Transporte Simultâneo de Calor e Massa – FT III

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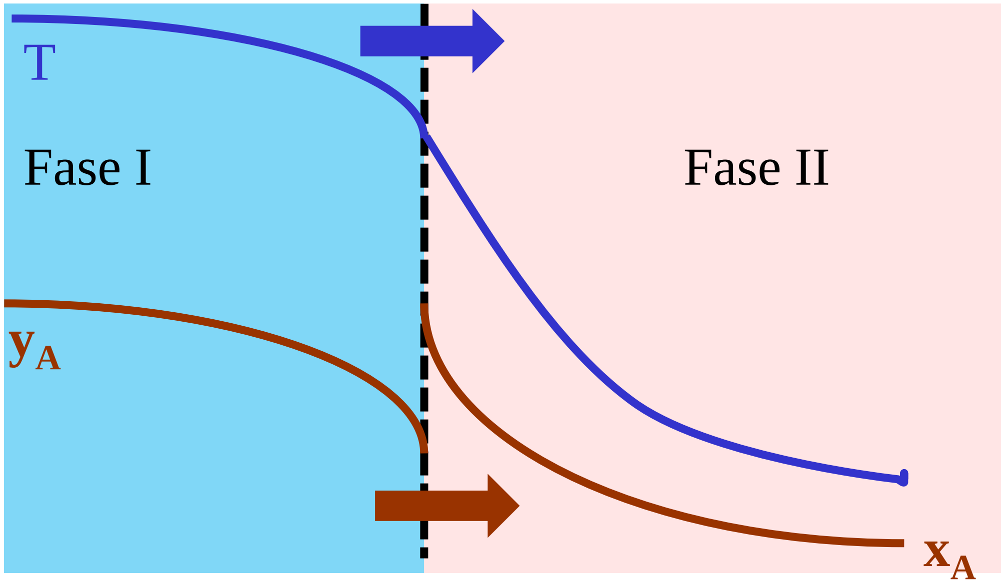
EPUSP

Transporte simultâneo de calor e massa

$$\vec{q} = -\vec{\vec{k}}\,.\,\mathrm{gr\vec{a}d}\,T + \sum \vec{j}_i \hat{H}_i + \vec{q}^{\,x}$$

DIFUSÃO DE CALOR | **CONDUÇÃO FOURIER** | **DIFUSÃO** | **TERMODIFUSÃO DUFOUR**



$$-\left(k\,.\,\mathrm{gr\vec{a}d}\,T\right)_I + \vec{j}_A \hat{H}_{A,I} = -\left(k\,.\,\mathrm{gr\vec{a}d}\,T\right)_{II} + \vec{j}_A \hat{H}_{A,II}$$

Exemplo : Evaporação de Água

Balanço de Energia

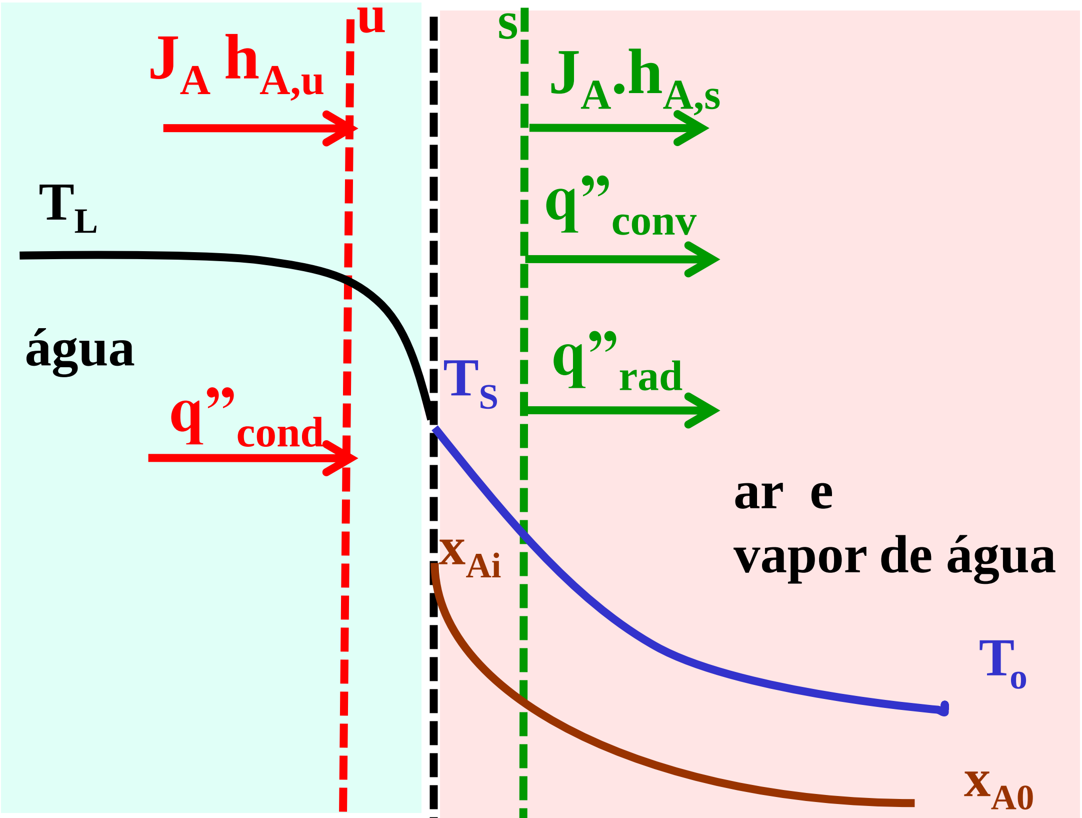
$$J_A\left(h_{A,s} - h_{A,u}\right) = q''_{cond} - q''_{conv} - q''_{rad}$$

Entalpia de vaporização

$$\left(h_{A,s} - h_{A,u}\right) = h_{fg}$$

Fluxo evaporativo

$$J_A = k_x\left(x_{A,i} - x_{A,0}\right)$$



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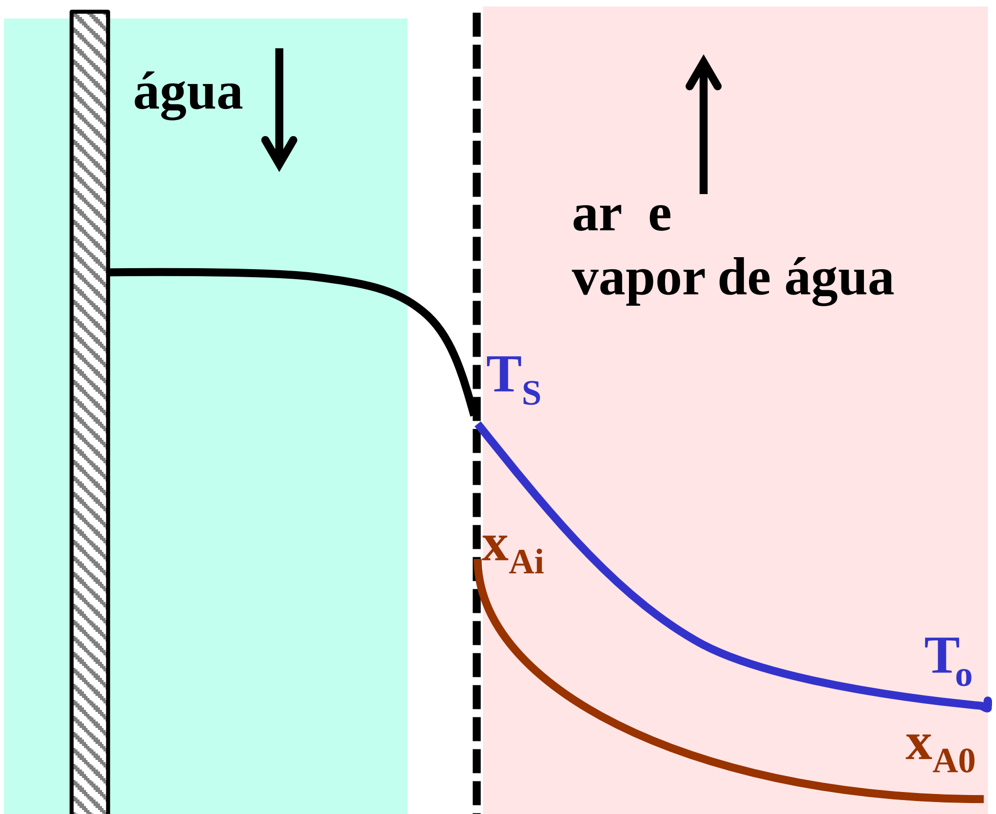

