Chapter 6
DRYING

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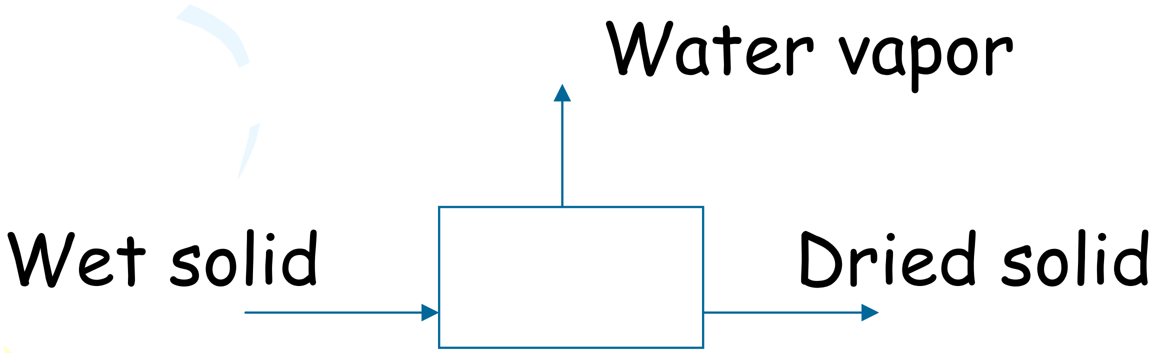
Topic Outcomes

Drying	*It is expected that students will be able to:*
❑ Introduction and methods of Drying ❑ Equipment of Drying ❑ Vapor Pressure of Water and Humidity ❑ Equilibrium Moisture Content ❑ Rate of Drying ❑ Constant-Rate Drying Curve ❑ Calculation methods for Constant-Rate Drying Period	❑ Explain the principle of drying of materials ❑ Identify a different types of dryers ❑ Use the <u>humidity chart</u> to estimate <u>humidity</u> ❑ Calculate <u>the equilibrium moisture content</u> of the materials ❑ Calculate the <u>rate of drying</u> ❑ Calculate <u>drying time</u> for <u>constant-rate and falling-rate period</u>

Drying

- Removal of relatively small amounts of water as vapor by air
- Removal of water from process material and other substances
- Removal of other organic liquids from solids
- Evaporation – removal of large amounts of water
- Usually the final processing step before packaging - as a preservation technique especially for food



General Methods of Drying

- **Batch** – material is inserted into the drying equipment and drying proceeds for a given period of time

- **Continuous** – material is continuously added to the dryer and dried material continuously removed

- Drying is categorized according to physical conditions used to remove water

✓ Direct contact with heated air at the atmospheric pressure - water vapor removed by air

