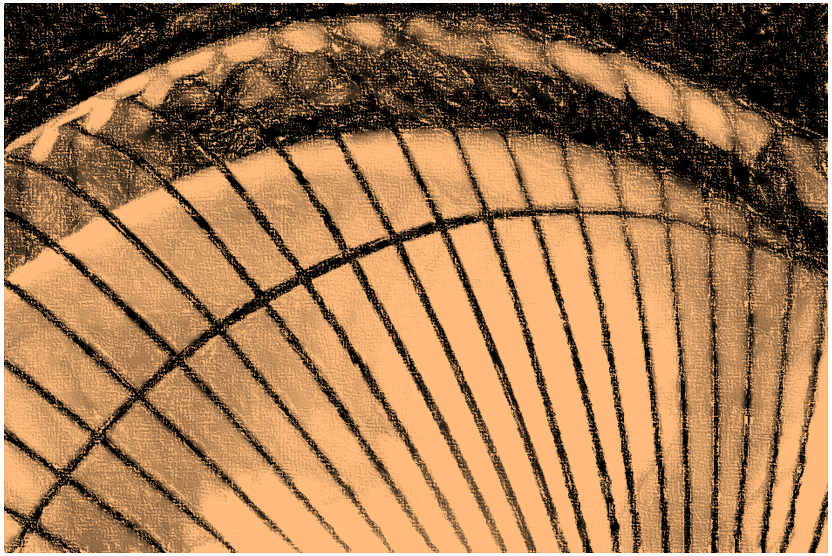


Drying Process

Separation Processes

Chemical and Biological Engineering

Engenharia Química e Biológica (EQB)

Dimensioning of a drying operation

☞ **Complex process!**

It depends on:

- the shape and size of the material to be dried;

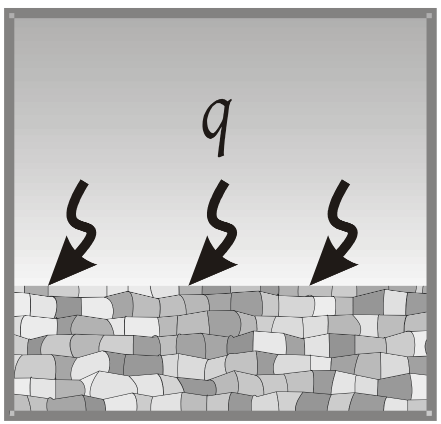
- the mechanism of moisture flow through the material;

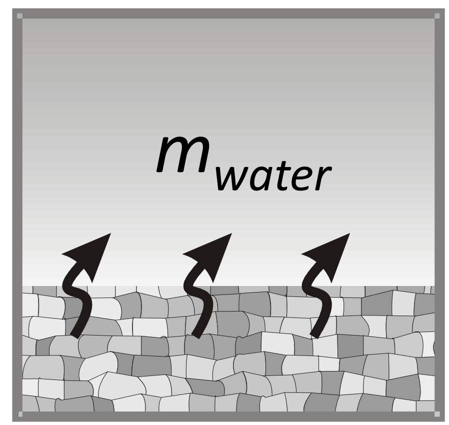
- the method of heat supply

There are basically two processes in the drying of a solid:

1) Heat transfer from the gas phase to the solid to evaporate surface moisture and corresponding mass transport (water) from the surface of the solid to the gas phase (<u>EXTERNAL DRYING MECHANISM</u>)

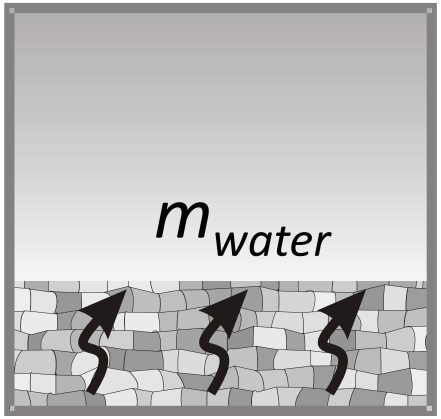
psychrometric chart!
carta psicrométrica!





<u>Convection</u> transport of moisture from the surface of the solid to the gas phase

2) Transfer of internal mass (moisture) to the surface of the solid and its evaporation to the gas phase (INTERNAL DRYING MECHANISM)



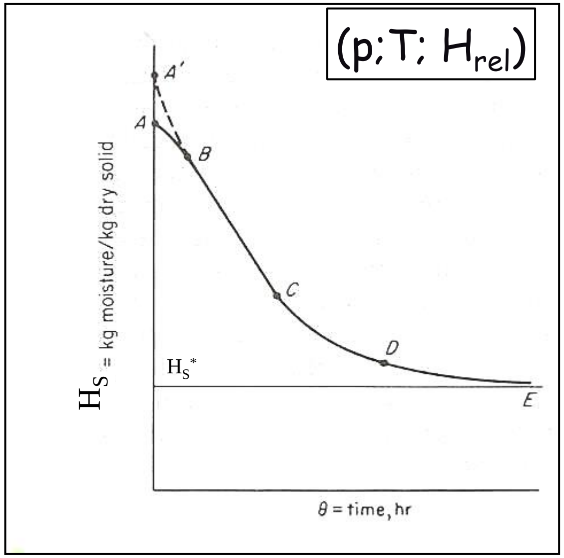
Internal diffusion of moisture from the solid to the surface

Migration of moisture from the interior to the surface of the solid: mechanisms by diffusion, capillarity, internal pressure gradients due to solid shrinkage.

Drying curve of a solid

It describes the behavior of a solid in the drying process in contact with a gas at a given temperature and humidity.

