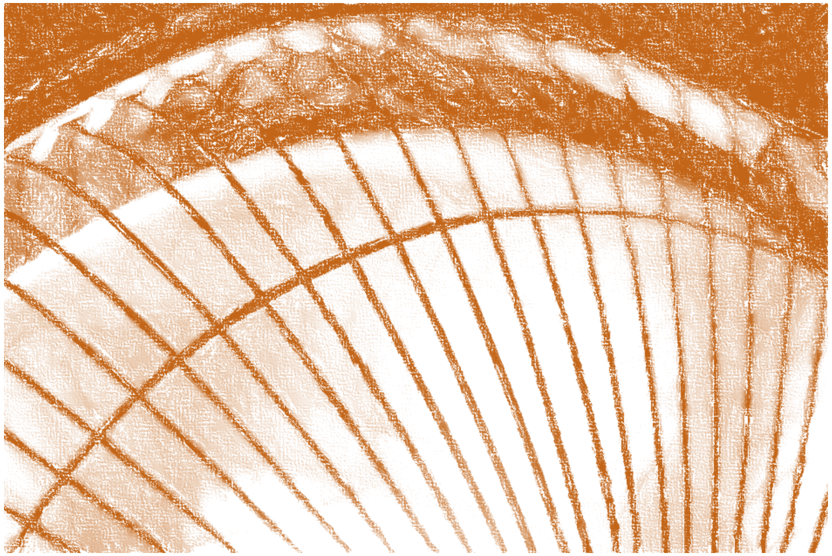


Drying Process

Separation Processes

Chemical and Biological Engineering

Engenharia Química e Biológica (EQB)

Removal of moisture from a substance (solid or liquid) by evaporation in a gaseous stream

Typically: "Humidity"≡ Water "Gas" ≡ Air

Objectives:

- Achieve a certain final quality of the solid product
- Facilitate the handling of the solids (when dry)
- Improve the conservation and storage of solids (when dry)
- Reduce the cost of transporting solids

Examples:

- Drying of solids by evaporation of moisture in a hot gas stream

- Drying of liquid solutions by spraying in drops in a stream of dry and hot gas

Essential operation in the chemical, food, pharmaceutical, ceramics, agricultural, polymer, biotechnology, pulp and wood industries

Usually, it constitutes the **final step** of the manufacturing process

But not always!

Complex Operation

Process highly dependent on experimentation

(laboratory and/or pilot scale)

It involves:

- Heat and mass transport, in a **<u>transient state</u>**
- Kinetic processes associated with the physical transformation of the solid (shrinkage; crystallization, glass transition; modification of color, texture, odor...)

Operation is strongly intensive from an energy point of view

- High (water) vaporization enthalpies (~103 kJ/kg)!
- Air is inefficient as an extraction solvent and thermal fluid...

- 12 – 25% of industrial energy consumption in developed countries!
- Average energy efficiency of industrial dryers ≈ 50%!
- Operating costs (energy) >> Capital costs (equipment)

NOMENCLATURE

- <u>Solid</u>

H_s – solid humidity/moisture

(i) humid basis: $\dfrac{m_{\text{humidity}}}{m_{\text{dry solid}} + m_{\text{humidity}}}$

(ii) dry basis: $\dfrac{m_{\text{humidity}}}{m_{\text{dry solid}}}$

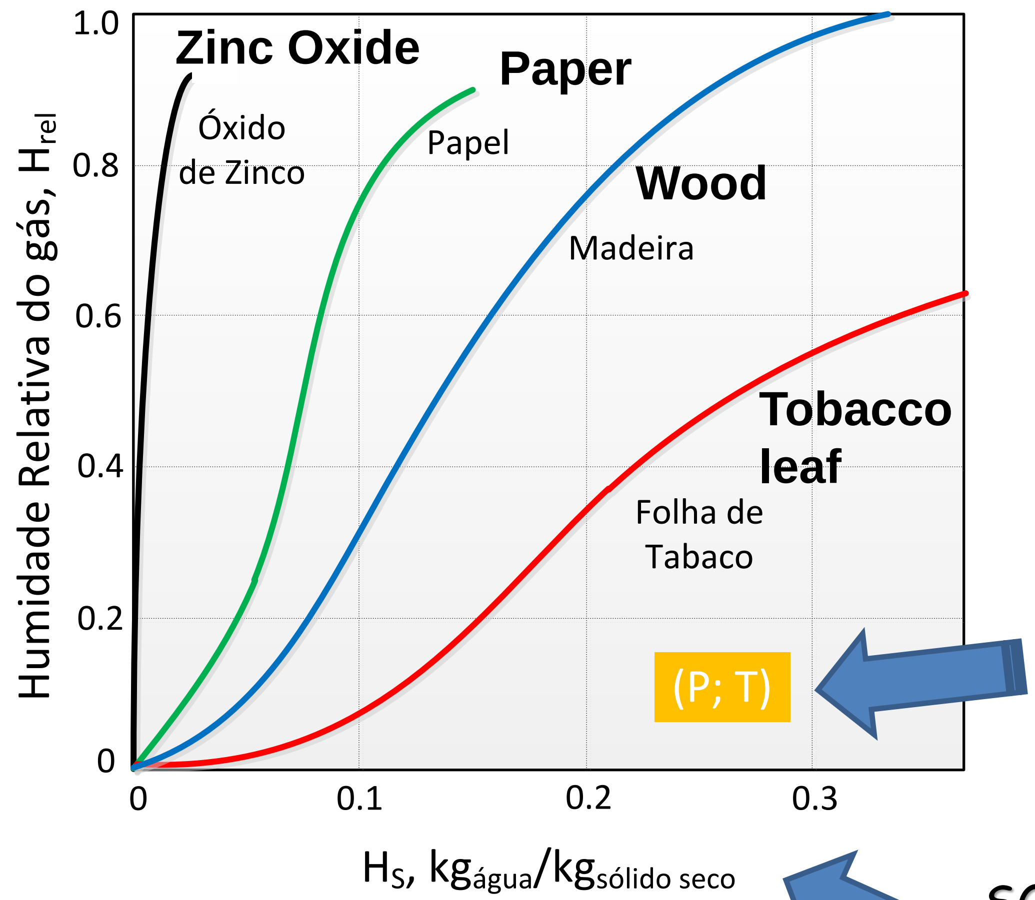
- <u>Gas</u>

H'_G, H_{rel}, $\%H'$ – Absolute humidity, Relative humidity or % of Humidity in gas stream

Equilibrium moisture curves

Curvas de humidade de equilíbrio

GAS Humidity

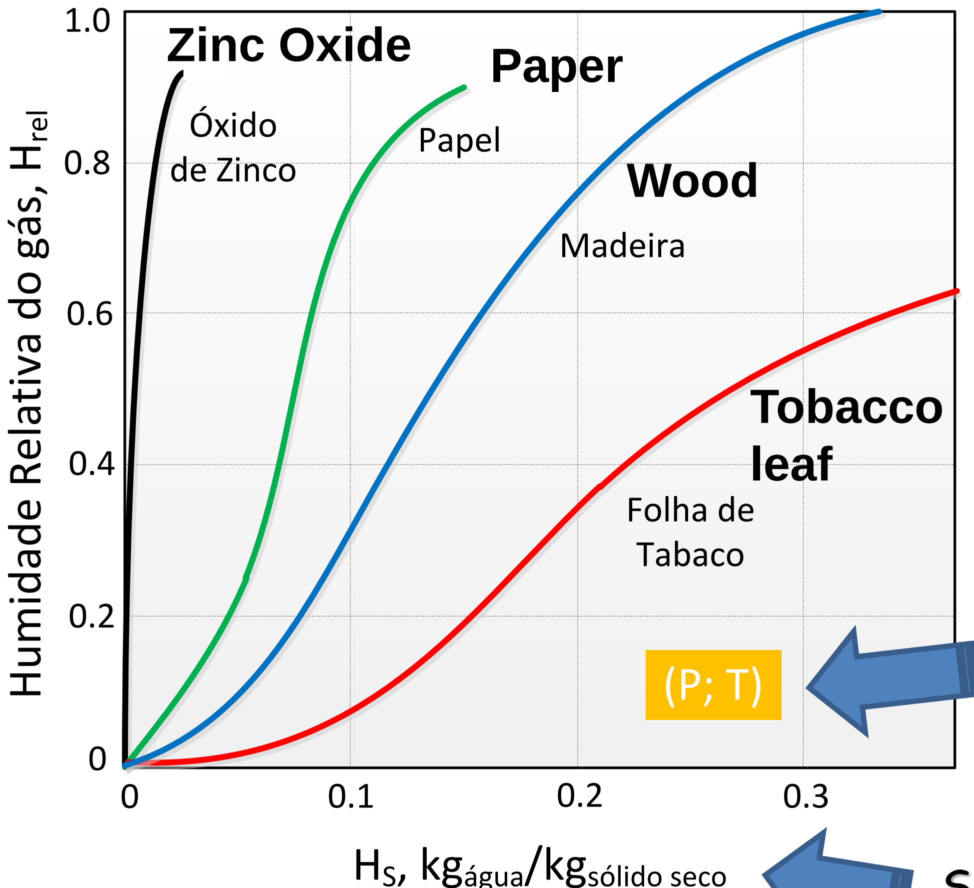


SOLID Humidity

Equilibrium moisture curves

Curvas de humidade de equilíbrio

GAS Humidity



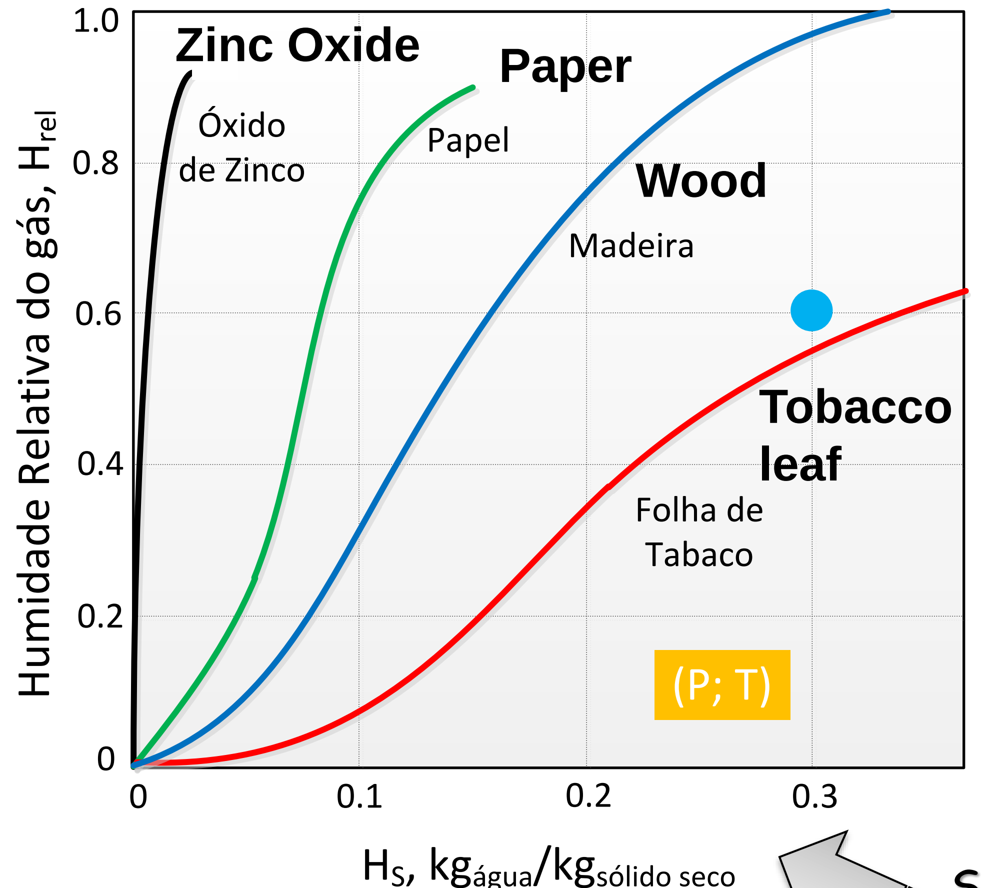
SOLID Humidity

When exposed to a stream of gas (at T_G and H'_G) the solid "loses" its moisture until it reaches equilibrium.

Equilibrium moisture curves

Curvas de humidade de equilíbrio

GAS
Humidity



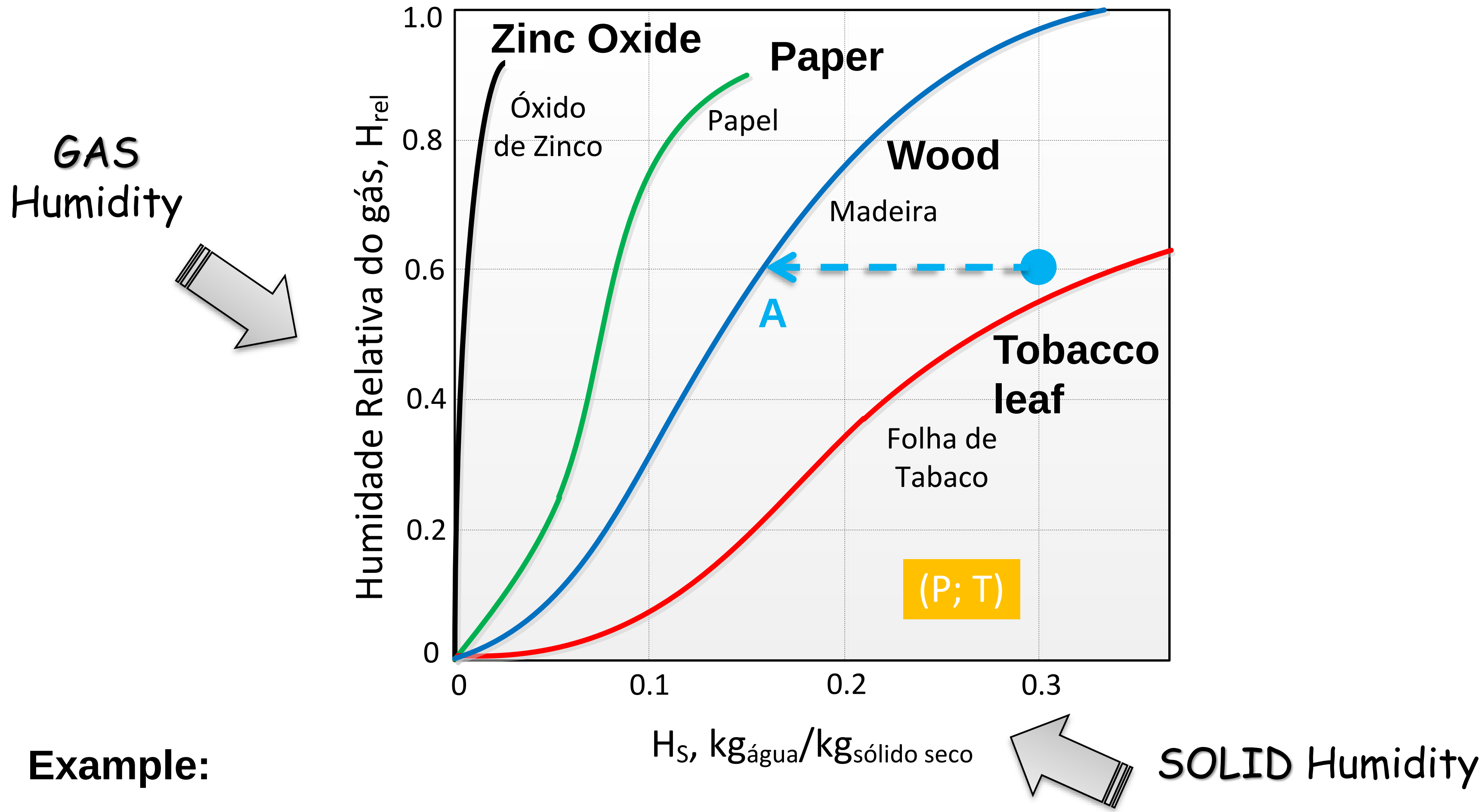
SOLID Humidity

Example:

Wood with H_s = 0.3 is contacted with air with H_{rel} = 60%.