✓ Vacuum drying – heated indirectly by contact with a metal wall or by radiation

✓ Freeze drying – water is sublimed from frozen material……**Why??**

Drying Equipment

Tray dryer

Drum dryer

Continuous microwave dryer

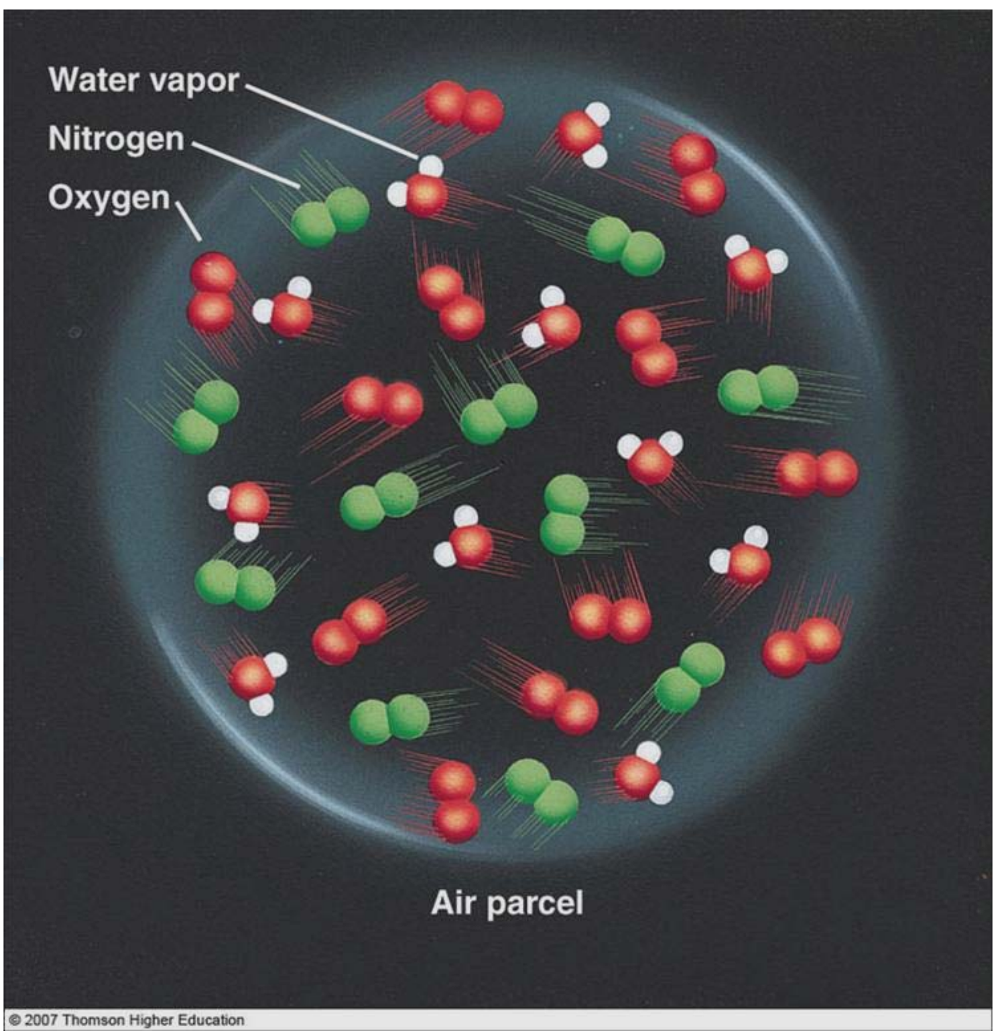
Spray Dryer

Application??

Humidity

- Humidification - transfer of water from the liquid phase into a gaseous mixture of air and water vapor.

- Dehumidification - water vapor is transferred from the vapor state to the liquid state.



Humidity

- Humidity, H of an air-water vapor mixture is the kg of water vapor contained in 1 kg of dry air.

$$H = \frac{18.02}{28.97}\frac{p_A}{P - p_A}$$

Where P is the total pressure and p_A is the partial pressure of water vapor in the air.

- Percentage Humidy, H_p – percent of actual humidity H divided by the humidity H_s, air saturated with water vapor at the same temperature and pressure.

$$H_p = 100\frac{H}{H_S}$$

- Relative Humidity, H_R – the amount of saturation of an air-water vapor mixture

$$H_R = 100\frac{p_A}{p_{AS}}$$

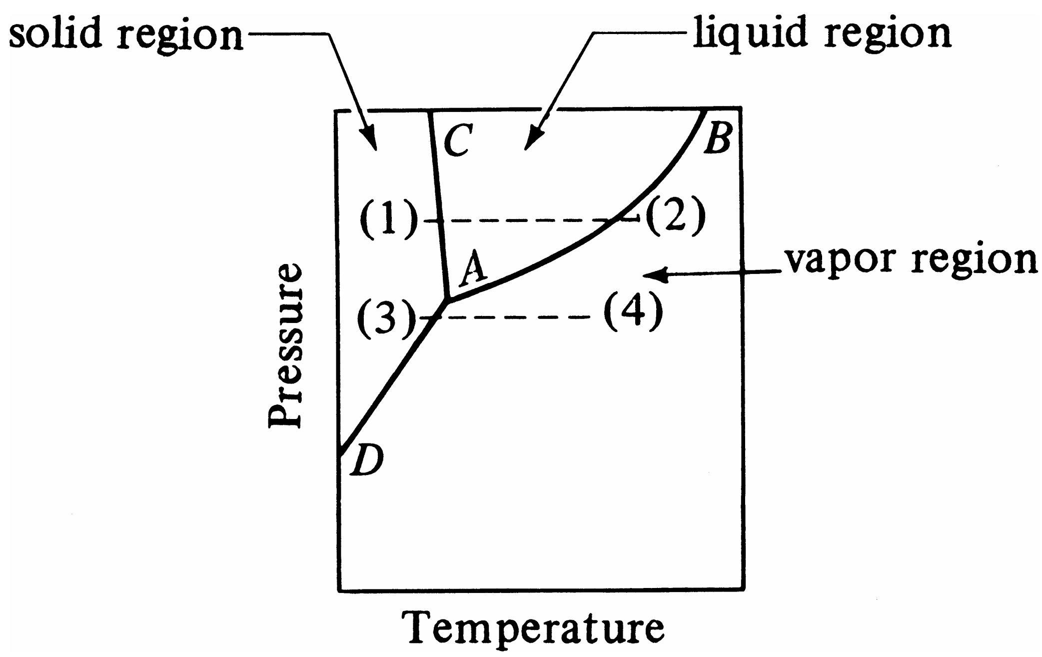
Note : MW of water 18.02 kg/kg mol and air 28.97 kg/kg mol

