EPUSP

COEFICIENTES CONVECTIVOS

PQI 3301 - Fenômenos de Transporte III

Equação de Conservação Generalizada

Balanço microscópico de φ:

$$\rho \frac{D\varphi}{Dt} = \frac{\partial \rho\varphi}{\partial t} + \operatorname{div}\left(\rho\varphi\vec{v}\right) = -\operatorname{div}\vec{j}_{\phi} + \dot{\sigma}_{\forall\Phi}$$

$$\boxed{\frac{\partial \rho\varphi}{\partial t} + \operatorname{div}\left(\rho\vec{v}\varphi + \vec{j}_{\Phi}\right) = \dot{\sigma}_{\forall_{\Phi}}}$$

Equação constitutiva de difusão:

$$\boxed{\vec{j}_{\Phi} = -\rho\,\Gamma_{\varphi}\,\vec{\operatorname{grad}}\,\varphi}$$

φ	Γ_{Φ}	ν/Γ_{Φ}
V	ν	1
w_A	D_{AB}	Sc
c_pT	α	Pr

$$\boxed{\frac{\partial \rho\boldsymbol{\varphi}}{\partial t} + \operatorname{div}\rho\left(\vec{v}\boldsymbol{\varphi} - \Gamma_{\varphi}\operatorname{grad}\boldsymbol{\varphi}\right) = \dot{\sigma}_{\forall_{\Phi}}}$$

Equação de Conservação Generalizada - Adimensionalização

$$\frac{\partial \rho\varphi}{\partial t} + \operatorname{div} \rho\left(\vec{v}\varphi - \Gamma_{\varphi}\operatorname{grad}\varphi\right) = \dot{\sigma}_{\forall_{\Phi}}$$

$$\rho = \rho_0\,\hat{\rho} \quad ; \quad \vec{v} = v_0\,\hat{\vec{v}} \quad ; \quad \vec{r} = L\,\hat{\vec{r}} \quad ; \quad t = t_0\,\hat{t} \quad ; \quad \varphi = \hat{\varphi}\,\Delta\varphi + \varphi_0$$

$$\frac{1}{Sr}\frac{\partial \hat{\rho}\hat{\varphi}}{\partial \hat{t}} + \operatorname{div}\hat{\rho}\left(\hat{\vec{v}}\hat{\varphi} - \frac{1}{Pe}\operatorname{gr\hat{a}d}\hat{\varphi}\right) = \frac{\dot{\sigma}_{\forall_{\Phi}} L}{\rho_0\,\Delta\varphi\, v_0}$$

Equação de Conservação Generalizada - Adimensionalização

$\varphi = \omega_A$ *fração mássica* $\hat{\varphi} = \hat{\omega}_A = \dfrac{\omega_A - \omega_{A0}}{\omega_{AS} - \omega_{A0}}$

Reação química

Equação Cinética:

$$\boxed{\dot{\sigma}_{\forall T} = r_A \quad \left(\frac{\text{kg de A}}{\text{m}^3}\right)}$$

$$\boxed{\frac{L}{t_0 v_0}\frac{\partial \hat{\rho}\hat{\omega}_A}{\partial \hat{t}} + \hat{\text{div}}\,\hat{\rho}\left(\hat{\vec{v}}\hat{\omega}_A - \frac{D_{AB}}{v_0 L}\,\hat{\text{grad}}\;\hat{\omega}_A\right) = \frac{r_A L}{\rho_0\,\Delta\omega_A\,v_0}}$$

Equação da Continuidade para espécie A

$$\frac{1}{Sr}\frac{\partial \hat{\rho}\,\hat{\omega}_A}{\partial \hat{t}} + \hat{div}\,\hat{\rho}\left(\hat{\vec{v}}\,\hat{\omega}_A - \frac{1}{Pe}\,\hat{grad}\;\hat{\omega}_A\right) = \frac{r_A L}{\rho_0\,\Delta\omega_A\,v_0}$$

PECLET

$$\boxed{Pe = \frac{v_0 L}{\Gamma_\varphi} = \frac{\nu}{\Gamma_\varphi}\frac{v_0 L}{\nu} = Re\frac{\nu}{\Gamma_\varphi}}$$

$$\boxed{Pe = Re\frac{\nu}{\Gamma_\varphi}}$$

Coeficientes Convectivos

ADIMENSIONALIZAÇÃO

$$\frac{1}{Sr}\frac{\partial\hat{\rho}\hat{\varphi}}{\partial\hat{t}}+\operatorname{div}\hat{\rho}\underbrace{\left(\hat{\vec{v}}\hat{\varphi}-\frac{1}{Pe}\operatorname{gr\hat{a}d}\hat{\varphi}\right)}=\frac{\dot{\sigma}_{\forall_\Phi}L}{\rho_0\,\Delta\varphi\,v_0}$$