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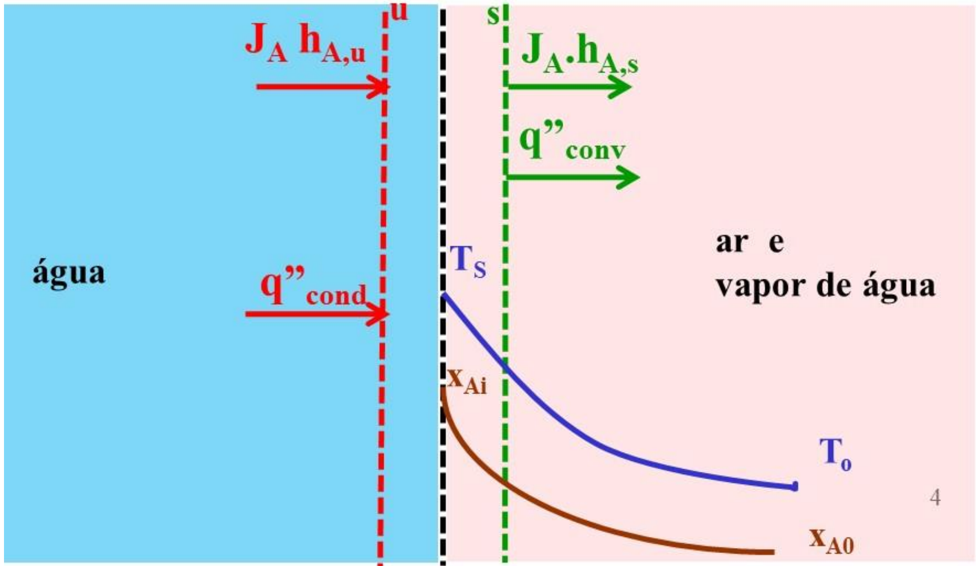
$$\left(h_{A,s} - h_{A,u}\right) = h_{fg}$$

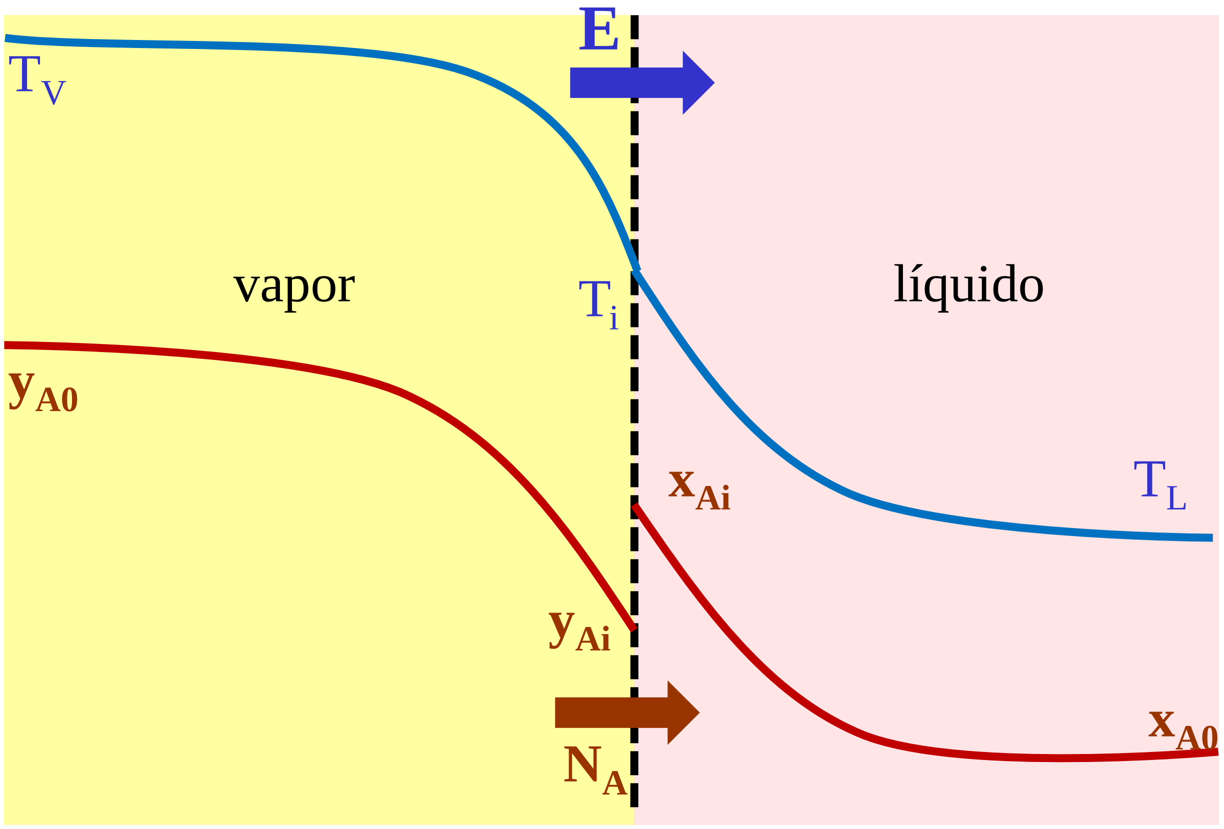
$$-\left(k.\frac{\partial T}{\partial y}\right)_u$$