Equilibrium moisture curves

Curvas de humidade de equilíbrio

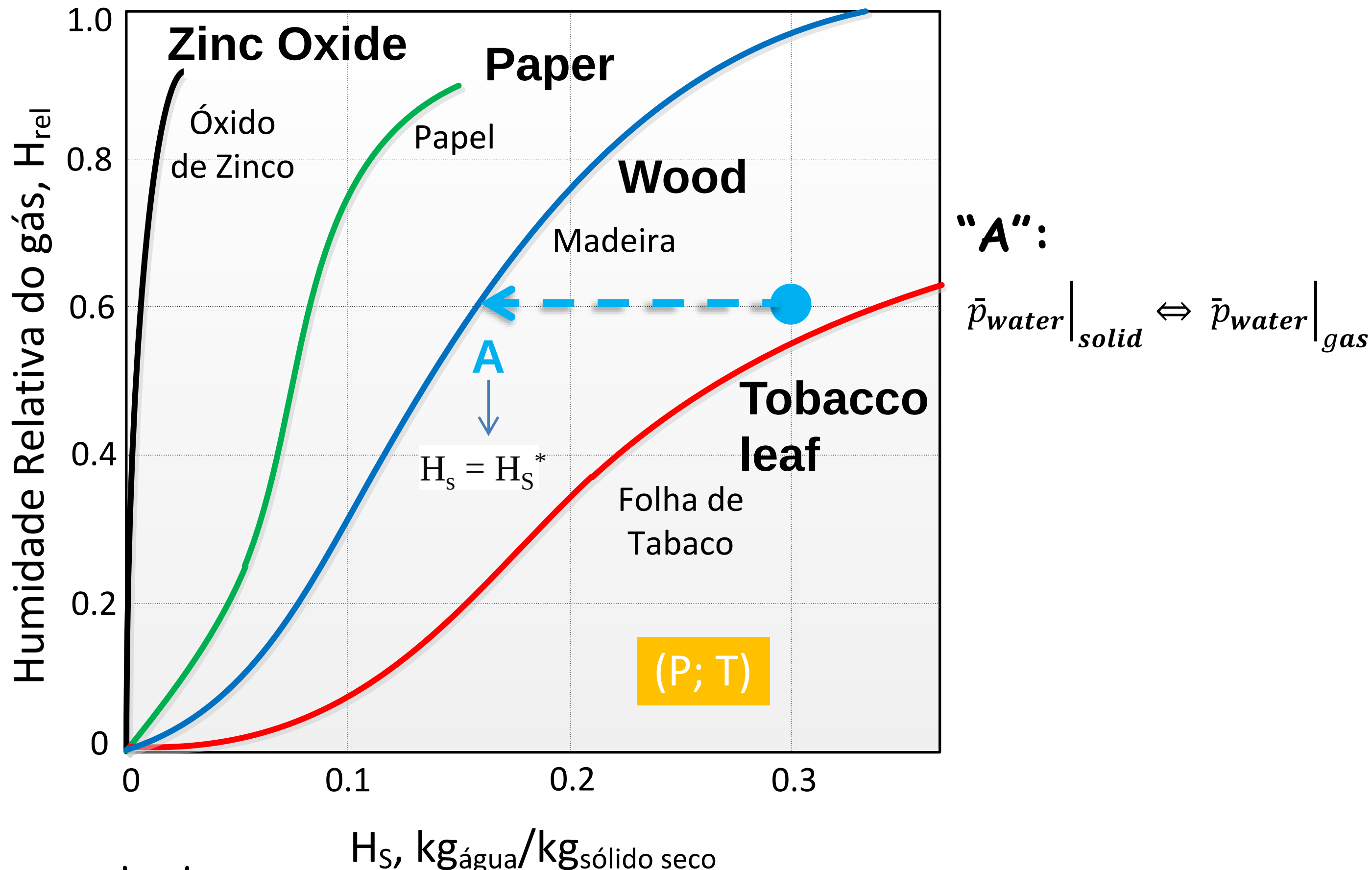


Example:

Wood is dried until reach the equilibrium A.

Equilibrium moisture curves

Curvas de humidade de equilíbrio



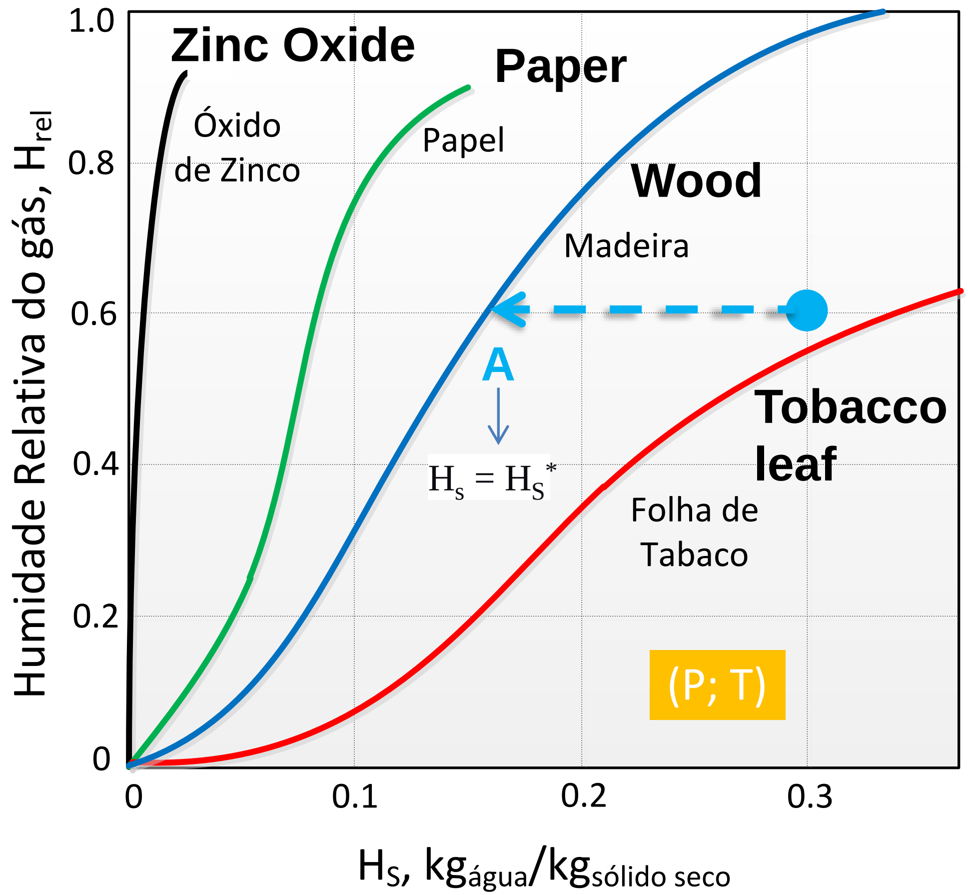
When equilibrium is reached:

partial pressure of water$|_{gas}$ ⇔ partial pressure of water$|_{solid}$

At this point, the humidity content in the solid ≡ **Equilibrium humidity**, H_S^*

Equilibrium moisture curves

Curvas de humidade de equilíbrio

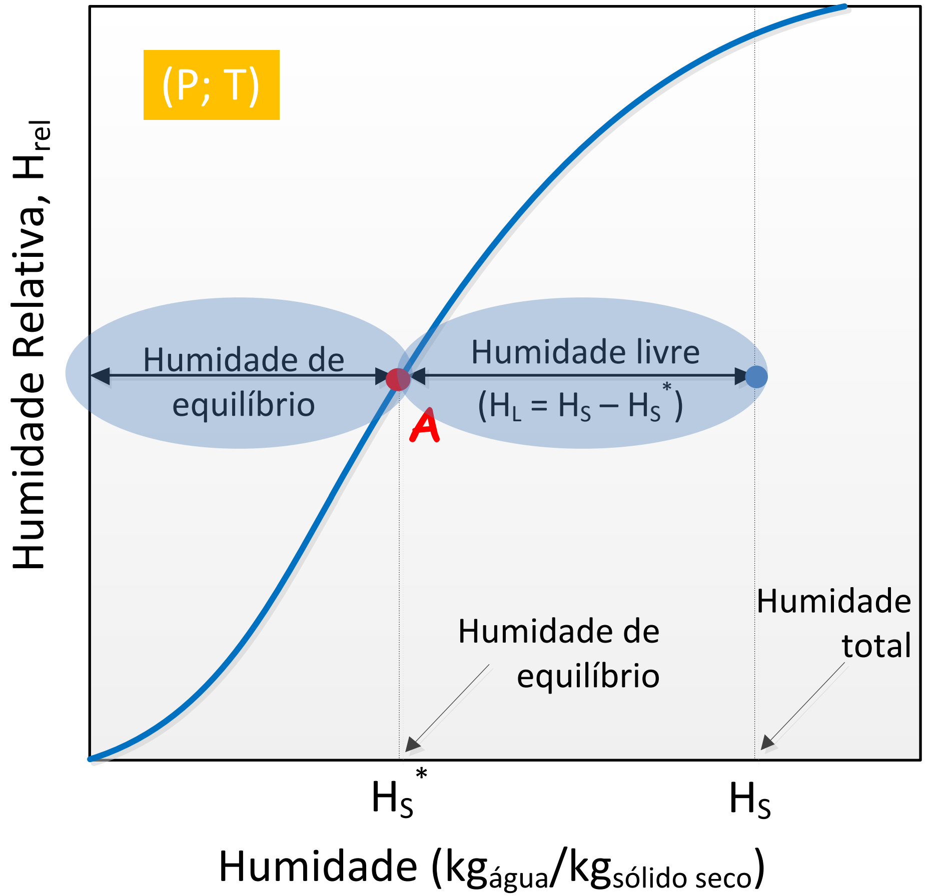


"A":

$$\bar{p}_{water}\Big|_{solid} \Leftrightarrow \bar{p}_{water}\Big|_{gas}$$

H_S^* <u>depends on</u>:

- Temperature and humidity of the gas
- Characteristics of the solid (particle size; porosity; surface area)



Equilibrium Humidity, H_S^*: humidity/moisture that remains in the solid no matter how long the drying operation is prolonged.

Free Humidity, H_L: excess humidity relative to the equilibrium value.

Drying Operation

Classified according to:

1) Method of operation

   - Discontinuous

   - Continuous

1) Method of heat supply

   - Direct (*Convection*): direct contact of the solid with the hot gas.

   - Indirect (*Conduction*): heat supply is independent of the gas (hot surface). Gas is the drag media of the moisture.

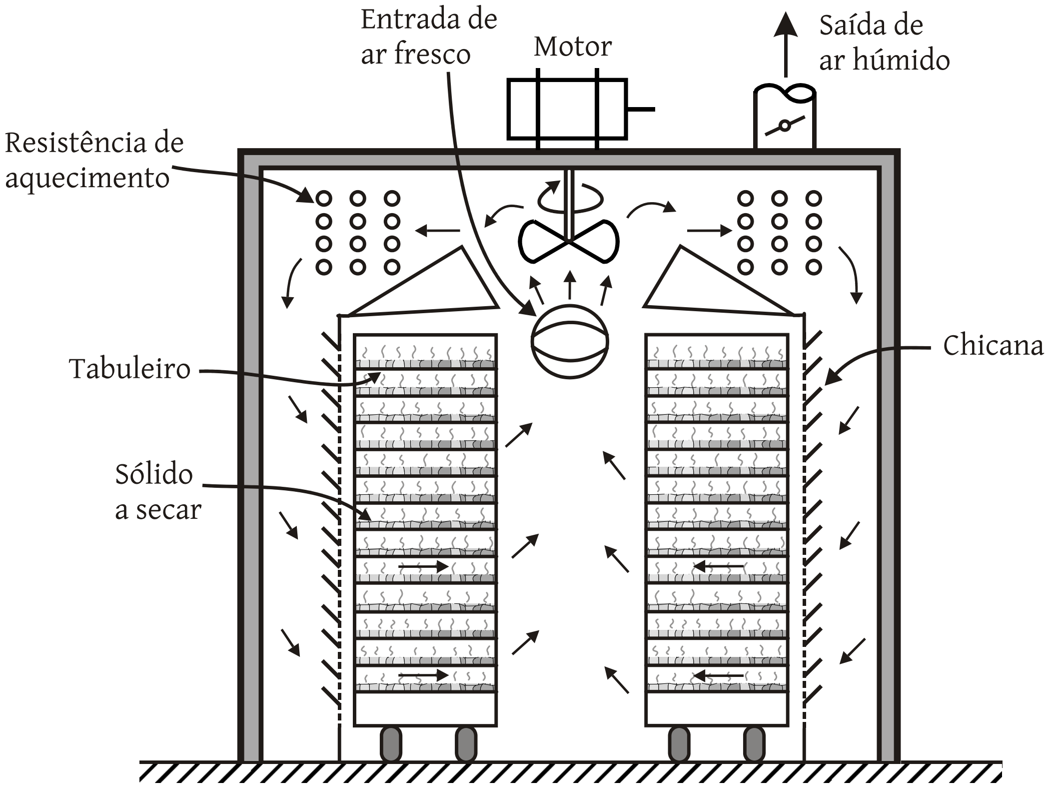
Types of dryers Classification

- Solid Dryers
  - Direct Contact (convection)
    - Continuous
      - Trays
      - Pneumatic transport
      - Atomization
      - Tunnel
      - Fluidized bed
      - Transverse circulation
    - Discontinuous
      - Trays
      - Transverse circulation
      - Fluidized bed
  - Indirect Contact (conduction)
    - Continuous
      - Cylinder
      - Drum
      - Screw
      - Steam pipes
      - Vibrating trays
    - Discontinuous
      - Stirred pot
      - Freezing
      - Vacuum rotaries
      - Vacuum trays

Engenharia de Processos de Separação; Edmundo de Azevedo, Ana Alves

Discontinuous Dryers

- **Tray dryers**



Discontinuous Dryers

- **Tray dryers**

  – Relatively expensive operation

  - High value-added materials

Disadvantages

i) Low homogeneity in the moisture content of the dry product

ii) Gas recirculation may be defective

iii) Thermal insulation (cold walls = > moisture condensation!)

