solution:



a)



$T_{wb} \cong 22°C$

b) $H_2 - H_1 = 0,023 - 0,013 = 0,01 \frac{kgH_2O}{kgDA}$ removed

c) $0,01 \frac{kgH_2O}{\cancel{kg}DA} \times 1000\ \cancel{kgDA} = 10\ kg\ H_2O$ removed

d) $\hat{H}_1 - \hat{H}_0 = (85-65)\frac{kJ}{\cancel{kgDA}} \times 1000\ \cancel{kgDA} = 20000\ kJ$ energy

<u>Example:</u> 2000 lb of a food material is to be dried in a dehydrator. It has an initial moisture content of 30 %(wb). Temperature of ambient air to be used for drying is at 80°F and 60 % RH. It is heated in a heater to 150°F and introduced to the dryer and exits the dryer at 120°F. The volumetric flow rate of air is 3000 ft^3/min and has a specific volume of 14 ft^3/lb dry air at 80°F. Determine

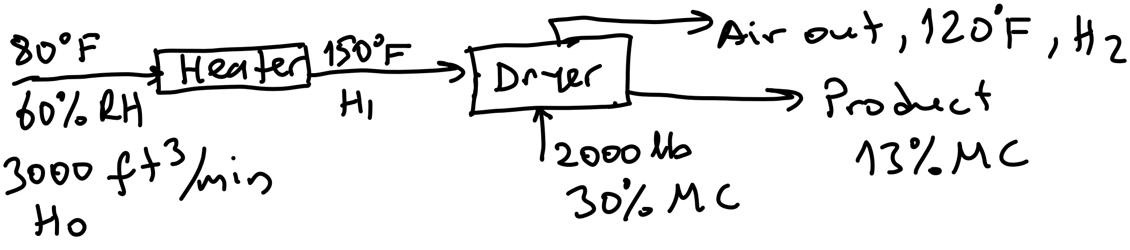
a) amount of dry solids

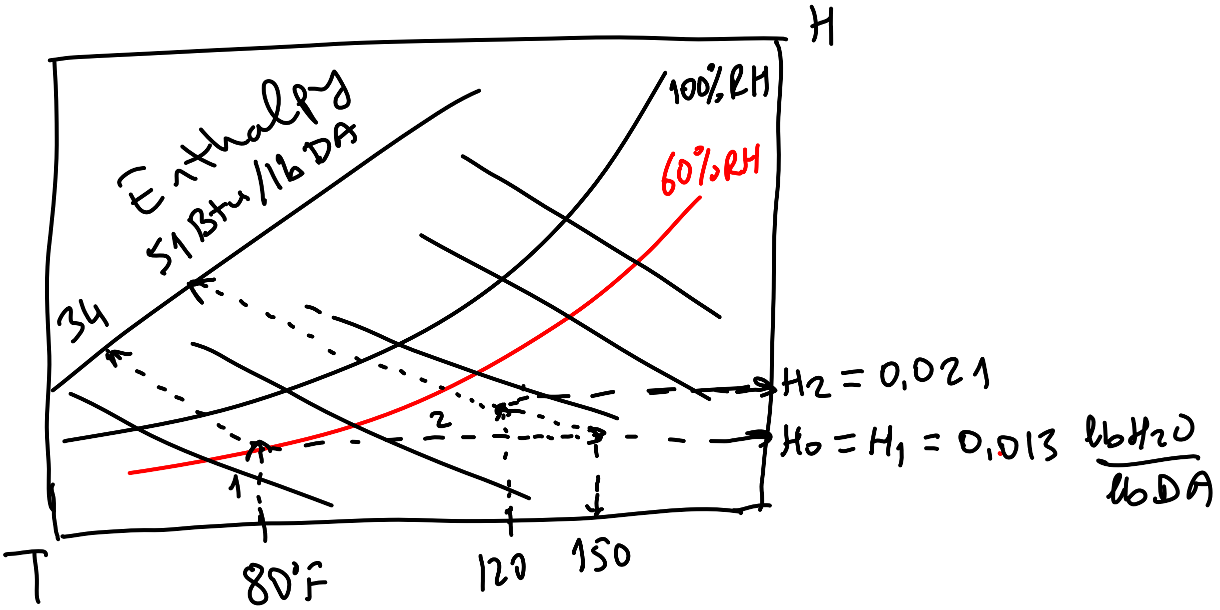
b) heat required to heat air (Btu/h)

c) amount of water evaporated (lb H_2O/h)

d) time required to dry this material from 30 % to 13 % (wb).

<u>Solution:</u>





a) $DS = 2000 \times (1 - 0{,}3) = 1400$ lb.

b) $Q = \dot{m} \times (\hat{H}_2 - \hat{H}_1)$. Calculate mass flow rate of air ⇒

$$\dot{m} = \frac{3000\ ft^3/min}{14\ ft^3/lb} \times \frac{60\ min}{1\ hr} = 12857\ lb/hr\ \text{air}$$

$$Q = 12857\ \frac{lb\cancel{DA}}{hr} \times (51 - 34)\ \frac{Btu}{lb\cancel{DA}} = 218569\ Btu/hr.$$

c) H_2O evaporated $= \dot{m} \times (H_2 - H_1) \Rightarrow$

$$= 12857\ \frac{\cancel{lbDA}}{hr} \times (0{,}021 - 0{,}013)\ \frac{lbH_2O}{lb\cancel{DA}}$$

$$\cong 103\ lbH_2O/hr.$$

d) Convert moisture contents in dry basis ⇒

$$30\%\ wb = \frac{30}{100-30} = 0{,}428\ \frac{lbH_2O}{lbDS}$$

$$13\%\ wb = \frac{13}{100-13} = 0{,}149\ \frac{lbH_2O}{lbDS} \Rightarrow$$

Calculate mass of H_2O removed in lb $\Rightarrow$

$$1400\ \cancel{lb\,DS} \times (0{,}428 - 0{,}149)\ \frac{lb\,H_2O}{\cancel{lb\,DS}} = 390.6\ lb\,H_2O$$

$$\text{Drying time} = \frac{390.6\ \cancel{lb\,H_2O}}{103\ \cancel{lb\,H_2O}/hr} \cong 3.8\ hr.$$

Homework: Hot air with dry bulb temperature of 80°C and a wet bulb temperature of 30°C enters the adiabatic dryer to dry a food products. It exits from the dryer at 50°C.

a) Determine absolute humidity and dew point temperature of air at the dryer inlet.

b) Determine absolute humidity and dew point temperature of air at the dryer exit.

c) If the exit air from the dryer is further cooled down to 20°C in a cooler, determine the amount of water collected in the condenser per kg of dry air.

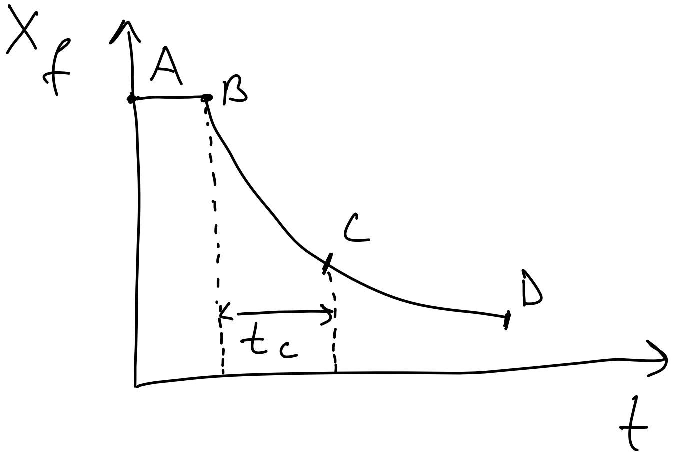
DRYING KINETICS

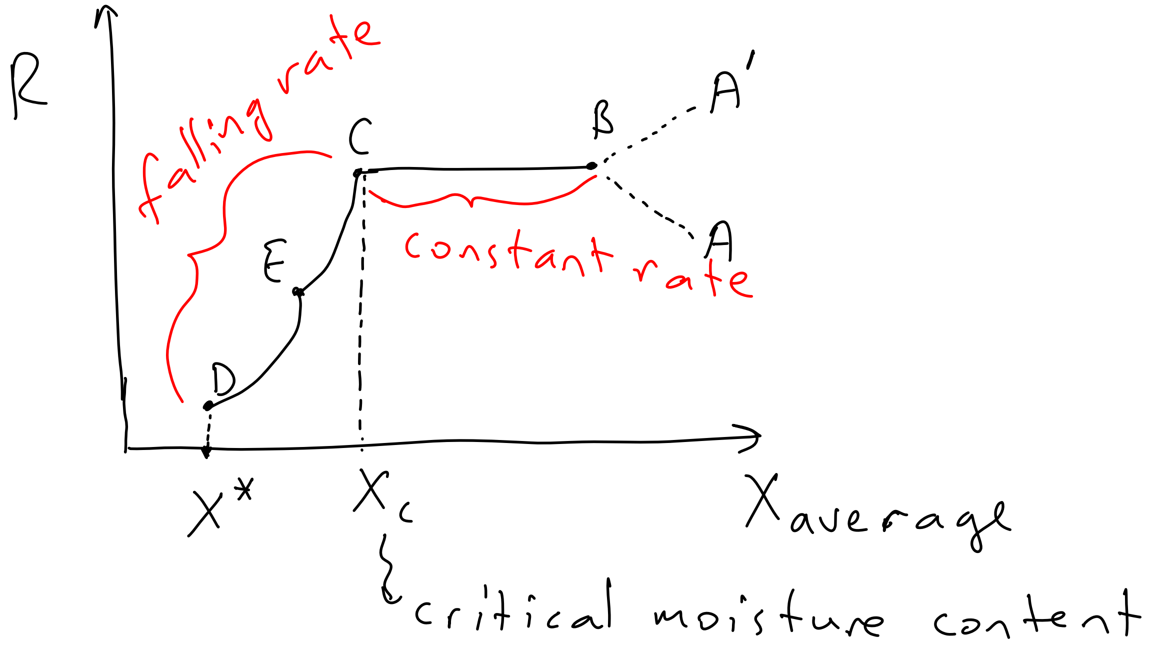
Consider drying of a wet food under fixed drying conditions (e.g., T, P, air velocity, etc.), then,

