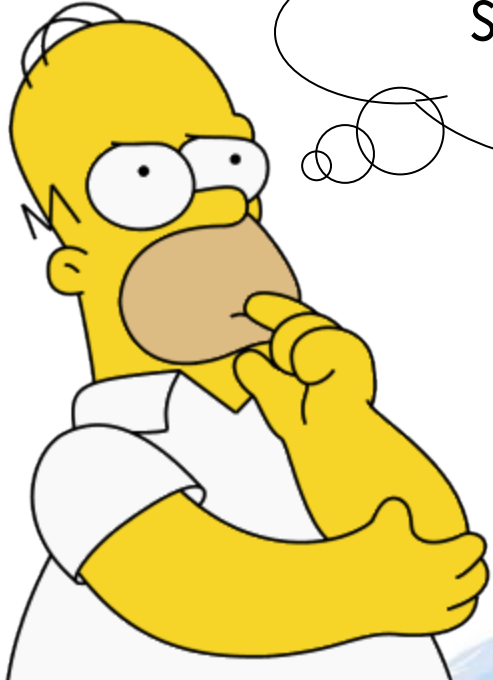


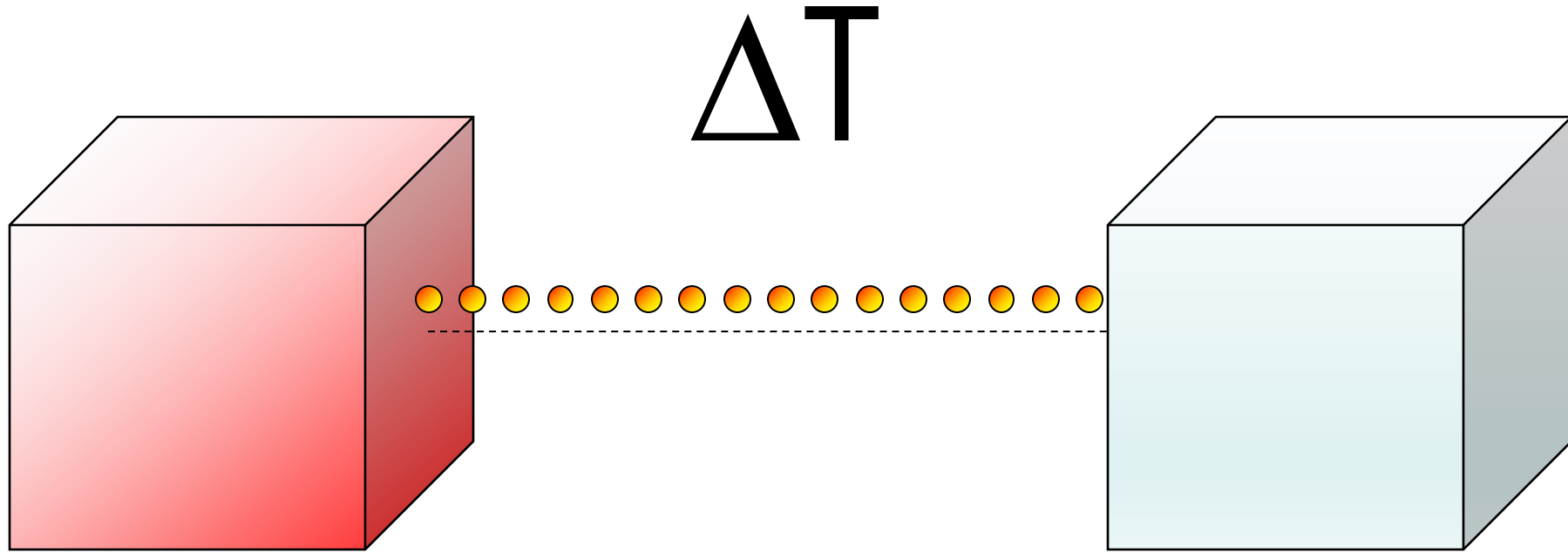
CONVECÇÃO DE CALOR E ESCOAMENTOS INTERNOS

Paulo Seleglim Jr.
Universidade de São Paulo

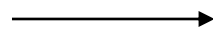


A cartoon illustration of Homer Simpson, a yellow-skinned man with a large nose and a white shirt, looking thoughtful with his hand on his chin. A large thought bubble is positioned above him, containing text in Portuguese. The background features a range of blue mountains.

Por que algumas
aves podem voar
sem bater as asas ?

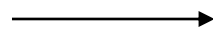


CONDUÇÃO



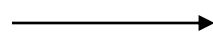
Lei de Fourier

CONVECÇÃO

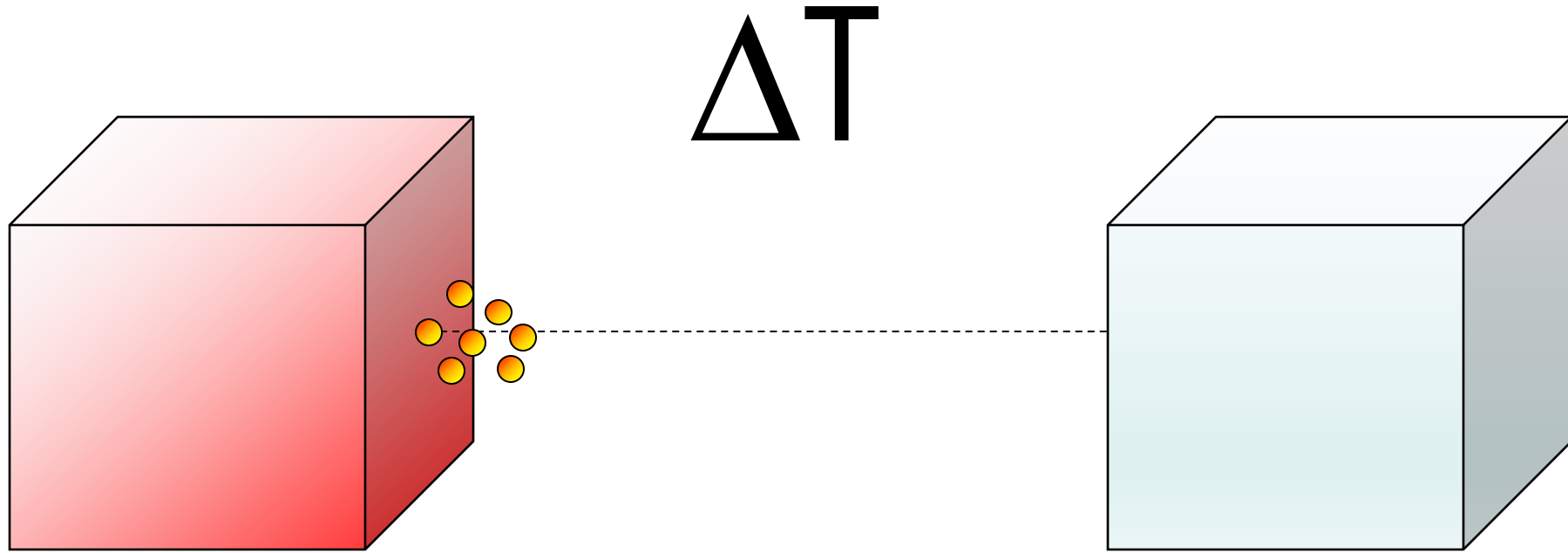


Lei de Newton

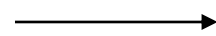
RADIAÇÃO



Lei de Stefan-Boltzmann

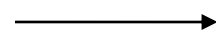


CONDUÇÃO



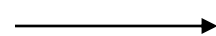
Lei de Fourier

CONVECÇÃO

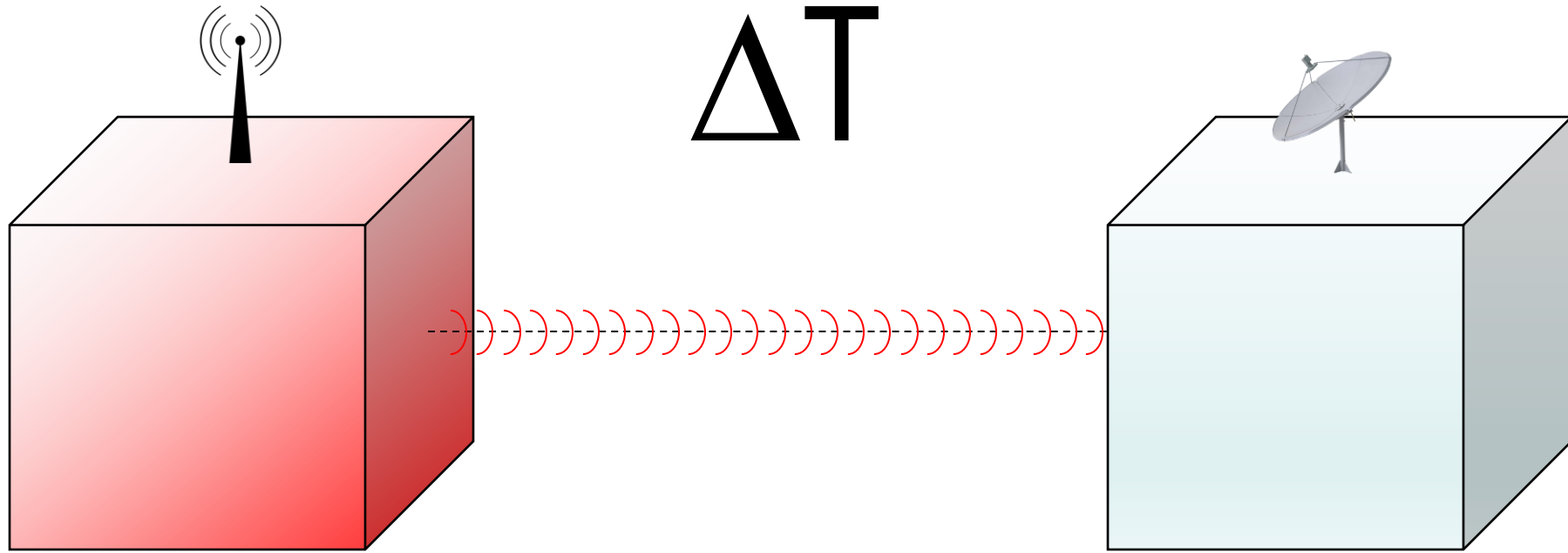


Lei de Newton

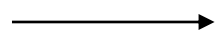
RADIAÇÃO



Lei de Stefan–Boltzmann

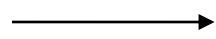


CONDUÇÃO



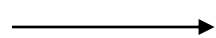
Lei de Fourier

CONVECÇÃO



Lei de Newton

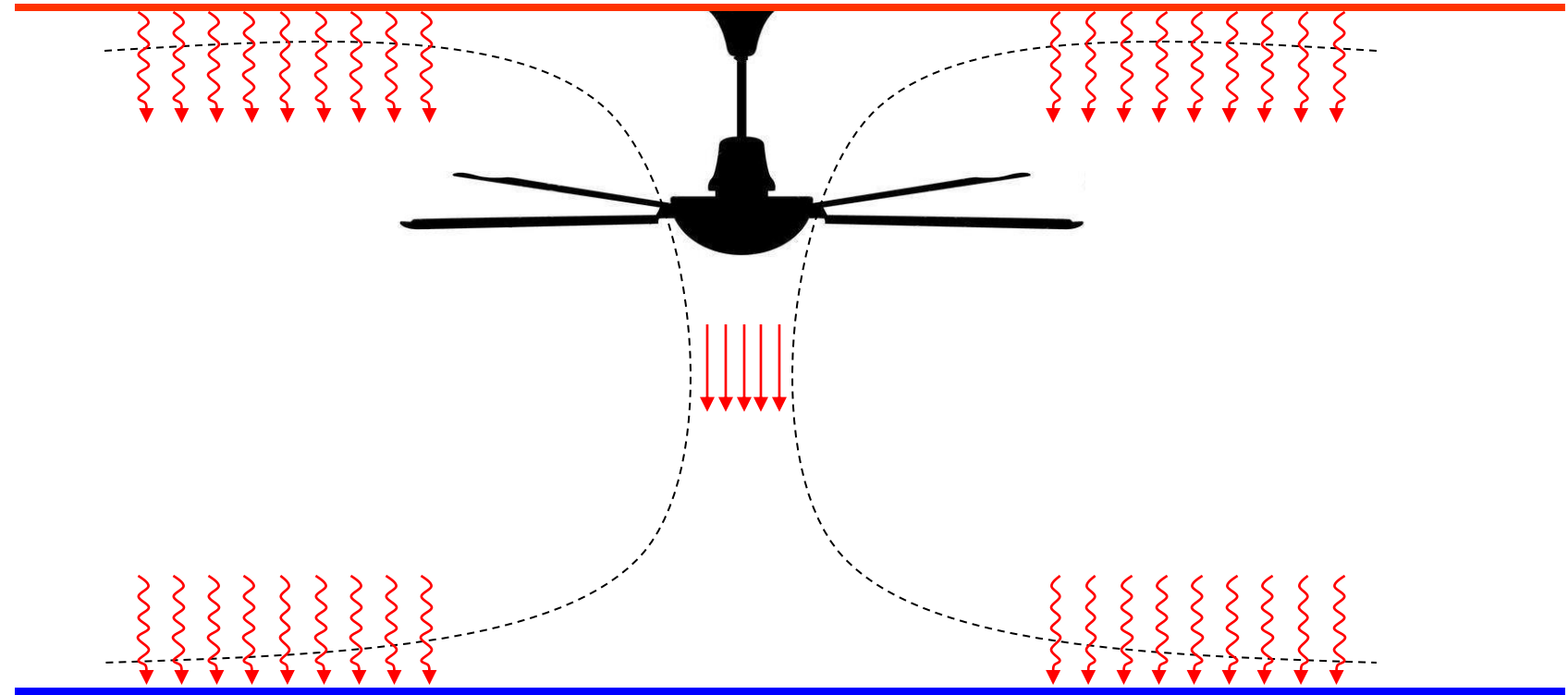
RADIAÇÃO



Lei de Stefan-Boltzmann

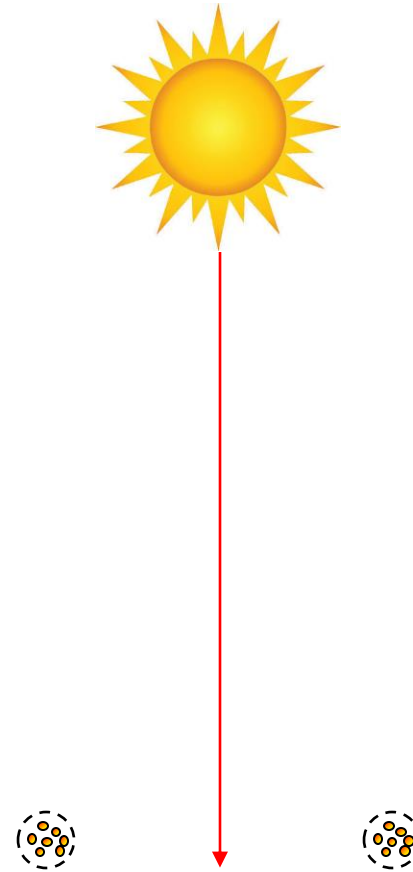
Convecção natural × convecção forçada...

Forçada: a movimentação do fluido é induzida por forças **externas**...



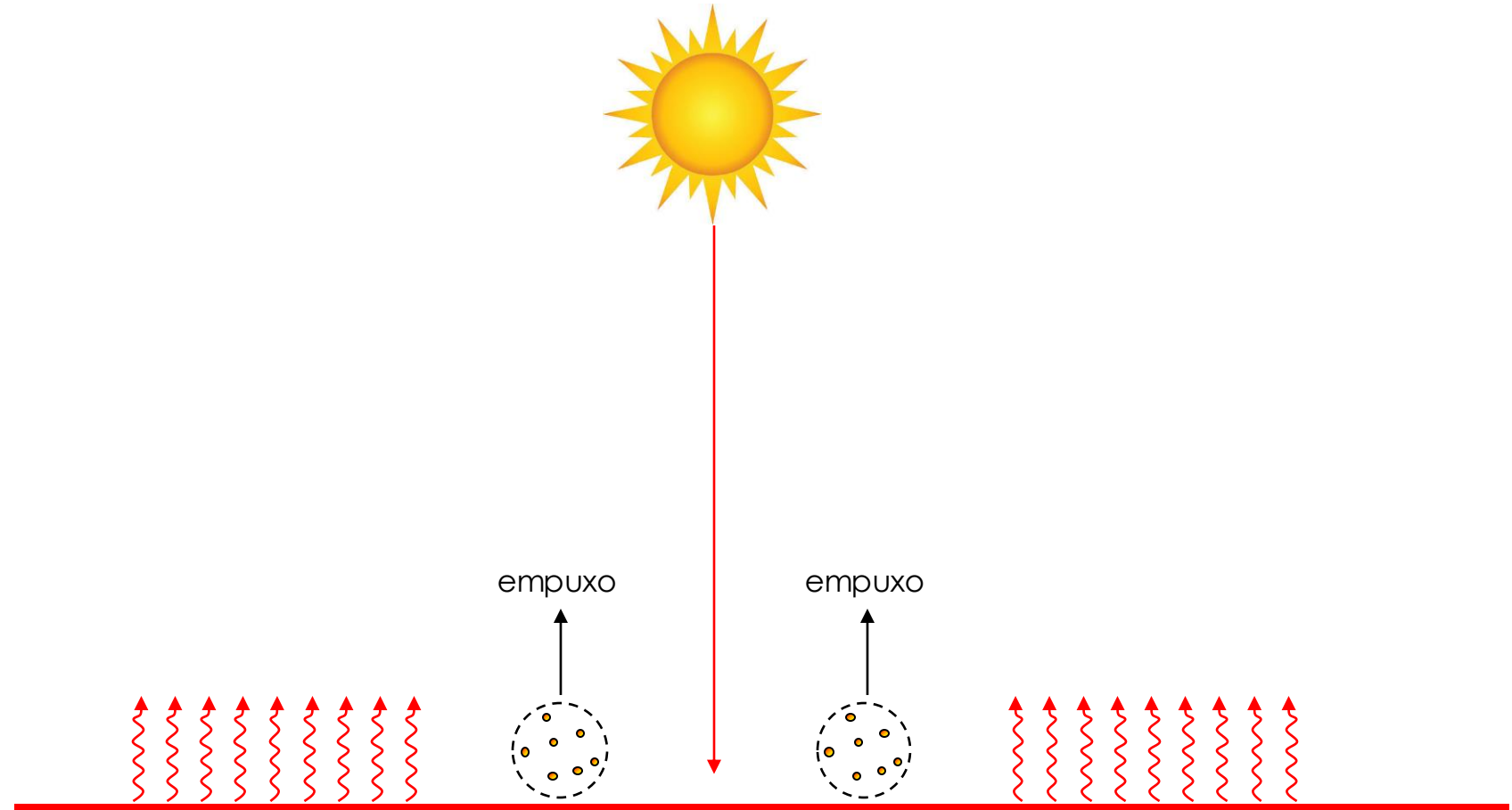
Convecção natural × convecção forçada...

Natural: a movimentação do fluido é induzida por forças de **empuxo**...



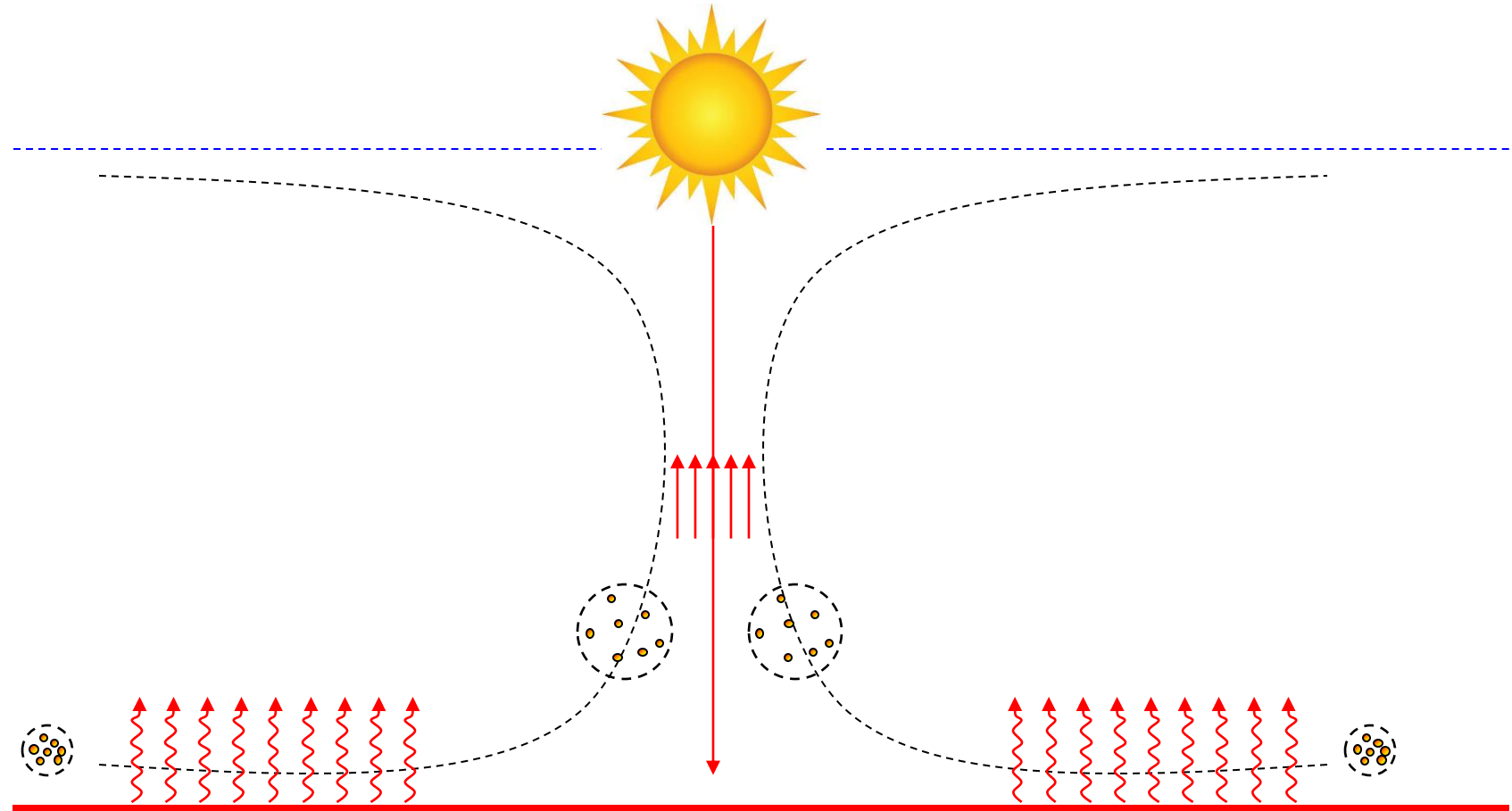
Convecção natural × convecção forçada...

Natural: a movimentação do fluido é induzida por forças de **empuxo**...



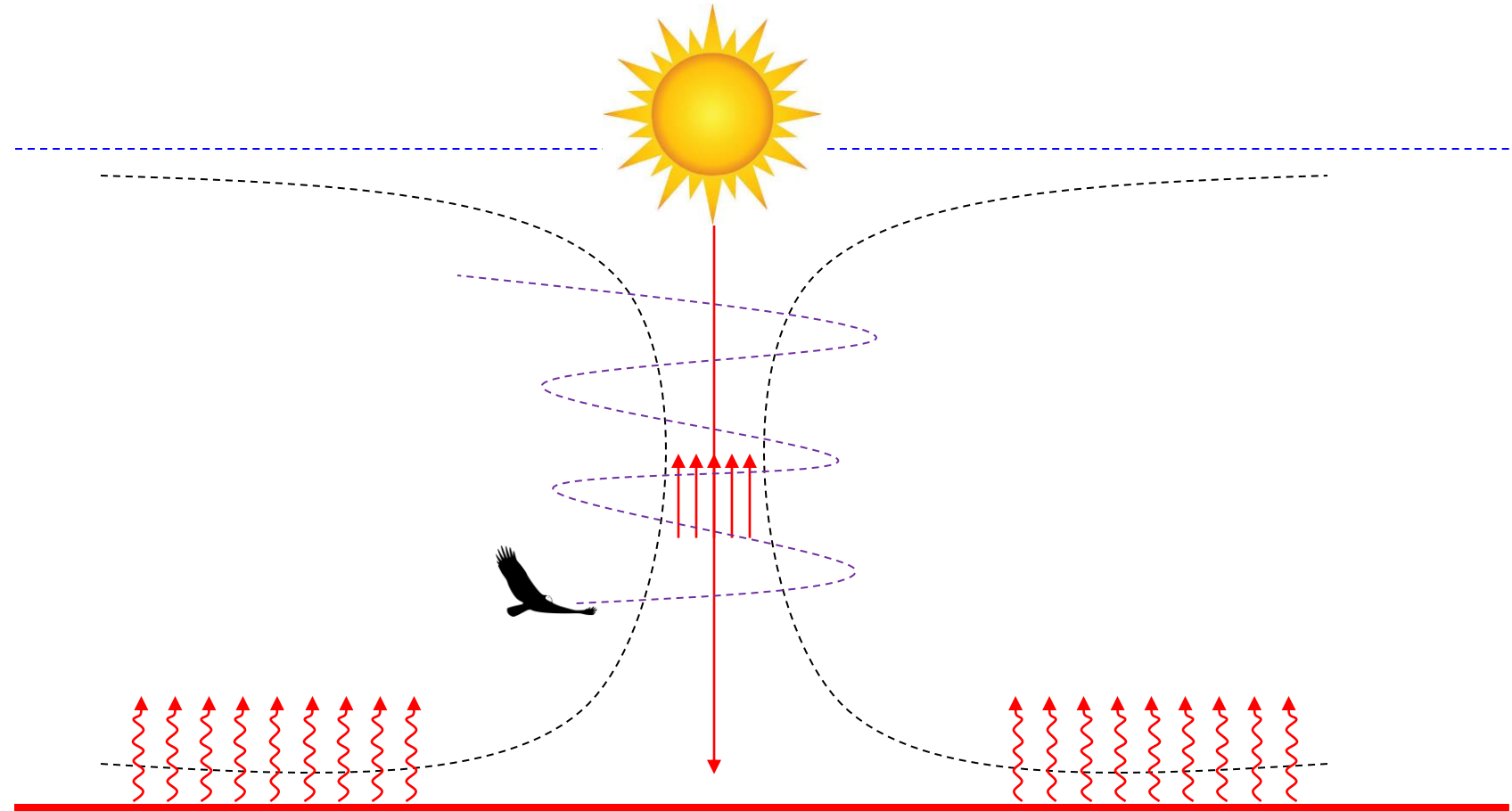
Convecção natural × convecção forçada...