$$h_c\left(T_s - T_0\right)$$

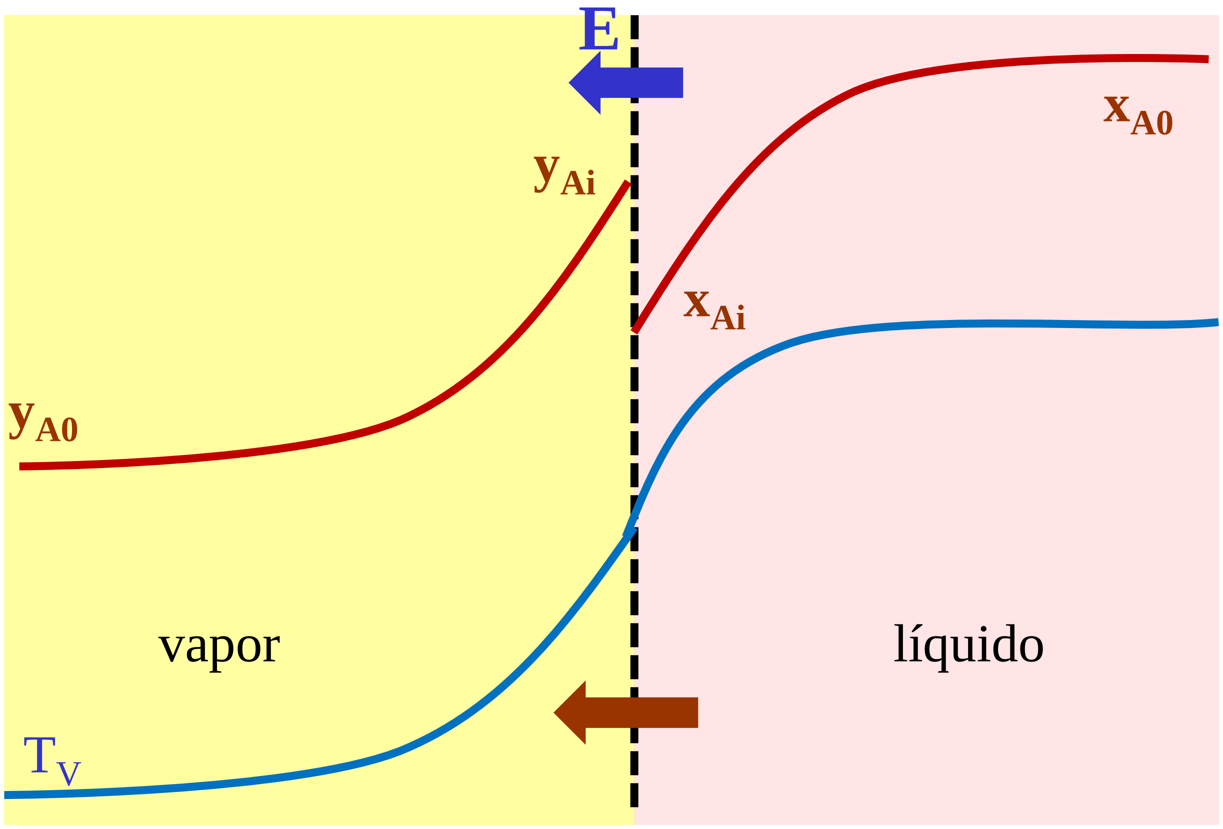
$$-\left(k.\frac{\partial T}{\partial y}\right)_u = h_c\left(T_s - T_0\right) + k_x\left(x_{A,i} - x_{A,0}\right)h_{fg}$$