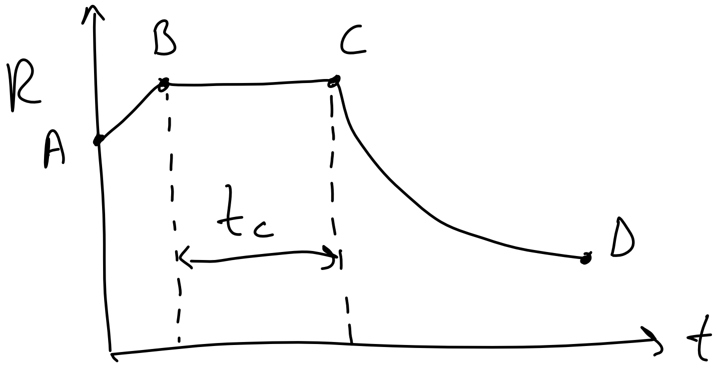
If you have X vs time data $\Longrightarrow$

$$X_f = X - X^*, \quad \text{when } X_f = 0 \Rightarrow \frac{dX_f}{dt} = 0$$

X_f	t
⋮	⋮







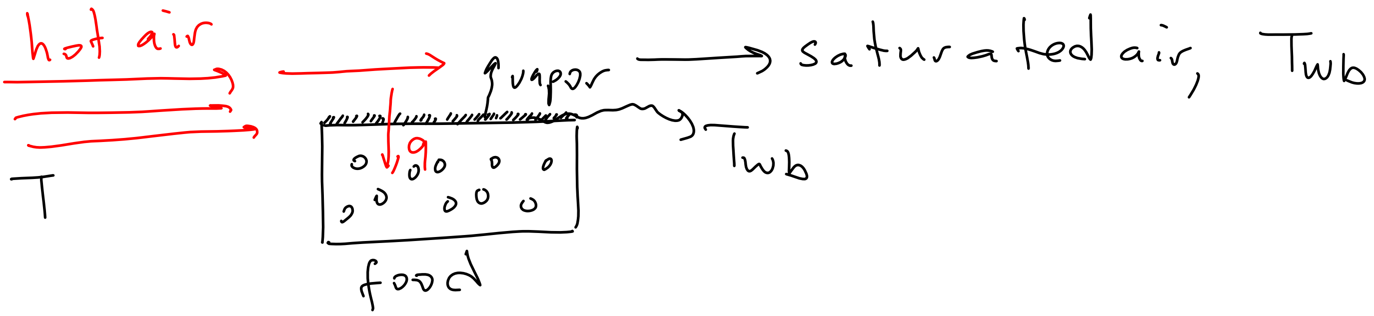
- **Stage A-B and A´- B:** These stages represent a settling down period during which the solid surface conditions come into equilibrium with the drying air.

- This period is generally negligible.
- At A - B, the solid is at a colder T than its drying T ⟹R ↗
- At A´- B, the solid is quite hotter than its drying T ⟹ R ↙

- **Stage B – C:** This stage is known as the constant rate period of drying.

During this period;

- a film of water is always available at evaporating surface.
- the surface of the solid is saturated with liquid water.
- drying takes place by movement of water vapor from the saturated surface into the main stream of drying air.



- **Stage C – D:** **At point C, the drying rate begins to fall and the falling rate period starts.**

- **the surface T begins to increase continuously approaching the T_{db} of the air as the material approaches dryness.**

- **Stage C – E:** **It is the first falling rate period.**

- **the surface is drying out and drying rate falls.**

- **Stage E – D:** **It is the second falling rate period.**

- **the plane of evaporation moves into the solid and drying rate falls further.**
- **in this case the driving force is the water vapor pressure rather than moisture content.**

RATE OF DRYING CURVE FOR CONSTANT DRYING CONDITIONS

In drying experiments the data; W vs time is obtained periodically and then, processed to determine/solve the problem of interest (drying time, drying rates, diffusion constant etc.)

W	t
⋮	⋮ during drying.

W: total weight of food during drying period.

t: drying time

L_s: kg dry solids in food material

X_t : MC at any time.

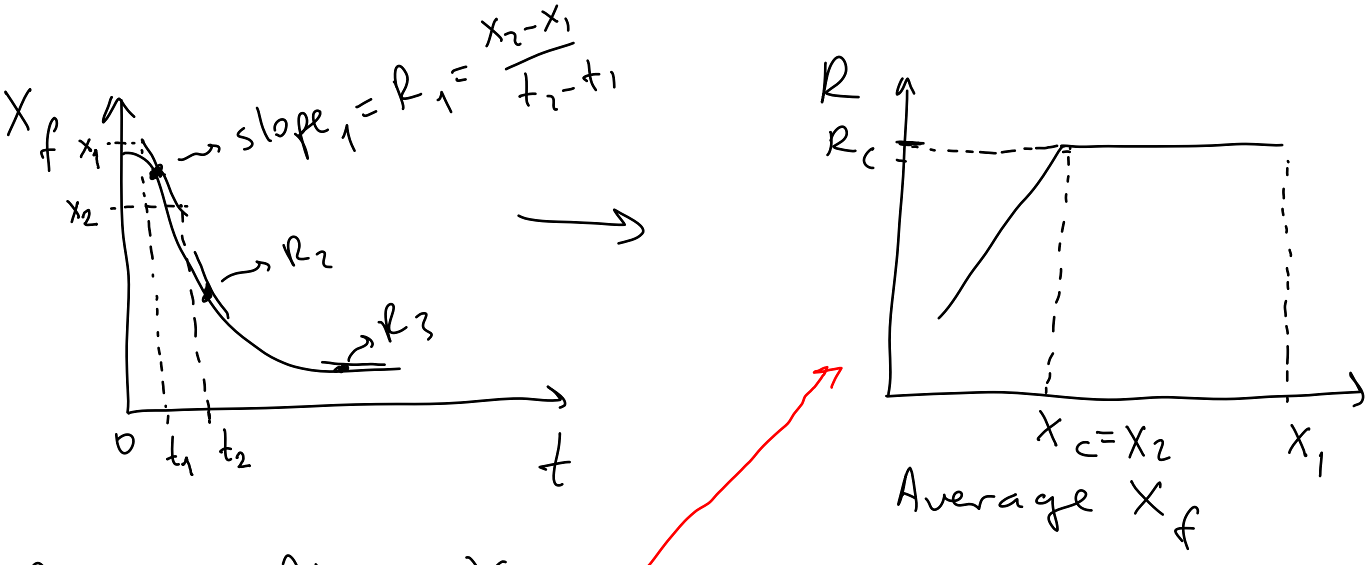
X_f : free moisture content

$$X_t = \frac{W - L_s}{L_s} = \frac{kg\ H_2O}{kg\ DS}$$

$$X_f = X_t - X^*$$

X_f	t
⋮	⋮

} transfer this data into drying rate (R). $R = \frac{dx}{dt}$



R		Average X_f
R_1	→	$\frac{x_2 + x_1}{2}$
⋮		⋮

$$R_c = -\frac{L_s}{A} \times \frac{dX_f}{dt} = -\frac{L_s}{A} \times \frac{(\overset{X_c}{X_2} - X_1)}{(t_2 - t_1)}$$

X: free MC

R: drying rate $(kg\,H_2O/h.m^2)$

A: exposed surface are for drying (m^2).

$$R_1 = -\frac{L_s}{A}\times\frac{(X_2-X_1)}{(t_2-t_1)}, \quad X_{average_1} = \frac{X_2+X_1}{2}$$

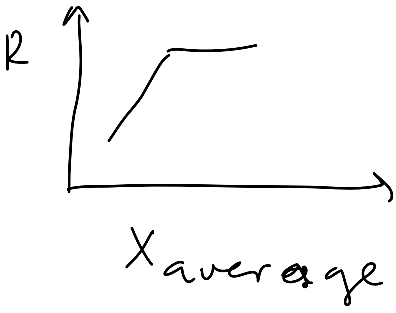
$$R_2 = -\frac{L_s}{A}\times\frac{(X_3-X_2)}{(t_3-t_2)}, \quad X_{average_2} = \frac{X_3+X_2}{2}$$

$$\vdots \qquad\qquad \vdots$$

$$R_f \qquad\qquad X_{average_f}$$

R	Xaverage
R	⋮
⋮	⋮

$\Rightarrow$



CONSTANT DRYING RATE PERIOD

$$R_c = -\frac{L_s}{A}\times\frac{dx}{dt} \Rightarrow \int_{t_1=0}^{t_2=t} dt = -\int_{X_1}^{x_2}\frac{L_s}{A}\times\frac{dx}{R} \Rightarrow$$

$$t = +\frac{L_s}{A}\times\int_{X_2}^{X_1}\frac{dx}{R}, \quad \text{if } R = R_c \Rightarrow t = t_c$$

