

Drying

Lecture 2

Fundamentals

We are interested in being able to measure and calculate:

Water content of material being dried

Rate of drying

Time of drying (the time it takes to dry something)

How moisture content varies inside something being dried

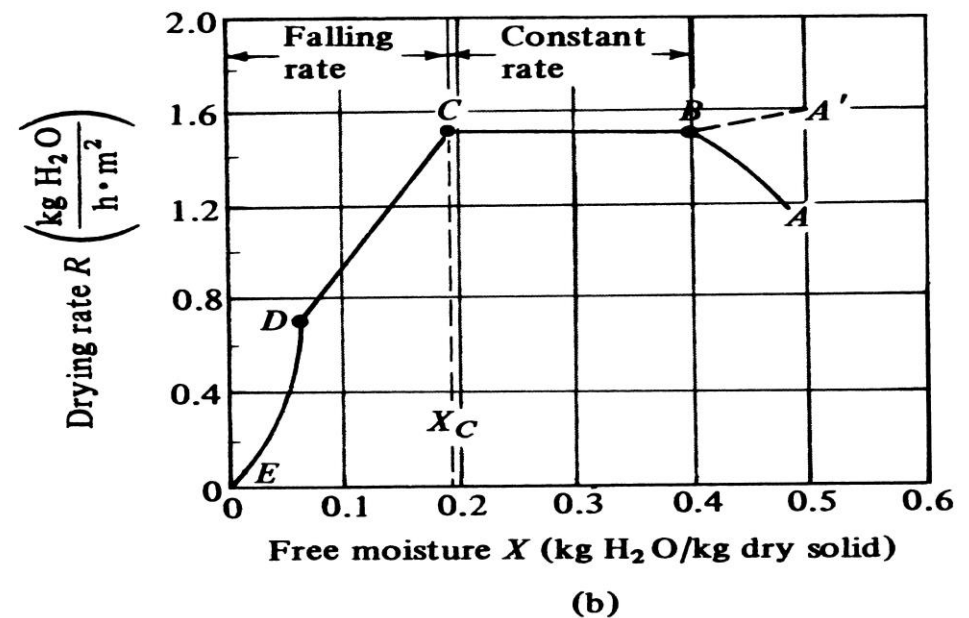
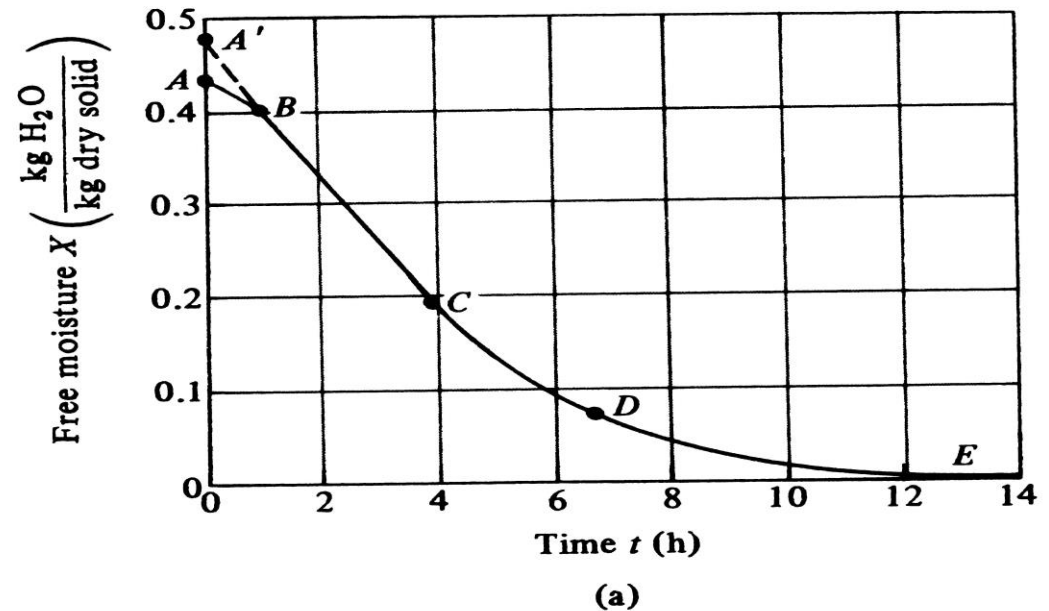
Solids and Air flowrates in drying equipment

