



Transporte Simultâneo de Calor e Massa – FT III

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Transporte simultâneo de calor e massa

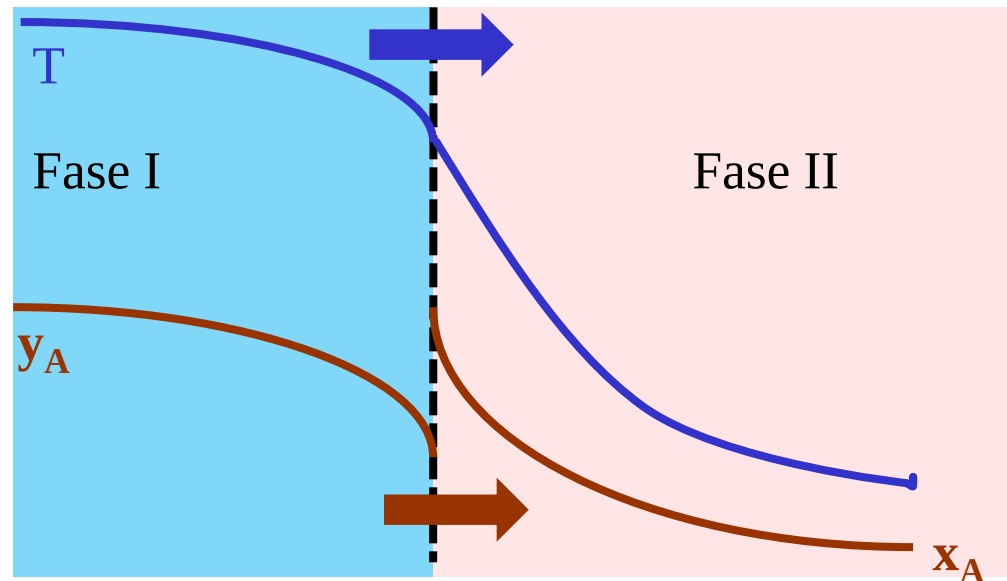
$$\vec{q} = -\vec{k} \cdot \text{grad } T + \sum \vec{j}_i \hat{H}_i + \vec{q}^x$$

**DIFUSÃO DE
CALOR**

**CONDUÇÃO
FOURIER**

DIFUSÃO

**TERMODIFUSÃO
DUFOUR**



$$-(k \cdot \text{grad } T)_I + \vec{j}_A \hat{H}_{A,I} = -(k \cdot \text{grad } T)_{II} + \vec{j}_A \hat{H}_{A,II}$$

Exemplo : Evaporação de Água

Balanço de Energia

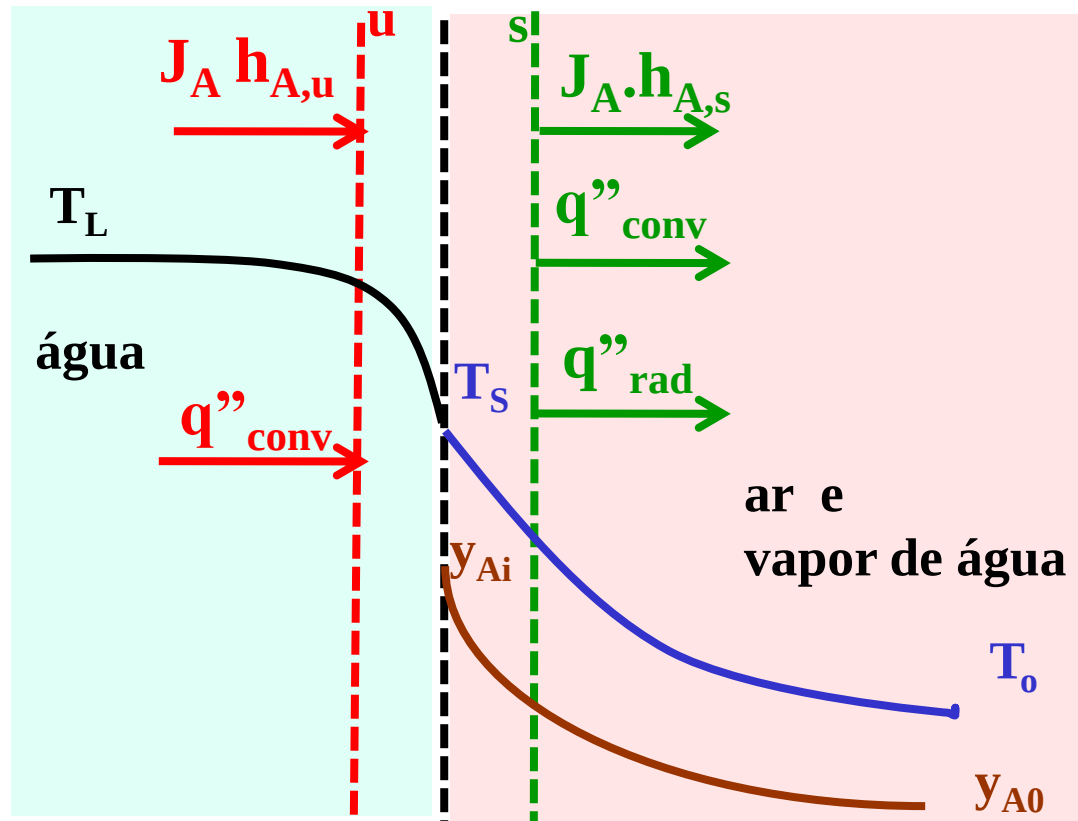
$$J_A (h_{A,s} - h_{A,u}) = q''_{\text{cond}} - q''_{\text{conv}} - q''_{\text{rad}}$$