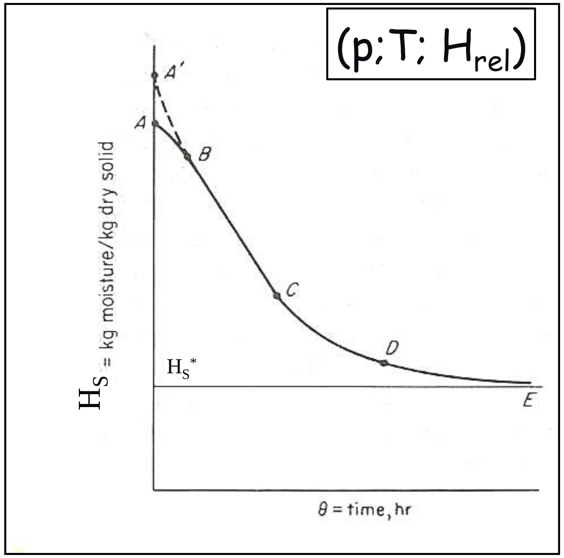
Drying curve of a solid



← **Solid moisture** vs Drying time

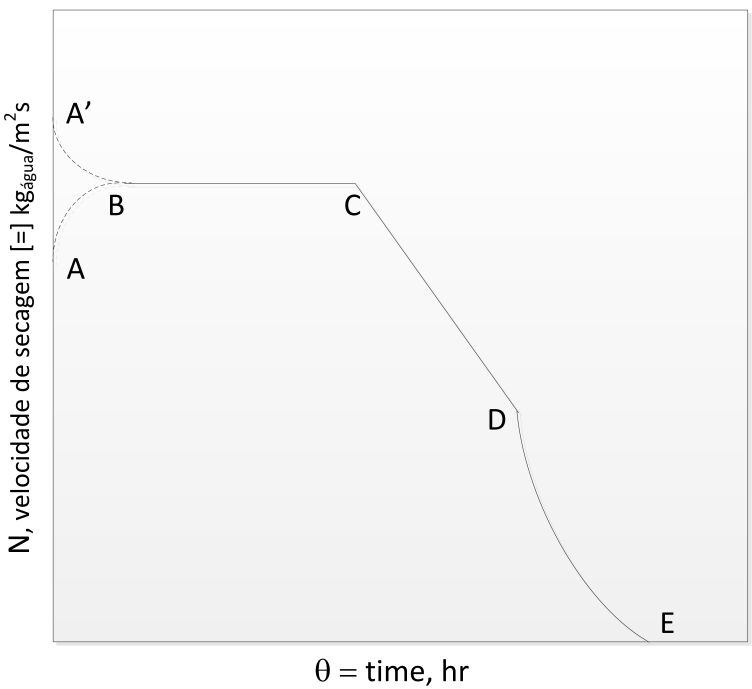
H_s* vs *t

Drying curve of a solid



← **Solid moisture** vs Drying time

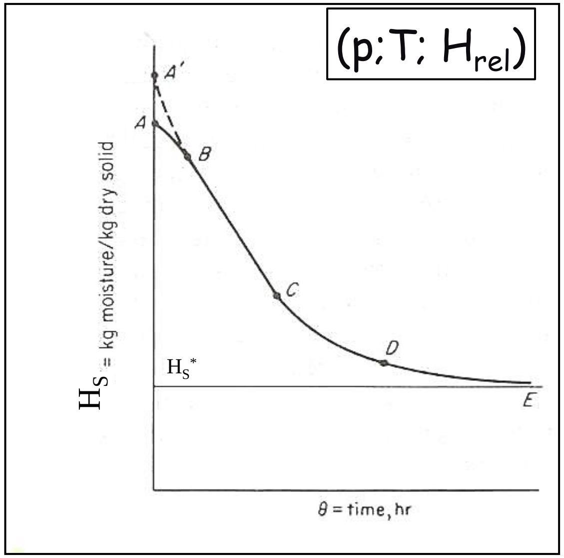
H_s vs t



← **Drying velocity, N,** vs drying time, t

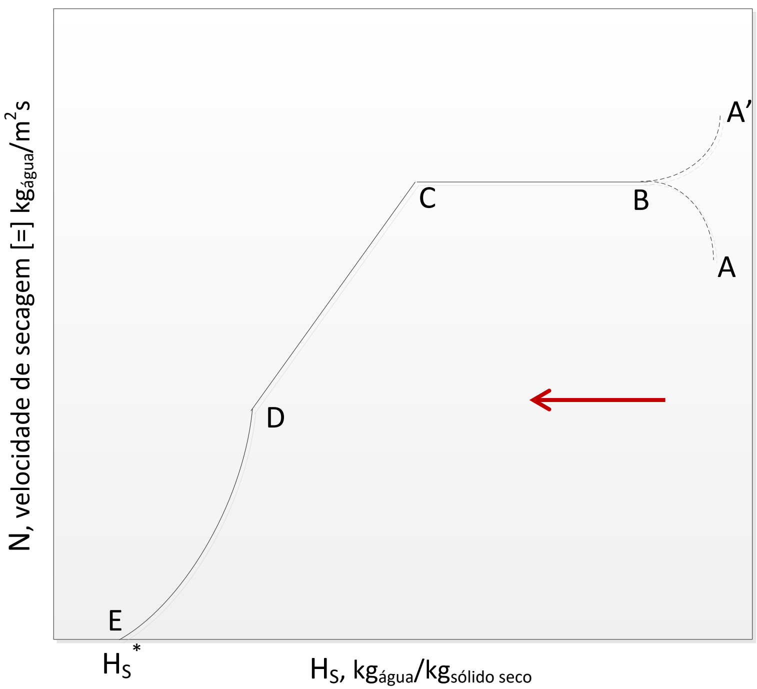
$$N \;[=]\; \frac{\text{evaporated humidity mass}}{\text{area . time}} \;[=]\; kg\ m^{-2}\ s^{-1}$$

Drying curve of a solid



← **Solid moisture** vs Drying time

H_s* vs *t

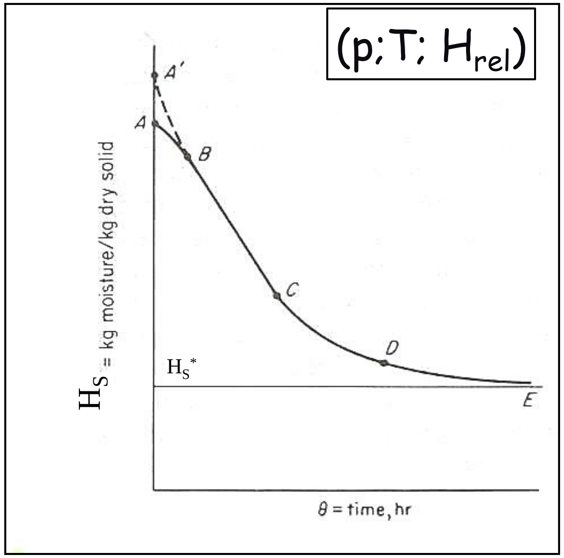


← **Drying velocity, N,** vs **Solid moisture, *H_s***

$$N\ [=]\ \frac{\text{evaporated humidity mass}}{\text{area . time}}\ [=]\ kg\ m^{-2}\ s^{-1}$$

