Humidification / Dehumidification Processes

(System Air - Water)

Processos de Separação

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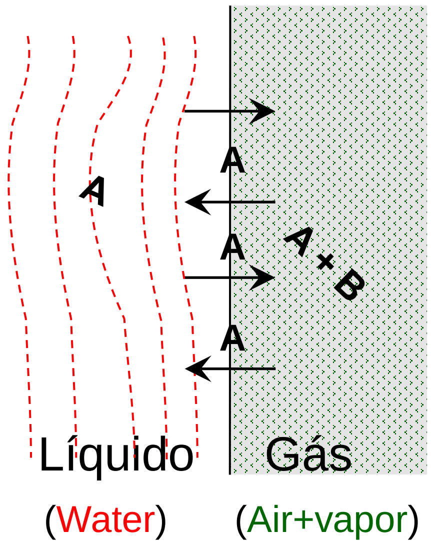
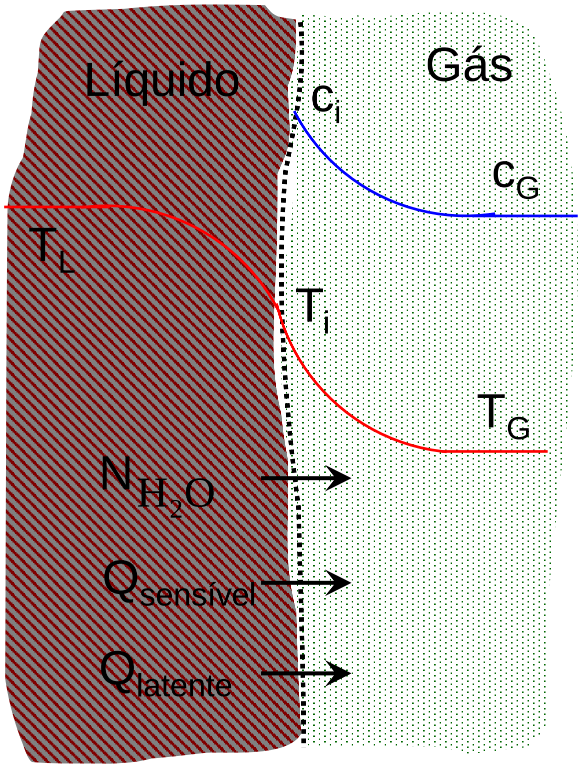
Humidification / Dehumidification

Transfer of heat and mass that occurs when a gas phase contacts a liquid phase (pure or not)



The two phases are immiscible.

Humidification Process



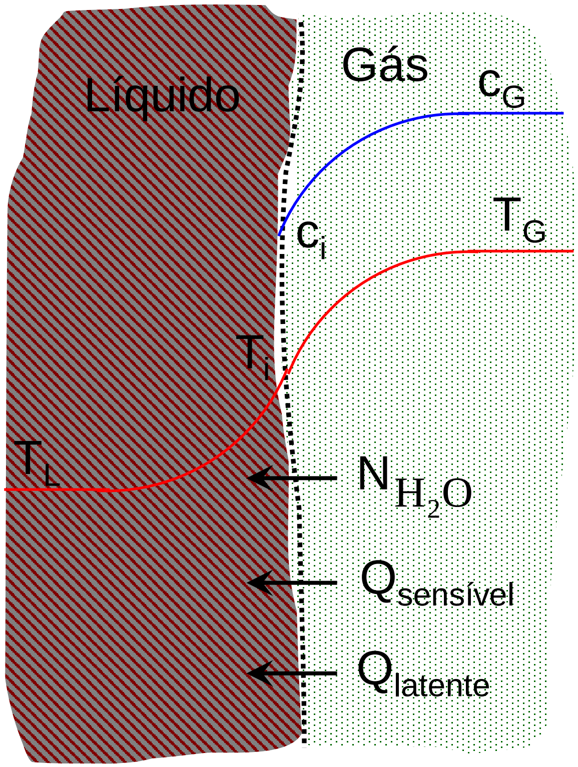
$T_G < T_L$

- evaporation of water
- transport of heat $L \rightarrow G$
- transport of mass $L \rightarrow G$

→ Cooling of water

cooling towers

Dehumidification Process



$T_G > T_L$

- condensation of vapor
- transport of heat $G \rightarrow L$
- transport of mass $G \rightarrow L$

$\rightarrow$ Cooling of gas!

Mixtures VAPOR (A) - GAS (B)

Moisture

Is the amount, in moles or mass, of vapor (A) present per unit of mol or mass of gas (B). (mol_A/mol_B or kg_A/kg_B)

Air at a certain temperature supports a defined quantity of moisture, which is designed as moisture at equilibrium or at saturation.

- Moisture content, H

$$H_{molar} = \frac{y_A}{y_B} = \frac{\bar{p}_A}{\bar{p}_B} = \frac{\bar{p}_A}{P - \bar{p}_A} \equiv \frac{\text{moles de A}}{\text{moles de B}}$$

$$H'_{mássico} = H_{molar}\frac{M_A}{M_B} \equiv \frac{\text{massa de A}}{\text{massa de B}}$$

<u>At saturation:</u>

$$\bar{p}_A \Leftrightarrow p_{\mathrm{v}_A}\Big|_T$$

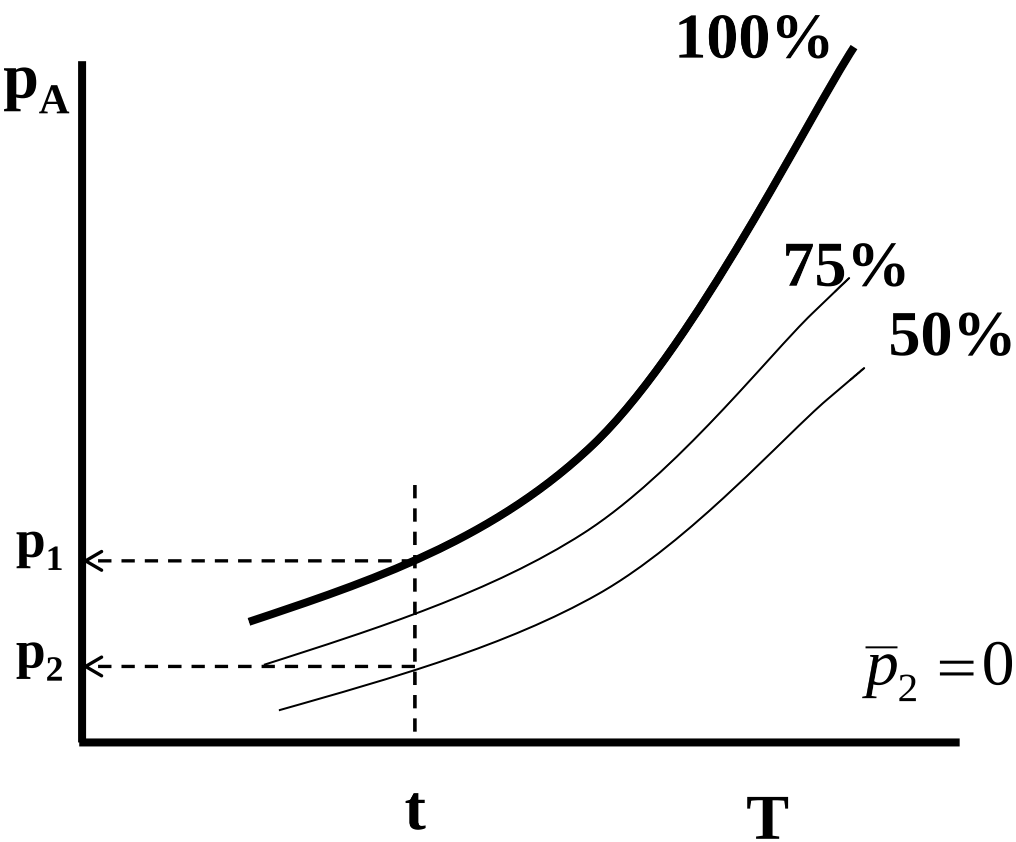
$$H_{saturação} = \frac{\bar{p}_A}{\bar{p}_B} = \frac{p_{\mathrm{v_A}}}{P - p_{v_A}}$$

$$H'_s = H_s\frac{M_A}{M_B}$$

Relative saturation, H_{rel}

Ratio partial pressure and vapor pressure of *A*, at a given temperature.

$$H_{rel} = 100 \times \left.\frac{\bar{p}_A}{p_{v_A}}\right|_T$$

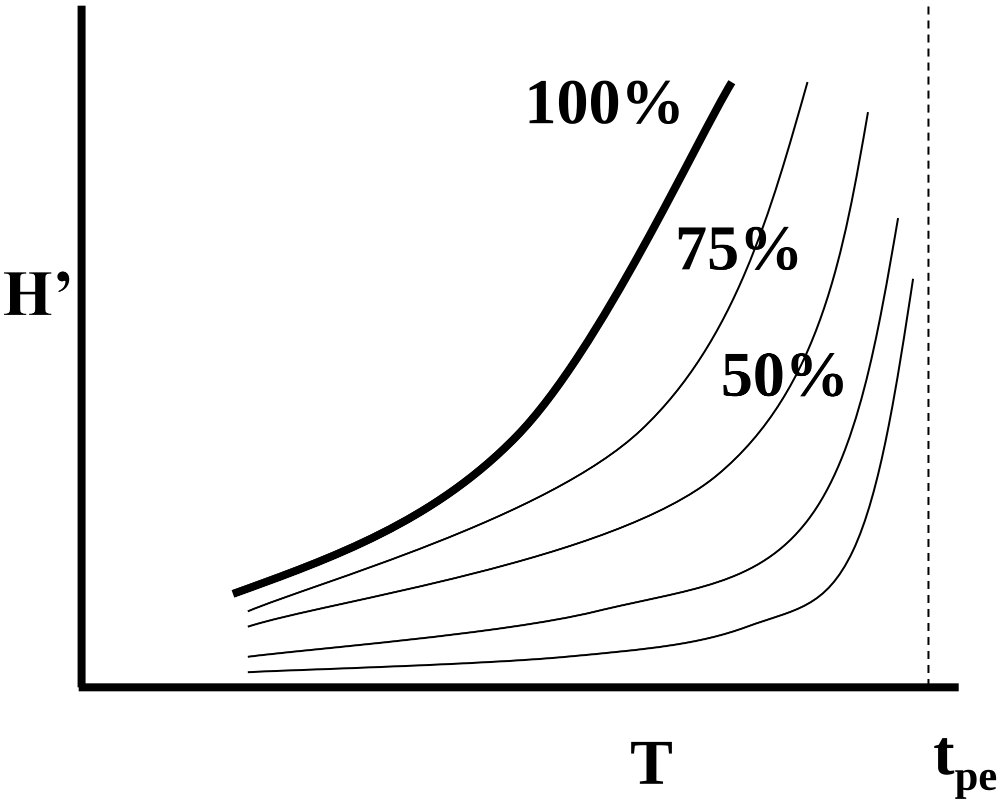


$$\bar{p}_2 = 0.5 \times \bar{p}_1$$

$$\equiv \left. p_{v_A} \right|_T$$

Percentage of saturation), %H

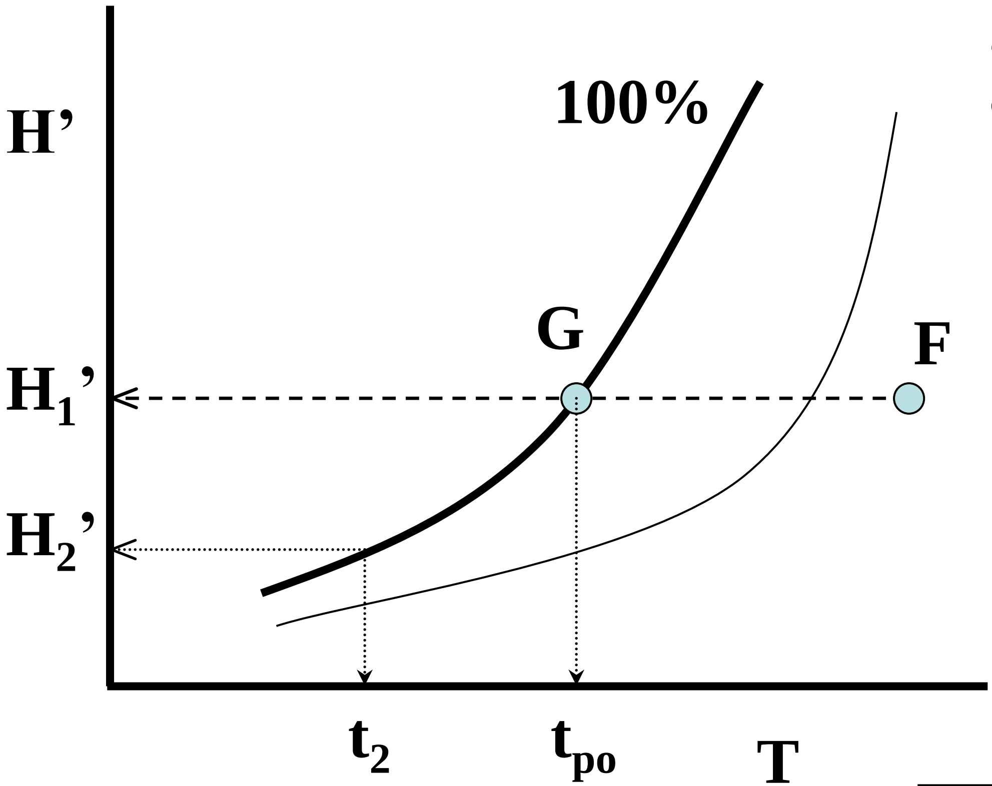
Ratio of moisture contente and moisture at saturation at a given temperature.



$$\%H = 100 \times \left.\frac{H}{H_s}\right|_T = 100 \times \left.\frac{H'}{H'_s}\right|_T$$

Dew point, t_{po}

Temperature at which mixture A+B becomes saturated by cooling.



Mixture with H'_1 saturates in G by cooling from F

if $t < t_{po}$ => vapor condenses!

(following the saturation curve)

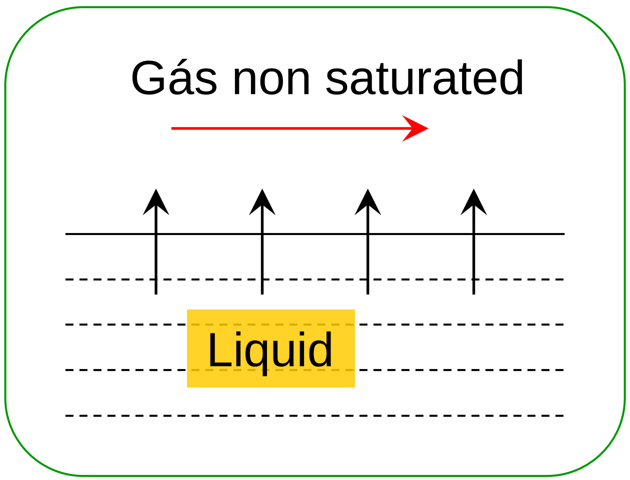
<u>Exemple</u>

Condensation $t_{po} \rightarrow t_2$:

$$\frac{\text{massa de vapor condensado}}{\text{massa de gás seco}} = H'_1 - H'_2$$

Wet bulb temperature, t_h

Temperature obtained at steady-state by a low quantity of liquid *A* phevaporating in a large quantity of gas fase *A+B* insaturated.



<u>Evaporation of liquid</u>

=> Temperature of liquid decreases being lower than the gas: $T_L < T_G$

=> Flux of heat: $G \rightarrow L$

∴ In equilibrium, the heat given by the gas = heat necessary to evaporate the liquid!

Wet bulb temperature ≡ temperature of liquid at equilibrium!

Dry bulb temperature, t_b

Temperature of gas phase measured by a thermometer; is independent of moisture.