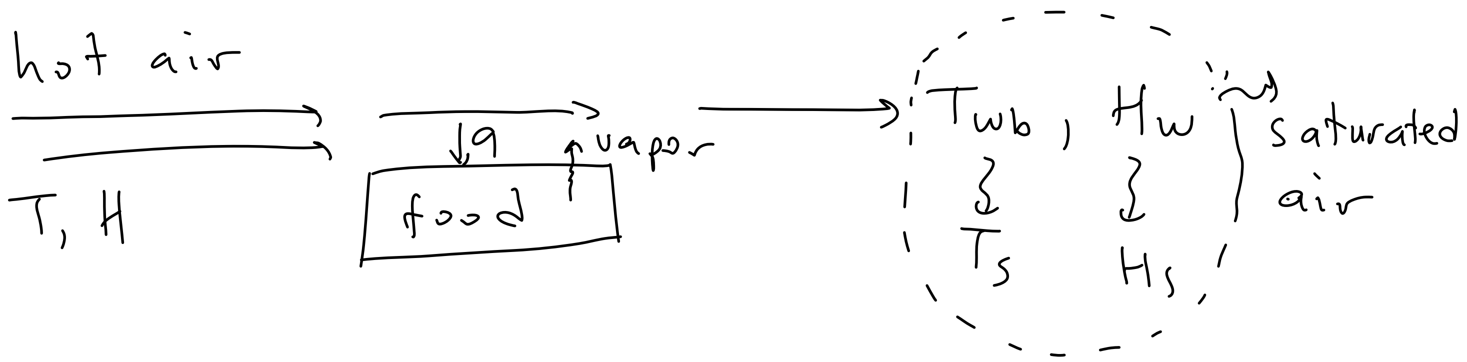
$$\boxed{t_c = \frac{L_s}{A\cdot R_c}\times(X_1-X_2)} \Rightarrow \boxed{R_c = \frac{L_s\times(X_1-X_2)}{A\times t_c}}$$

Example: **A solid is to be dried from the free moisture content $X_1 = 0.38$ kg water/kg DS to $X_2 = 0.2$ kg water/kg DS. Estimate the time required for drying . Given : $L_s/A = 21.5$ kg/m^2, Rc = 1.51 kg/ h.m^2)**

Solution:

$$t_c = \frac{L_s}{A \cdot R_c} \times (X_1 - X_2) = \frac{21.5 \text{ kg DS/m}^2}{1.51 \text{ kg H}_2\text{O/h.m}^2} \times (0.38 - 0.2) \frac{\text{kg H}_2\text{O}}{\text{kg DS}}$$

$$t_c = 2.56 \text{ h}$$



$$R_c = \frac{q}{A \cdot \lambda_w} = \frac{h \cdot (T - T_{wb})}{\lambda_w}$$

q = heat flow rate, J/s = W or kJ/s = kW

λ_w = latent heat of vaporization at T_{wb}; **λ_w = kJ/kgH_2O**

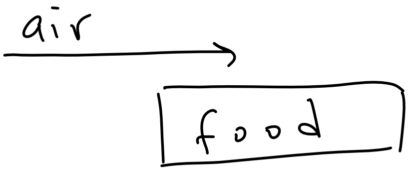
T_{wb} = wet bulb T

h = convective heat transfer coefficient; h = W/(m2.K), kJ/(h.m2.K)

h = ?

- **For air T of 45 – 150°C and mass velocity G of 2450 – 29300 kg/(h.m^2) or a velocity of 0.61 – 7.6 m/s and air flowing parallel to drying surface ⟹**

$$h = 0.0204 \times (G)^{0.8} \rightsquigarrow SI$$



- **For air T of 45 – 150°C and mass velocity G of 3900 – 19500 kg/(h.m^2) or a velocity of 0.9 – 4.6 m/s and air flowing perpendicular to drying surface** ⟹

$$h = 1.17 \times (G)^{0.37} \rightsquigarrow SI$$

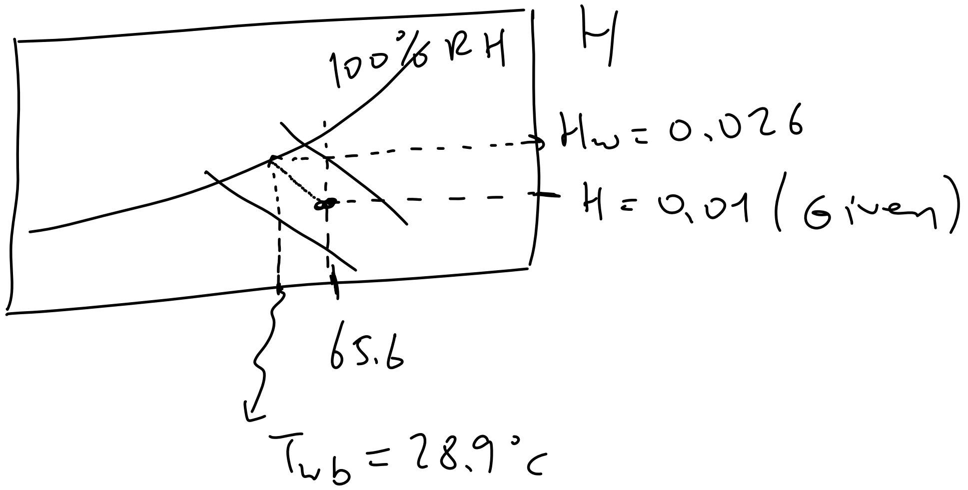
$$G = v \times \rho = \frac{m}{s} \times \frac{kg}{m^3} = \frac{kg\ air}{m^2 . s}$$

Drying time during constant rate period ⇒

$$t_c = \frac{L_s \times \lambda_w \times (X_1 - X_2)}{A \times h \times (T - T_{wb})} = \frac{L_s \times (X_1 - X_2)}{A \times k_y \times \underbrace{M_B}_{\text{Molecular weight of air}} \times (\underset{\hookrightarrow H_s}{H_w} - H)}$$

<u>Example:</u> An insoluble wet granular material is dried in a pan 0.457x0.457 m and 25.4 mm deep. The material 25.4 mm deep in the pan and the sides and bottom can be considered to be insulated. Heat transfer is by convection from an air stream flowing paralel the surface at a velocity of 6.1 m/s. The air is at 65.6ºC and has a humidity of 0.01 kg water/kg DA. Estimate the rate of drying for the constant rate period.

<u>Solution:</u>



$$\underbrace{V_H}_{\text{humid volume}} = (2.83\times10^{-3} + 4{,}56\times10^{-3}\times H)\times T$$

$$V_H = (2.83\times10^{-3} + 4.56\times10^{-3}\times 0{,}01)(273+65{,}6)$$

$$= 0{,}974\ m^3/kg\,DA$$

$H = 0{,}01 \dfrac{kg\,H_2O}{1\,kg\,DA}$ ⇒ mass of this air $= 1 + 0{,}01$

$= 1.01$ kg wet air

$$\rho_{air} = \frac{1.01\ kg/kg\,DA}{0{,}974\ m^3/kg\,DA} = 1.037\ \frac{kg}{m^3}\ \text{air}$$

$$G = V\times\rho = \left(6.1\ \frac{m}{s}\right)\left(1.037\ \frac{kg}{m^3}\right)\times\frac{3600\,s}{1\,hr} = 22770\ \frac{kg}{m^2.h}$$

$h = 0.0204(G)^{0.8}$ ⇝ for parallel flow

$$h = 0.0204\,(22770)^{0.8} = 62.45\ \mathrm{W/m^2.K}$$

At $T_{wb} = 28.9\,°C \Rightarrow \lambda_w = 2433\ \frac{kJ}{kg\,H_2O}$ (from saturated steam table)

$$R_c = \frac{h}{\lambda_w}(T - T_w) = \frac{62.45\ \mathrm{J/s.m^2.K}}{2433\ \frac{kJ}{kg\,H_2O} \times \frac{1000\,J}{1\,kJ}} \times (65.6 - 28.9)\,K \times \frac{3600\,s}{1\,h} \Rightarrow$$

$$R_c = 3.39\ kg\,H_2O/m^2.h$$

Total evaporation rate for a surface area of $0.457 \times 0.457\ m^2 = R_c \times A \Rightarrow$

$$\text{Total } R_c = 3.39\ \frac{kg}{m^2.h} \times (0.457 \times 0.457)\,m^2 \Rightarrow$$

$$= 0.708\ kg/h$$

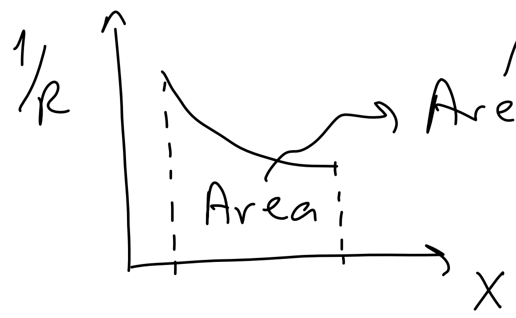
CALCULATION METHODS FOR FALLING RATE DRYING PERIOD

- Method using graphical integration:

$$t_f = \frac{L_s}{A} \times \int_{X_2}^{X_1} \frac{dx}{R} = \frac{L_s}{A} \times \int_{X_2}^{X_1} \frac{1}{R} \cdot dx$$

From drying data find several R values ⇒

i.e., R vs X and calculate 1/R



$$\text{Area} = \int_{X_2}^{X_1} \frac{dx}{R} \Rightarrow t_f = \frac{L_S}{A} \times \text{Area}$$

assume constant A

We assume negligible shrinkage ⇒

$A = \text{constant}$

If $A \neq \text{constant} \Rightarrow A = f(x) = A(x)$

⇒ integrate it.

$$t_f = L_S \times \int_{x_2}^{x_1} \frac{dx}{A(x) \cdot R} \rightsquigarrow \text{if } A \neq \text{constant}$$

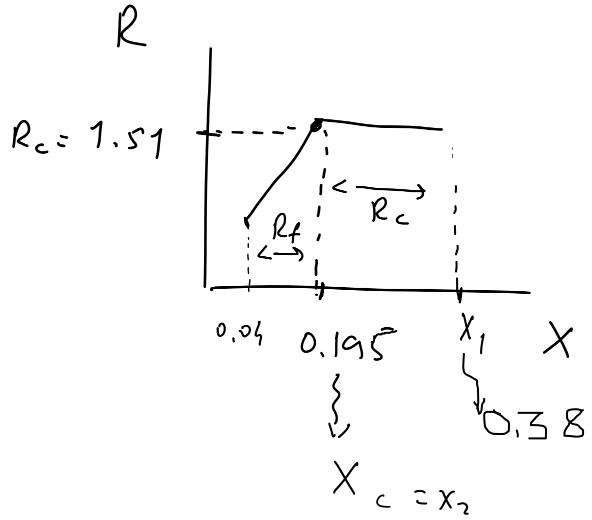
Example: A batch of wet solid whose data are given below is to be dried from a moisture content of $X_1 = 0.38$ to $X_f = 0.04$ kg H_2O/kg DS. The weight of the dry solids is $L_s = 399$ kg and $A = 18.58$ m^2 of top drying surface.