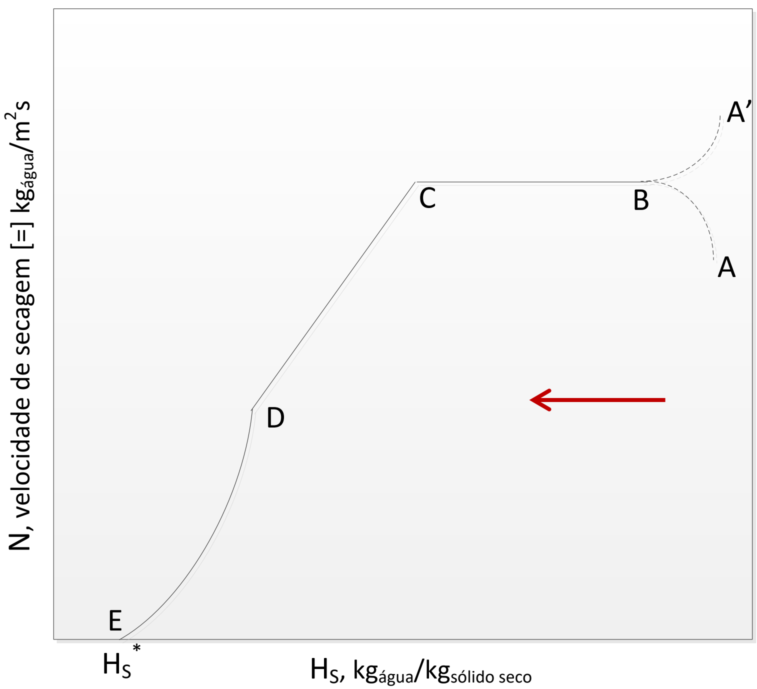
How to determine ***N*** ?

Drying curve of a solid



← **Solid moisture** vs Drying time

H_s* vs *t



← **Drying velocity, N,** vs **Solid moisture, *H_s***

☞ Derivative of the previous curve:

H_s vs t

$$N = -\frac{M_S}{A}\left(\frac{dH_S}{dt}\right)$$

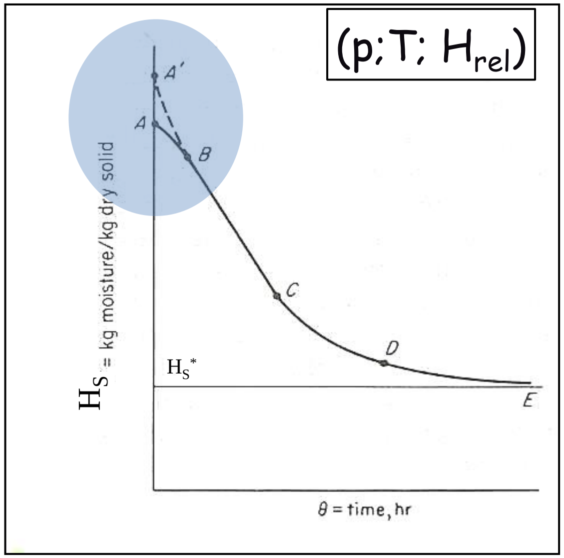
N [=] evaporated humidity mass / (area × time)