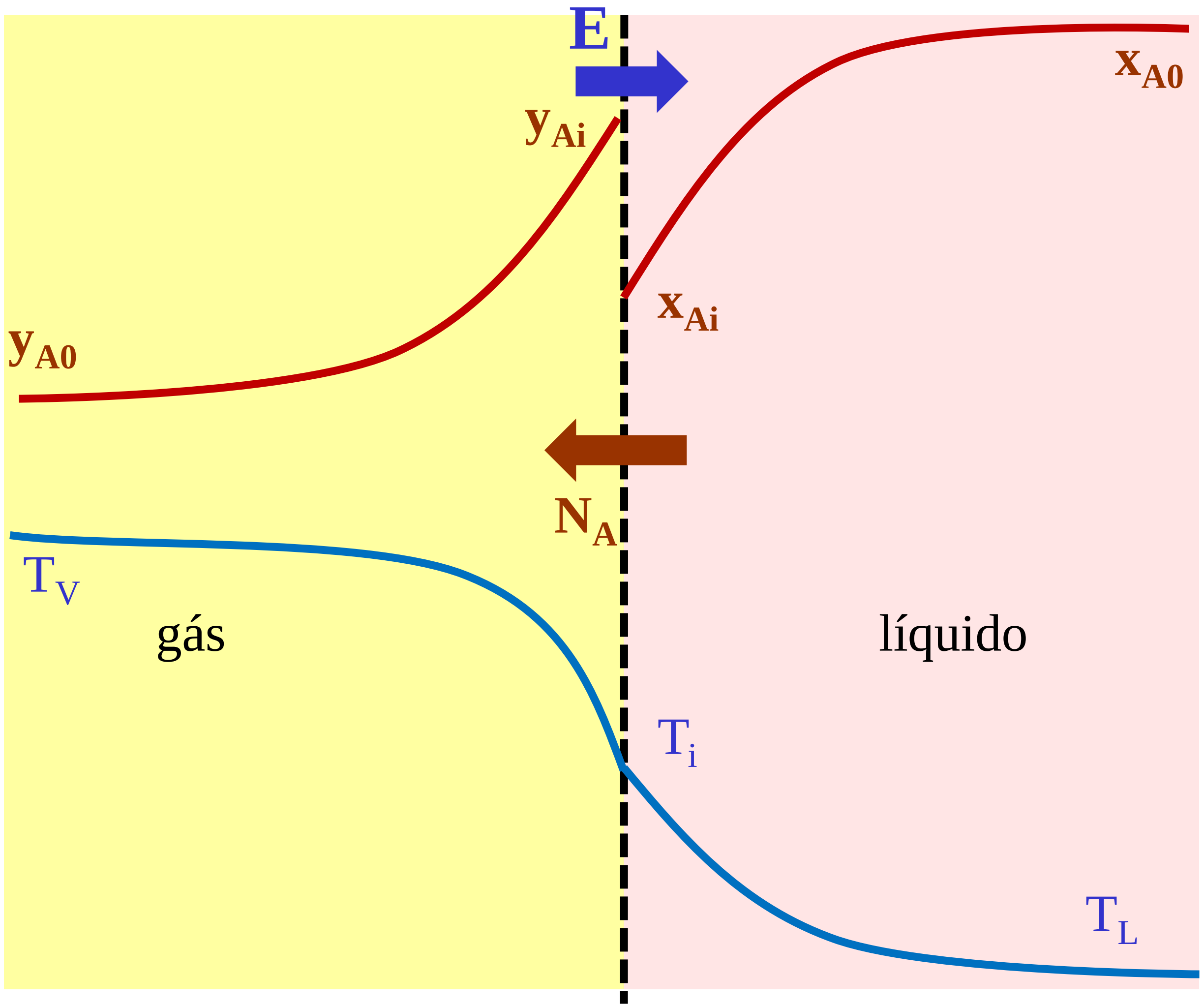
Condensação



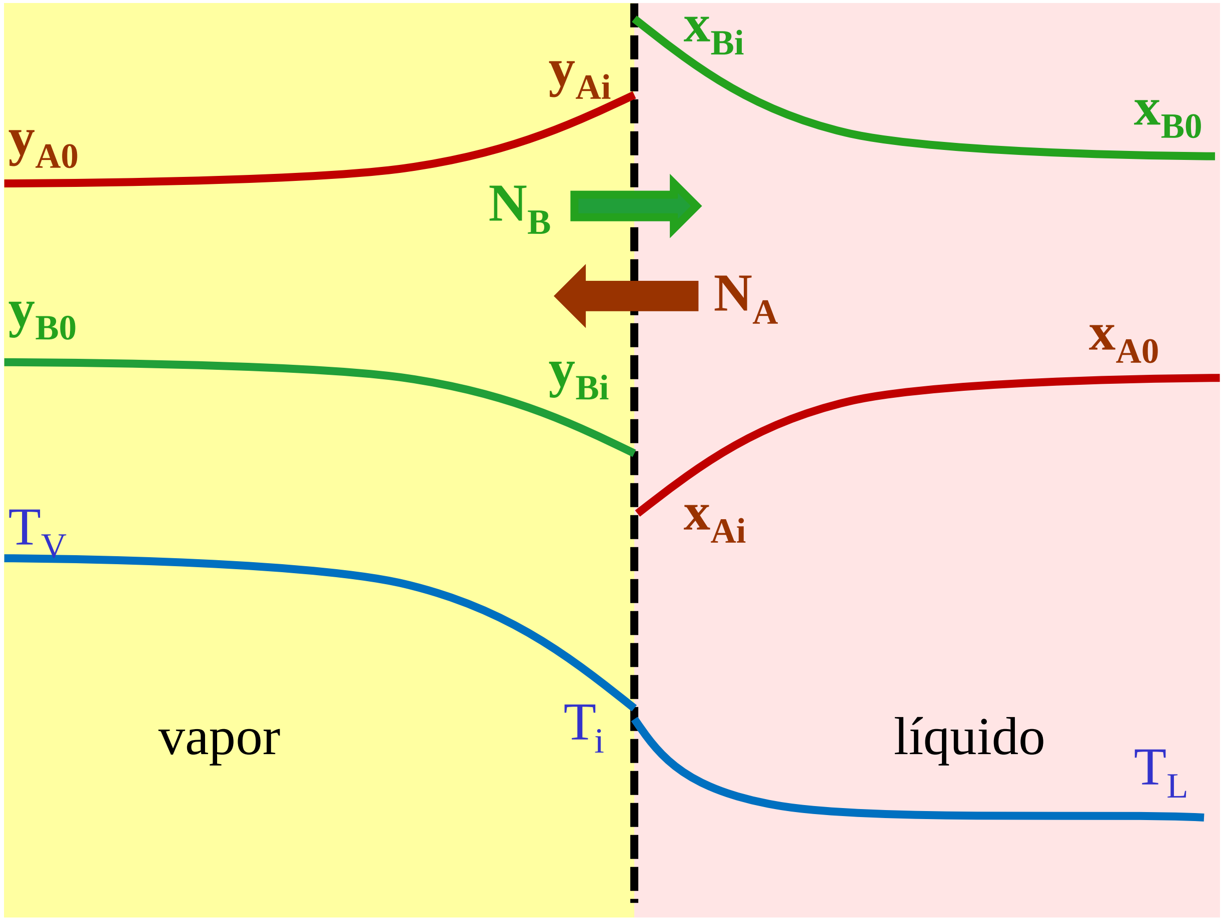
Evaporação



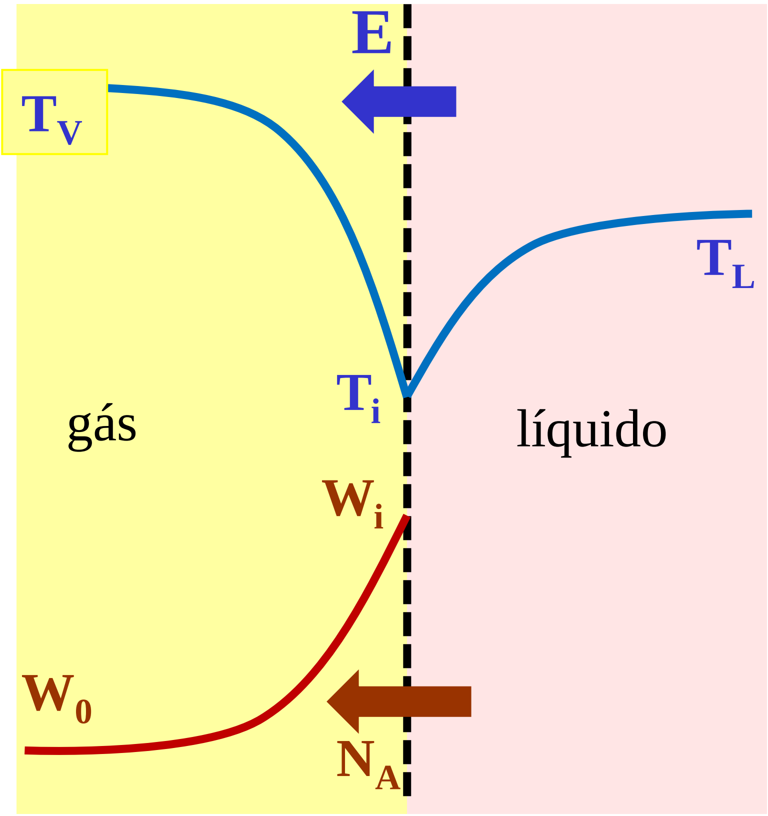
Secagem

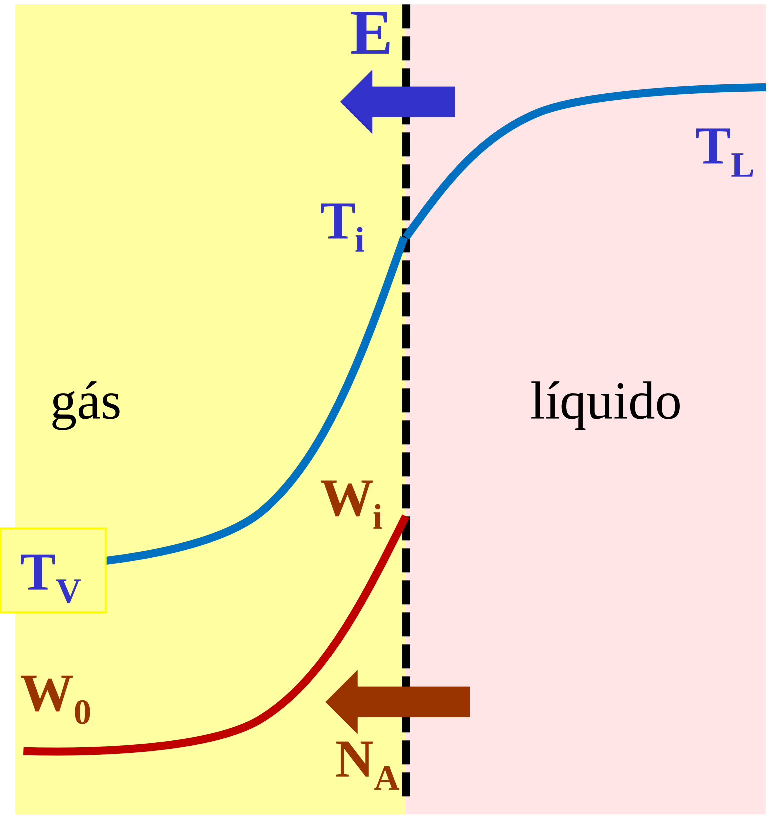


Destilação

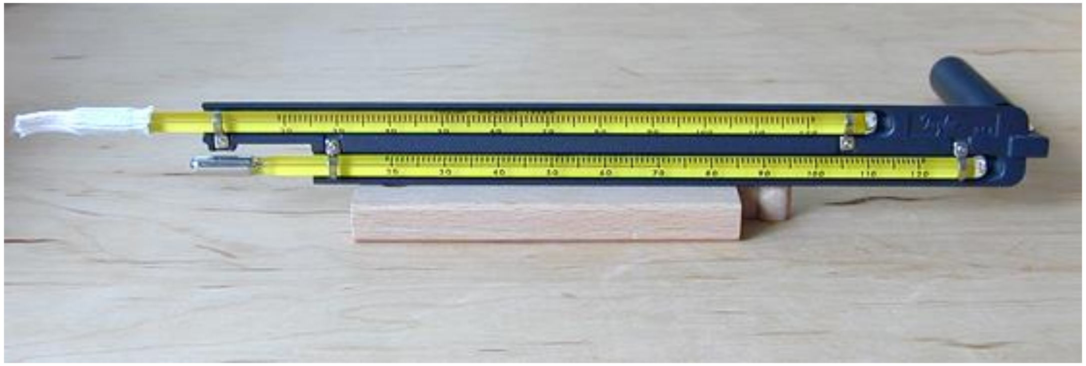


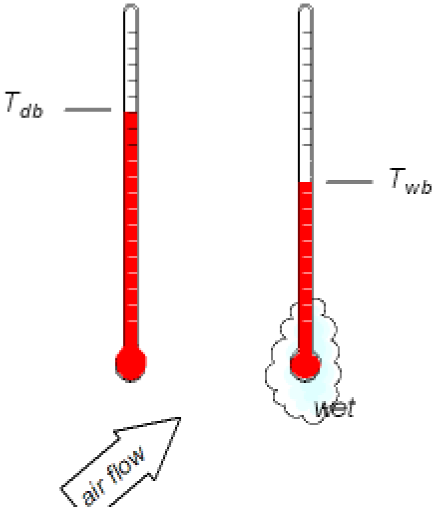
Resfriamento Evaporativo
Torre de Resfriamento