Entalpia de vaporização

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

Fluxo evaporativo

$$J_A = k_x (X_{A,i} - X_{A,0})$$



Exemplo : Evaporação de Água

Balanço de Energia

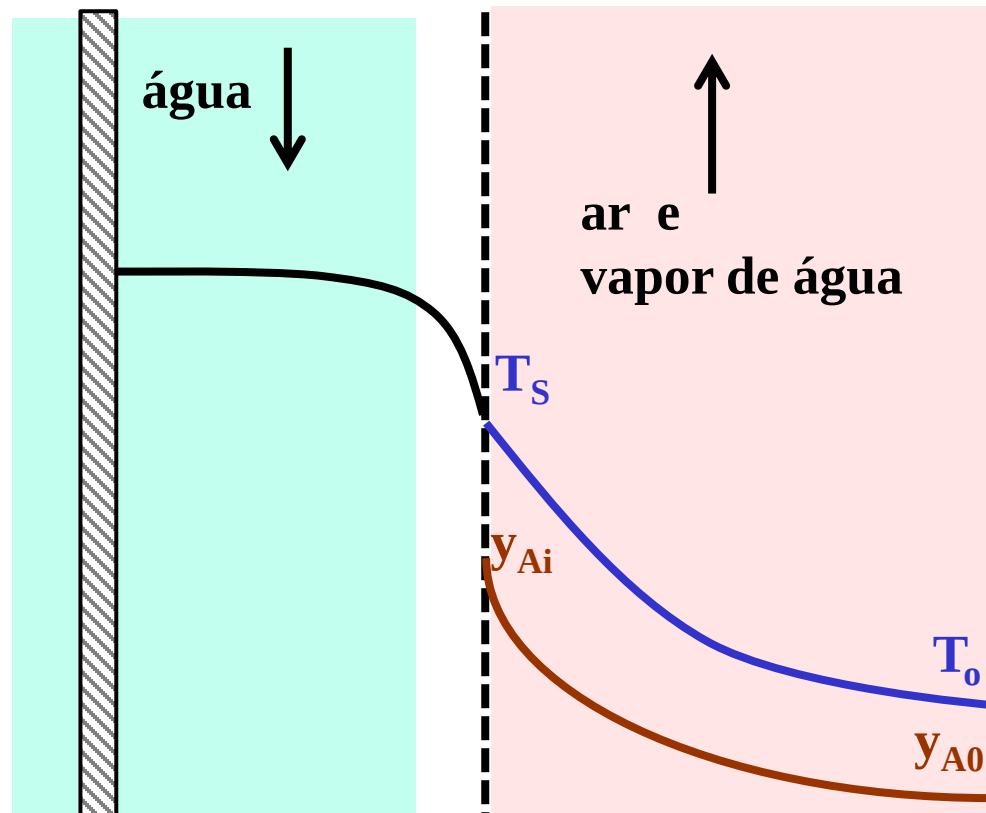
$$J_A (h_{A,s} - h_{A,u}) = q''_{\text{cond}} - q''_{\text{conv}} - q''_{\text{rad}}$$

Entalpia de vaporização

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Fluxo evaporativo

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Exemplo : Evaporação de Água

Balanco de Energia

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

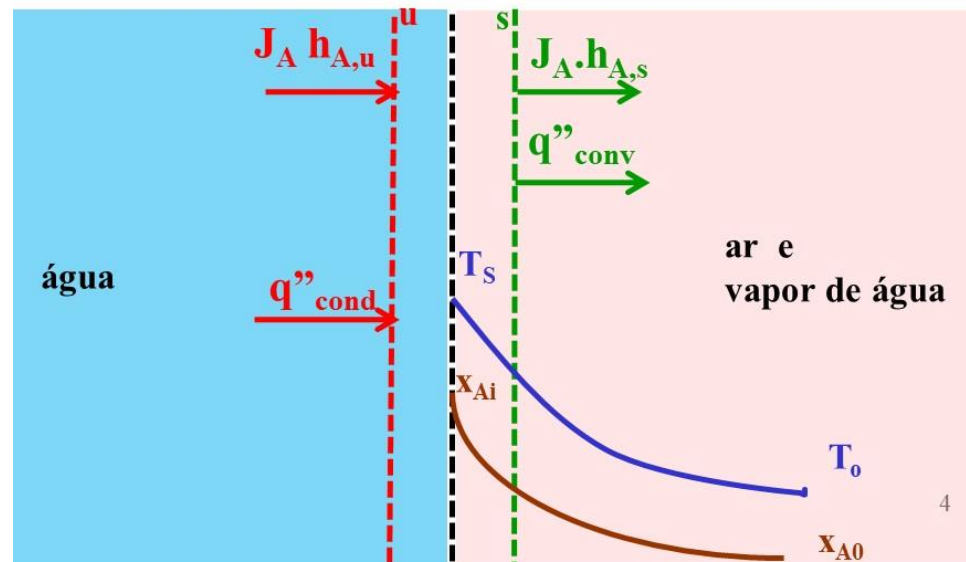
$$J_A = k_x (X_{A,i} - X_{A,0})$$

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

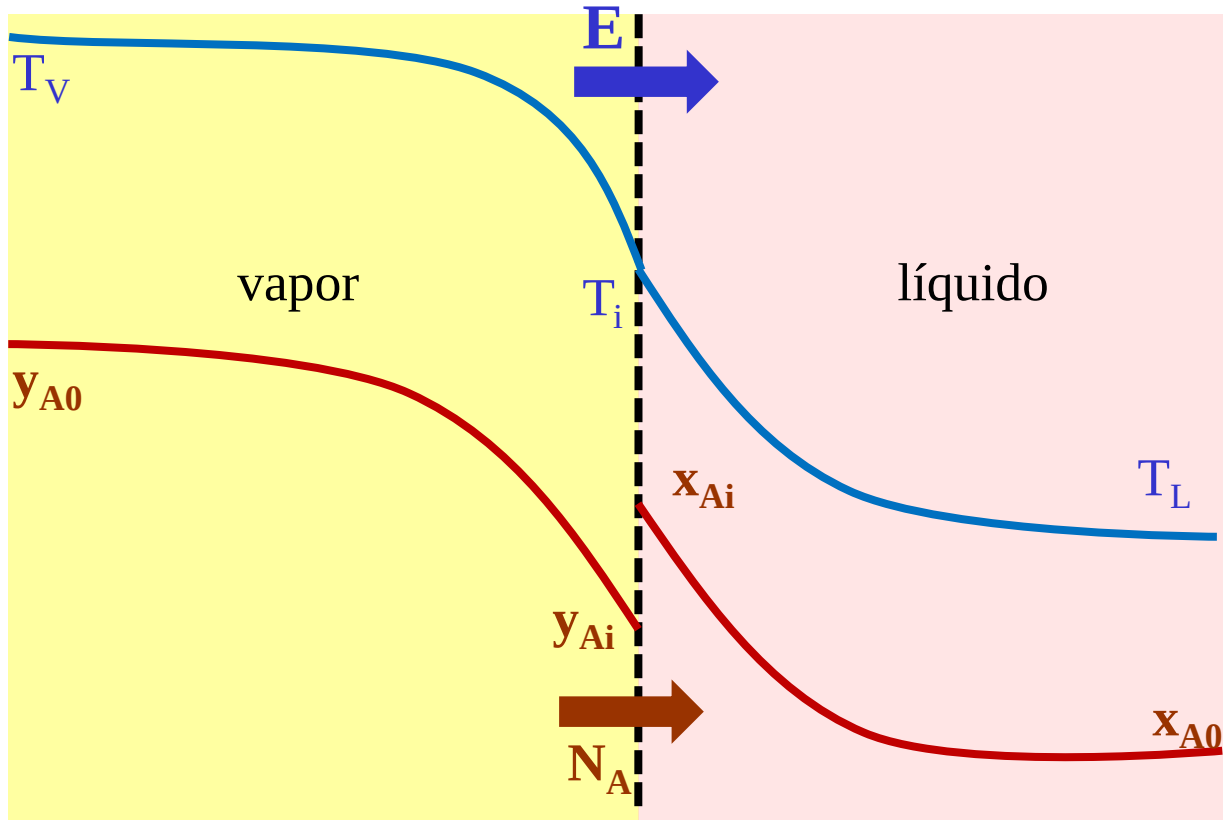
$$-\left(k \cdot \frac{\partial T}{\partial y}\right)_u$$