Constinuous Dryers

– Large-scale operation

- Greater uniformity of product moisture

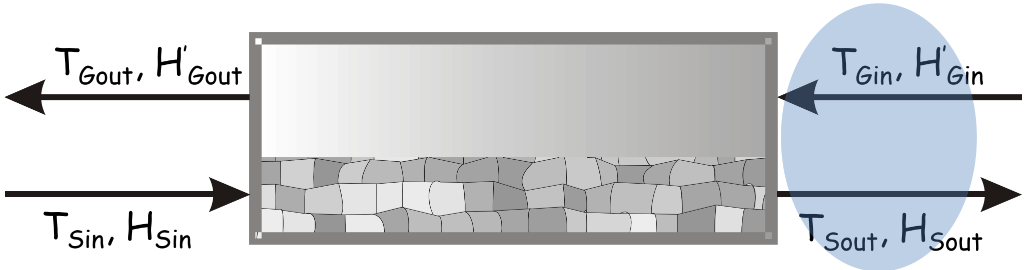
- Lower cost/processed product

Contact between gas and solid:

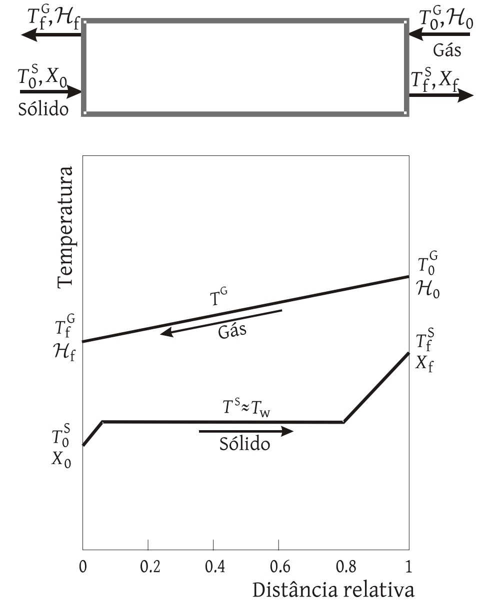
i) Countercurrent – thermally stable materials

ii) Cocurrent – thermally sensitive materials

In countercurrent

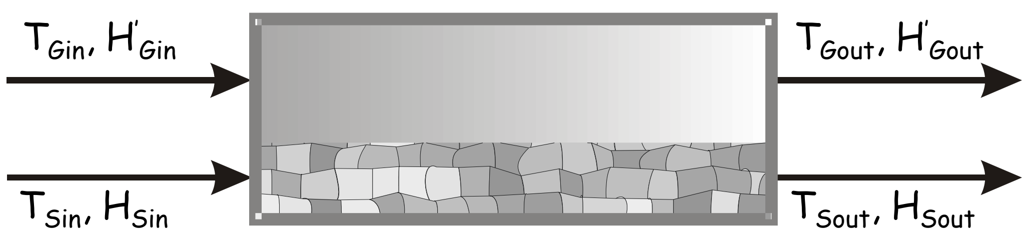


thermally **stable** materials (more efficient operation: driving force for mass and heat transfer is greater!)

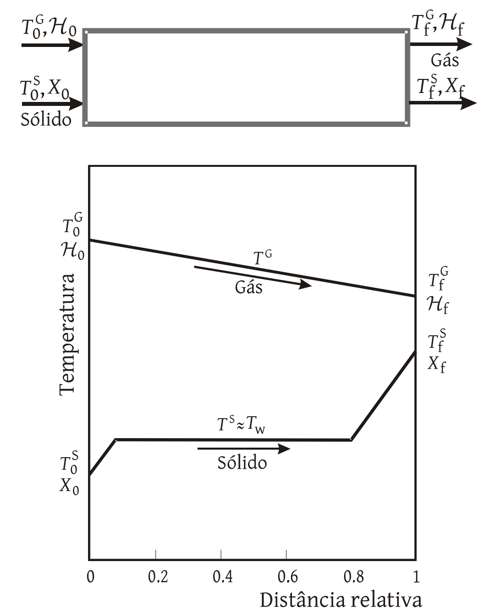


In countercurrent

In cocurrent

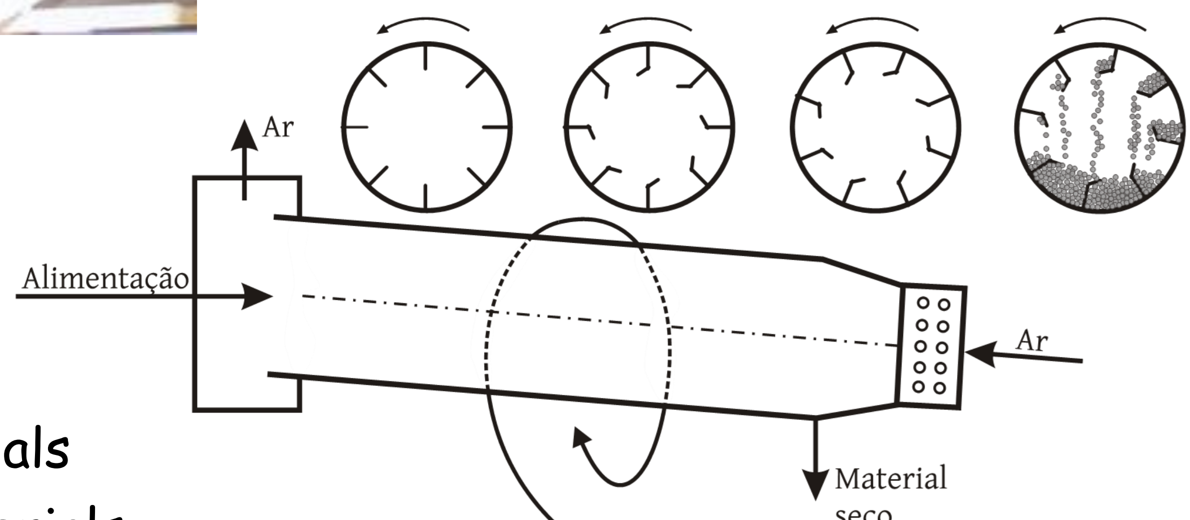


thermally **sensitive** materials



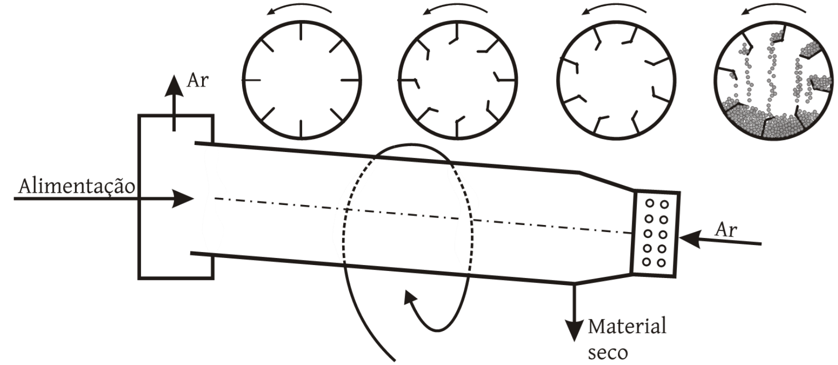
In cocurrent

Rotary Dryers

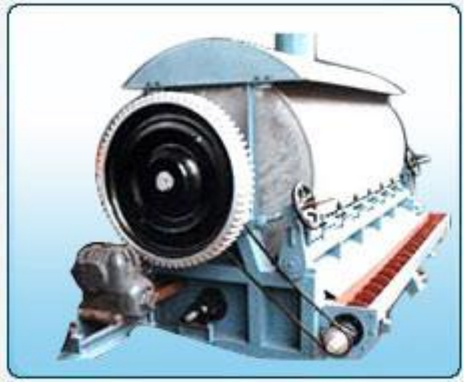


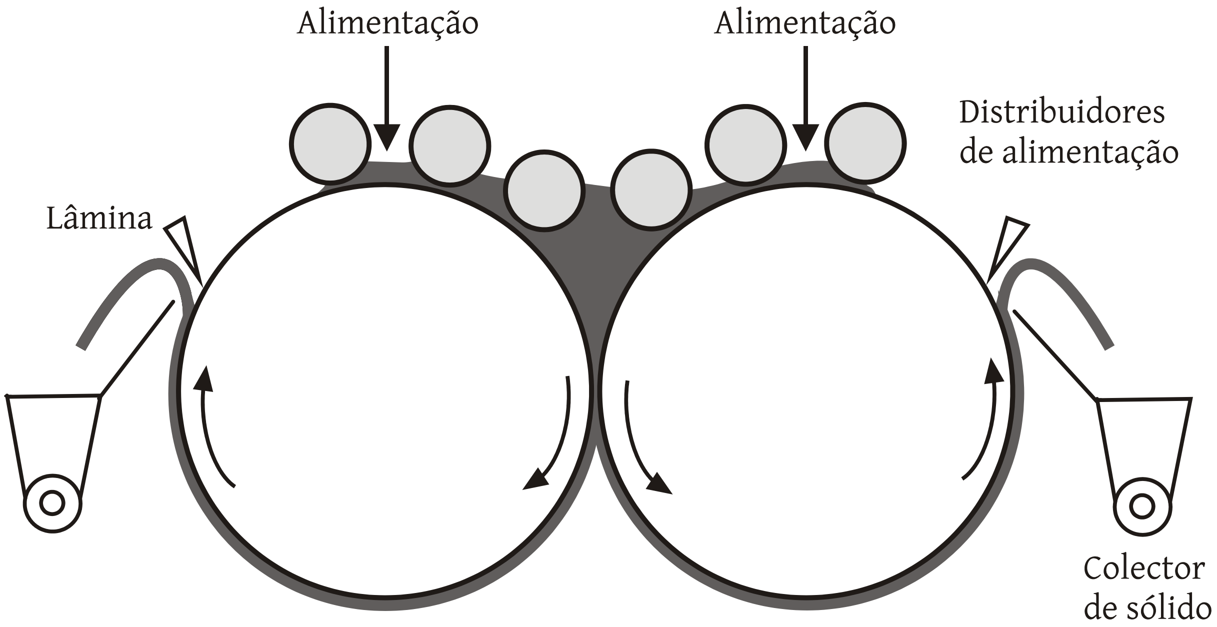
- granular materials
- crystalline materials