⇓

ESCOAMENTO + DIFUSÃO

⇓

INTERFACE / PAREDE

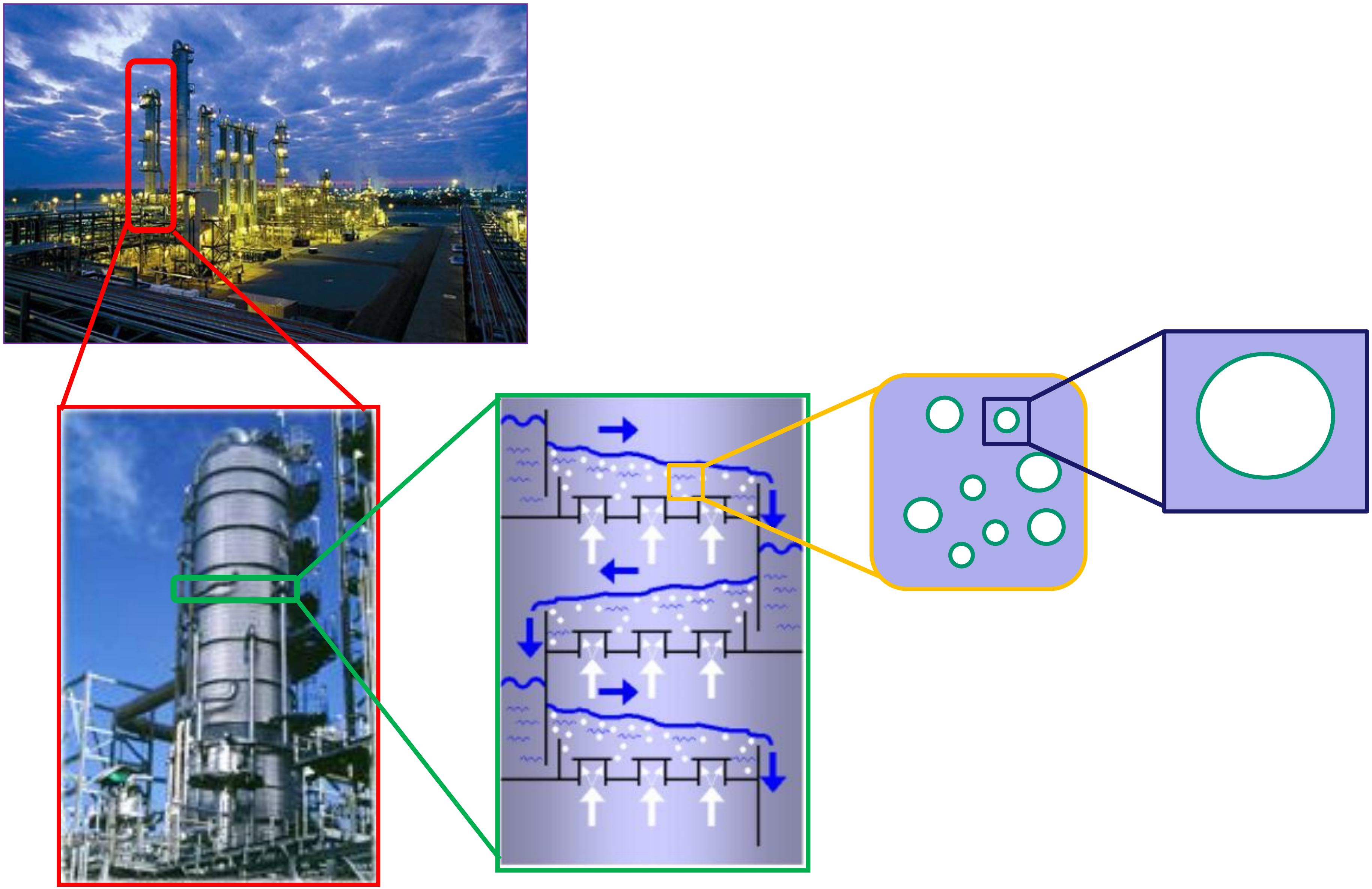
⇓

COEFICIENTE DE CONVECÇÃO

⇓

$$\vec{j}_{\phi,parede}=CO_{\varphi}\left(\varphi_S-\varphi_0\right)$$

Estágio de Equilíbrio e FT's



FLUXOS MÁSSICOS E MOLARES: DIFUSIVOS E CONVECTIVOS - BIRD

	Quantity	With Respect to Stationary Axes	With Respect to $\boldsymbol{v}$	With Respect to $\boldsymbol{v}^\star$
Basic definitions	Velocity of species A (cm $\sec^{-1}$)	$\boldsymbol{v}_A$ (A)	$\boldsymbol{v}_A - \boldsymbol{v}$ (B)	$\boldsymbol{v}_A - \boldsymbol{v}^\star$ (C)
	Mass flux of species A (g cm^{-2} $\sec^{-1}$)	$\boldsymbol{n}_A = \rho_A \boldsymbol{v}_A$ (D)	$\boldsymbol{j}_A = \rho_A(\boldsymbol{v}_A - \boldsymbol{v})$ (E)	$\boldsymbol{j}_A^\star = \rho_A(\boldsymbol{v}_A - \boldsymbol{v}^\star)$ (F)
	Molar flux of species A (g-moles cm^{-2} $\sec^{-1}$)	$\boldsymbol{N}_A = c_A \boldsymbol{v}_A$ (G)	$\boldsymbol{J}_A = c_A(\boldsymbol{v}_A - \boldsymbol{v})$ (H)	$\boldsymbol{J}_A^\star = c_A(\boldsymbol{v}_A - \boldsymbol{v}^\star)$ (I)
Relations among the fluxes, for reference only	Sum of mass fluxes (g cm^{-2} $\sec^{-1}$)	$\boldsymbol{n}_A + \boldsymbol{n}_B = \rho \boldsymbol{v}$ (J)	$\boldsymbol{j}_A + \boldsymbol{j}_B = 0$ (K)	$\boldsymbol{j}_A^\star + \boldsymbol{j}_B^\star = \rho(\boldsymbol{v} - \boldsymbol{v}^\star)$ (L)
	Sum of molar fluxes (g-moles cm^{-2} $\sec^{-1}$)	$\boldsymbol{N}_A + \boldsymbol{N}_B = c\boldsymbol{v}^\star$ (M)	$\boldsymbol{J}_A + \boldsymbol{J}_B = c(\boldsymbol{v}^\star - \boldsymbol{v})$ (N)	$\boldsymbol{J}_A^\star + \boldsymbol{J}_B^\star = 0$ (O)
	Fluxes in terms of $\boldsymbol{n}_A$ and $\boldsymbol{n}_B$	$\boldsymbol{N}_A = \dfrac{\boldsymbol{n}_A}{M_A}$ (P)	$\boldsymbol{j}_A = \boldsymbol{n}_A - \omega_A(\boldsymbol{n}_A + \boldsymbol{n}_B)$ (Q)	$\boldsymbol{j}_A^\star = \boldsymbol{n}_A - x_A\left(\boldsymbol{n}_A + \dfrac{M_A}{M_B}\boldsymbol{n}_B\right)$ (R)
	Fluxes in terms of $\boldsymbol{N}_A$ and $\boldsymbol{N}_B$	$\boldsymbol{n}_A = \boldsymbol{N}_A M_A$ (S)	$\boldsymbol{J}_A = \boldsymbol{N}_A - \omega_A\left(\boldsymbol{N}_A + \dfrac{M_B}{M_A}\boldsymbol{N}_B\right)$ (T)	$\boldsymbol{J}_A^\star = \boldsymbol{N}_A - x_A(\boldsymbol{N}_A + \boldsymbol{N}_B)$ (U)
	Fluxes in terms of $\boldsymbol{j}_A$ and $\boldsymbol{v}$	$\boldsymbol{n}_A = \boldsymbol{j}_A + \rho_A \boldsymbol{v}$ (V)	$\boldsymbol{J}_A = \dfrac{\boldsymbol{j}_A}{M_A}$ (W)	$\boldsymbol{j}_A^\star = \dfrac{M}{M_B}\boldsymbol{j}_A$ (X)
	Fluxes in terms of $\boldsymbol{J}_A^\star$ and $\boldsymbol{v}^\star$	$\boldsymbol{N}_A = \boldsymbol{J}_A^\star + c_A \boldsymbol{v}^\star$ (Y)	$\boldsymbol{J}_A = \dfrac{M_B}{M}\boldsymbol{J}_A^\star$ (Z)	$\boldsymbol{j}_A^\star = \boldsymbol{J}_A^\star M_A$ (AA)

CONCENTRAÇÕES USUAIS EM TRANSPORTE DE MASSA

	mass fraction ω [–]	mole fraction x [–]	absolute humidity $H\left[\frac{\text{kg}-\text{A}}{\text{kg}-\text{B}}\right]$	mole ratio $X\left[\frac{\text{mol}-\text{A}}{\text{mol}-\text{B}}\right]$
mass fraction ω [–]	ω	$\dfrac{x}{\frac{M_B}{M_A}+\left\{1-\frac{M_B}{M_A}\right\}x}$	$\dfrac{H}{1+H}$	$\dfrac{X}{\frac{M_B}{M_A}+X}$
mole fraction x [–]	$\dfrac{\omega}{\frac{M_A}{M_B}+\left\{1-\frac{M_A}{M_B}\right\}\omega}$	x	$\dfrac{H}{\frac{M_A}{M_B}+H}$	$\dfrac{X}{1+X}$
absolute humidity $H\left[\frac{\text{kg}-\text{A}}{\text{kg}-\text{B}}\right]$	$\dfrac{\omega}{1-\omega}$	$\left(\dfrac{x}{1-x}\right)\left(\dfrac{M_A}{M_B}\right)$	H	$\left(\dfrac{M_A}{M_B}\right)X$
mole ratio $X\left[\frac{\text{mol}-\text{A}}{\text{mol}-\text{B}}\right]$	$\left(\dfrac{M_B}{M_A}\right)\left(\dfrac{\omega}{1-\omega}\right)$	$\left(\dfrac{x}{1-x}\right)$	$\left(\dfrac{M_B}{M_A}\right)H$	X