Wet bulb temperature

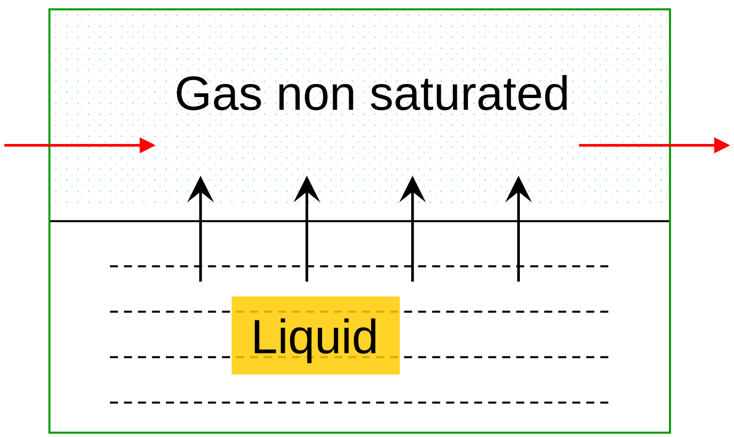
- ✓ Depends on air moisture
- ✓ If $t_h < t_b$ => mixture A+B is insaturated!

  If $t_h = t_b$ => mixture A+B is saturated!

Adiabatic saturation temperature, t_{sa}

Temperature of a gas mixture A+B when saturated at adiabatic conditions

Adiabatic Operation



<u>Enough time of contact</u>

=> Equilibrium of phases

✭ Gas becomes saturated

✭ Both phases at the same temperature: t_{sa}

T_{gas} decreases from t to t_{sa} and moisture increases from H' to H'_{sa}

✓ The heat necessary to evaporate the liquid comes from the gas:

$$\underbrace{-\lambda(H'-H'_{sa})} = \underbrace{c_p(T-T_{sa})}$$

$$\boxed{H'-H'_{sa} = -\frac{c_p}{\lambda}(T-T_{sa})}$$

→ Equation of the curve: curve de adiabatic saturation a

With slope c_p/λ and with coordinates (H'_i, t_i) and (H'_{sa}, t_{sa})

100% H'

Enthalpy, E, of a mixture A+B

At temperature, t_G, and moisture H´ :

$$E = \underbrace{c_{p_B}(t_G - t_0)}_{E_B} + H'\underbrace{\left[\lambda_0 + c_{p_A}(t_G - t_0)\right]}_{E_A} \qquad [=]\, J/kg_{\text{ar seco}}$$

$$\boxed{E = c_{p_h}(t_G - t_0) + H'\lambda_0}$$

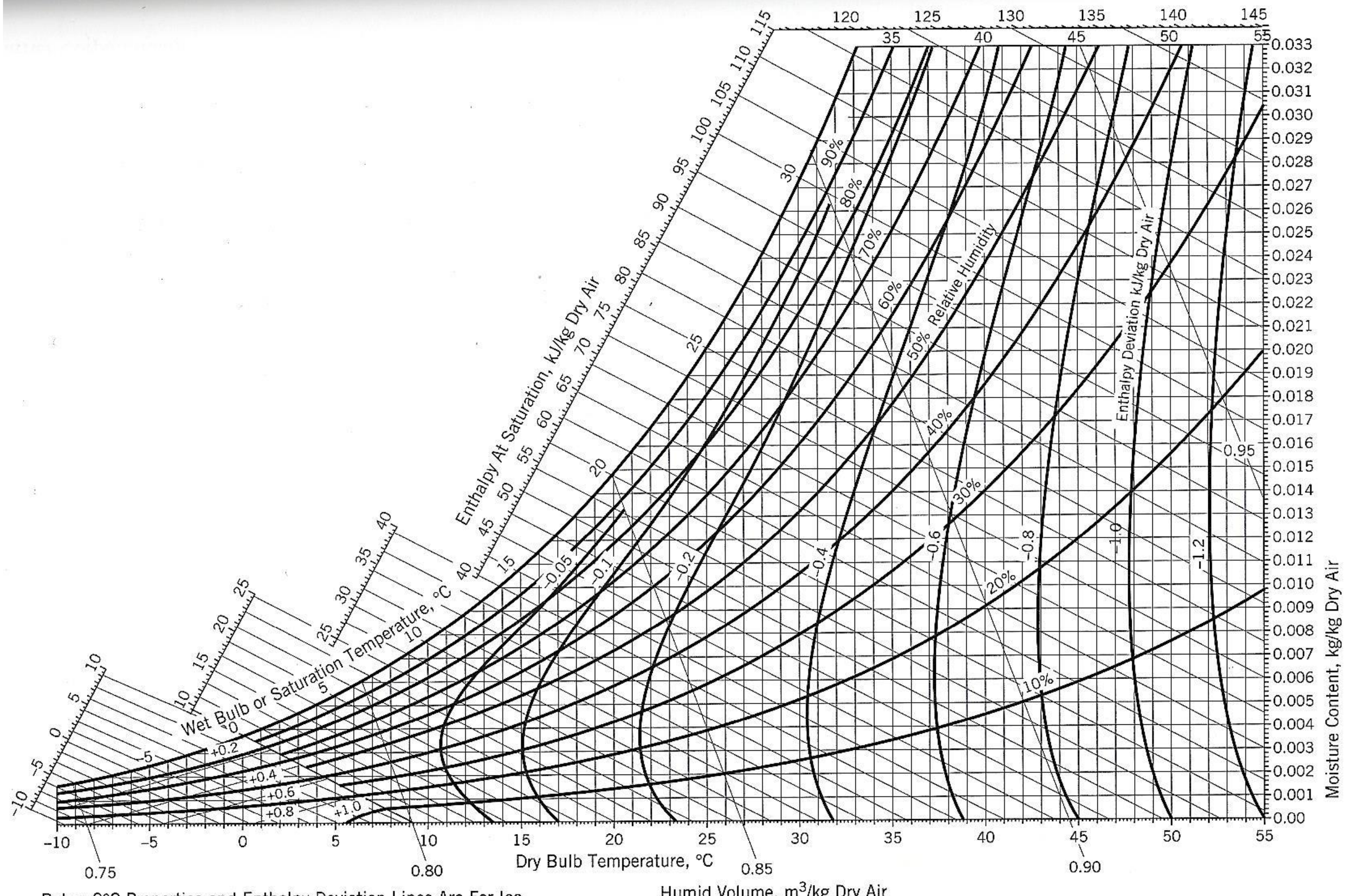
Humid specific heat $\quad c_{p_h} = c_{p_B} + H' c_{p_A}$

System Air + Water - psycrometric chart

Psycrometry: study of air and variation of the properties with climate.