Natural: a movimentação do fluido é induzida por forças de **empuxo**...



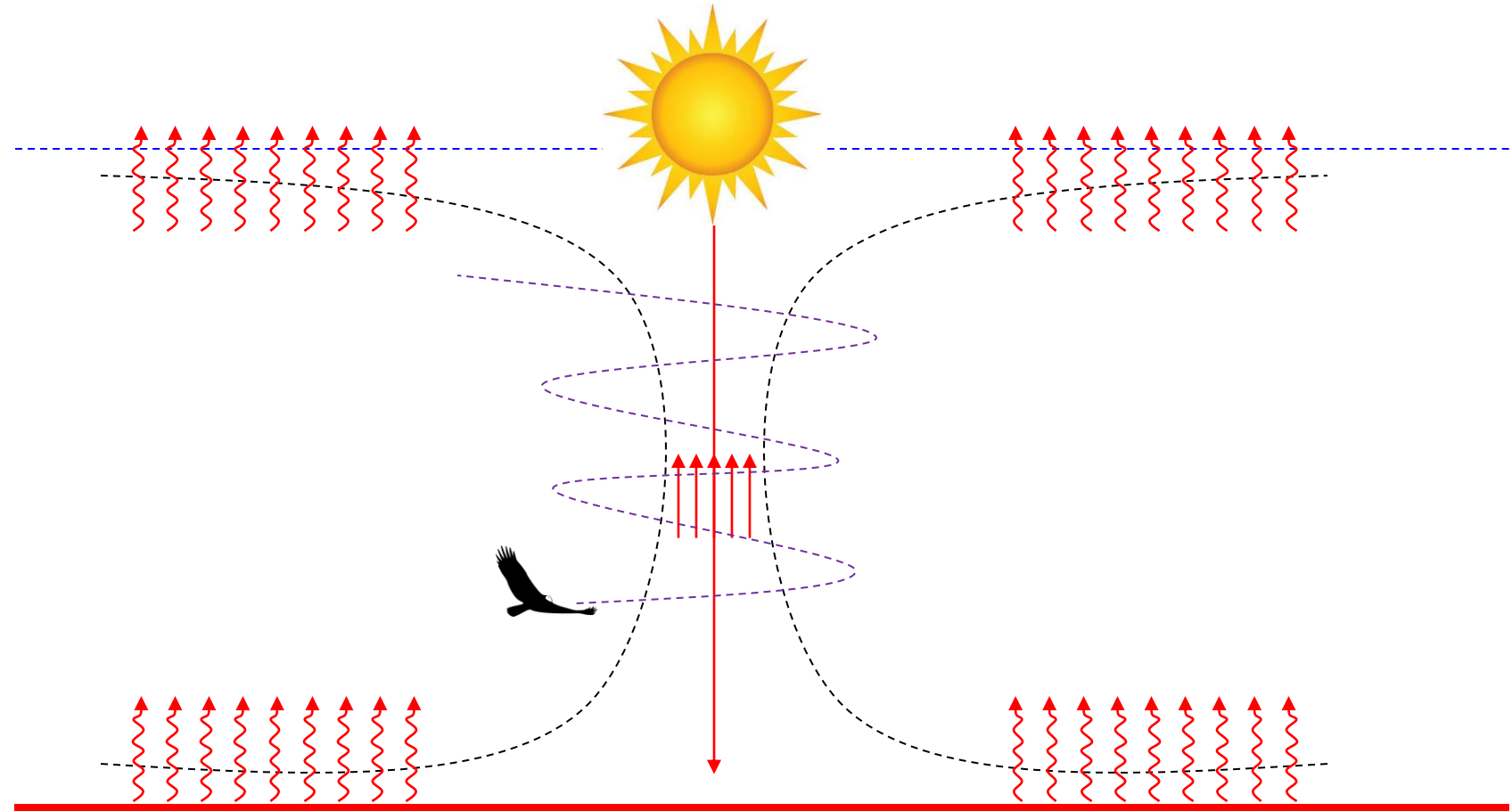
Convecção natural × convecção forçada...

Natural: a movimentação do fluido é induzida por forças de **empuxo**...



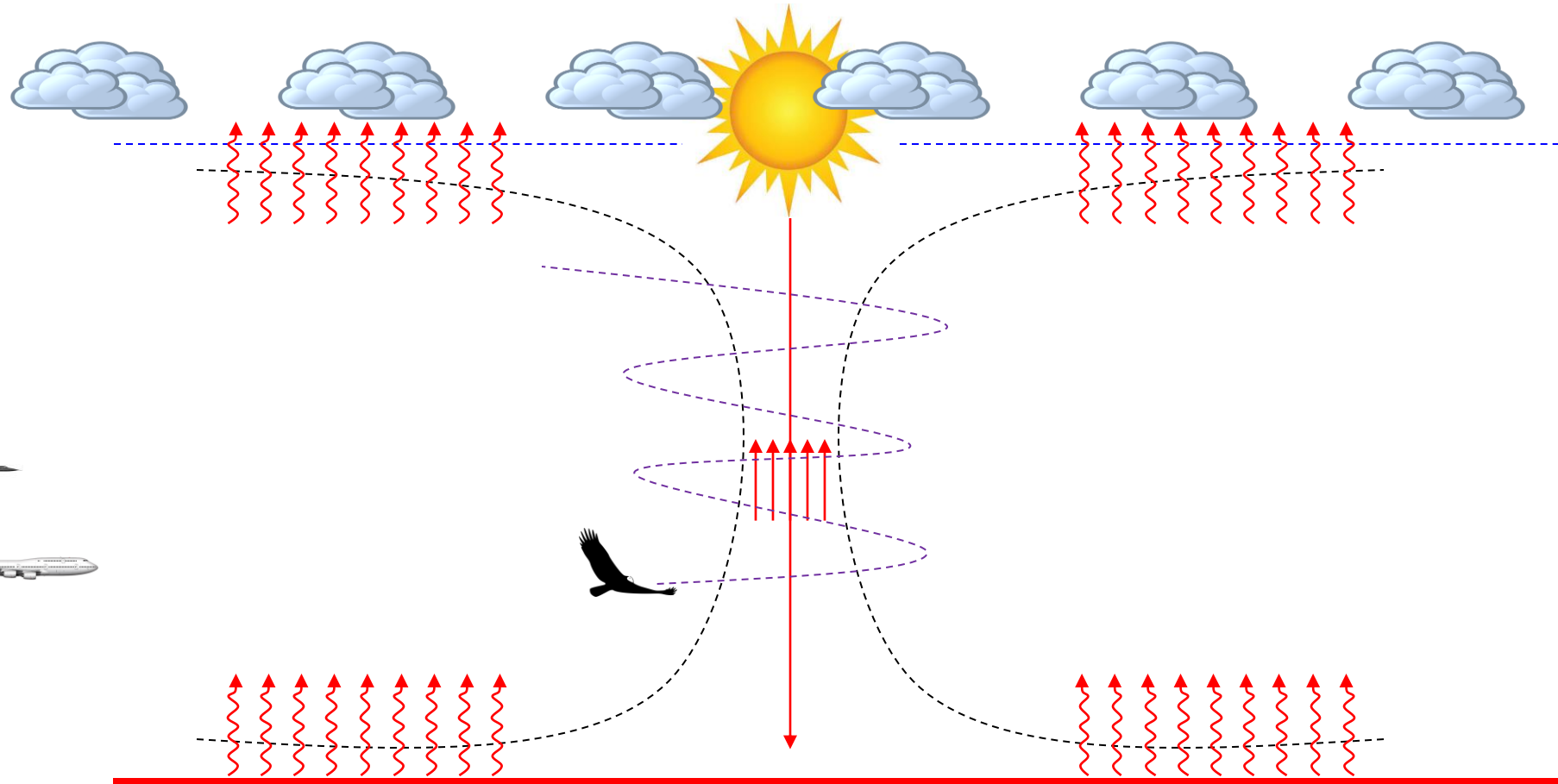
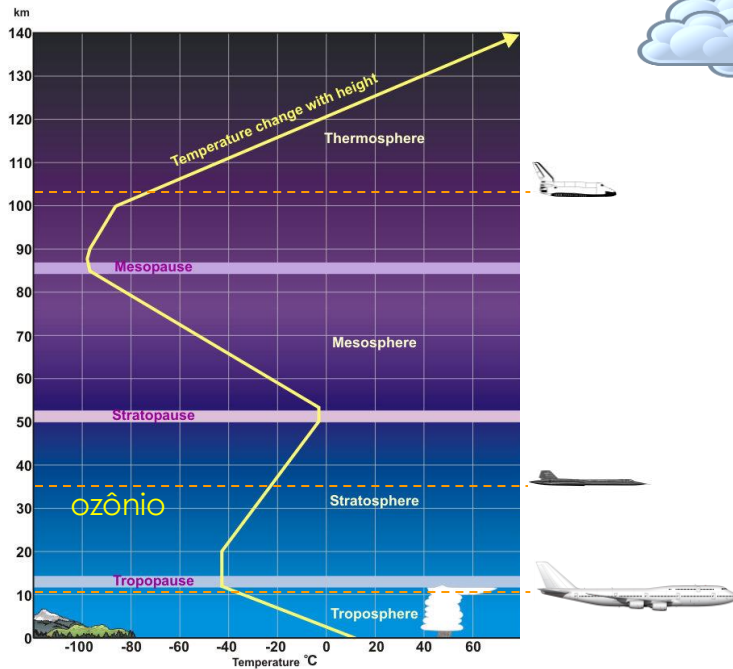
Convecção natural × convecção forçada...

Natural: a movimentação do fluido é induzida por forças de **empuxo**...



Convecção natural × convecção forçada...

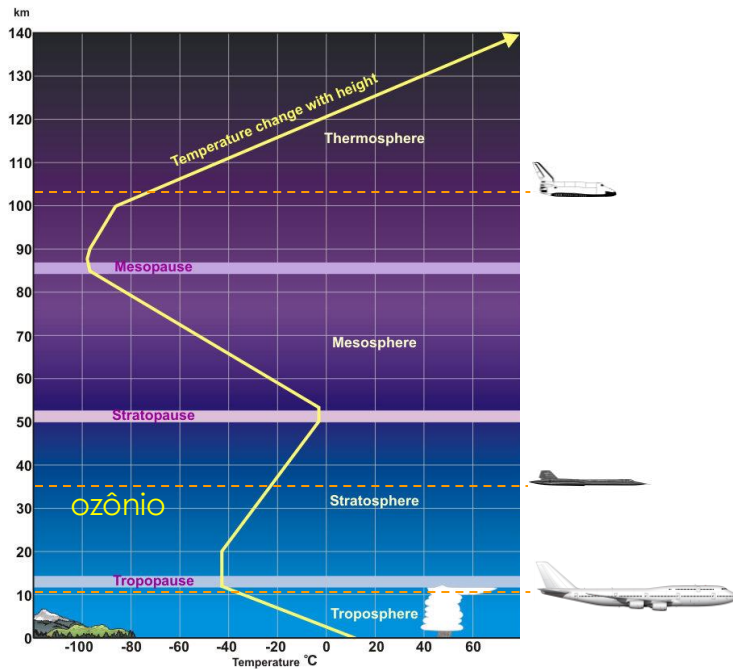
Natural: a movimentação do fluido é induzida por forças de **empuxo**...



Cumulonimbus !

Modelos atmosféricos...

Troposfera:



$$dP = -\rho g dH$$

← dividindo pela eq. estado

$$\frac{dP}{P} = -\frac{\rho g dH}{\rho R T} = -\frac{g}{R T} dH$$

$$\alpha \stackrel{\text{def}}{=} \frac{dT}{dH}$$

← gradiente (lapse rate)

$$(T - T_1) = (H - H_1) \cdot \alpha$$

$$\frac{dP}{P} = -\frac{g}{\alpha R} \frac{dT}{T}$$

$$\int_{P_1}^P \frac{dP}{P} = -\frac{g}{\alpha R} \int_{T_1}^T \frac{dT}{T} \rightarrow$$

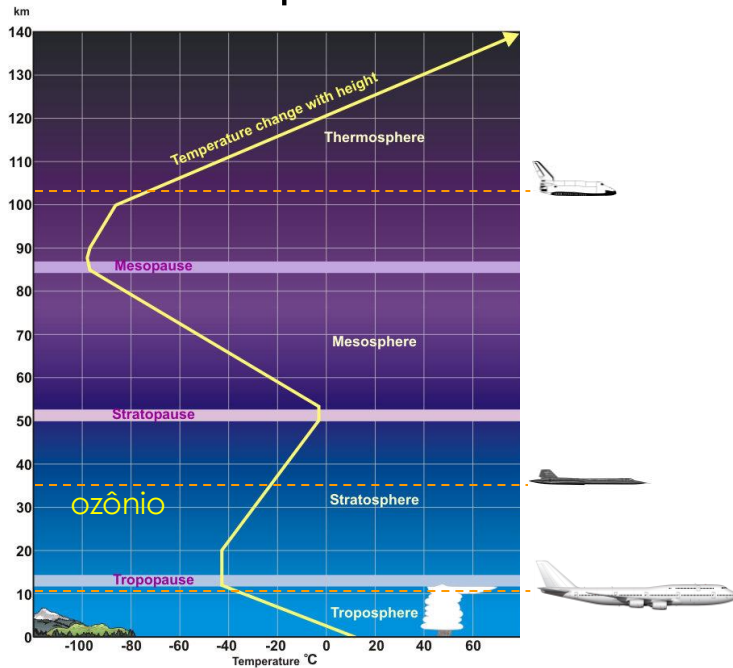
$$P = P_1 \left(T / T_1 \right)^{-g / (\alpha R)}$$

$$\int_{P_1}^P \frac{dP}{P} = -\frac{g}{\alpha R} \int_{T_1}^T \frac{dT}{T} \rightarrow$$

$$\rho = \rho_1 \left(T / T_1 \right)^{-g / (\alpha R) - 1}$$

Modelos atmosféricos...

Tropopausa:
Estratopausa:



$$dP = -\rho g dH$$

← dividindo pela eq. estado

$$\frac{dP}{P} = -\frac{\rho g dH}{\rho R T} = -\frac{g}{R T} dH$$

$$\int_{P_1}^P \frac{dP}{P} = -\frac{g}{R T} \int_{H_1}^H dH$$

← região isotérmica

$$\ln\left(\frac{P}{P_1}\right) - \frac{g}{R T} (H - H_1) \rightarrow$$

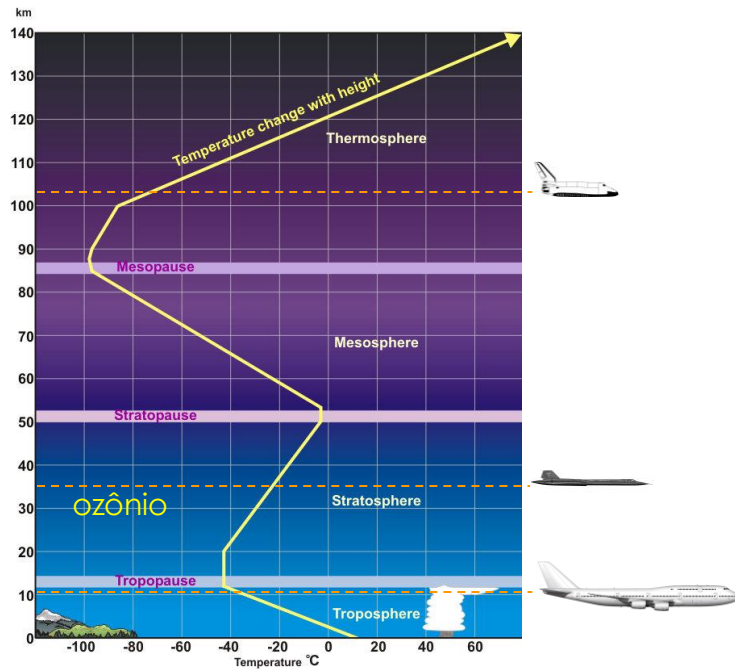
$$P = P_1 \exp\left(-\frac{g}{R T} (H - H_1)\right)$$

$$\ln\left(\frac{\rho R T}{P_1}\right) - \frac{g}{R T} (H - H_1) \rightarrow$$

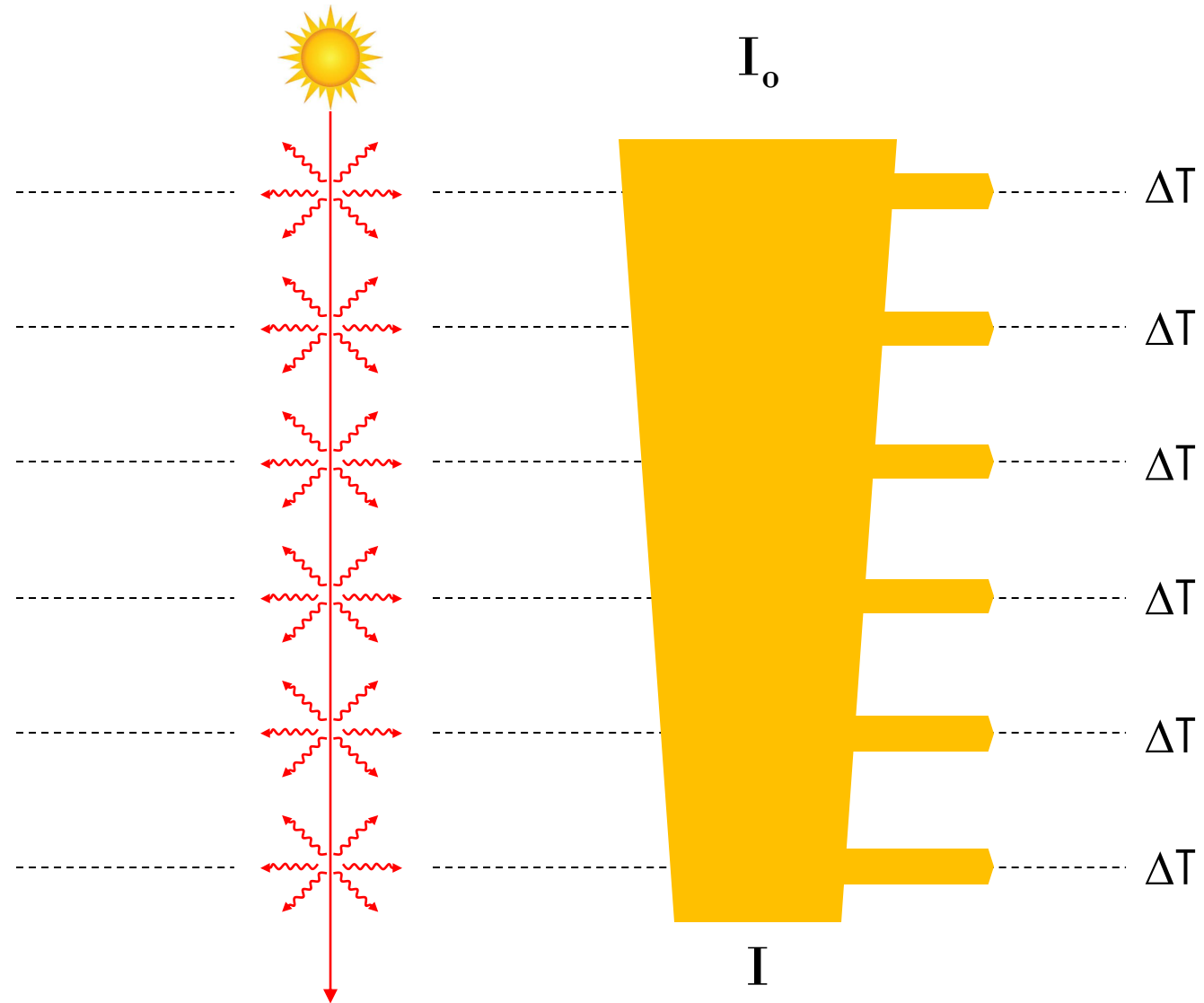
$$\rho = \frac{P_1}{R T} \exp\left(-\frac{g}{R T} (H - H_1)\right)$$

Modelos atmosféricos...

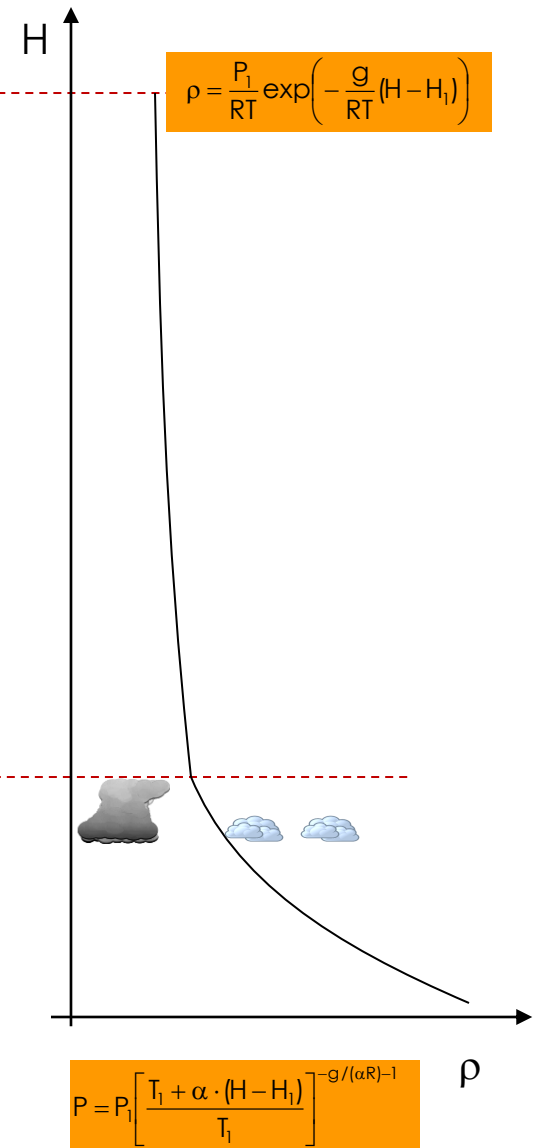
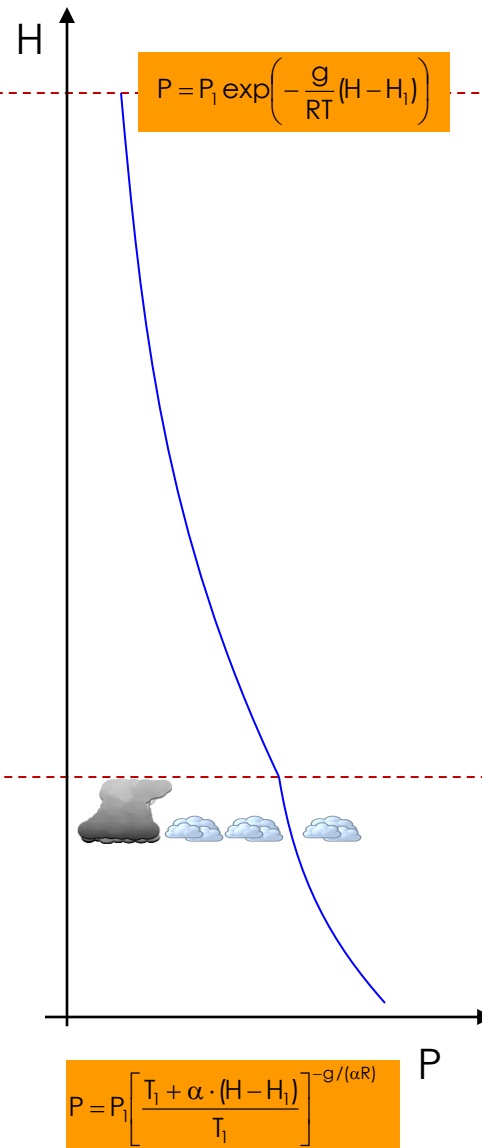
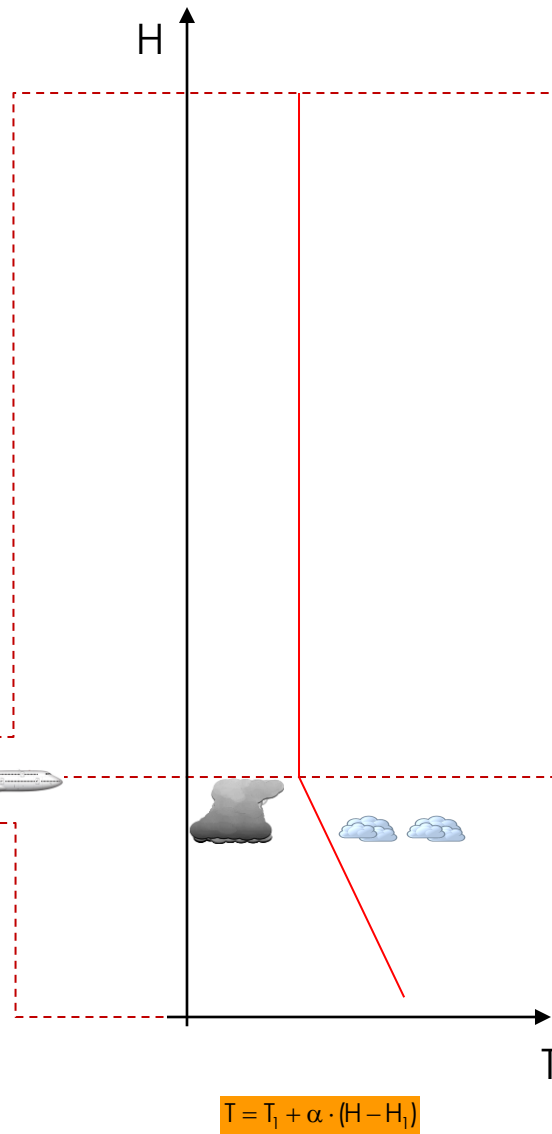
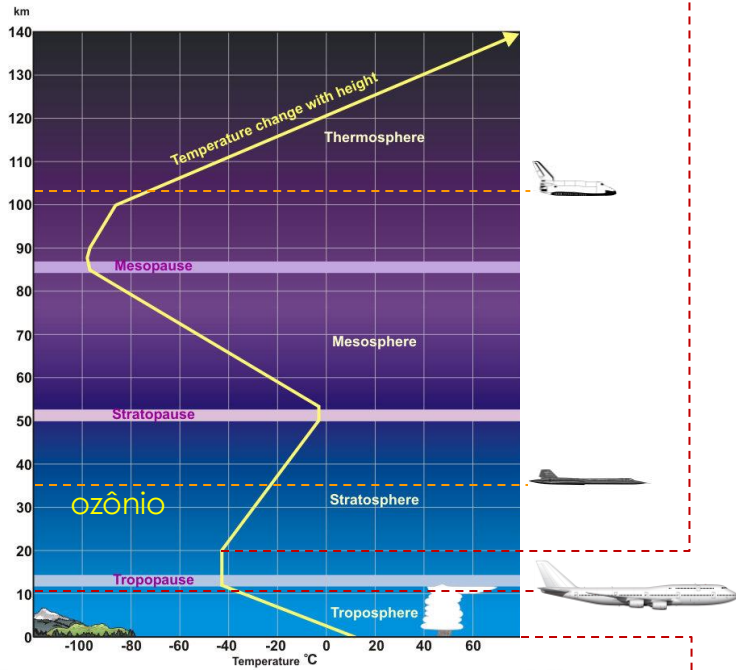
Estratosfera:



Radiação em
meio participativo



Modelos atmosféricos...