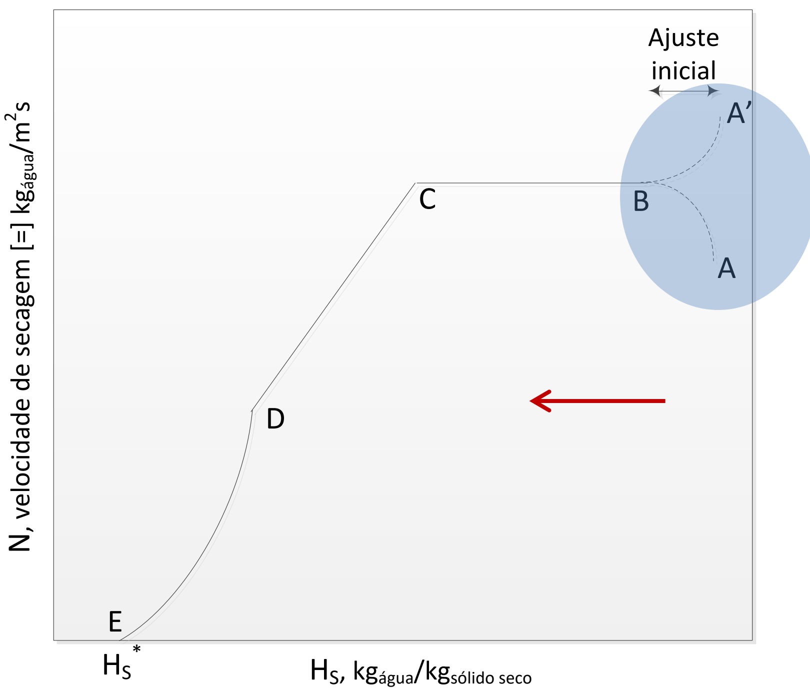
A [=] drying surface area

M_S [=] mass of dry solid

H_s [=] humidity mass / dry solid mass

Stages of the drying process

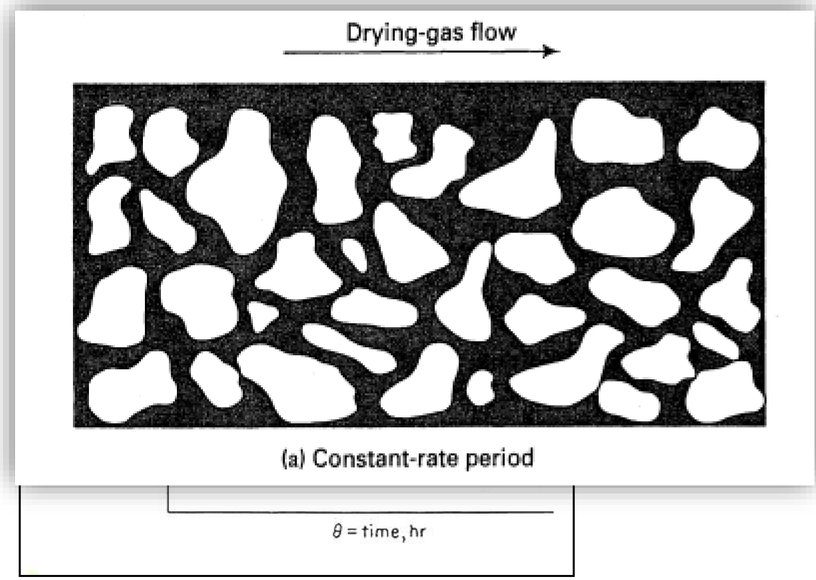




A-B: Initial adjustment period

☞ Thermal equilibrium at the surface of the solid

Stages of the drying process

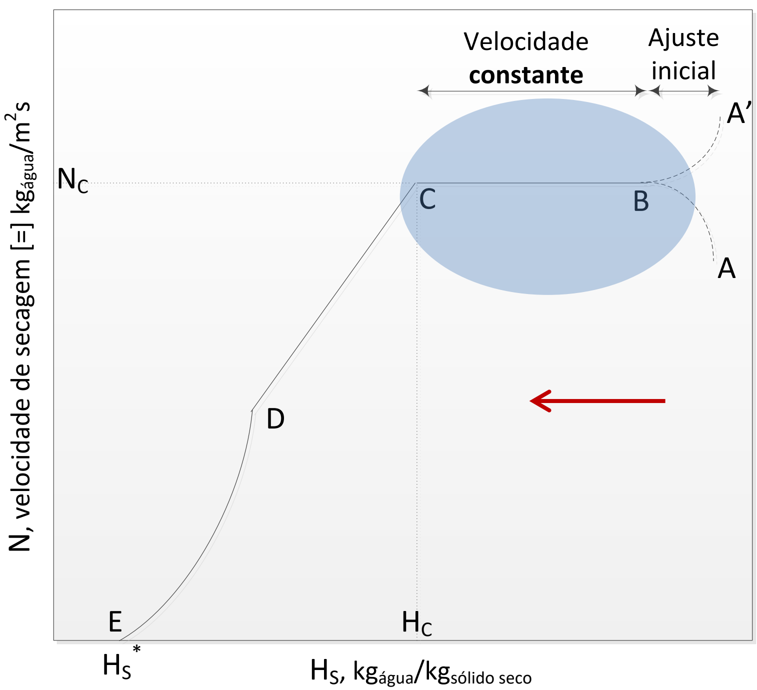


A-B: Initial adjustment period

☞ Thermal equilibrium at the surface of the solid

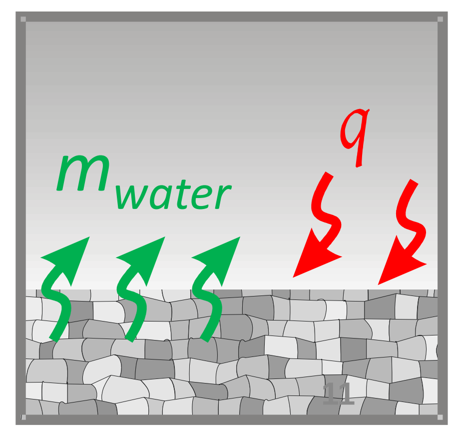
B-C: Constant velocity period

☞ The transport velocity of the water inside the solid is equal to the evaporation velocity at the surface of the solid (kinetic control by convection)



Evaporated liquid is mostly from the surface of the solid.

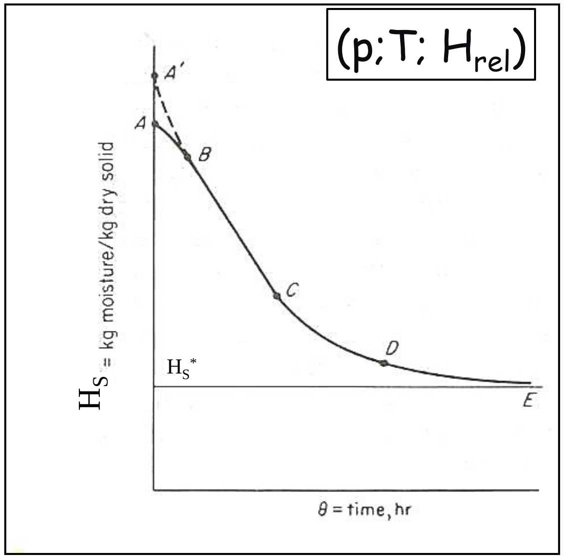
=> $T_{surface}$ in the solid $\simeq t_h$ of the gas