Temperatura de bulbo úmido e bulbo seco





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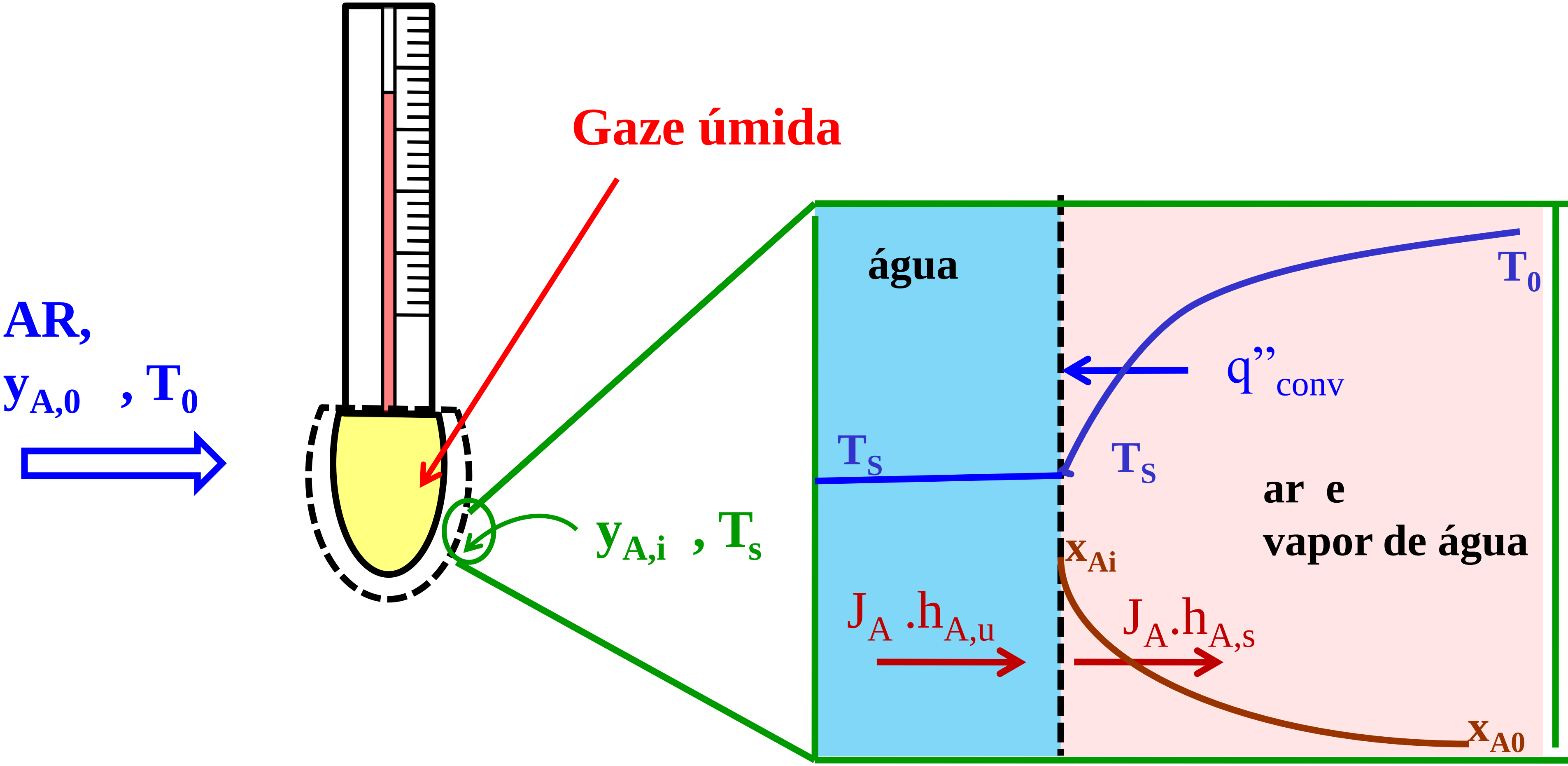
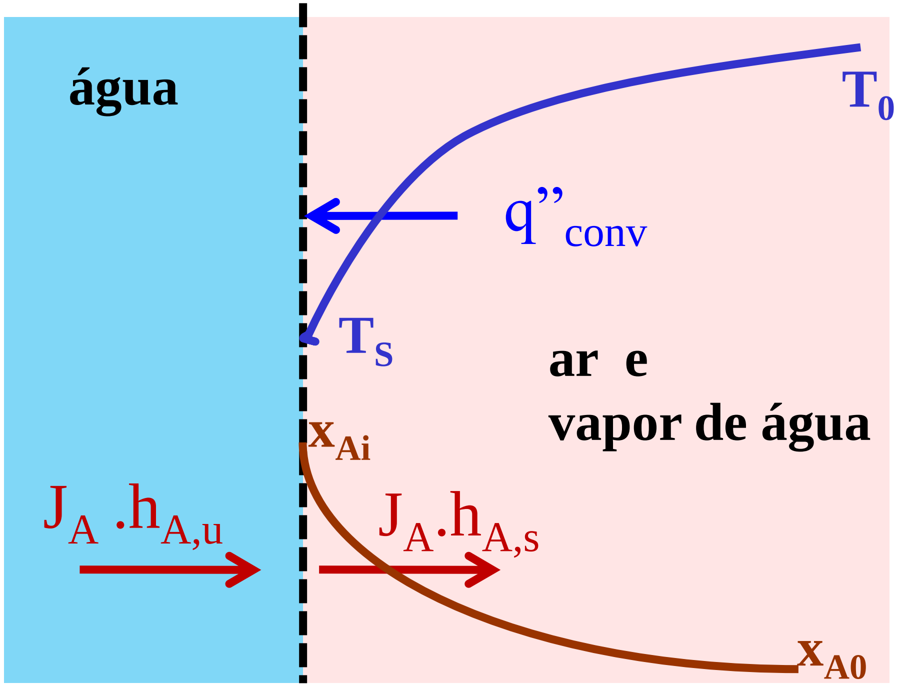


-Condição de regime permanente

$T_{BS} = T_0$: temperatura de bulbo seco

$T_{BU} = T_s$: temperatura de bulbo úmido



Balanço de Energia

$$0 = h_c (T_s - T_0) + k_x (x_{A,i} - x_{A,0}) h_{fg}$$

$$x_{A,0} = x_{A,i} - \frac{h_c}{k_x h_{fg}} (T_0 - T_s)$$

ANALOGIA DE COLBURN:

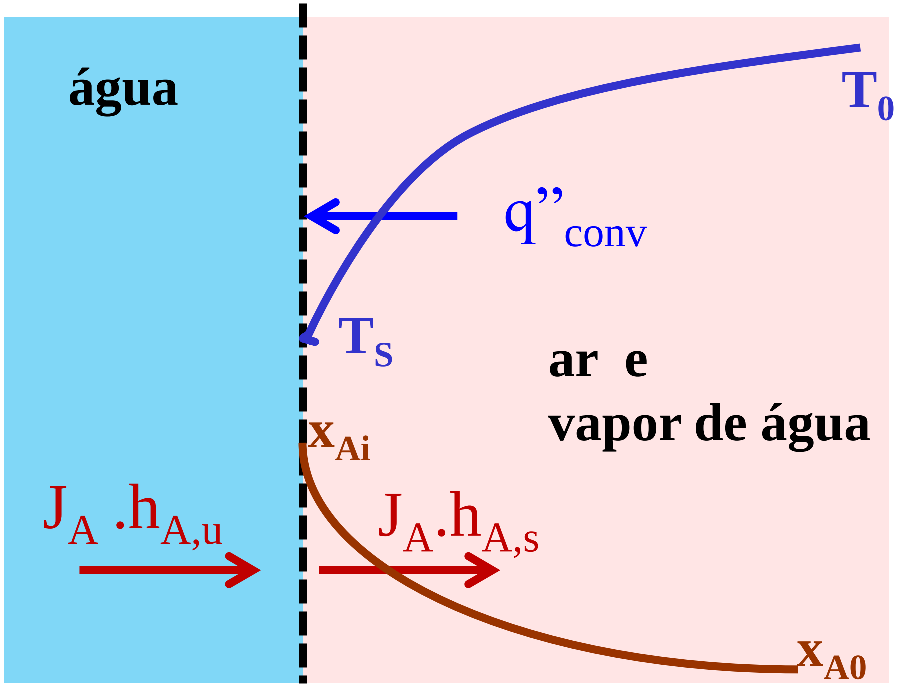
CALOR

$$j_H = \frac{Nu}{Re\,Pr^{1/3}}$$

MASSA

$$j_M = \frac{Sh}{Re\,Sc^{1/3}}$$

$$j_H = \frac{Nu}{Re\,Pr^{1/3}} = j_M = \frac{Sh}{Re\,Sc^{1/3}} \Rightarrow \frac{Nu}{Sh} = \frac{Pr^{1/3}}{Sc^{1/3}}$$



$$Nu = \frac{h_c L}{k}$$

$$Sh = \frac{k_x L}{\rho D_{AB}}$$

$$\frac{Nu}{Sh} = \frac{hD_{AB}\rho}{k_x k} = \frac{h_c D_{AB}\rho}{k_x k}\frac{c_{P,ar}}{c_{P,ar}} = \frac{h_c D_{AB}}{k_x \alpha\, c_{P,ar}} = \frac{h_c D_{AB}}{k_x \alpha\, c_{P,ar}}\frac{\nu}{\nu} = \frac{h_c}{k_x\, c_{P,ar}}\frac{Pr}{Sc}$$

$$\frac{Nu}{Sh} = \frac{h_c}{k_x\, c_{P,ar}}\frac{Pr}{Sc}$$

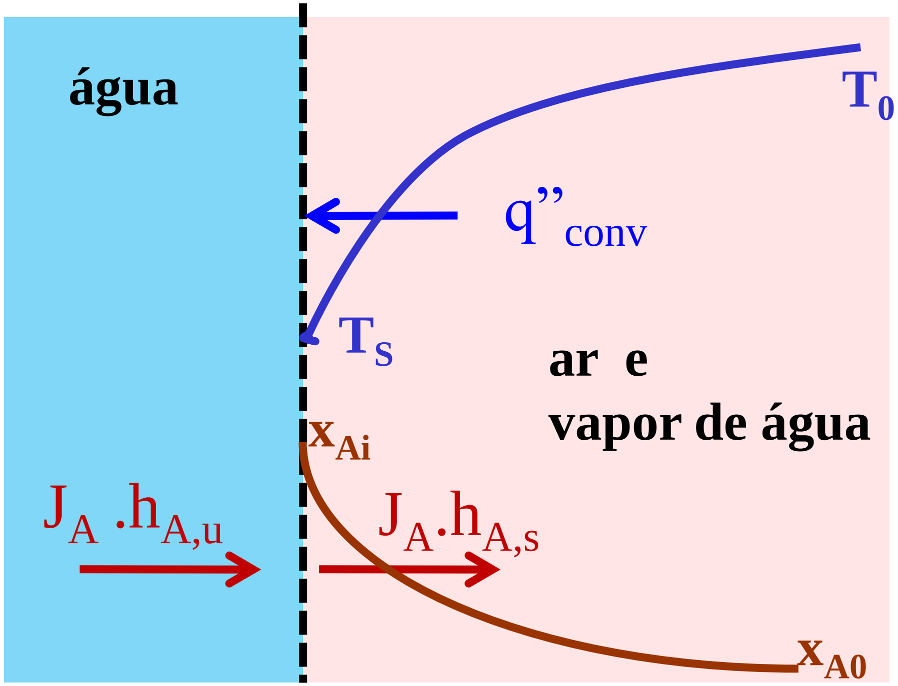
$$\frac{Nu}{Sh} = \frac{Pr^{1/3}}{Sc^{1/3}}$$

$$\frac{Nu}{Sh} = \frac{h_c}{k_x\, c_{P,ar}}\frac{Pr}{Sc} = \frac{Pr^{1/3}}{Sc^{1/3}} \Rightarrow$$

$$\frac{h_c}{k_x} = c_{P,ar}\frac{Pr^{-2/3}}{Sc^{-2/3}}$$

$$x_{A,0} = x_{A,i} - \frac{h_c}{k\,h_{fg}}\left(T_0 - T_s\right)$$

$$\frac{h_c}{k_x} = c_{P,ar}\frac{Pr^{-2/3}}{Sc^{-2/3}}$$



Número de Lewis

$$\frac{Pr}{Sc} = Le \cong \frac{0.69}{0.61} = 1.13$$

$$x_{A,0} = x_{A,i} - \frac{Pr^{-2/3}}{Sc^{-2/3}}\frac{c_{P,ar}}{h_{fg}}\left(T_0 - T_s\right)$$

$$x_{A,0} = x_{A,i} - \frac{c_{P,ar}}{1.08\,h_{fg}}\left(T_{BS} - T_{BU}\right)$$

Dado de equilíbrio

$$x_{A,i} = x_{A,i}\left(T_{BU}\,,\,P\right)$$

TORRE DE RESFRIAMENTO

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- **Resfriamento evaporativo** (wet cooling towers)
  - transporte simultâneo de calor e massa entre a água e o ar.
  - CONTATO AR-ÁGUA
    - -ENTALPIA DE VAPORIZAÇÃO ~ 80 %
    - -RESFRIAMENTO DA ÁGUA ~ 20 %

RANGE = $T_{ÁGUA\ QUENTE} - T_{ÁGUA\ FRIA}$

TEMPERATURA DE BULBO ÚMIDO DO AR - T_{BU}

APPROACH = $T_{ÁGUA\ FRIA} - T_{BU}$

APPROACH > 3 ºC

- **Resfriamento não-evaporativo** (dry cooling towers)