$$h_c (T_s - T_0)$$

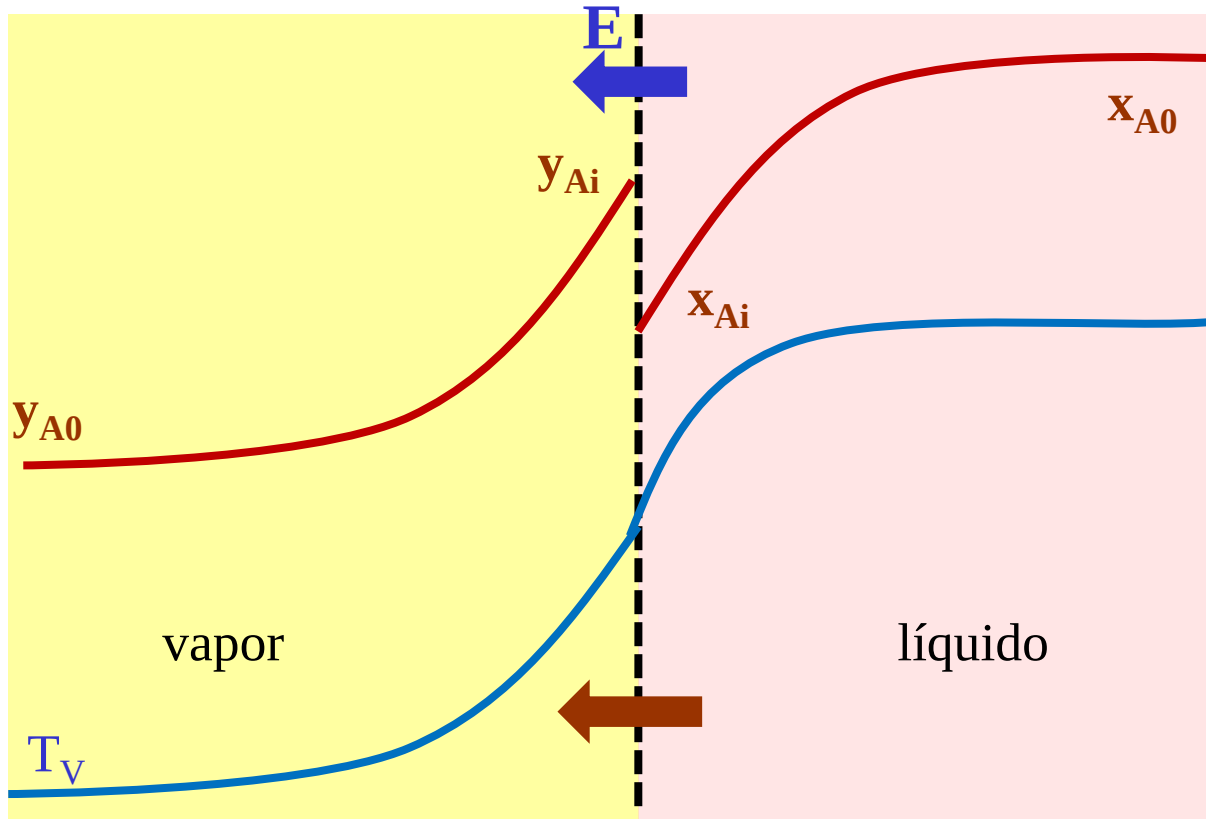
$$-\left(k \cdot \frac{\partial T}{\partial y}\right)_u = h_c (T_s - T_0) + k_x (X_{A,i} - X_{A,0}) h_{fg}$$