Calculate the time for drying. (Given that $R_c = 1.51$ kg H_2O/h.m^2).

For falling rate period:

	X		R		1/R
X_c	0,195	→	1,51	···	✓
	0,150	→	1,21		✓
	0,100	→	0,90		✓
	0,065	→	0,71		✓
	0,50	→	0,37		✓
	0,04	→	0,27		✓

⇒



Solution: Find 1/R values ⇒

$$\frac{L_s}{A} = \frac{399}{18.58} = 21.5 \ kg/m^2$$

$$t_c = \frac{L_s}{A \times R_c} \times (X_1 - X_2), \quad X_1 = 0,38, \quad X_2 = X_c = 0.195$$

$$t_c = 21.5 \times \frac{1}{1.51} \times (0,38 - 0.195) = 2.63 \ h$$

In the falling rate period ⇒ $t_f = ?$

Find t_f graphically ⇒

$$t_f = \frac{L_s}{A} \int_{X_2}^{X_1} \frac{dx}{R} \quad \Rightarrow$$

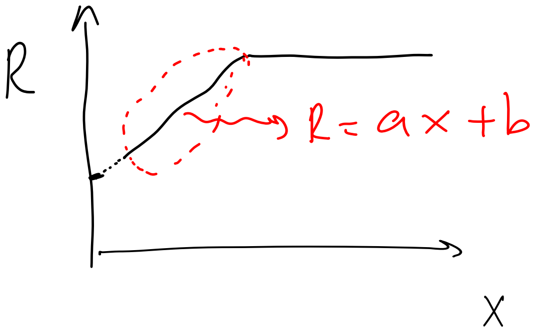
[redacted]

$$\text{Area} = \int \frac{dx}{R} = 0,189$$

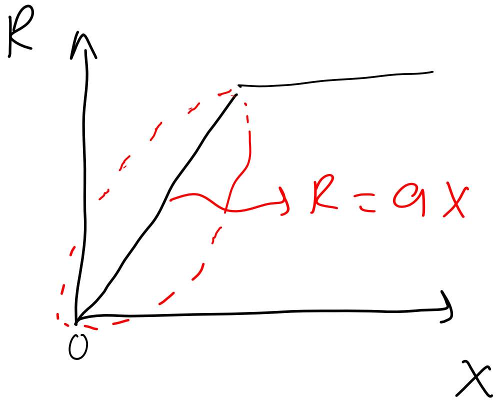
$$t_f = 21.5 \times (0.189) = 4.06 \text{ h}$$

$$\text{total drying time} = t_c + t_f = 2.63 + 4.06$$
$$= 6.69 \text{ h}$$

⊛ Calculation methods for special cases in falling rate period:



OR



1) Rate is linear function of X.

i.e., $R = ax + b \Rightarrow$ differentiate it $\Rightarrow$

$$t_f = \frac{M_s}{A}\int_{x_2}^{x_1}\frac{dx}{R}$$

$$dR = a.dx \Rightarrow dx = \frac{dR}{a} \Rightarrow$$

$$t_f = \frac{M_s}{A}\times\int_{x_2}^{x_1}\frac{1}{a}\times\frac{dR}{R} = \frac{M_s}{a.A}\cdot\int_{R_2}^{R_1}\frac{dR}{R} \Rightarrow$$

$$t_f = \frac{M_s}{a.A}\times \ln\frac{R_1}{R_2}$$

Since $R_1 = a \cdot X_1 + \cancel{b}$

$\mp R_2 = \mp a \cdot X_2 \mp \cancel{b}$

$+$

$R_1 - R_2 = a\,(x_1 - X_2) \Rightarrow a = \dfrac{R_1 - R_2}{X_1 - X_2}$

$$t_f = \frac{M_s}{A}\times\frac{(x_1-x_2)}{(R_1-R_2)}\times\ln\frac{R_1}{R_2}$$

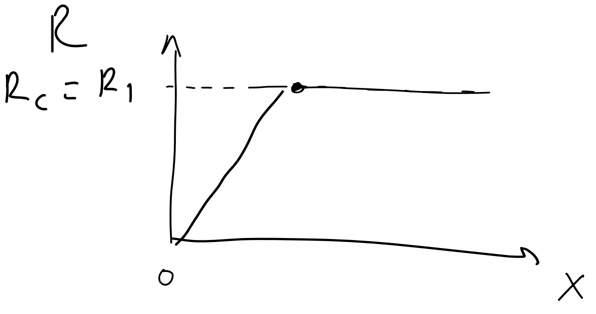
2) Rate is a linear function through origin:

$R = aX \Rightarrow$ differentiate $\Rightarrow dR = a.dx \Rightarrow$

$dx = \dfrac{dR}{a}$

$$t_f = \frac{M_s}{A}\int_{x_2}^{x_1}\frac{dx}{R} \Rightarrow$$

$$t_f = \frac{M_s}{A} \int_{R_2}^{R_1} \frac{1}{a} \times \frac{dR}{R} = \frac{M_s}{a \cdot A} \times \ln \frac{R_1}{R_2}$$



$$R_1 = a\,X_1$$
$$\mp R_2 = \mp a\,X_2$$
$$+\quad R_1 - R_2 = a\,(x_1 - x_2)$$

$$a = \frac{R_1 - R_2}{x_1 - x_2}$$

$$R_f \quad R_1 = R_c \Rightarrow x_1 = X_c$$

$$X_2 = 0 \Rightarrow R_2 = 0 \Rightarrow a = \frac{R_1}{x_1} = \frac{R_c}{X_c}$$

$$t_f = \frac{M_s}{A \times \frac{R_c}{x_c}} \times \ln \frac{R_c}{R_2} \Rightarrow \boxed{t_f = \frac{M_s}{A} \times \frac{X_c}{R_c} \times \ln \frac{X_c}{X_2}}$$

$$\frac{R_c}{R_2} = \frac{\cancel{a} \cdot X_c}{\cancel{a} \cdot X_2} = \frac{X_c}{X_2}$$

$$\boxed{R_f = R_c \times \frac{X}{x_c}}$$

Example: **Repeat the previous example, but as an approximation assume a straight line of the rate R vs X through the origin from point Xc to X = 0 for the falling rate.**

Solution: $R = a \cdot x \rightarrow$ straight line passing through origin.

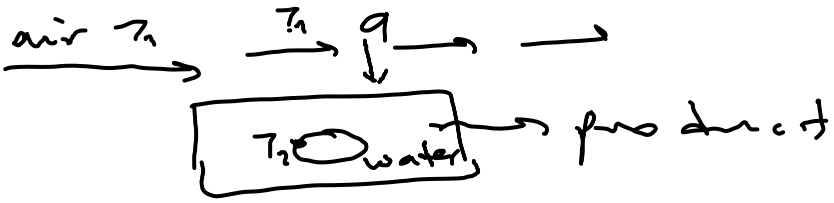
$R_c = 1.51$, $X_c = 0.195$, $X_2 = 0.04$

$$t_f = \frac{L_s}{A} \times \frac{X_c}{R_c} \times \ln \frac{X_c}{X_2} = \left(\frac{399}{18.58}\right) \times \frac{0.195}{1.51} \times \ln \frac{0.195}{0.04}$$

$t_f = 4.39$ h

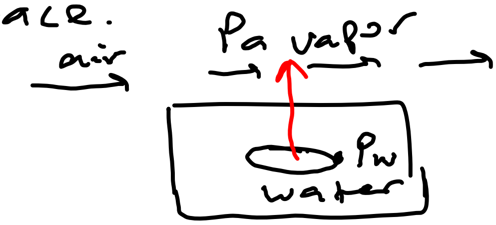
Heat and Mass Transfer

Heat transfer occurs within the product structure and is related to the temperature gradient between product surface and water surface at the same location within the product.



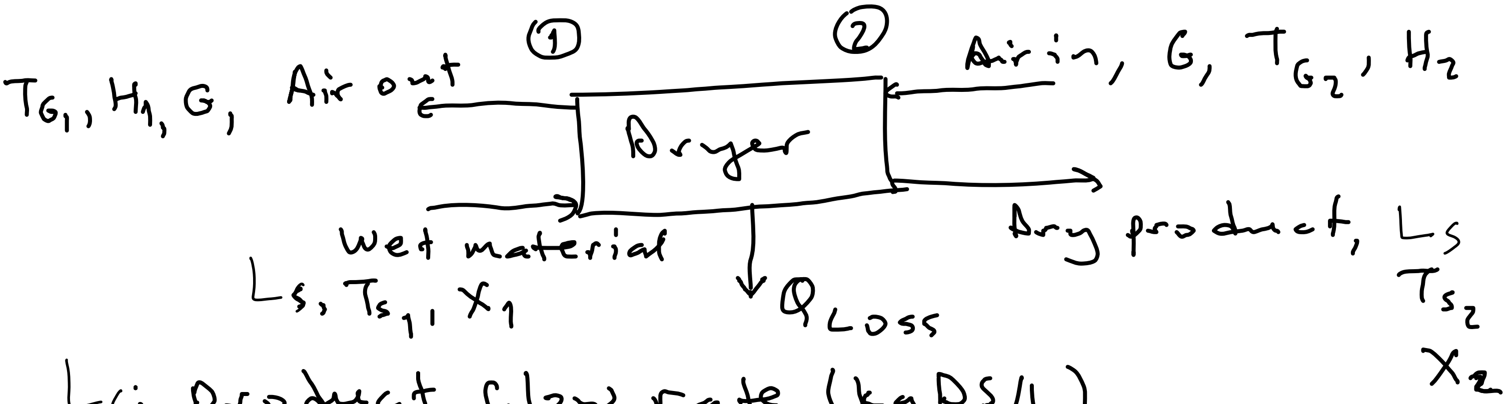
$T_1 > T_2$

⊗ The vapors are transported from water surface within the product to product surface.