Vapor Pressure of Water

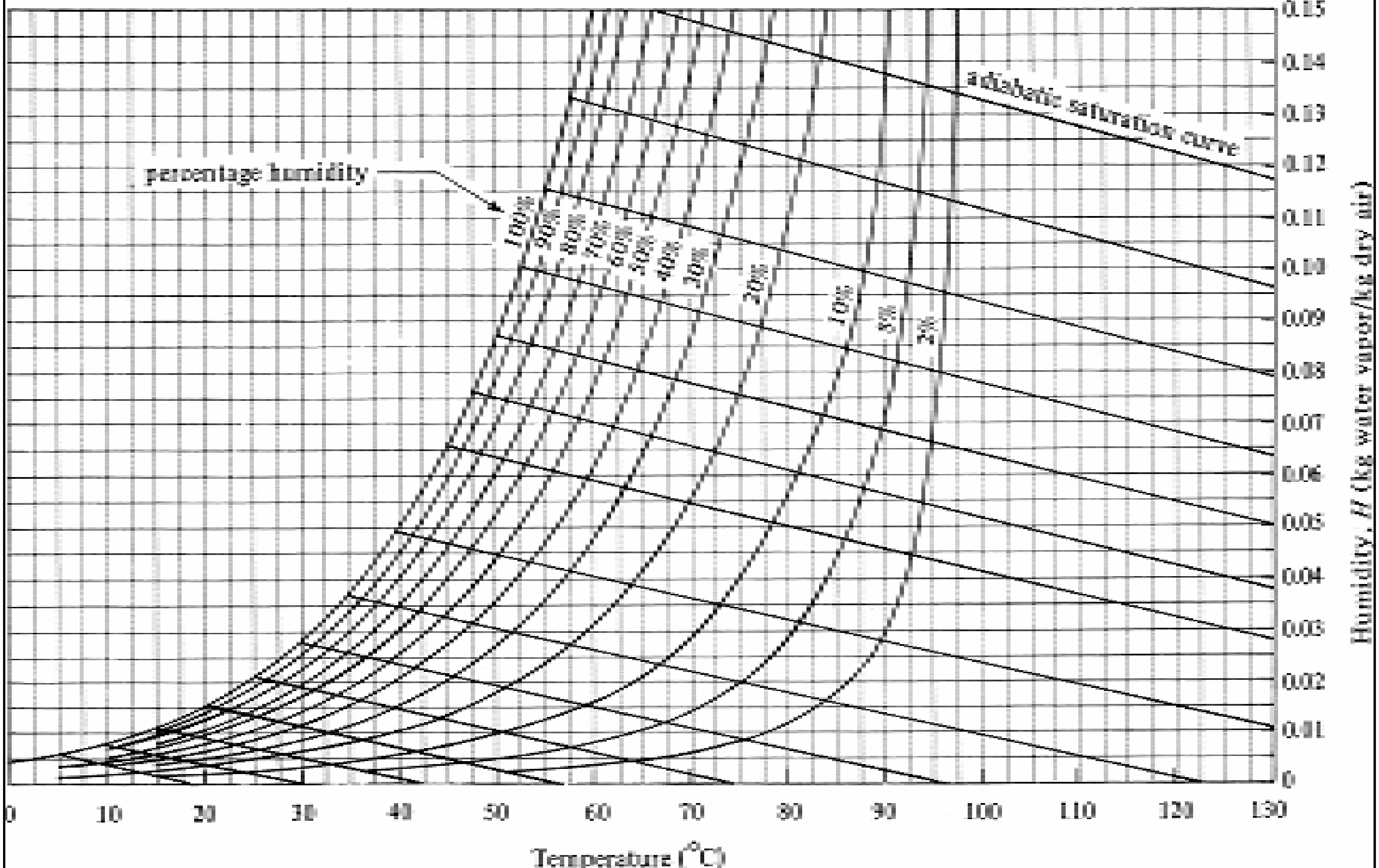
- Pure water can exist in three physical states: solid ice, liquid and vapor; depends on the pressure and temperature.

- If ice at point (1) is heated at constant pressure, the temperature rises and the physical condition is shown horizontally. From point (3) to (4), ice sublimes (vaporizes) to a vapor without becoming a liquid.