Temperatures and Humidities

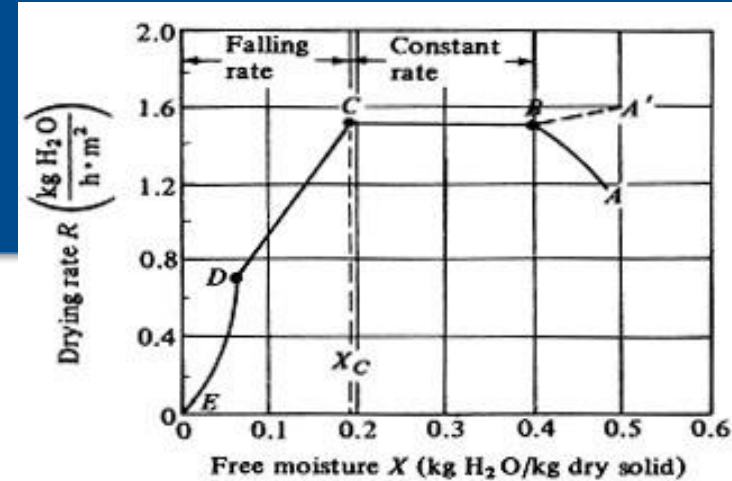
Stages of drying

- Three regimes
 - Heating up
 - Constant rate
 - Falling rate

Geankoplis uses the symbol X for free moisture content
In these notes, we use X_{free}

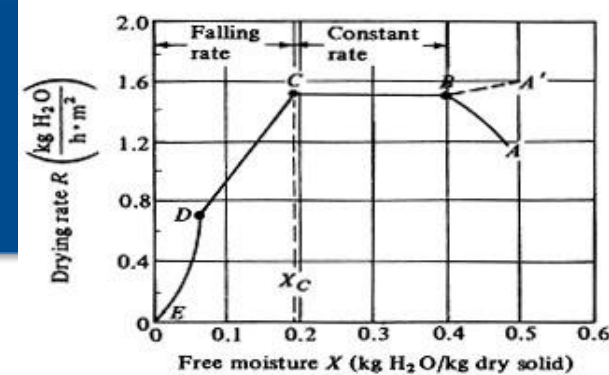


Recap: Constant rate period



- Steady state
- Saturated surface \rightarrow constant temperature θ_{surface}
- Heat transfer to surface = heat removal by evaporation.
- Rate of evaporation (R_c) is constant
- Rate controlled by external factors (air temperature, air flow rate)
- Removal of unbound water
- Period ends when X_c reached, when rate of water movement to surface $<$ rate water is evaporated
- X_c dependent on material, obtained experimentally