RELAÇÕES ENTRE AS DEFINIÇÕES DE CONCENTRAÇÃO

	mass fraction ω_A [–]	mole fraction x_A [–]	partial density ρ_A [kg m^{-3}]	molar density c_A [kmol m^{-3}]	partial pressure p_A [kPa]
mass fraction ω_A [–]	ω	$\dfrac{x_A M_A}{\sum_i x_i M_i}$	$\dfrac{\rho_A}{\sum_i \rho_i}$	$\dfrac{c_A M_A}{\sum_i c_i M_i}$	$\dfrac{p_A M_A}{\sum_i p_i M_i}$
mole fraction x_A [–]	$\dfrac{(\omega_A/M_A)}{\sum_i (\omega_i/M_i)}$	x_A	$\dfrac{\rho_A/M_A}{\sum_i (\rho_i/M_i)}$	$\dfrac{c_A}{\sum_i c_i}$	$\dfrac{p_A}{\sum_i p_i}$
partial density ρ_A [kg m^{-3}]	$\rho\,\omega_A$	$\dfrac{\rho\, x_A M_A}{\sum_i x_i M_i}$	ρ_A	$c_A M_A$	$\dfrac{M_A p_A}{RT}$
molar density c_A [kmol m^{-3}]	$\dfrac{\rho\,\omega_A}{M_A}$	$c x_A$	$\dfrac{\rho_A}{M_A}$	c_A	$\dfrac{p_A}{RT}$
partial pressure p_A [kPA]	$\dfrac{(\omega_A/M_A)P}{\sum_i (\omega_i/M_i)}$	$P x_A$	$\dfrac{RT\rho_A}{M_A}$	$c_A RT$	p_A

Mixture: $\sum_i x_i = 1,\ \sum_i \omega_i = 1,\ \rho = \sum_i \rho_i,\ c = \sum_i c_i,\ P = \sum_i p_i$

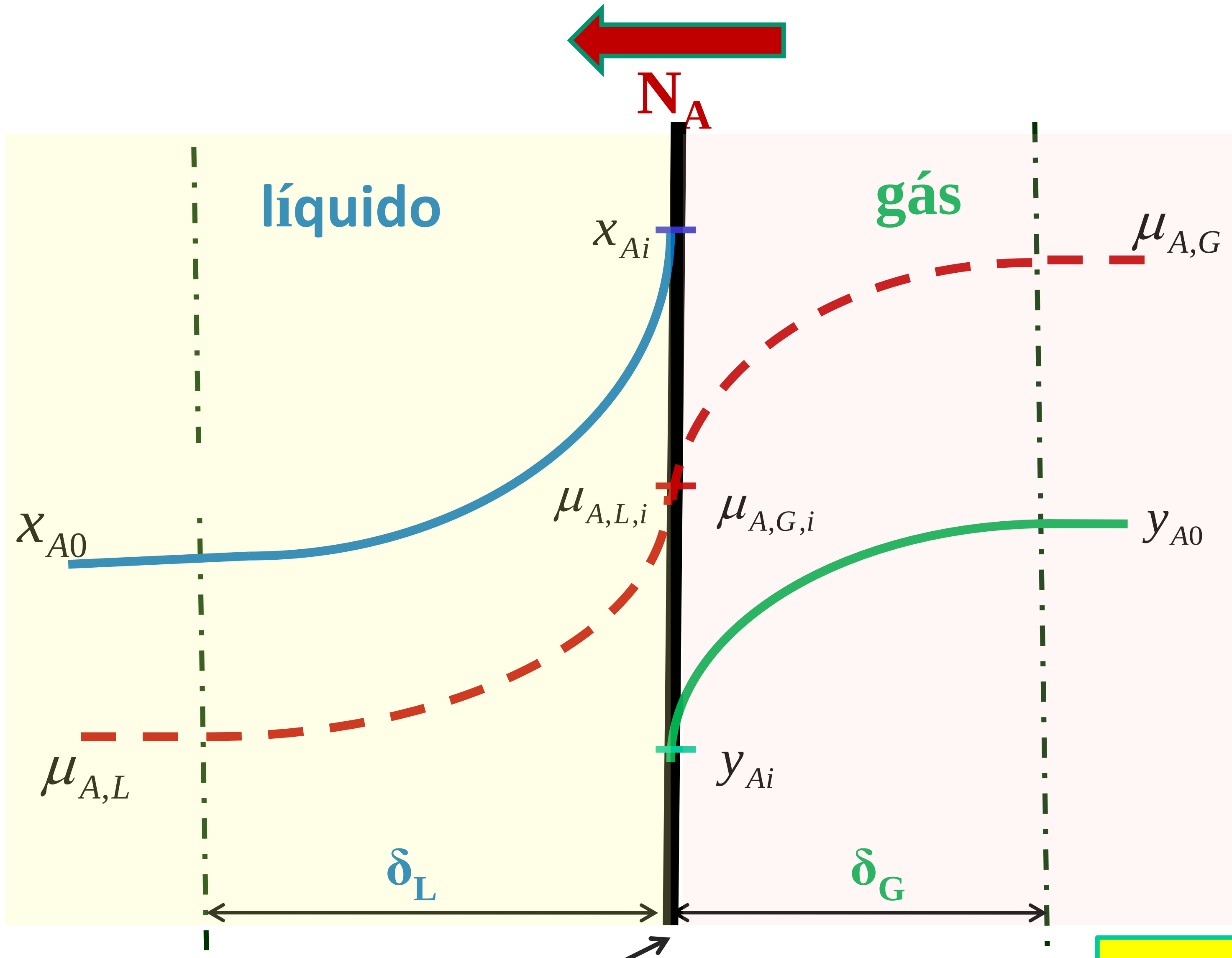
$$M = \sum_i M_i x_i = \left(\sum_i \frac{\omega_i}{M_i}\right)^{-1}$$