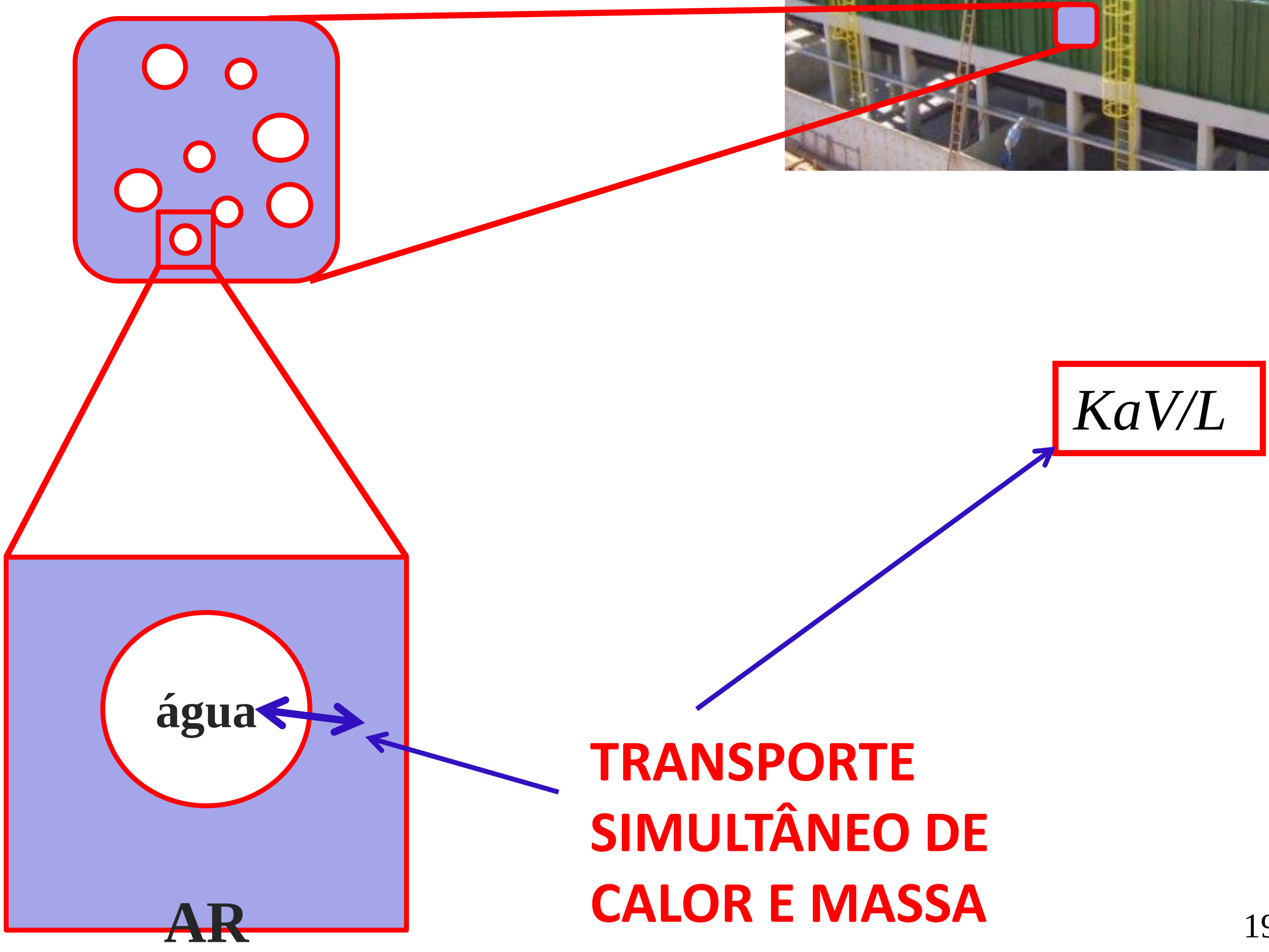
- **Resfriamento combinado** (wet-dry cooling towers)