Recap: Falling rate period

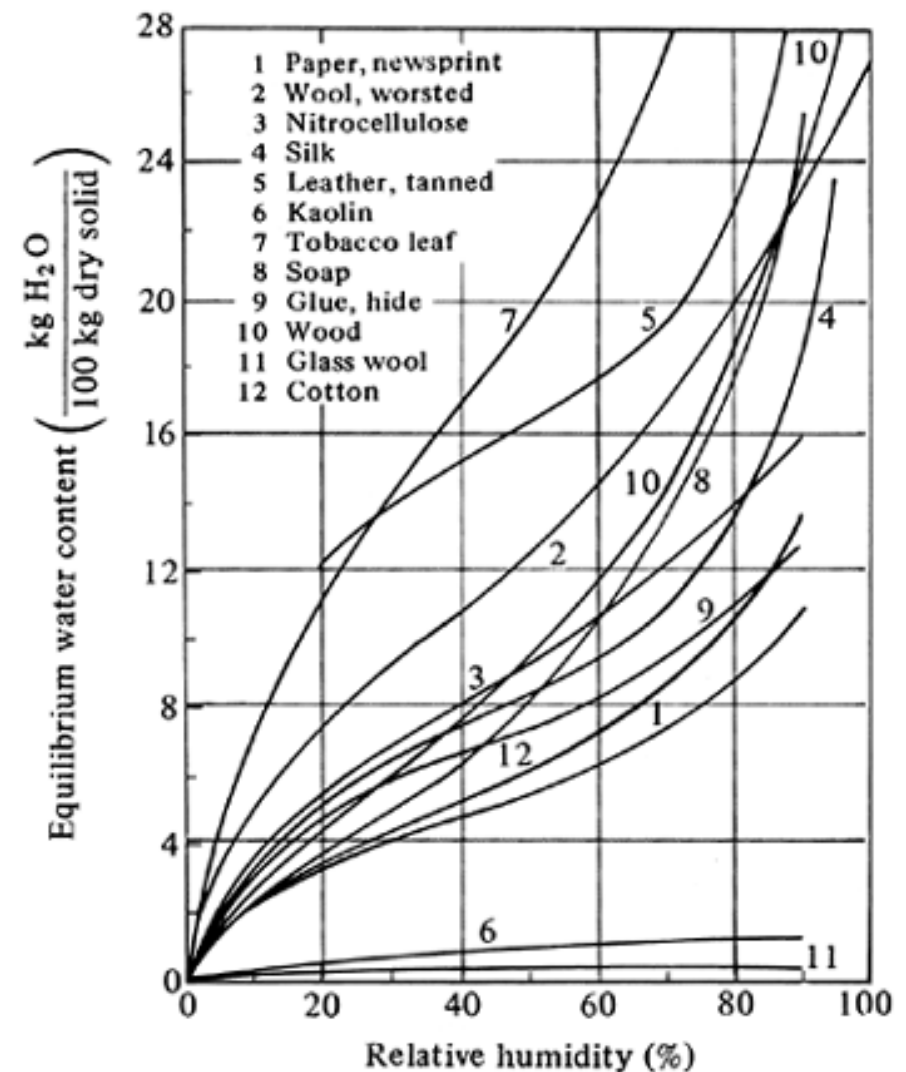


Moisture no longer can be drawn out from the centre of the particle \neq evaporation rate

- Rate of evaporation reduces.
- Dynamic equilibrium is broken
- Surface begins to dry out and particle heats up
- Maximum temperature reached when
 - particle has lost all its available moisture
 - θ approaches that of the θ_{air} .
- Drying stops when $X_{\text{product}} \approx X_{\text{air}}$.
- Corresponding to equilibrium moisture content at dryer conditions for that material

Equilibrium moisture content X^*

- Residual moisture content at equilibrium (X^* kg/kg)
- Function of the air conditions and attraction of moisture to solid.
- X^* is where $a_w = RH$ and is determined by the moisture desorption isotherm