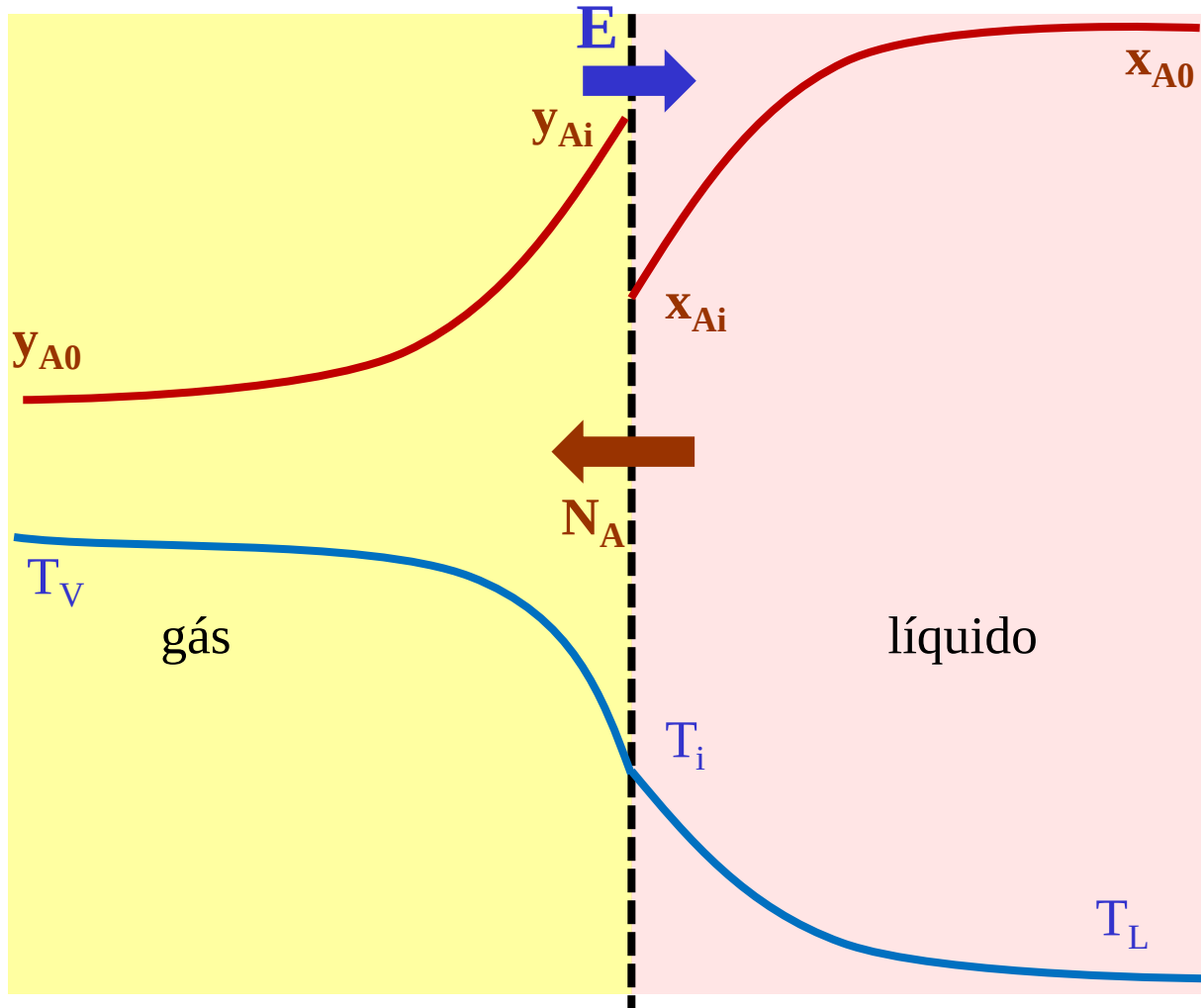
Condensação



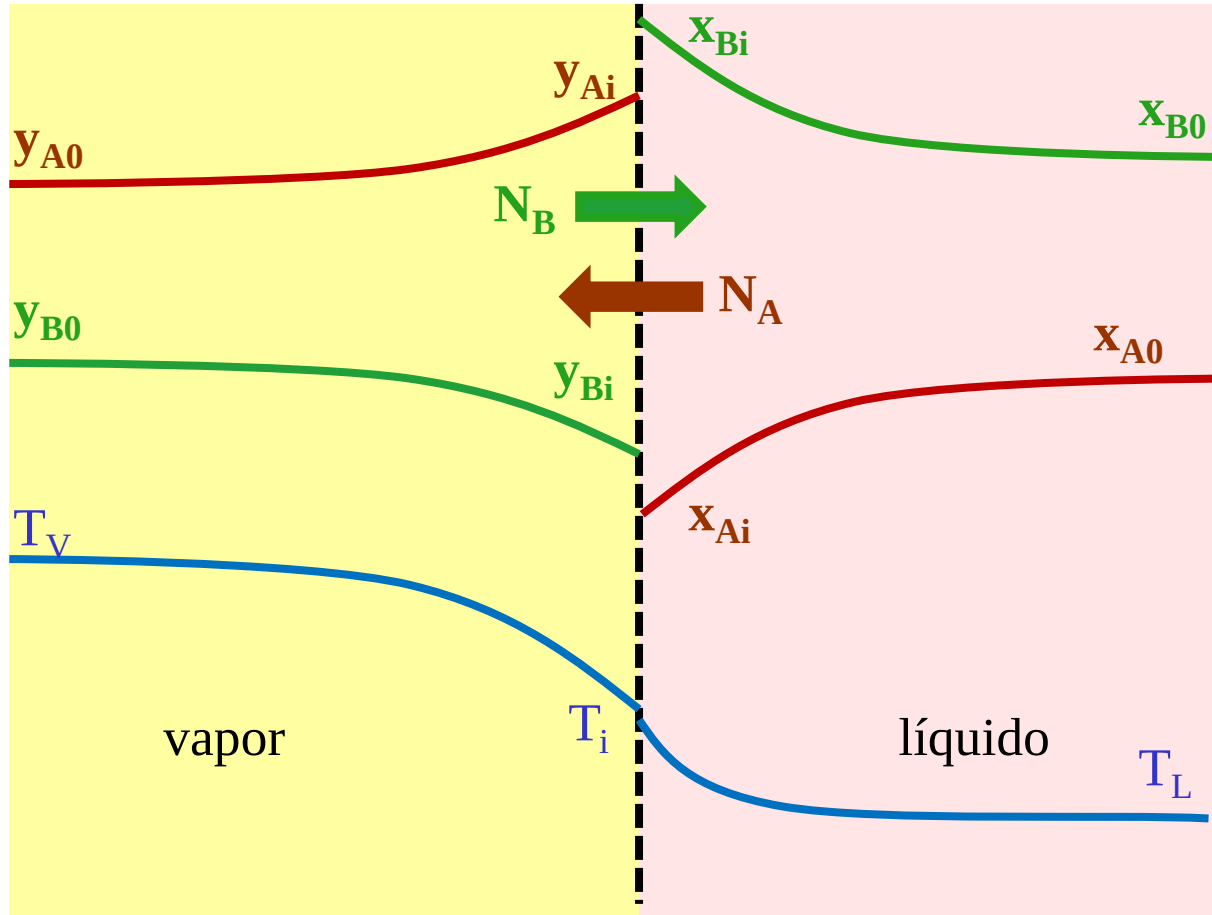
Evaporação



Secagem

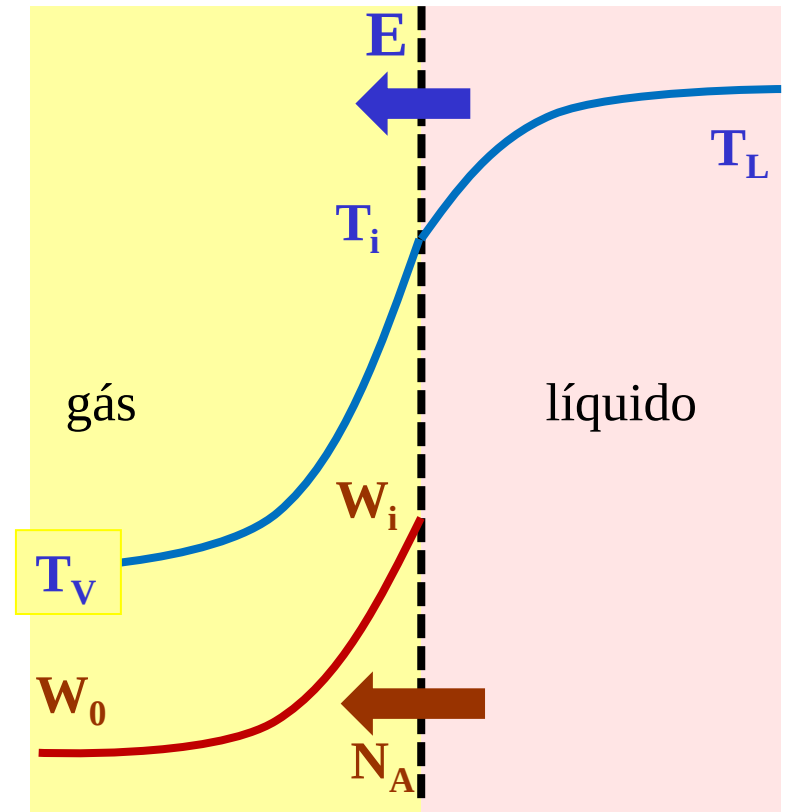
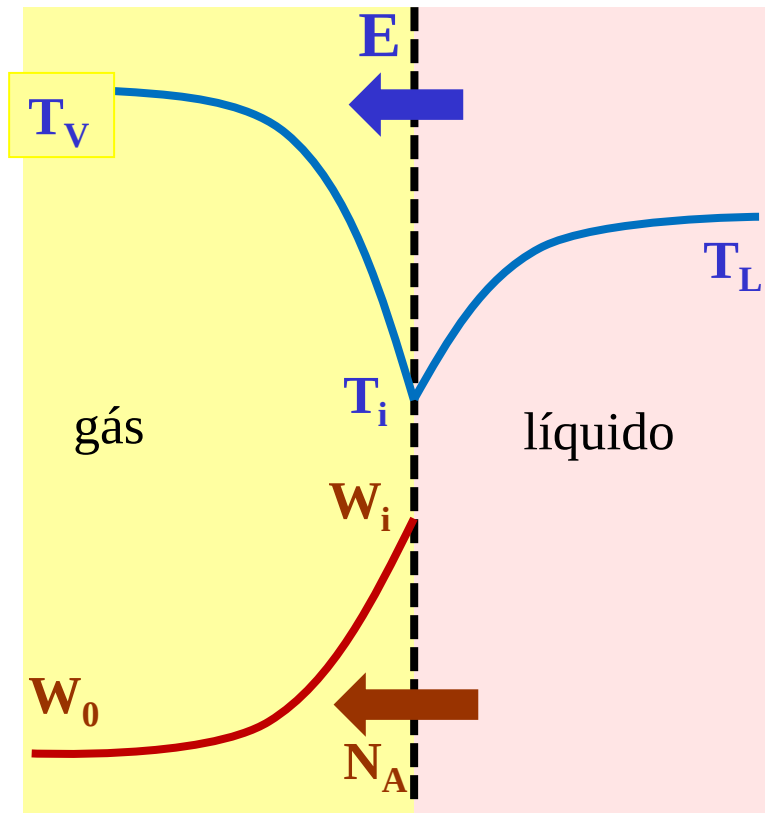