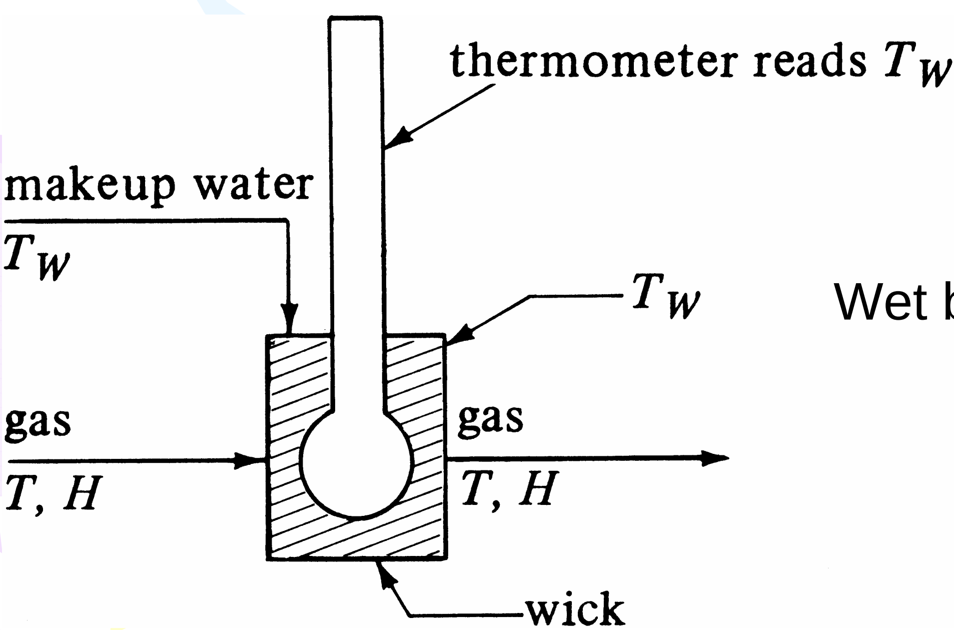
- Along line AB, the phases liquid and vapor coexist in equilibrium along the line AB, which is the vapor pressure line of water. Boiling occurs when the vapor pressure of the water is equal to the total pressure above the water surface.



Humidity Chart



Humidity chart for mixtures of air and water vapor at a total pressure of 101.325 kPa



Wet bulb temperature

Q1 The air in a room is at 26.7 ^oC and a pressure of 101.325 kPa and contains water vapor with a partial pressure p_A = 2.76 kPa. Calculate the following :

a) Humidity, H

b) Saturation humidity, H_S, and percentage humidity, H_P

c) Percentage relative humidity, H_R

Q2 An air stream at 87.8 ^oC having a humidity H = 0.030 kg H_2O/kg dry air is contacted in an adiabatic saturator with water. It is cooled and humidified to 90% saturation.

a) What are the final values of H and T?

b) For 100% saturation, what would be the values of H and T?

Give Yourself a Try!!

Q3 Air having a dry bulb temperature of 37.8 ^oC and a wet bulb of 26.7 ^oC is to be dried by first cooling to 15.6 ^oC to condense water vapor and then heating to 23.9 ^oC.

a) Determine the initial humidity and percentage humidity

b) Determine the final humidity and percentage humidity

Q4 Air entering an adiabatic cooling chamber has a temperature of 32.2 ^oC and a percentage humidity of 65%. It is cooled by a cold water spray and saturated with water vapor in the chamber. After leaving, it is heated to 23.9 ^oC. The final air has a percentage humidity of 40%