circulação natural

circulação forçada

circulação induzida

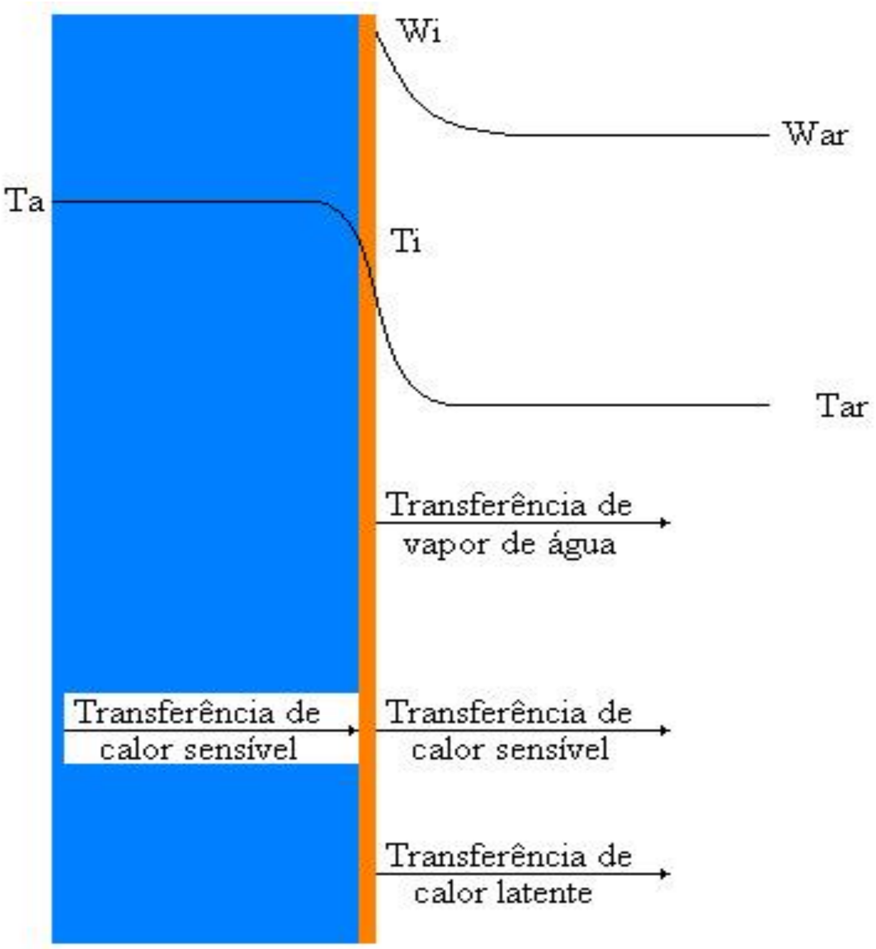
TORRE DE RESFRIAMENTO



TRANSPORTE SIMULTÂNEO DE CALOR E MASSA

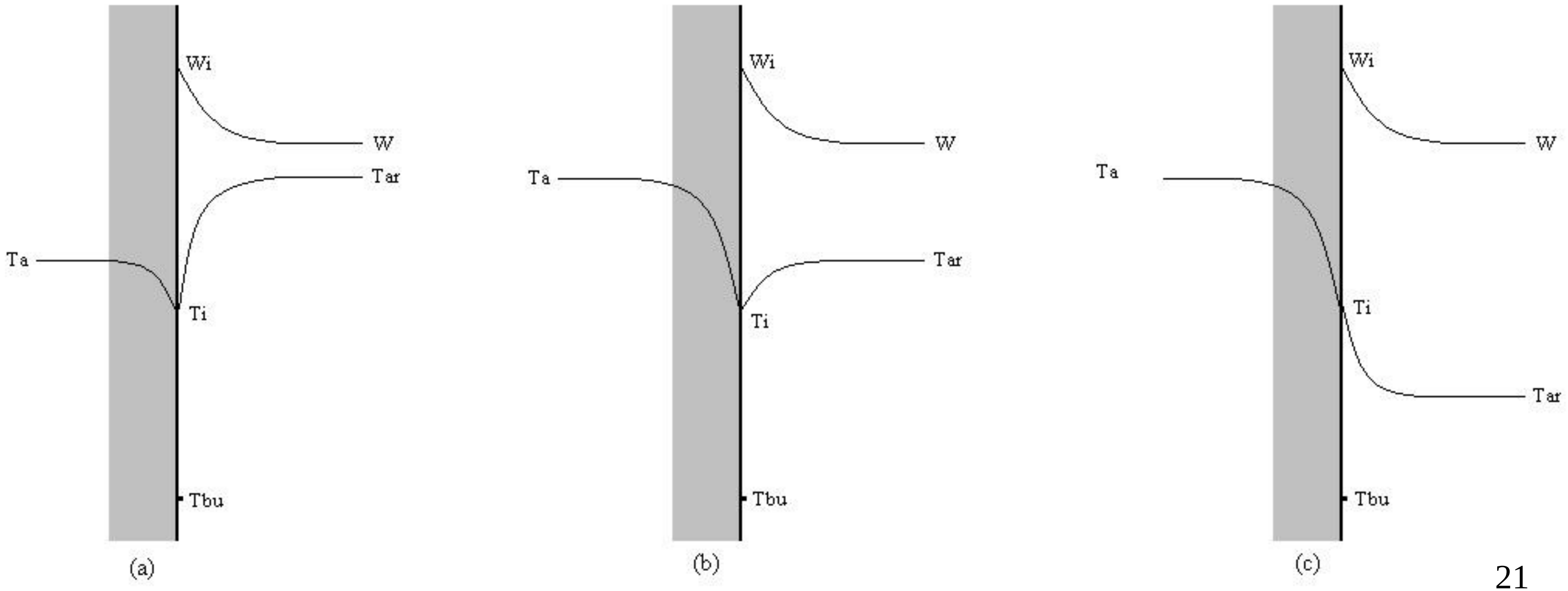
TORRE DE RESFRIAMENTO

Transferência de calor na interface ar - água.



TORRE DE RESFRIAMENTO

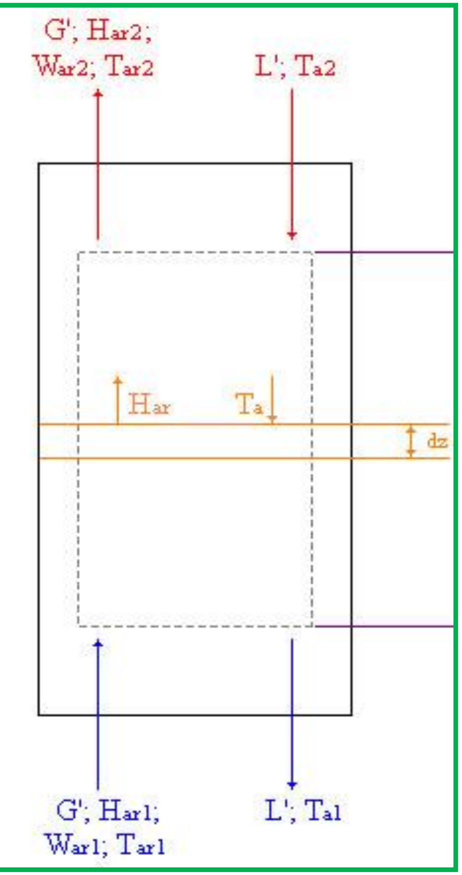
Perfis de umidade e de temperatura de possíveis condições no fundo da torre (a), (b) e no topo da torre (c). (McCABE et al. 1993)

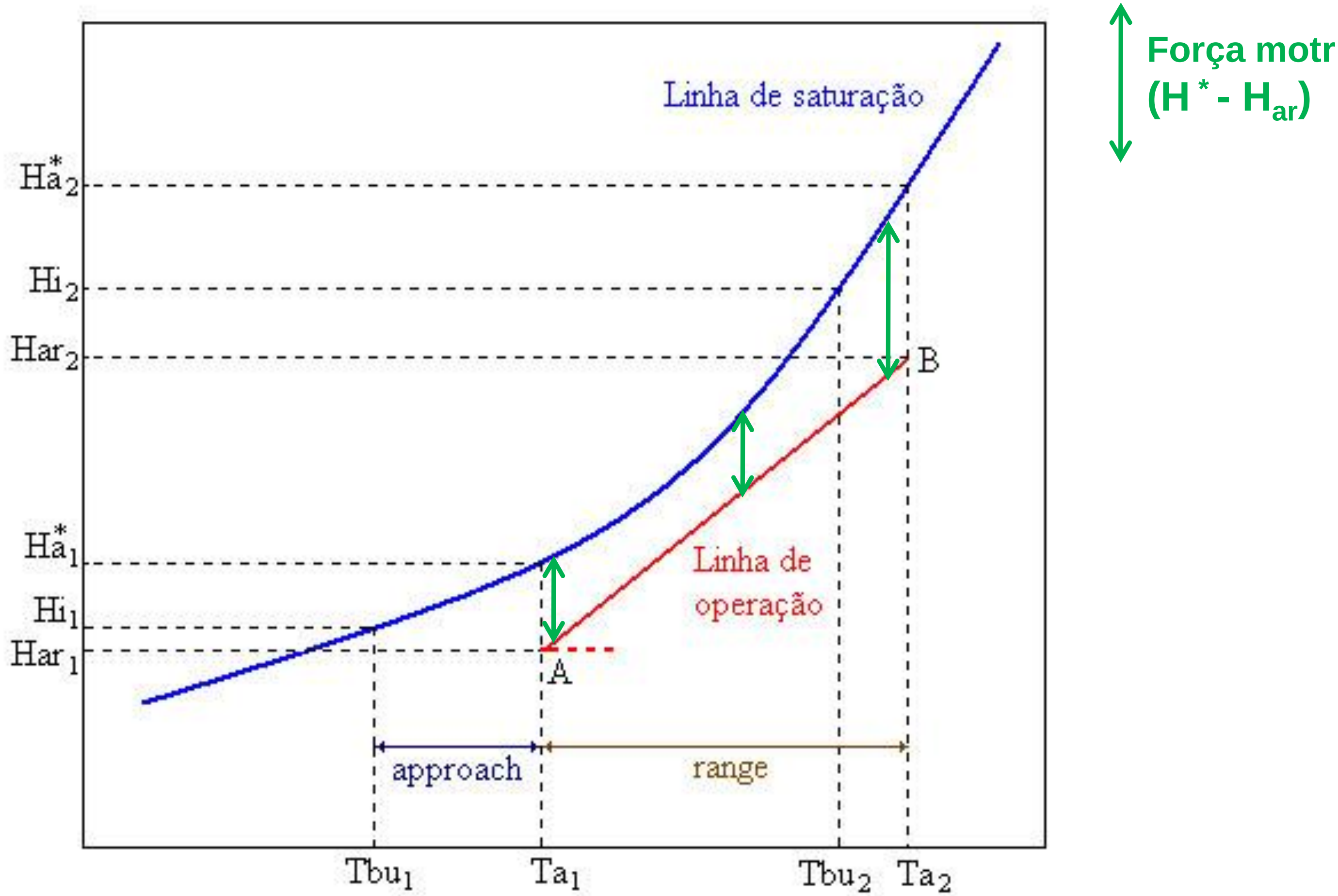


$$H_{ar2} - H_{ar1} = \left(\frac{L'}{G'}\right) \cdot c_L \cdot (T_{a1} - T_{a2})$$

TORRE DE RESFRIAMENTO

Transporte simultâneo de calor e massa





Carga térmica da torre:

$$Q = w \cdot c_L \cdot (T_Q - T_F)$$

TORRE DE RESFRIAMENTO – Desempenho típico