Pressure: 1 atm

Reference: 0°C; air, water



Below 0°C Properties and Enthalpy Deviation Lines Are For Ice

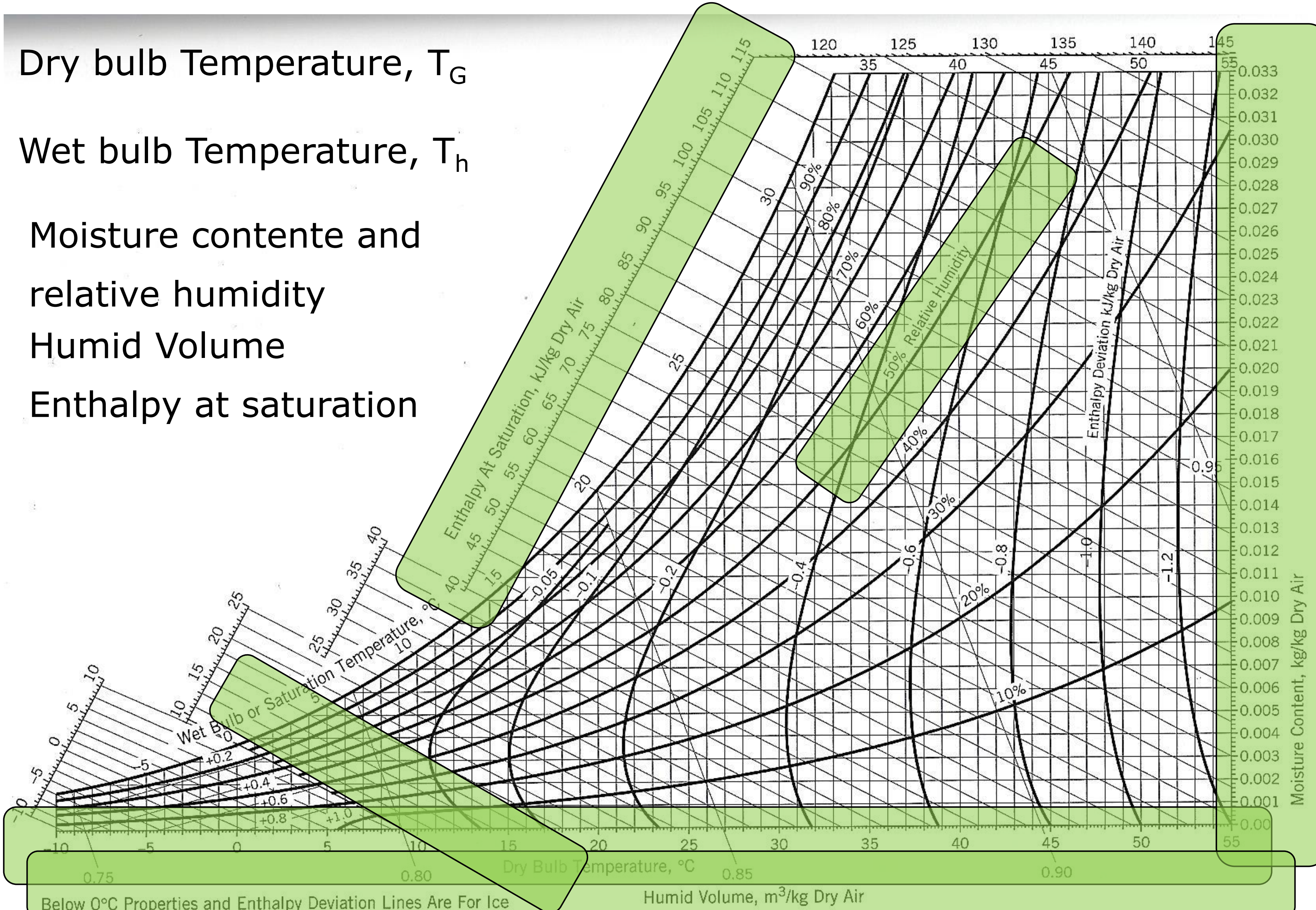
Dry bulb Temperature, T_G

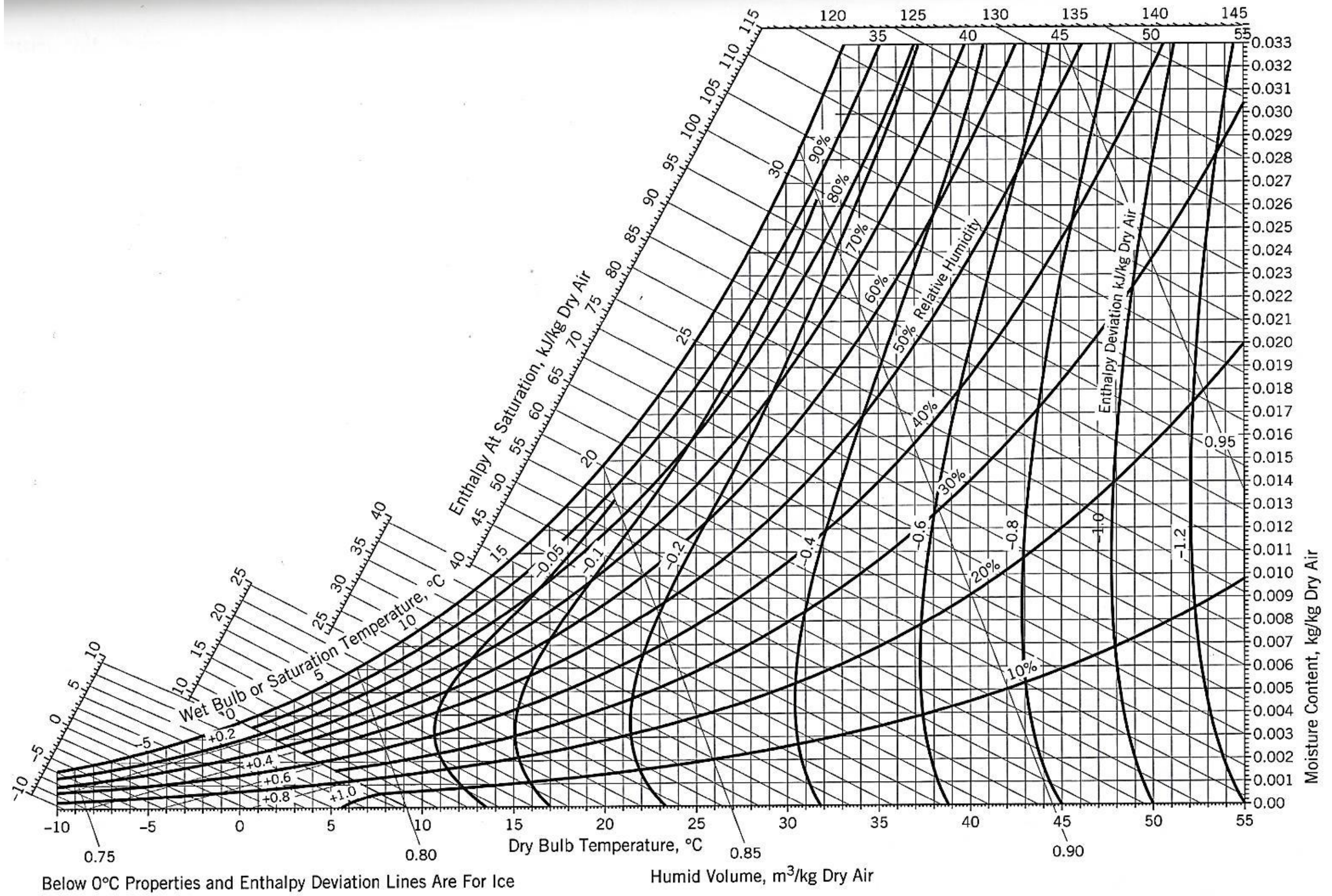
Wet bulb Temperature, T_h

Moisture contente and relative humidity

Humid Volume

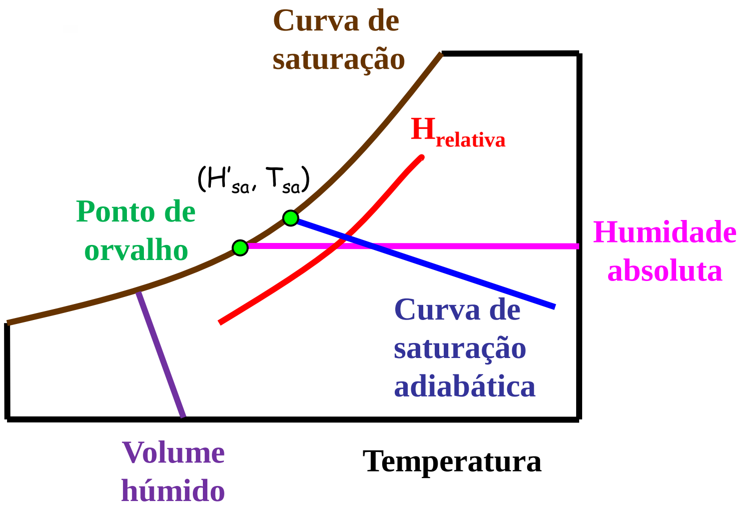
Enthalpy at saturation

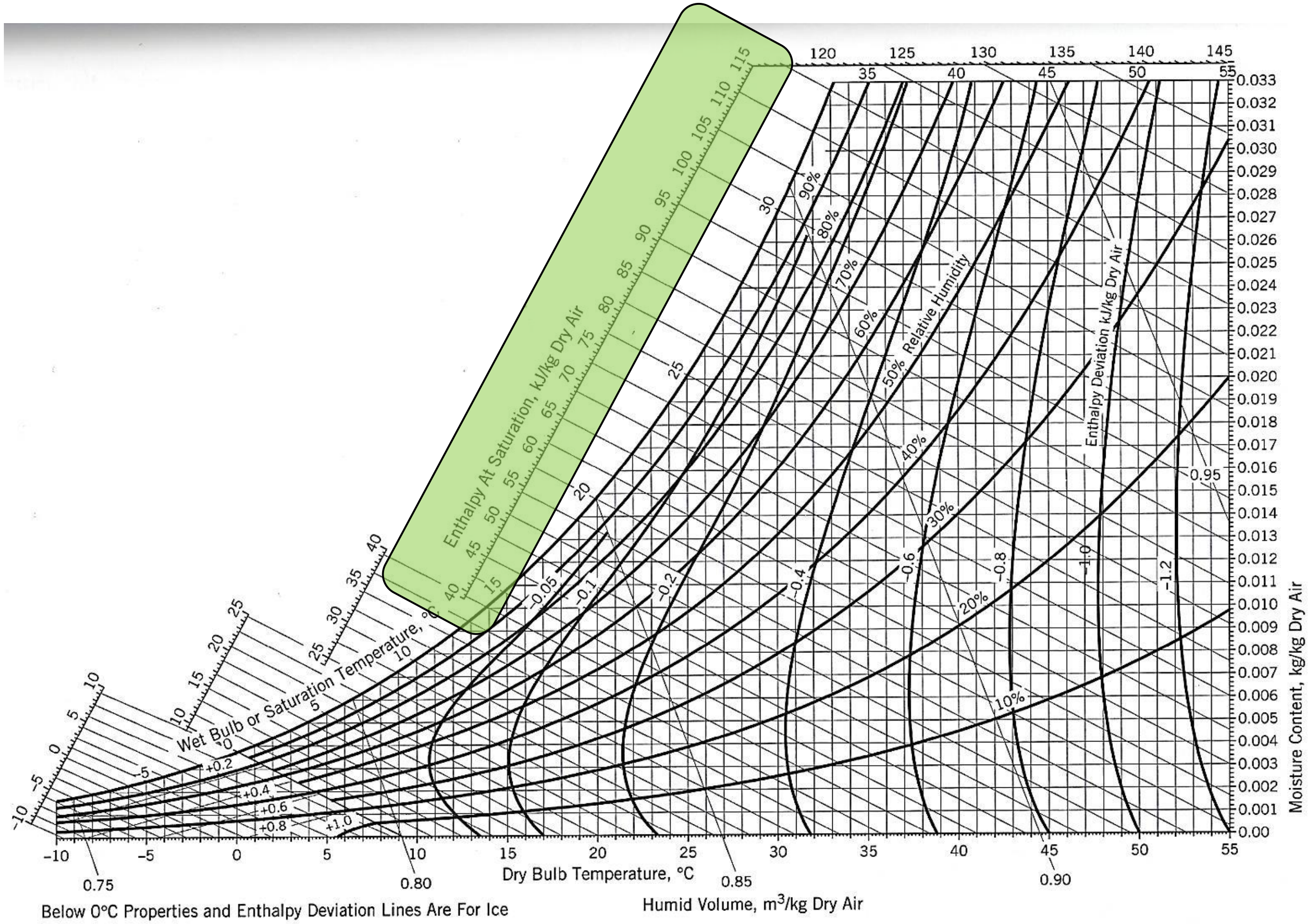




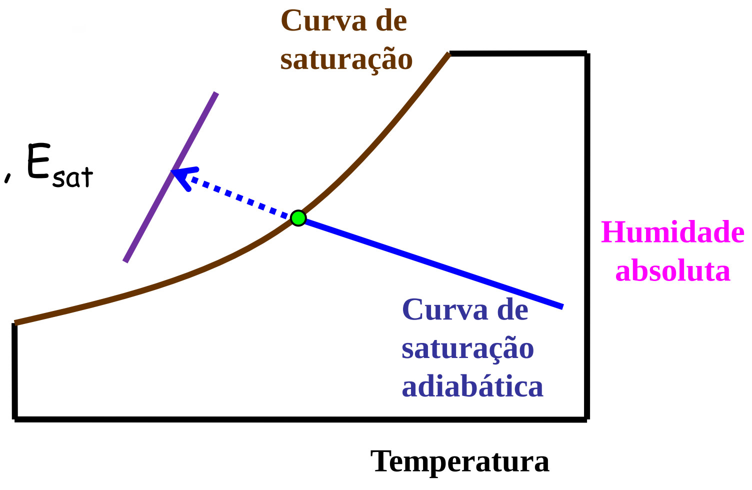
$H_{rel} \cong \%H$!

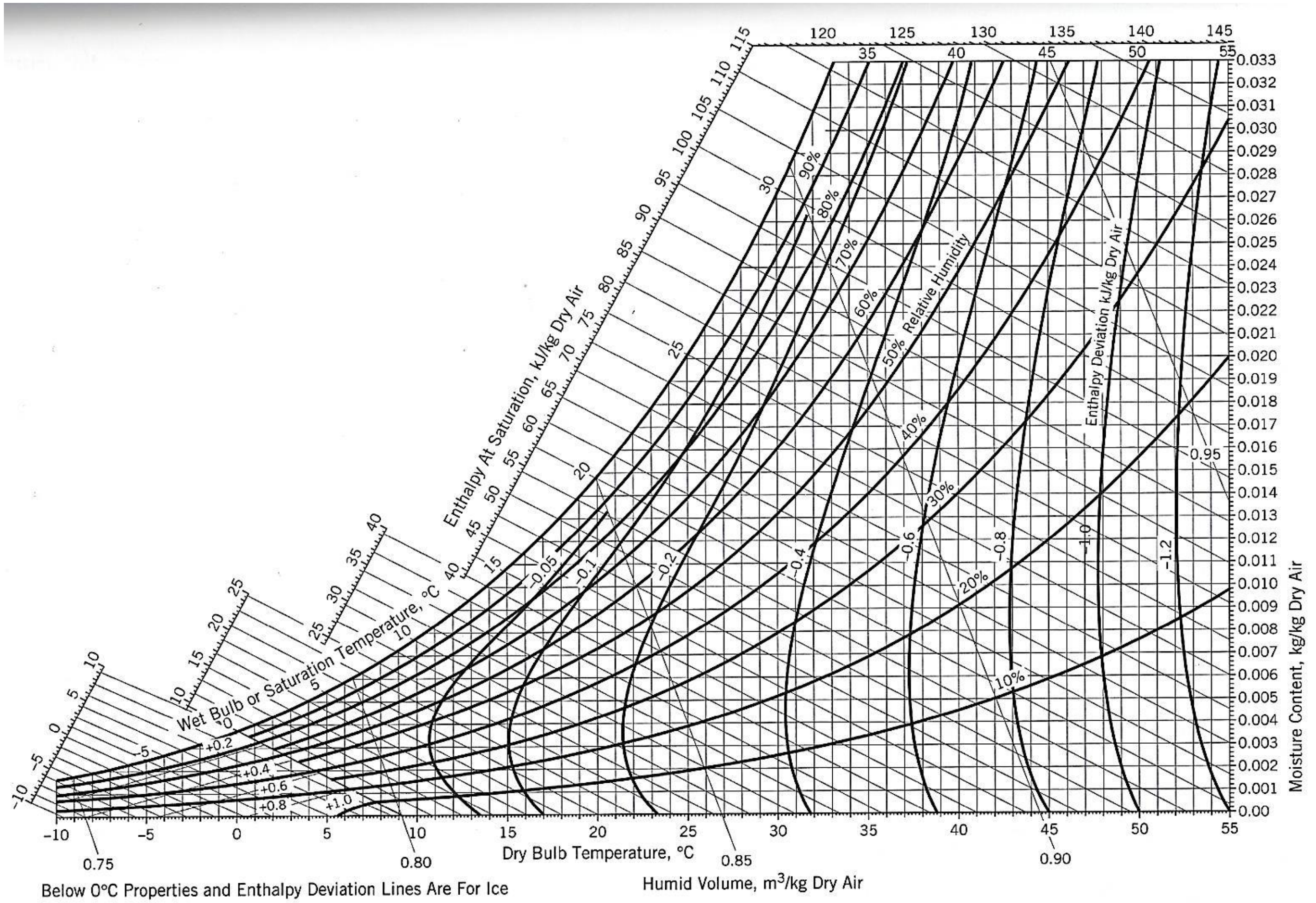
$T_h \cong T_{sa}$!



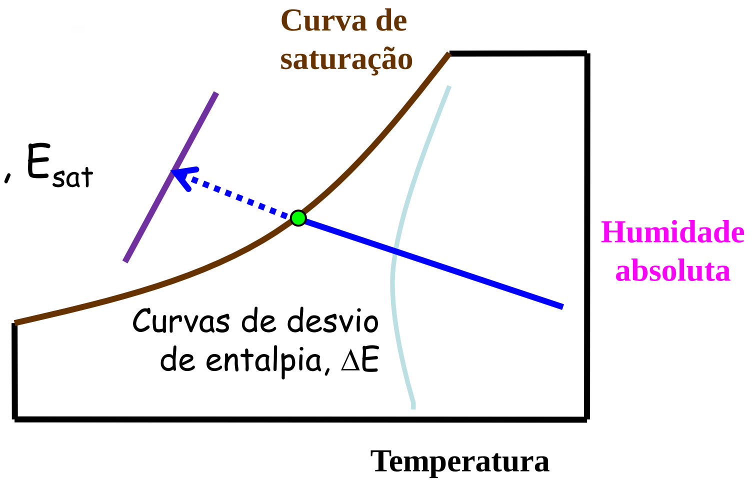


Entalpia de ar saturado, E_{sat}





Entalpia de ar saturado, E_{sat}

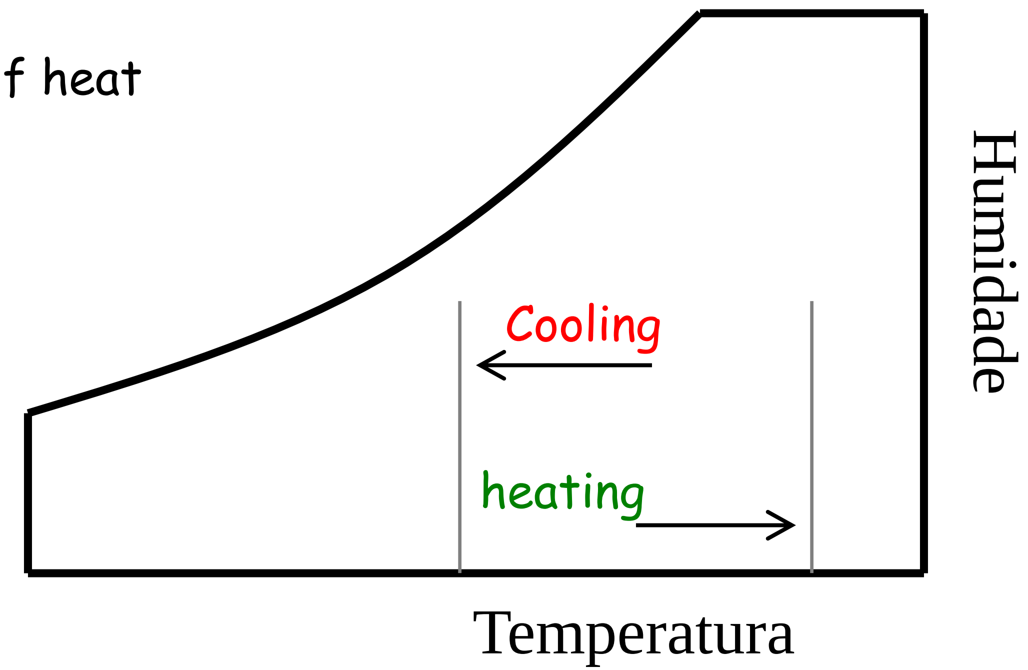


$$\boxed{E_{\mathrm{ar},T_G} = E_{\mathrm{sat},T_G} + \Delta E}$$

Psycrometric Processes

1. Heating / cooling

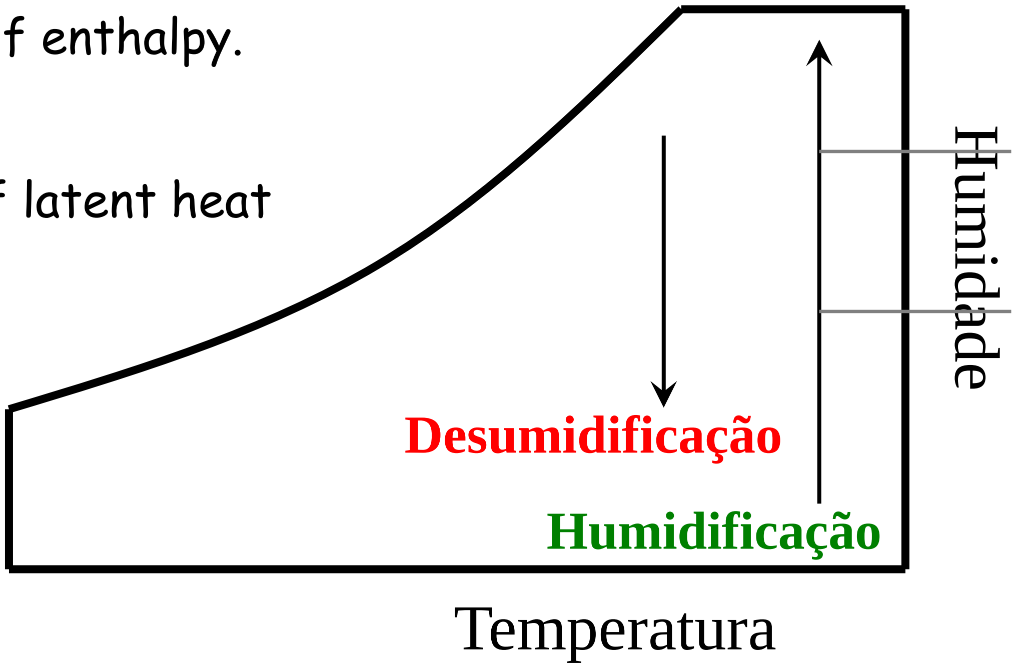
- Moisture does not change
- Heat variation of mixture A+B
- Necessary addition or removal of heat



2. Humidification / dehumidification

- Humidification: water vapor added to the mixture A+B; increase of the enthalpy of mixture.
- Dehumidification: removal of moisture from the mixture A+B by water condensation; decrease of enthalpy.