Destilação

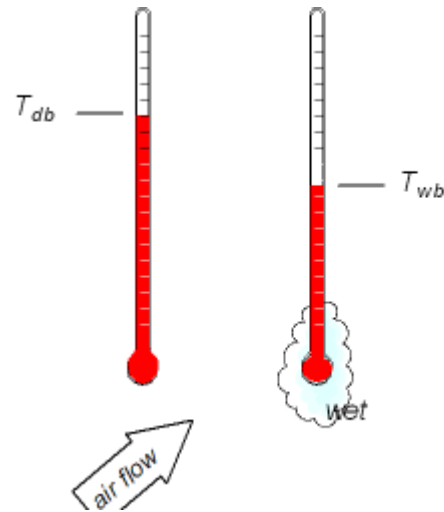
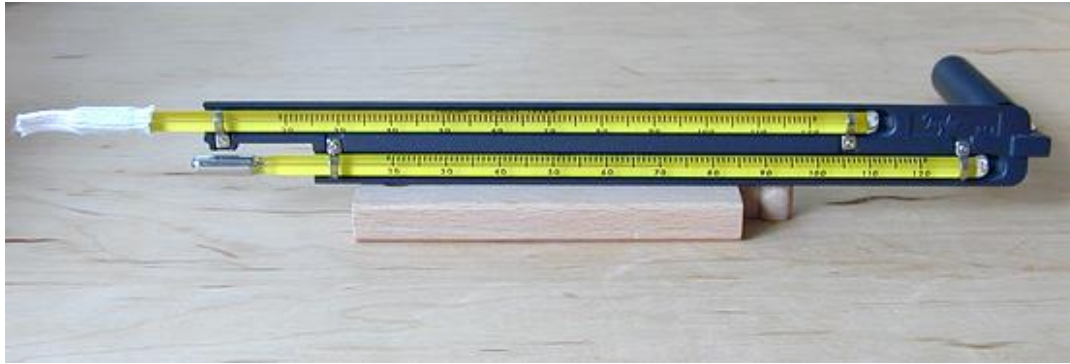


Resfriamento Evaporativo

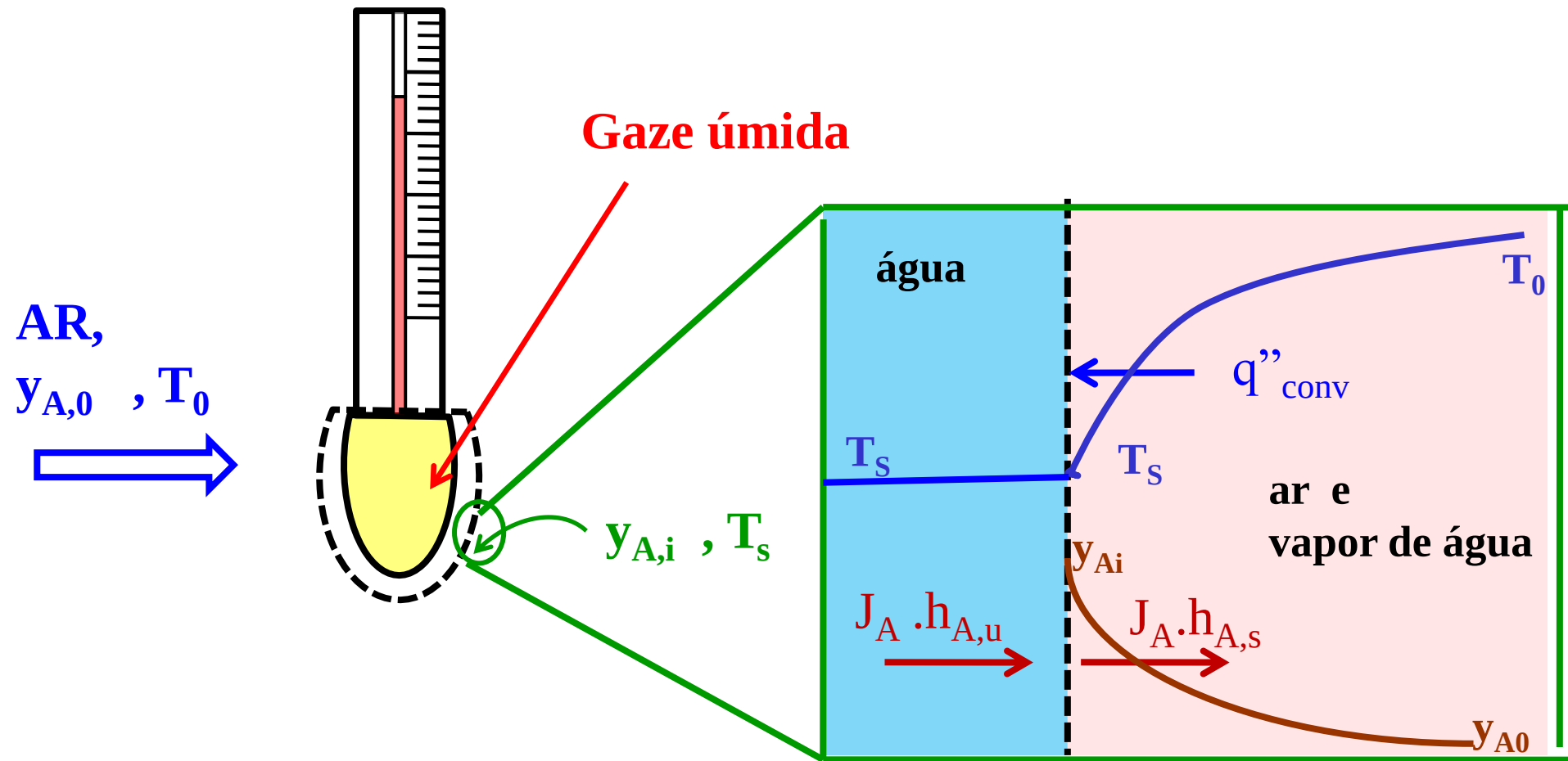
Torre de Resfriamento



Temperatura de bulbo úmido e bulbo seco



Temperatura de bulbo úmido e bulbo seco



-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:

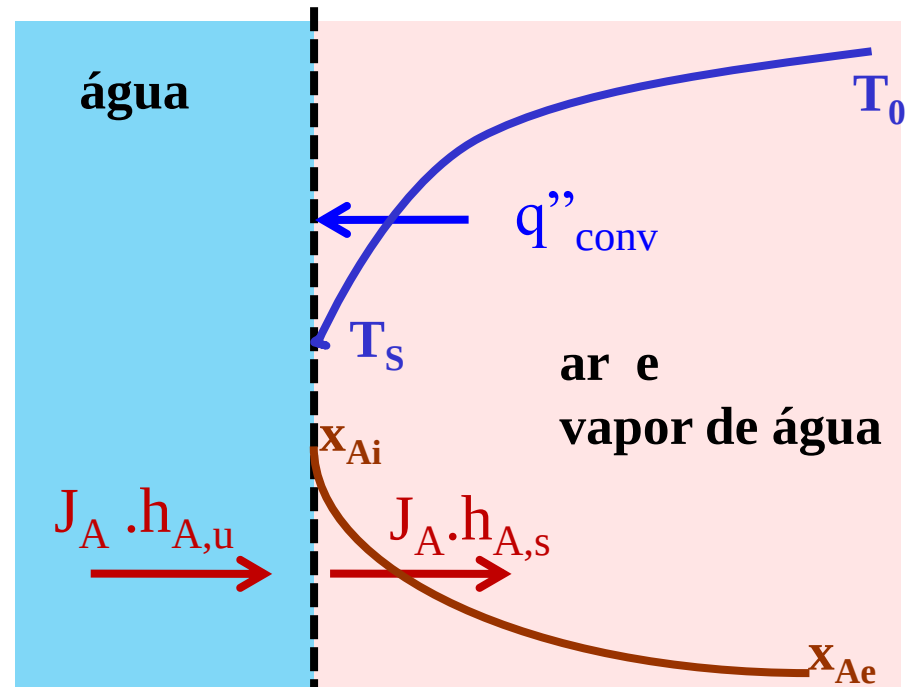
CALOR

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

MASSA

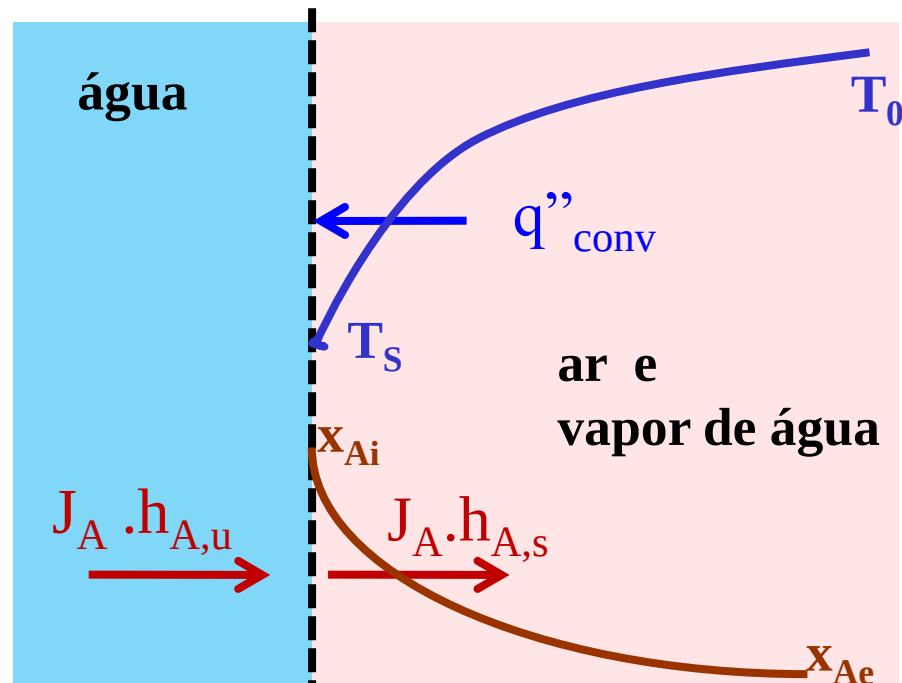
$$j_M = \frac{Sh}{Re Sc^{1/3}}$$

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



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

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



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

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

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

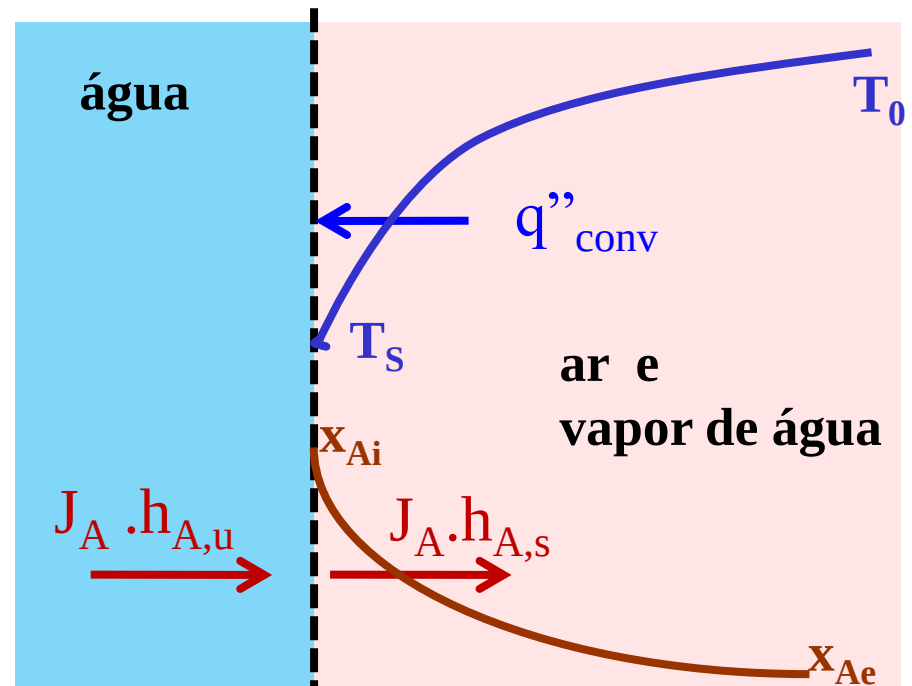
$$\frac{\text{Nu}}{\text{Sh}} = \frac{h_c}{k_x c_{P,\text{ar}}} \frac{\text{Pr}}{\text{Sc}} = \frac{\text{Pr}^{1/3}}{\text{Sc}^{1/3}} \Rightarrow$$