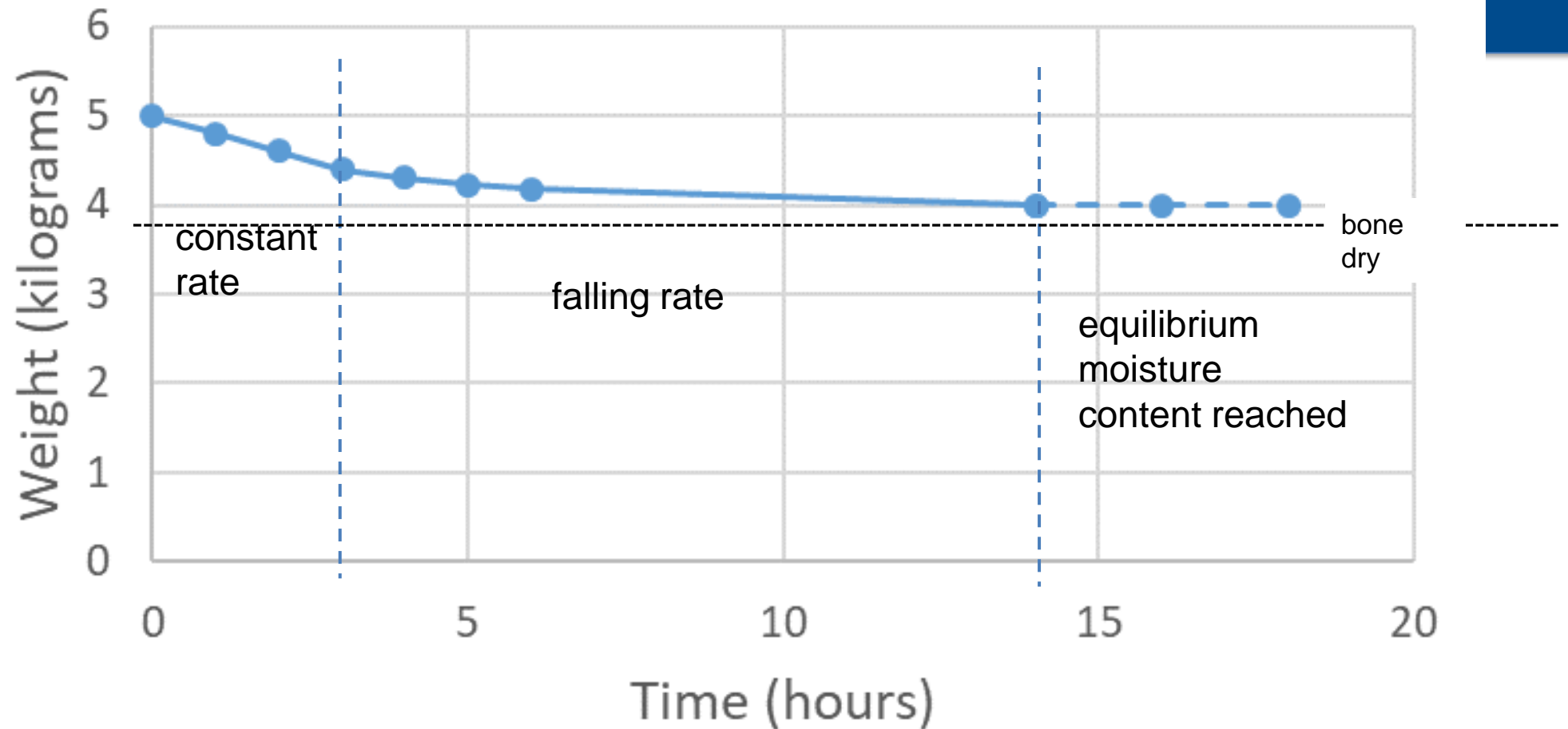


X^* & free moisture content

- X^* is best determined by experiment.
- To artificially ensure that the final moisture content is zero we can use the “**free moisture content**” which is the actual moisture content less the equilibrium moisture content
- Free moisture content

$$X_{\text{free}} = X - X^*$$

Drying of rice



- Drying can take a long time
- After a heating up period, the rate of weight loss is constant Constant rate period
- Then the rate of weight loss decreases Falling rate period
(Two regimes: capillary and diffusion)
- Finally, there is no further weight loss Equilibrium moisture content reached

Example to find X^* and X_{free}

The following data was obtained for drying rice grains in a tray dryer.
The dry solid weight of rice grains was determined to be 3.8 kg.

Time (h)	Weight (kg)
0	5.0
1	4.8
2	4.6
3	4.4
6	4.2
9	4.1
14	4.0

After 14 hours drying the weight of the rice grains does not change.

What is the equilibrium moisture content (X^* kg/kg) of the rice grains?

$X^* = ?$

Example to find X^* and X_{free}

The following data was obtained for drying rice grains in a tray dryer.
The dry solid weight of rice grains was determined to be 3.8 kg.

Knowing X^* calculate the free moisture content at each time step

Time (h)	Weight (kg)	X_{free} (kg/kg)
0	5.0	
1	4.8	
2	4.6	
3	4.4	
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9	4.1	
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$$X_{\text{free}} = X - X^*$$

Example to find X^* and X_{free}

The following data was obtained for drying rice grains in a tray dryer.
The dry solid weight of rice grains was determined to be 3.8 kg.

Calculate the drying rate R ($\text{kg m}^{-2} \text{h}^{-1}$), knowing the tray area is 0.5 m^2

Time (h)	Weight (kg)	X_{free} (kg/kg)	R ($\text{kg m}^{-2} \text{h}^{-1}$)
0	5.0	0.26	
1	4.8	0.21	
2	4.6	0.16	
3	4.4	0.11	
6	4.2	0.05	
9	4.1	0.03	
14	4.0	0.00	

$$R = \frac{m_v}{A}$$

$$R = -\frac{L_s}{A} \frac{\Delta X}{\Delta t}$$

m_v evaporation rate kg.s^{-1} (or w kg.s^{-1})

A area (m^2)

L_s mass bone dry solid (kg s^{-1})

R drying rate ($\text{kg s}^{-1} \text{m}^{-2}$)

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14	4.0	0.00	

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

$$R = \frac{3.8}{0.5} \frac{(0.26-0.16)}{(0-2)} = 0.40 \text{ kg m}^{-2} \text{h}^{-1}$$

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14	4.0	0.00	

$$R = \frac{m_v}{A}$$

$$R = \frac{1}{0.5} \frac{(5.0-4.6)}{(2-0)} = 0.40 \text{ kg m}^{-2} \text{h}^{-1}$$