COEFICIENTES DE TRANSPORTE DE MASSA

Mass transfer coefficient	Unit	Definition	Driving force	Phase
k_y	$[\text{kmol m}^{-2}\text{ s}^{-1}]$	$N_A^* = k_y(y_s - y_\infty)$	Δy	Gas phase
k_G	$[\text{kmol m}^{-2}\text{ s}^{-1}\text{ kPa}^{-1}]$	$N_A^* = k_G(p_s - p_\infty)$	Δp	
k_Y	$[\text{kmol m}^{-2}\text{ s}^{-1}]$	$N_A^* = k_Y(Y_s - Y_\infty)$	ΔY	
k	$[\text{m s}^{-1}]$	$N_A = \rho_G k(\omega_{Gs} - \omega_{G\infty})$	$\Delta\omega_G$	
k_H	$[\text{kg m}^{-2}\text{ s}^{-1}]$	$N_A = k_H(H_s - H_\infty)$	ΔH	
k_L	$[\text{m s}^{-1}]$	$N_A^* = k_L(c_s - c_\infty)$	Δc	Liquid phase
k_x	$[\text{kmol m}^{-2}\text{ s}^{-1}]$	$N_A^* = k_x(x_s - x_\infty)$	Δx	
k_X	$[\text{kmol m}^{-2}\text{ s}^{-1}]$	$N_A^* = k_X(X_s - X_\infty)$	ΔX	
k	$[\text{m s}^{-1}]$	$N_A = \rho_L k(\omega_{Ls} - \omega_{L\infty})$	$\Delta\omega_L$	

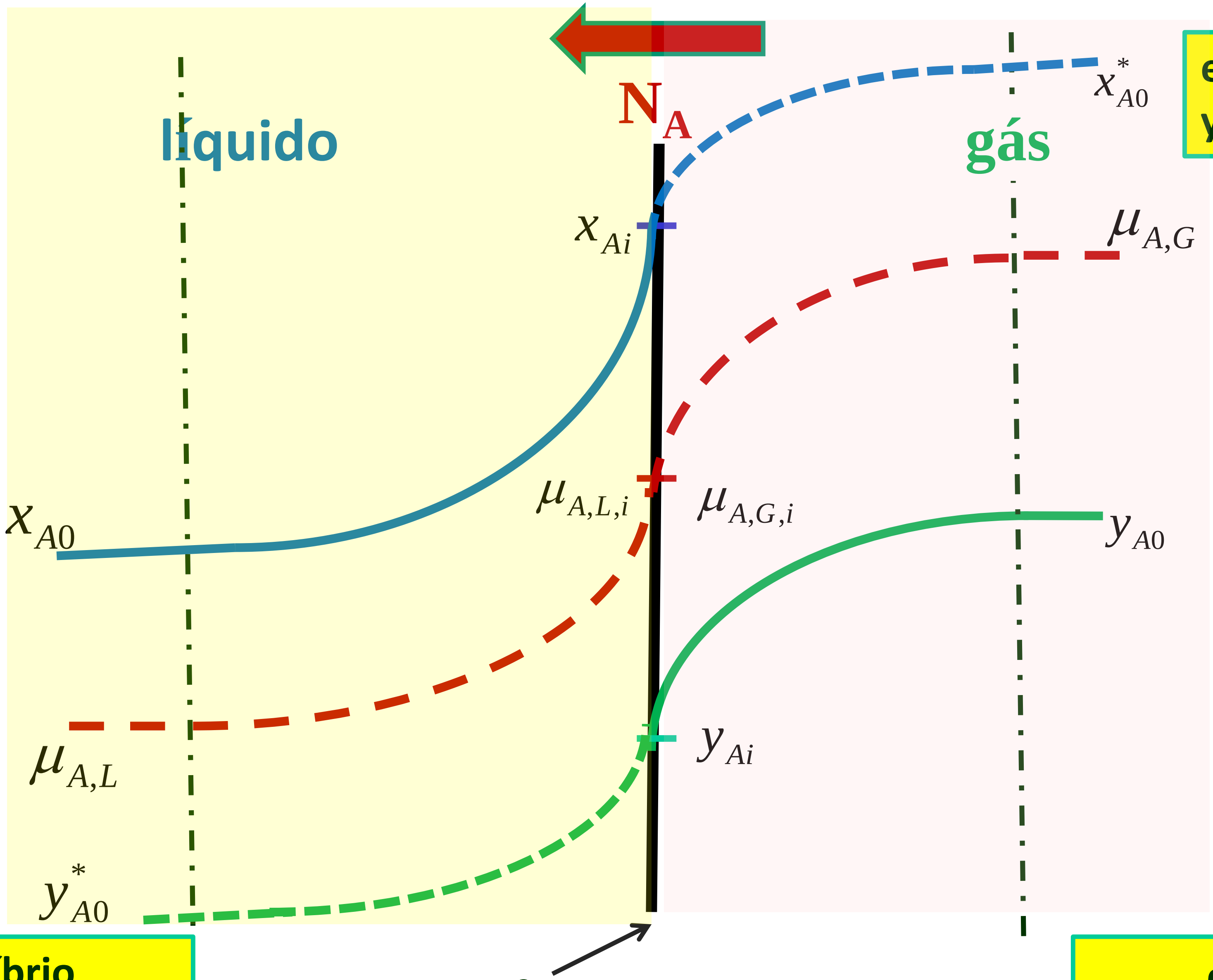
c = molar density [mol m^{-3}], H = absolute humidity [–], M_A = molecular weight [kg kmol^{-1}], N_A = mass flux [kg m^{-2} s^{-1}], $N_A^* = N_A/M_A$ = molar flux [kmol m^{-2} s^{-1}], p = partial pressure [kPa], x,y = mole fraction [–], $X = x/(1-x)$ [–], $Y = y/(1-x)$ [–], ω = mass fraction [–].