Rotary Dryers



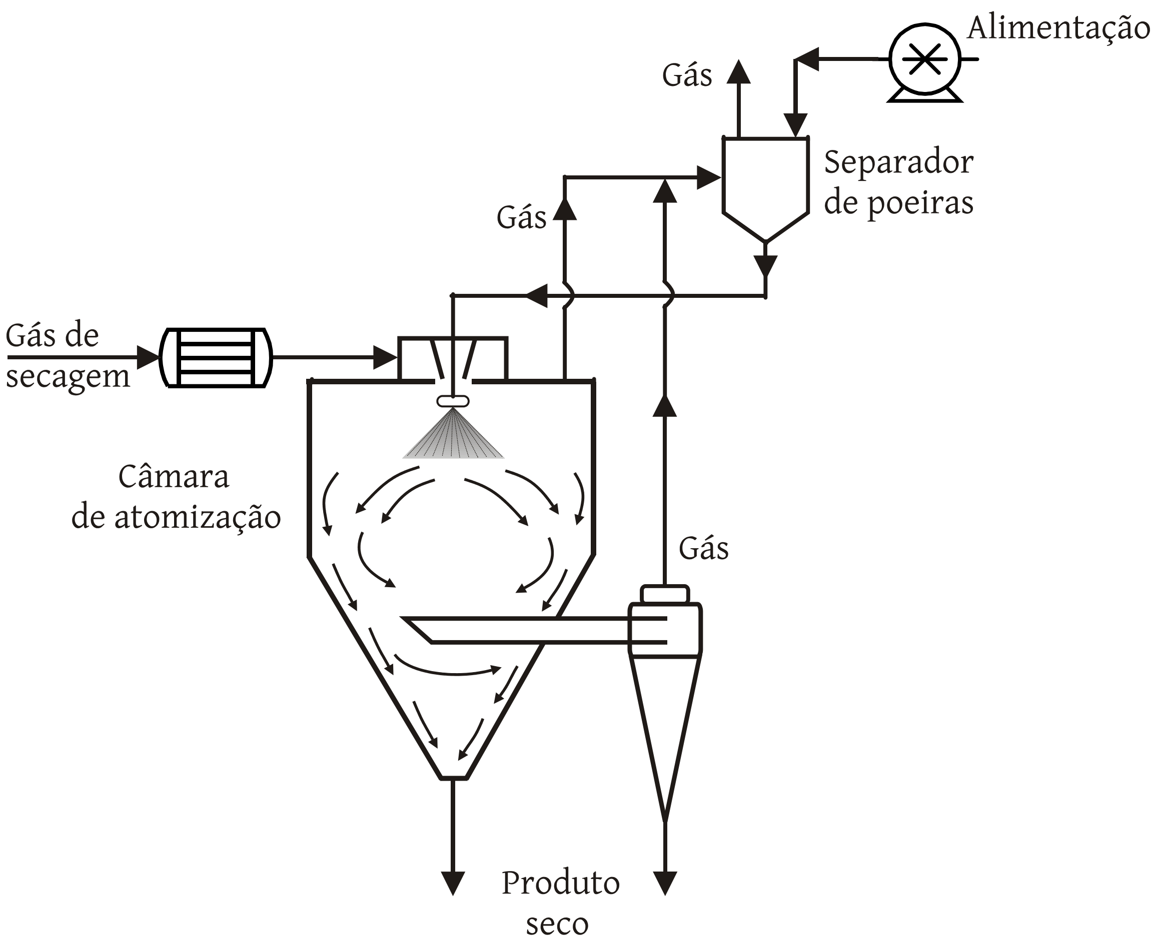
Drum Dryers





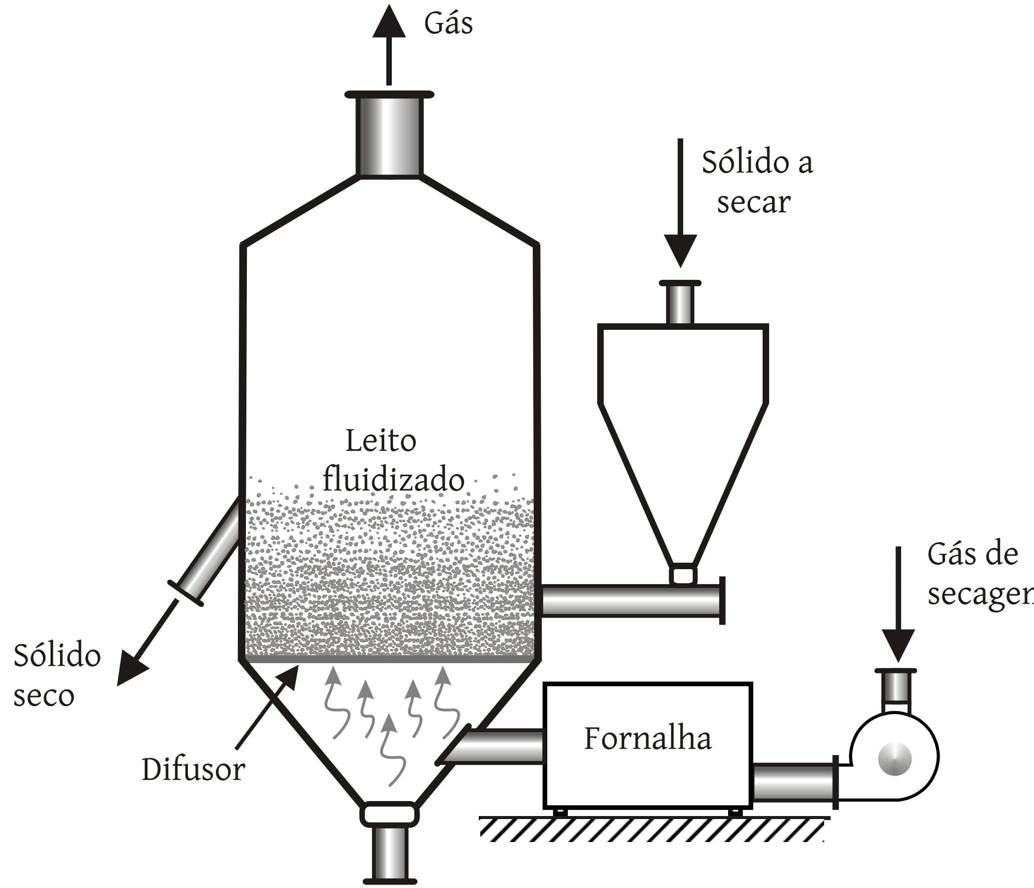
- fluid or semi-fluid materials; solutions, pastes, sludges.

Spray Dryers



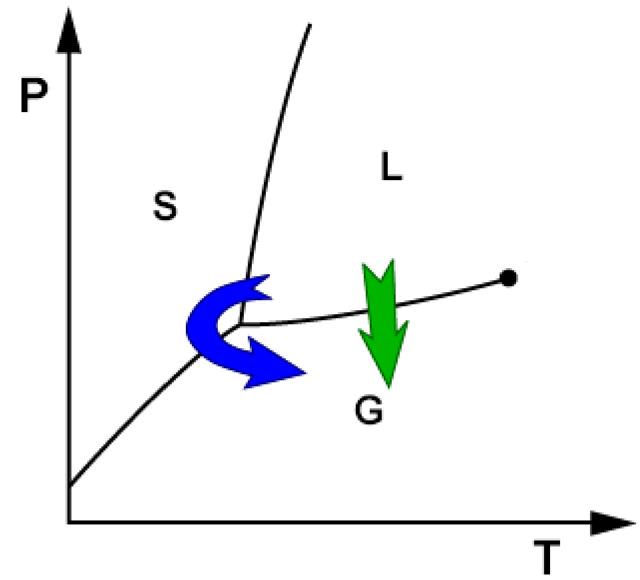
- low drying time
- crystallization!

Fluidized Bed Dryers



- Controllable residence times
- Uniformity in temperature and humidity of the gas in the particle bed in the fluidized state

FREEZE DRYING (*Liofilização*)



- preserve perishable materials
- facilitate the transport of the material

- Substance to dry is frozen by exposure to cold air (e.g.-10°C).

- It is placed in a vacuum chamber where the humidity sublimates by lowering the pressure (e.g. 0.1-2 mmHg) + adding heat (latent heat of sublimation)

Dehydration processes

Conventional Drying

Freeze Drying (*Liofilização*)

Process with high energy cost

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;

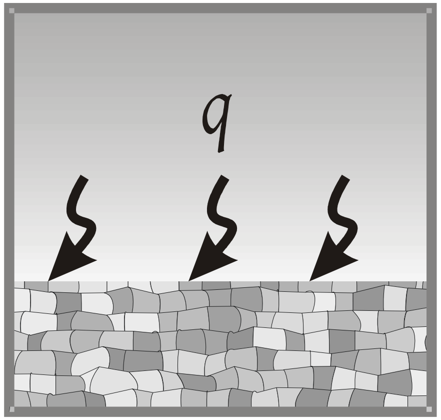
- the method of heat supply

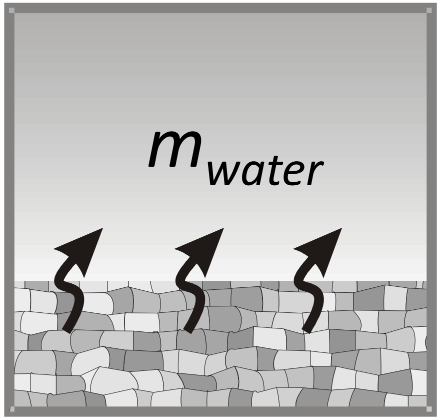
There are basically two processes in the drying of a solid:

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 (EXTERNAL DRYING MECHANISM)

psychrometric chart!

carta psicrométrica!

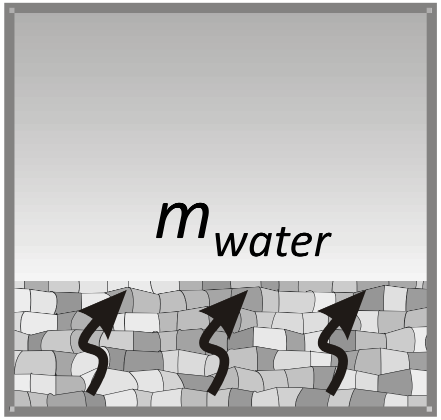




Convection transport of moisture from the surface of the solid to the gas phase

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

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

Example

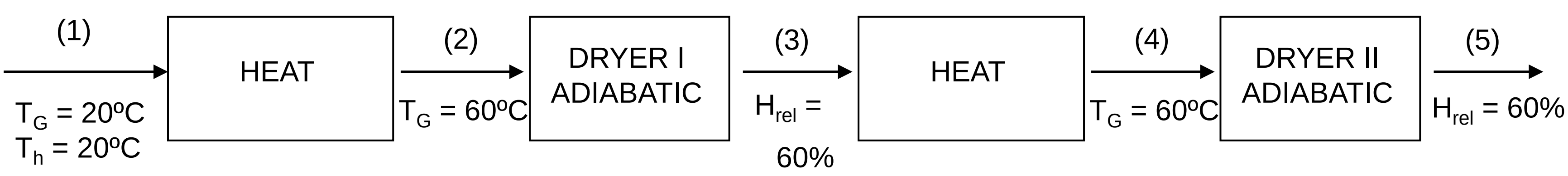
In a drying process, a **dryer with two sets of trays is used to dry a wet solid**.

Air saturated to 20ºC is previously heated to 60ºC before passing through the first set of trays. The air leaves this 1st stage with a relative humidity of 60% and is heated again to 60ºC before entering the second set of trays. At the exit of this 2nd stage, the air has again a relative humidity of 60%.

Assuming that the drying process takes place adiabatically and that the final temperature of the solid on each shelf equals the wet thermometer temperature of the air that contacts it, calculate:

a) The final temperature of the solid in each set of trays.

b) The total amount of water taken from the solid per kg of dry air.



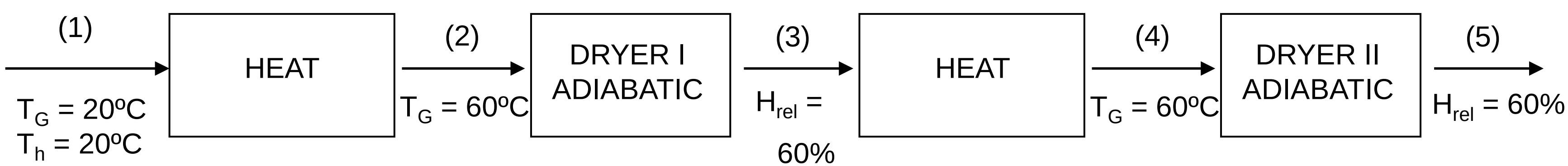
In a drying process, a **dryer with two sets of trays is used to dry a wet solid**.

Air saturated to 20ºC is previously heated to 60ºC before passing through the first set of trays. The air leaves this 1st stage with a relative humidity of 60% and is heated again to 60ºC before entering the second set of trays. At the exit of this 2nd stage, the air has again a relative humidity of 60%.

Assuming that the drying process takes place adiabatically and that the final temperature of the solid on each shelf equals the wet thermometer temperature of the air that contacts it, calculate:

a) The final temperature of the solid in each set of trays.

b) The total amount of water taken from the solid per kg of dry air.



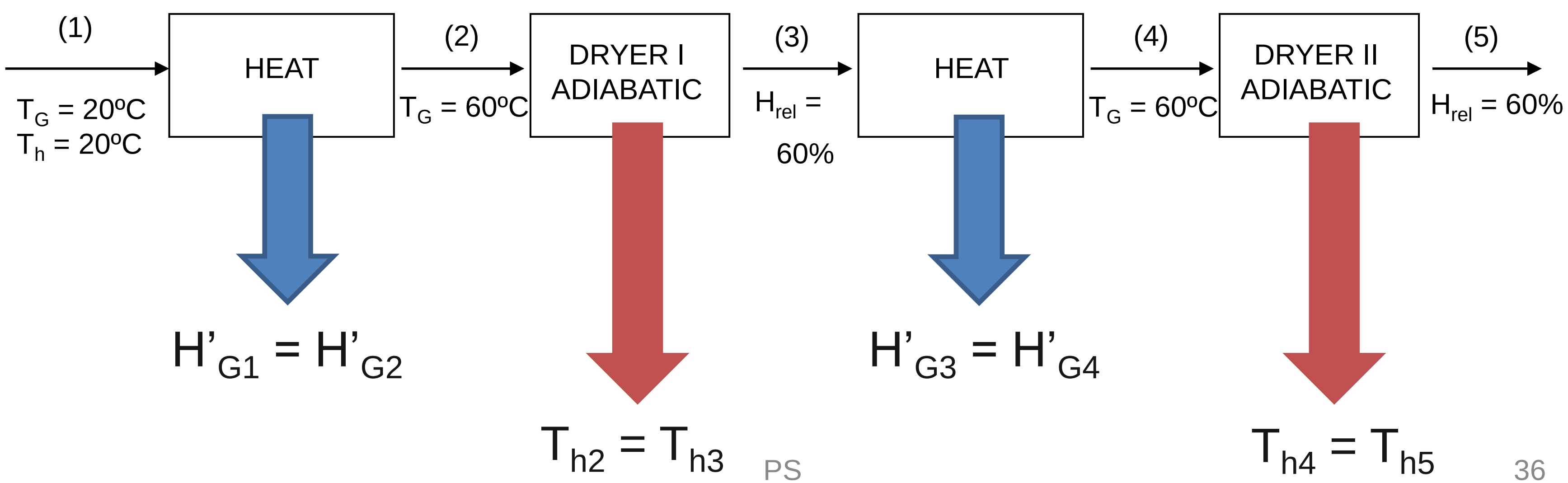
In a drying process, a **dryer with two sets of trays is used to dry a wet solid**.

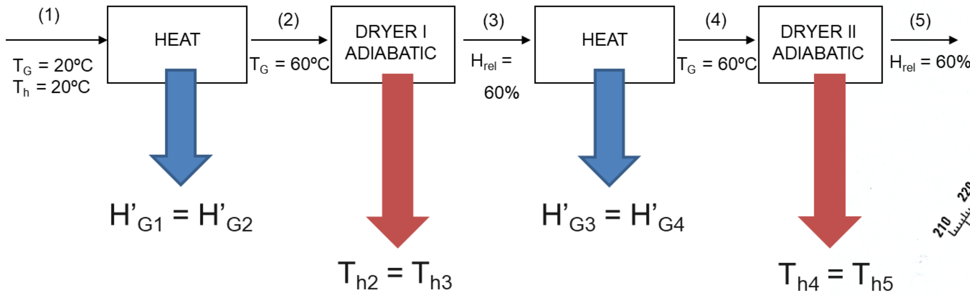
Air saturated to 20ºC is previously heated to 60ºC before passing through the first set of trays. The air leaves this 1st stage with a relative humidity of 60% and is heated again to 60ºC before entering the second set of trays. At the exit of this 2nd stage, the air has again a relative humidity of 60%.

Assuming that the drying process takes place adiabatically and that the final temperature of the solid on each shelf equals the wet thermometer temperature of the air that contacts it, calculate:

a) The final temperature of the solid in each set of trays.