Example to find X^* and X_{free}

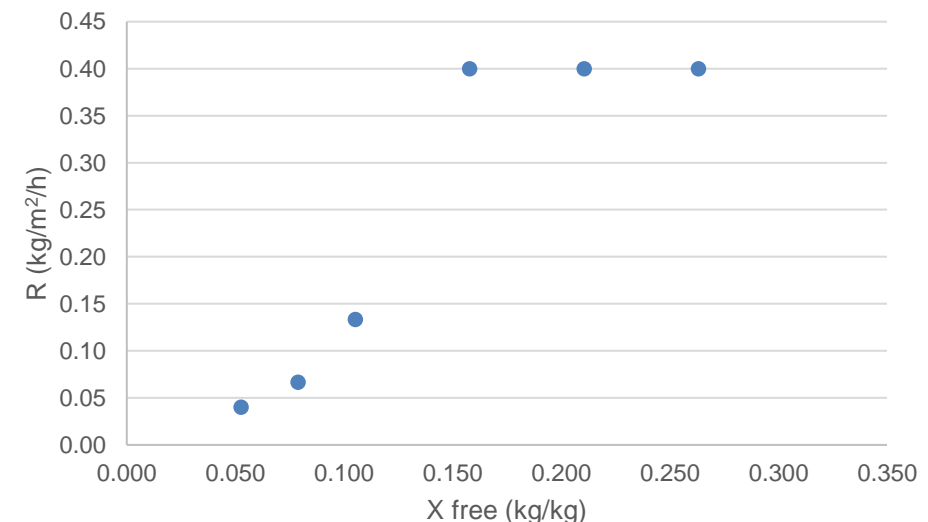
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Calculate the drying rate R ($\text{kg m}^{-2} \text{h}^{-1}$), knowing the tray area is 0.5 m^2

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2	4.6	0.16	0.4
3	4.4	0.11	0.4
6	4.2	0.05	0.13
9	4.1	0.03	0.07
14	4.0	0.00	0.04

$$R = \frac{m_v}{A}$$

$$R = \frac{1}{0.5} \frac{(5.0 - 4.6)}{(2 - 0)} = 0.40 \text{ kg m}^{-2} \text{h}^{-1}$$



Mass Transfer in Falling Rate Drying

Two modes of water removal are possible in the falling rate period.

- Capillary Diffusion

Notes (Geankoplis (1993)).

Constant rate period: “Drying of different solids under different constant conditions of drying will often give curves of different shapes in the falling rate period. But in general, the two major portions of the drying-rate curve are present, the constant-rate period and the falling-rate period.

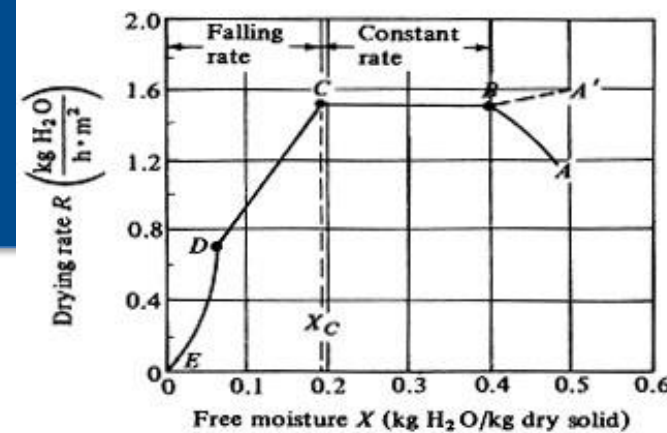
In the constant rate period, the surface of the solid is initially very wet, and a continuous film of water exists on the drying surface. This water acts as if the solid were not present. The rate of evaporation under given conditions is independent of the solid and is essentially the same as the rate from a free liquid surface.

If the solid is porous, most of the water evaporated in the constant rate period is supplied from the interior of the solid. This period only continues as long as the water is supplied to the surface as fast as it is evaporated. In the absence of heat transfer by radiation or conduction, the surface temperature is approximately that of the wet bulb temperature.”

Falling rate period: “After the critical moisture content, X_c is reached (point C) there is insufficient water on the surface to maintain a continuous film. The entire surface is no longer wetted, and the wetted area continually decreases until it is completely dry (point D). When the surface is completely dry, the plane of evaporation recedes from the surface.