$P_w > P_a$

The gradient causing moisture-vapor diffusion is vapor P_w at water surface and at P_a of air at product surface.



L_s: product flow rate (kg DS/h)

X : MC (kg H_2O/kg DS)

T_s : Solids T (K)

G : Air flow rate (kg DA/h)

H: Absolute humidity (kg H_2O/kg DA)

T_G. Air T (K)

H'_G: Enthalpy of air (kJ/kg DA)

H'_S: " " solids (kJ/kg DS)

λ_0: Latent heat of vaporization of water at Tref (kJ/kg H_2O)

(usually $T_{ref} = 0°C \Rightarrow \lambda_0 = 2501$ kJ/kg H_2O)

⊛ Overall Moisture Balance:

$$G\times H_2 + L_S\times X_1 = G H_1 + L_S\cdot X_2$$

Enthalpy of air

$$H'_G = \underbrace{C_s}_{} (T_G - T_{ref}) + H\times\lambda_0$$

Humid heat $= 1.005 + 1.88\times H \rightsquigarrow$ kJ/kg DA.K

Enthalpy of wet solid

$$H'_S = C_{pS}(T_S - T_{ref}) + X\cdot C_{pA}(T_S - T_{ref})$$

C_{pS}: heat capacity of the dry solid in kJ/kgDS.K

C_{pA}: " " " liquid moisture in kJ/kgH_2O.

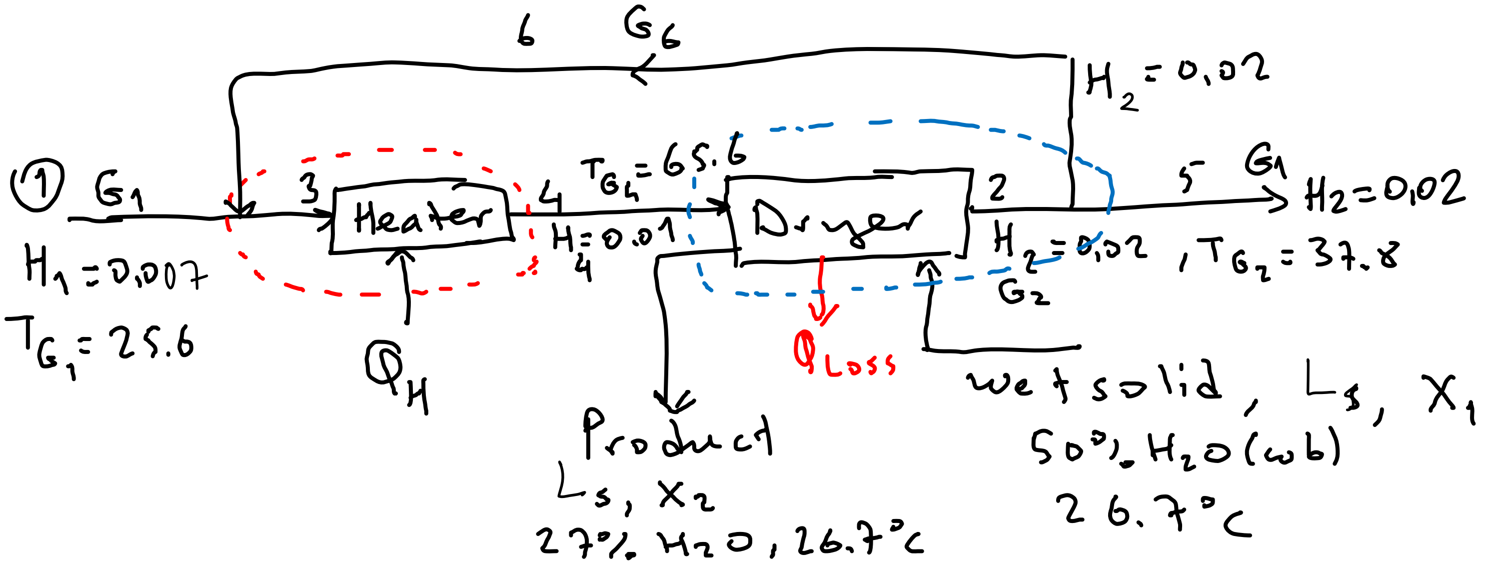
⊛ Heat Balance on the Dryer

$$G\times H'_{G_2} + L_S\times H'_{S_1} = G H'_{G_1} + L_S\times H'_{S_2} + Q_{Loss}$$

For an adiabatic process $\Rightarrow Q_{Loss} \cong 0$.

Example: The wet feed material to a continuous dryer contains 50 wt % water on a wet basis and is dried to 27 wt % by countercurrent air flow. The dried product leaves at the rate of 907.2 kg/h. Fresh air to the system is at 25.6°C and has a humidity of H = 0.007 kg H_2O/kg DA. The moist air leaves the dryer at 37.8°C and H = 0.020 and part of it is recirculated and mixed with the fresh air before entering a heater. The heated mixed air enters the dryer at 65.6°C, and H = 0.01. The solid enters at 26.7°C and leaves at 26.7°C. Calculate the fresh air flow, the percent air leaving the dryer that is recycled, the heat added in the heater and the heat loss from the dryer.

Solution:



rate of product = 907.2 kg/h.

$$L_s = 907.2 \times \underset{\overset{\downarrow}{DS}}{(0,73)} = 662.25 \text{ kg DS/h}$$

$$X_1 = \frac{50}{100-50} = 1 \text{ kg } H_2O/\text{kg DS}$$

$$X_2 = \frac{27}{100-27} = 0,37 \text{ kg } H_2O/\text{kg DS}$$

Material balance for H_2O on heater:

$$G_1 \times H_1 + G_6 \times H_2 = (G_1 + G_6) \times H_4$$

$$G_1 \times (0{,}007) + G_6 \times (0{,}02) = (G_1 + G_6)\cdot(0{,}01) \rightsquigarrow ①$$

Material balance for H_2O on dryer:

$$(G_1 + G_6) \times H_4 + L_s \times X_1 = (G_1 + G_6) \times H_2 + L_s \times X_2$$

$$② \rightsquigarrow (G_1 + G_6)(0{,}01) + 662.25 \times 1 = (G_1 + G_6) \times (0{,}02) + 662.25 \times 0.37$$

Solving eqns ① and ② ⇒

$G_1 = 32094$ kg fresh air/h

$G_6 = 9628$ kg air/h.

$$\text{Recycled air} = \frac{9628}{32094 + 9628} \times 100 = \underline{\underline{23\%}}$$

Heat balance on heater, $T_{ref} = 0°C$ ⇒

$$H'_{G_1} = C_s(T_G - T_{ref}) + H \cdot \lambda_0$$
$$= \left[(1.005 + 1.88H)(T_G - T_{ref}) + H(2501)\right]$$

$$G_1 \times H'_{G_1} + G_6 \times H'_{G_6} + Q_H = (G_1 + G_6) \times H'_{G_4} \Rightarrow$$

$$32094 \times \left[(1.005 + 1.88 \times 0{,}007)(25.6 - 0) + 0{,}007 \times (2501)\right] +$$
$$9628\left[(1.005 + 1.88 \times 0.02)(37.8 - 0) + 0.02(2501)\right] + Q_H$$
$$= (32094 + 9628)\left[(1.005 + 1.88 \times 0.01)(65.6 - 0) + 0{,}01(2501)\right]$$

$$Q_H = 1586138 \frac{kJ}{h} = 1586138 \frac{kJ}{h} \times \frac{1h}{3600\,s} \Rightarrow$$

$$Q_H = 440.6\ kW$$

Heat balance on dryer, $T_{ref} = 0°C \Rightarrow$

$$H'_s = Cp_s(T_s - T_{ref}) + X \cdot Cp_A(T_s - T_{ref})$$

$$(G_1+G_6)H'_{G_4} + L_s \times H'_{s_1} = (G_1+G_6)\times H'_{G_2} + L_s \cdot H'_{s_2} + Q_{Loss}$$

$$(32094+9628)\left[(1.005+1.88\times0.01)(65.6-0)+0.01\times(2501)\right] +$$
$$662.25\left[Cp_s\cancel{(26.7-0)} + 1\times4.187\,(26.7-0)\right] =$$
$$(32094+9628)\left[(1.005+1.88\times0.02)(37.8-0)+0.02\,(2501)\right] +$$
$$662.25\left[Cp_s\cancel{(26.7-0)} + 0.37\times(4.187)(26.7-0)\right] + Q_{Loss}$$

$$Q_{Loss} = 161001.9\,\frac{kJ}{h} \cong 44.7\ kW$$

Overall Thermal Efficiency of Some Dryers

The cost of drying is an important factor in dryer design. For evaporation of water, 3 Mj/kg water (spray dryers) to 6 Mj/kg water (tray dryers) energy is needed.