- Necessary addition or removal of latent heat



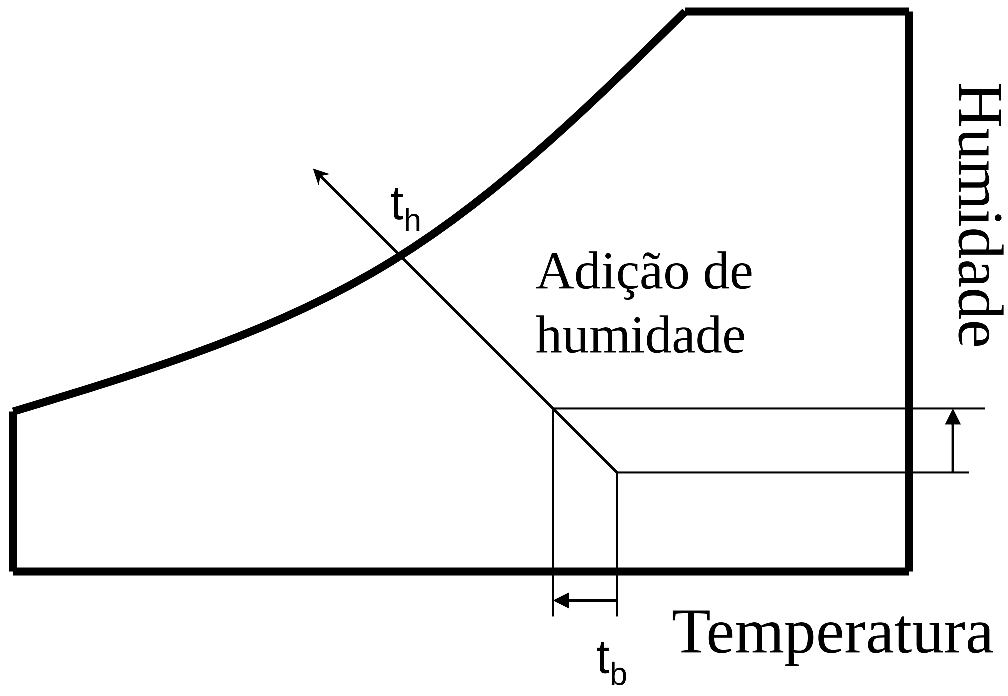
3. Adiabatic Saturation

• transfer of heat from the gas to the liquid; water evaporates to gas increasing its moisture.

• there is no gain or loss of heat in the system; heat removed = latent heat.

$\Rightarrow t_b \searrow$

$\Rightarrow \Delta t$ máximo: $t_b - t_h$



Problem 1

Consider air at 1 atm and 30°C with relative humidity of 30%. Using the psicrometric chart, determine:

a) The wet bulb temperature

b) The moisture content

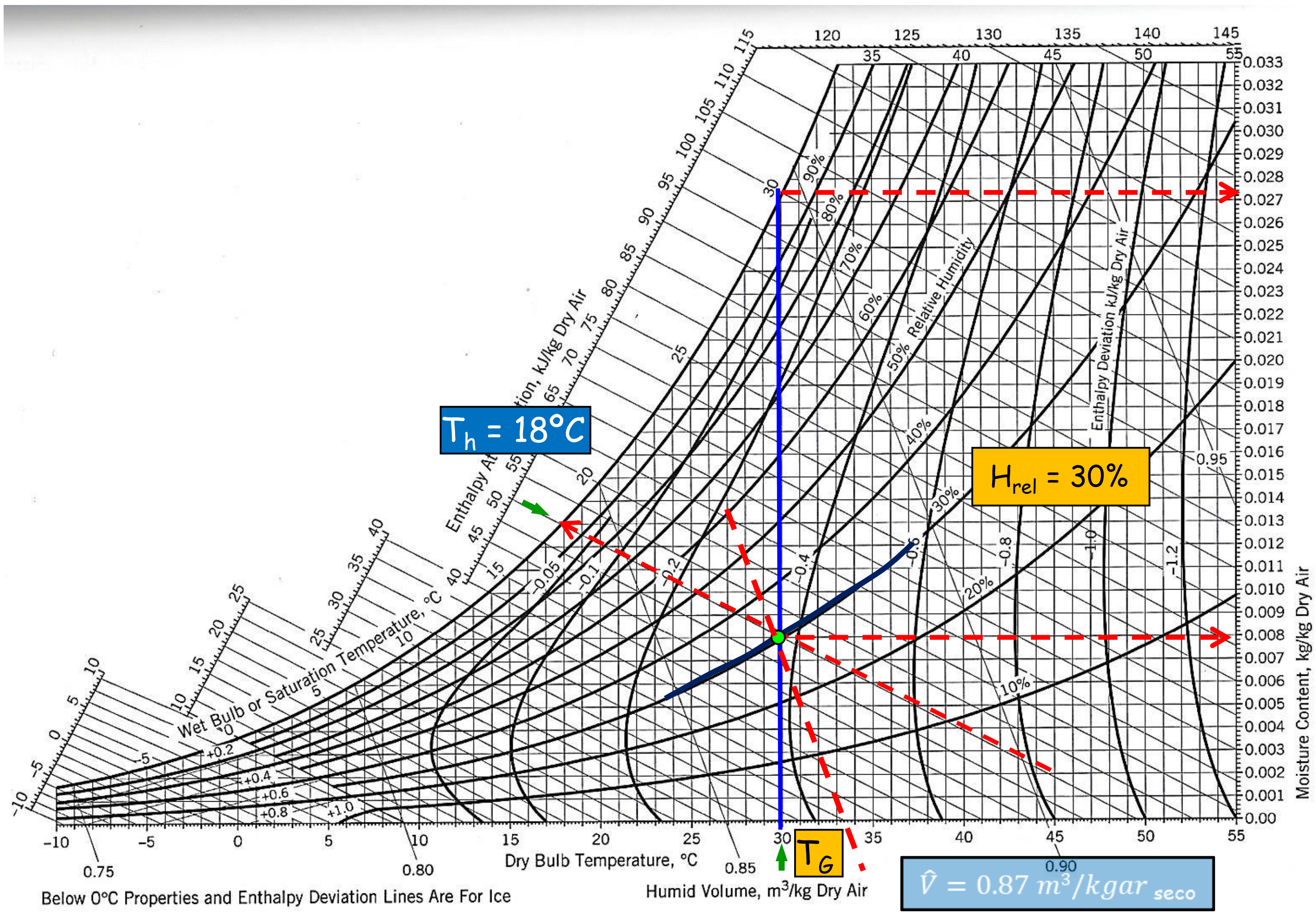
c) The moisture at saturation

d) The enthalpy of the gas

e) The amount of water in 150 m^3 of air

(a) T_h; H'; H_{sat}

$$\begin{cases} H_{rel} = 30\% \\ T_G = 30°C \end{cases}$$

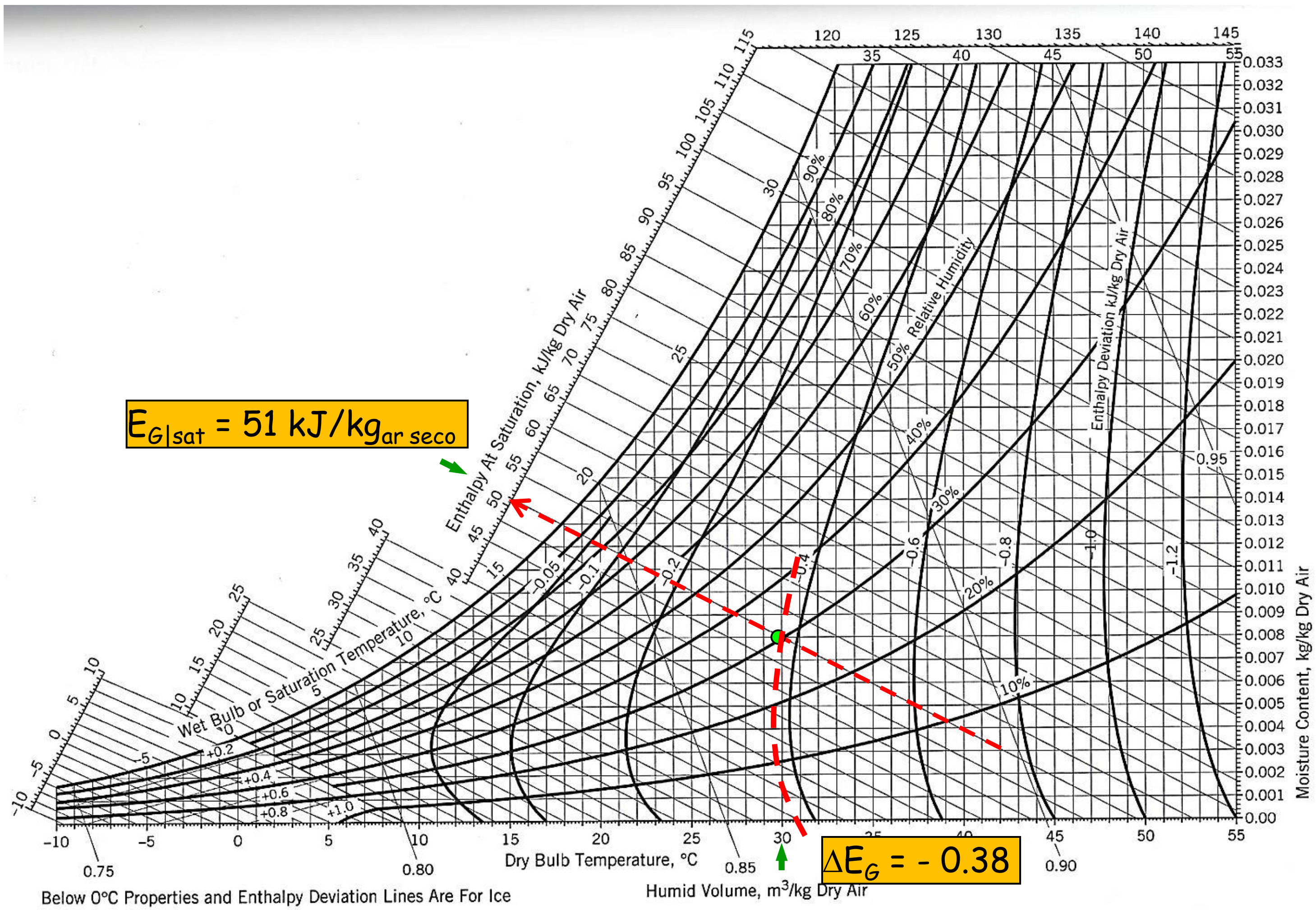


$H'_{sat} = 0.0272\ kg_{água}/kg_{ar\ seco}$

$H' = 0.008\ kg_{água}/kg_{ar\ seco}$

(d) E_G

$$E_{\mathrm{ar},T_G} = E_{\mathrm{sat},T_G} + \Delta E = 51 + (-0.38) = 50.62\, kJ / kg_{ar\,\mathrm{sec}\,o}$$

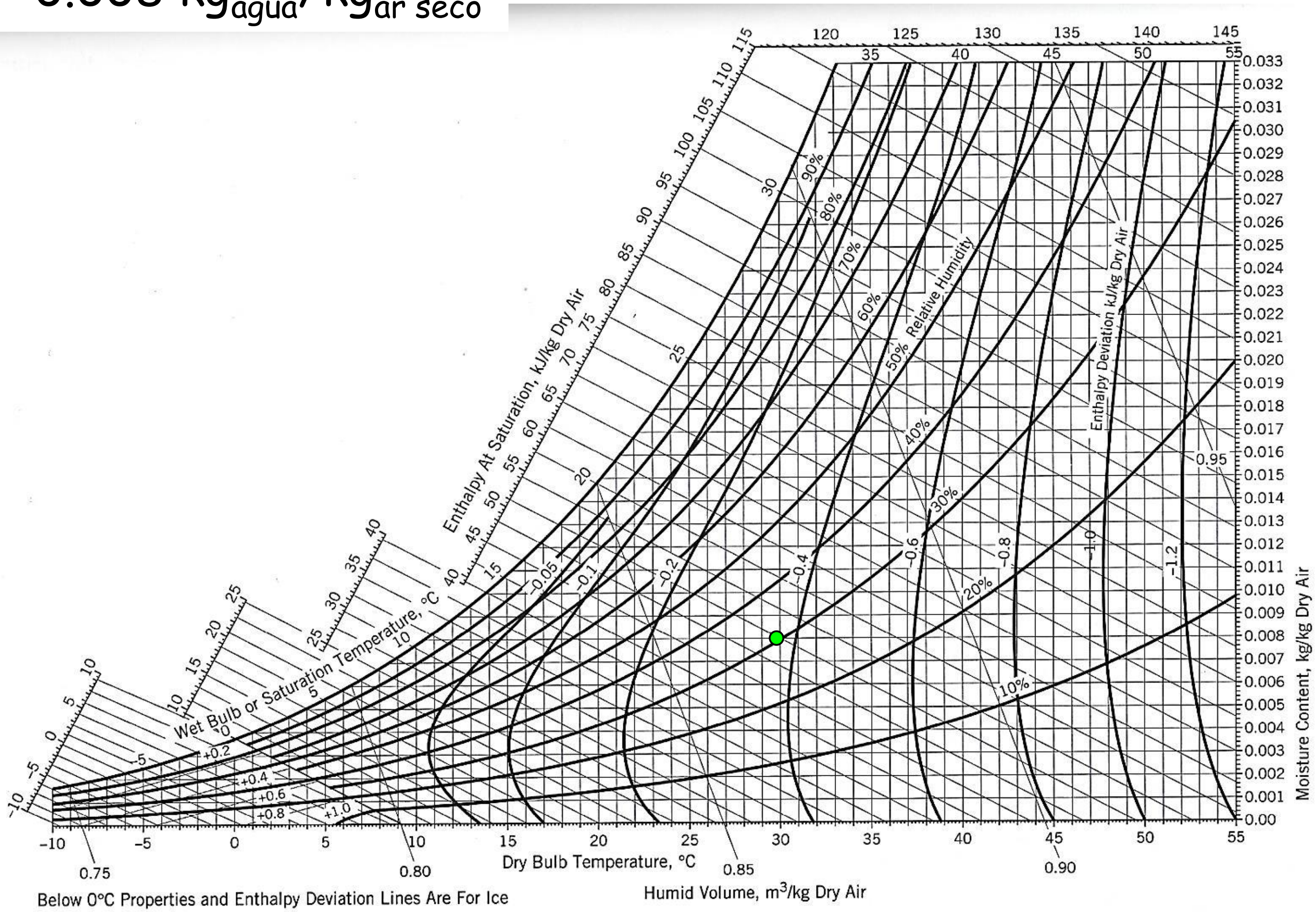


(e) massa de água contida em 150 m³ de ar a 30°C e 30% H_{rel}

$$\hat{V} = 0.87\ m^3/kg_{\text{ar seco}}$$

$$m_{água} = \frac{150\ m^3}{0.87\,\frac{m^3}{kg_{ar\ seco}}} \times 0.008\,\frac{kg_{água}}{kg_{ar\ seco}} = 1.38\ kg_{água}$$

$$H' = 0.008\ kg_{água}/kg_{\text{ar seco}}$$



Problem 2

Air at 45°C has a moisture corresponding at a wet bulb temperature of 30°C.