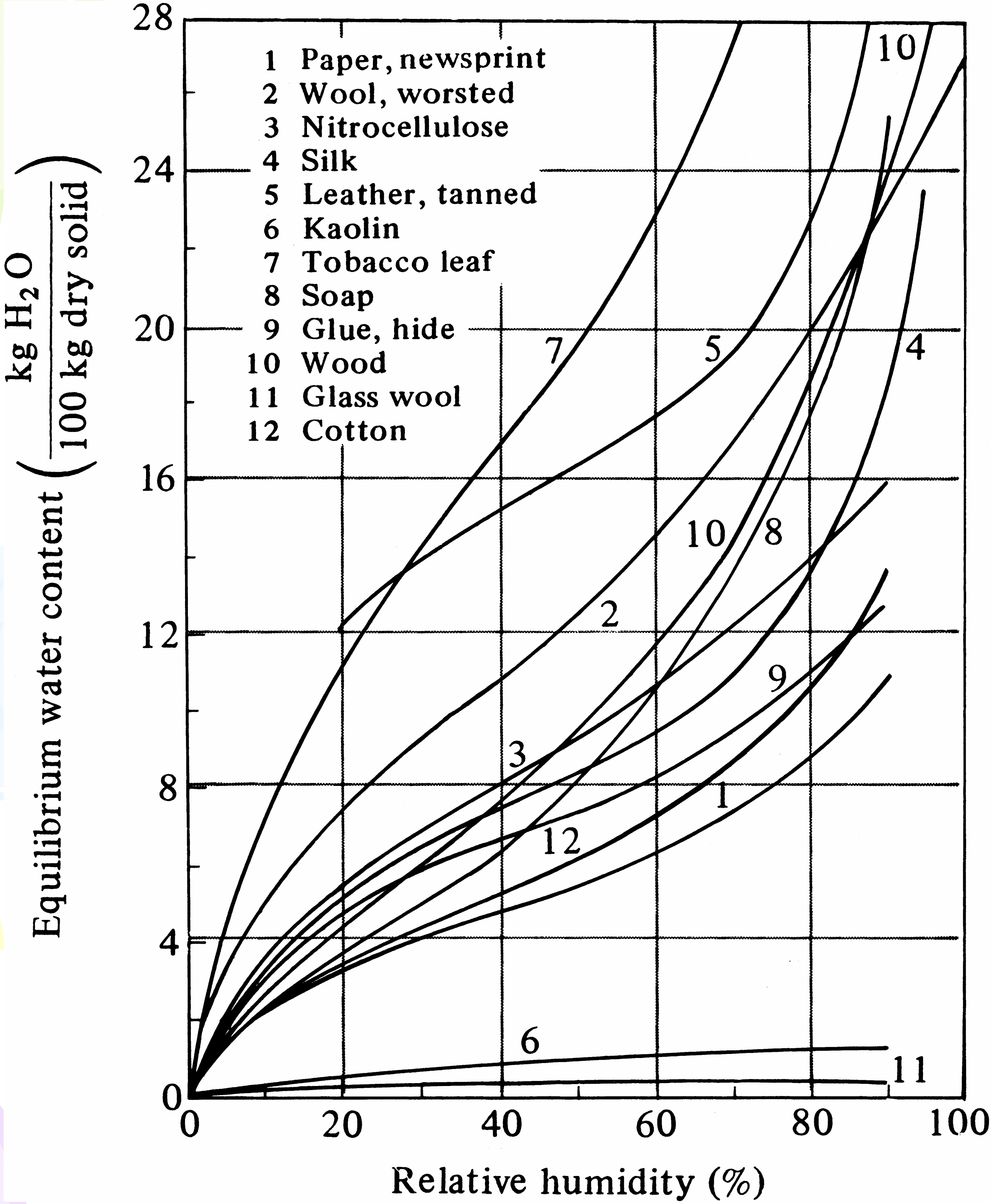
a) What is the initial humidity of the air?

b) What is the final humidity after heating?