The energy efficiency of the dryers (ratio of the heat of evaporation to heat input to the dryer):

- **It is higher in contact (40-80 %) than convective drying (20-40 %).**
- **Rotary dryers are more efficient than tray and spray dryers.**

Dryer Efficiency: That fraction of the total heat supplied during a drying operation which is usefully used in evaporating moisture.

e.g.,

- **Drum dryers: 35 - 80 %**
- **Spray dryers: 20 - 50 %**
- **Radiant dryers (IR, MW, Radio frequency): 30 – 40 %**

Efficiency $= \frac{2}{5} \times 100 = 40\%$

Cost Picture For Some Dryers

If rough costs per kg water evaporated = x,

- **Cost of forced air drying = 0.70x**
- **Cost of drum drying = 0.80x**
- **Cost of spray drying = 1.0x**
- **Cost of vacuum drying = 2.0x**
- **Cost of freeze drying = 4.0x**

11.7 DRYING EQUIPMENT

11.7.1 SUN DRYING

Large quantities of fruits, particularly grapes (raisins), apricots, figs, prunes, and dates are dried by direct exposure to sunlight in hot and dry climates. Coffee beans, cereal grains, and fish are also sun-dried prior to storage and preservation. Sun-dried fruits contain about 15%–20% moisture (wet basis), which is near the equilibrium moisture content at ambient air conditions, and they can be stored in bulk, without the danger of microbial spoilage.

Seedless (Sultana) grapes are usually pretreated by dipping in alkali solutions, containing vegetable oil or ethyl oleate, which increases the drying rate by increasing the moisture permeability of the grape skin. The grape bunches are spread in trays and dried by exposure to direct sunlight. The grapes may also be dried by hanging the bunches from a string, while they are covered by a transparent plastic cloth, which protects the product from adverse weather conditions. The sun drying time varies from 10 to 20 days, depending on the insolation (solar radiation). The ripe apricots are usually cut into halves before sun drying on trays, placed on the ground.

Dried fruits, especially figs and apricots, may require fumigation treatment with sulfur dioxide or other permitted insecticide during storage and also before packaging.

11.7.2 SOLAR DRYERS

Solar drying is a form of convective drying, in which the air is heated by solar energy in a solar collector. Flat-plate collectors are used with either natural or forced circulation of the air. Figure 11.8 shows a simple solar dryer with a flat-plate solar collector connected to a batch tray dryer. The air movement is by natural convection, but addition of an electrical fan will increase considerably the collector efficiency and the drying rate of the product (Saravacos and Kostaropoulos, 2001).

Several types of solar collectors and drying systems have been proposed for drying various food and agricultural products, such as fruits, vegetables, and grains. The common flat-plate collector consists of a black plate, which absorbs the incident solar radiation, a transparent cover, and insulation material.

The incident solar energy (insolation) varies with the geographical location and the season of the year. A typical insolation for a hot climate would be 0.6 kW/m^2 with an average sunshine time of 7 h/day. This energy corresponds to about $0.6 \times 3600 = 2.16$ MJ/h or 15 MJ/m^2 day. The evaporation of water at 40°C requires theoretically 2.4 MJ/kg and practically about 3 MJ/kg. Therefore, the mean evaporation rate of water will be about $2.16/3 = 0.72$ kg/m^2 h (intermittent operation 7 h/day).

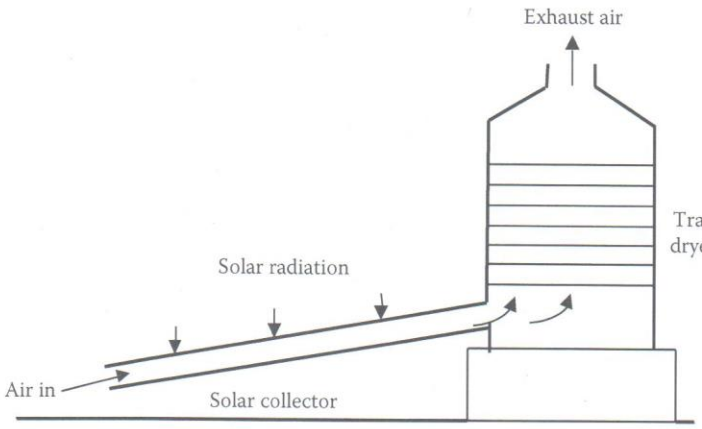


FIGURE 11.8 Simple solar dryer.

The relatively low intensity of incident solar radiation is a serious limitation for food drying applications, where large amounts of thermal energy are required for the evaporation of water.

Large surfaces of solar collectors are needed for drying significant amounts of food materials. For example, evaporation of 1000 kg/h of water (capacity of a typical mechanical convective dryer) would require about 1000/0.72 = 1400 m^2 of collector surface for a hot climate (intermittent operation 7 h/day). A larger surface would be required in a temperate zone. Solar drying is considered effective for relatively small drying operations for fruits, such as grapes and apricots, in high insolation regions.

Intermittent solar radiation (day–night) can be supplemented by the use of auxiliary energy, such as fuel or electricity. Thermal storage of solar energy can also be applied, using rock beds or water to absorb extra solar energy during the day, which can be used during the night or during cloudy weather.

Some other solar collectors, proposed for solar drying are (a) a low-cost tunnel collector 1 × 20 m connected to a tunnel dryer for drying a batch of 1000 kg of grapes; (b) a solar collector with V-grooves, attaining temperatures 50°C–70°C at 0.7 kW/m^2 insolation; and (c) an evacuated tubular solar collector (glass tubes 12.6 cm diameter and 2.13 m length), capable of heating the air to 90°C–110°C.

Solar collectors, integrated on the roof or the walls of a farm building can provide heated air for drying grain in a bin or silo.

11.7.3 SILO AND BIN DRYERS

Silo dryers are used for partial drying of large quantities of grains (wheat, corn, etc.) from moisture contents (wet basis) of about 25% (harvest) to 18% (storage). Hot air at 40°C–60°C is blown from the bottom of the fixed bed through the grains for several hours (Figure 11.9). Continuous tower dryers are more effective, using higher air temperatures (e.g., 80°C), while the grain slowly moves down.

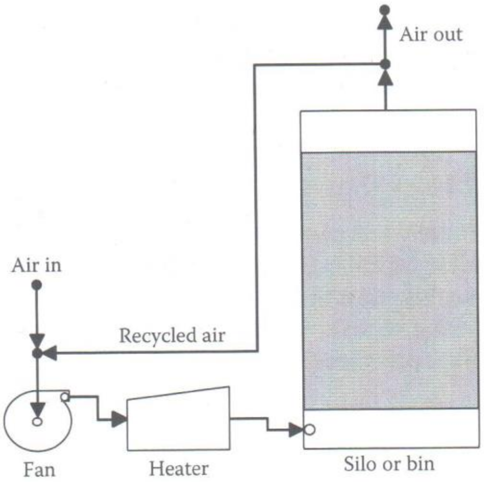


FIGURE 11.9 Batch silo or bin dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.3.)

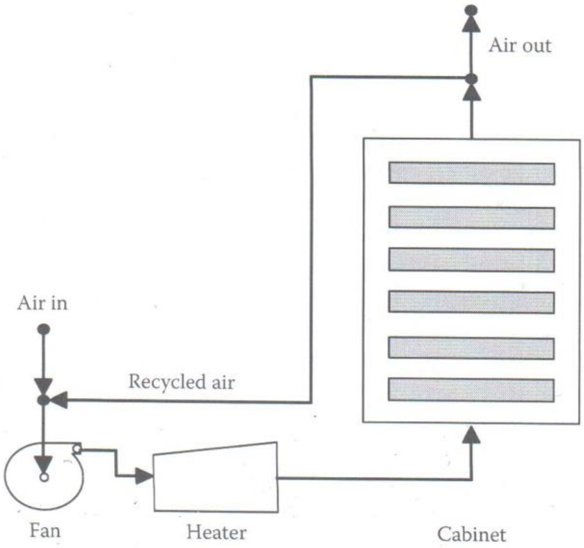


FIGURE 11.10 Diagram of a cabinet (tray) dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.4.)

Bin dryers are similar but generally smaller than silo dryers and they are used as finish dryers of partially dried vegetables. Normal convective drying of vegetables reduces their moisture content to about 10%, and bin drying can bring it down to 2%–4%, which is necessary for preservation and storage. Bin dryers operate at relatively low temperatures with dry dehumidified air, blown upward.

11.7.4 TRAY DRYERS

Tray dryers are relatively small batch units for drying small quantities of food products (Figure 11.10). The air is heated in a heat exchanger outside the dryer, and it is usually recirculated to increase the thermal efficiency. The product in the form of pieces, particles, or pastes is placed in metallic trays, which are reused after the drying operation.

11.7.5 TUNNEL OR TRUCK DRYERS

Tunnel dryers are relatively low cost constructions, with the product trays (pieces or pastes) loaded on trucks, which move slowly co-current or countercurrent to the hot air (Figure 11.11). The thermal efficiency of the dryer is improved by recirculation. The system runs semicontinuously, and the trays are loaded and unloaded manually. Tunnel or truck dryers are used mainly in the drying of fruits and vegetables.

11.7.6 BELT DRYERS

Belt or conveyor dryers are used extensively in food processing for continuous drying of food pieces (Figure 11.12). The product, in the form of pieces, such as fruits and vegetables, is dried on a long perforated conveyor belt, which moves slowly

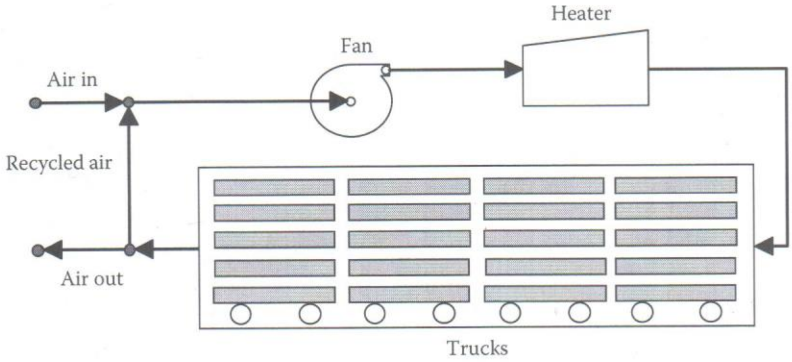


FIGURE 11.11 Diagram of a tunnel or truck dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.5.)