Determine:

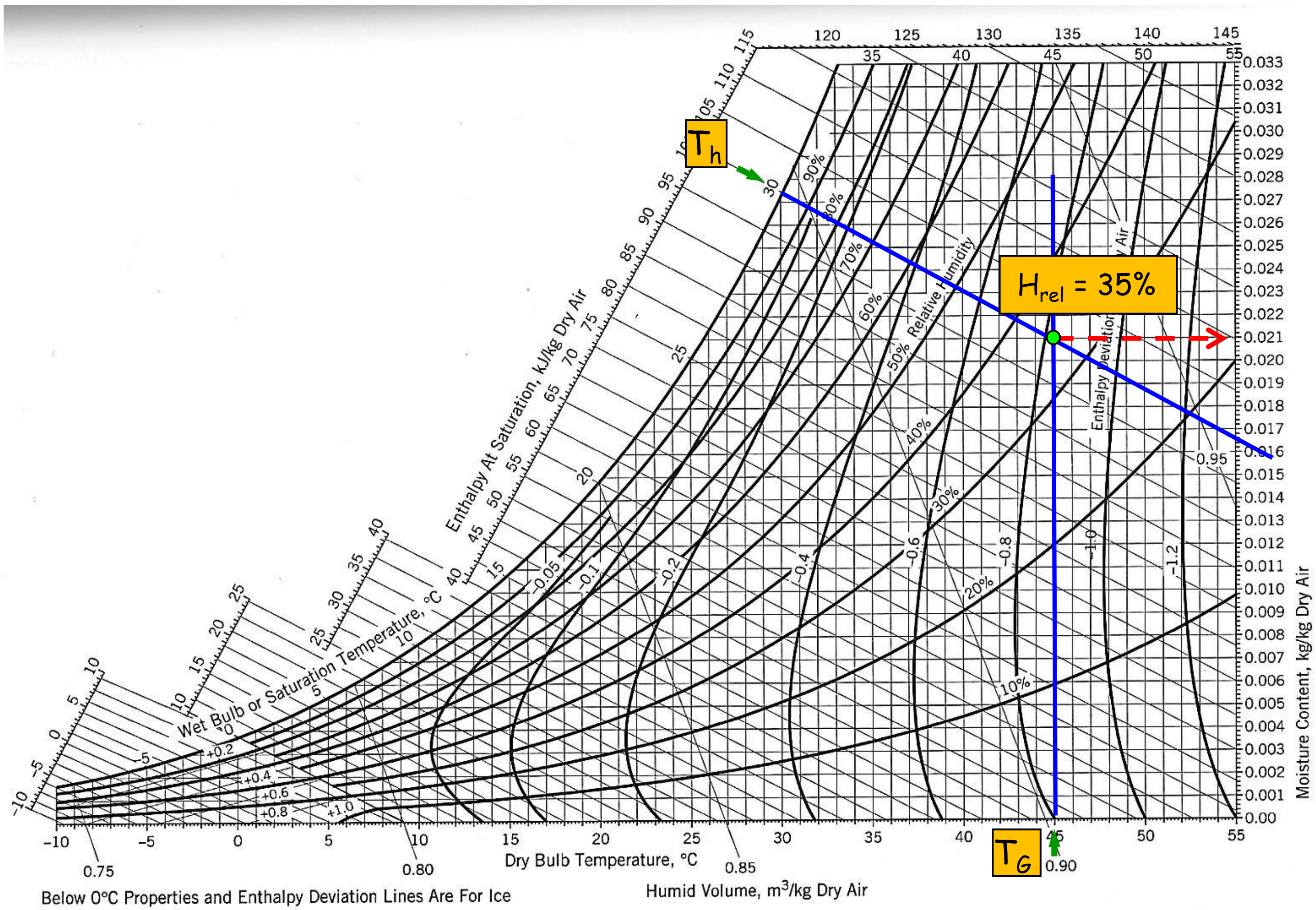
1) The moisture and the relative humidity of the.

2) The dew point temperature.

3) The amount of condensate if air is cooled to 15°C.

1) H', %H

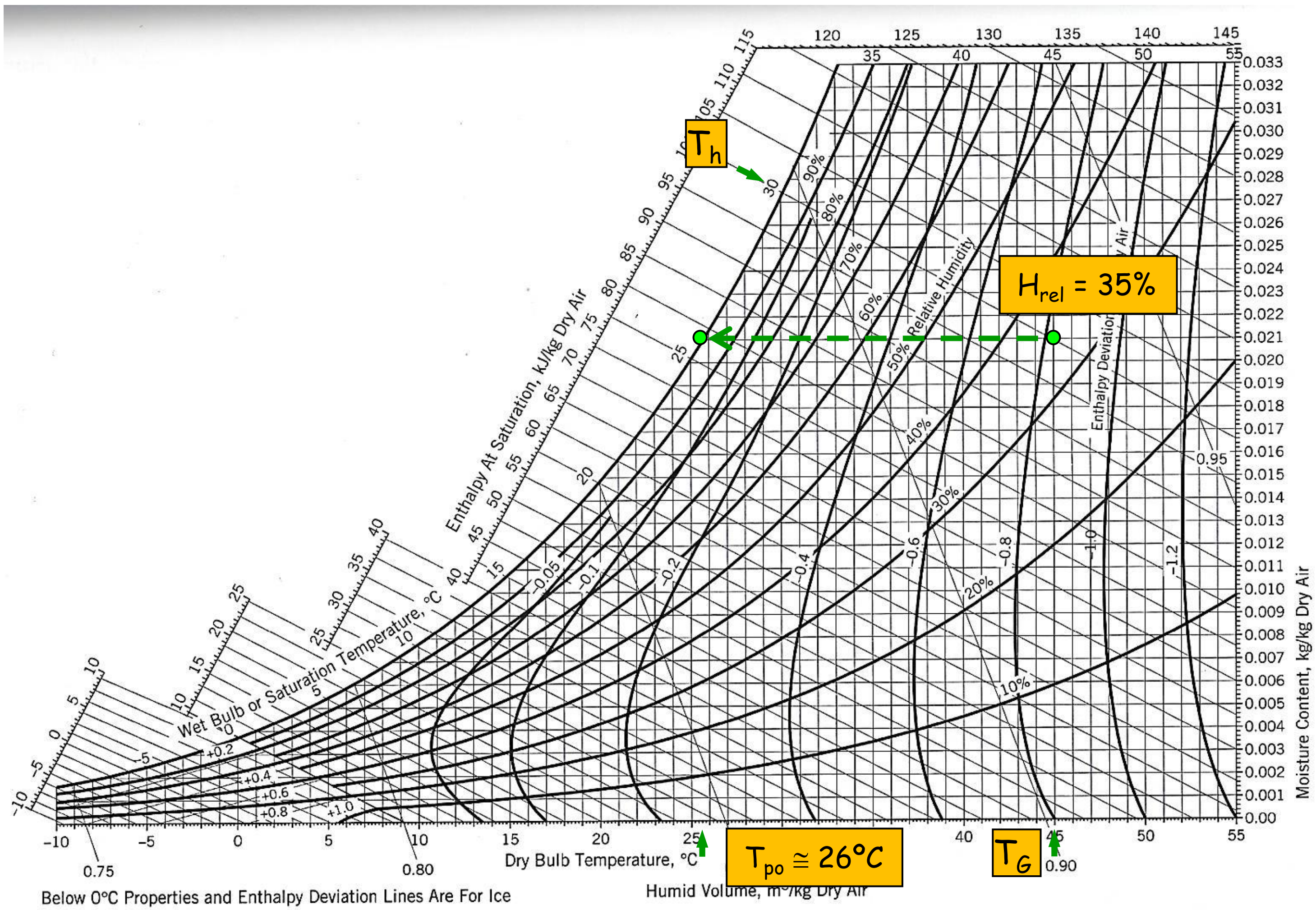
$$\begin{cases} T_h = 30°C \\ T_G = 45°C \end{cases}$$



H' = 0.021 $kg_{água}/kg_{ar\ seco}$

2) T_{po}

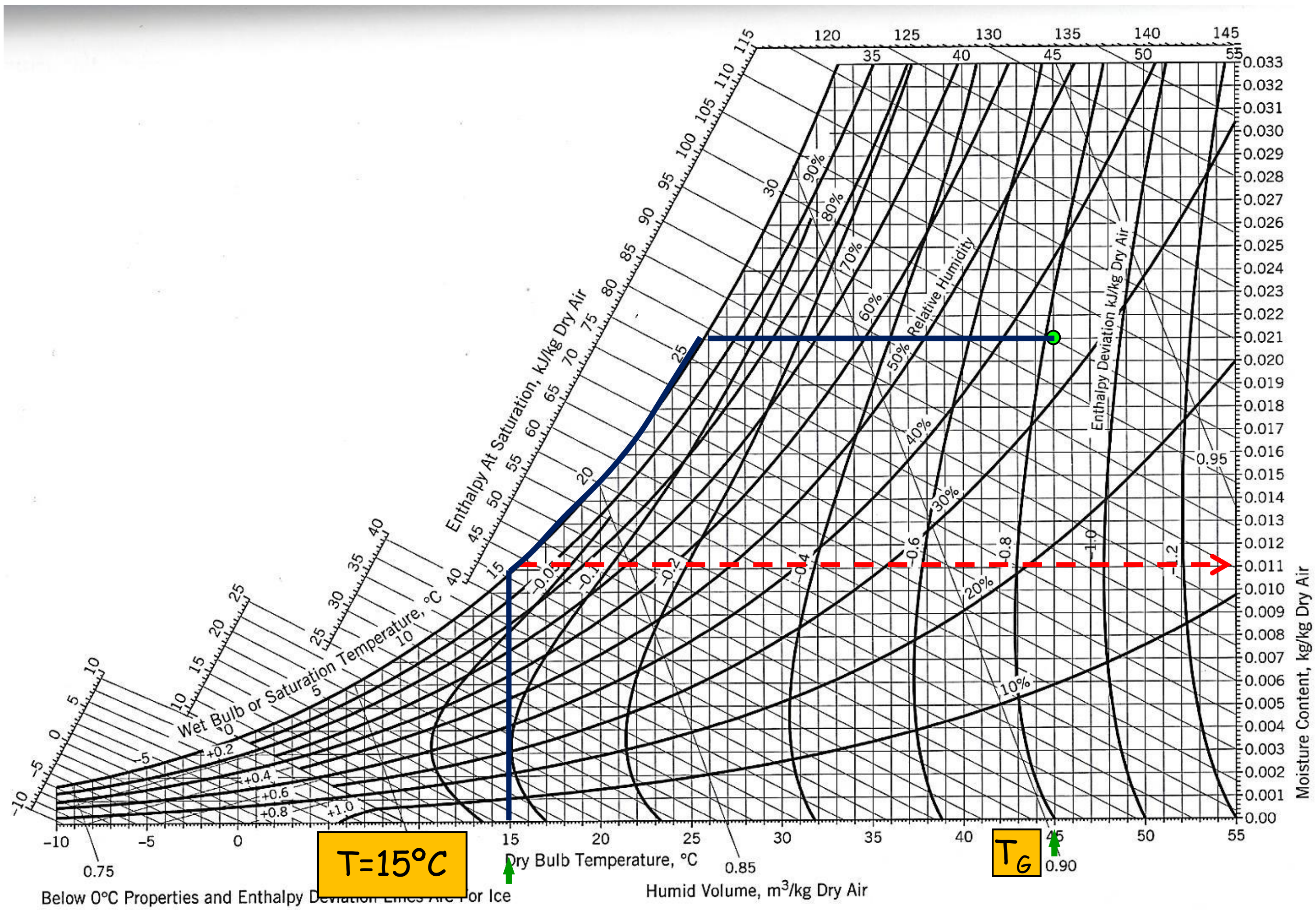
$$\begin{cases} T_h = 30°C \\ T_G = 45°C \end{cases}$$



H' = 0.021 $kg_{água}/kg_{ar\ seco}$

3) T_G: 45°C → 15°C

$$\frac{m_{\text{condensado}}}{m_{\text{ar seco}}} = H'_1 - H'_2 = 0.021 - 0.011 = 0.01\, kg_{\text{água}}/kg_{\text{ar seco}}$$



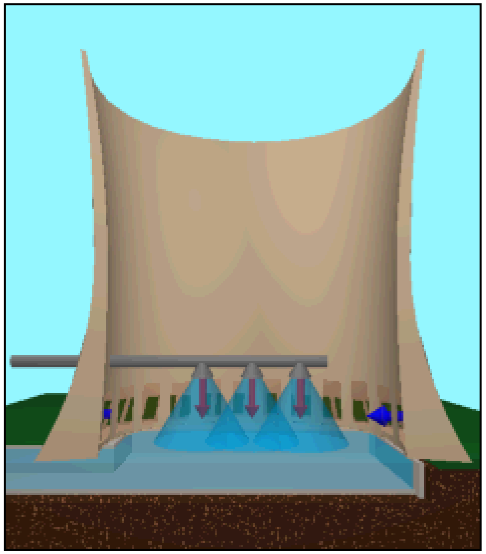
H' = 0.021 $kg_{\text{água}}/kg_{\text{ar seco}}$

H' = 0.011 $kg_{\text{água}}/kg_{\text{ar seco}}$

Equipment in de <u>Humidification</u> / <u>Dehumidification</u> processes

Cooling towers

- Cooling towers
- (natural extraction)



- high volumes processed
- low cost of equipment

LIMITATIONS OF THE PROCESS:

- $T_{water,\ out} \leq T_h$ ar atmosférico
- $Air_{out} \rightarrow$ saturated! (at $T_{water\ inlet}$)

-Advantages:

i) high resistance

ii) Hyperbolic shape increases the hydrodynamic; not necessary the use of fans

iii) Minimum operational costs

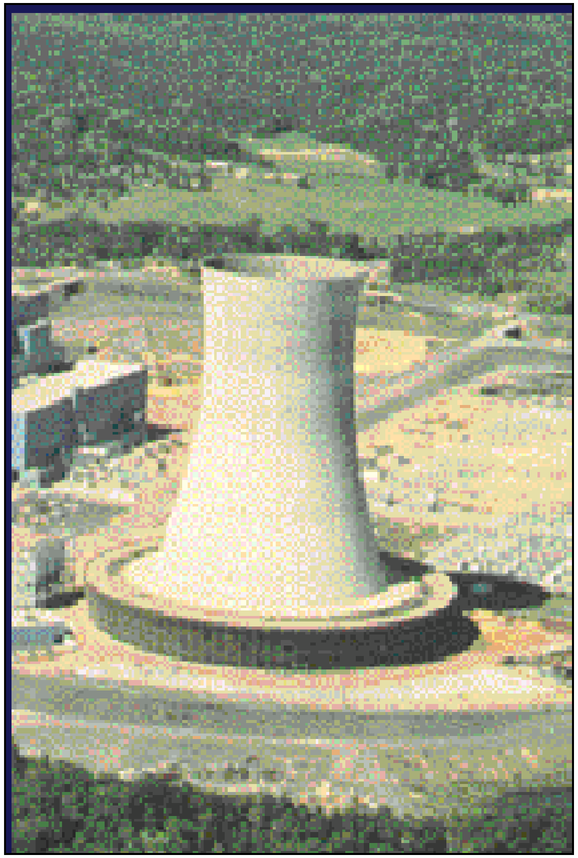
- Disadvantages:

i) Adequate only for high flowrates of water (*e.g.*, 5000 m^3/min)

ii) Sensible to climateric changes

iii) Visual aspect negative for public opinion!