Equações governantes:
massa, forças e energia



Equações governantes: massa, forças e energia

Continuidade (massa) $\rightarrow \frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{U}) = 0$

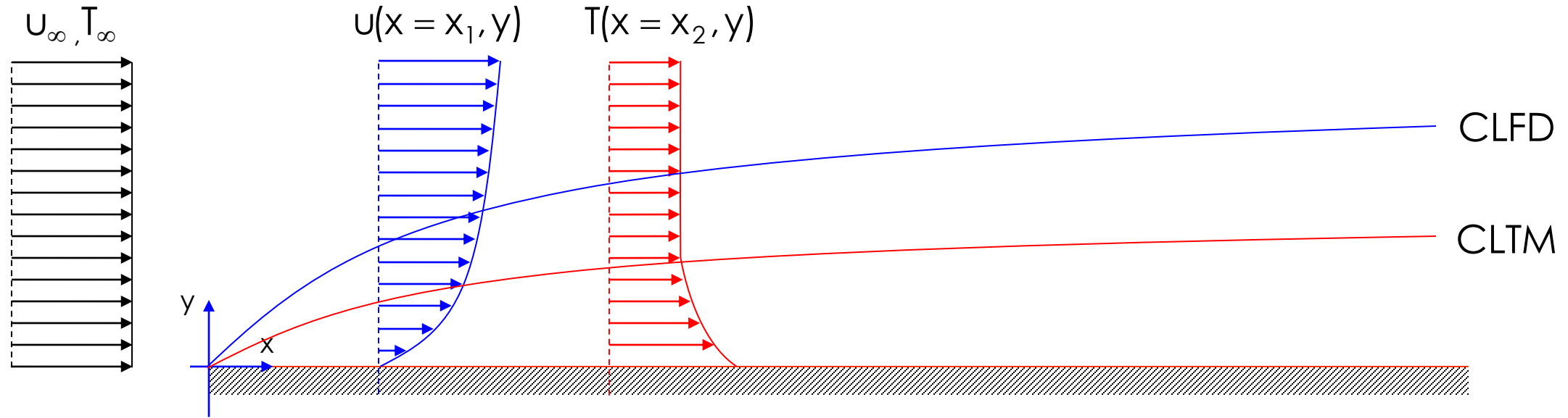
Q. de movimento (Navier-Stokes) $\rightarrow \rho \cdot \left(\frac{\partial \vec{U}}{\partial t} + \vec{U} \cdot \vec{\nabla} \vec{U} \right) = -\vec{\nabla} P + \vec{\nabla} \cdot \vec{\tilde{T}} + \sum \vec{F}_{3D}$

Energia (1ª lei) $\rightarrow \rho C_p \left(\frac{\partial T}{\partial t} + \vec{U} \cdot \vec{\nabla} T \right) = \vec{\nabla} \cdot (k \vec{\nabla} T) + \vec{\tilde{T}} : \vec{\tilde{D}}$

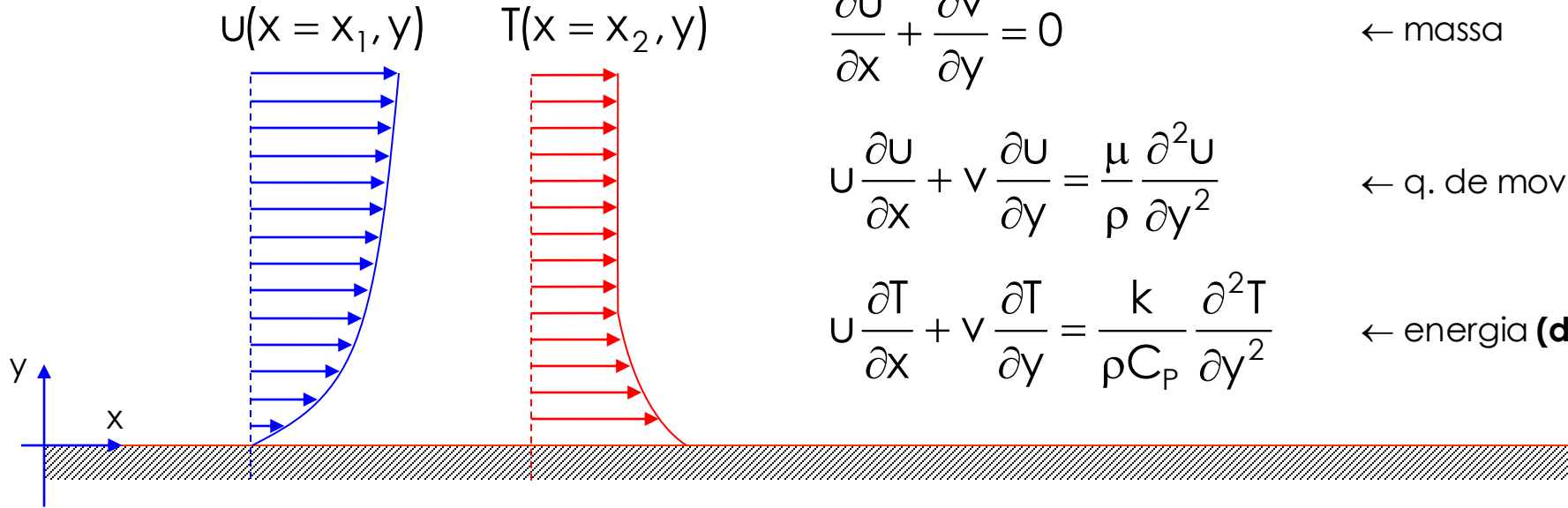
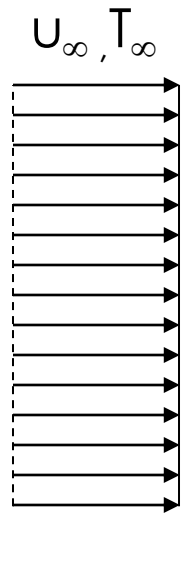
Escalas microscópicas (Kolmogorov) a escalas planetária (sinótica)...



Cálculo das camadas limites hidrodinâmica e térmica...



Cálculo das camadas limites hidrodinâmica e térmica...



$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

← massa

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \frac{\mu}{\rho} \frac{\partial^2 u}{\partial y^2}$$

← q. de movimento

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{k}{\rho C_p} \frac{\partial^2 T}{\partial y^2}$$

← energia **(desacoplada)**

$$p / x = 0 \rightarrow u(0, y) = u_\infty \text{ e } T(0, y) = T_\infty$$

$$p / y = 0 \rightarrow u(x, 0) = 0, v(x, 0) = 0 \text{ e } T(x, 0) = T_s$$

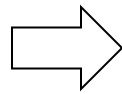
$$p / y \rightarrow \infty \rightarrow u(x, \infty) = u_\infty \text{ e } T(x, \infty) = T_\infty$$

Solução de Blasius (1908)... **velocidades**

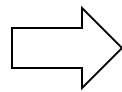
$$\frac{\partial u}{\partial x} = -\frac{u_\infty}{2x} \eta \frac{d^2 f}{d\eta^2}$$

$$\frac{\partial u}{\partial y} = u_\infty \sqrt{\frac{u_\infty}{\nu x}} \frac{d^2 f}{d\eta^2}$$

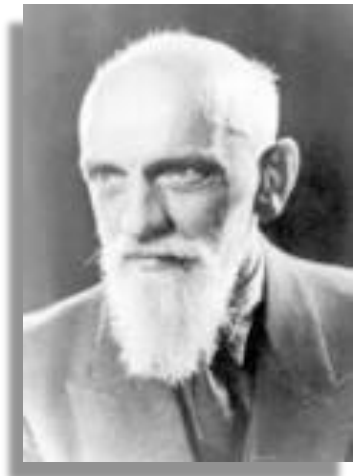
$$\frac{\partial^2 u}{\partial y^2} = \frac{u_\infty^2}{\nu x} \frac{d^3 f}{d\eta^3}$$



$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \frac{\mu}{\rho} \frac{\partial^2 u}{\partial y^2}$$



$$2 \frac{d^3 f}{d\eta^3} + f \frac{d^2 f}{d\eta^2} = 0$$

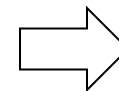


Paul R.H. Blasius
(1883–1970)

$$p/x = 0 \rightarrow u(0, y) = u_\infty$$

$$p/y = 0 \rightarrow u(x, 0) = 0, \quad v(x, 0) = 0$$

$$p/y \rightarrow \infty \rightarrow u(x, \infty) = u_\infty$$

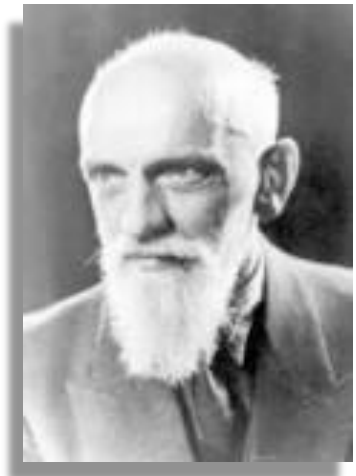


$$p/\eta = 0 \rightarrow f(\eta) = 0$$

$$p/\eta = 0 \rightarrow df/d\eta = 0$$

$$p/\eta = \infty \rightarrow df/d\eta = 1$$

Solução de Blasius (1908)... **c. limite térmica**



Paul R.H. Blasius
(1883–1970)

$$u_{\infty} \frac{df}{d\eta} \frac{\partial \theta}{\partial \eta} \frac{\partial \eta}{\partial x} + \frac{1}{2} \sqrt{\frac{u_{\infty} \nu}{x}} \left(\eta \frac{df}{d\eta} - f \right) \frac{\partial \theta}{\partial \eta} \frac{\partial \eta}{\partial y} = \frac{k}{\rho C_p} \frac{d^2 \theta}{d\eta^2} \left(\frac{\partial \eta}{\partial y} \right)^2$$

⋮

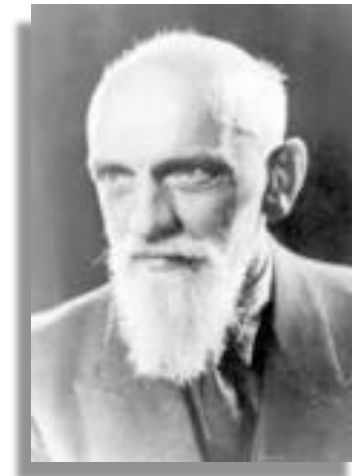
$$Pr = \frac{\mu}{k/C_p} \Rightarrow$$

$$2 \frac{d^2 \theta}{d\eta^2} + Pr \cdot f \frac{d\theta}{d\eta} = 0$$

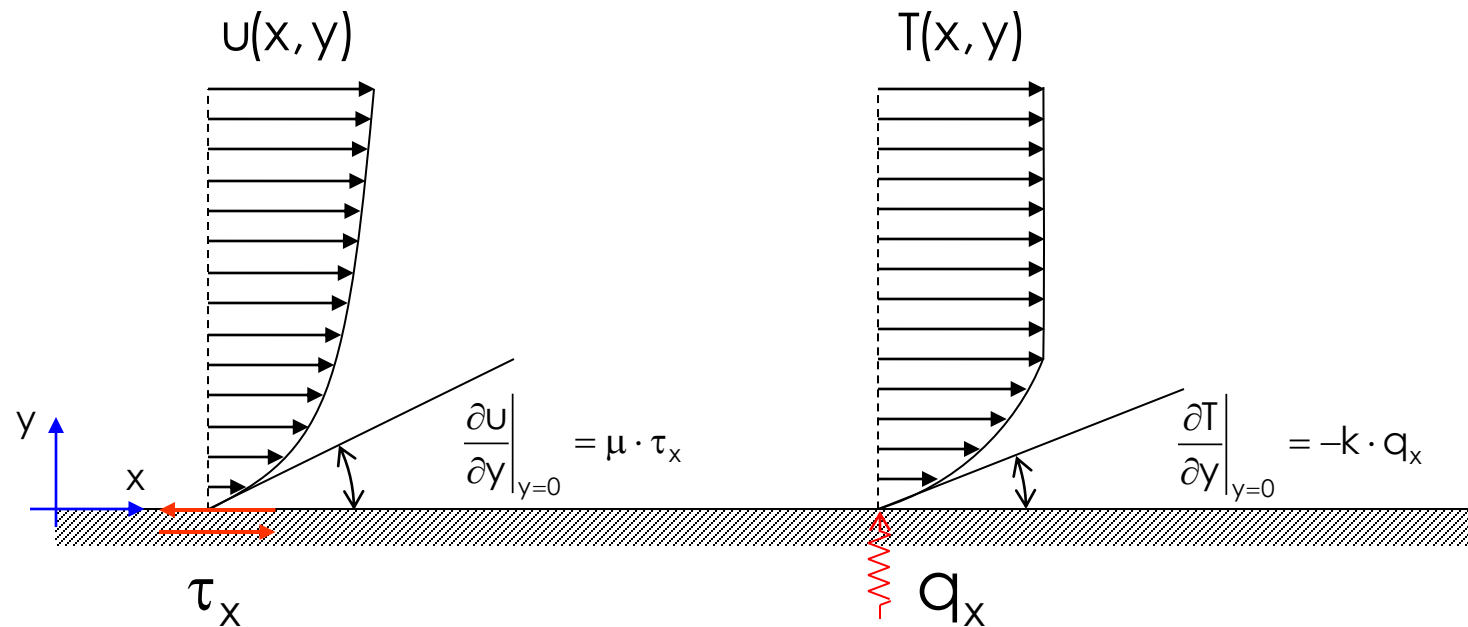
$$\theta(0) = 0 \quad e \quad \theta(\infty) = 1$$

| η | f | $\frac{df}{d\eta} = \frac{u}{u_{\infty}}$ | $\frac{d^2 f}{d\eta^2}$ |
|----------|----------|---|-------------------------|
| 0 | 0 | 0 | 0.332 |
| 0.5 | 0.042 | 0.166 | 0.331 |
| 1.0 | 0.166 | 0.330 | 0.323 |
| 1.5 | 0.370 | 0.487 | 0.303 |
| 2.0 | 0.650 | 0.630 | 0.267 |
| 2.5 | 0.996 | 0.751 | 0.217 |
| 3.0 | 1.397 | 0.846 | 0.161 |
| 3.5 | 1.838 | 0.913 | 0.108 |
| 4.0 | 2.306 | 0.956 | 0.064 |
| 4.5 | 2.790 | 0.980 | 0.034 |
| 5.0 | 3.283 | 0.992 | 0.016 |
| 5.5 | 3.781 | 0.997 | 0.007 |
| 6.0 | 4.280 | 0.999 | 0.002 |
| ∞ | ∞ | 1 | 0 |

Solução de Blasius (1908)... c. limite térmica



Paul R.H. Blasius
(1883–1970)



$$\tau_x = 0.332 \frac{\rho U_\infty^2}{\sqrt{Re_x}}$$

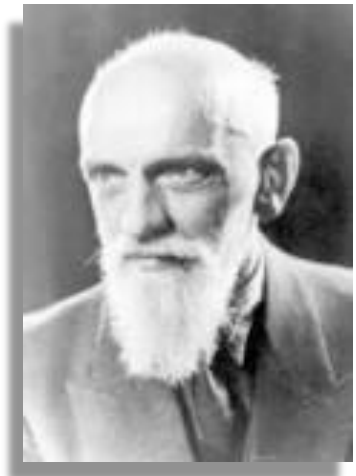
$$-\frac{q_x}{k} = 0.332 \cdot Pr^{1/3} (T_\infty - T_s) \sqrt{\frac{U_\infty}{\nu x}}$$

$$\delta_{FD} = \frac{5.0 \cdot x}{\sqrt{Re_x}}$$

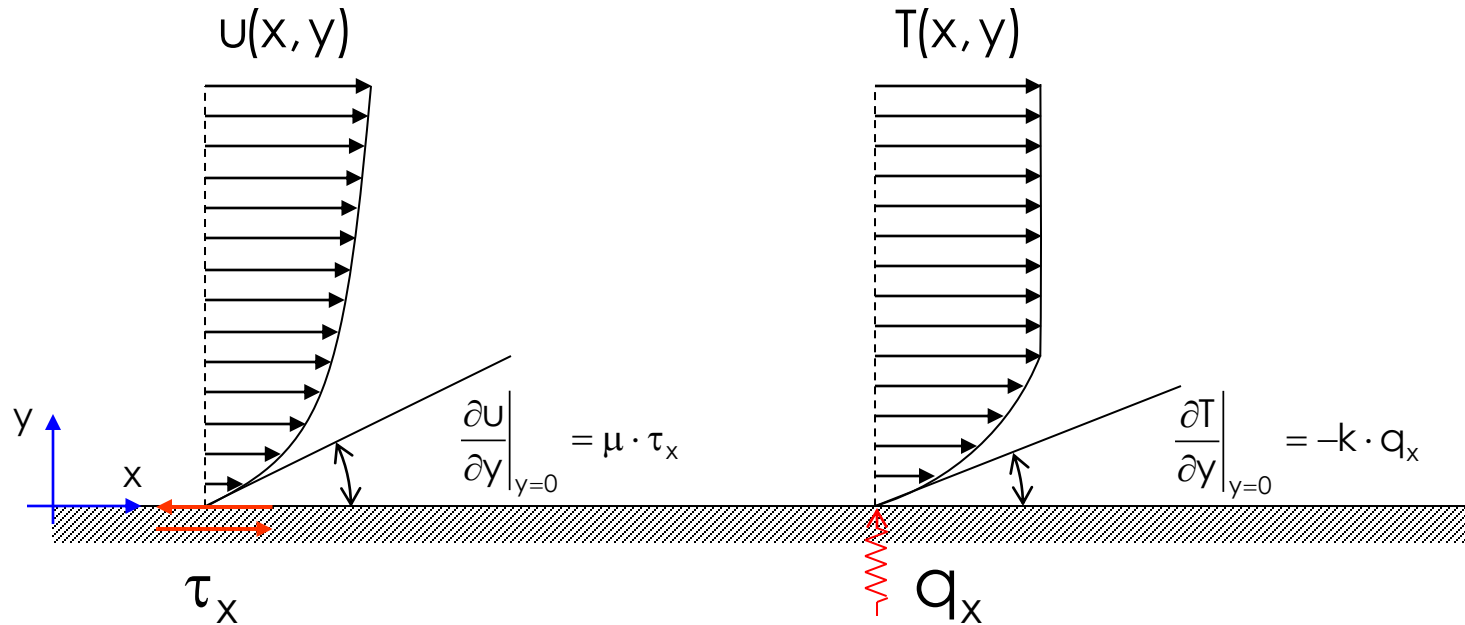
$$\delta_{TM} = \frac{5.0 \cdot x}{Pr^{1/3} \sqrt{Re_x}}$$

| η | f | $\frac{df}{d\eta} = \frac{u}{U_\infty}$ | $\frac{d^2f}{d\eta^2}$ |
|----------|----------|---|------------------------|
| 0 | 0 | 0 | 0.332 |
| 0.5 | 0.042 | 0.166 | 0.331 |
| 1.0 | 0.166 | 0.330 | 0.323 |
| 1.5 | 0.370 | 0.487 | 0.303 |
| 2.0 | 0.650 | 0.630 | 0.267 |
| 2.5 | 0.996 | 0.751 | 0.217 |
| 3.0 | 1.397 | 0.846 | 0.161 |
| 3.5 | 1.838 | 0.913 | 0.108 |
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| 4.5 | 2.790 | 0.980 | 0.034 |
| 5.0 | 3.283 | 0.992 | 0.016 |
| 5.5 | 3.781 | 0.997 | 0.007 |
| 6.0 | 4.280 | 0.999 | 0.002 |
| ∞ | ∞ | 1 | 0 |

Solução de Blasius (1908)... c. limite térmica



Paul R.H. Blasius
(1883–1970)



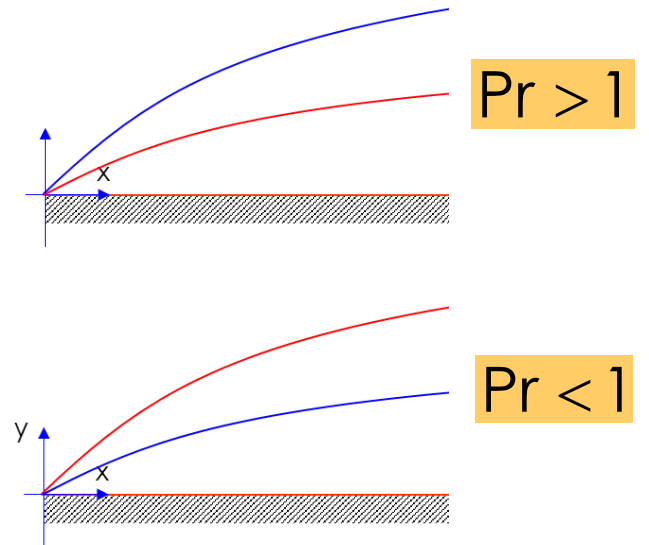
$$\tau_x = 0.332 \frac{\rho U_\infty^2}{\sqrt{Re_x}}$$

$$-\frac{q_x}{k} = 0.332 \cdot Pr^{1/3} (T_\infty - T_s) \sqrt{\frac{U_\infty}{\nu x}}$$

$$\delta_{FD} = \frac{5.0 \cdot x}{\sqrt{Re_x}}$$

$$\delta_{TM} = \frac{5.0 \cdot x}{Pr^{1/3} \sqrt{Re_x}}$$

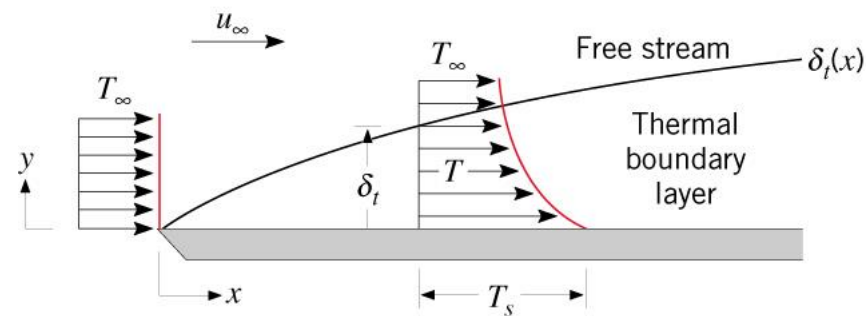
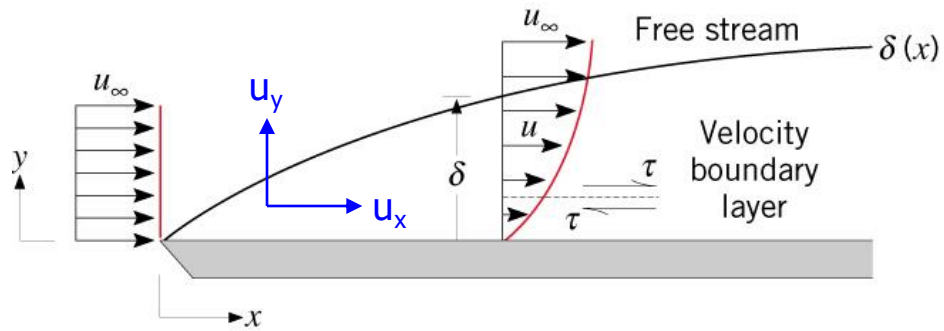
$$\frac{\delta_{FD}}{\delta_{TM}} = Pr^{1/3}$$



OBTENÇÃO DOS COEFICIENTES EMPÍRICOS DE CONVECÇÃO:

A convecção de calor ocorre em função do escoamento de um fluido. Portanto, pode ser descrito por equações de balanço de massa (continuidade), quantidade de movimento (forças) e energia (1ª lei da termodinâmica).