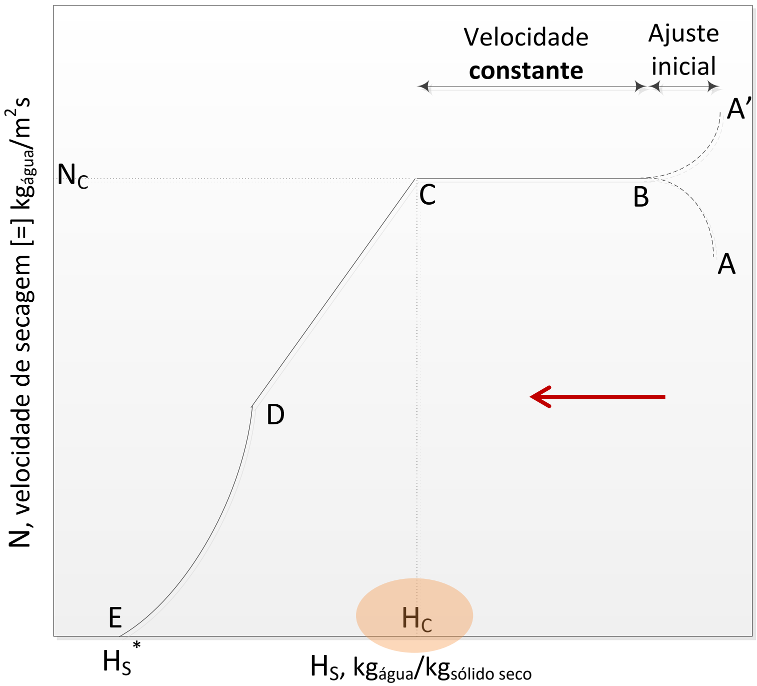


Critical Humidity, H_c

- Moisture content at the end of the drying period at constant velocity

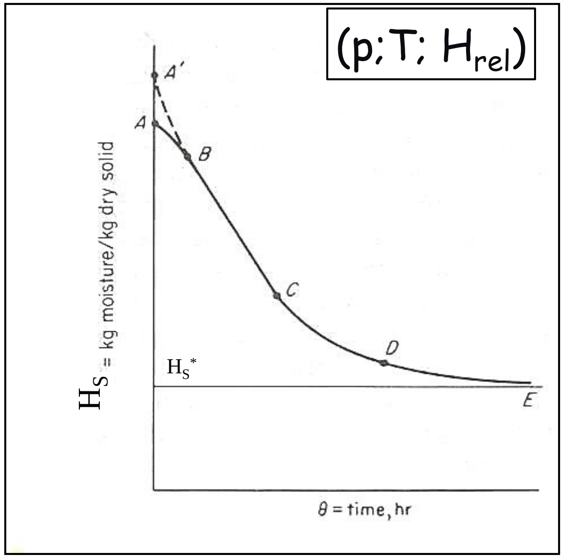
It depends on the mechanism of movement of moisture within the solid, the porous structure of the solid and the drying velocity (i.e. air passage flow).





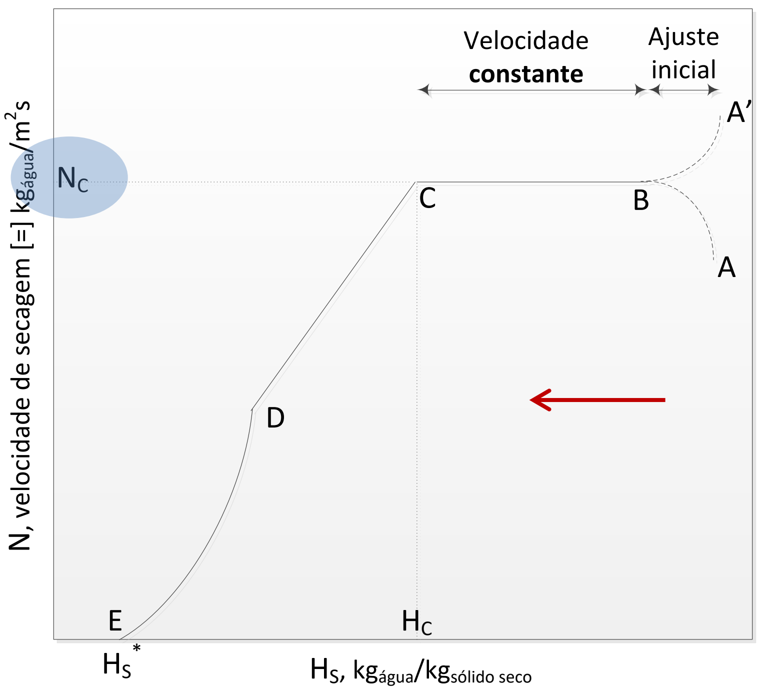
Constant drying speed, N_c

- Drying speed of the solid in the constant period



How to estimate N_c ?

All the heat that reaches the surface is used to evaporate water

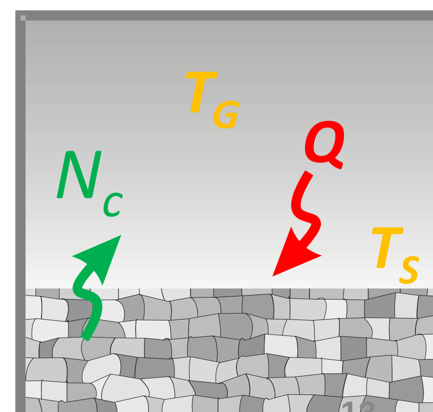


=> $\boxed{Q = h_G(T_G - T_{\mathbf{surface}}) = N_C \lambda_{vap}}$

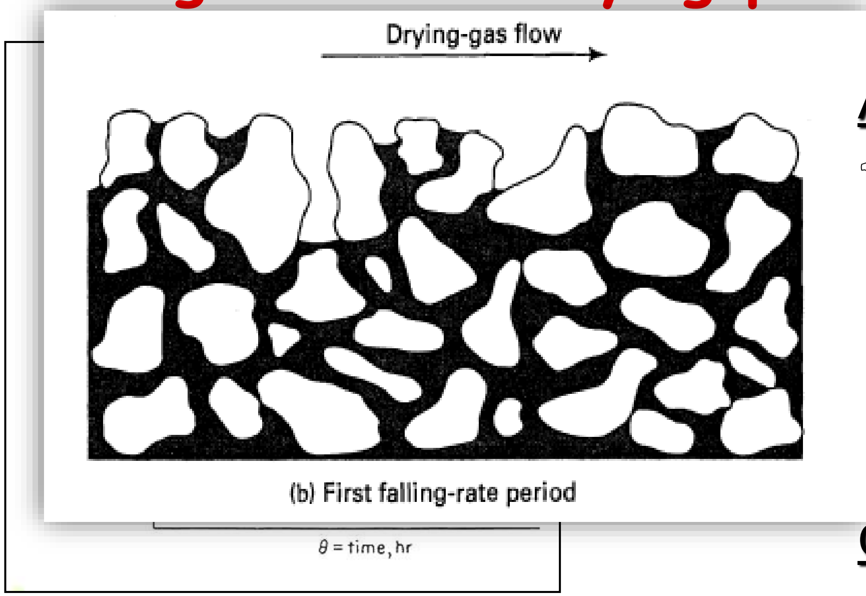
h_G: heat transfer coefficient by convection