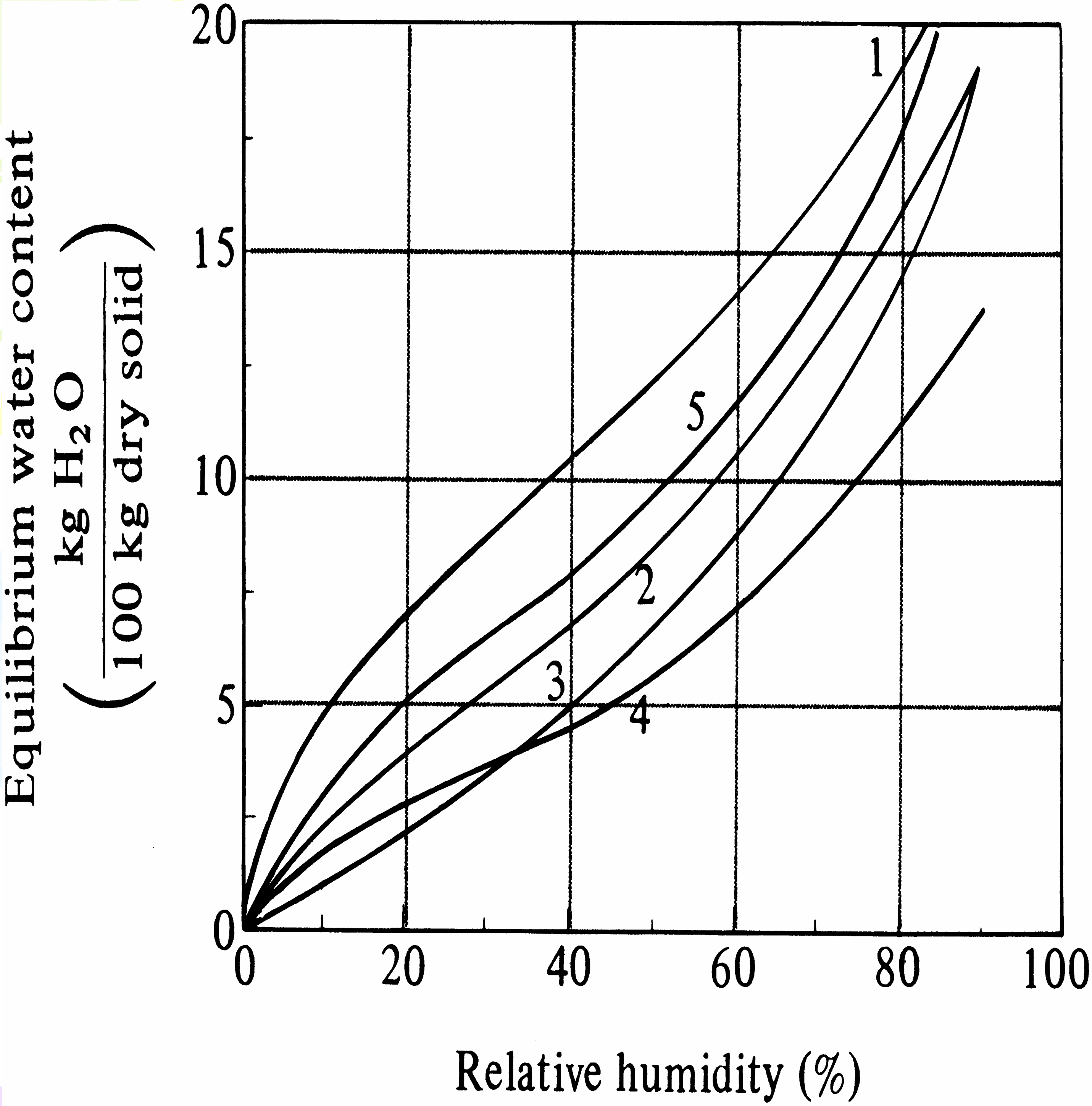
Moisture Content

1. Equilibrium Moisture Content, *X**

- The lowest moisture content obtainable at equilibrium under the drying conditions used
- Expressed on a dry basis (kg of water per kg of moisture-free solid)
- It depends on the structure of the solid, the temperature of the gas and the moisture content of the gas
- Varies greatly with the type of material for any given % relative humidity
- Decreases with an increase in temperature
- Assumed constant for moderate temperature ranges



Typical equilibrium moisture contents of some solids at approximately 298 K (25º C)



Typical equilibrium moisture contents of some food materials at approximately 298 K (25º C): (1) macaroni; (2) flour; (3) bread; (4) crackers; (5) egg albumin

2. Free moisture content X

- Moisture above the equilibrium moisture content

- Moisture that can be removed by drying under the given % relative humidity

$$X = X_t - X^*$$

where ;

X_t = total moisture content

X^* = equilibrium moisture content

Drying: Experimental Procedures

- Solid placed on a tray
- Only top surface exposed to air stream
- Tray suspended from a balance
- Record loss in weight during drying
- Condition closely resemble actual large scale operations
- Ratio of drying to non-drying surface, bed depth, air velocity, humidity, temperature and direction of air

Rate of Drying Curves

- Data :