Transporte de massa - Interface



interface => Equilíbrio => $y_{Ai} = f\,(x_{Ai})$

Transporte de massa - Interface



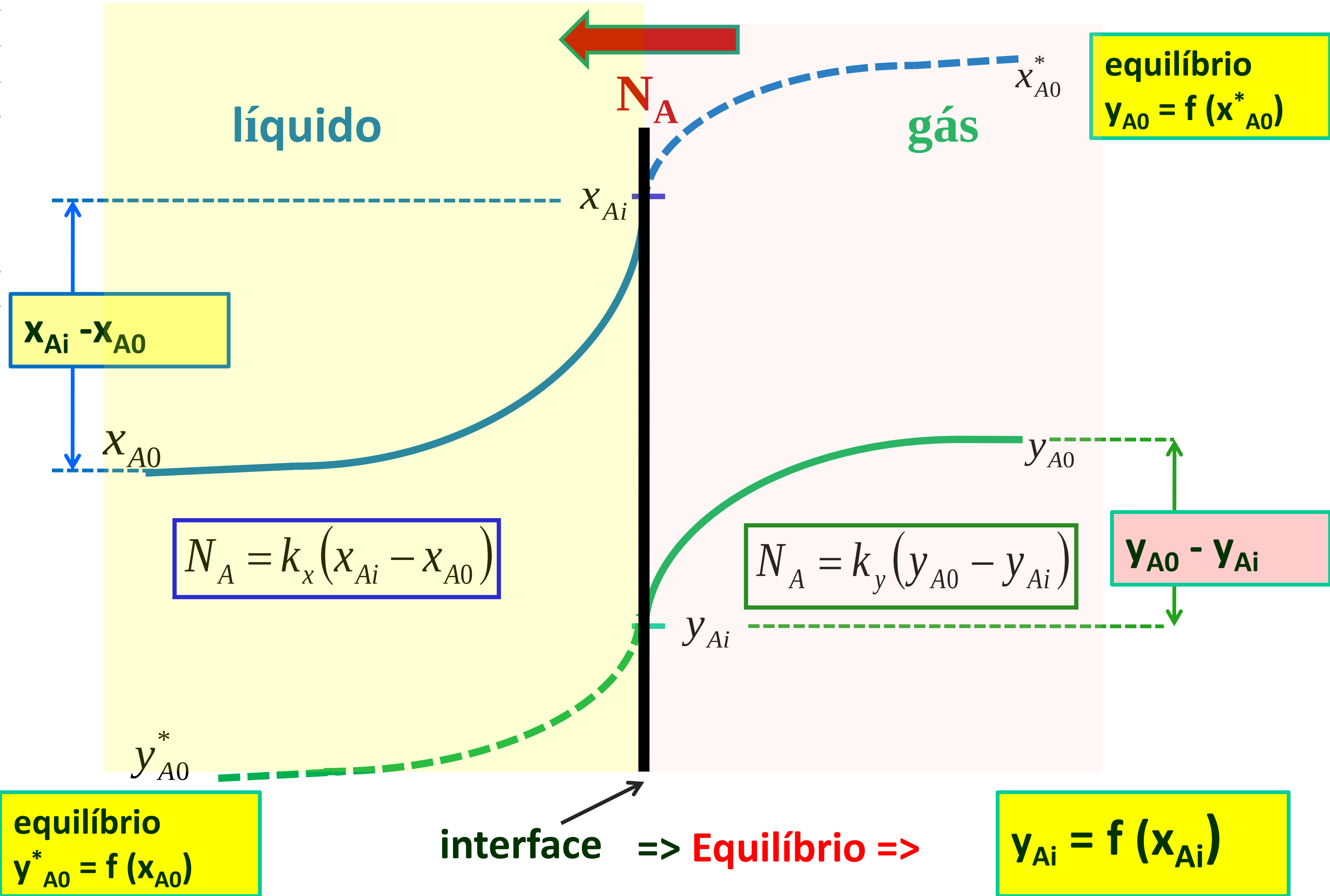
equilíbrio
$y_{A0} = f\,(x^*_{A0})$

equilíbrio
$y^*_{A0} = f\,(x_{A0})$

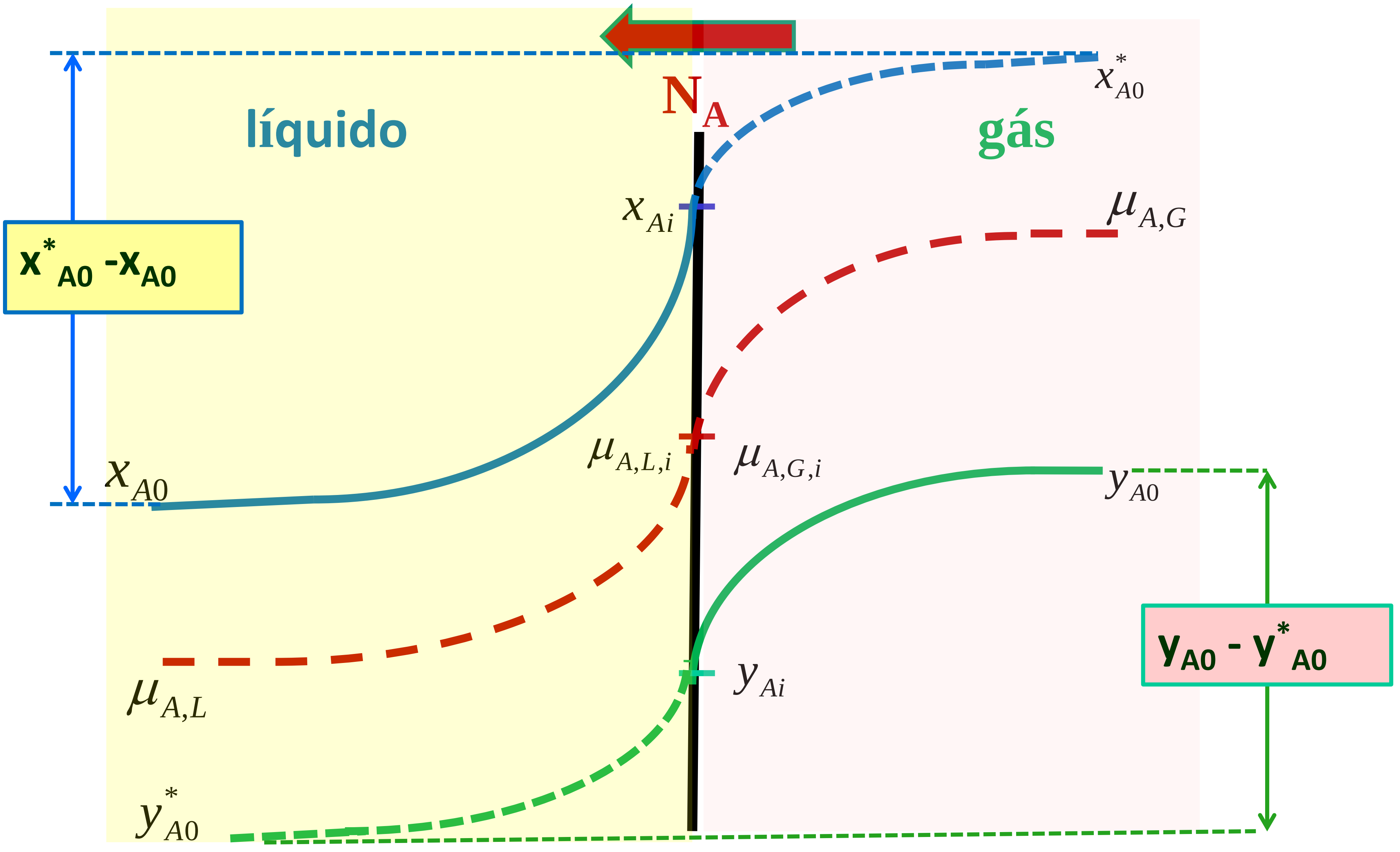
interface => Equilíbrio =>

$y_{Ai} = f\,(x_{Ai})$

Interface – Coeficientes de T. de Massa



Interface – Coeficientes de T. de Massa



$$N_A = K_x\left(x^*_{A0} - x_{A0}\right) = K_y\left(y_{A0} - y^*_{A0}\right)$$

$$N_A = k_x\left(x_{Ai} - x_{A0}\right) = k_y\left(y_{A0} - y_{Ai}\right)$$

Coeficiente Global de Transporte de Massa

$$\left(\mu_{A0,G}-\mu_{A0,L}\right)=\left(\mu_{A0,G}-\mu_{Ai,G}\right)+\left(\mu_{Ai,L}-\mu_{A0,L}\right)$$

$$\left(y_{A0}-y^{*}_{A0}\right)=\left(y_{A0}-y_{Ai}\right)+\left(\underbrace{mx_{Ai}}_{y_{Ai}}-\underbrace{mx_{A0}}_{y^{*}_{A0}}\right)$$

$$\left(y_{A0}-y^{*}_{A0}\right)=\left(y_{A0}-y_{Ai}\right)+m\left(x_{Ai}-x_{A0}\right)$$

$$\left(y_{A0}-y^{*}_{A0}\right)=\frac{N_A}{k_y}+m\frac{N_A}{k_x}$$

$$\boxed{N_A=K_y\left(y_{A0}-y^{*}_{A0}\right)}$$

$$\boxed{\frac{1}{K_{\tilde{y}}}=\frac{1}{k_{\tilde{y}}}+\frac{m}{k_{\tilde{x}}}}$$

$$\boxed{N_A=K_x\left(x^{*}_{A0}-x_{A0}\right)}$$

$$\boxed{\frac{1}{K_{\tilde{x}}}=\frac{1}{mk_{\tilde{y}}}+\frac{1}{k_{\tilde{x}}}}$$