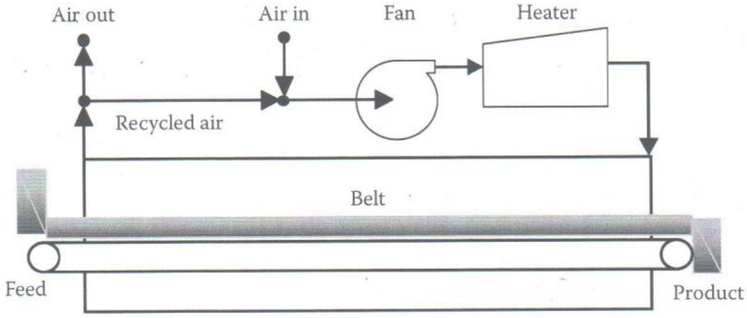


FIGURE 11.12 Diagram of a single-belt conveyor dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.6.)

for the required drying time. The air is heated to the desired temperature in a heat exchanger or is mixed with the combustion gases of suitable fuels, and it is directed against the product in up- or down-flow. Long residence times are obtained using multibelt dryers (e.g., three belts), which run in opposite directions.

11.7.7 ROTARY DRYERS

The rotary dryers consist of an inclined long cylinder rotating slowly, while the material (grains, granules, powders) flows with the tumbling (cascading) action of the internal flights (Figure 11.13). The air is heated either in heat exchangers or by mixing with combustion gases of suitable fuel, e.g., natural gas. Rotary dryers are less expensive than belt dryers, but they cannot handle large food pieces, which may be damaged by mechanical abrasion during tumbling (Perry and Green, 1997).

11.7.8 FLUIDIZED BED DRYERS

Fluidized bed dryers are used for fast drying of food pieces and particles that can be suspended in a stream of hot air (Figure 11.14). High drying rates are obtained due to high heat and mass transfer.

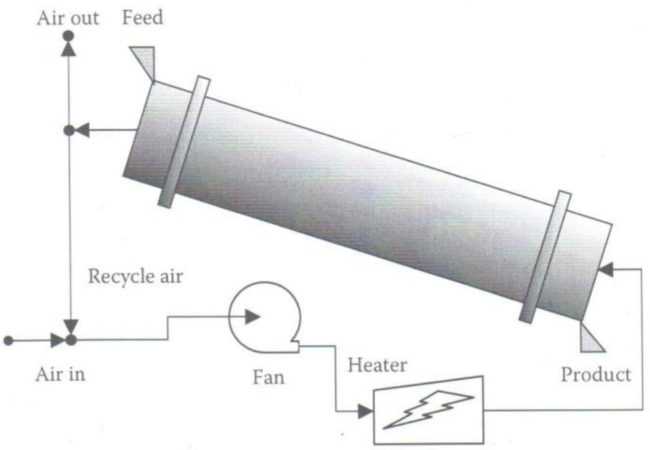


FIGURE 11.13 Diagram of a rotary dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.7.)

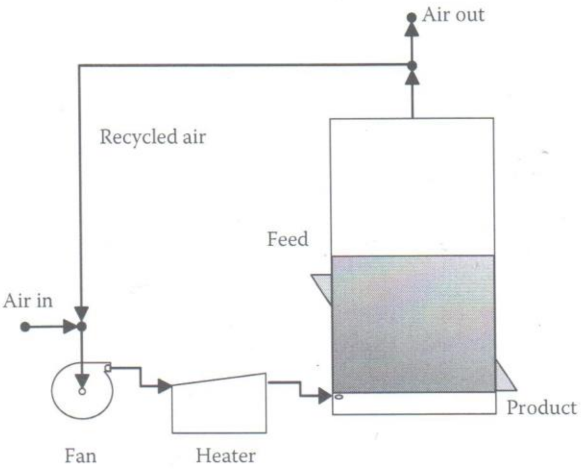


FIGURE 11.14 Diagram of a fluidized bed dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.8.)

11.7.9 SPOUTED BED DRYERS

Spouted bed dryers are a special type of fluidized-bed equipment, in which the granular material is circulated vertically in a tall drying chamber. The heated gas enters as a jet at the center of the conical base of the vessel, carrying the granular material upward, which is dried partially and thrown to the annular space. The material in the bed moves slowly by gravity to the bottom, and the cycle is repeated continuously (Figure 11.15). Spouted bed dryers are suitable for granular materials larger than 5 mm, such as wheat grain.

11.7.10 PNEUMATIC OR FLASH DRYERS

Pneumatic or flash dryers are used for fast and efficient drying of food particles that can be suspended and transported in the stream of heating air (Figure 11.16). The residence time in pneumatic dryers is much shorter than in fluidized-bed units.

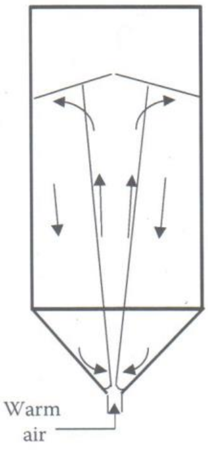


FIGURE 11.15 Diagram of a spouted bed dryer.

11.7.11 SPRAY DRYERS

Spray dryers are used to dehydrate liquid foods or food suspensions into dry powders or agglomerates. The liquid feed is atomized in special valves (Chapter 7) and the droplets are dried by hot air as they fall in a large chamber (Figure 11.17). The flow of hot air can be cocurrent or countercurrent to the flow (fall) of the droplets and dried particles. The dryers are equipped with cyclone collectors and bag filters to collect the small particles from the exhaust air/gases, and prevent air pollution. Spray dryers are usually combined with agglomeration equipment, which produces food agglomerates of desirable quality (Masters, 1991).

The engineering of particles (liquid and solid) and agglomerates is discussed in the section of Mechanical Processing (Chapter 7). Pressure atomizers are preferred in spray drying because they produce droplets of approximately uniform size. The other two atomizers (centrifugal and pneumatic) produce a wider dispersion of droplet sizes, which dehydrate unevenly.

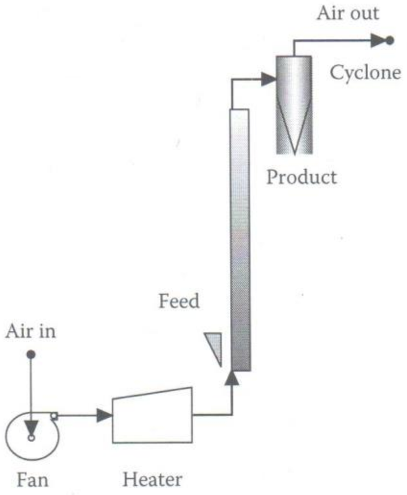


FIGURE 11.16 Diagram of a pneumatic dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.9.)

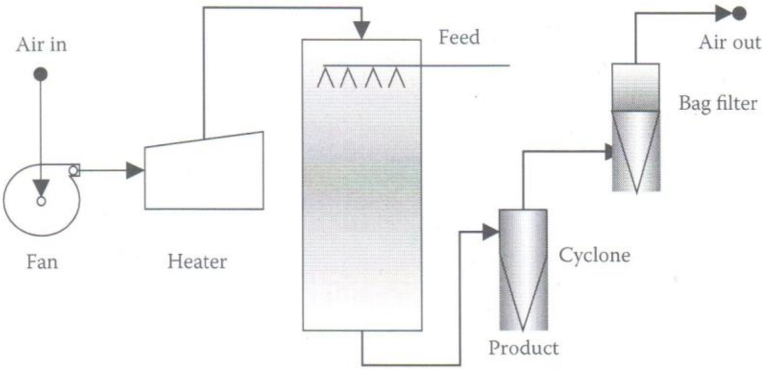


FIGURE 11.17 Diagram of a co-current flow spray-dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.10.)

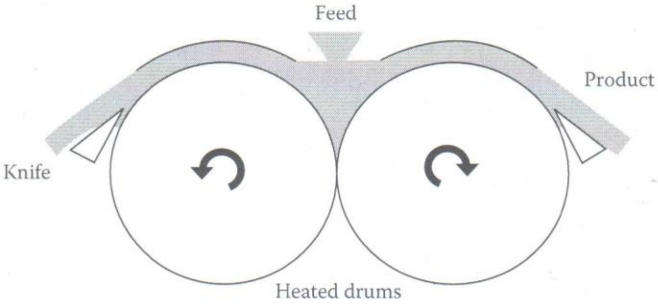


FIGURE 11.18 Diagram of a double drum dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.11.)

11.7.12 DRUM DRYERS

Drum dryers are used to dehydrate concentrated liquid foods or suspensions and food pastes. They consist of one or two slowly rotating drums, heated internally by steam, with the product dried on the cylindrical surface (Figure 11.18). They are more efficient thermally than convective (air) dryers and they are operated either at atmospheric pressure or in vacuum.

11.7.13 VACUUM DRYERS

Vacuum dryers are used for the dehydration of heat-sensitive food products, such as fruit juices. They operate at pressures of about 10 mbar and temperatures around 10°C (drying from the liquid state). They require vacuum pumping and low-temperature condensing equipment. Heat transfer is by contact to a heated shelf, infrared radiation, or microwaves. The product is dried either in trays or in a belt (Figure 11.19). Both batch and continuous operating systems are used.

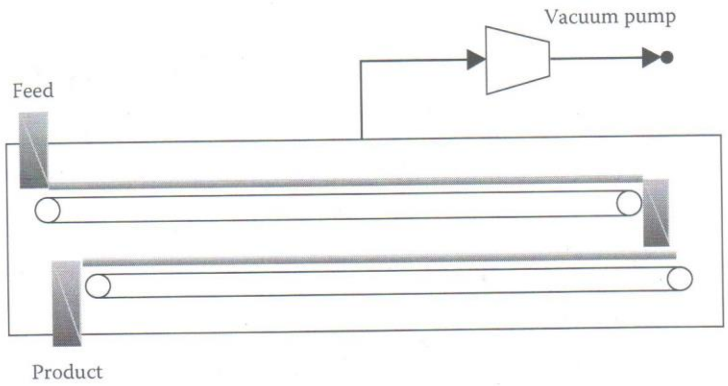


FIGURE 11.19 Diagram of a continuous belt-vacuum dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.12.)