Exemplo: escoamento sobre uma placa plana...

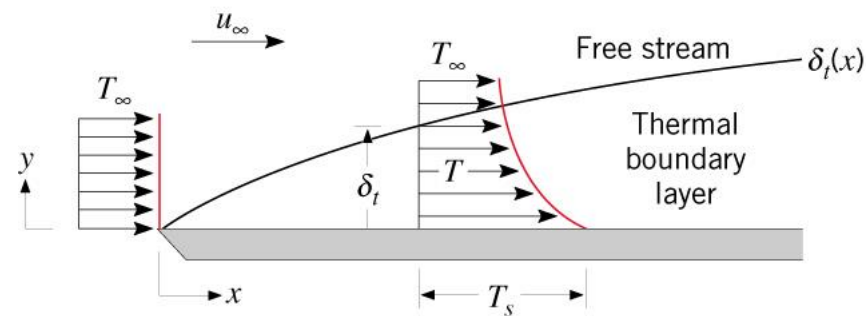
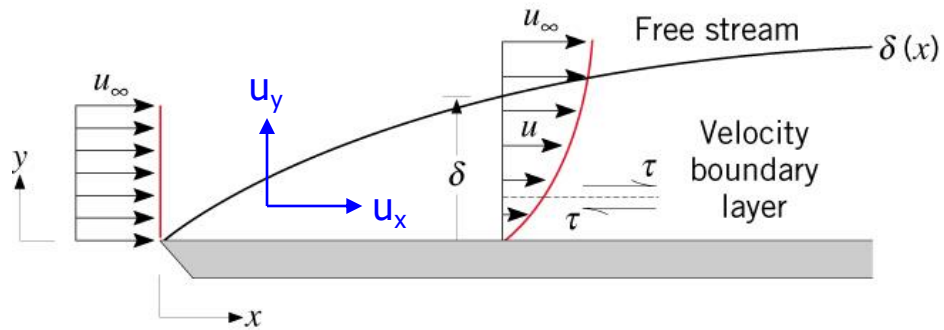


$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{U}) = 0$$

$$\rho \cdot \left(\frac{\partial \vec{U}}{\partial t} + \vec{U} \cdot \vec{\nabla} \vec{U} \right) = -\vec{\nabla} P + \mu \nabla^2 \vec{U} + \sum \vec{F}_{3D}$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + \vec{U} \cdot \vec{\nabla} T \right) = \vec{\nabla} \cdot (k \vec{\nabla} T) + \tilde{T} : \tilde{D}$$

Exemplo: escoamento sobre uma placa plana...



$$x^* \leftarrow x/D \dots$$

$$U^* \leftarrow U/U_0 \dots$$

$$t^* \leftarrow t/(D/U_0) \dots$$

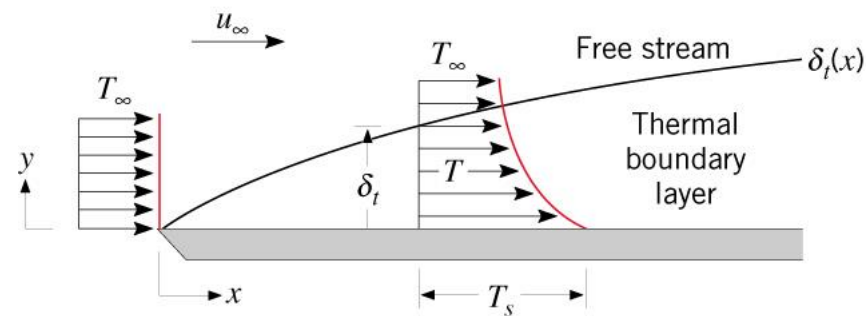
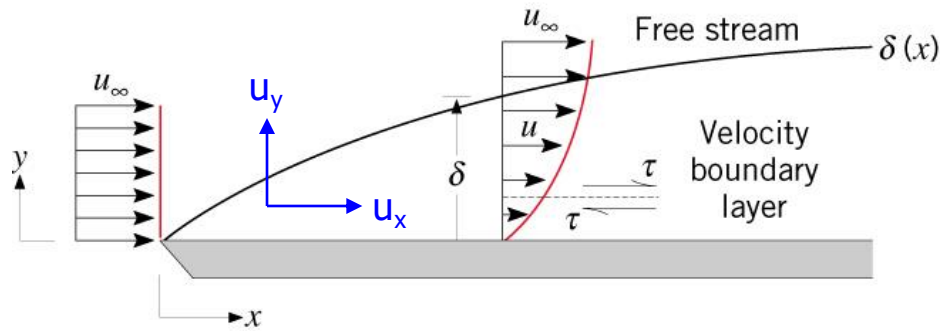


$$\frac{\partial \rho^*}{\partial t^*} + \vec{\nabla} \cdot (\rho^* \vec{U}^*) = 0$$

$$\rho^* \cdot \left(\frac{\partial \vec{U}^*}{\partial t^*} + \vec{U}^* \cdot \vec{\nabla} \vec{U}^* \right) = -E_U \cdot \vec{\nabla} P^* + \frac{1}{Re} \nabla^2 \vec{U}^* + \sum \vec{F}_{3D}^*$$

$$\rho^* \left(\frac{\partial T^*}{\partial t^*} + \vec{U}^* \cdot \vec{\nabla} T^* \right) = \frac{1}{Re \cdot Pr} \vec{\nabla} \cdot (k^* \vec{\nabla} T^*) + \tilde{T}^* : \tilde{D}^*$$

Exemplo: escoamento sobre uma placa plana...



$$\frac{\partial \rho^*}{\partial t^*} + \vec{\nabla} \cdot (\rho^* \vec{U}^*) = 0$$

$$\rho^* \cdot \left(\frac{\partial \vec{U}^*}{\partial t^*} + \vec{U}^* \cdot \vec{\nabla} \vec{U}^* \right) = -E_U \cdot \vec{\nabla} P^* + \frac{1}{Re} \nabla^2 \vec{U}^* + \sum \vec{F}_{3D}^*$$

$$\rho^* \left(\frac{\partial T^*}{\partial t^*} + \vec{U}^* \cdot \vec{\nabla} T^* \right) = \frac{1}{Re \cdot Pr} \vec{\nabla} \cdot (k^* \vec{\nabla} T^*) + \tilde{T}^* : \tilde{D}^*$$

$$x^* \leftarrow x/D \dots$$

$$U^* \leftarrow U/U_0 \dots$$

$$t^* \leftarrow t/(D/U_0) \dots$$

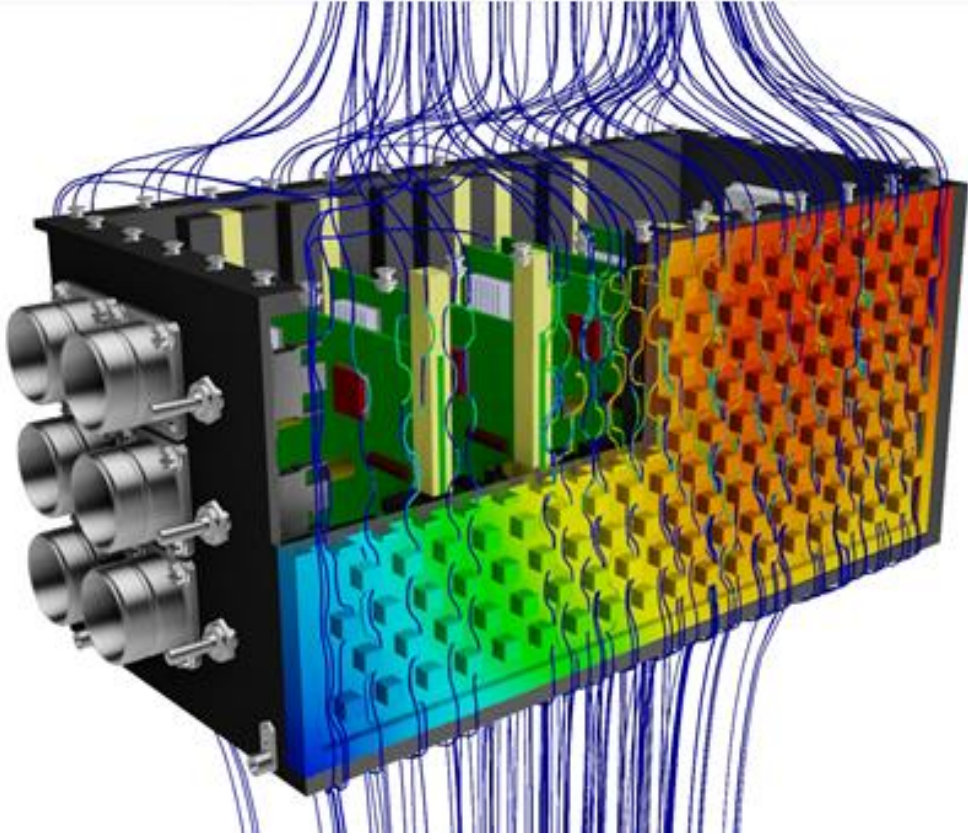
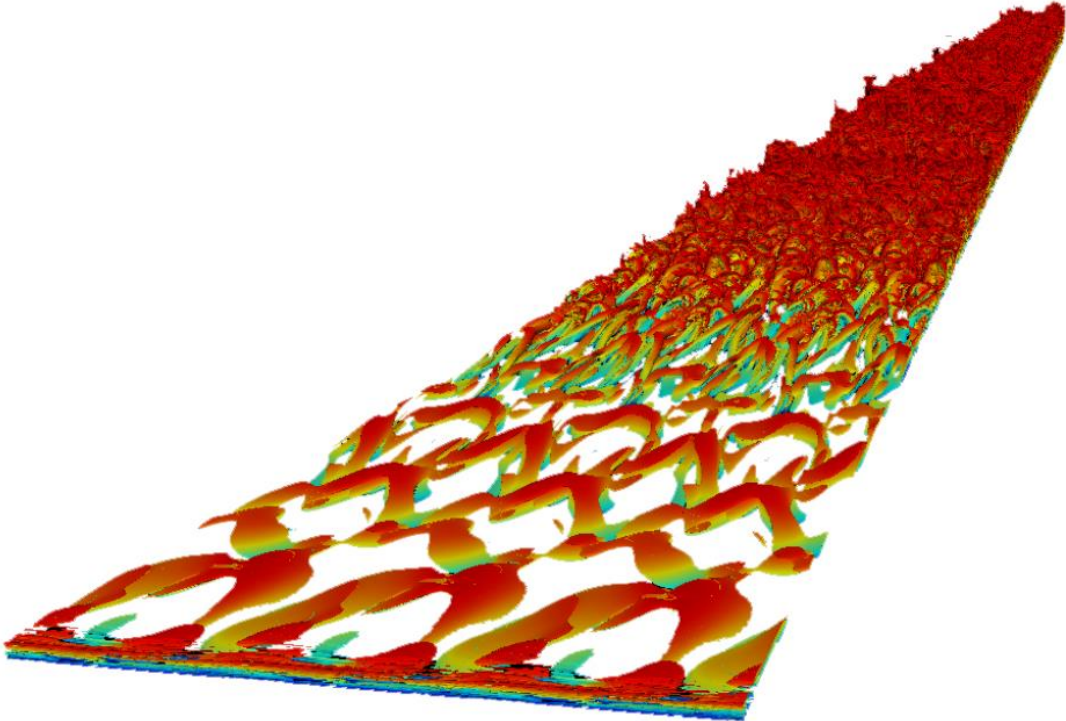
$$Re = \frac{\rho U_0 D}{\mu}$$

$$Pr = \frac{C_p \mu}{k}$$

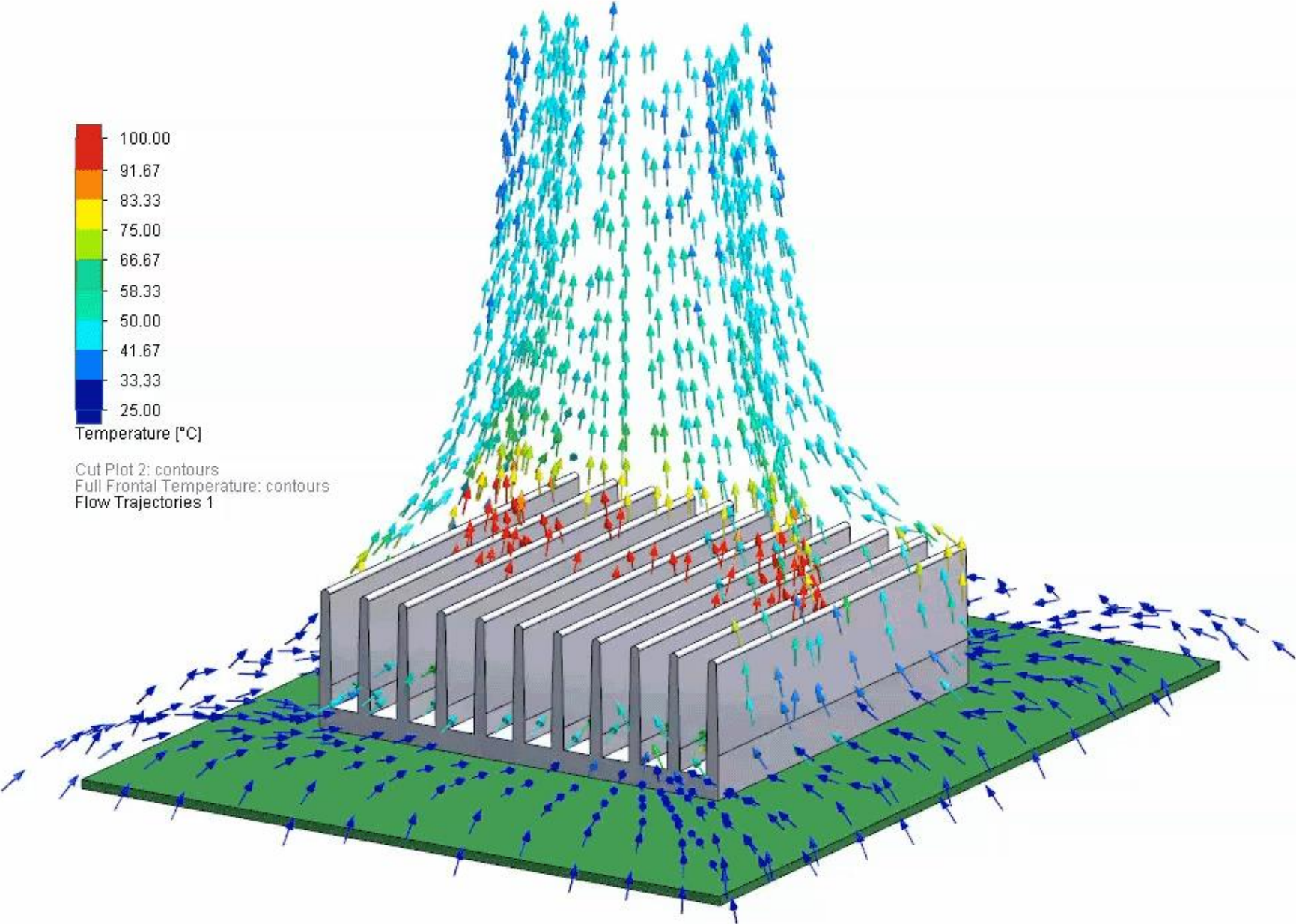
$$EU = \frac{P_0}{\rho U_0^2}$$

$$Fr = \frac{U_0}{\sqrt{L \cdot g_0}}$$

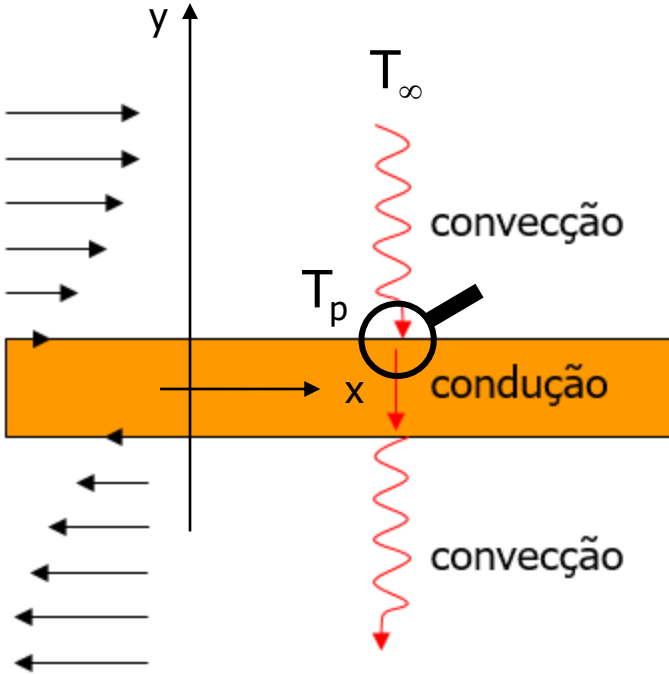
Simulações numéricas (CFD)...



Simulações numéricas (CFD)...



Abordagem empírica...



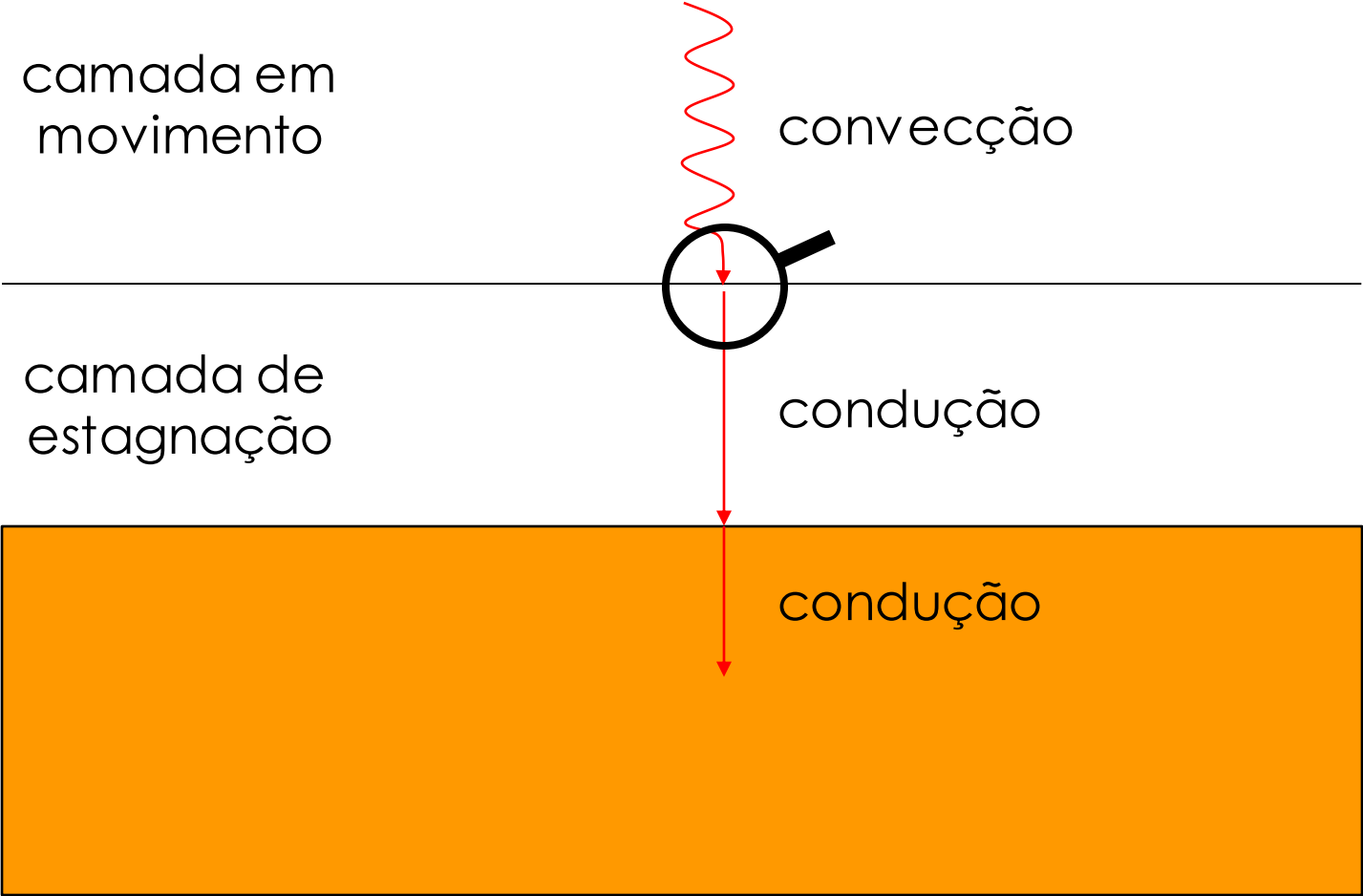
camada em movimento

convecção

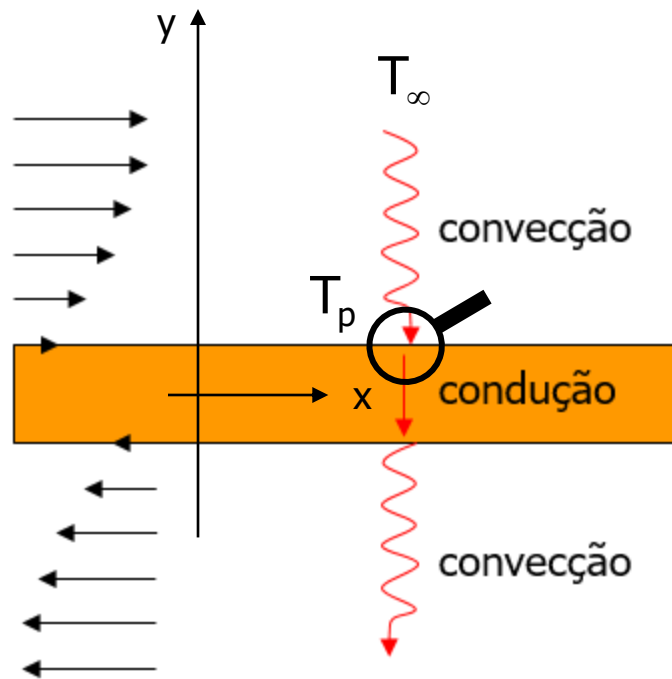
camada de estagnação

condução

condução



Abordagem empírica...



$$q = h_q \cdot (T_\infty - T_p) = -k \cdot \frac{dT}{dy} \Big|_{\text{camada limite}}$$

$$y^* \leftarrow y/D \quad T^* \leftarrow \frac{T - T_p}{T_\infty - T_p}$$

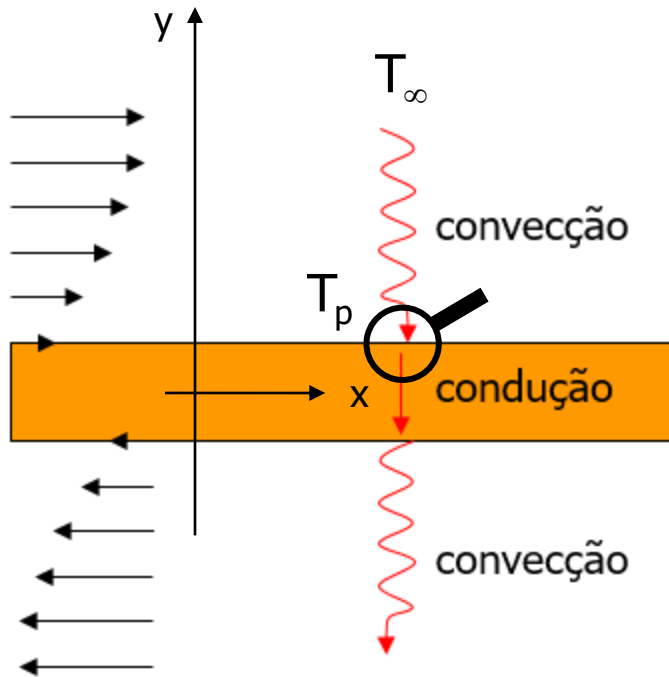
$$h_q \cdot (T_\infty - T_p) = -k \cdot \frac{d}{dy} (T_p + (T_\infty - T_p) \cdot T^*)$$

$$h_q \cdot (T_\infty - T_p) = -k(T_\infty - T_p) \cdot \frac{dT^*}{dy}$$

$$h_q = -k \cdot \frac{dT^*}{dy^*} \frac{dy^*}{dy}$$

$$\text{Nr. de Nusselt} \rightarrow \frac{h_q}{k/D} = -\frac{dT^*}{dy^*} \leftarrow \frac{\text{convecção}}{\text{condução}}$$