Equilíbrio

$$\boxed{\mu_{Ai,G}=\mu_{Ai,L}}$$

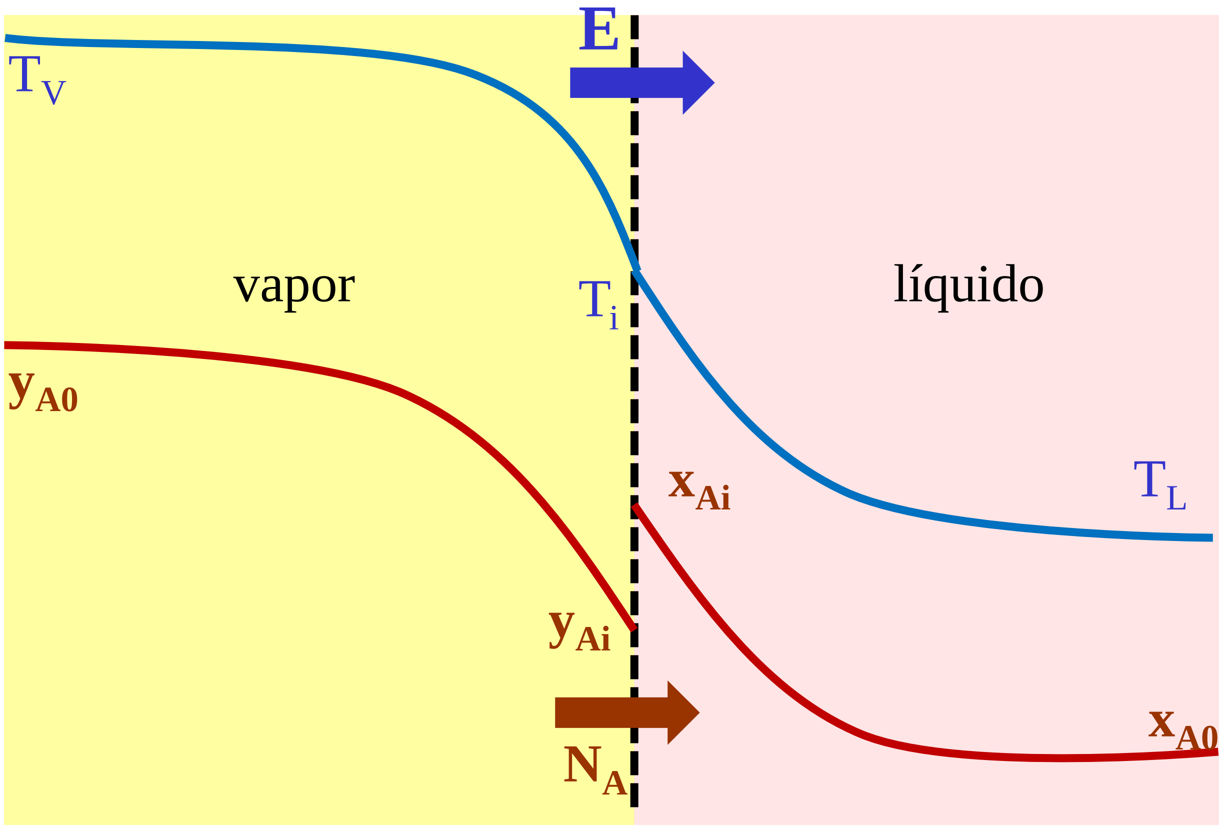
$$\boxed{y_{Ai}=m\,x_{Ai}}$$

Fluxos

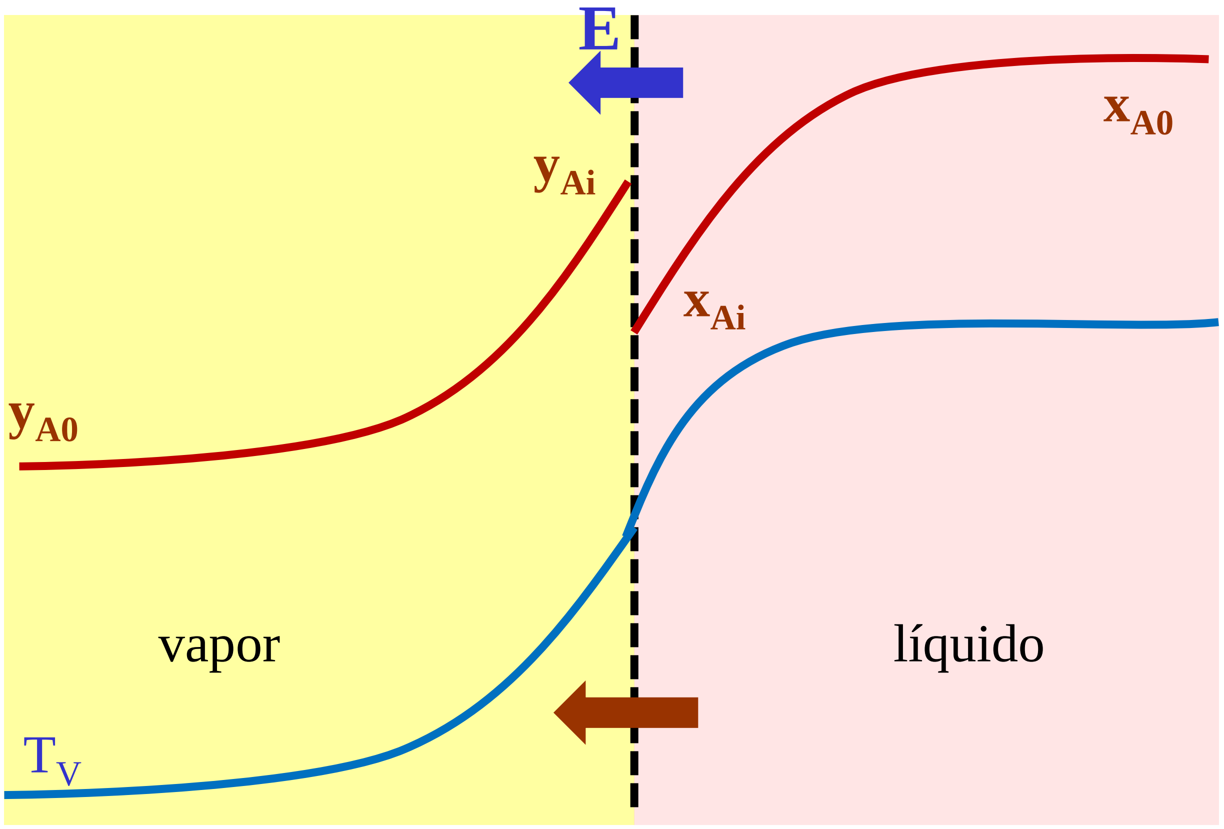
$$\boxed{N_A=k_y\left(y_{A0}-y_{Ai}\right)}$$