W: total weight of wet solid

W_s: weight of dry solid

- To obtain data as free moisture X vs time, t

- **Total moisture**, $X_t = (W-W_s)/W_s$ kg total water/kg dry solid

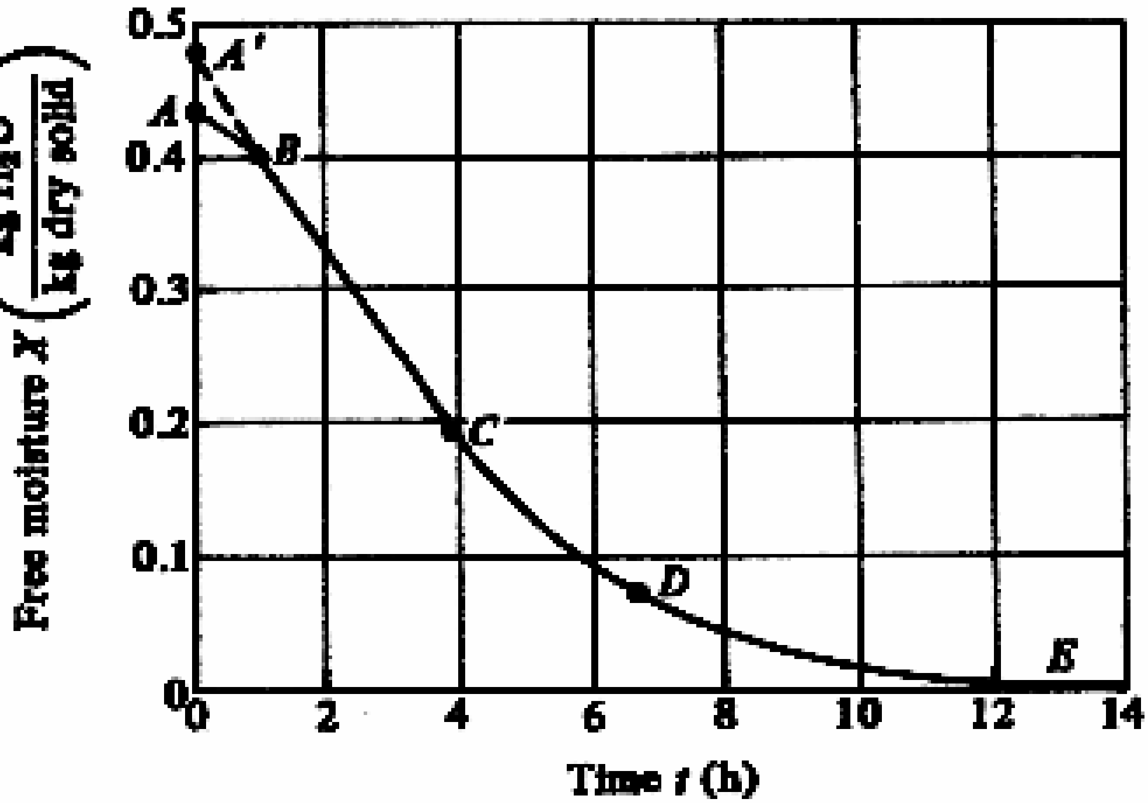
- **Free moisture** content $X = X_t - X^*$