➢ Cooling towers with fans



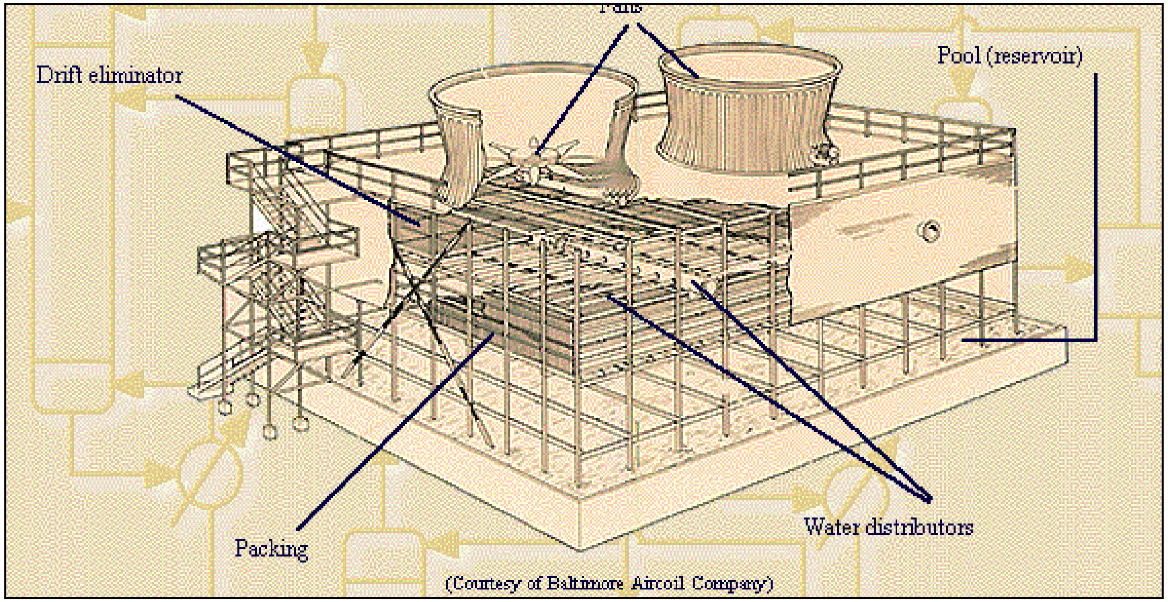
- Mechanical extraction: fans in the bootom of the tower

- Induced extraction: fan extracts humid air in the top of the tower

- Advantages: Higher control of the movement of air

-Disadvantages: problems of recirculation

- Cooling towers with induced extraction in counter- or co- current operation



- Advantages:

i) highly efficient

ii) Avoids problems of recirculation of humid air

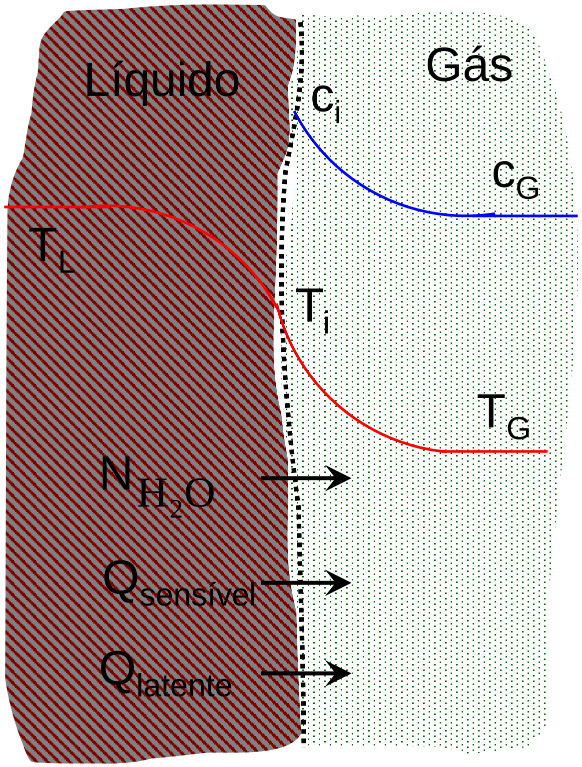
iii) more economical than cooling towers with natural extraction for water flowrates lower than 70 m^3/min

- Disavantages:

i) Costs with fan!

ii) High impact (noise and structural) due to the fan on the top of the tower.

Humidification Process



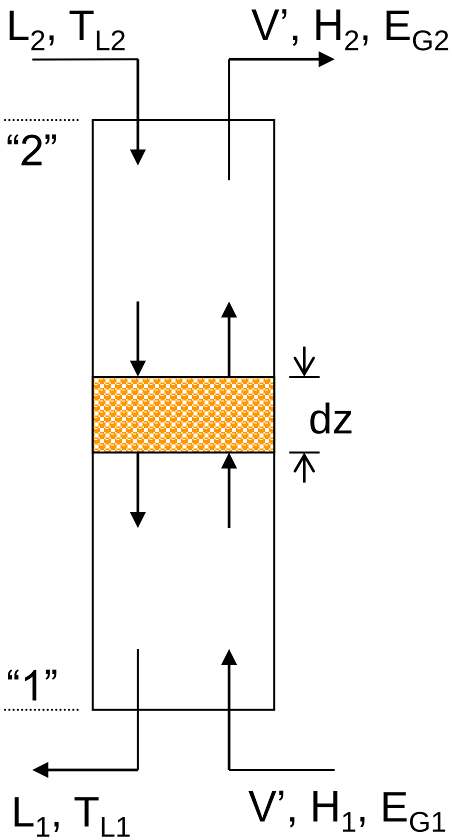
$T_G < T_L$

- **evaporation of water**
- **transport of heat L → G**
- **transport of mass L → G**

→ Cooling of water

cooling towers

Adiabatic Operation - Humidification



L: liquid flowrate, kg/s

V': dry air flowrate (B), kg/s

E_G: enthalpy of the gas, J/kg$_{ar\ seco}$

E_L: enthalpy of the liquid, J/kg$_{líquido}$

A: interfacial area, m^2

a: interfacial area /unit of volume of tower, m^2/m^3

S: cross section area, m^2

Global Balances

- Mass: $$V'(H_2 - H_1) = (L_2 - L_1)$$

- Energy: $$(L_2 \times E_{L_2}) + (V' \times E_{G_1}) = (L_1 \times E_{L_1}) + (V' \times E_{G_2}) \qquad (1)$$

Diferencial Balances

- Mass: $$V'dH = dL$$

- Energy: $$\boxed{V'dE_G = L\,dE_L} \qquad (2)$$

with: $L1 \cong \bar{L}2 \cong L$

$$\bar{L}\,dE_L \cong \bar{L}\,c_{p_L}\,dT_L$$

$$= \underbrace{h_L\,S\,a\,(T_L - T_i)\,dZ}_{\text{Transport of heat in the liquid}} \qquad (3)$$

h_L (heat transfer coefficient in the liquid) [=] J/(m^2 s °C)

$$V'dE_G = V'd\left[c_{p_G}(T_G - T_{ref}) + H\lambda_{vap}\right] = (V'c_{p_G}\,dT_G) + (V'\lambda_{vap}dH)$$

$$V'dE_G = \underbrace{\left[h_G\,S\,a\,(T_i - T_G)\,dZ\right]}_{\text{Transport of heat in the gas}} + \underbrace{\left[\lambda_{vap}\,S\,a\,k_H\,(H_i - H_G)\,dZ\right]}_{\text{Transport of latent heat (due to mass transport by water evaporation)}}$$

h_G (heat transfer coefficient in the gas) [=] J/(m^2 s °C)

k_H (mass transfer coefficient) [=] kg/(m^2 s kg/kg)

$$\boxed{V'dE_G = (E_i - E_G)(k_H a)\,S\,dZ} \qquad (4)$$

$$\boxed{V' dE_G = \left[h_G \, S \, a \, (T_i - T_G) \, dZ\right] + \left[\lambda_{vap} \, S \, a \, k_H \, (H_i - H_G) \, dZ\right]}$$

$$\Downarrow$$

$$V' dE_G = \left\{\left[h_G \, a \, T_i + \lambda_{vap} \, a \, k_H \, H_i\right] - \left[h_G \, a \, T_G + \lambda_{vap} \, a \, k_H \, H_G\right]\right\} S \, dZ$$

$$\Downarrow$$

$$V' dE_G = \left\{\left[b \, c_{p_h} T_i + \lambda_{vap} \, H_i\right] - \left[b \, c_{p_h} T_G + \lambda_{vap} \, H_G\right]\right\} (k_H \, a) \, S \, dZ$$

since: $b = \dfrac{h_G \, a}{k_H \, a \, c_p}$

$$\Downarrow$$

$$\boxed{V' dE_G = (E_i - E_G)(k_H a) \, S \, dZ}$$

For system air – water: $b = 1$

$$E_i = c_{p_h} T_i + \lambda_{vap} \, H_i$$

de (4): $V'dE_G = (E_i - E_G)(k_H a) S\, dZ$

=> $$\boxed{\int_{E_{G_1}}^{E_{G_2}} \frac{V'dE_G}{(k_H a) S (E_i - E_G)} = \int_0^Z dZ = Z}\qquad (5)$$

Equation of design

To solve (5) it is necessary :

1. Value (E_i-E_G) along the tower

$$\boxed{V'dE_G = L\, dE_L} \qquad (2)$$

$$\begin{cases} \bar{L}\, dE_L = h_L\, S\, a\, (T_L - T_i)\, dZ & (3) \\ \boxed{V'dE_G = (E_i - E_G)(k_H a) S\, dZ} & (4) \end{cases}$$

and: $$\boxed{\frac{E_i - E_G}{T_i - T_L} = \left[-\frac{h_L a}{k_H a} \right]} \qquad (6)$$

(E_i,T_i): values at saturation

2. Relation between E_G and T_L

$$(L_2 \times E_{L_2}) + (V' \times E_{G_1}) = (L_1 \times E_{L_1}) + (V' \times E_{G_2}) \qquad (1)$$

$$=> \qquad V'(E_{G_2} - E_{G_1}) = \bar{L}(E_{L_2} - E_{L_1}) = \bar{L}\, c_{p_L} (T_{L_2} - T_{L_1})$$

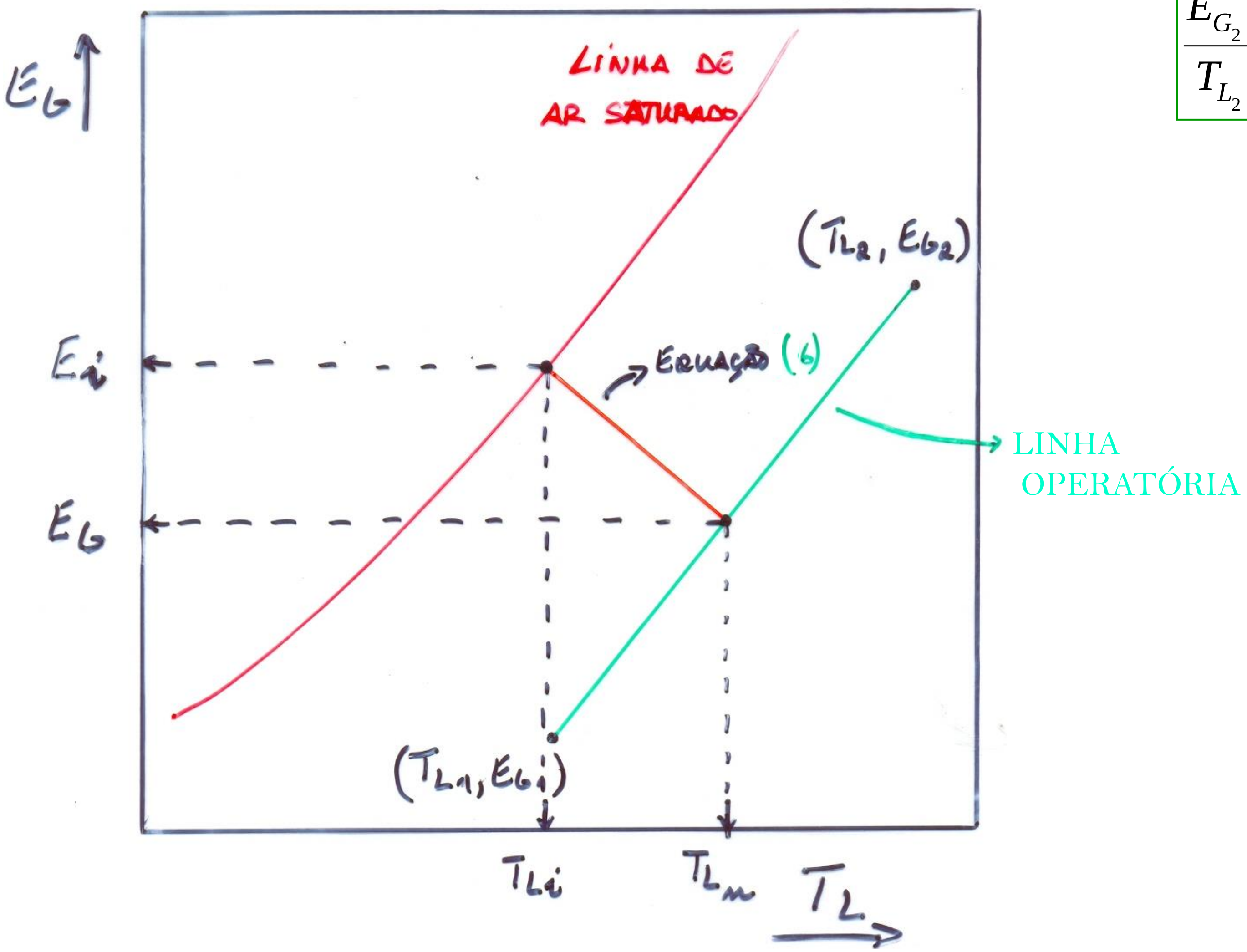
$$=> \qquad \boxed{\frac{E_{G_2} - E_{G_1}}{T_{L_2} - T_{L_1}} = \left[\frac{\bar{L}\, c_{p_L}}{V'} \right]} \qquad (7)$$

Operating line

$$\int_{E_{G_1}}^{E_{G_2}} \frac{V' dE_G}{(k_H a) S (E_i - E_G)} = \int_0^Z dZ = Z \qquad (5)$$

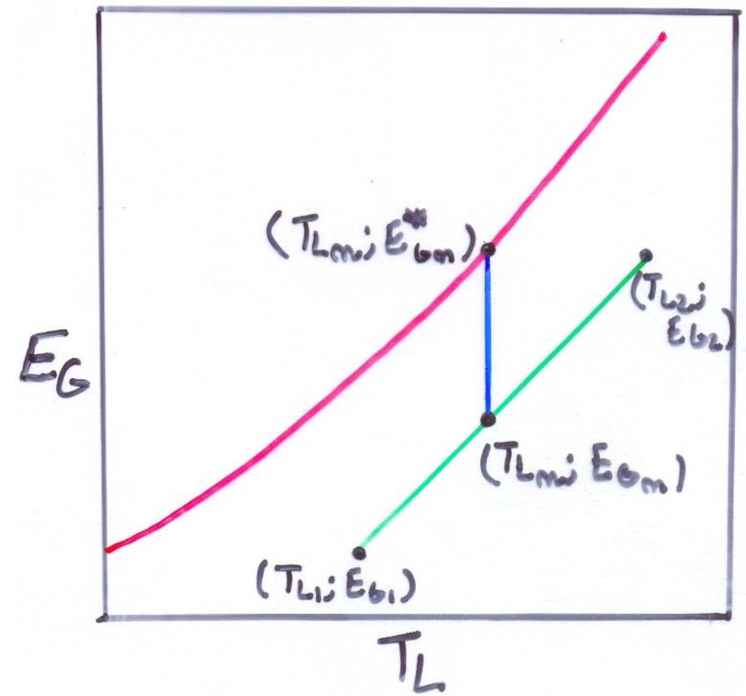
$$\frac{E_i - E_G}{T_i - T_L} = \left[-\frac{h_L a}{k_H a} \right] \qquad (6)$$

$$\frac{E_{G_2} - E_{G_1}}{T_{L_2} - T_{L_1}} = \left[\frac{\bar{L}\, c_{p_L}}{V'} \right] \qquad (7)$$



If: $h_L a \nearrow$ => $\left[-\dfrac{h_L a}{k_H a}\right] \rightarrow \infty$ => eq. (6) has slope ∞

$E_i \approx E^*$: air saturated at liquid phase temperature, $T_i \cong T_L$



=> $$\boxed{\int_{E_{G_1}}^{E_{G_2}} \frac{V' dE_G}{(k_H a) S (E_n^* - E_{G,n})} = Z}$$

Equation solved: a) numerically

b) grafically (area $\left[\dfrac{1}{E_n^* - E_{G,n}}\right]$ vs. E_G)

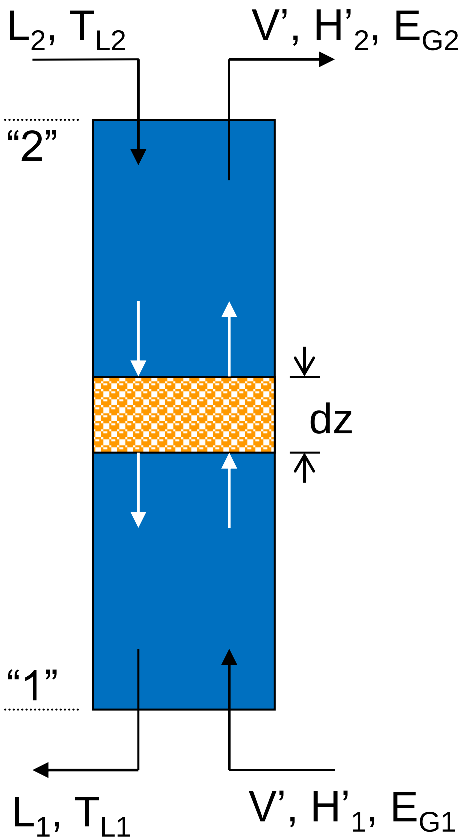
Problem

It is necessary a cooled water flowrate of 15 kg/s to be used in the condenser of a distillation column. The water leaves the condenser at 45ºC and we want to cool it to 29ºC by contact with humid air at 30ºC with a wet bulb temperature of 24ºC. The dry ais flowrate is10.97 kg/s.