Abordagem empírica...



$$Nu \stackrel{\text{def}}{=} \frac{h_q}{k/D}$$

As equações diferenciais de balanço indicam que:

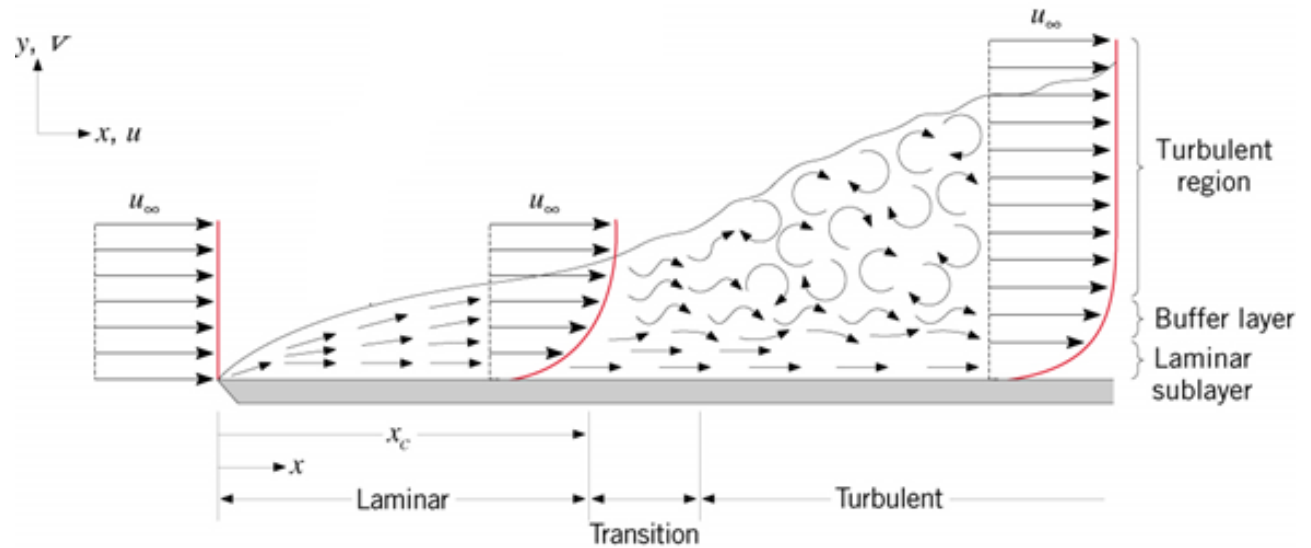
$$Nu = f(Re, Pr)$$

$$Re = \frac{\rho u_0 D}{\mu}$$

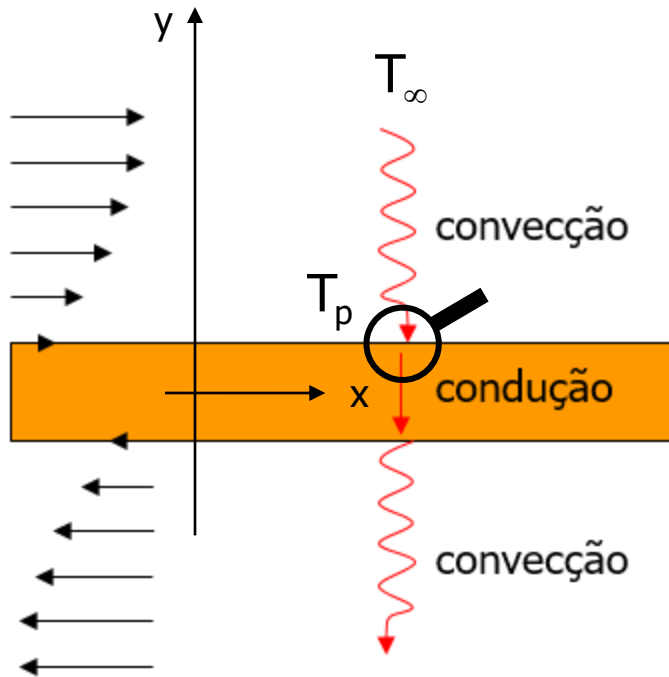
caracteriza o escoamento

caracteriza o fluido

$$Pr = \frac{C_p \mu}{k}$$



Abordagem empírica...



$$Nu \stackrel{\text{def}}{=} \frac{h_q}{k/D}$$

As equações diferenciais de balanço indicam que:

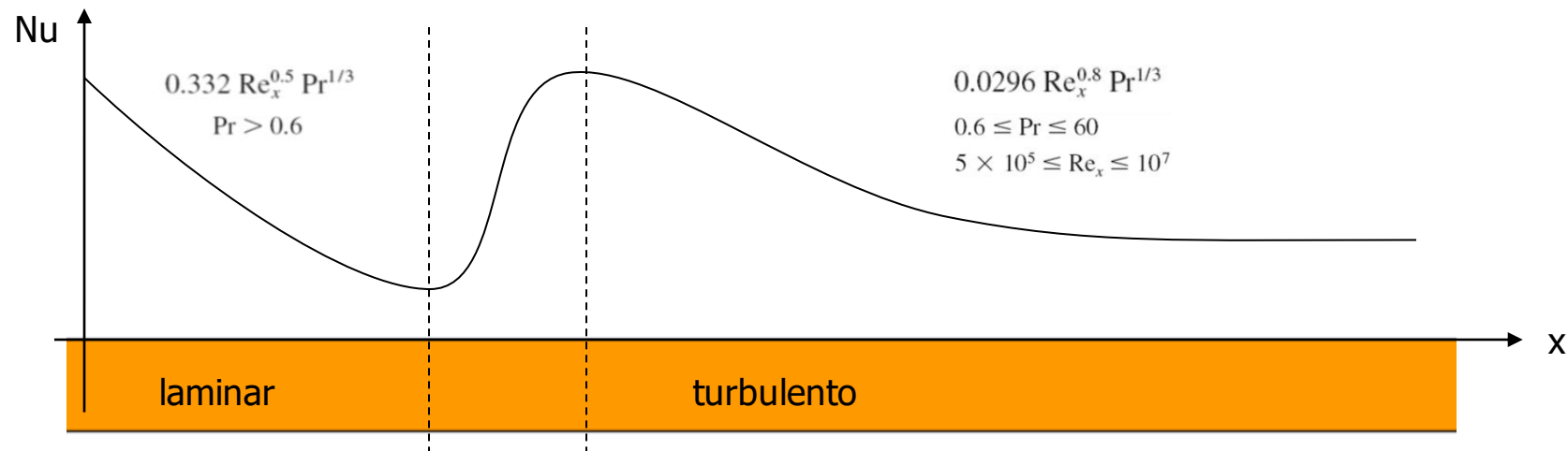
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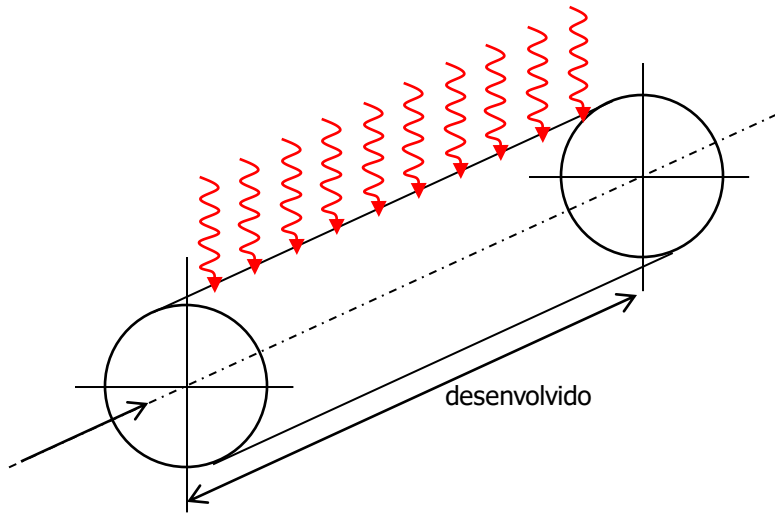
caracteriza o escoamento

caracteriza o fluido

$$Pr = \frac{C_p \mu}{k}$$



Correlações para escoamentos internos...



$$Re = \frac{\rho u_0 D}{\mu} \quad Pr = \frac{C_p \mu}{k}$$

Escoamento laminar:

Fluxo de calor constante: $Nu = 4.36$

Temperatura constante: $Nu = 3.66$

Escoamento turbulento desenvolvido ($Re > 10^4$):

Superfície lisa:

(Dittus-Boelter)

$$Nu = 0.023 \cdot Re^{4/5} \cdot Pr^n$$

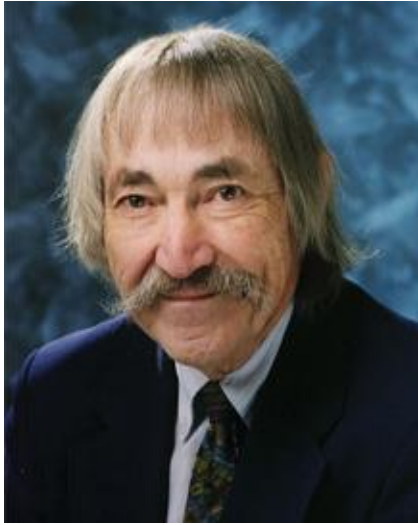
$$\left[\begin{array}{l} n = 0.3 \quad p / T_s < T_m \\ n = 0.4 \quad p / T_s > T_m \end{array} \right. \left. \begin{array}{l} 0.7 \leq Pr \leq 160 \\ Re_D \geq 10,000 \\ \frac{L}{D} \geq 10 \end{array} \right]$$

Superfície rugosa:

$$Nu = \frac{f}{8} \cdot \frac{(Re - 1000) \cdot Pr}{1 + 12.7(f/8)^{1/2} (Pr^{2/3} - 1)}$$

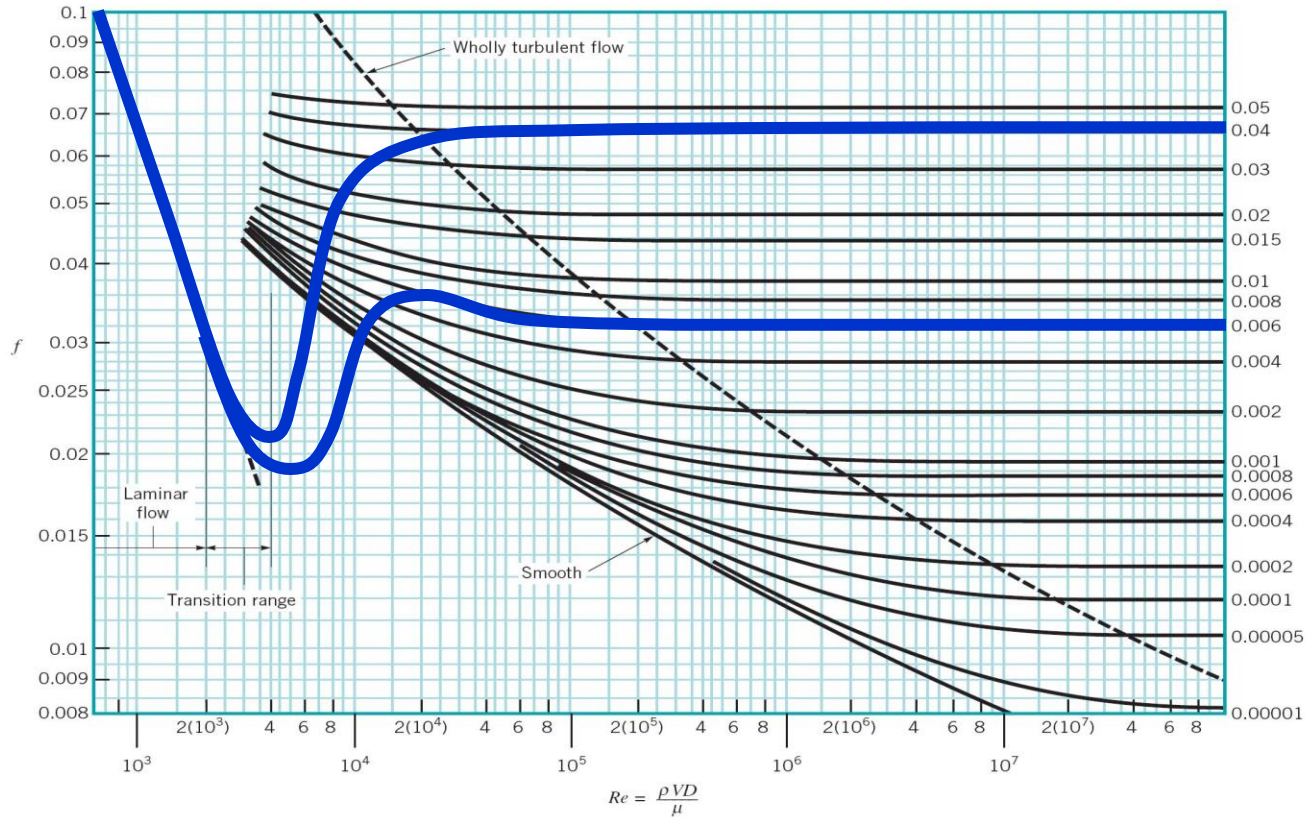
f = friction factor

A equação de Darcy e cálculo do fator de atrito...



Stuart W. Churchill

Diagrama de Moody



Laminar ($Re < 2500$)

$$f = \frac{64}{Re}$$

Turbulento ($Re > 4000$)

$$\frac{1}{\sqrt{f}} = -2 \log \left(3.7 \frac{e}{D} + \frac{2.51}{Re \sqrt{f}} \right)$$

Colebrook-White

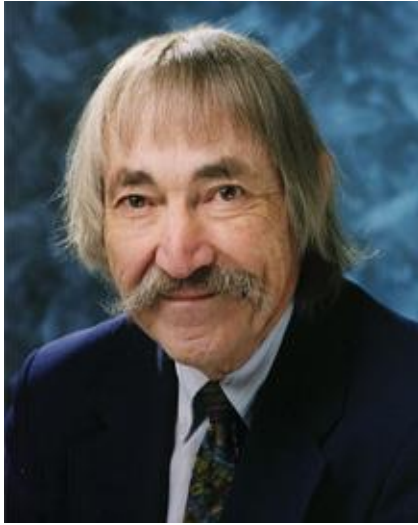
$$f = 8 \cdot \left[\left(\frac{8}{Re} \right)^{12} + (A + B)^{-1,5} \right]^{1/12}$$

$$A = \left\{ 2,457 \ln \left(\left(\left(\frac{7}{Re} \right)^{0,9} + 0,27 \cdot \frac{\varepsilon}{D} \right)^{-1} \right) \right\}^{16}$$

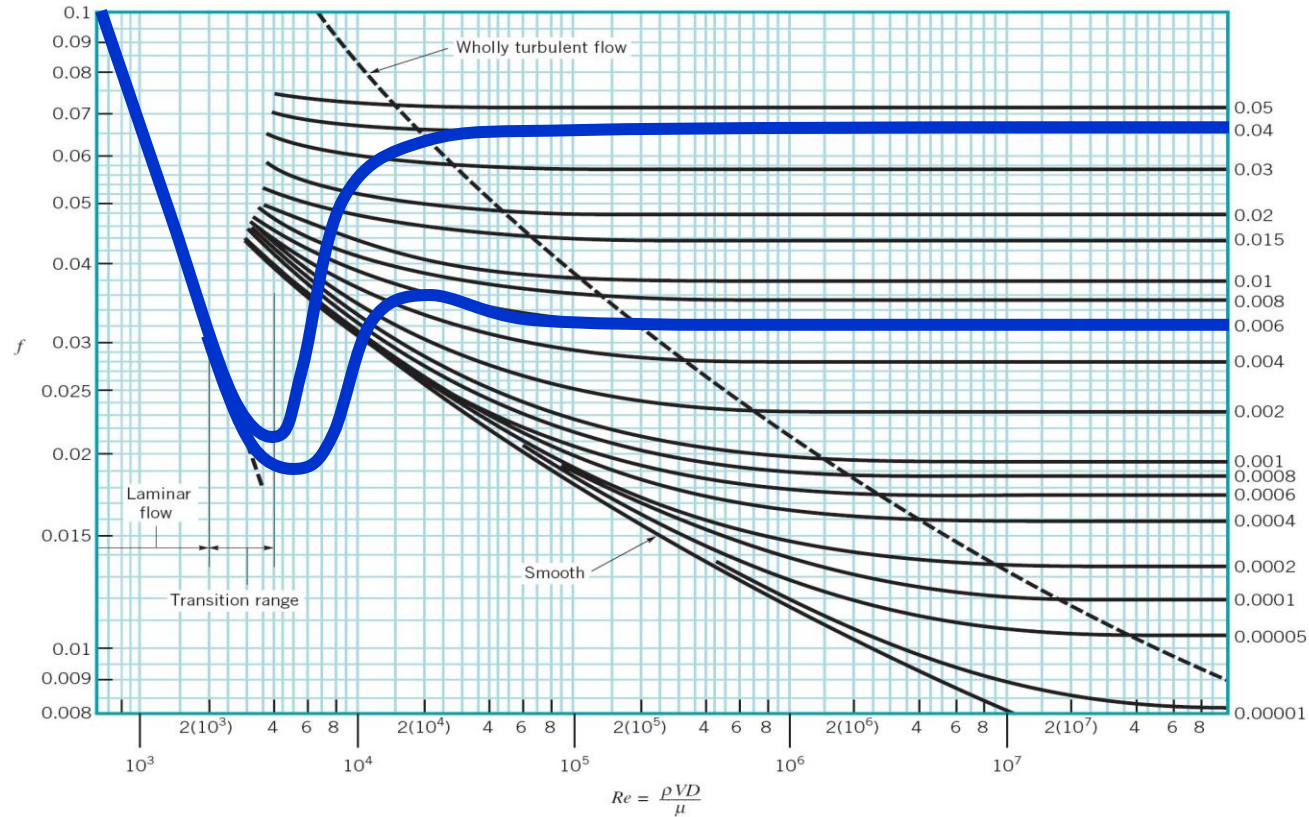
$$B = \left(\frac{37530}{Re} \right)^{16} \quad Re = \frac{4 \cdot m}{\mu \pi D}$$

A equação de Darcy e cálculo do fator de atrito...

Diagrama de Moody



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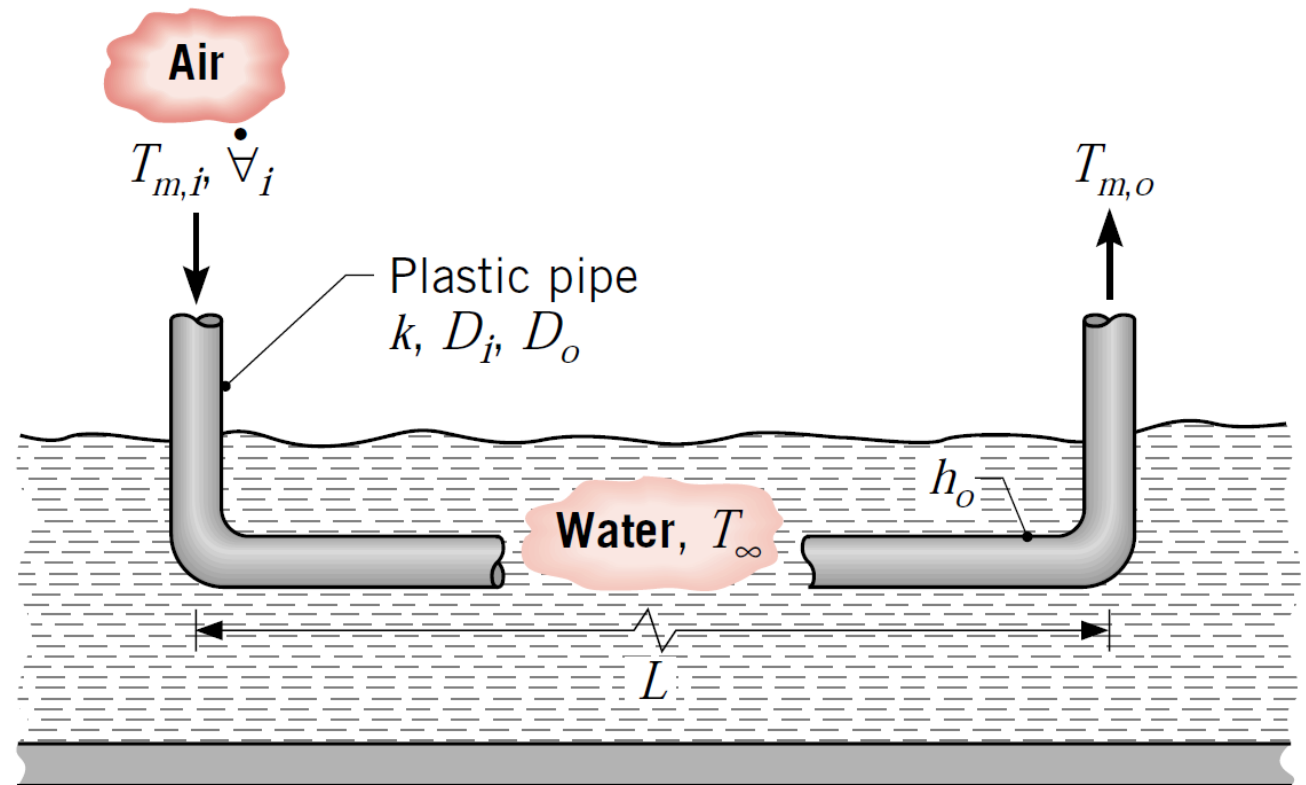


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8.31: Para resfriar uma casa de verão sem uso de um ciclo frigorífico, ar é encaminhado através de uma tubulação de plástico ($k=0.15\text{W/m/K}$, $D_i=0.15\text{m}$, $D_o=0.17\text{m}$) submersa em um corpo d'água adjacente. A temperatura da água é normalmente de $T_\infty=17^\circ\text{C}$, e o coeficiente de convecção é mantido em $h_o=1500\text{ W/m}^2/\text{K}$ na superfície externa da tubulação. Se ar proveniente da casa entra no tubo a uma temperatura de $T_{m,i}=29^\circ\text{C}$ e uma vazão volumétrica de $V_i=0.025\text{m}^3/\text{s}$, qual extensão L é necessária para que a temperatura na saída seja de $T_{m,o}=21^\circ\text{C}$?