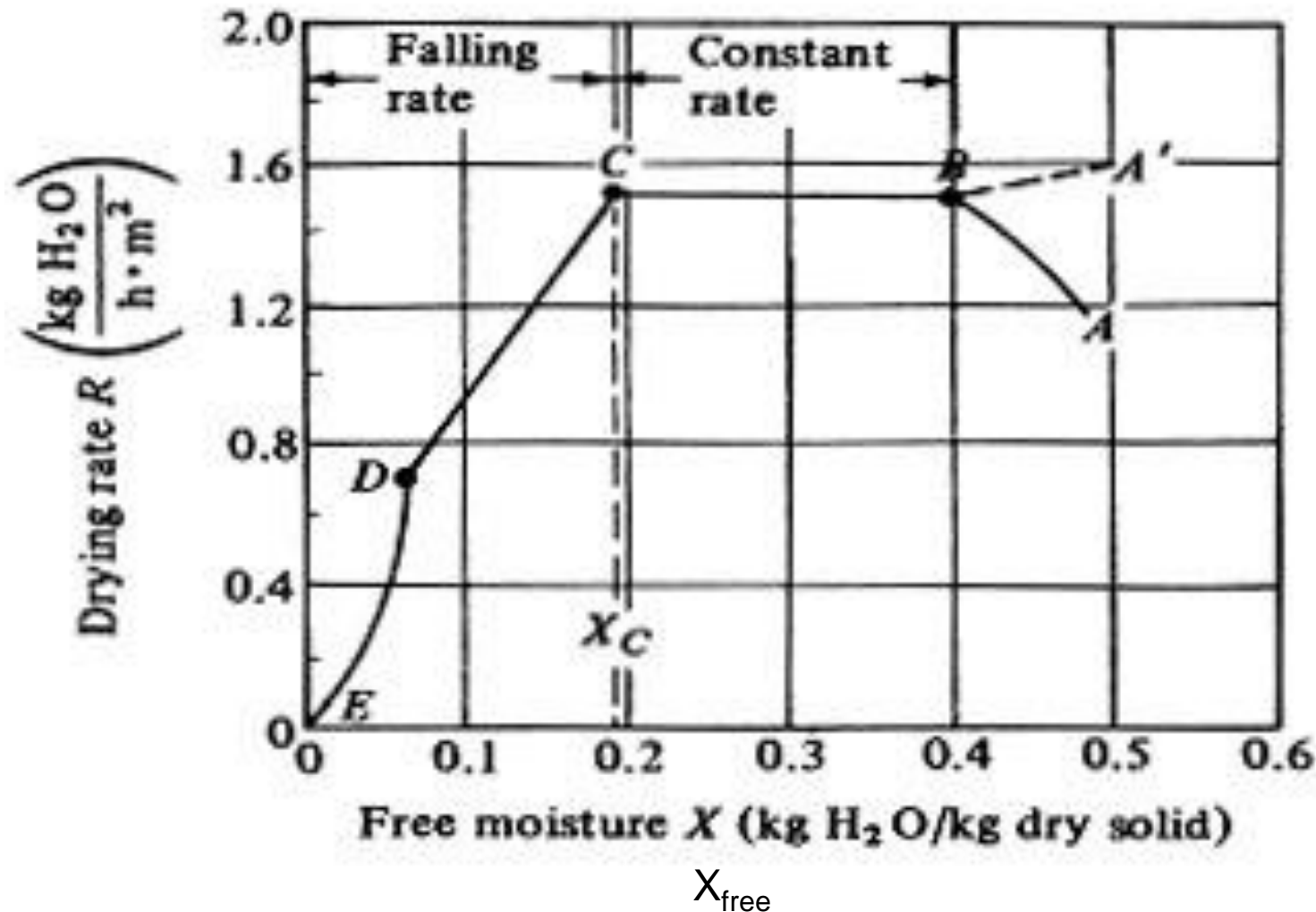
In capillary-type drying, the mechanism is the same as in the constant-rate period; the effects of gas velocity, temperature and humidity will be the same as in the constant rate period. The rate of drying varies linearly with X^* .

In diffusion-type drying, the resistance to mass transfer of water vapour from the surface is usually very small, and the diffusion in the solid controls the rate of drying; the moisture content at the surface is at the equilibrium value, X^* .