11.7.14 FREEZE DRYERS

Freeze dryers are the most expensive drying equipment, and they are justified economically only for drying certain expensive food products of unique quality, such as instant coffee. They are used mainly in the freeze drying of pharmaceutical products, which can afford the high cost (Liapis and Bruttini, 1995; Oetjen, 1999).

Freeze-dryers operate at pressures below 1 mbar and temperatures below −10°C (drying from the frozen state). The prefrozen product is placed in trays (Figure 11.20) and heated by contact, infrared radiation, or microwaves. Freeze-drying rate is limited by heat transfer to the drying surface. Batch freeze dryers are normally used, but there are some semicontinuous systems for large operations.

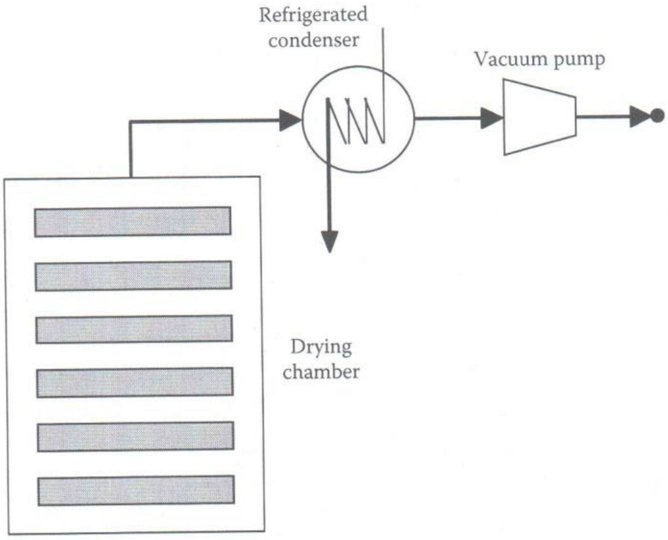


FIGURE 11.20 Diagram of a batch freeze-dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.13.)

11.7.15 AGITATED DRYERS

Various types of agitated dryers are used for the drying of food pieces and particles, improving the heat and mass transfer rates and reducing the drying time. Among them, the agitated horizontal dryers have a rather small size and employ mechanical scrapers, suitable for paste products. Pan dryers use rotating paddles (scrapers) and they are suitable for pulps and pastes.

The tumbling dryers consist of rotating cone or V-shaped vessels, which can be operated at atmospheric pressure or in vacuum. The vessels are jacketed to allow heating by steam or other medium. The sensitive food material slides inside the rotating vessels, drying at a fast rate and moderate temperature, which improves the quality of the product.

The turbo dryer (Figure 11.21) is a special tray dryer with the particulate product flowing slowly down, following a helical path, while it is agitated by air blown countercurrently by two fans.

11.7.16 MICROWAVE DRYERS

Microwave (MW) and dielectric or radio frequency (RF) energy at 915 or 2450 MHz (Megacycles/s) are used to remove water from food materials at atmospheric or in vacuum. MW and RF energy heat the material internally, without the need of external convective or contact heat transfer. Water has a higher dielectric constant (about 8) than the other food components (about 2). Therefore, food materials of high moisture content absorb more MW or RF energy, facilitating the drying process. Free water can be removed more easily, because it absorbs more energy than adsorbed water (Chapter 8).

Internal absorption of the MW/RF energy by a wet material will increase its temperature and vapor pressure, creating a puffing effect on the product, and increasing the drying rate during convective or vacuum drying.

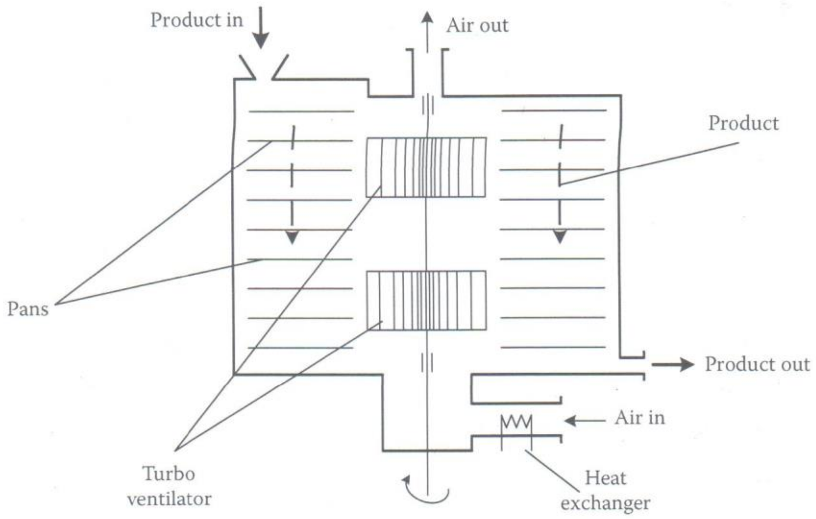


FIGURE 11.21 Diagram of a turbo dryer.

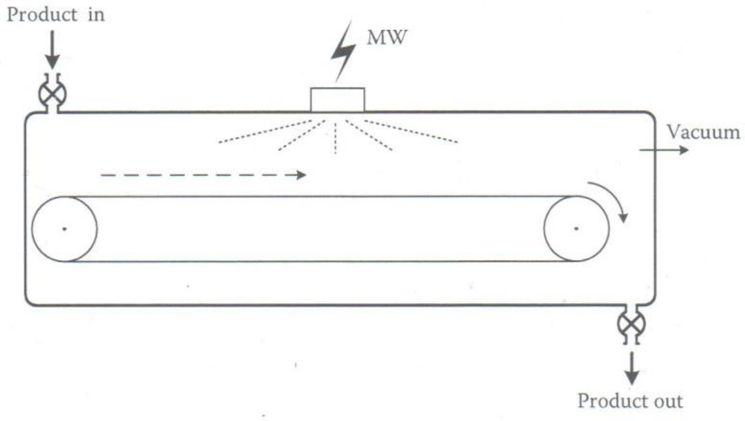


FIGURE 11.22 Diagram of a continuous MW-vacuum dryer.

MW energy improves the vacuum- and freeze-drying operations of food materials by better energy (heat) absorption within the product, or by the development of a porous structure (puffing) in the material, which increases substantially the effective moisture diffusivity.

RF drying is used in various post-baking systems, following the commercial fuel-heated oven, increasing the production rate of cookies, biscuits, etc. by 30%–50%. MW drying can be applied to pasta drying operations, reducing substantially the drying time of conventional hot-air drying, and improving the product quality.

Figure 11.22 shows a continuous MW-vacuum dryer, suitable for food products.

11.7.17 IMPINGEMENT DRYERS

Impingement jets of hot air (high speed) can be used in drying operations to increase the dying rate of food materials, due to the resulting higher heat and mass transfer coefficients. Nozzle design and geometry of the dryer-food material system are important factors in effective drying application. Specific energy consumption in impingement dryers is about 3.1 MJ/kg water evaporated.

11.7.18 SPECIAL DRYERS

Several dryers have been tested and some of them have been applied in the food process industry. They are mostly batch food processing operations used to dry some sensitive food products, such as fruits and vegetables. Some of the special dryers are still in the development stage, and their commercial application will depend on the process economics and the acceptance of the new products by the consumers.

11.7.18.1 Centrifugal Dryers

The centrifugal fluid bed (CFB) dryers consist of a cylindrical vessel with perforated walls, which rotates horizontally at high velocity, and is heated by a cross flow air stream. Food material pieces move through the rotating cylinder and are dried fast, due to the high heat and mass transfer rates in the centrifugal field. Centrifugal forces of 3–15 g, and air velocities up to 15 m/s are applied, higher than in fluidized-bed drying.

CFB drying is suitable for predrying high moisture food materials, such as vegetables, followed by conventional drying (convective or vacuum). The capacity of the CFB dryers is relatively small (up to about 200 kg/h), limiting their economic commercial application.

11.7.18.2 Explosion-Puff Drying

Explosion-puff drying is based on the development of a highly porous structure in fruit and vegetable materials, which increases greatly the drying rate of the product. The wet food material is dehydrated by conventional convective drying to about 25% moisture and then heated in a rotating cylindrical vessel ("gun") until a high pressure is developed (2–4 bar). The pressure is released instantly, producing a puffed product, which is dried fast to the desired moisture content in a conventional dryer. The dehydrated porous product has improved rehydration properties, an important quality factor in many food products.

11.7.18.3 Foam-Mat Drying

Foam-mat drying is used in small scale for the drying of sensitive food products, such as concentrated fruit juices, fruit purees, and food slurries. The fluid food is foamed by incorporating a gas in a special mixer, using a foam stabilizer. The foamed material is applied as a thin film of 1.5 mm on a perforated tray or belt, and it is dried at moderate temperatures and air velocities. Very fast drying is achieved, e.g., 15 min at 70°C, and the product has a porous structure, which improves its rehydration properties. The operating cost of foam-mat drying is lower than vacuum drying, but, for commercial applications, large spray dryers are more cost effective.

11.7.18.4 Acoustic Dryers

Acoustic or sonic dryers can improve the drying rate of various food materials. Low frequency sound waves increase considerably the heat and mass transfer rates at the particle/air interface. The short drying times, achieved by sonic drying, improve the product quality, such as color, flavor, and retention of volatile aroma components. Food liquids of 5%–75% total solids have been dried to low moistures, e.g., citrus juices and tomato paste.