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REFPROP (air (dry)) - NIST Reference Fluid Properties (DLL version 9,1)

File Edit Options Substance Calculate Plot Window Help Cautions

2: air (dry): Specified state points

| | Temperature (°C) | Pressure (bar) | Density (kg/m³) | Enthalpy (kJ/kg) | Cp (kJ/kg-K) | Therm. Cond. (mW/m-K) | Viscosity (μPa-s) | Prandtl |
|---|------------------|----------------|-----------------|------------------|--------------|-----------------------|-------------------|---------|
| 1 | 29,000 | 1,0000 | 1,1533 | 428,46 | 1,0064 | 26,544 | 18,641 | 0,70678 |
| 2 | 25,000 | 1,0000 | 1,1688 | 424,44 | 1,0063 | 26,247 | 18,448 | 0,70729 |
| 3 | 21,000 | 1,0000 | 1,1848 | 420,41 | 1,0062 | 25,948 | 18,254 | 0,70781 |
| 4 | | | | | | | | |

$$Q = \dot{m} \cdot (h_i - h_o) = \rho_i V_i \cdot (h_i - h_o)$$

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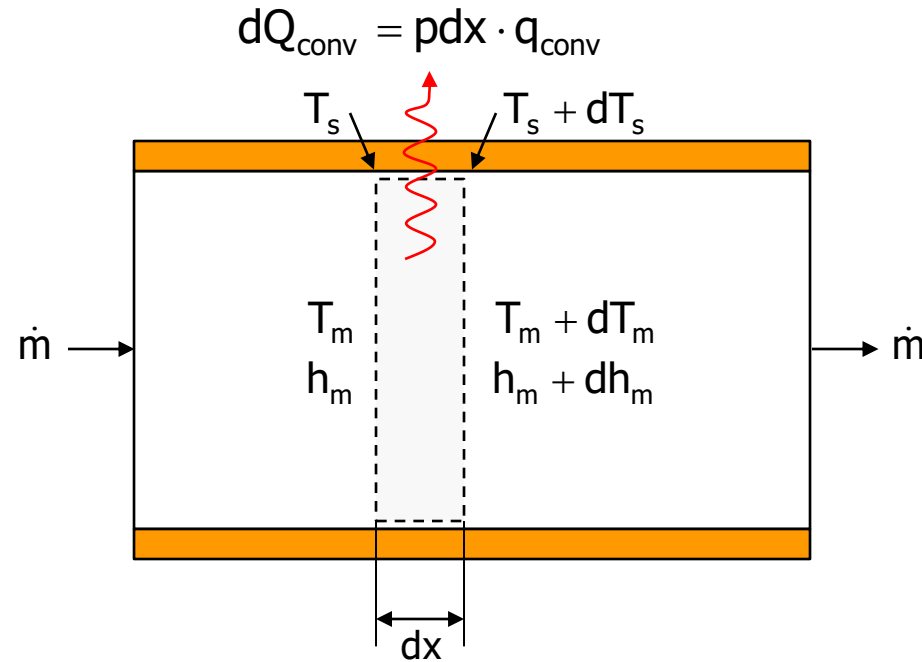
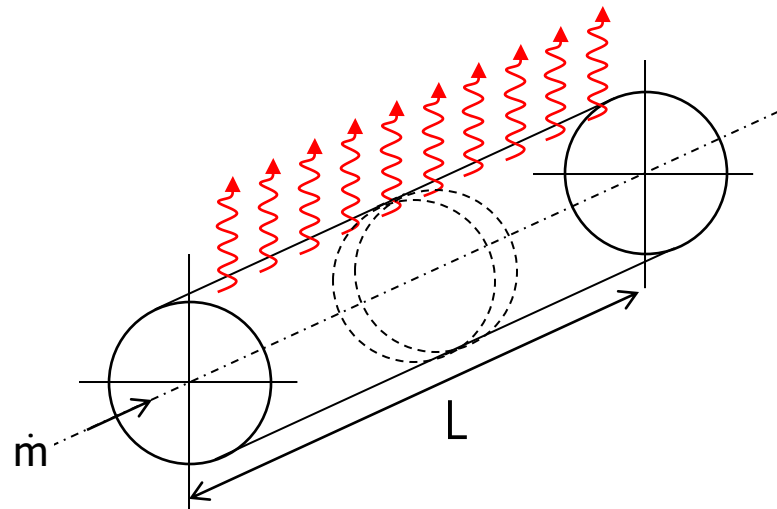
$$Q = 1.1533 \frac{\text{kg}}{\text{m}^3} \cdot 0.025 \frac{\text{m}^3}{\text{s}} \cdot (428.46 - 420.41) \frac{\text{kJ}}{\text{kg}}$$

$$\dot{m} = 0.02883 \text{ kg/s}$$

$$Q = 0.2321 \text{ kW}$$

Equação do decaimento da temperatura
ao longo da tubulação

Balço global de energia...



$$\dot{Q} - \dot{W} = \sum_{\text{sai}} \dot{m}_k \cdot (\cancel{h_k} + \cancel{gz_k} + \cancel{v_k^2 / 2}) - \sum_{\text{entra}} \dot{m}_k \cdot (\cancel{h_k} + \cancel{gz_k} + \cancel{v_k^2 / 2})$$

$$p q_{\text{conv}} dx = \dot{m} \cdot (\cancel{h_m} + \cancel{dh_m}) - \dot{m} \cdot \cancel{h_m}$$

p = perímetro

$$q_{\text{conv}} = h_{\text{conv}} \cdot (T_s - T_m) \rightarrow$$

$$\dot{m} \cdot \frac{dh_m}{dx} - p h_{\text{conv}} \cdot (T_s - T_m) = 0$$

Balço global de energia...

$$\dot{m} \cdot \frac{dh_m}{dx} - ph_{\text{conv}} \cdot (T_s - T_m) = 0$$

Soluço direta via mto numrico de
soluço de equaço diferencial

$$h = h(P, T) \downarrow$$

Implementaço numrica...

Balço global de energia...

$$\dot{m} \cdot \frac{dh_m}{dx} - ph_{conv} \cdot (T_s - T_m) = 0$$

Soluço direta via mto numérico de soluço de equaço diferencial

$$h = h(P, T) \downarrow$$

Implementaço numérica...

Soluço analítica a partir de hipóteses simplificadoras

$$h = C_p \cdot T \downarrow \begin{array}{l} \text{gases perfeitos} \\ \text{"fluido incompressível"} (C_p = C_v) \end{array}$$

$$\dot{m} \cdot \frac{dT_m}{dx} - \frac{ph_{conv}}{C_p} \cdot (T_s - T_m) = 0$$



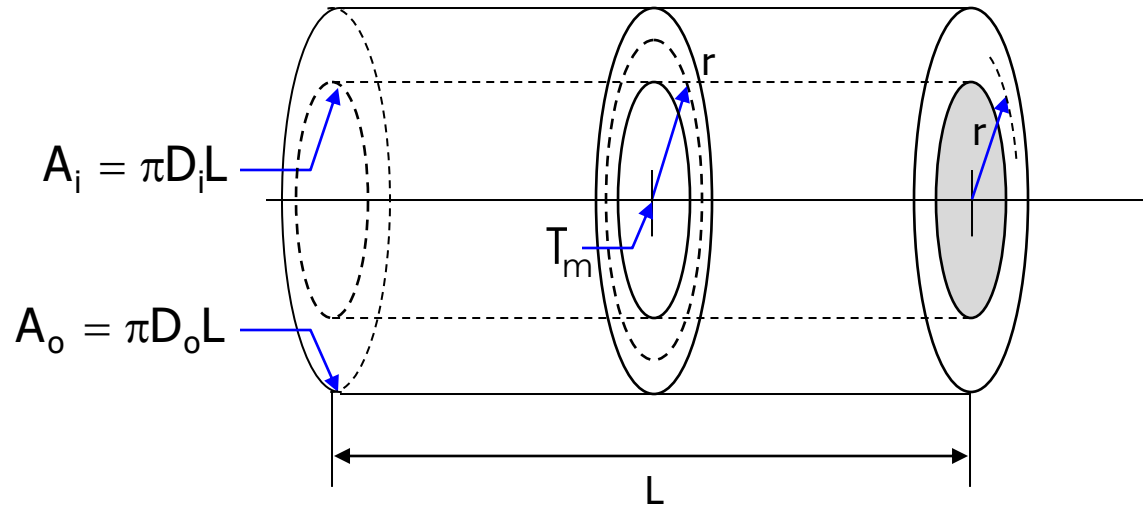
Fluxo de calor constante →

$$T_m(x) = T_{m,i} + \frac{pq_{conv}}{\dot{m}C_p} \cdot x$$

Temperatura superficial constante →

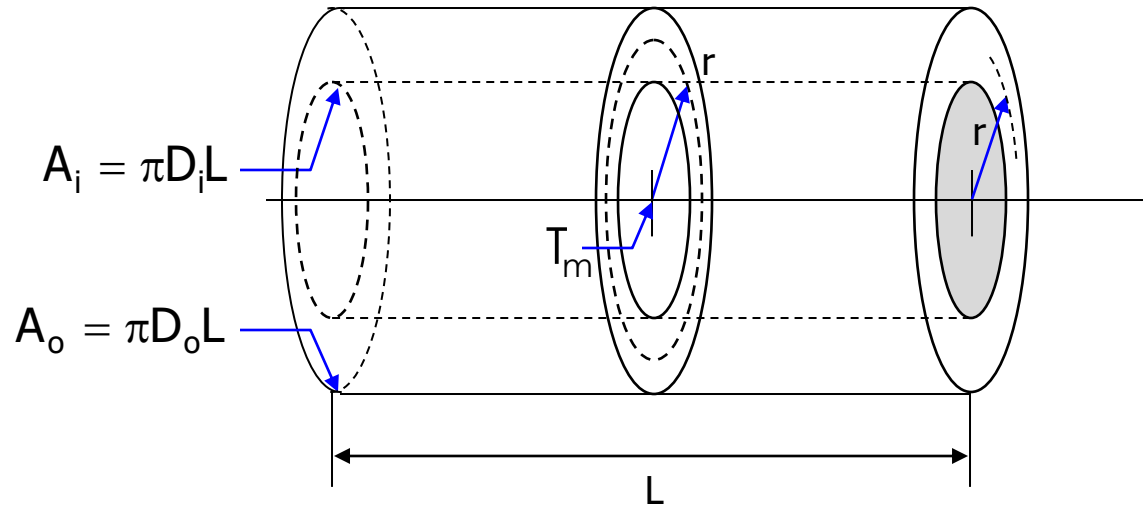
$$T_m(x) = T_s - (T_s - T_{m,i}) \cdot \exp\left(\frac{p\bar{h}_{conv}}{\dot{m}C_p} \cdot x\right)$$

Geometria cilíndrica... variação radial da temperatura



Obs.: $Q = q_i \cdot A_i = q_o \cdot A_o$

Geometria cilíndrica... variação radial da temperatura



$$\vec{\nabla} \cdot (k\vec{\nabla}T) = 0 \rightarrow \frac{d}{dr} \left(kr \frac{dT}{dr} \right) = 0$$

$$\rightarrow \frac{dT}{dr} = C_1 + \frac{C_2}{r}$$

Obs.: $\lim_{r \rightarrow \infty} \frac{dT}{dr} = 0$

$$\rightarrow dT = \frac{C_2}{r} dr$$

$$\rightarrow \int_{T_i}^{T(r)} dT = \int_{r_i}^r \frac{C_2}{r} dr$$

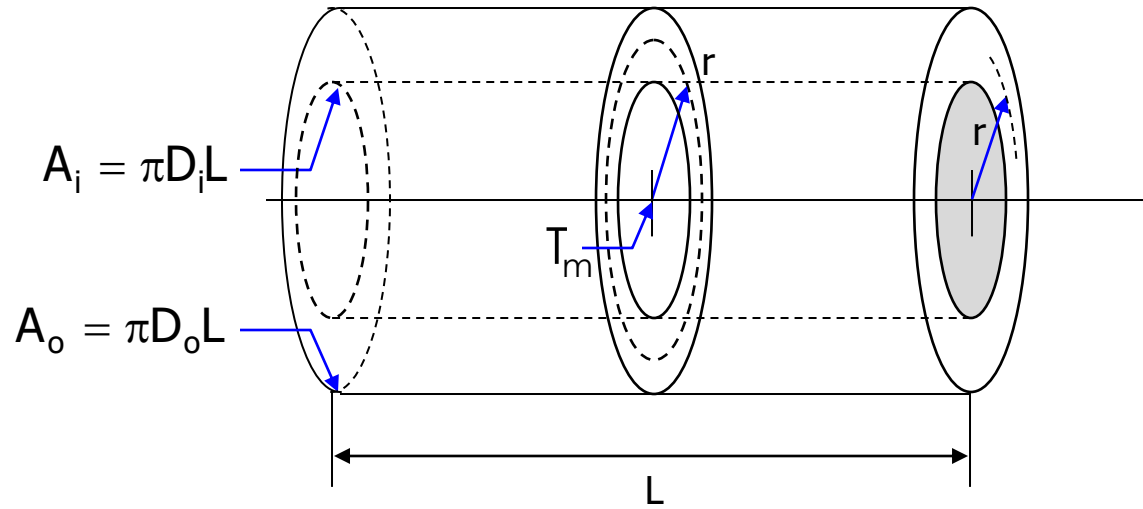
$$\rightarrow T(r) - T_i = \ln\left(\frac{r}{r_i}\right) \cdot C_2 \quad \leftarrow T(r_o) = T_o$$

Obs.: $Q = q_i \cdot A_i = q_o \cdot A_o$

Equação do decaimento radial da temperatura

$$\rightarrow T(r) = T_i + \frac{T_o - T_i}{\ln(r_o / r_i)} \cdot \ln\left(\frac{r}{r_i}\right)$$

Geometria cilíndrica... variação radial da temperatura

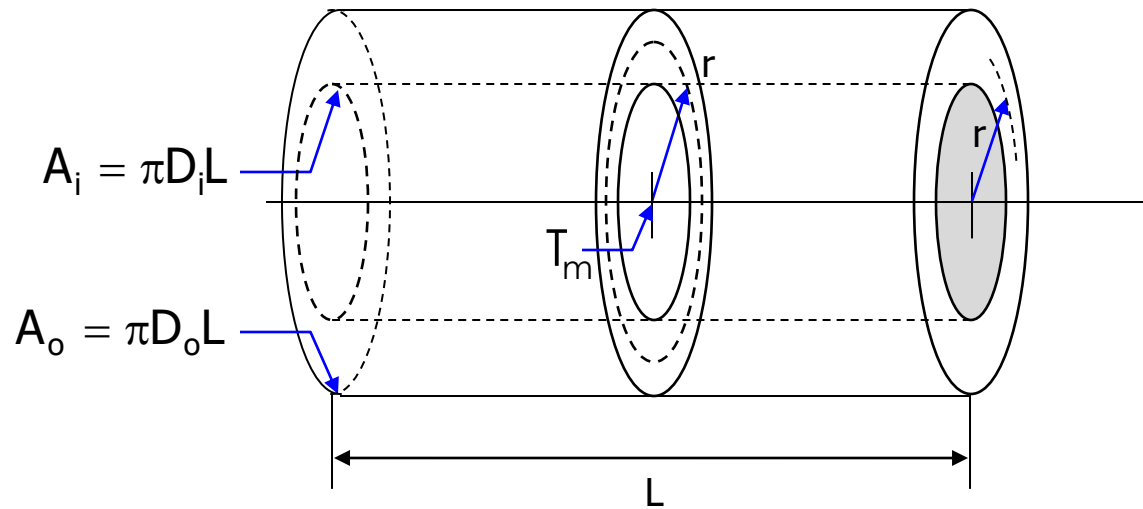


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Geometria cilíndrica... variação radial da temperatura



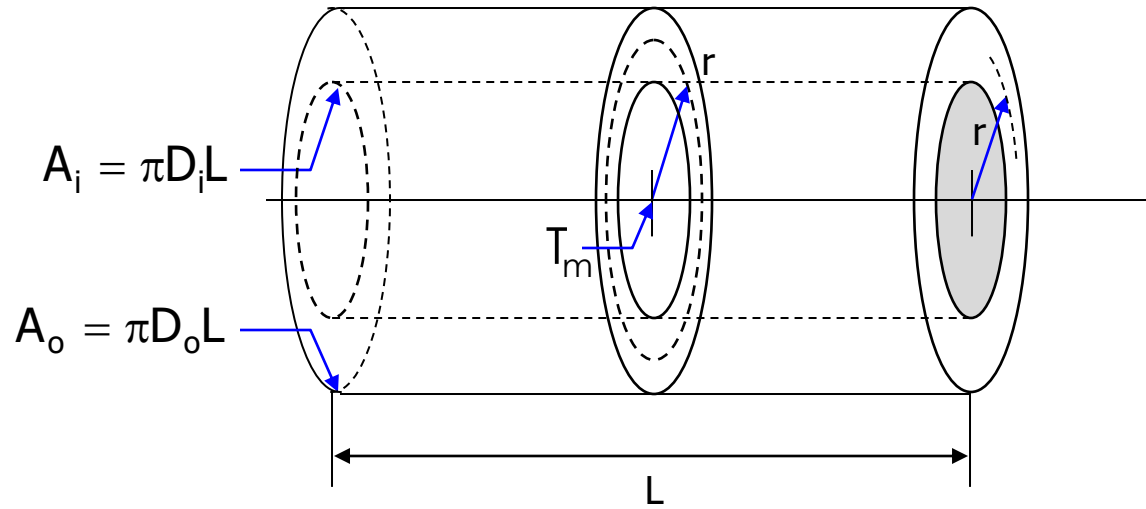
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$$Q = -kA \frac{dT}{dr}(r_o) = \frac{2\pi Lk}{\ln(r_o / r_i)} \cdot (T_o - T_i)$$

Obs.: $Q = q_i \cdot A_i = q_o \cdot A_o$

Geometria cilíndrica... variação radial da temperatura



$$\vec{\nabla} \cdot (k \vec{\nabla} T) = 0 \rightarrow \frac{d}{dr} \left(kr \frac{dT}{dr} \right) = 0$$

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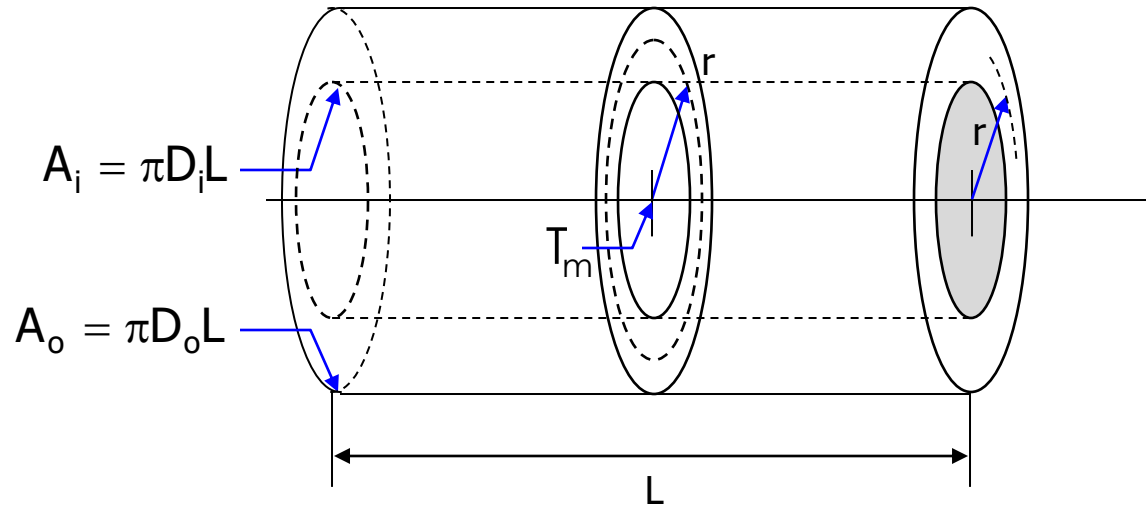
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Obs.: $Q = q_i \cdot A_i = q_o \cdot A_o$

$$Q = \frac{T_m - T_\infty}{\frac{1}{2\pi r_i L h_i} + \frac{\ln(r_o / r_i)}{2\pi L k} + \frac{1}{2\pi r_o L h_o}}$$

$$\dots = \frac{T_m - T_\infty}{R_{\text{total}}} = UA \cdot (T_m - T_\infty)$$

Geometria cilíndrica... variação radial da temperatura



$$\vec{\nabla} \cdot (k \vec{\nabla} T) = 0 \rightarrow \frac{d}{dr} \left(kr \frac{dT}{dr} \right) = 0$$

$$T(r) = T_i + \frac{T_o - T_i}{\ln(r_o / r_i)} \cdot \ln\left(\frac{r}{r_i}\right)$$

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Obs.: $Q = q_i \cdot A_i = q_o \cdot A_o$

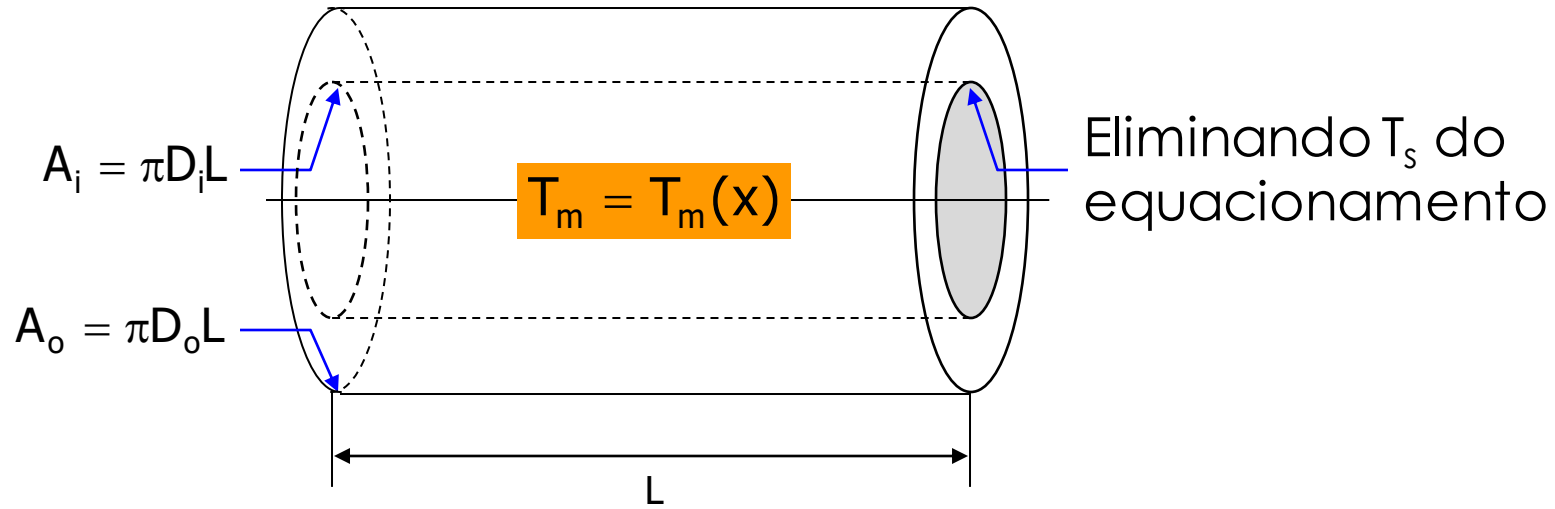
$$Q = \frac{T_m - T_\infty}{\frac{1}{2\pi r_i L h_i} + \frac{\ln(r_o / r_i)}{2\pi L k} + \frac{1}{2\pi r_o L h_o}}$$

$$\dots = \frac{T_m - T_\infty}{R_{\text{total}}} = UA \cdot (T_m - T_\infty)$$

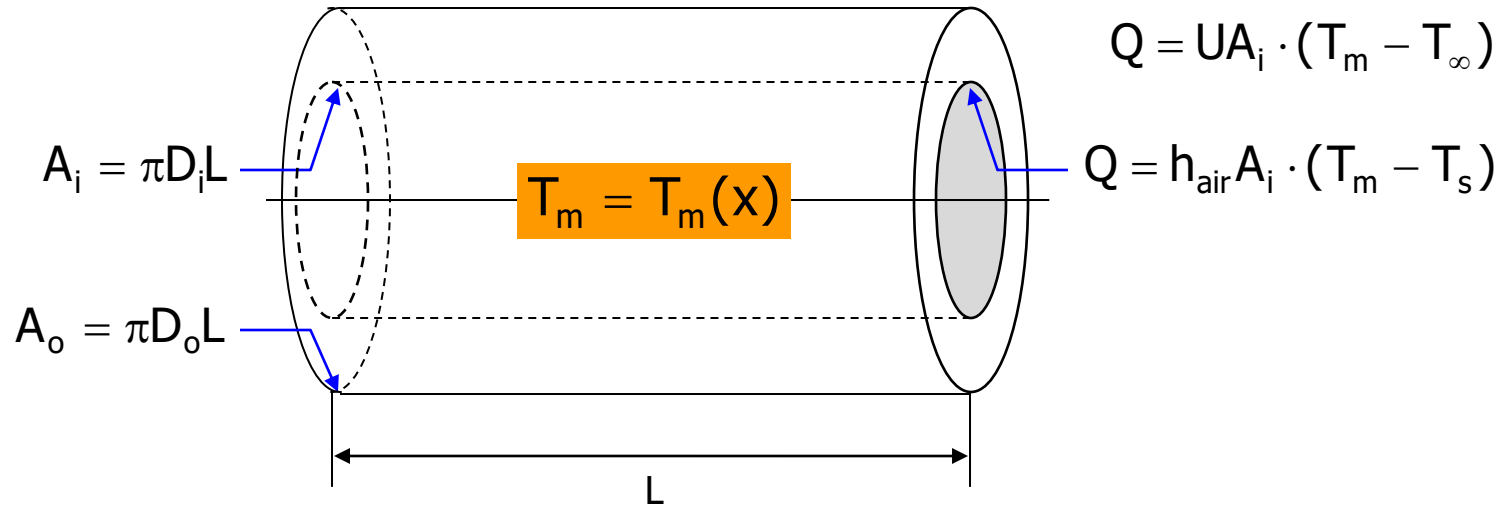
$$A = \pi D_i L \xrightarrow{\text{def}} U = \left[\frac{1}{h_i} + \frac{r_i}{k} \ln\left(\frac{r_o}{r_i}\right) + \frac{1}{h_o} \cdot \frac{r_i}{r_o} \right]^{-1}$$

coeficiente global de transferência de calor (condutância)

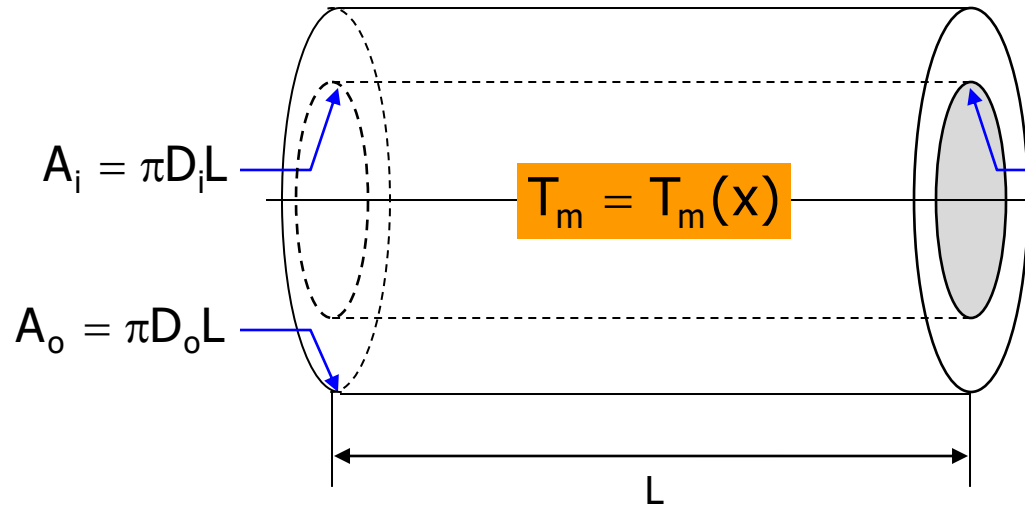
Geometria cilíndrica... variação axial da temperatura