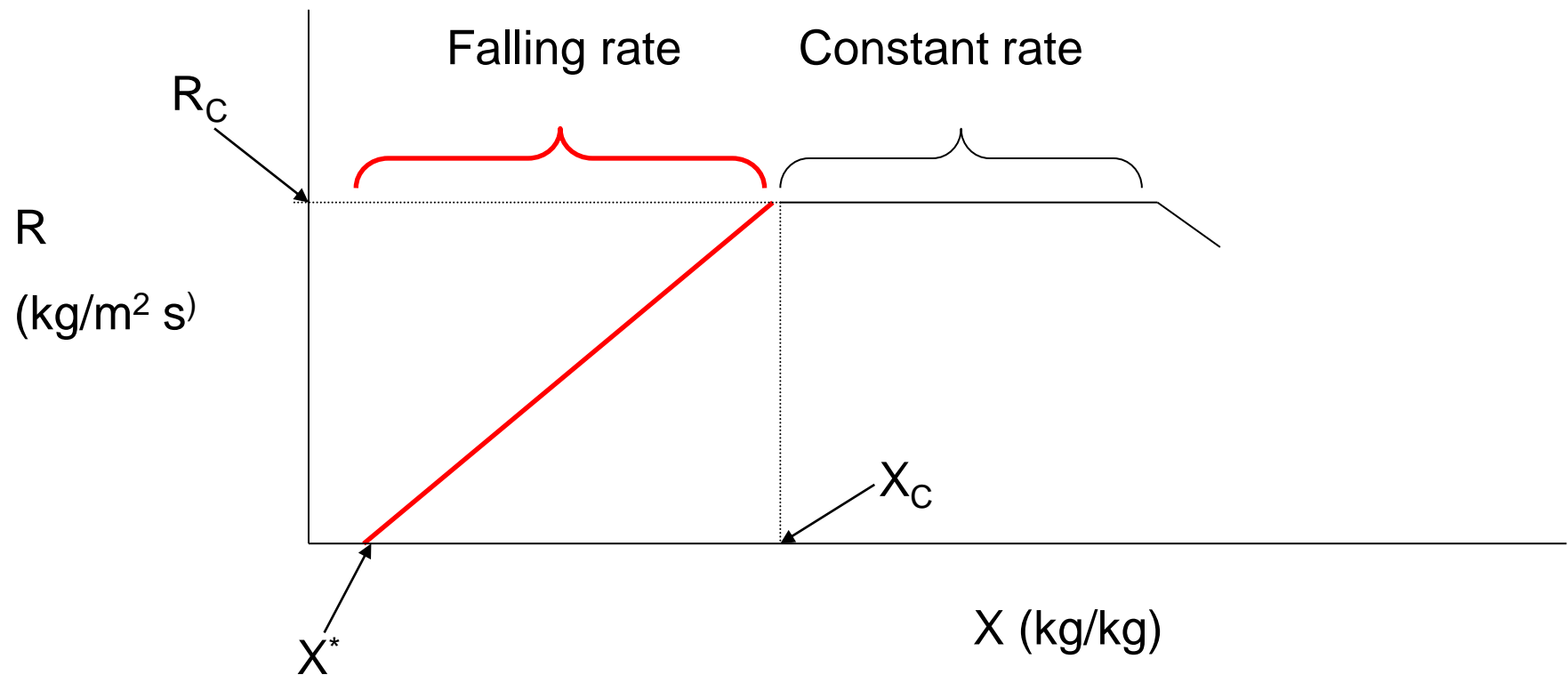
Drying in the Falling Rate Period

- C-D capillary action
- D-E Diffusion



Capillary action – Falling rate period

$$\text{slope} = \frac{\Delta y}{\Delta x} = \frac{(R_c - 0)}{(X_c - X^*)} = \frac{(R - 0)}{(X - X^*)} \qquad R = R_c \frac{(X - X^*)}{(X_c - X^*)}$$



Capillary flow

- Rate falls linearly with moisture content.
- The rate of drying (R) at a given moisture content (X) is located on the straight line connecting $(X^*, 0)$ and (X_c, R_c) .

$$R = R_c \frac{X - X^*}{X_c - X^*}$$

- Empirical approach
- Integration of drying rate equation over the drying period gives an equation for the drying time.