If $K_y a = 0.9\ kg/m^3$ and the cross section area is 5.5 m^2, wich is the height of the cooling tower.

Cp water = 4.187 kJ/kg.ºC

Humidification / Cooling of water



$\bar{L}$ = 15 kg/s
T_{L2} = 45ºC
T_{L1} = 29ºC

V' = 10.97 kg/s de ar seco
T_{G1} = 30ºC
T_{h1} = 24ºC

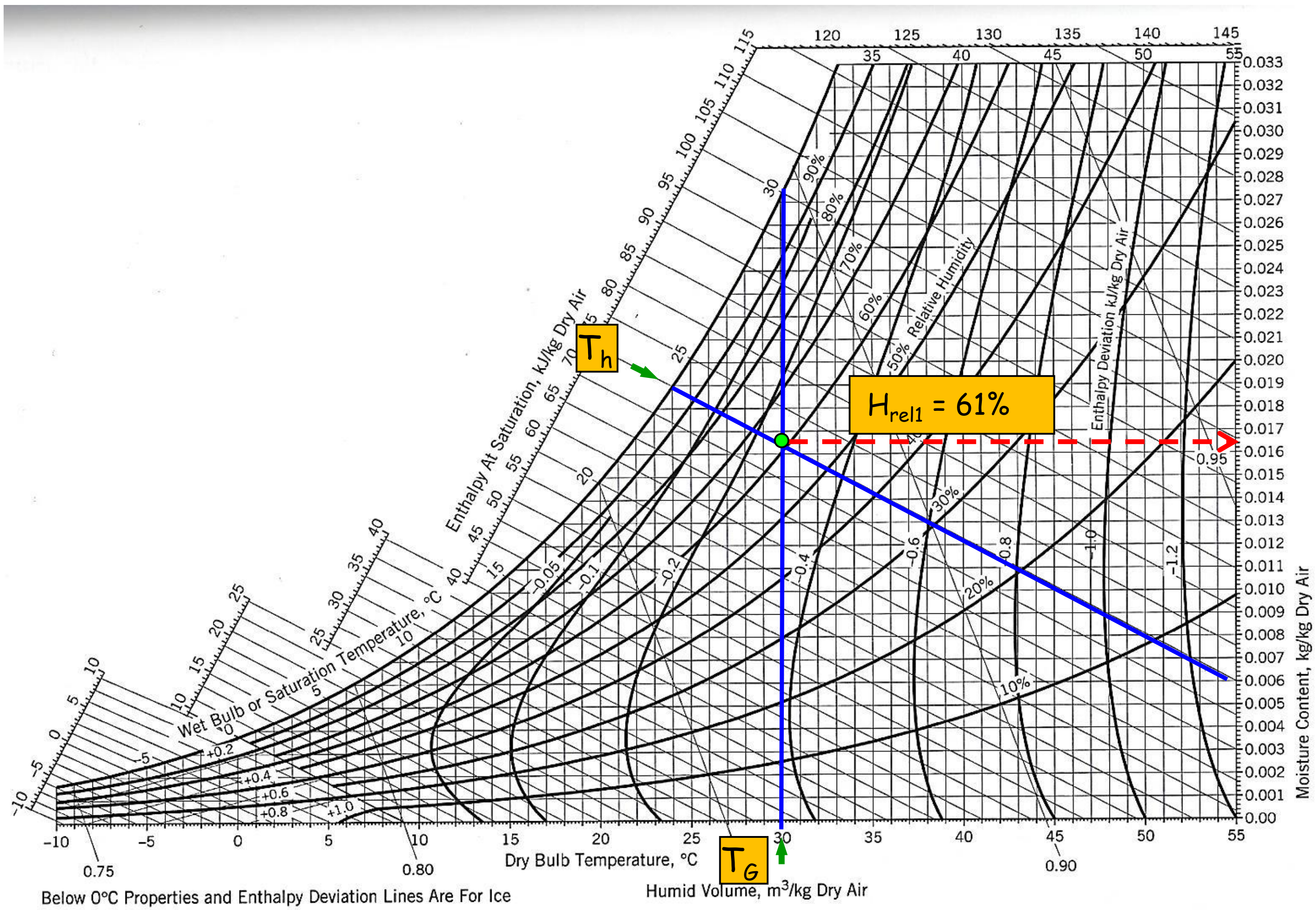
Equations

Operating line: $$\frac{E_{G_2} - E_{G_1}}{T_{L_2} - T_{L_1}} = \left[\frac{\bar{L}\, c_{p_L}}{V'}\right]$$

Design equation: $$Z = \frac{V'}{(K_H a) S} \int_{E_{G_1}}^{E_{G_2}} \frac{dE_G}{(E_G^* - E_G)}$$

(a) H'_1, H'_{rel1}

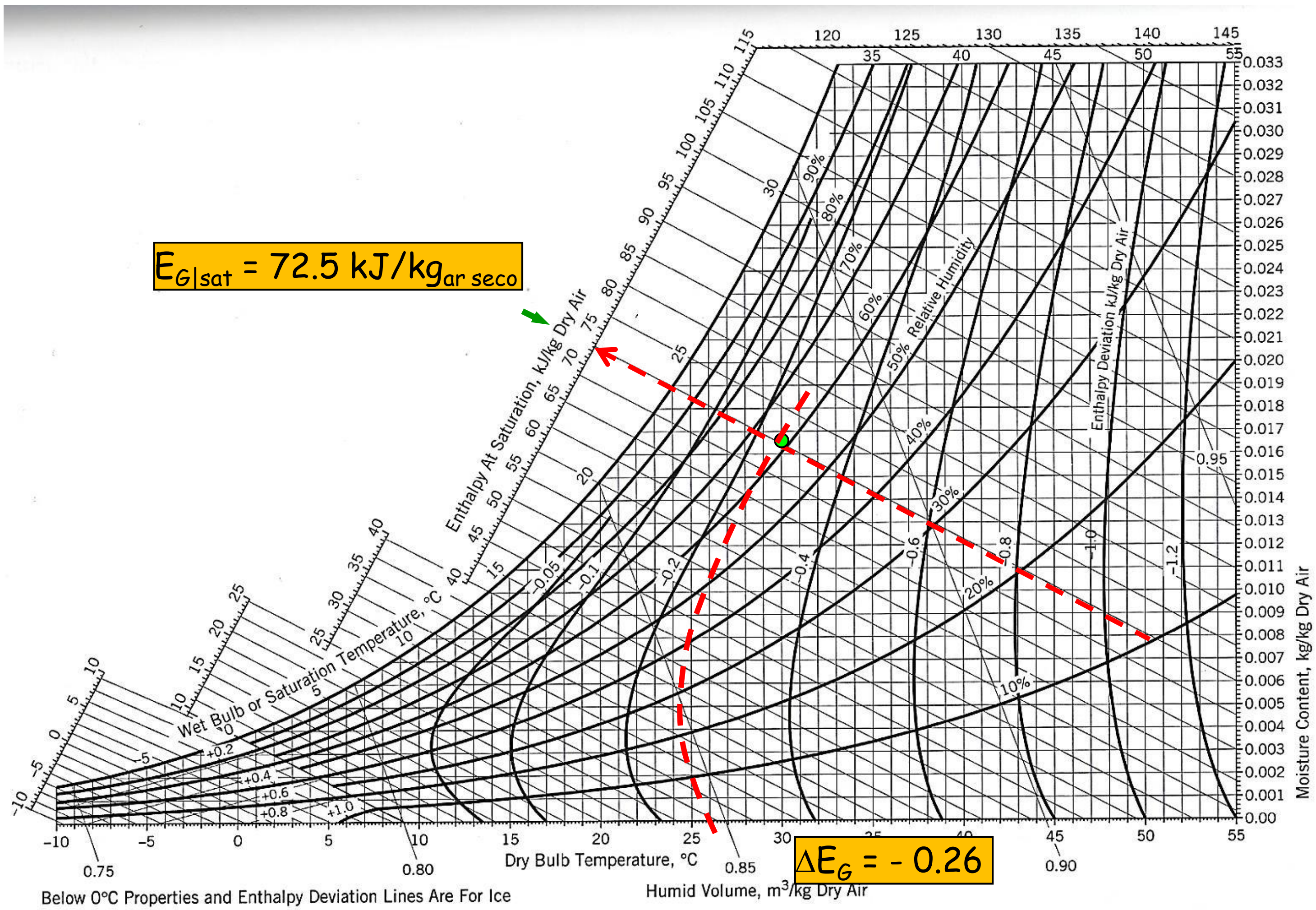
$$\begin{cases} T_{h1} = 24°C \\ T_{G1} = 30°C \end{cases}$$



H'_1 = 0.0164 $kg_{água}/kg_{ar\ seco}$

(b) E_{G1}

$$E_{\mathrm{ar},T_{G1}} = E_{\mathrm{sat},T_{G1}} + \Delta E = 72.5 + (-0.26) = 72.24\, kJ / kg_{ar\,\mathrm{sec}\,o}$$



(i) Condições do ar húmido à entrada, H'_1; H'_{rel1}; E_{G1}

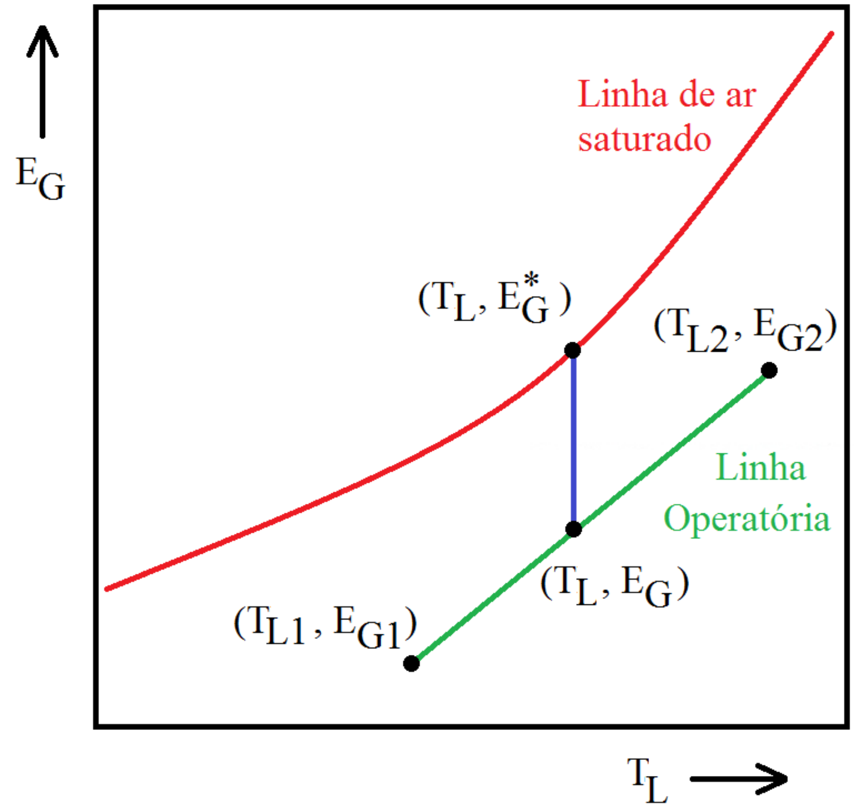
$$\begin{cases} T_{G1} = 30^{o}C \\ T_{h1} = 24^{o}C \end{cases} \qquad \begin{cases} H'_1 = 0.0164 \\ H'_{rel1} = 61\% \end{cases} \quad ; \quad E_{G1} = 72.24 \text{ kJ/kg}_{\text{ar seco}}$$

(ii) Entalpia do ar à saída da torre, E_{G2}

$$\boxed{\frac{E_{G_2} - E_{G_1}}{T_{L_2} - T_{L_1}} = \left[\frac{\bar{L}\, c_{p_L}}{V'}\right]}$$

$$\frac{E_{G_2} - 72.24}{45-29} = \left[\frac{15\times 4{,}187}{10.97}\right] \qquad => E_{G_2} = 164\,\text{kJ/kg}$$

(iii) $$\boxed{Z = \frac{V'}{(K_H a) S} \int_{E_{G_1}}^{E_{G_2}} \frac{dE_G}{(E_G^* - E_G)}}$$



Resolution numerical!

$K_H a = 0.9$ kg/m^{3}s

$S = 5.5$ m^2

$T_{L1} = 29^oC$ $E_{G1} = 72.24$ kJ/kg$_{ar\ seco}$

$T_{L2} = 45^oC$ $E_{G2} = 164$ kJ/kg$_{ar\ seco}$

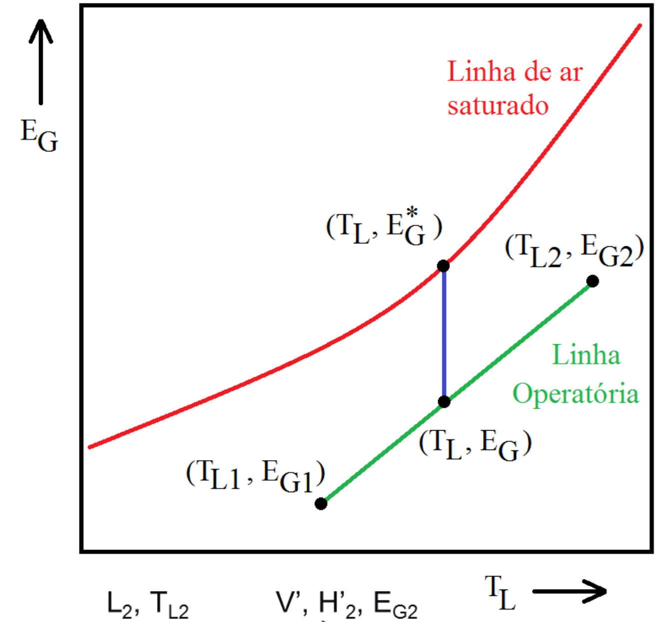
$$\int_{E_{G_1}}^{E_{G_2}} \left[\frac{1}{(E_G^* - E_G)} \right] dE_G$$

$$\frac{E_{G_2} - E_{G_1}}{T_{L_2} - T_{L_1}} = \left[\frac{\bar{L}\, c_{p_L}}{V'} \right]$$

$T_{L1} = 29^oC$ $E_{G1} = 72.24\ kJ/kg_{ar\ seco}$

$T_{L2} = 45^oC$ $E_{G2} = 164\ kJ/kg_{ar\ seco}$

T_L (ºC)	E* (kJ/kg)	E_G (kJ/kg)	$\frac{1}{E_G^* - E_G}$
29		72.24	
31			
33			
35			
37			
39			
41			
43			
45		164	