Geometria cilíndrica... variação axial da temperatura

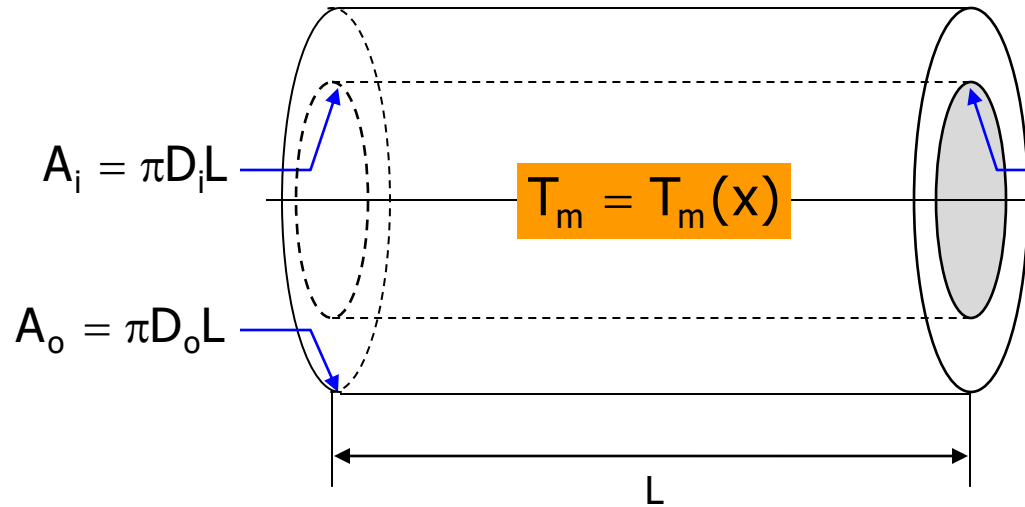


Geometria cilíndrica... variação axial da temperatura



$$Q = UA_i \cdot (T_m - T_\infty)$$
$$Q = h_{\text{air}} A_i \cdot (T_m - T_s) \rightarrow T_s = T_m - \frac{U}{h_{\text{air}}} \cdot (T_m - T_\infty)$$

Geometria cilíndrica... variação axial da temperatura



$$Q = UA_i \cdot (T_m - T_\infty)$$

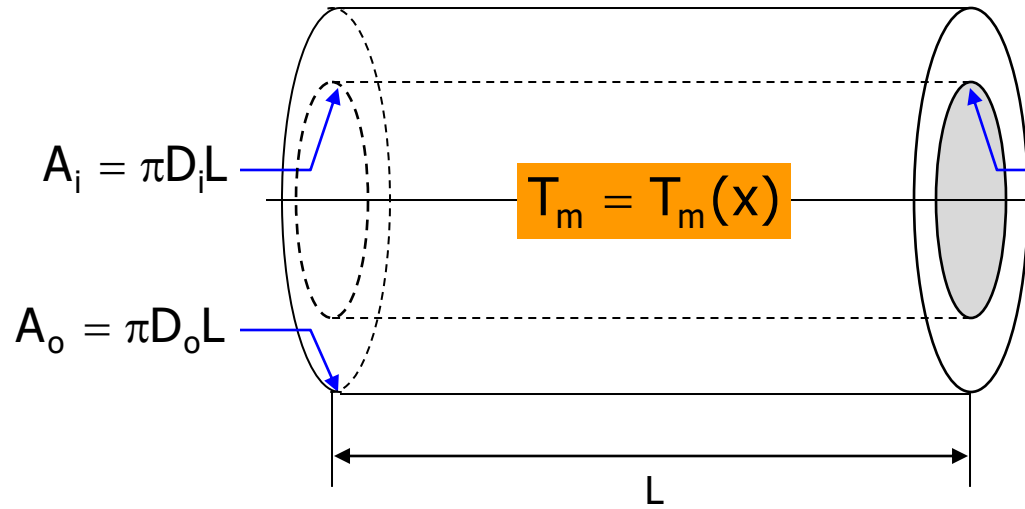
$$Q = h_{\text{air}} A_i \cdot (T_m - T_s)$$

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equação do
balanço global
de energia

$$\dot{m}C_p \cdot \frac{dT_m}{dx} - ph_{\text{air}} \cdot (T_s - T_m) = 0$$

Geometria cilíndrica... variação axial da temperatura



$$Q = UA_i \cdot (T_m - T_\infty)$$

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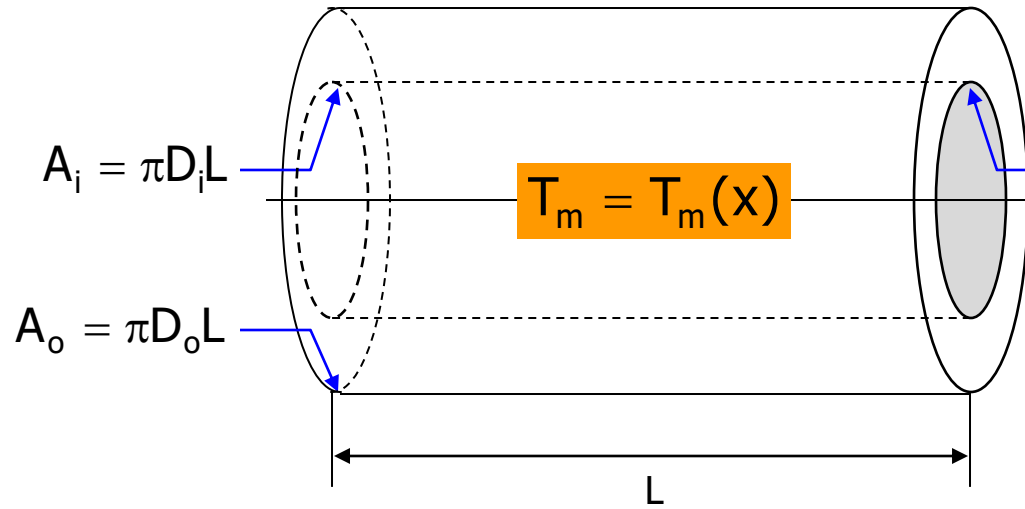
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Geometria cilíndrica... variação axial da temperatura



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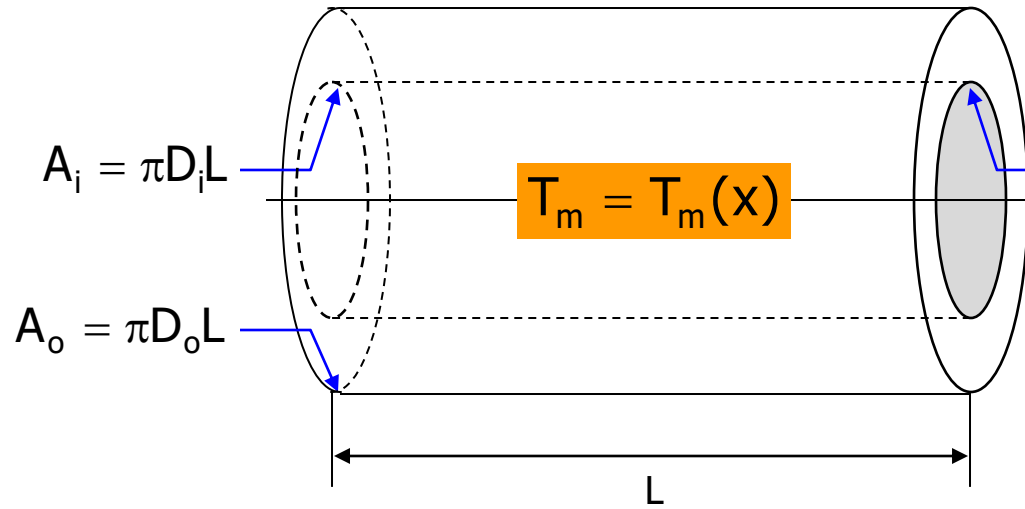


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Geometria cilíndrica... variação axial da temperatura



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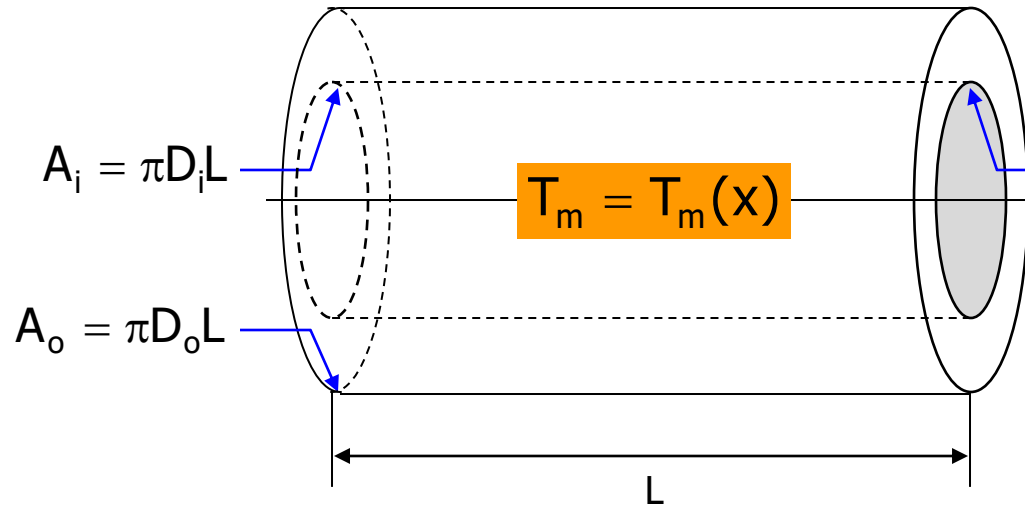
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Geometria cilíndrica... variação axial da temperatura



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equação do
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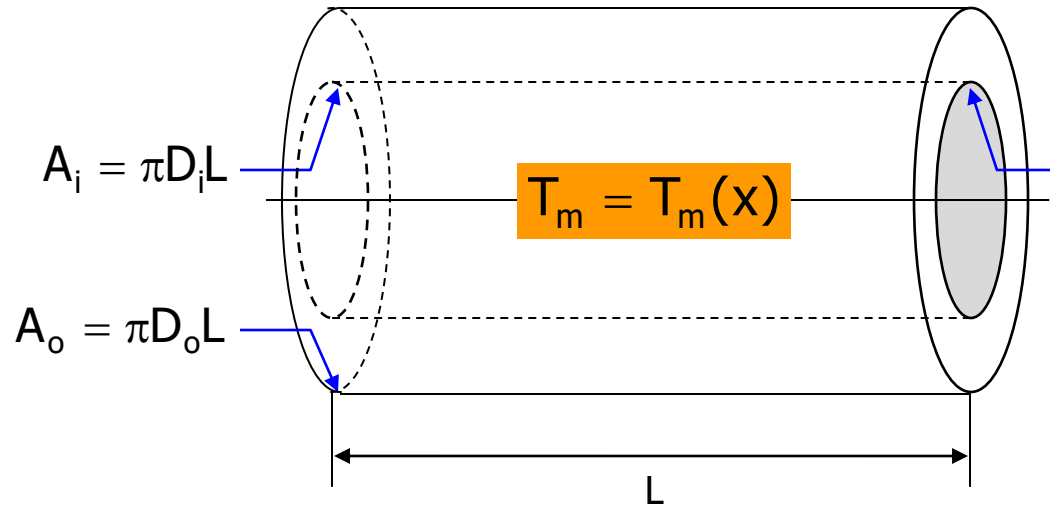
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$$\int_{T_{m,e}}^{T_{m,s}} \frac{d(T_m - T_\infty)}{T_m - T_\infty} = -\frac{pL}{\dot{m}C_p} \cdot \frac{1}{L} \int_0^L U dx$$

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$$\frac{T_{m,s} - T_\infty}{T_{m,e} - T_\infty} = \exp\left(-\frac{\bar{U}A}{\dot{m}C_p}\right)$$

... calculado @
temperatura axial
média

$$\frac{T_{m,s} - T_{\infty}}{T_{m,e} - T_{\infty}} = \exp\left(-\frac{\bar{U}A}{\dot{m}C_p}\right) \rightarrow$$

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Dittus-Boelter ?

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=cte

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Escoamento turbulento desenvolvido ($Re > 10^4$):

Superfície lisa:

$$Nu = 0.023 \cdot Re^{4/5} \cdot Pr^n$$

(Dittus-Boelter)

$$n = 0.3 \quad p / T_s < T_m$$

$$n = 0.4 \quad p / T_s > T_m$$

$$\left[\begin{array}{l} 0.7 \leq Pr \leq 160 \\ Re_D \geq 10,000 \\ \frac{L}{D} \geq 10 \end{array} \right]$$

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$$k = 26.247 \text{ mW/m/K} \quad Pr = 0.70729$$



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$$Re = \frac{\rho U D}{\mu} = \frac{\rho D}{\mu} \frac{V_i}{\pi D_i^2 / 4} = \frac{1.1688 \cdot 0.15}{18.448 \cdot 10^{-6}} \cdot \frac{0.025}{\pi \cdot 0.15^2 / 4} = 1.344 \cdot 10^4$$



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$$Nu = 0.023 \cdot Re^{4/5} \cdot Pr^{0.3} = 0.023 \cdot (1.344 \cdot 10^4)^{4/5} \cdot (0.70729)^{0.4} = 40.206$$



$$\frac{T_{m,s} - T_{\infty}}{T_{m,e} - T_{\infty}} = \exp\left(-\frac{\bar{U}A}{\dot{m}C_p}\right) \rightarrow$$

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Dittus-Boelter ?

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$$Nu = \frac{h_i D_i}{k} \rightarrow h_i = \frac{26.247 \cdot 10^{-3} \cdot 40.206}{0.15} = 7.035 \frac{\text{W}}{\text{m}^2 \text{K}}$$

$$\frac{T_{m,s} - T_{\infty}}{T_{m,e} - T_{\infty}} = \exp\left(-\frac{\bar{U}A}{\dot{m}C_p}\right) \rightarrow$$

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$$7.035 \frac{\text{W}}{\text{m}^2 \text{K}}$$

$$0.15 \frac{\text{W}}{\text{mK}}$$

$$1500 \frac{\text{W}}{\text{m}^2 \text{K}}$$

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$$7.035 \frac{W}{m^2 K}$$

$$0.15 \frac{W}{mK}$$

$$1500 \frac{W}{m^2 K}$$

$$(\bar{U}A_i)^{-1} = \frac{1}{\pi L} \left(\frac{1}{7.035 \cdot 0.15} + \frac{1}{2 \cdot 0.15} \ln\left(\frac{0.17}{0.15}\right) + \frac{1}{1500 \cdot 0.17} \right) \rightarrow \bar{U}A_i = 2.295 \cdot L$$

$$\frac{T_{m,s} - T_{\infty}}{T_{m,e} - T_{\infty}} = \exp\left(-\frac{\bar{U}A}{\dot{m}C_p}\right) \rightarrow$$

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$$L = 13.88 \text{ m}$$

Considerando propriedades termofísicas variáveis...

$$Re = \frac{\rho u_0 D}{\mu}$$

$$Pr = \frac{C_p \mu}{k}$$

Balço global de energia...

$$\dot{m} \cdot \frac{dh_m}{dx} - ph_{conv} \cdot (T_s - T_m) = 0$$

Soluço direta via mto numrico de
soluço de equaço diferencial

$$h = h(P, T) \downarrow$$

Implementaço numrica...

Soluço analtica a partir de hipoteses
simplificadoras

$$h = C_p \cdot T \downarrow \begin{array}{l} \text{gases perfeitos} \\ \text{"fluido incompressvel"} (C_p=C_v) \end{array}$$

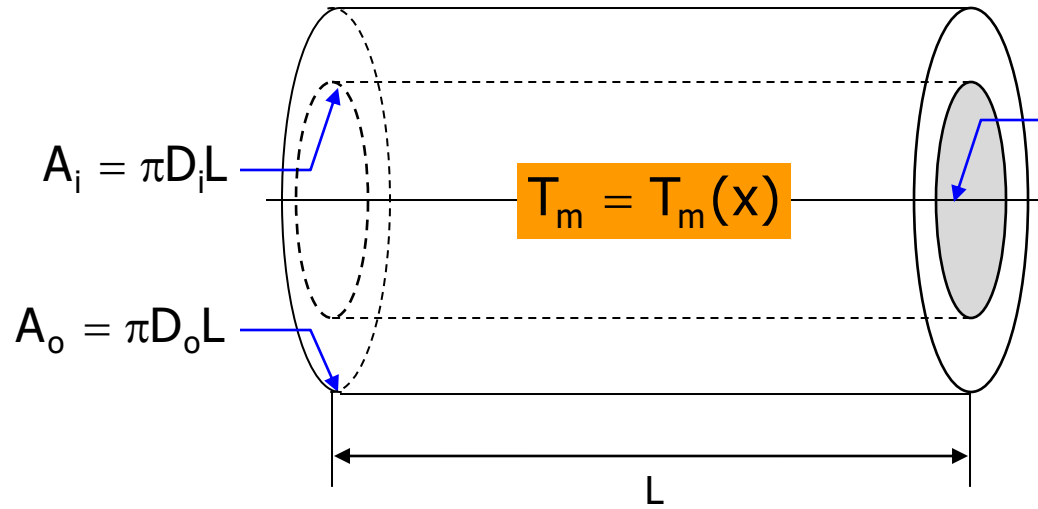
$$\dot{m} \cdot \frac{dT_m}{dx} - \frac{ph_{conv}}{C_p} \cdot (T_s - T_m) = 0$$



$$\mu = \mu(P, T), \dots \downarrow$$

Implementaço numrica...

Geometria cilíndrica... variação axial da temperatura



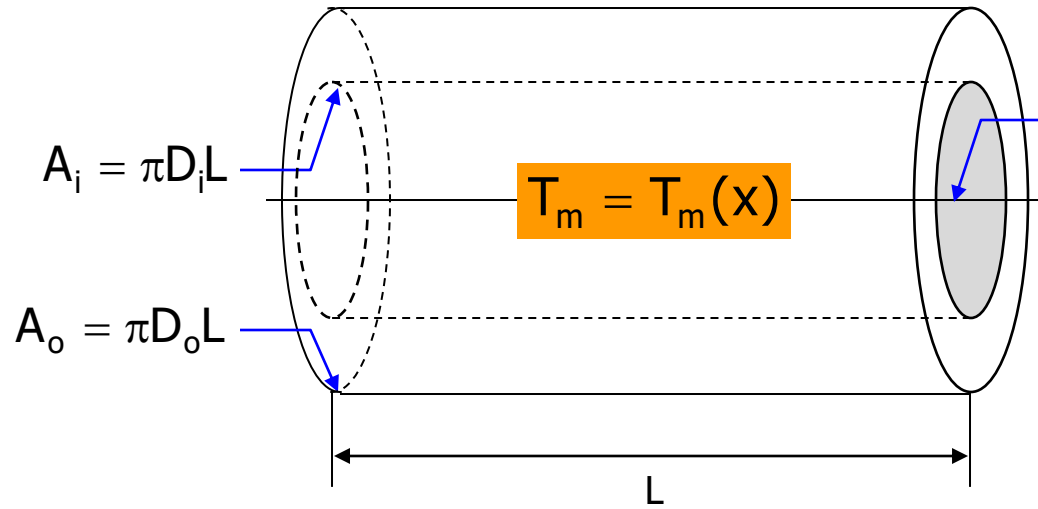
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Eliminada T_s da eq.



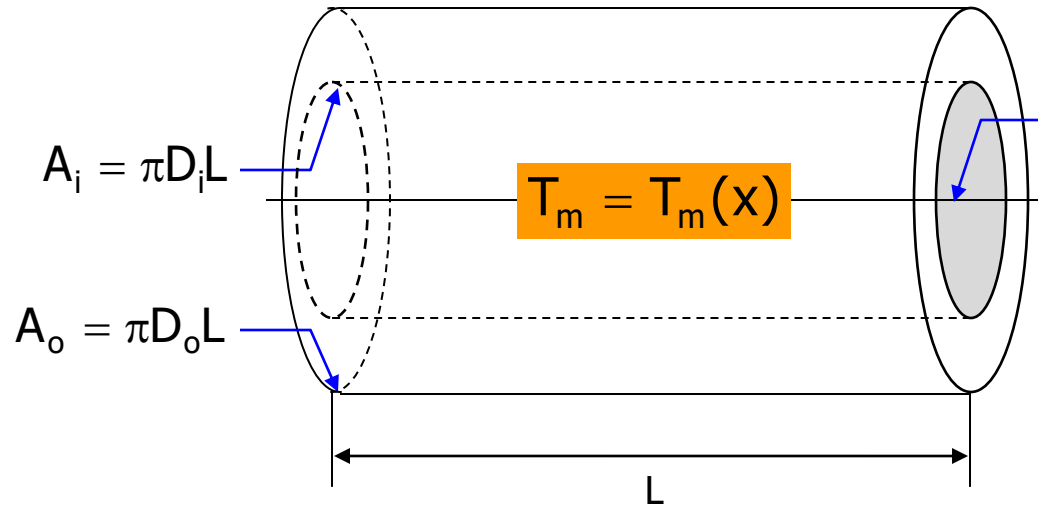
Geometria cilíndrica... variação axial da temperatura



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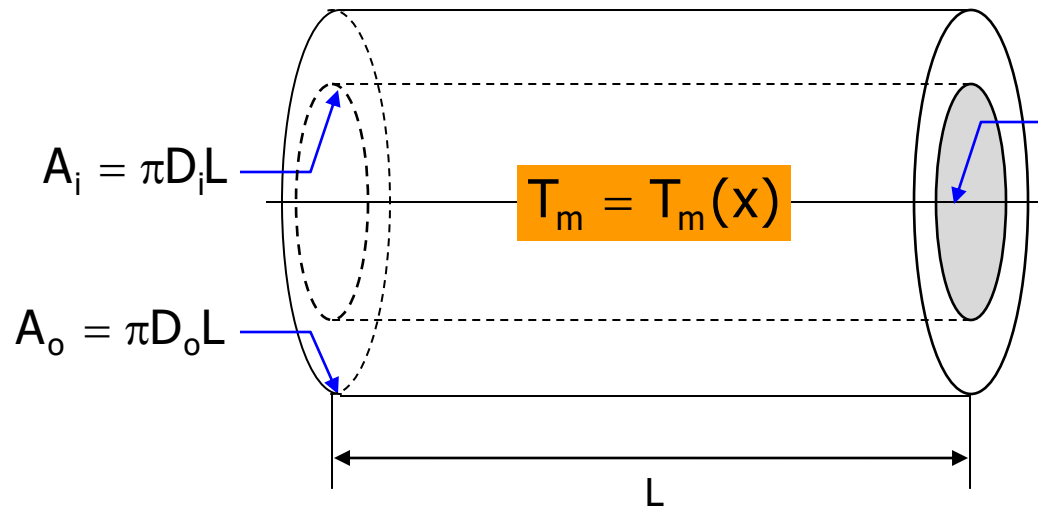
Dittus-Boelter

=cte

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Dittus-Boelter

$$Nu = 0.023 \cdot Re^{4/5} \cdot Pr^n$$

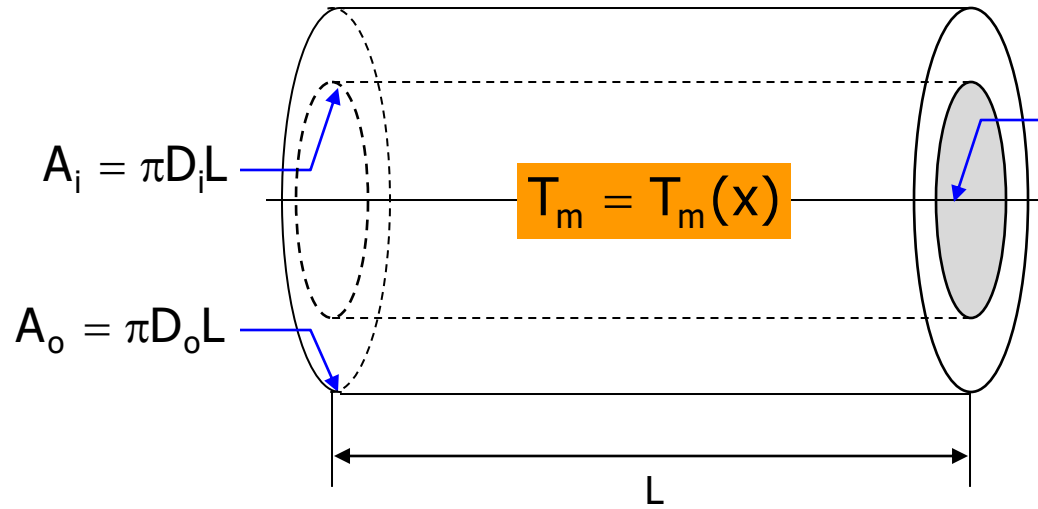
$$Re = \frac{\rho U_0 D}{\mu} \Big|_{T_m}$$

$$Pr = \frac{C_p \mu}{k} \Big|_{T_m}$$

=cte

=cte

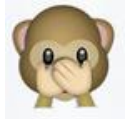
Geometria cilíndrica... variação axial da temperatura