λ_{vap}: latent heat of water vaporization

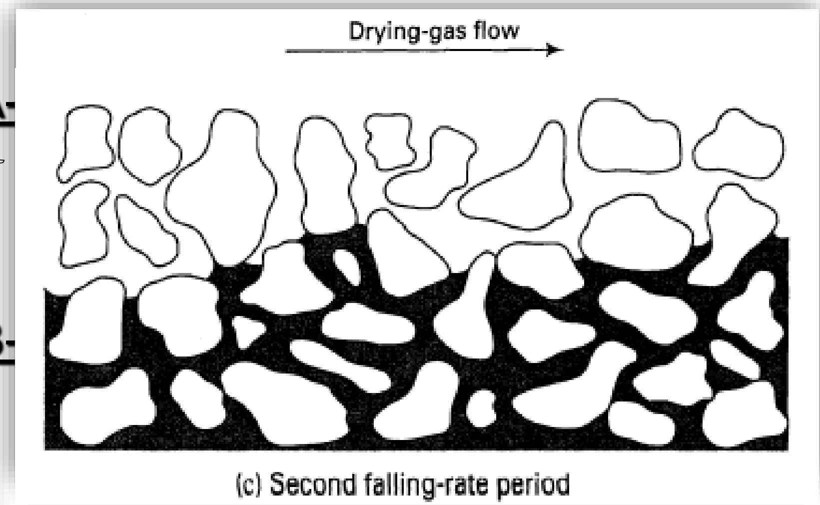
$T_{surface} \cong t_h$



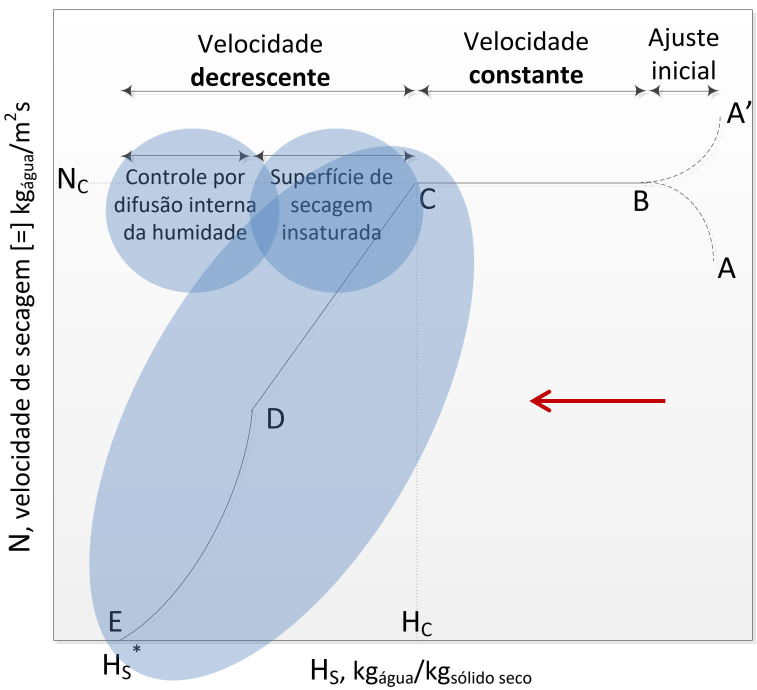
Stages of the drying process



(b) First falling-rate period



(c) Second falling-rate period



C-E: Period of decreasing velocity

☞ $H_S < H_C$ => **N decreases** (existence of dry spots on the surface)

☞ Velocity of transfer of water to the surface is lower than the rate of evaporation (diffusional control).

☞ No water at the surface; keeping the heat supplied constant, $T_{surface}$ reaches T_{air}.

Estimate the drying time of a given solid

Why?

✷ Plan the drying process

✷ Determine the capacity of the dryer

How?

→ Experimental testing

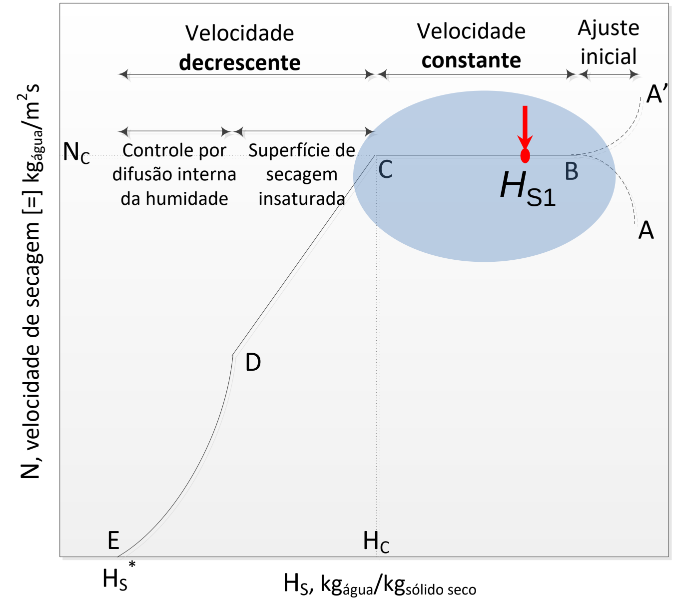
=> drying velocity curve (estimative)

❑ Period of constant drying velocity, N_C

N_C – drying velocity in the constant period

H_C – critical humidity

H_{S1} – solid initial humidity

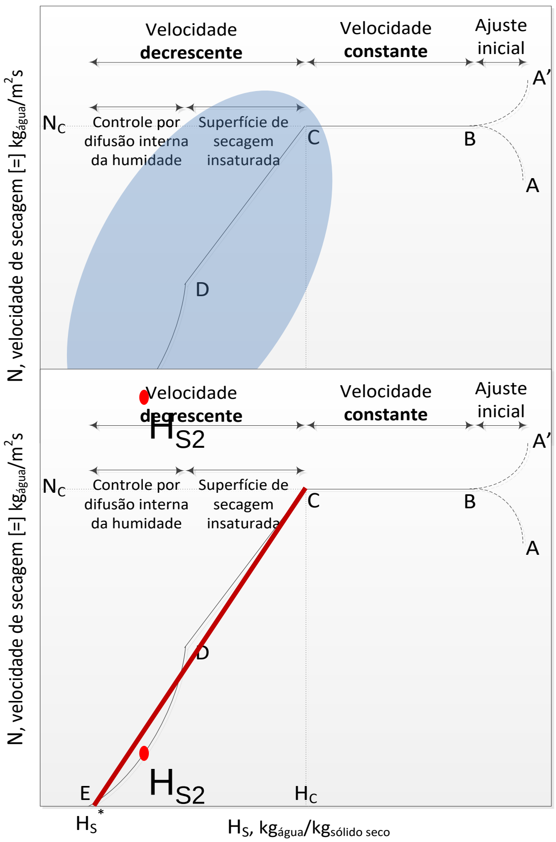


$$N = -\frac{M_S}{A}\left(\frac{dH_S}{dt}\right)$$

$$\int_0^t dt = -\frac{M_S}{A}\int_{H_{S1}}^{H_C}\frac{dH_S}{N_C}$$

$$\Rightarrow \quad t = -\frac{M_S}{A}\frac{(H_C - H_{S1})}{N_C}$$

❑ Period of decreasing drying velocity



General case

Graphic resolution of the integral:

$$t = -\frac{M_S}{A}\int_{H_C}^{H_{S2}}\frac{dH_S}{N}$$

Special case (approximation)