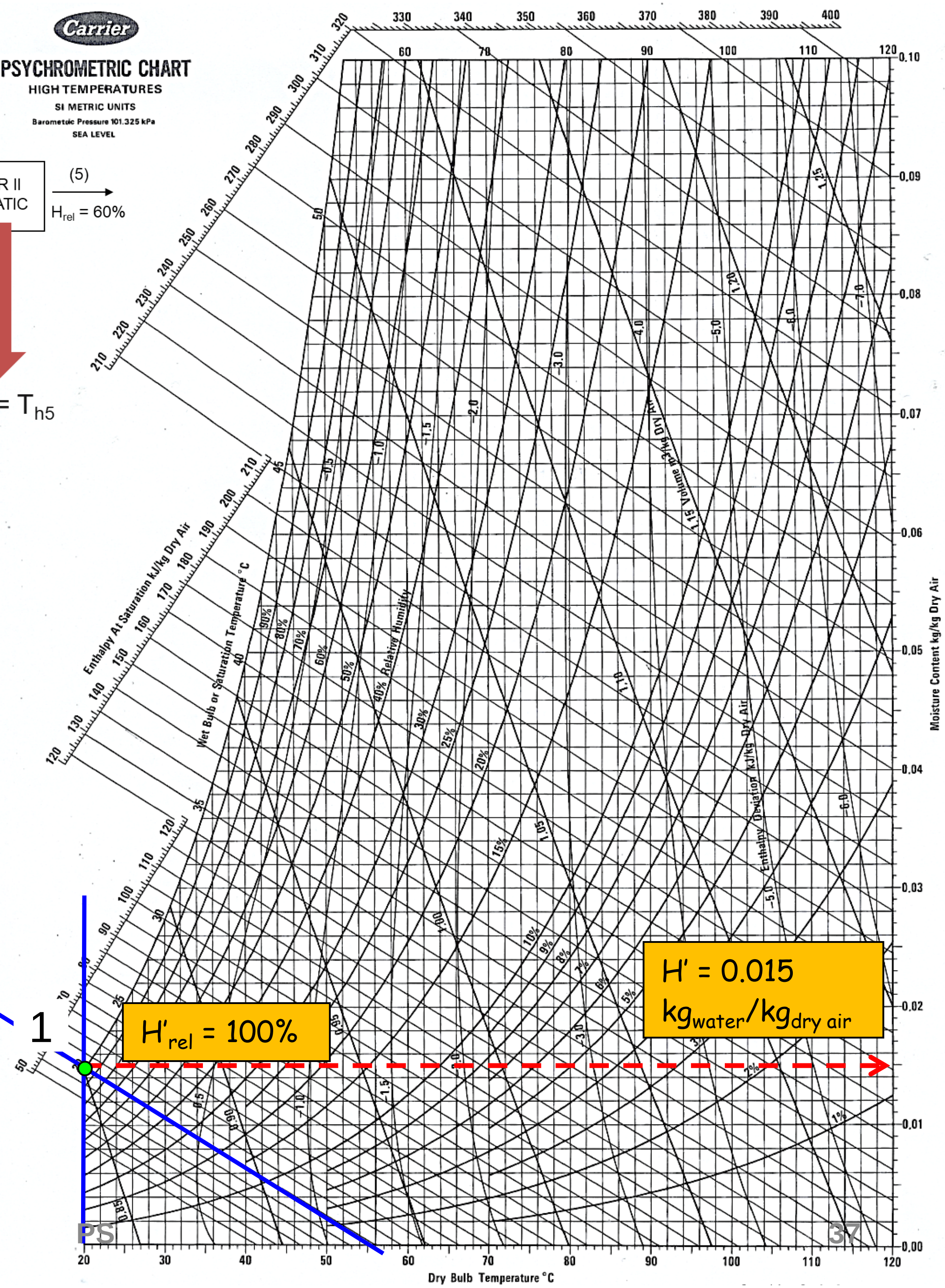
b) The total amount of water taken from the solid per kg of dry air.

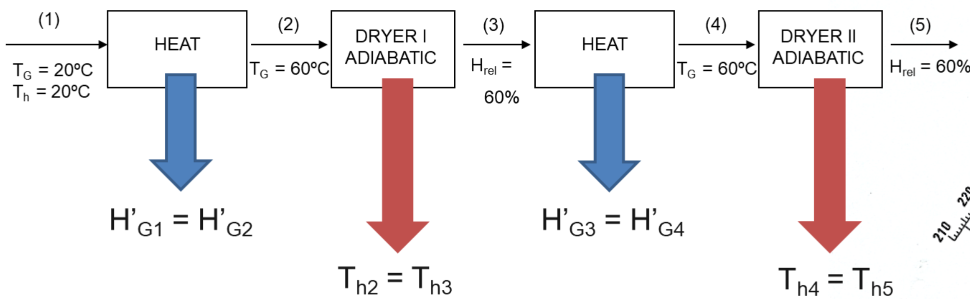


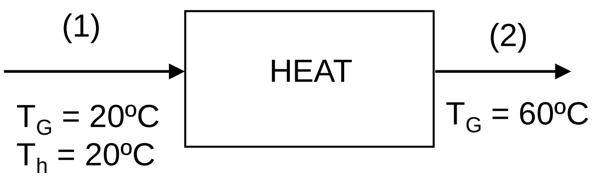


(1) $\begin{cases} T_{h1} = 20°C \\ T_{G1} = 20°C \end{cases}$

$\begin{cases} H'_1 = 0.015 \text{ kg/kg} \\ H_{rel1} = 100\% \end{cases}$

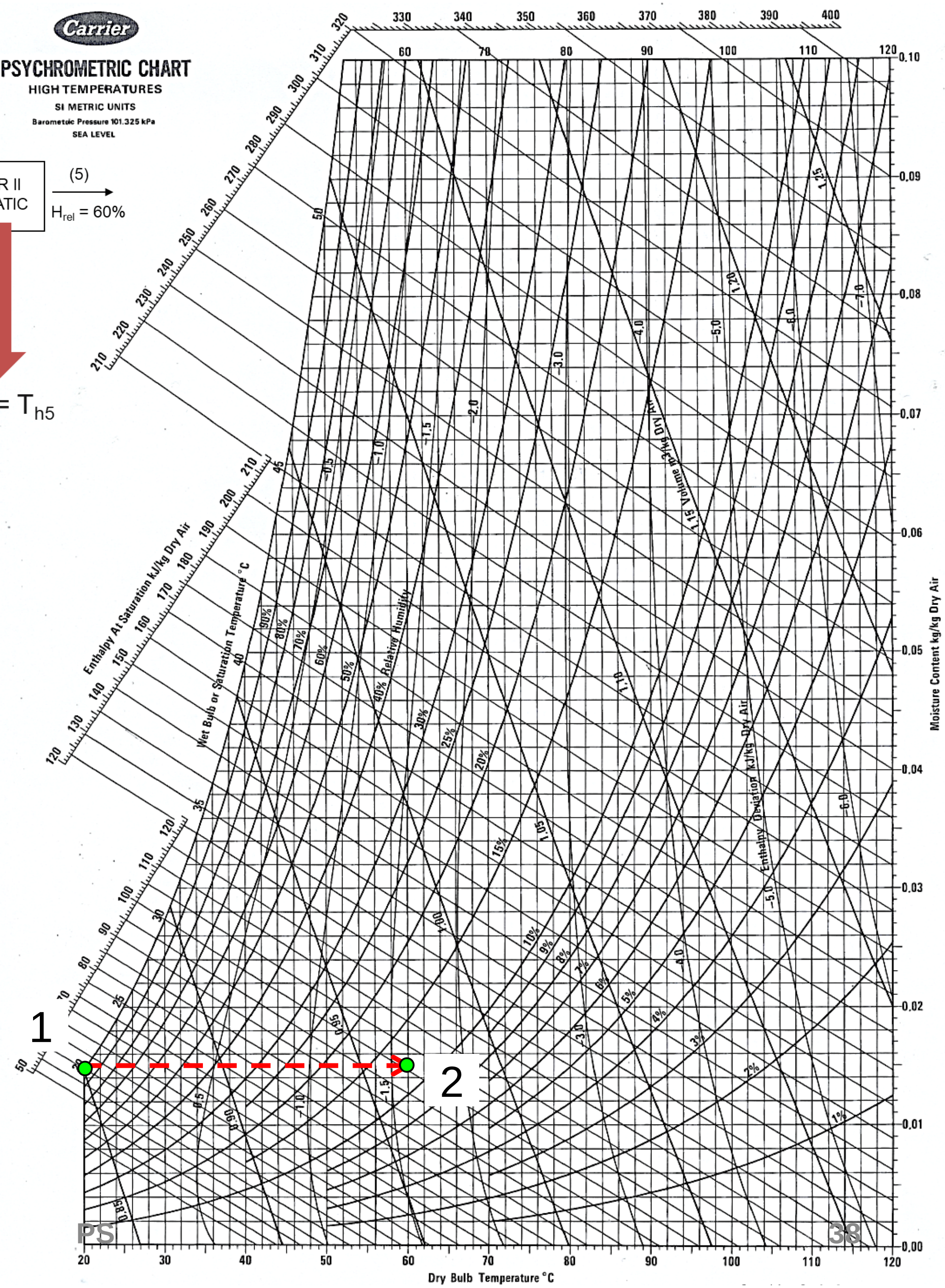






$$\begin{cases} H'_2 = H'_1 = 0.015 \\ T_{G2} = 60°C \end{cases}$$

$$\triangleright \begin{cases} H_{rel2} = 12.5\% \\ T_{h2} \cong 30°C \end{cases}$$



(1) $T_G = 20^oC$, $T_h = 20^oC$ → HEAT → (2) $T_G = 60^oC$ → DRYER I ADIABATIC → (3) $H_{rel} = 60\%$ → HEAT → (4) $T_G = 60^oC$ → DRYER II ADIABATIC → (5) $H_{rel} = 60\%$

$H'_{G1} = H'_{G2}$

$T_{h2} = T_{h3}$

$H'_{G3} = H'_{G4}$

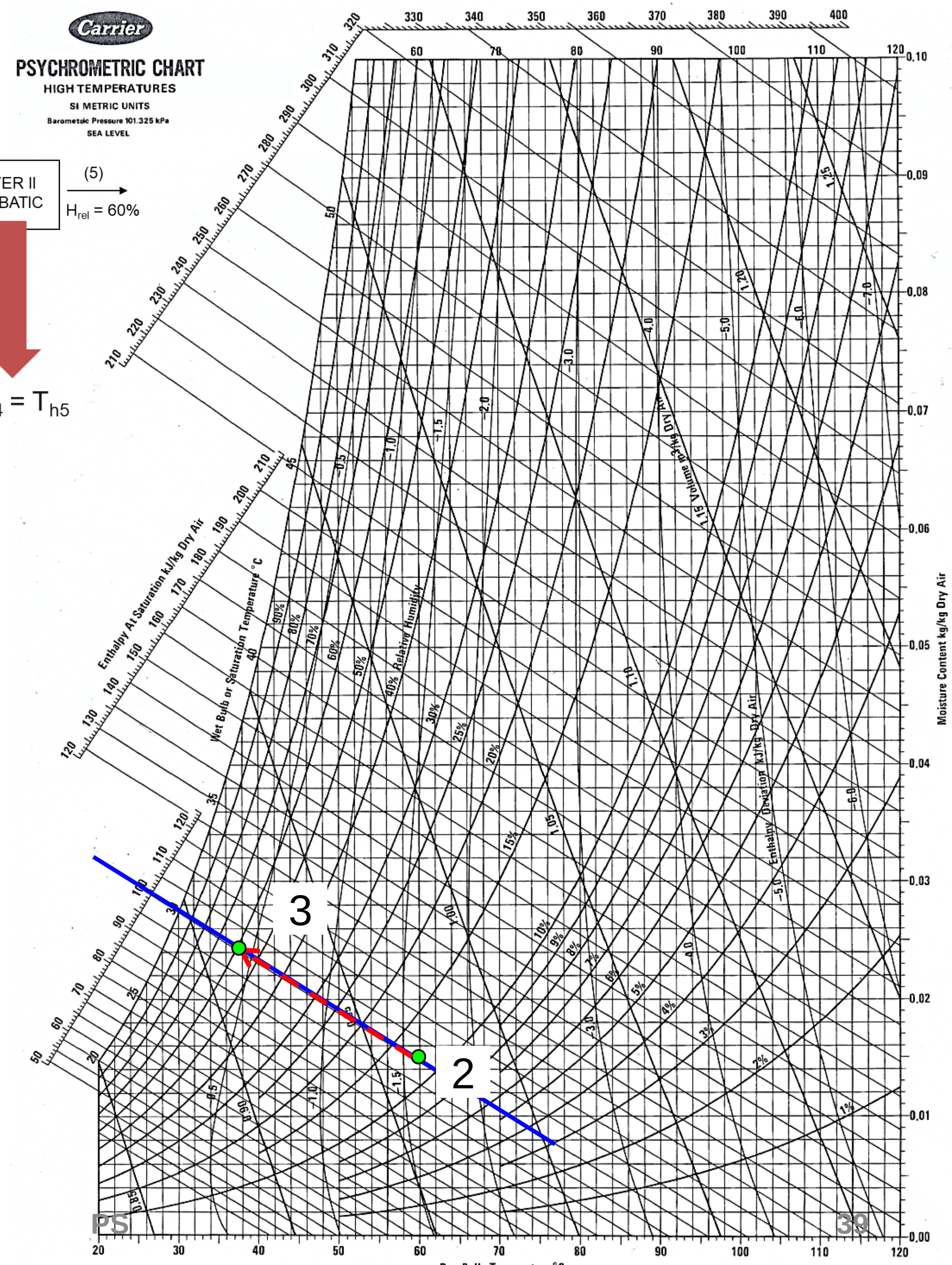
$T_{h4} = T_{h5}$

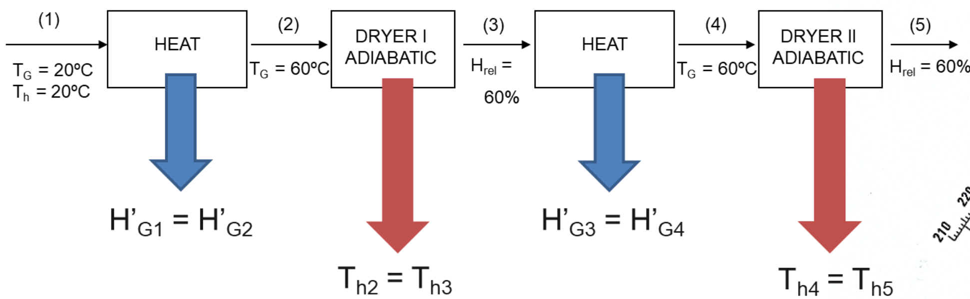
(2) $T_G = 60^oC$ → DRYER I ADIABATIC → (3) $H_{rel} = 60\%$