- To obtain rate of drying R: get slope of tangents at different value of t

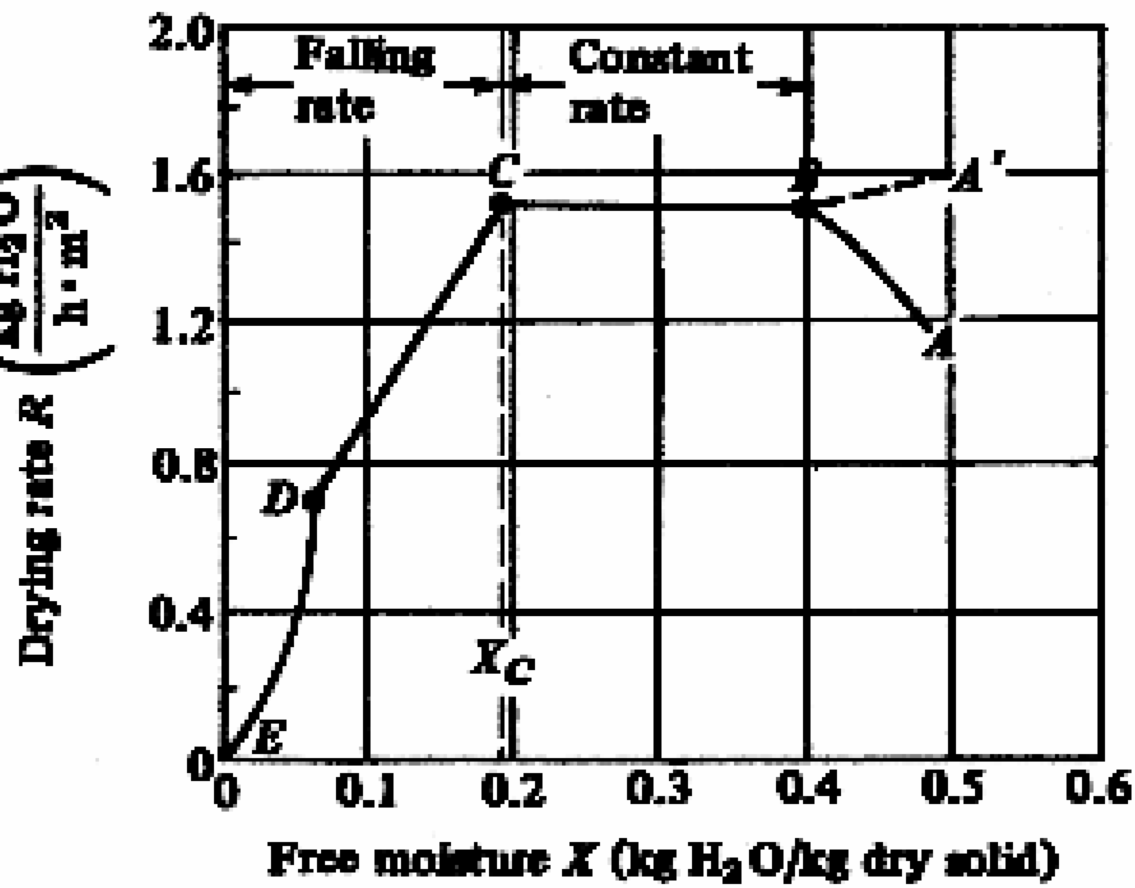
$$R = -\frac{L_S}{A}\frac{dX}{dt}$$

- Where *R* is drying rate in kg $H_2O/h.m^2$, L_S kg of dry solid, *A* exposed surface area for drying in m^2.

Rate of Drying Curves



(a)



(b)

Calculation Method for Constant-Rate Drying Period

Time of Drying

- Instead of using the drying curve, the rate-of-drying can be used
- The rate of drying R is defined as

$$R = -\frac{L_S}{A}\frac{dX}{dt}$$

- This can be rearranged and integrated over time interval to dry from X_1 at $t_1 = 0$ to X_2 at $t_2 = t$,

$$t = \int_{t_1=0}^{t_2=t} dt = \frac{L_S}{A}\int_{X_2}^{X_1}\frac{dX}{R}$$

- And R is a constant = R_c,

$$t = \frac{L_S}{AR_c}\left(X_1 - X_2\right)$$

Calculation Methods for Falling-Rate Drying Period

- Method using graphical integration
- In the falling-rate drying period, the rate of drying, *R* is not constant but decreases when drying proceeds past the critical free moisture content X_c.
- When the free moisture content X is zero, the rate drops to zero.
- In the falling-rate period, R varies. So it can not be integrated as in the constant-rate period.
- However, it can be graphically integrated by plotting 1/R versus X and determining the area under the curve.

$$t = \frac{L_S}{A} \int_{X_2}^{X_1} \frac{dX}{R}$$

Calculation Methods for Special Cases in Falling-Rate

$$t = \frac{L_S}{A}\int_{X_2}^{X_1}\frac{dX}{R}$$

- R is linear in X

R=aX+b and dR=adX

$$t = \frac{L_S}{aA}\int_{R2}^{R1}\frac{dR}{R} = \frac{L_S}{aA}\ln\frac{R_1}{R_2}$$

$$a = slope = \frac{R_1 - R_2}{X_1 - X_2}$$

- R is linear through origin

R=aX and dR=adX

$$a = slope = \frac{R_C}{X_C}$$

$$t = \frac{L_S X_C}{AR_C}\ln\frac{R_C}{R_2}$$

$$t = \frac{L_S X_C}{AR_C}\ln\frac{X_C}{X_2}$$

Tutorial

Q5 A solid whose drying curve is represented in slide #19 is to be dried from a free moisture content X_1 = 0.38 kg H_2O/kg dry solid to X_2 = 0.25 kg H_2O/kg dry solid. Estimate the time required.

Q6 A batch of wet solid whose graphical drying-rate curve is represented in slide #19 is to be dried from a free moisture content of X_1 = 0.38 kg H_2O/kg dry solid to X_2 = 0.04 kg H_2O/kg dry solid. The weight of the dry solid is L_S = 399 kg dry solid and A = 18.58 m^2 of top drying surface. Calculate the time for drying.

Q7 A wet solid is to be dried in a tray dryer under steady-state conditions from a free moisture content of $X_1 = 0.40$ kg H_2O/kg dry solid to $X_2 = 0.02$ kg H_2O/kg dry solid. The dry solid weight is 99.8 kg dry solid and the top surface area for drying is 4.645 m^2. The drying-rate curve can be represented by figure shown in slide #19.

a) Calculate the time for drying using graphical integration in the falling-rate period.

b) Repeat but use a straight line through the origin for the drying rate in the falling-rate period.