Single descending period (segment **CE** is a straight line)

$(N = a + b\,H_S)$

$$N = \frac{N_C}{H_C - H_S^*}(H_S - H_S^*)$$ **?**

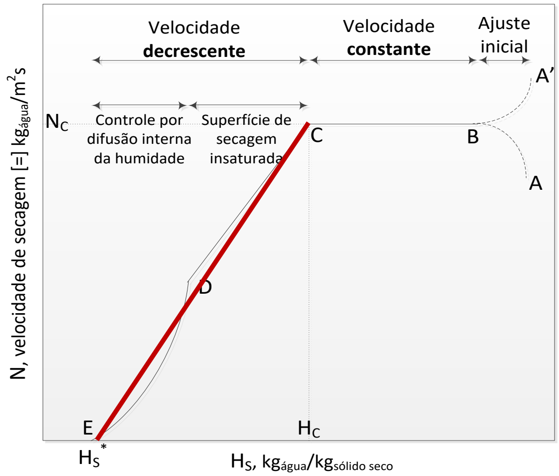
=> $$t = -\frac{M_S(H_C - H_S^*)}{N_C A}\ln\frac{H_{S2} - H_S^*}{H_C - H_S^*}$$

N_C – drying velocity in the constant period
H_C – critical humidity
H_{S2} – final humidity of the solid

❑ Period of decreasing drying velocity

Special case (approximation)

Single descending period (segment **CE** is a straight line)



$$N = a + bH_S$$

$$H_S = H_C \quad => \quad N_C = a + bH_C$$

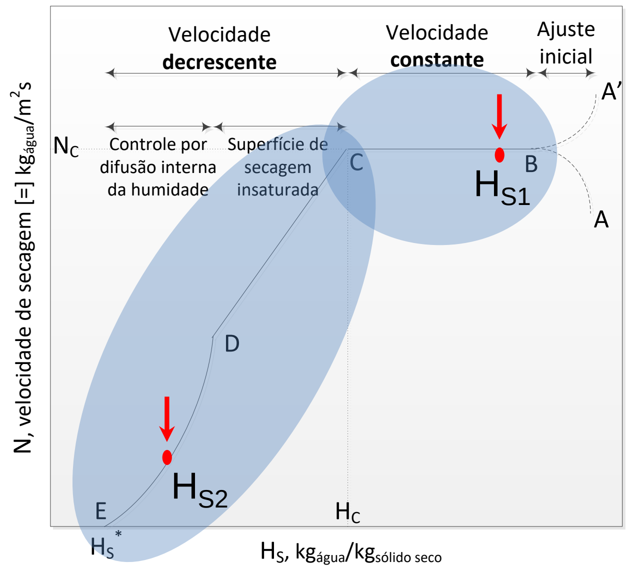
$$H_S = H_S^* \quad => \quad 0 = a + bH_S^*$$

$$=> \quad a = -bH_S^*$$

$$b = \frac{N_C}{H_C - H_S^*}$$

$$=> \quad \boxed{N = \frac{N_C}{H_C - H_S^*}(H_S - H_S^*)}$$

$$t_{\text{total drying}} = t_{\text{constant veloc}} + t_{\text{decreasing veloc}}$$



$$t_{\text{constant veloc}} = -\frac{M_S}{A}\frac{(H_C - H_{S1})}{N_C}$$

$$t_{\text{decreasing veloc}} = -\frac{M_S(H_C - H_S^*)}{N_C A}\ln\frac{H_{S2} - H_S^*}{H_C - H_S^*}$$

A – drying surface area
M_s – mass of dry solid
N_C – drying velocity in the constant period
H_C – critical humidity
H_{S1} – solid initial humidity
H_{S2} – solid final humidity

Problem

A **tray dryer** is used to dry raw cotton with 0.7 g/cm^3 of density when dried. It is intended to obtain a product with 0.1 g water/g dry cotton, starting from an initial humidity of 1 g water/g dry cotton.

The trays have dimensions of 60 × 60 cm. The material to be dried is arranged in the trays with a thickness of 1 cm. The trays are arranged in such a way that drying takes place only from the upper surface, the lower surface being insulated.

The drying air enters at 75ºC, and its humid thermometer temperature is 50ºC. The air flow through the surface of the dryer is 2500 kg/h/m^2.

Previous experiments under the same conditions have shown that critical humidity (H_c) is 0.4 g water/g dry solid, and that the drying velocity during the "Falling rate period" is proportional to the moisture of the mixture. Calculate the time it takes to get the desired moisture.

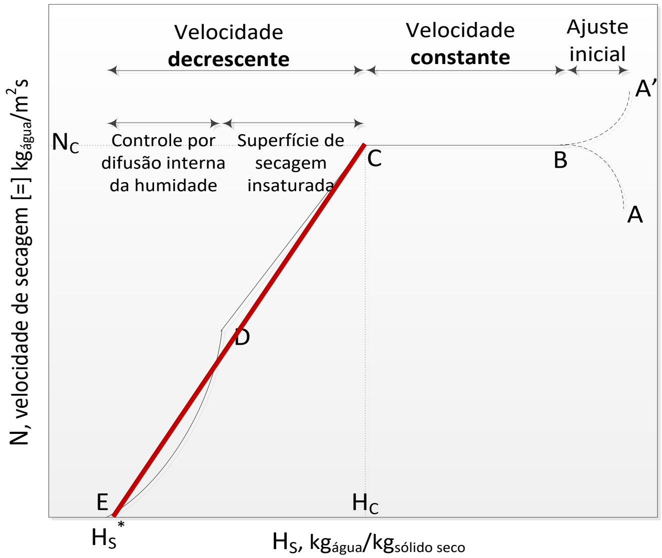
Data:

Equilibrium humidity (H_s*): 0.031

Water vaporization enthalpy (λ_{vap}): 2.383×10^3 kJ/kg

$h_G = 14.3\ G^{0.8}$ (airflow parallel to flat surfaces)

being h_G [=] W m^{-2} K^{-1}; G [=] kg m^{-2} s^{-1}



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- ***M_S* – mass of dry solids**

$$M_S = (60\ \text{cm} \times 60\ \text{cm} \times 1\ \text{cm}) \times 0.7\frac{\text{g}}{\text{cm}^3} \times n\ \text{trays} = 2.52n\ \ \text{kg}_{\text{dry solid}}$$

- ***A* – drying surface area**

$$A = (0.60\ \text{m} \times 0.60\ \text{m}) \times n\ \text{trays} = 0.36n\ \ \text{m}^2$$

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H_s^*: 0.031
λ_{vap}: 2.383×10^3 kJ/kg

- **N_C – drying velocity in constant period**

$$\boxed{h_G = 14.3\, G^{0.8}}$$

h_G [=] W m^{-2} K^{-1} $\quad$ G [=] kg m^{-2} s^{-1}

$$\boxed{Q = h_G\,(T_G - T_{\text{superf}}) = N_C\,\lambda_{vap}}$$

$$h_G = 14.3 G^{0.8} = 14.3 \times \left(\frac{2500 \text{kg h}^{-1}\,\text{m}^{-2}}{3600\ \text{s h}^{-1}}\right)^{0.8} = 10.7\ \text{W m}^{-2}\text{K}^{-1}$$

$$\Rightarrow N_C = \frac{10.7}{2.383\times10^6}(75-50) = 1.12\times10^{-4}\ \text{kg s}^{-1}\,\text{m}^{-2} = 0.402\ \text{kg h}^{-1}\,\text{m}^{-2}$$

A tray dryer is used to dry raw cotton with 0.7 g/cm^3 of density when dried. It is intended to obtain a product with 0.1 g water/g dry cotton, starting from an **initial humidity of 1 g water/g dry cotton**.

The trays have dimensions of 60 × 60 cm. The material to be dried is arranged in the trays with a thickness of 1 cm. The trays are arranged in such a way that drying takes place only from the upper surface, the lower surface being insulated.

<u>The drying air enters at 75ºC, and its humid thermometer temperature is 50ºC. The air flow through the surface of the dryer is 2500 kg/h/m^2.</u>

Previous experiments under the same conditions have shown that **critical humidity (H_c) is 0.4 g water/g dry solid**, and that the drying velocity during the "Falling rate period" is proportional to the moisture of the mixture. Calculate the time it takes to get the desired moisture.

H_s^*: 0.031

$N_c = 0.402$ kg h^{-1} m^{-2}

$M_s = 2.52n$ kg$_{\text{dry solid}}$

$A = 0.36n$ m^2

❑ Period of constant drying velocity N_C

$$\boxed{t_{\text{period 1}} = -\frac{M_S}{A}\frac{(H_C - H_{S1})}{N_C}}$$

$$\boxed{t_{\text{period 1}} = -\frac{2.52n}{0.36n}\frac{(0.4-1)}{0.402} = 10.5\ \text{h}}$$

A tray dryer is used to dry raw cotton with 0.7 g/cm^3 of density when dried. It is intended to obtain a **product with 0.1 g water/g dry cotton**, starting from an **initial humidity of 1 g water/g dry cotton**.

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H_s^*: 0.031

$N_c = 0.402$ kg h^{-1} m^{-2}

$M_s = 2.52n$ kg$_{\text{dry solid}}$

$A = 0.36n$ m^2

❑ Period of decreasing drying velocity N_C

$$\boxed{t_{\text{period 2}} = -\frac{M_S(H_C - H_S^*)}{N_C A} \ln \frac{H_{S2} - H_S^*}{H_C - H_S^*}}$$

$$t_{\text{period 2}} = -\frac{2.52n(0.4 - 0.031)}{0.36n \times 0.402} \ln \frac{0.1 - 0.031}{0.4 - 0.031} = 10.8 \text{ h}$$

$$\therefore \quad t_{\text{total}} = 10.5 + 10.8 = 21.3 \text{ h}$$

Drying with air

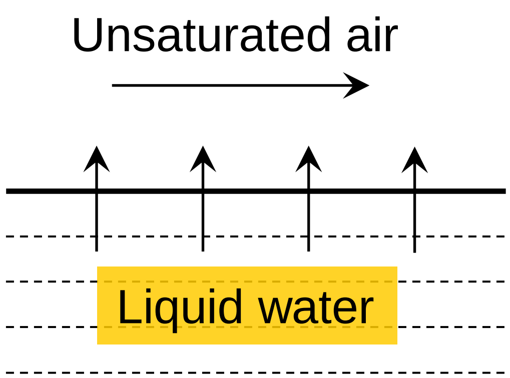
$h_G = 14.3\ G^{0.8}$ (airflow parallel to flat surfaces)

$h_G = 24.2\ G^{0.37}$ (airflow perpendicular to the surface)

$$\left\{ \begin{array}{l} h_G\ [=]\ \mathrm{W\ m^{-2}\ K^{-1}} \\ G\ [=]\ \mathrm{kg\ m^{-2}\ s^{-1}} \end{array} \right.$$

Wet thermometer temperature, T_h

It is the temperature reached at equilibrium by a small amount of liquid water evaporating into a large amount of unsaturated air.



∴ At the limit, thermal equilibrium is reached at the interface.

Liquid Temperature

≡

Gas temperature at the interface

☞ **Wet thermometer temperature**

(At the interface, the air is saturated to temperature T_h)

Wet thermometer temperature ≡ temperature reached by the liquid and gas at the interface, when in thermal equilibrium.

<u>heat supplied by the gas,</u> Q_1 ⇔ <u>heat of vaporization of the liquid,</u> Q_2

$$\boxed{Q_1 = h_G A\left(T_G - T_{superf}\right)} \quad \Leftrightarrow \quad \boxed{Q_2 = A N_C \lambda_{vap}}$$

$$\boxed{Q = h_G(T_G - T_{\text{superf}}) = N_C\, \lambda_{vap}}$$