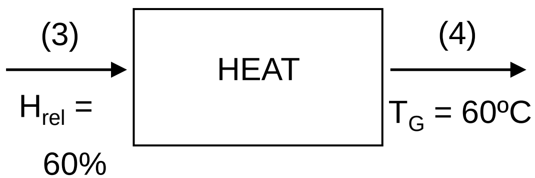
$$\begin{cases} H_{rel2} = 12.5\% \\ T_{h2} \cong 30^oC \end{cases}$$

$$\begin{cases} H_{rel3} = 60\% \\ T_{h3} = T_{h2} = 30^oC \end{cases}$$

$$\begin{cases} H'_3 = 0.024 \\ T_{G3} = 37^oC \end{cases}$$



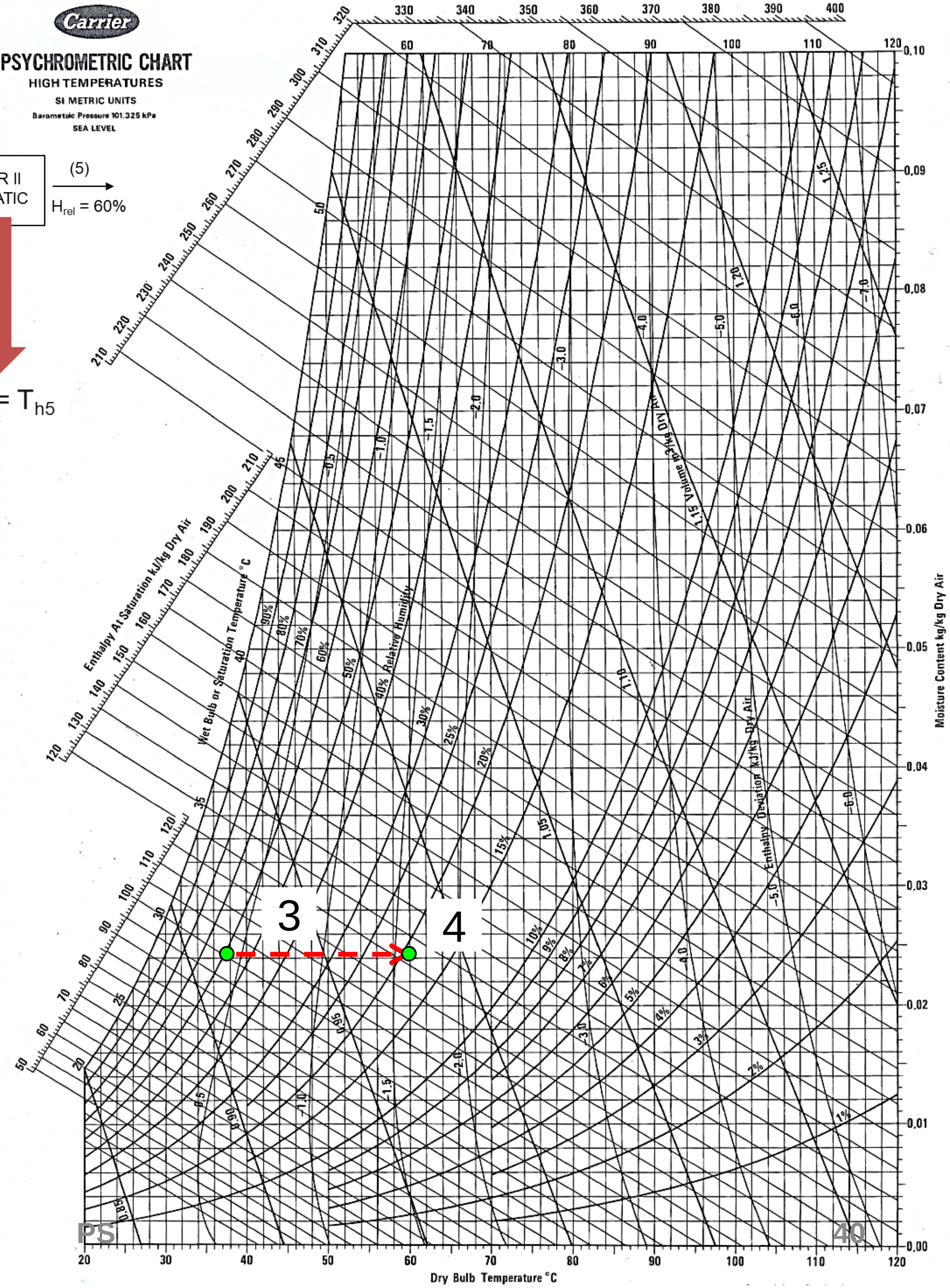


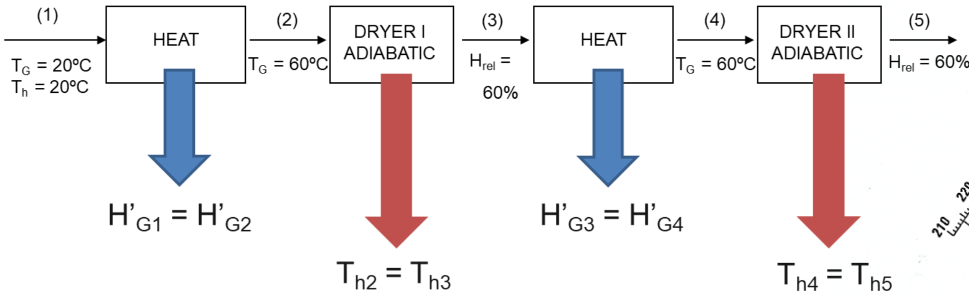


$$\begin{cases} H'_3 = 0.024 \\ T_{G3} = 37^\circ C \end{cases}$$

$$\begin{cases} H'_4 = H'_3 = 0.024 \\ T_{G4} = 60^\circ C \end{cases}$$

$$\begin{cases} H_{rel4} = 18\% \\ T_{h4} = 34^\circ C \end{cases}$$

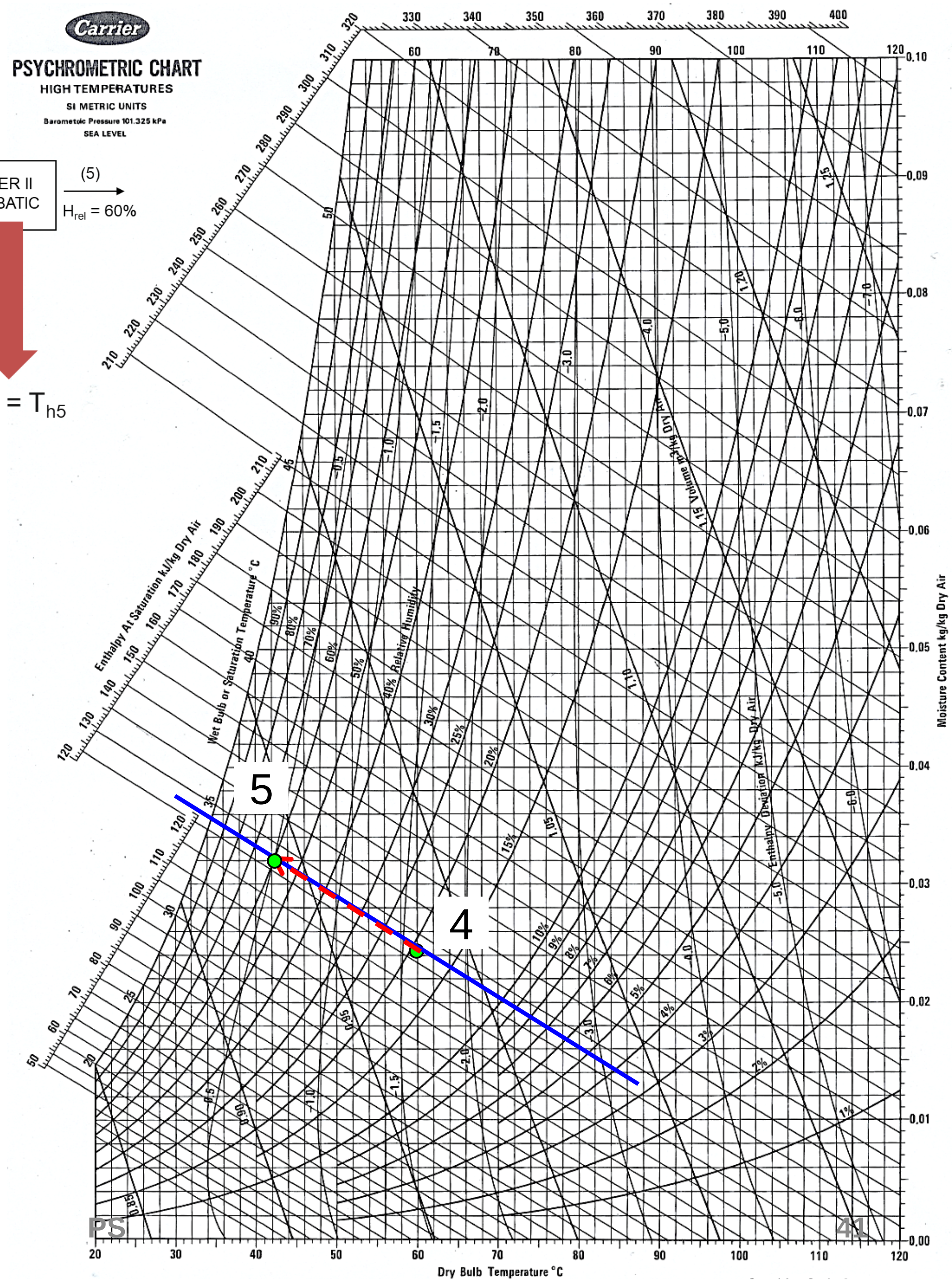




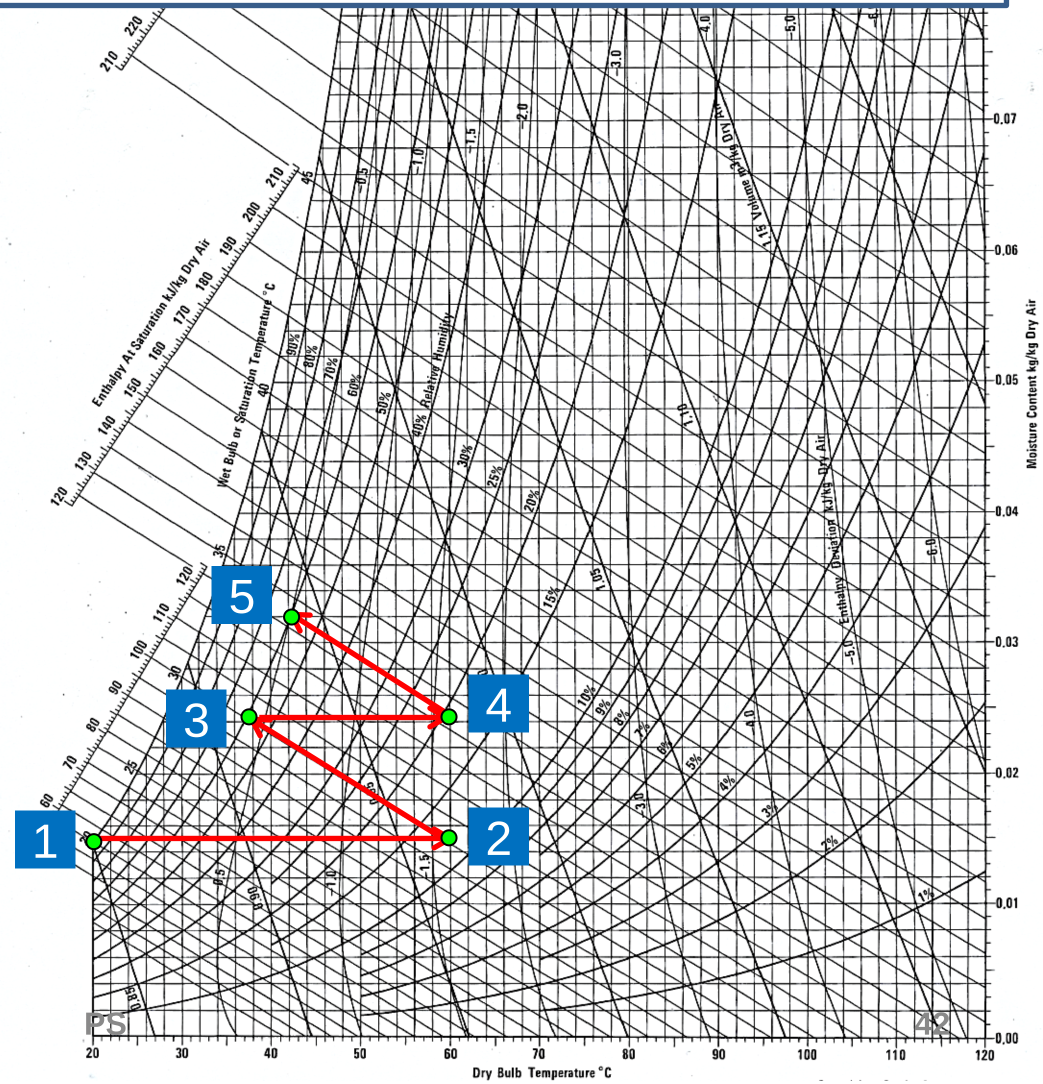
$$\begin{cases} H_{rel4} = 18\% \\ T_{h4} = 34°C \end{cases}$$

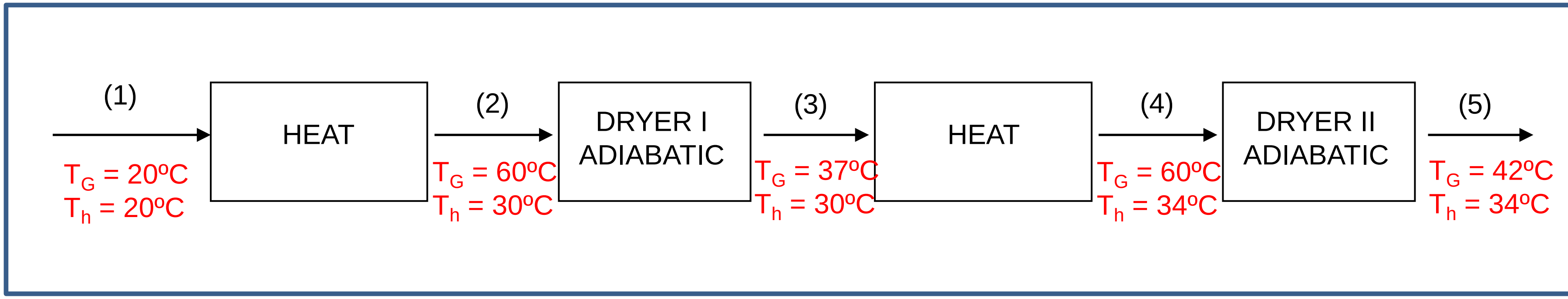
$$\begin{cases} H_{rel5} = 60\% \\ T_{h5} = T_{h4} = 34°C \end{cases}$$

$$\triangleright \quad \begin{cases} H'_5 = 0.031 \\ T_{G5} = 42°C \end{cases}$$



(1)		(2)		(3)		(4)		(5)
→	HEAT	→	DRYER I ADIABATIC	→	HEAT	→	DRYER II ADIABATIC	→
$T_G = 20^oC$ $T_h = 20^oC$		$T_G = 60^oC$ $T_h = 30^oC$		$T_G = 37^oC$ $T_h = 30^oC$		$T_G = 60^oC$ $T_h = 34^oC$		$T_G = 42^oC$ $T_h = 34^oC$

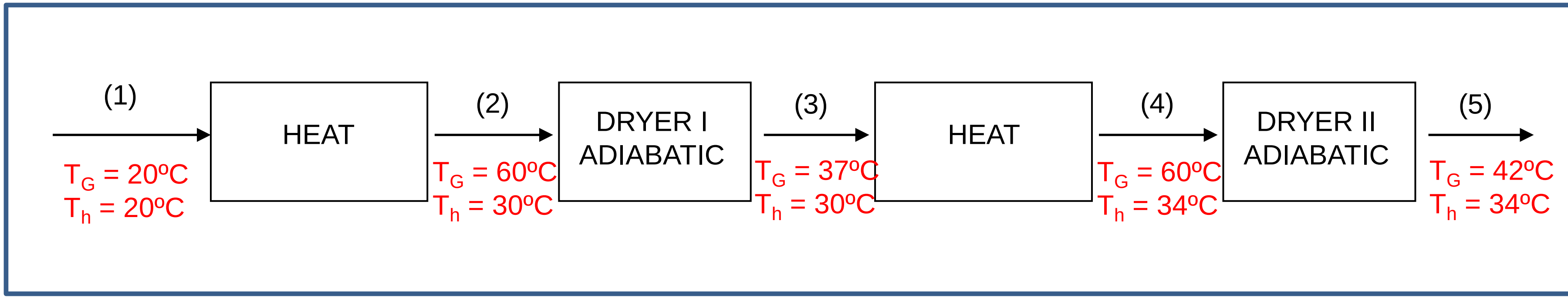




a) The final temperature of the solid in each set of trays.