$$\boxed{N_A=k_x\left(x_{Ai}-x_{A0}\right)}$$

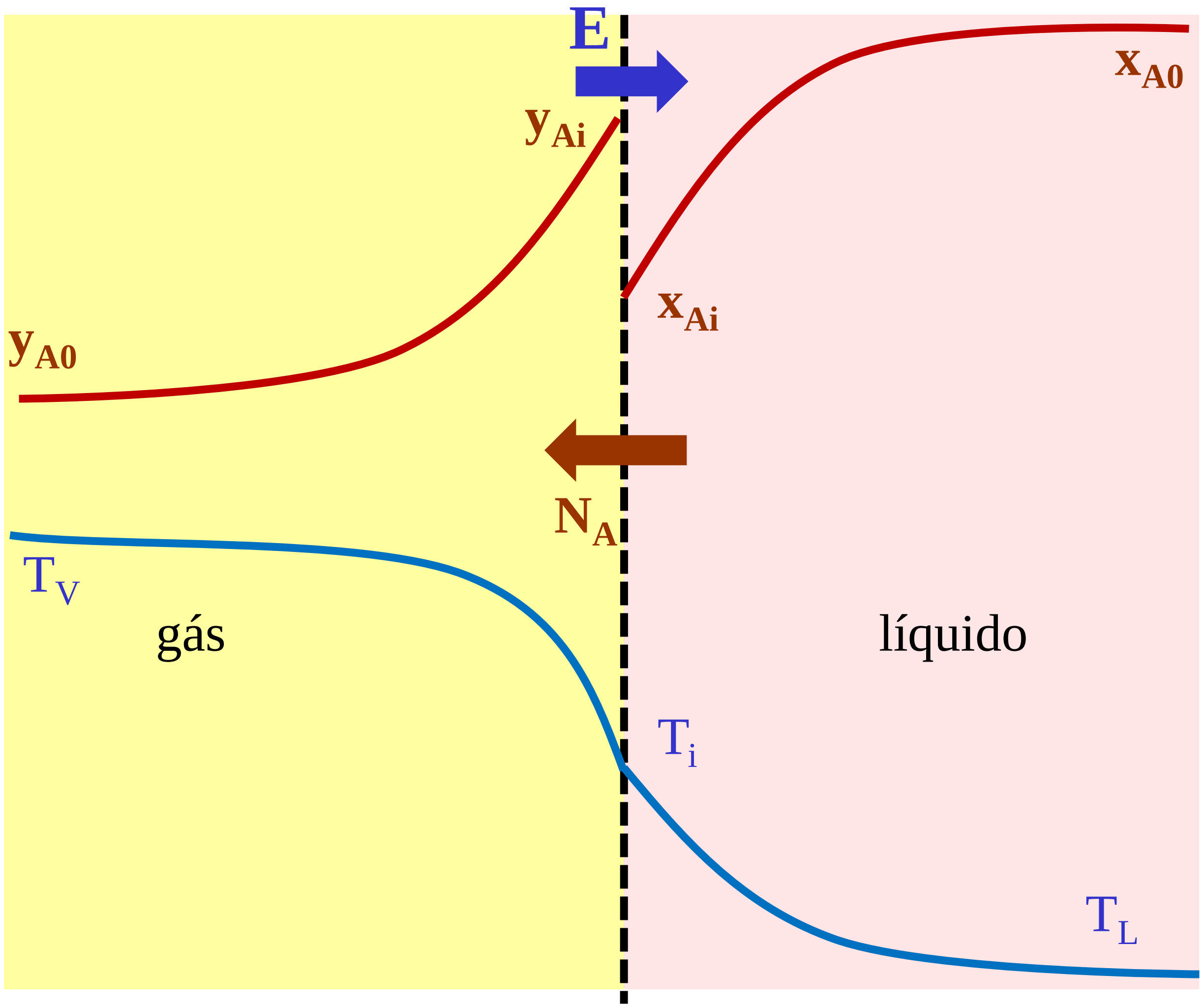
Condensação



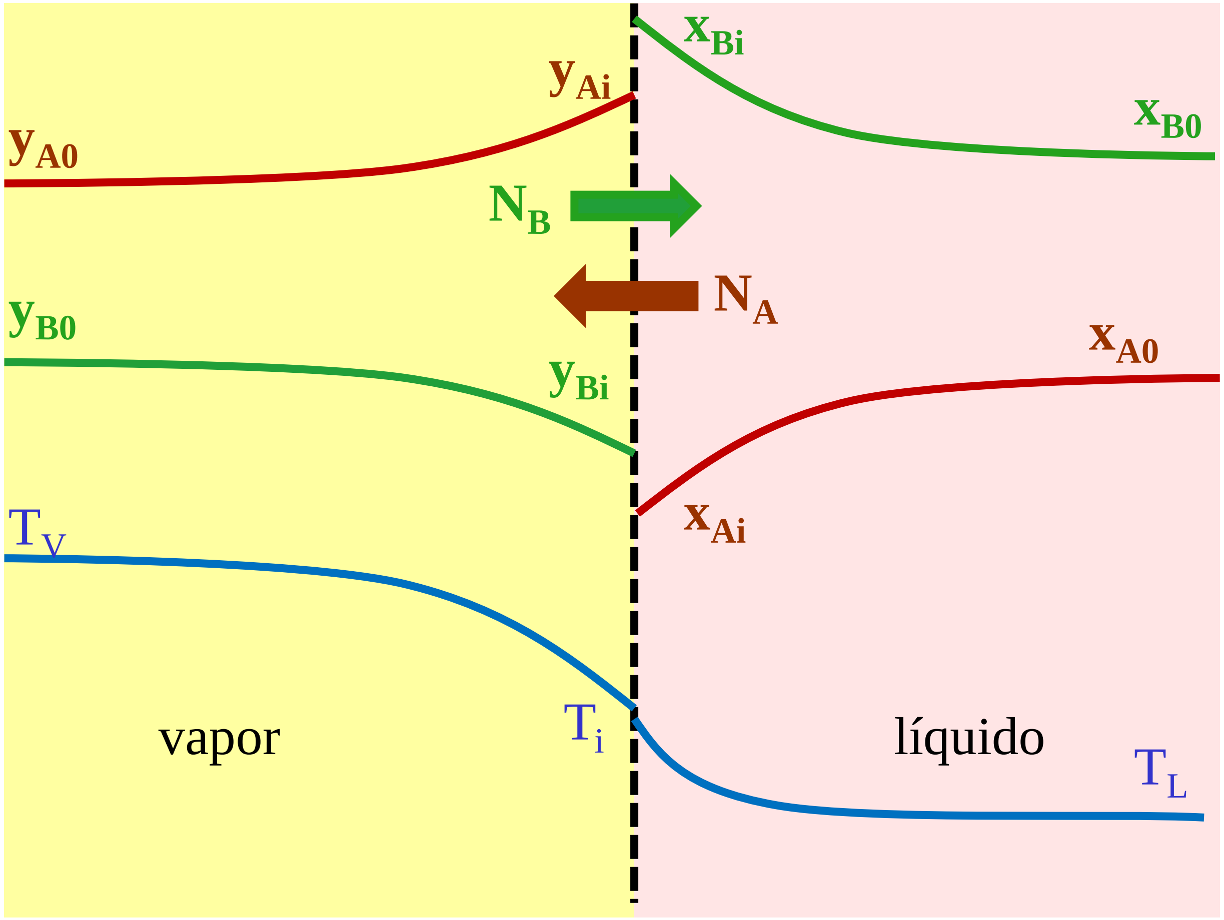
Evaporação



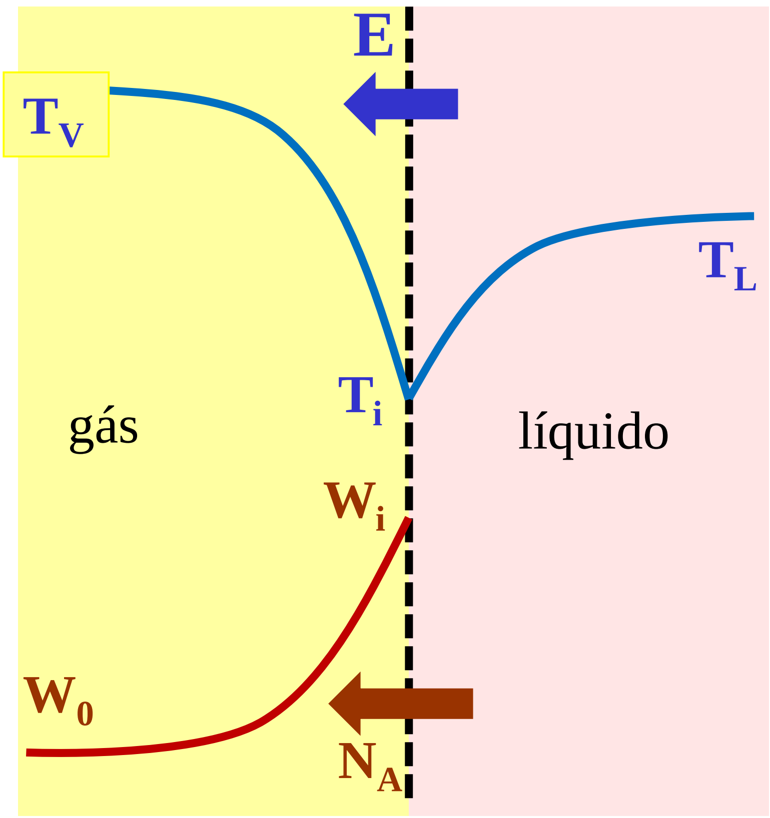
Secagem

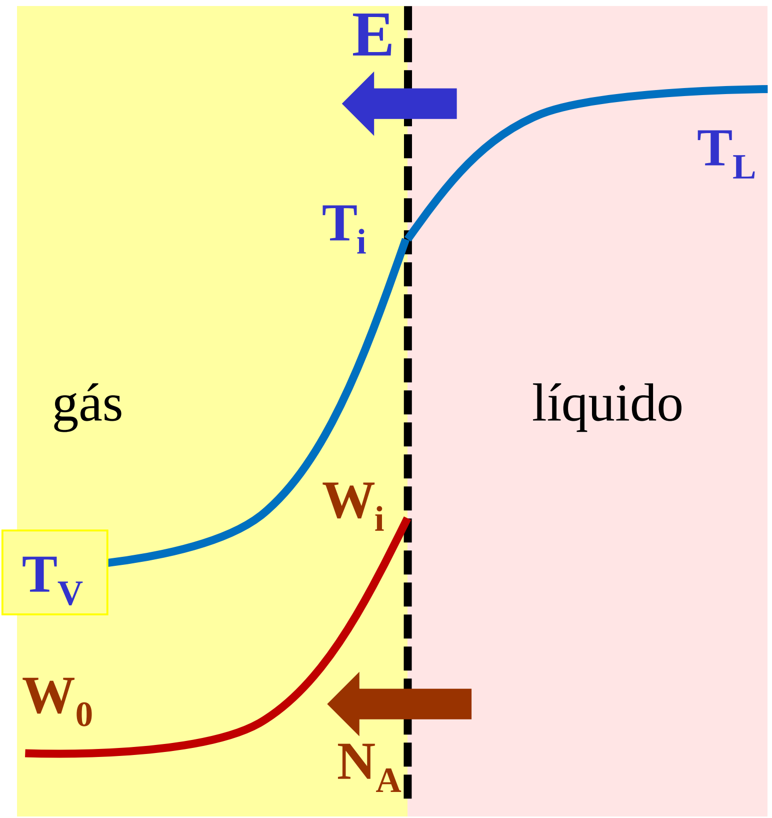


Destilação



Resfriamento Evaporativo