Capillary flow - equations

$$R = R_c \frac{(X - X^*)}{(X_c - X^*)}$$

$$R_c = \frac{w}{A} = s\rho_s \frac{dX}{dt}$$

m_v	evaporation rate kg.s^{-1} (or $w \text{ kg.s}^{-1}$)
A	area (m^2)
L_s	mass bone dry solid (kg s^{-1})
R	drying rate ($\text{kg s}^{-1} \text{ m}^{-2}$)
R_c	drying rate in constant rate regime
s	slab thickness (m)
r	radius of sphere (m)
ρ_s	density of dry solid ($\text{kg s}^{-1} \text{ m}^{-2}$)
t_d	drying time (s)

$$t_d = \frac{s\rho_s(X_c - X^*)}{R_c} \ln \left[\frac{(X_1 - X^*)}{(X_2 - X^*)} \right]$$

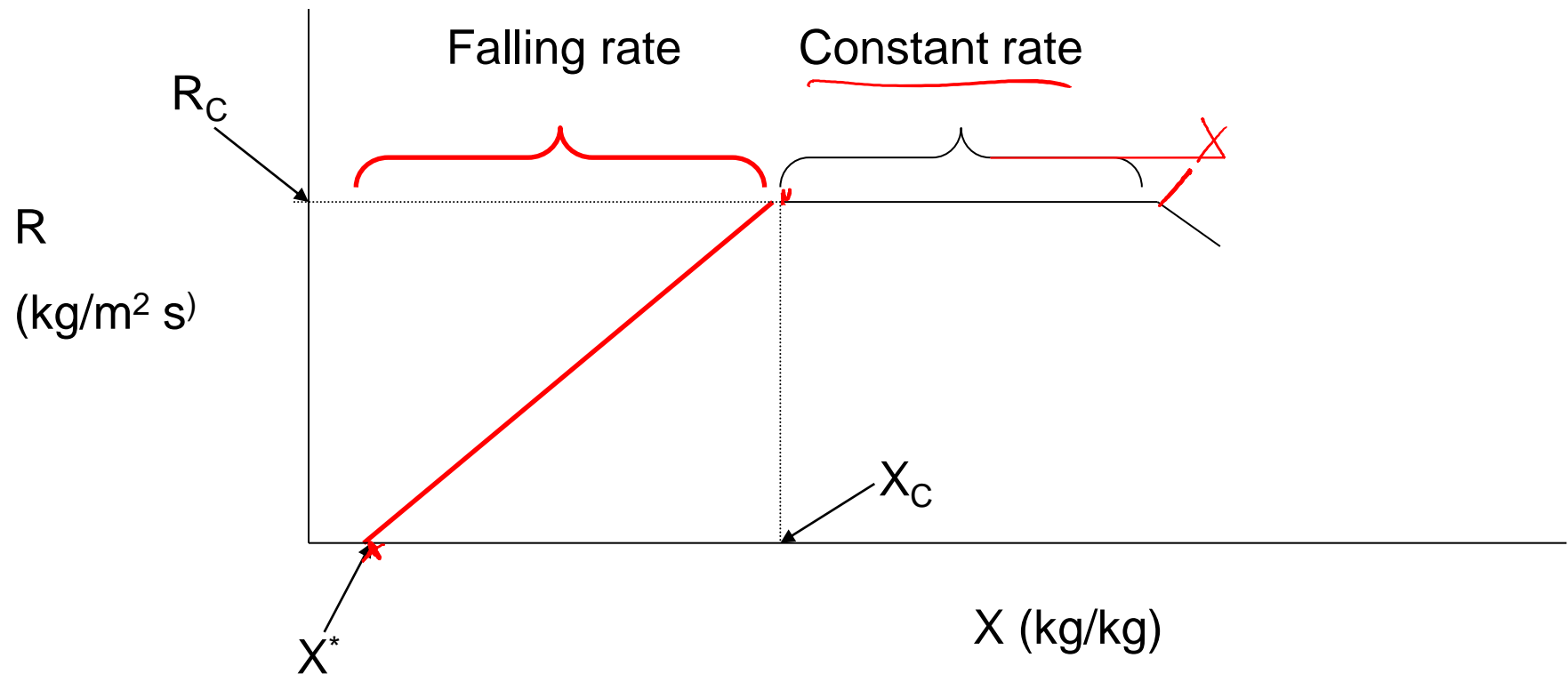
Drying time for capillary action in falling rate period

For a slab

$$t_d = \frac{s\rho_s(X_c - X^*)}{R_c} \ln \left[\frac{(X_1 - X^*)}{(X_2 - X^*)} \right]$$

For a sphere

$$t_d = \frac{r\rho_s(X_c - X^*)}{3R_c} \ln \left[\frac{(X_1 - X^*)}{(X_2 - X^*)} \right]$$



Drying in the Falling Rate Period

- C-D capillary action
- D-E Diffusion