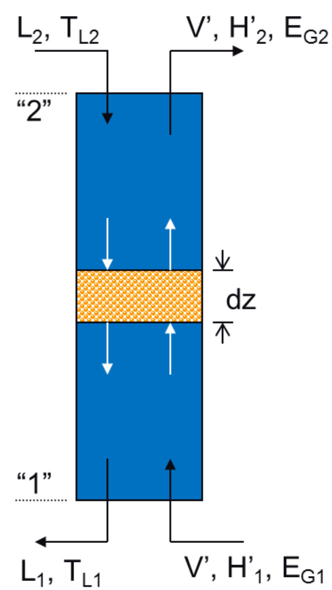


TABLE 4.8.1 Thermodynamic Properties of Water Vapor-Air Mixtures at 1 atm

Temp., °C	Saturation Mass Fraction	Specific Volume, m^3/kg		Enthalpy[a,b] kJ/kg		
		Dry Air	Saturated Air	Liquid Water	Dry Air	Saturated Air
10	0.007608	0.8018	0.8054	42.13	10.059	29.145
11	0.008136	0.8046	0.8086	46.32	11.065	31.481
12	0.008696	0.8075	0.8117	50.52	12.071	33.898
13	0.009289	0.8103	0.8148	54.71	13.077	36.401
14	0.009918	0.8131	0.8180	58.90	14.083	38.995
15	0.01058	0.8160	0.8212	63.08	15.089	41.684
16	0.01129	0.8188	0.8244	67.27	16.095	44.473
17	0 01204	0.8217	0.8276	71.45	17.101	47.367
18	0 01283	0.8245	0.8309	75.64	18.107	50.372
19	0.01366	0.8273	0.8341	79.82	19.113	53.493
20	0.01455	0.8302	0.8374	83.99	20.120	56.736
21	0.01548	0.8330	0.8408	88.17	21.128	60.107
22	0.01647	0.8359	0.8441	92.35	22.134	63.612
23	0.01751	0.8387	0.8475	96.53	23.140	67.259
24	0.01861	0.8415	0.8510	100.71	24.147	71.054
25	0.01978	0.8444	0.8544	104.89	25.153	75.004
26	0.02100	0.8472	0.8579	109.07	26.159	79.116
27	0.02229	0.8500	0.8615	113.25	27.166	83.400
28	0.02366	0.8529	0.8650	117.43	28.172	87.862
29	0.02509	0.8557	0.8686	121.61	29.178	92.511
30	0.02660	0.8586	0.8723	125.79	30.185	97.357
31	0.02820	0.8614	0.8760	129.97	31.191	102.408
32	0.02987	0.8642	0.8798	134.15	32.198	107.674
33	0.03164	0.8671	0.8836	138.32	33.204	113.166
34	0.03350	0.8699	0.8874	142.50	34.211	118.893
35	0.03545	0.8728	0.8914	146.68	35.218	124.868
36	0.03751	0.8756	0.8953	150.86	36.224	131.100
37	0.03967	0.8784	0.8994	155.04	37.231	137.604
38	0.04194	0.8813	0.9035	159.22	38.238	144.389
39	0.04432	0.8841	0.9077	163.40	39.245	151.471
40	0.04683	0.8870	0.9119	167.58	40.252	158.862
41	0.04946	0.8898	0.9162	171.76	41.259	166.577
42	0.05222	0.8926	0.9206	175.94	42.266	174.630
43	0.05512	0.8955	0.9251	180.12	43.273	183.037
44	0.05817	0.8983	0.9297	184.29	44.280	191.815
45	0.06137	0.9012	0.9343	188.47	45.287	200.980
46	0.06472	0.9040	0.9391	192.65	46.294	210.550
47	0.06842	0.9068	0.9439	196.83	47.301	220.543
48	0.07193	0.9097	0.9489	201.01	48.308	230.980
49	0.07580	0.9125	0.9539	205.19	49.316	241.881

[a] The enthalpies of dry air and liquid water are set equal to zero at a datum temperature of 0°C.

[b] The enthalpy of an unsaturated water vapor-air mixture can be calculated as $h = h_{dry\ air} + (m_1/m_{1,sat})(h_{sat} - h_{dry\ air})$.

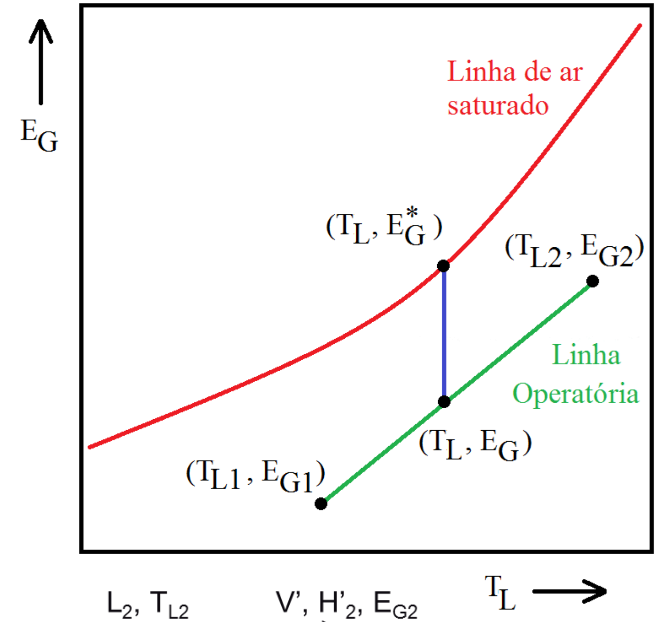
$$\int_{E_{G_1}}^{E_{G_2}} \left[\frac{1}{(E_G^* - E_G)} \right] dE_G$$

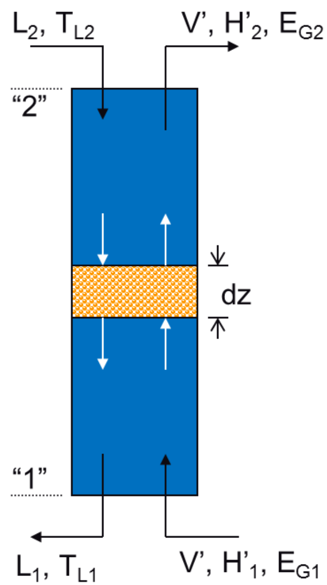
$$\frac{E_{G_2} - E_{G_1}}{T_{L_2} - T_{L_1}} = \left[\frac{\bar{L}\, c_{p_L}}{V'} \right]$$

$T_{L1} = 29°C$ $E_{G1} = 72.24$ kJ/kg$_{ar\ seco}$

$T_{L2} = 45°C$ $E_{G2} = 164$ kJ/kg$_{ar\ seco}$

T_L (ºC)	E* (kJ/kg)	E_G (kJ/kg)	$\frac{1}{E_G^* - E_G}$
29	92.51	72.24	0.049
31	102.41		
33	113.17		
35	124.87		
37	137.60		
39	151.47		
41	166.58		
43	183.04		
45	200.98	164	0.027



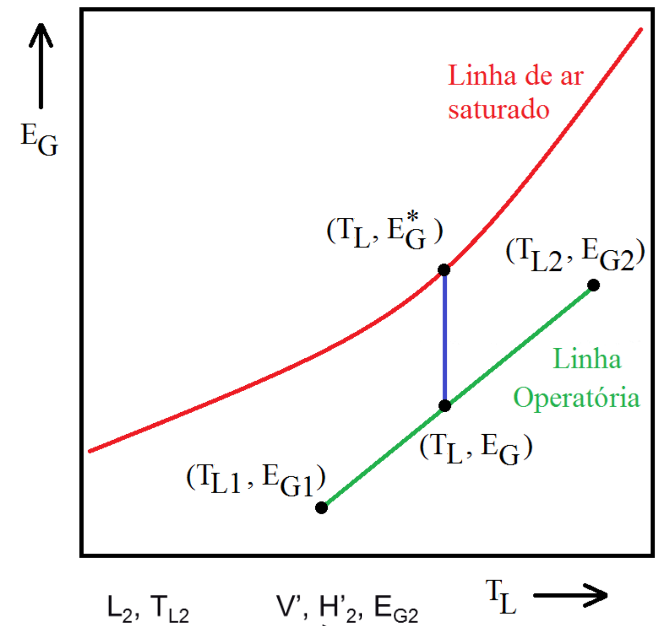


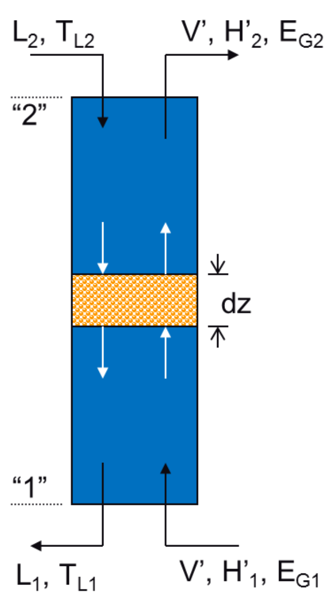
$$\int_{E_{G_1}}^{E_{G_2}} \left[\frac{1}{(E_G^* - E_G)} \right] dE_G$$

$$\frac{E_{G_2} - E_{G_1}}{T_{L_2} - T_{L_1}} = \left[\frac{\bar{L}\, c_{p_L}}{V'} \right]$$

$T_{L1} = 29^oC$ $E_{G1} = 72.24\ kJ/kg_{ar\ seco}$

$T_{L2} = 45^oC$ $E_{G2} = 164\ kJ/kg_{ar\ seco}$





T_L (ºC)	E^* (kJ/kg)	E_G (kJ/kg)	$\frac{1}{E_G^* - E_G}$
29	92.51	72.24	0.049
31	102.41	83.45	
33	113.17		
35	124.87		
37	137.60		
39	151.47		
41	166.58		
43	183.04		
45	200.98	164	0.027

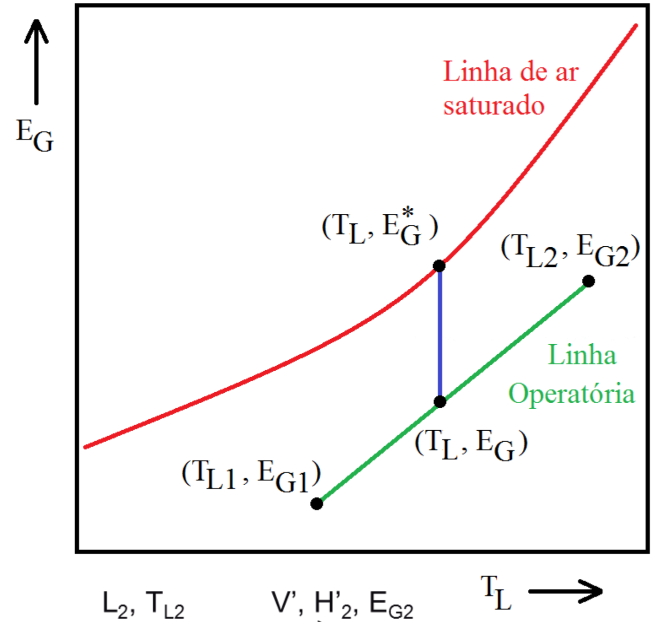
$$\int_{E_{G_1}}^{E_{G_2}} \left[\frac{1}{(E_G^* - E_G)} \right] dE_G$$

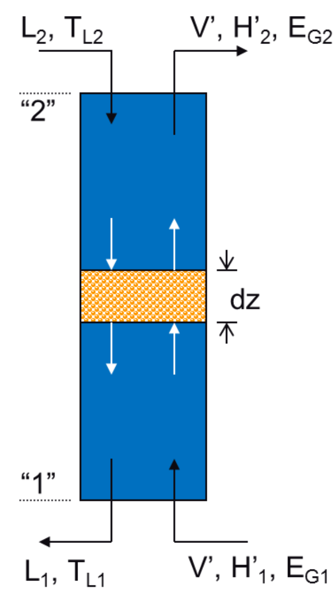
$$\frac{E_{G_2} - E_{G_1}}{T_{L_2} - T_{L_1}} = \left[\frac{\bar{L}\, c_{p_L}}{V'} \right]$$

$T_{L1} = 29^oC \qquad E_{G1} = 72.24\ kJ/kg_{ar\ seco}$

$T_{L2} = 45^oC \qquad E_{G2} = 164\ kJ/kg_{ar\ seco}$

T_L (ºC)	E* (kJ/kg)	E_G (kJ/kg)	$\frac{1}{E_G^* - E_G}$
29	92.51	72.24	0.049
31	102.41	83.45	0.053
33	113.17	94.90	0.055
35	124.87	106.35	0.054
37	137.60	117.80	0.050
39	151.47	129.25	0.045
41	166.58	140.70	0.039
43	183.04	152.15	0.032
45	200.98	164	0.027





$$\int_{E_{G_1}}^{E_{G_2}} \left[\frac{1}{(E_G^* - E_G)} \right] dE_G$$

$$\frac{E_{G_2} - E_{G_1}}{T_{L_2} - T_{L_1}} = \left[\frac{\bar{L}\, c_{p_L}}{V'} \right]$$

T_{L1} = 29ºC E_{G1} = 72.24 kJ/kg$_{\text{ar seco}}$

T_{L2} = 45ºC E_{G2} = 164 kJ/kg$_{\text{ar seco}}$

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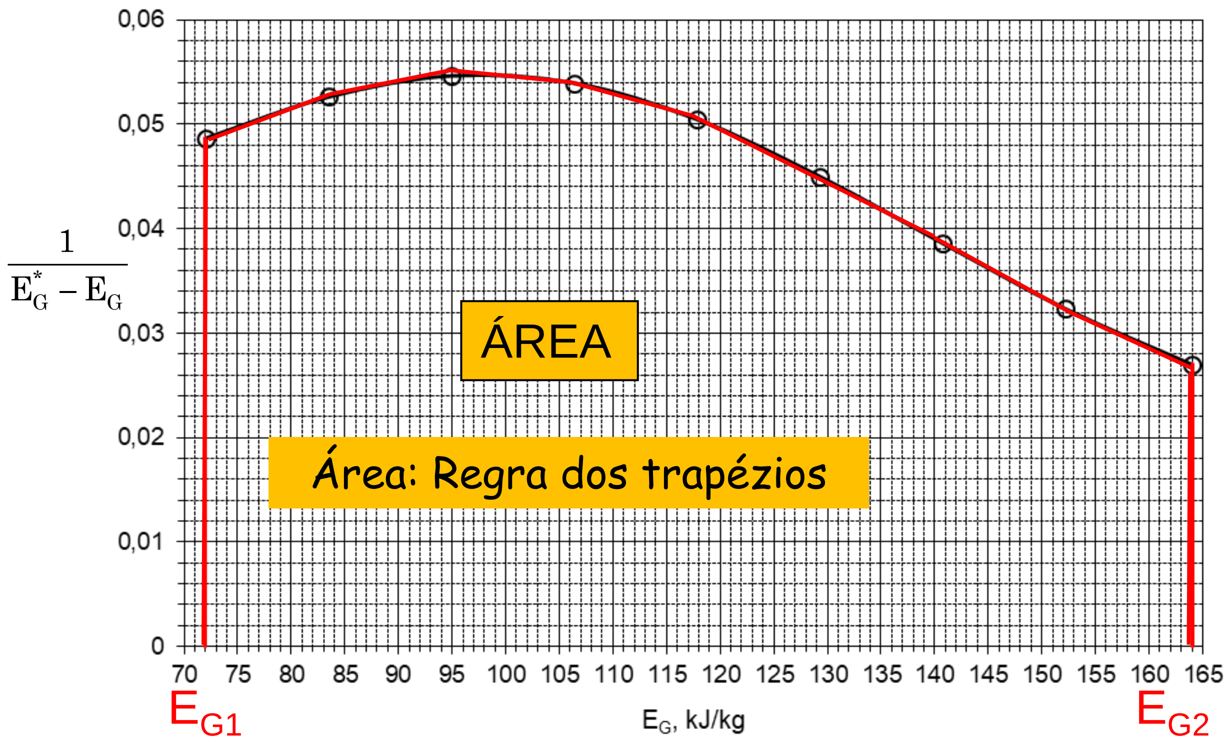
29	92.51	72.24	0.049
31	102.41	83.45	0.053
33	113.17	94.90	0.055
35	124.87	106.35	0.054
37	137.60	117.80	0.050
39	151.47	129.25	0.045
41	166.58	140.70	0.039
43	183.04	152.15	0.032
45	200.98	164	0.027



=> Area = 4.24

$$Z = \frac{V'}{(K_H a) S} \int_{E_{G_1}}^{E_{G_2}} \frac{dE_G}{(E_G^* - E_G)}$$

Z=10.97/(5.5x0.9)x4.24=9.4m