Torre de Resfriamento

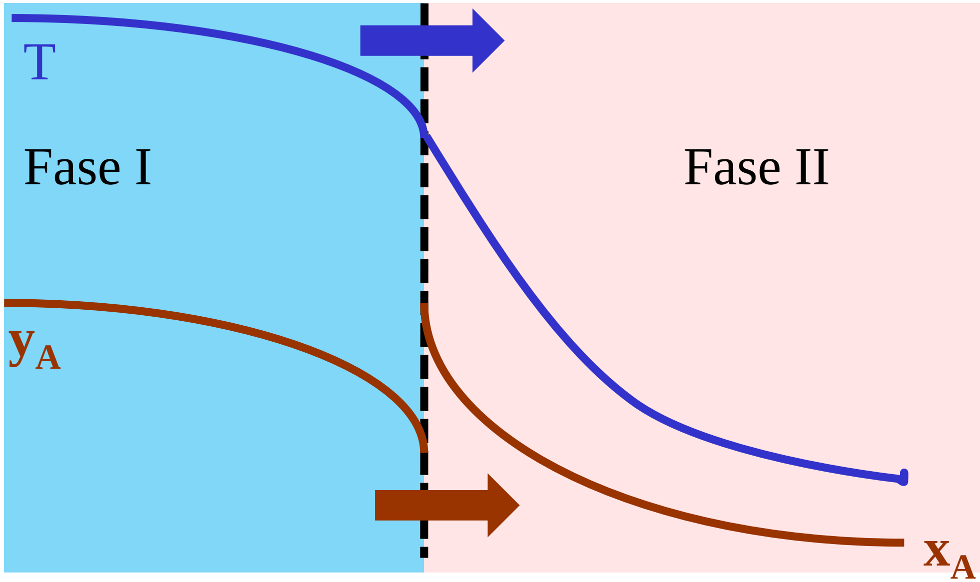




Transporte simultâneo de calor e massa

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

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



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