"The final temperature of the solid on each shelf equals the wet thermometer temperature of the air that contacts it."

$$T_{solid\ I} = T_{h3} = 30°C$$
$$T_{solid\ II} = T_{h5} = 34°C$$



b) The total amount of water taken from the solid per kg of dry air.

$$m_{condensed\ water} = (H_3' - H_2') + (H_5' - H_4')$$

$$\begin{aligned} m_{condensed\ water} &= (0.024 - 0.015) - (0.031 - 0.024) \\ &= 0.031 - 0.015 = 0.016\ kg_{water}/kg_{dry\ air} \end{aligned}$$

Problem

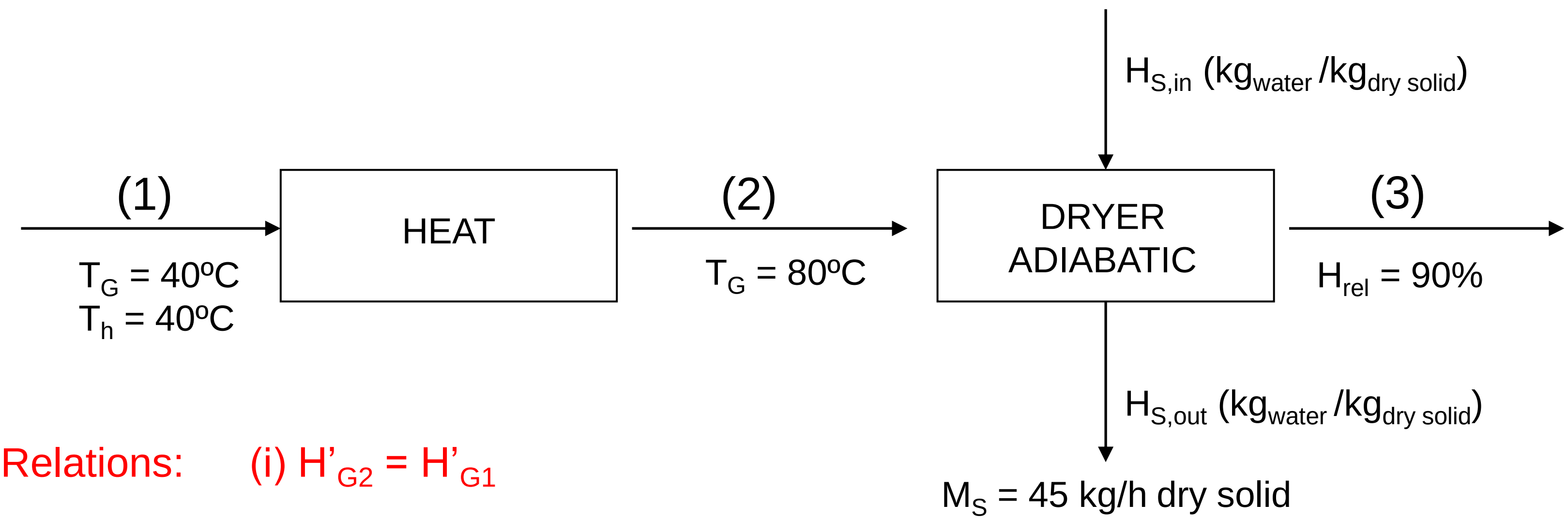
It is intended to dry a granular solid from 70% to 5% in water (weight percentages). In the drying process a **fluidized bed dryer** is used, with the aim of obtaining 45 kg/h of dry material. Atmospheric air is used for this effect, which is heated to 80ºC before being introduced into the dryer.

The air at the exit of the dryer has a relative humidity of 90%. Knowing that the atmospheric air before being heated has a temperature of 40ºC and a wet thermometer temperature of 40ºC, calculate the dry air flow required in the drying process. Admit that the dryer works adiabatically.

It is intended to dry a granular solid from 70% to 5% in water (weight percentages).

In the drying process a **fluidized bed dryer** is used, with the aim of obtaining 45 kg/h of dry material. Atmospheric air is used for this effect, which is heated to 80ºC before being introduced into the dryer.

The air at the exit of the dryer has a relative humidity of 90%. Knowing that the atmospheric air before being heated has a temperature of 40ºC and a wet thermometer temperature of 40ºC, calculate the dry air flow required in the drying process. Admit that the dryer works adiabatically.



Relations: (i) $H'_{G2} = H'_{G1}$

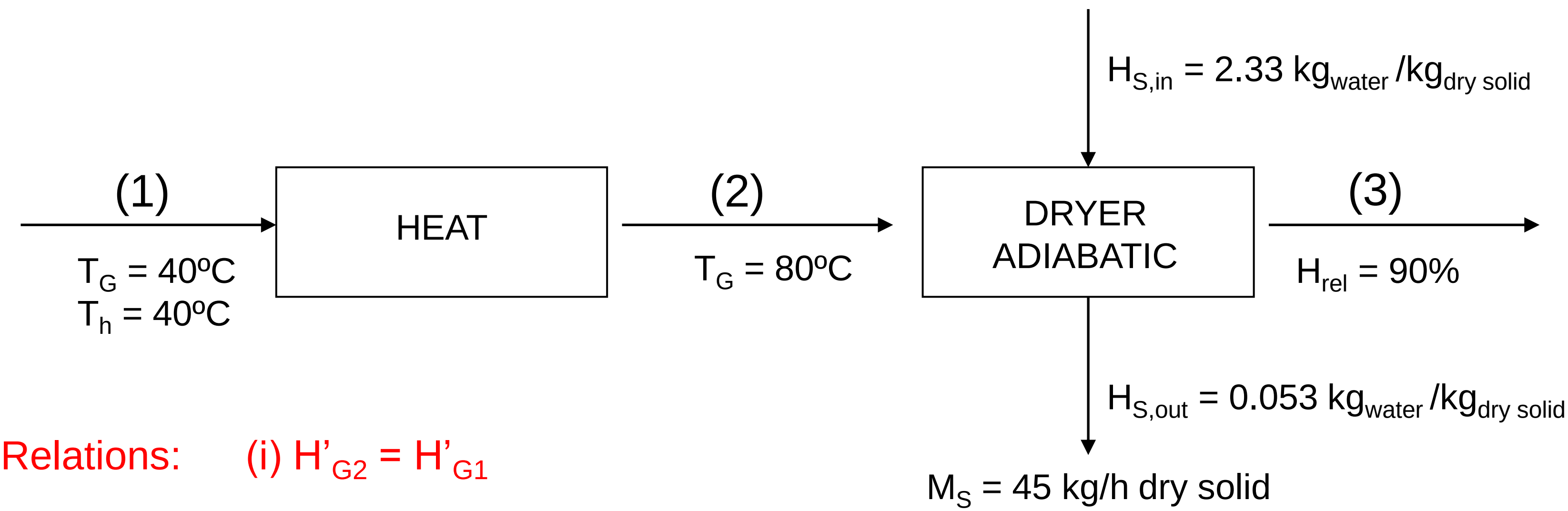
(ii) $T_{h3} = T_{h2}$

In the system water + air: $T_{sa} = T_h$

It is intended to dry a granular solid from 70% to 5% in water (weight percentages).

In the drying process a **fluidized bed dryer** is used, with the aim of obtaining 45 kg/h of dry material. Atmospheric air is used for this effect, which is heated to 80ºC before being introduced into the dryer.

The air at the exit of the dryer has a relative humidity of 90%. Knowing that the atmospheric air before being heated has a temperature of 40ºC and a wet thermometer temperature of 40ºC, calculate the dry air flow required in the drying process. Admit that the dryer works adiabatically.

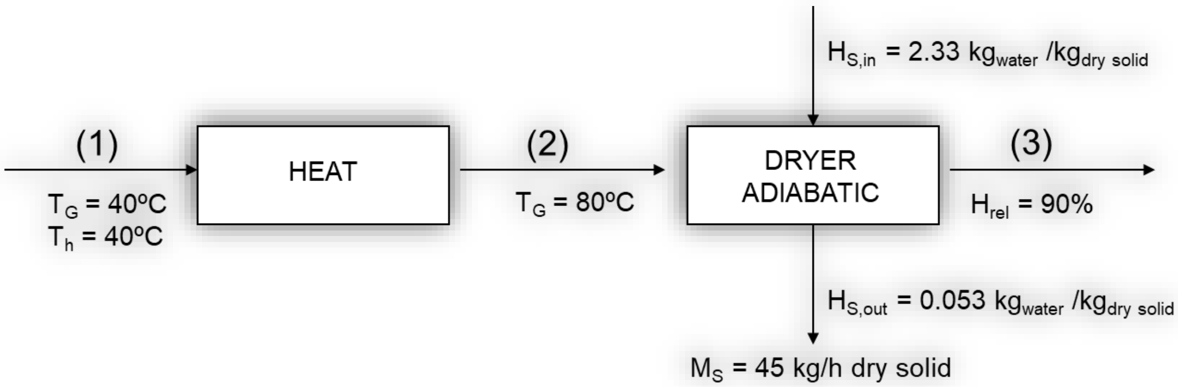


Relations: (i) $H'_{G2} = H'_{G1}$

(ii) $T_{h3} = T_{h2}$

In the system water + air: $T_{sa} = T_h$

It is intended to dry a granular solid from **70%** to **5%** in water (weight percentages).



$$0.7 = \frac{\mathrm{kg}_{\mathrm{H_2O}}}{\mathrm{kg}_{\mathrm{H_2O}} + \mathrm{kg}_{\text{dry solid}}}$$

$$H_s = \frac{\mathrm{kg}_{\mathrm{H_2O}}}{\mathrm{kg}_{\text{dry solid}}}$$

$$\frac{1}{0.7} = 1 + \frac{\mathrm{kg}_{\text{dry solid}}}{\mathrm{kg}_{\mathrm{H_2O}}} \Rightarrow \frac{1}{0.7} - 1 = \frac{1}{\mathrm{H}_s}$$

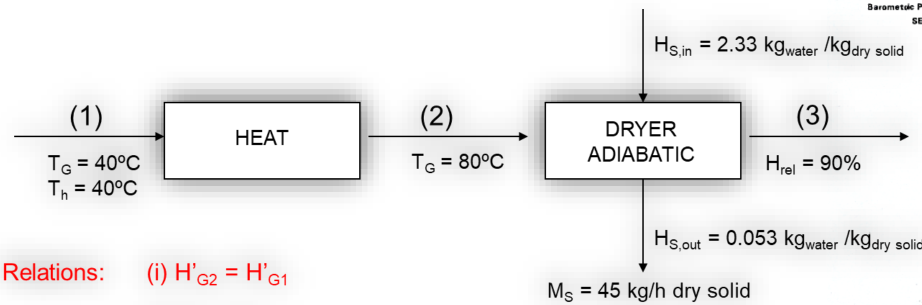
$$\Rightarrow \mathrm{H}_s = {}^{1}\!/_{\frac{1}{0.7}-1} = 2.33\ \mathrm{kg}_{\mathrm{H_2O}}/\ \mathrm{kg}_{\text{dry solid}}$$

$$0.05 = \frac{\mathrm{kg}_{\mathrm{H_2O}}}{\mathrm{kg}_{\mathrm{H_2O}} + \mathrm{kg}_{\text{dry solid}}}$$

$$H_s = \frac{\mathrm{kg}_{H_2O}}{\mathrm{kg}_{\text{dry solid}}}$$

$$\frac{1}{0.05} = 1 + \frac{\mathrm{kg}_{\text{dry solid}}}{\mathrm{kg}_{\mathrm{H_2O}}} \Rightarrow \frac{1}{0.05} - 1 = \frac{1}{\mathrm{H}_s}$$

$$\Rightarrow \mathrm{H}_s = {}^{1}\!/_{\frac{1}{0.05}-1} = 0.053\ \mathrm{kg}_{\mathrm{H_2O}}/\ \mathrm{kg}_{\text{dry solid}}$$



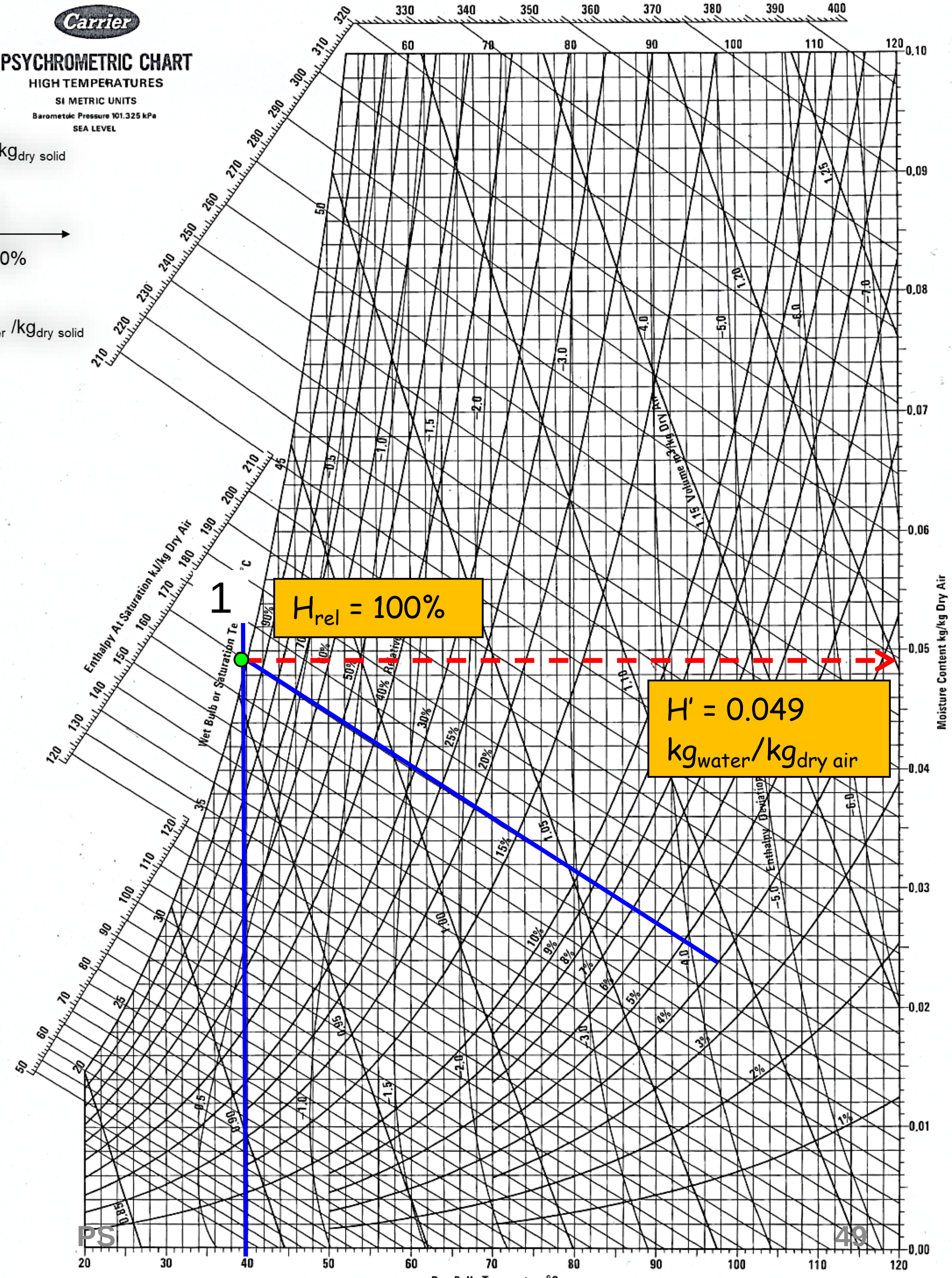
Relations: (i) $H'_{G2} = H'_{G1}$

(ii) $T_{h3} = T_{h2}$

In the system water + air: $T_{sa} = T_h$

$$(1)\begin{cases} T_{h1} = 40°C \\ T_{G1} = 40°C \end{cases}$$

$$\triangleright \begin{cases} H'_1 = 0.049\ kg/kg \\ H_{rel1} = 100\% \end{cases}$$