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

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

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

Número de Lewis



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

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

Dado de equilíbrio

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

$$X_{A,i} = X_{A,i}(T_{BU}, P)$$

TORRE DE RESFRIAMENTO



TORRE DE RESFRIAMENTO

- **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 %



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

$$\text{TEMPERATURA DE BULBO ÚMIDO DO AR} - T_{\text{BU}}$$

$$\text{APPROACH} = T_{\text{ÁGUA FRIA}} - T_{\text{BU}}$$

$$\text{APPROACH} > 3 \text{ }^{\circ}\text{C}$$

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

circulação natural



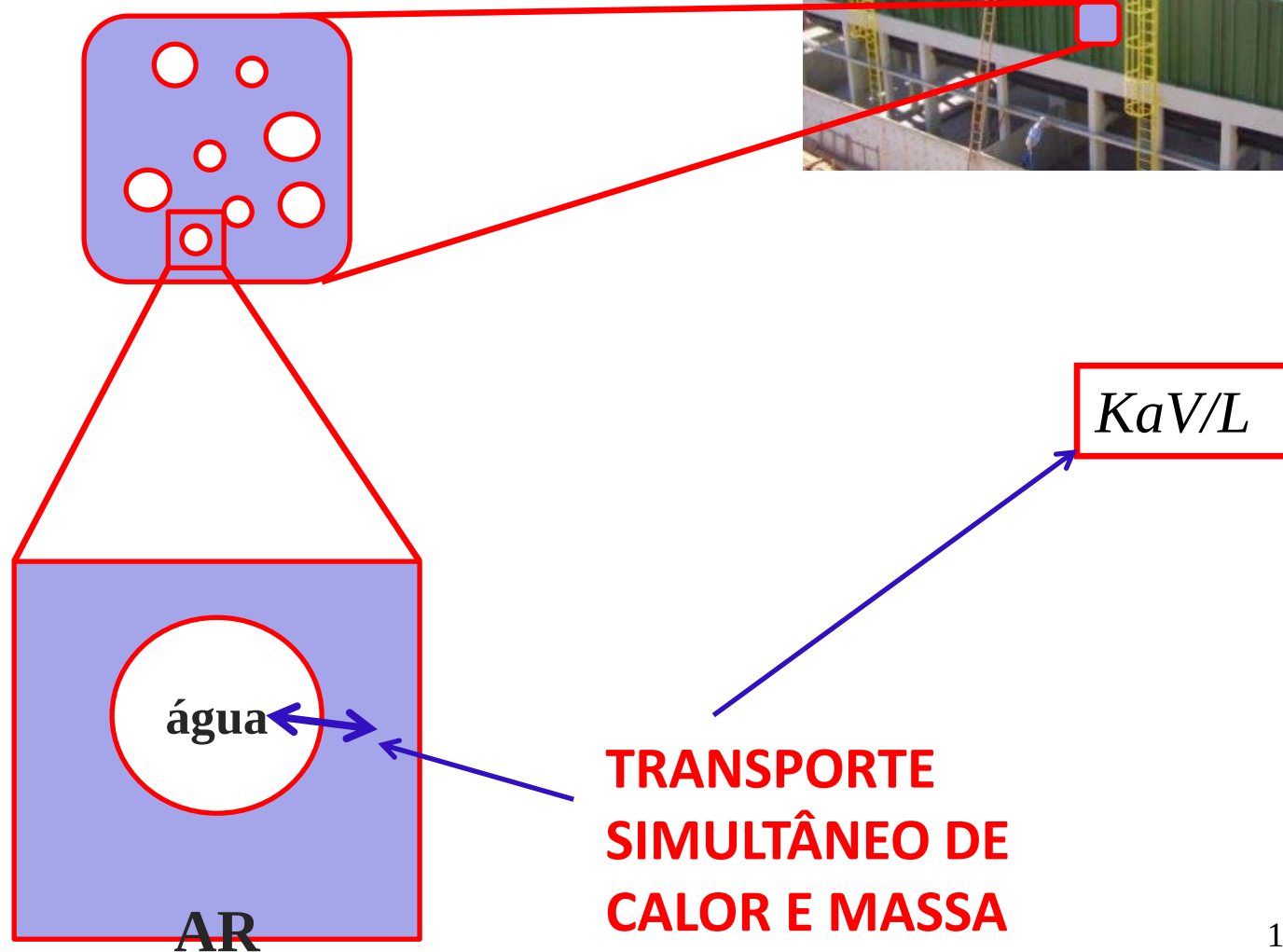
circulação forçada



circulação induzida

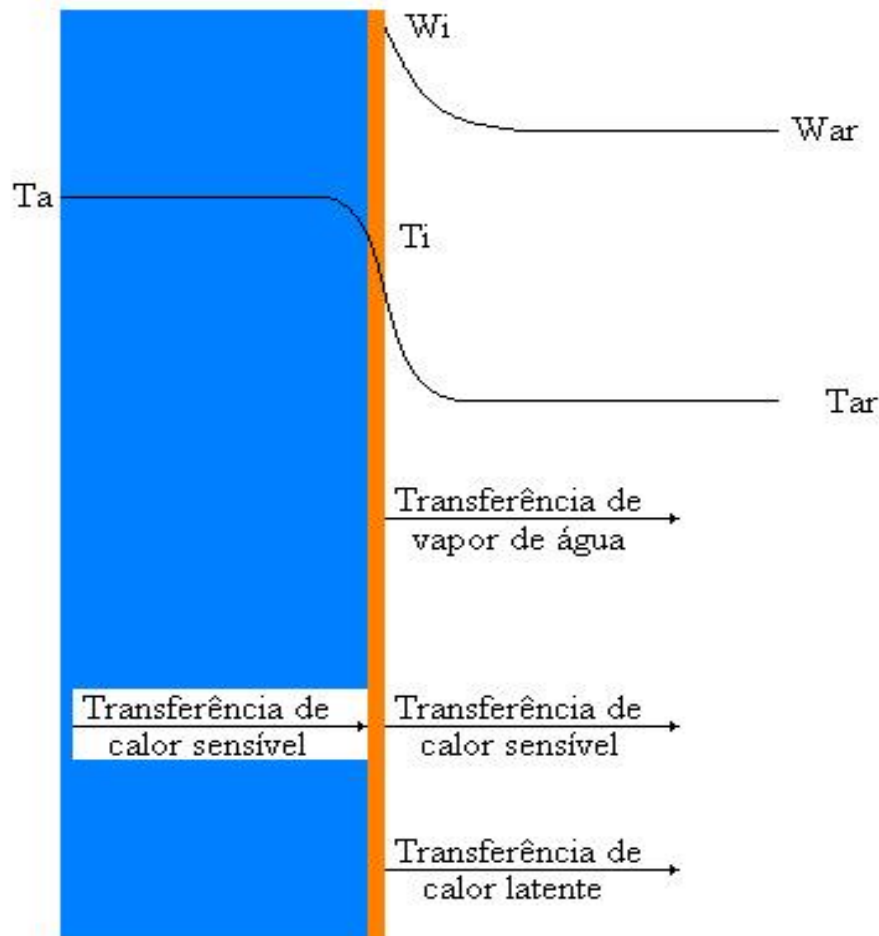


TORRE DE RESFRIAMENTO



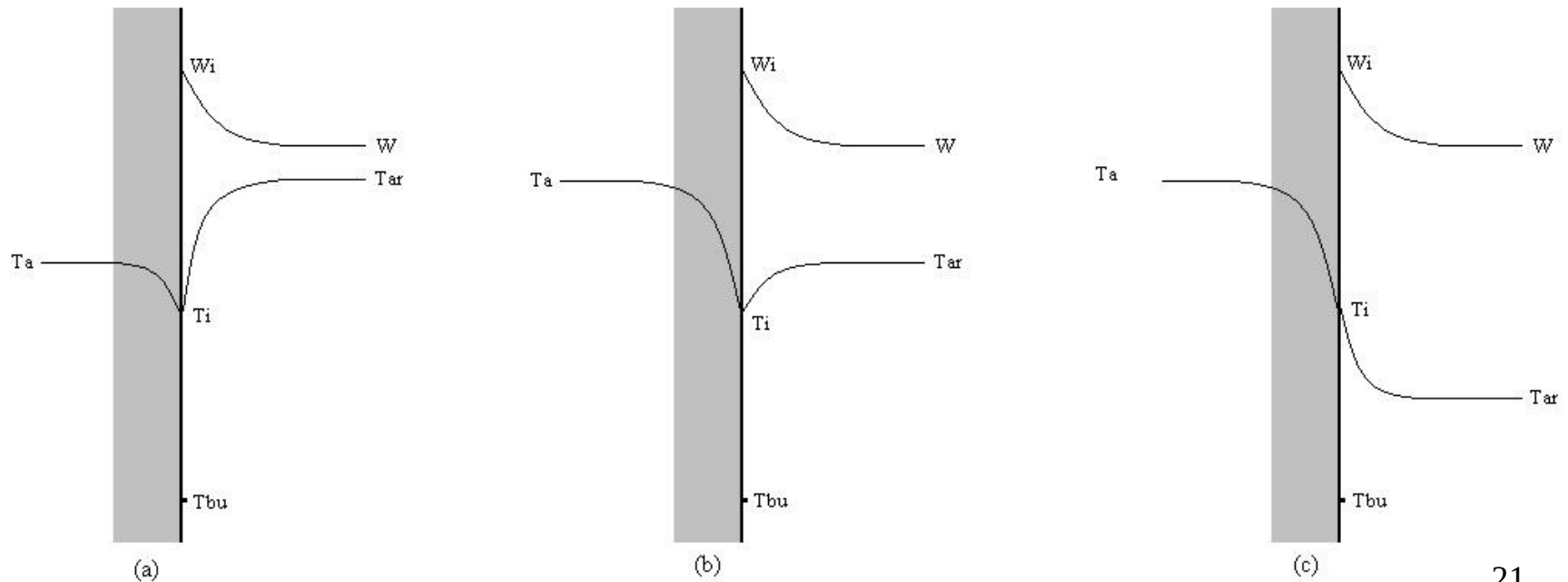
TORRE DE RESFRIAMENTO

Transferência de calor na interface ar - água.



TORRE DE RESFRIAMENTO

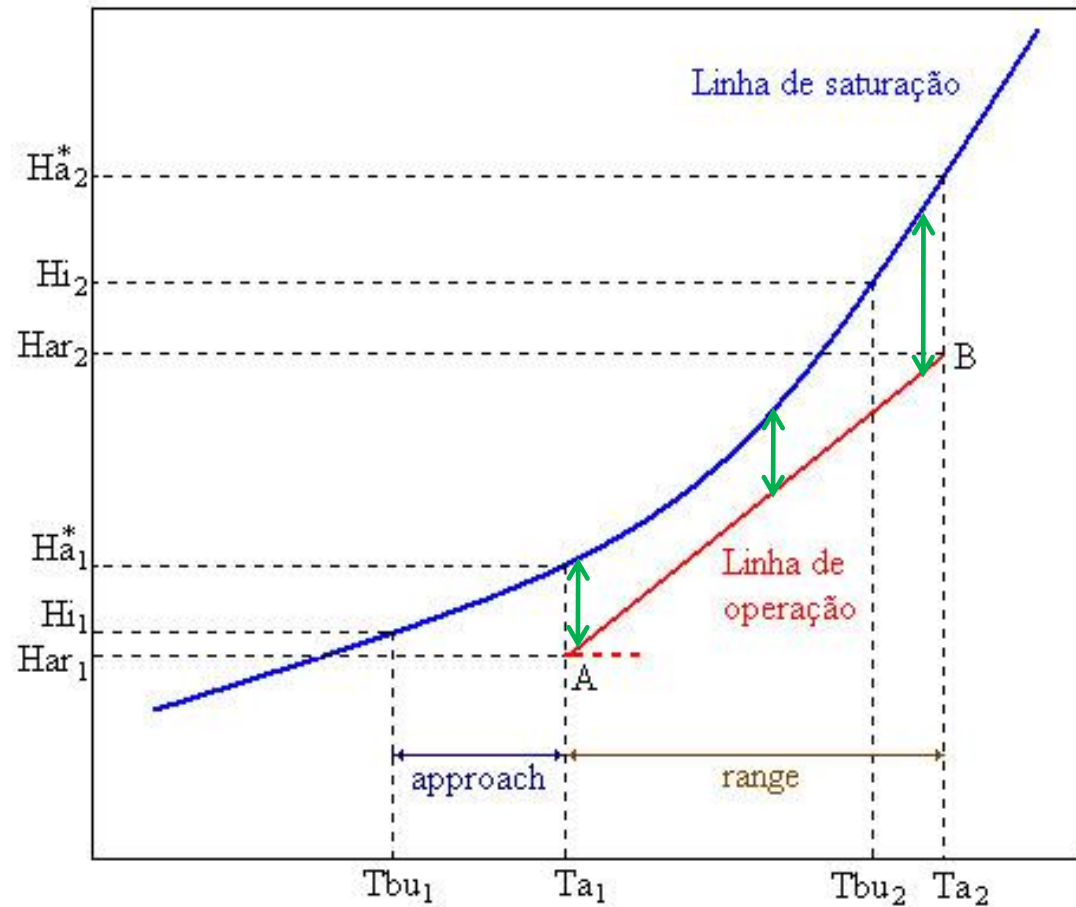
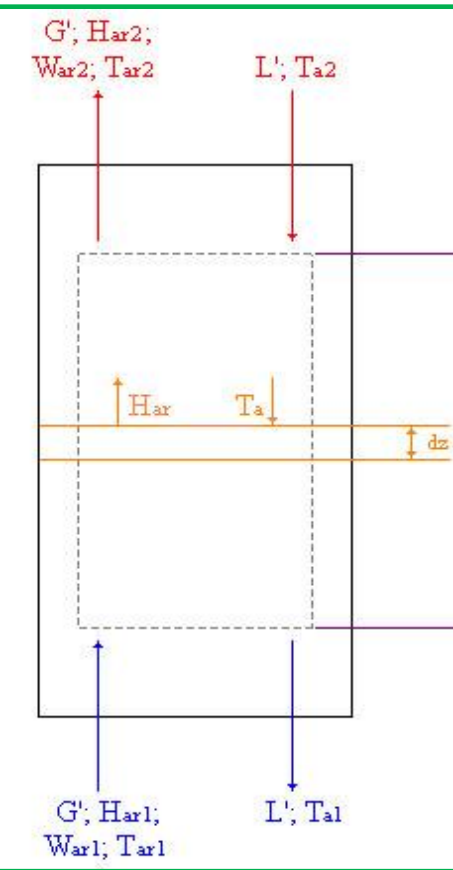
Perfis de umidade e de temperatura de possíveis condições no fundo da torre (a), (b) e no topo da torre (c). (McCABE et al. 1993)



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

TORRE DE RESFRIAMENTO

Transporte simultâneo de calor e massa



Força motriz
(H* - H_{ar})

Carga térmica da torre:

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

TORRE DE RESFRIAMENTO – Desempenho típico