$H_{S,in}$ = 2.33 kg_{water} /$kg_{dry\ solid}$

(1) → HEAT → (2) → DRYER ADIABATIC → (3)

(1): T_G = 40°C, T_h = 40°C

(2): T_G = 80°C

(3): H_{rel} = 90%

$H_{S,out}$ = 0.053 kg_{water} /$kg_{dry\ solid}$

M_S = 45 kg/h dry solid

Relations: (i) $H'_{G2} = H'_{G1}$

(ii) $T_{h3} = T_{h2}$

In the system water + air: $T_{sa} = T_h$

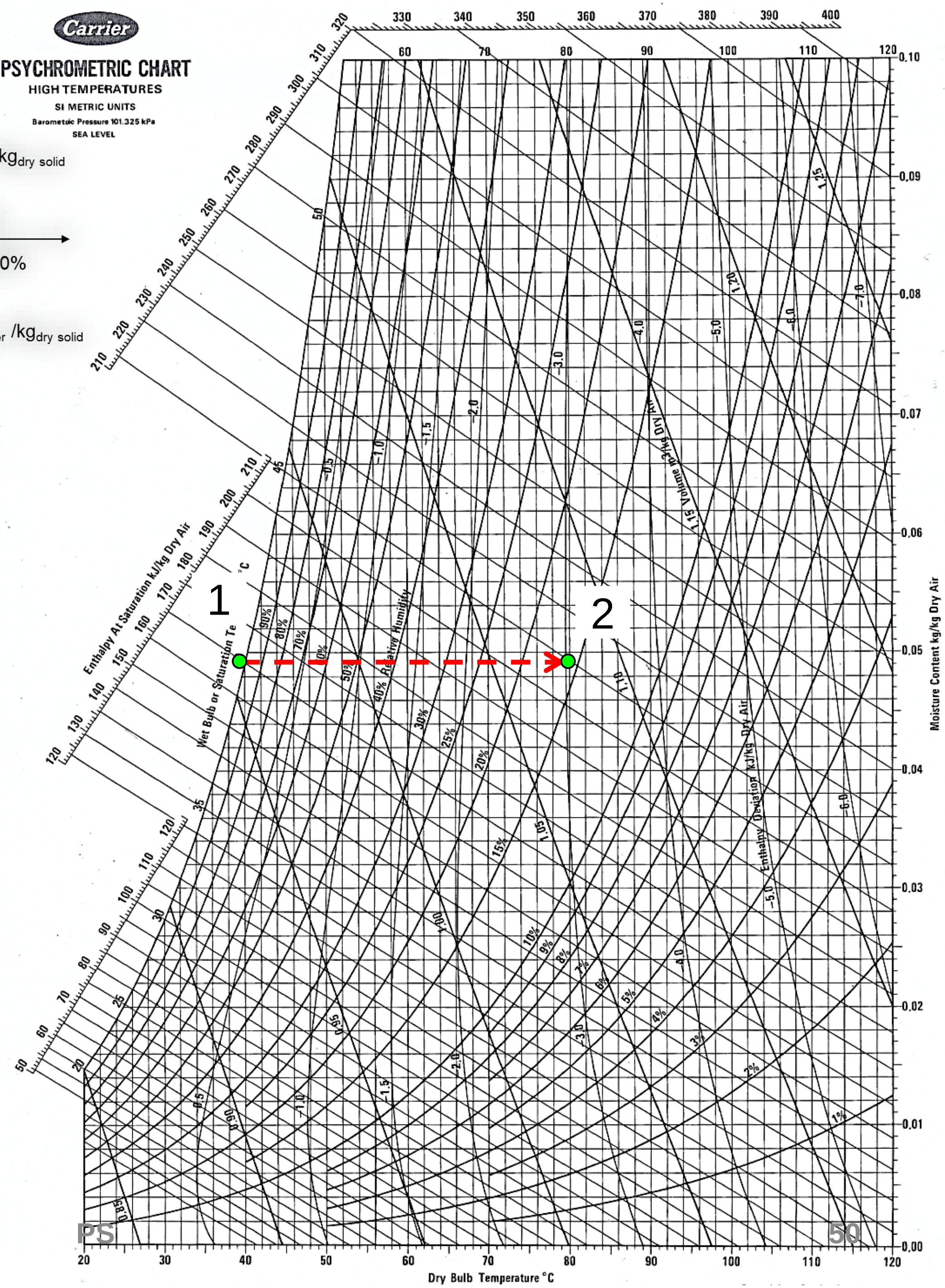
(1) → HEAT → (2)

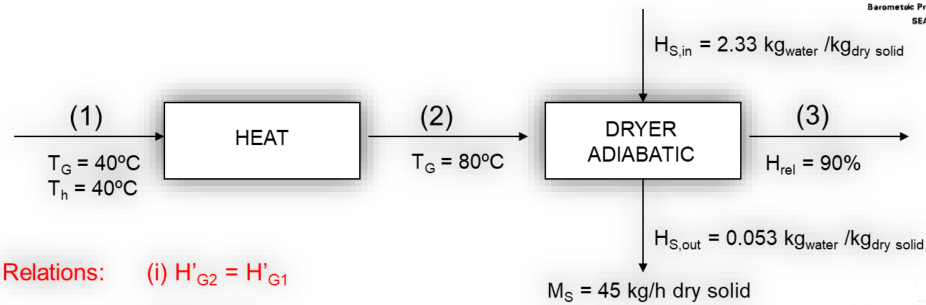
(1): T_G = 40°C, T_h = 40°C

(2): T_G = 80°C

$$\begin{cases} H'_2 = H'_1 = 0.049 \\ T_{G2} = 80°C \end{cases}$$

$$\begin{cases} H_{rel2} \cong 16\% \\ T_{h2} = 45°C \end{cases}$$

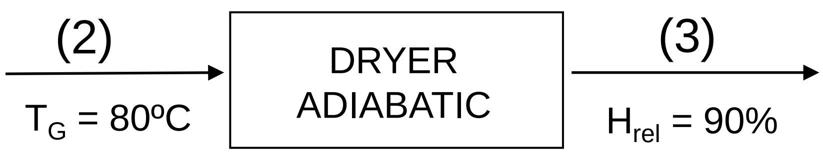




Relations: (i) $H'_{G2} = H'_{G1}$

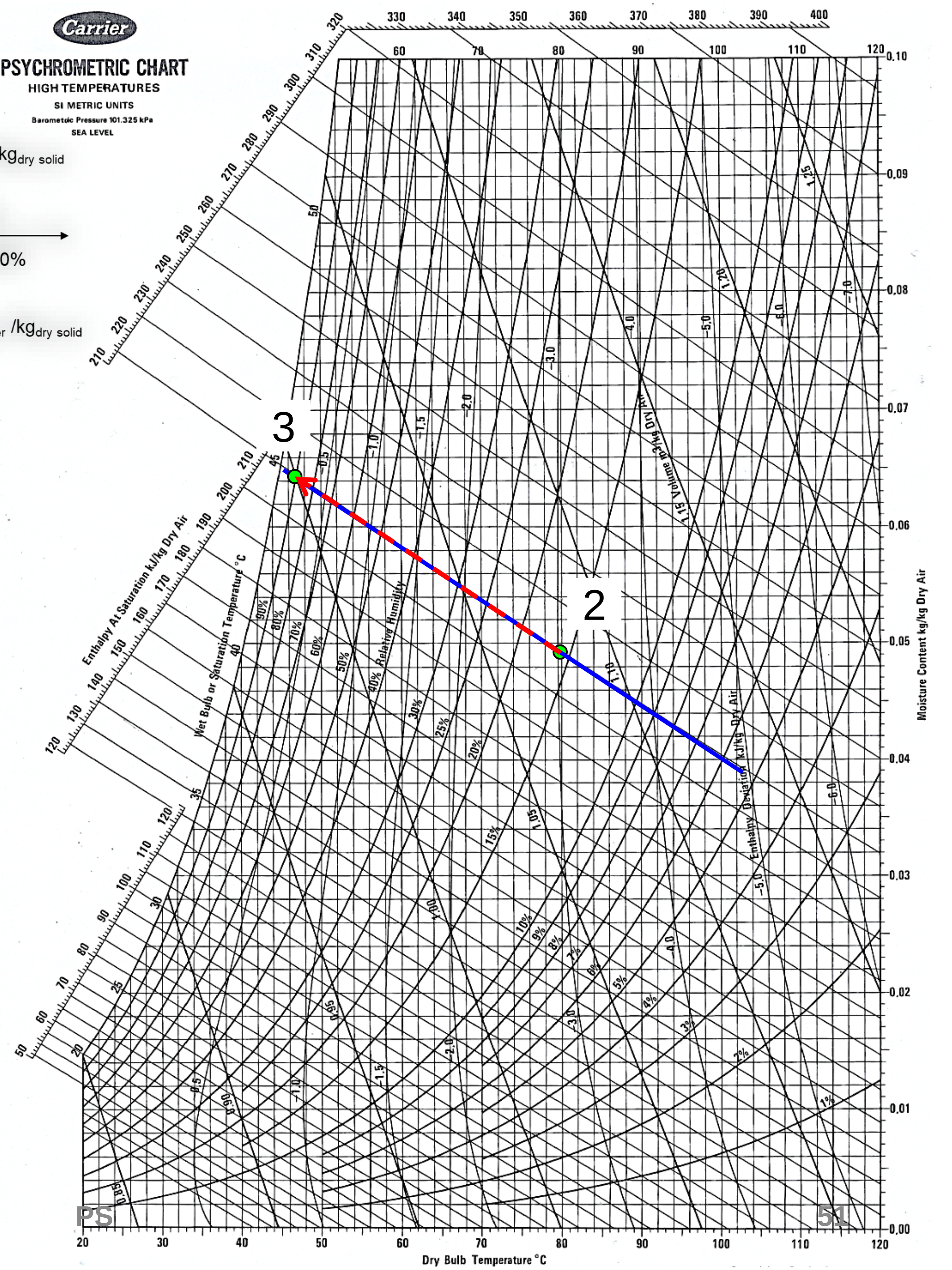
(ii) $T_{h3} = T_{h2}$

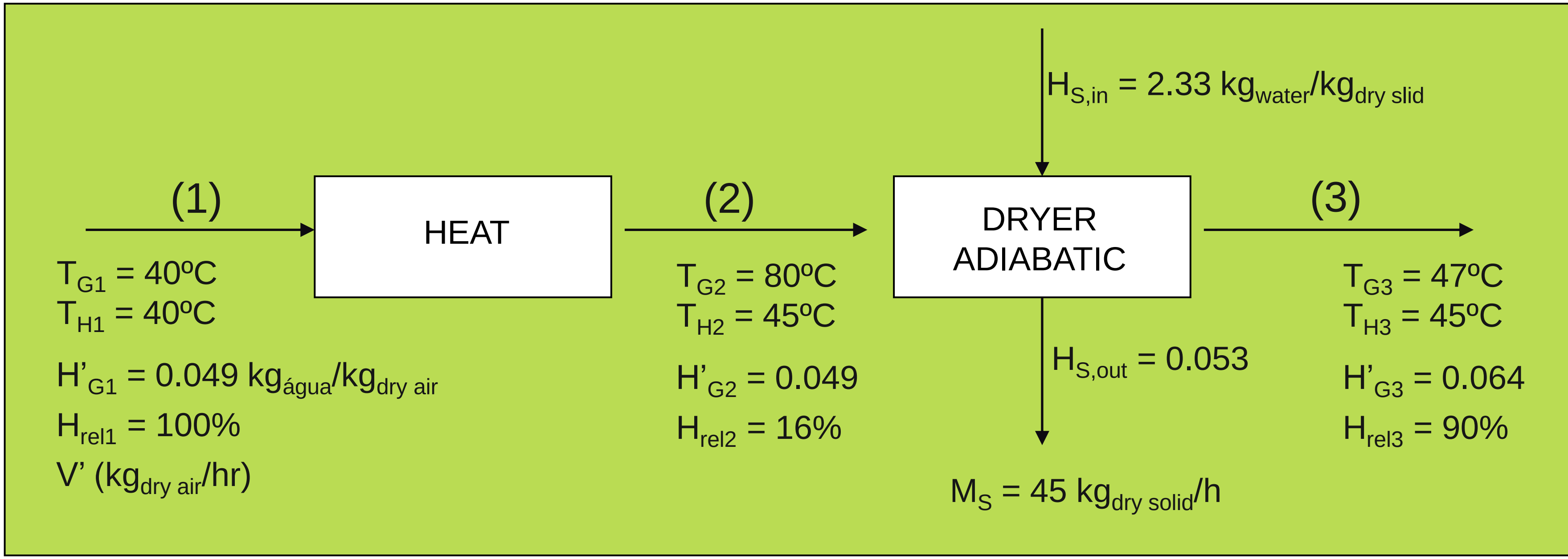
In the system water + air: $T_{sa} = T_h$



$$\begin{cases} H_{rel3} = 90\% \\ T_{h3} = T_{h2} = 45°C \end{cases}$$

$$\begin{cases} H'_3 = 0.064 \\ T_{G3} = 47°C \end{cases}$$





Mass of water that has come out of the solid per hour = Mass of water that has passed into the air per hour

$$M_S\,(H_{S,in} - H_{S,out}) = V'(H'_{G3} - H'_{G2})$$

$$\Rightarrow \quad V' = 45\,\frac{(2.33 - 0.053)}{(0.064 - 0.049)} = 6831\ \mathbf{kg_{dry\ air}/h}$$