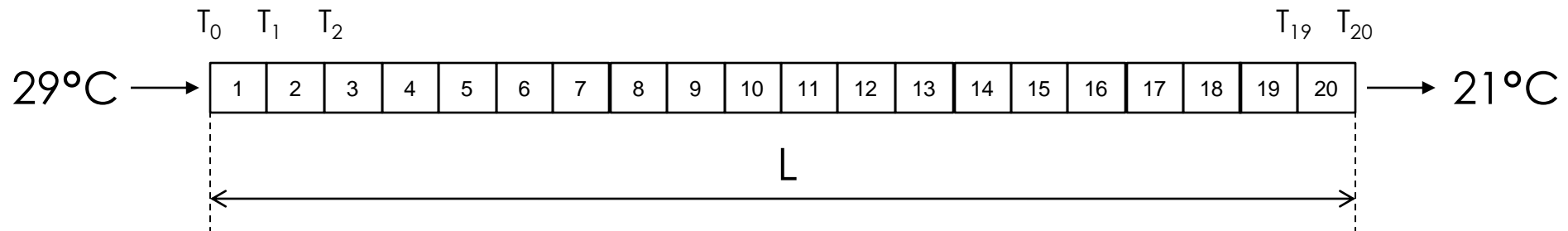
$$\dot{m} C_p \cdot \frac{dT_m}{dx} + pU \cdot (T_m - T_\infty) = 0$$

$$\frac{dT_m}{dx} + \alpha(T_m) \cdot (T_m - T_\infty) = 0 \quad \alpha(T_m) = \frac{p}{\dot{m}} \frac{U(T_m)}{C_p(T_m)}$$


$$\frac{T_{m,j+1} - T_{m,j}}{dx} + \alpha_j \cdot (T_{m,j} - T_\infty) = 0$$

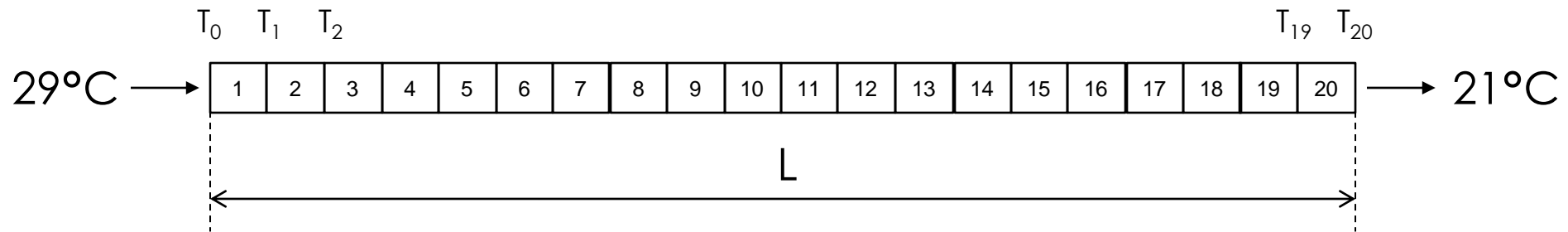
$$T_{m,j+1} = T_{m,j} - \alpha_j \cdot (T_{m,j} - T_\infty) \cdot dx$$


8.31: Para resfriar uma casa de verão sem uso de um ciclo frigorífico, ar é encaminhado através de uma tubulação de plástico ($k=0.15\text{W/m/K}$, $D_i=0.15\text{m}$, $D_o=0.17\text{m}$) submersa em um corpo d'água adjacente. A temperatura da água é normalmente de $T_\infty=17^\circ\text{C}$, e o coeficiente de convecção é mantido em $h_o=1500\text{ W/m}^2/\text{K}$ na superfície externa da tubulação. Se ar proveniente da casa entra no tubo a uma temperatura de $T_{m,i}=29^\circ\text{C}$ e uma vazão volumétrica de $V_i=0.025\text{m}^3/\text{s}$, qual extensão L é necessária para que a temperatura na saída seja de $T_{m,o}=21^\circ\text{C}$?



$$T_{m,j+1} = T_{m,j} - \alpha_j \cdot (T_{m,j} - T_\infty) \cdot dx \rightarrow$$

8.31: Para resfriar uma casa de verão sem uso de um ciclo frigorífico, ar é encaminhado através de uma tubulação de plástico ($k=0.15\text{W/m/K}$, $D_i=0.15\text{m}$, $D_o=0.17\text{m}$) submersa em um corpo d'água adjacente. A temperatura da água é normalmente de $T_\infty=17^\circ\text{C}$, e o coeficiente de convecção é mantido em $h_o=1500\text{ W/m}^2/\text{K}$ na superfície externa da tubulação. Se ar proveniente da casa entra no tubo a uma temperatura de $T_{m,i}=29^\circ\text{C}$ e uma vazão volumétrica de $V_i=0.025\text{m}^3/\text{s}$, qual extensão L é necessária para que a temperatura na saída seja de $T_{m,o}=21^\circ\text{C}$?



$$T_{m,j+1} = T_{m,j} - \alpha_j \cdot (T_{m,j} - T_\infty) \cdot dx \rightarrow \begin{cases} T_{m,1} = T_{m,0} - \alpha_0 \cdot (T_{m,0} - T_\infty) \cdot dx \\ T_{m,2} = T_{m,1} - \alpha_1 \cdot (T_{m,1} - T_\infty) \cdot dx \\ T_{m,3} = T_{m,2} - \alpha_2 \cdot (T_{m,2} - T_\infty) \cdot dx \\ \vdots \\ T_{m,20} = T_{m,19} - \alpha_{19} \cdot (T_{m,19} - T_\infty) \cdot dx \end{cases}$$



Salvamento Automático | exemplo aula TC3.xlsm - Excel | Entrar | Compartilhar

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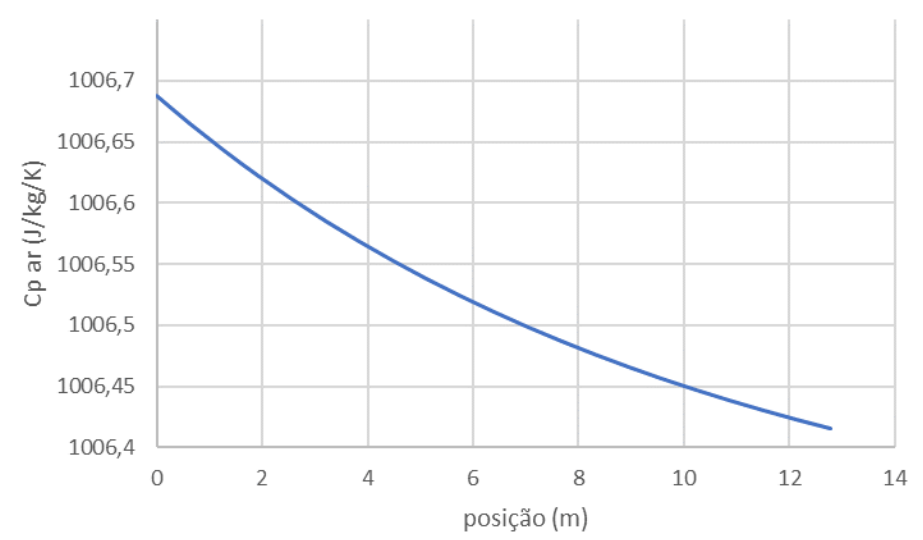
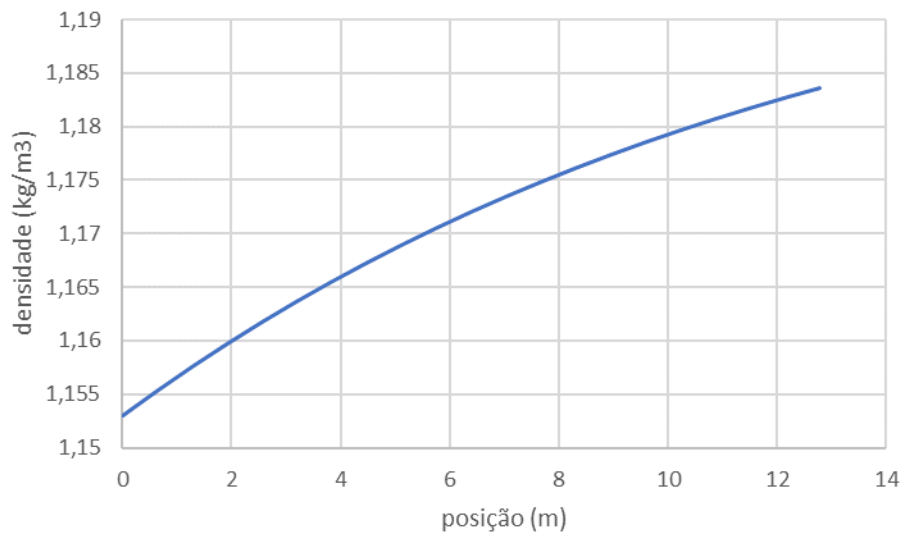
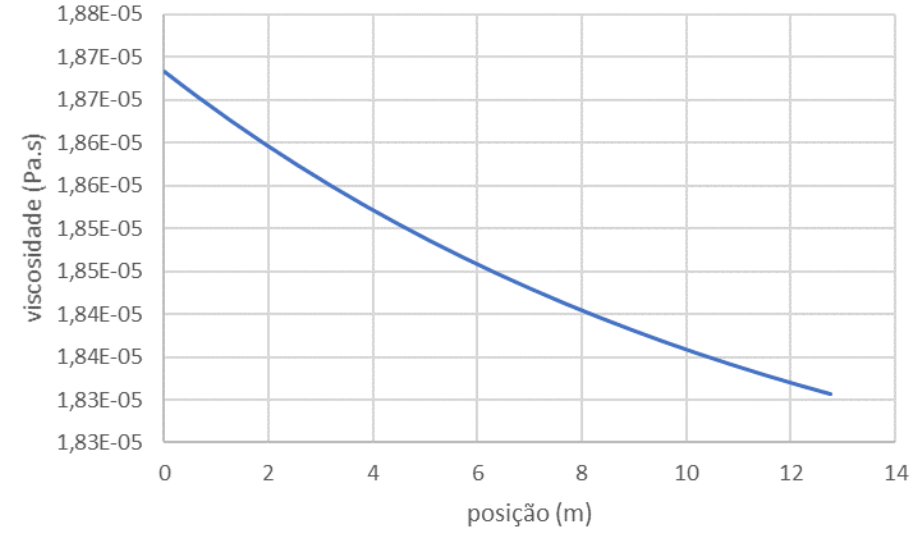
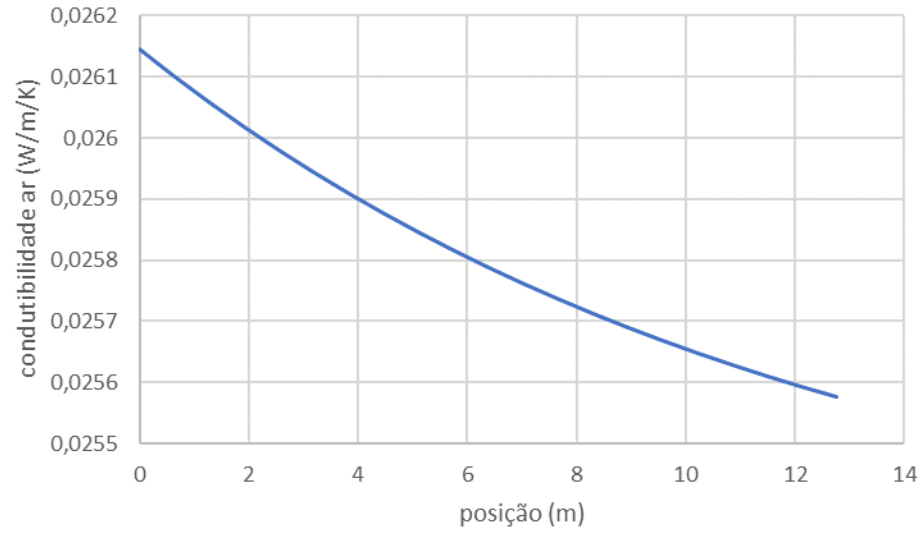
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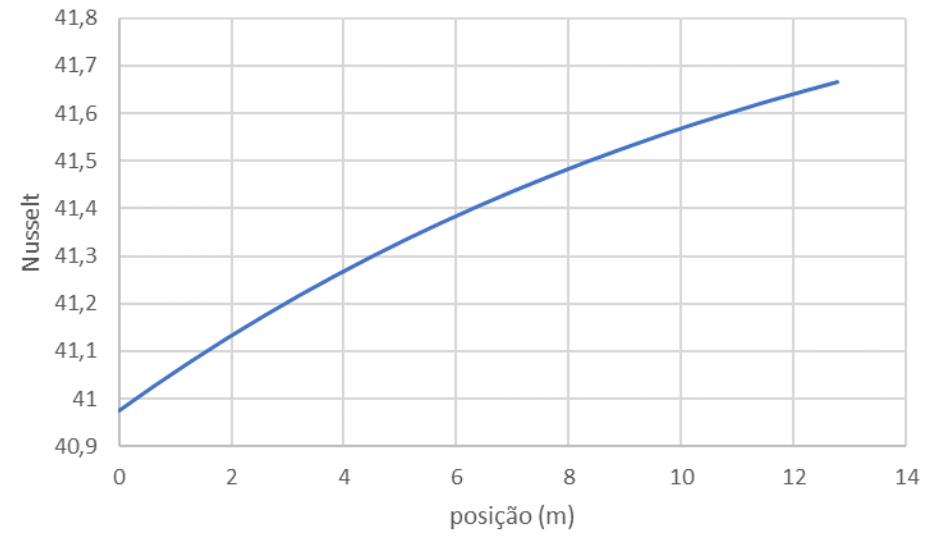
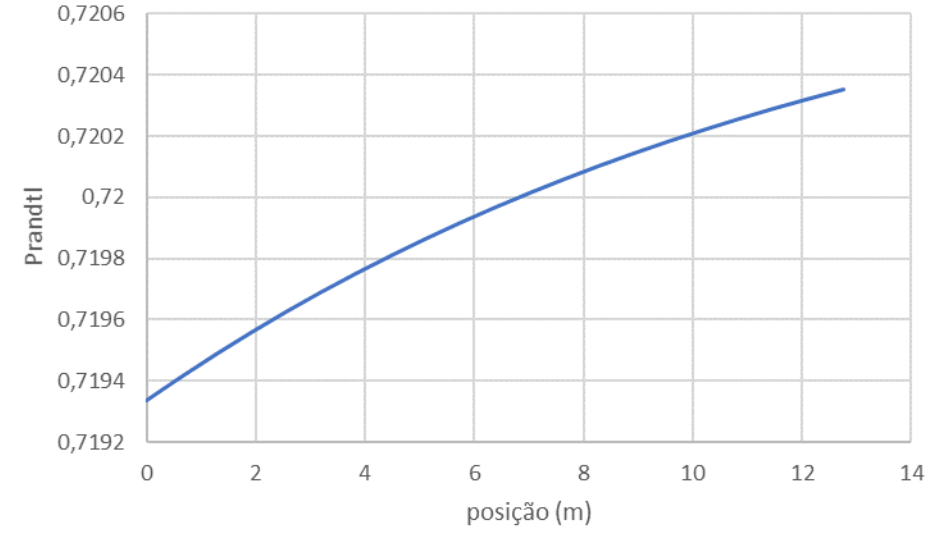
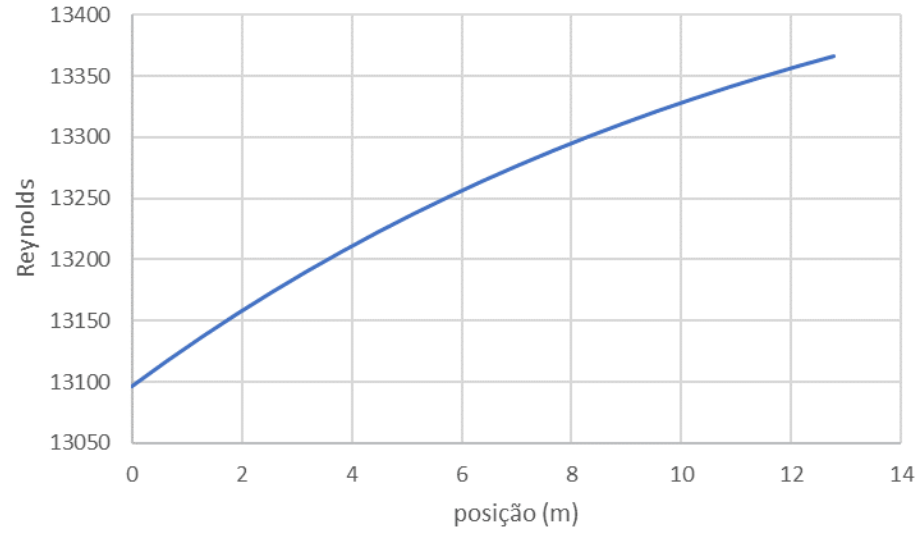
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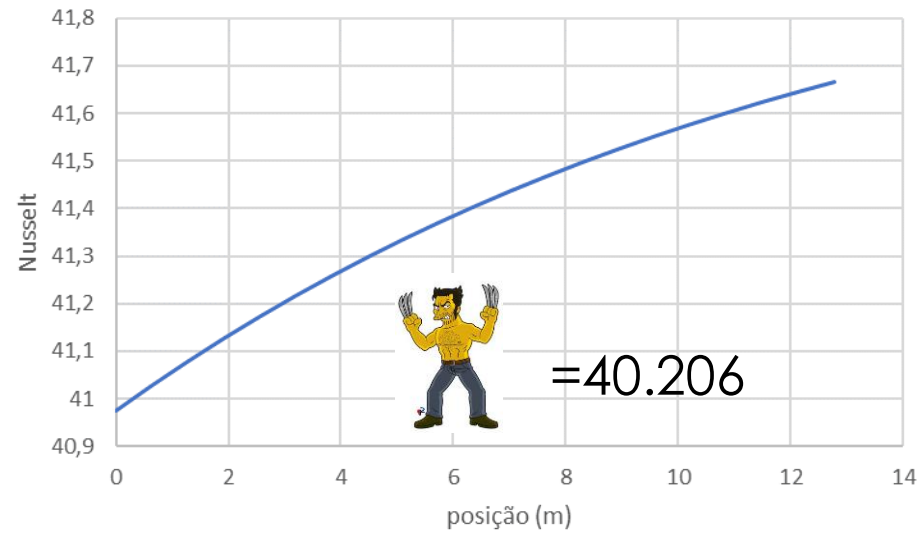
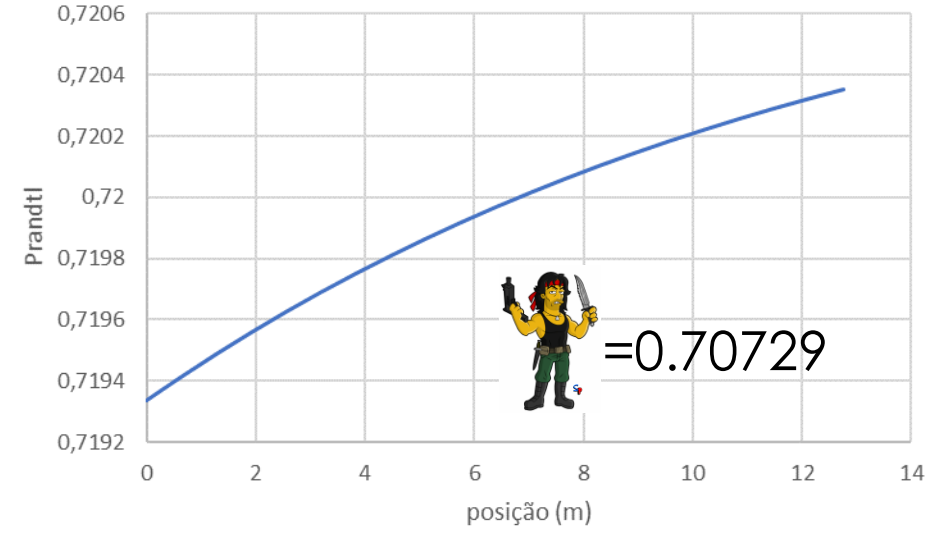
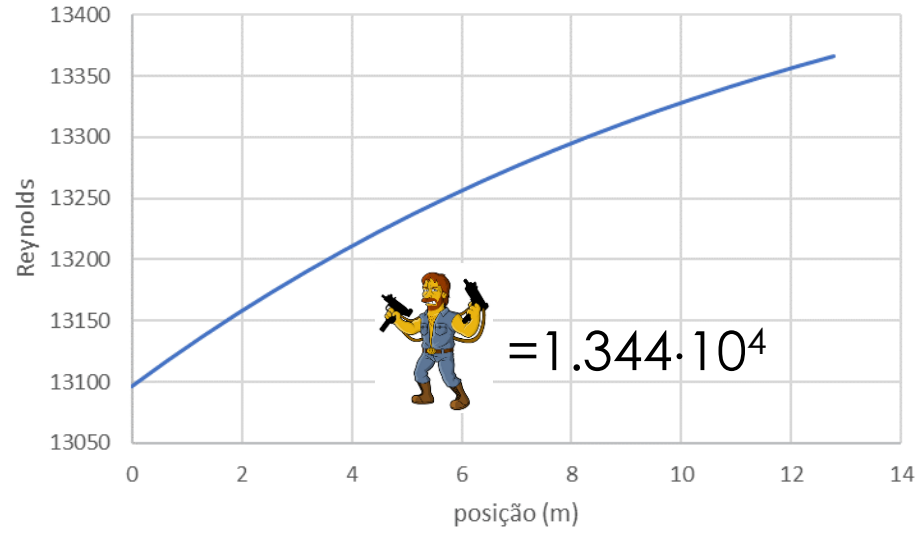
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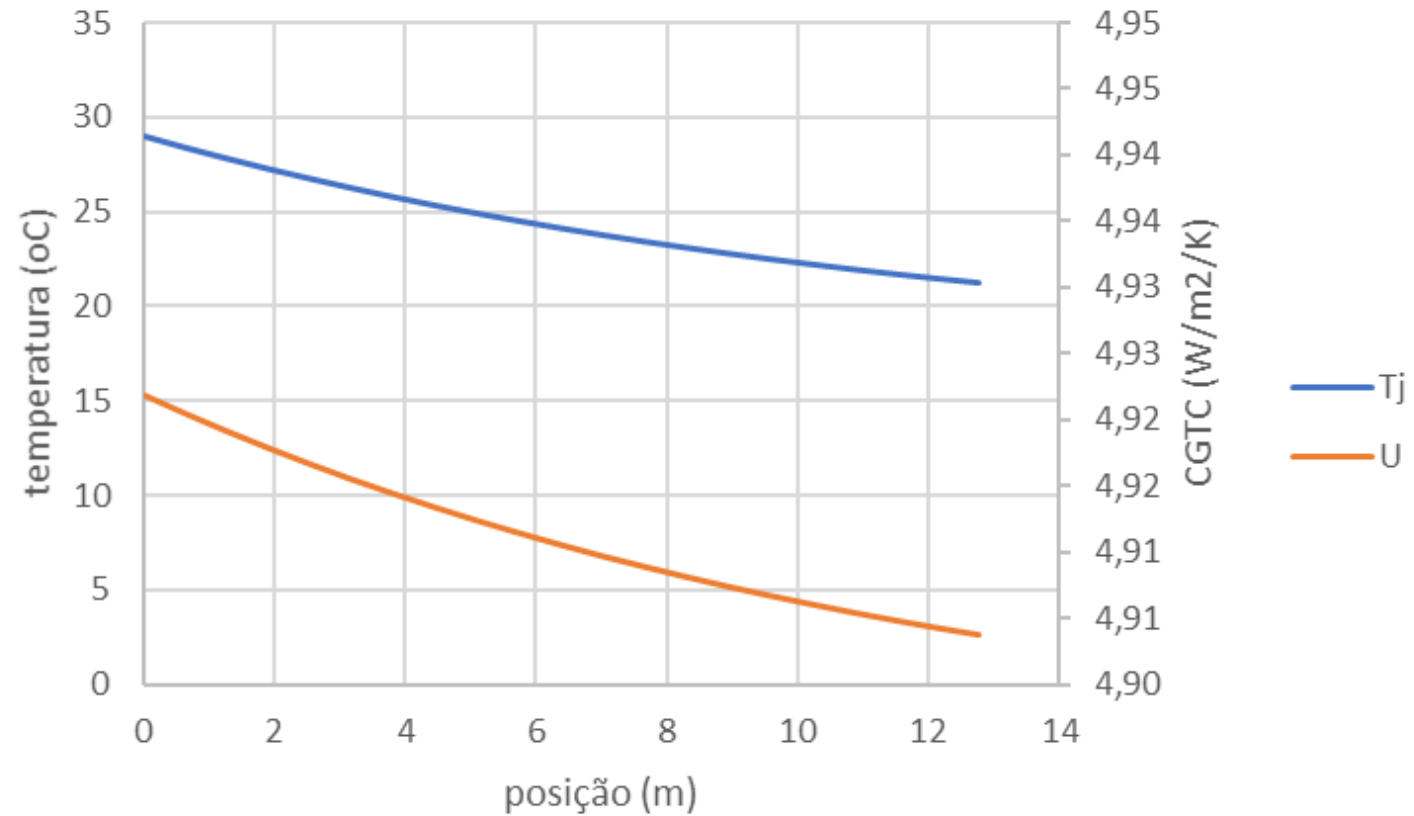
| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T |
|----|---------|--------------|---|---|---------|-------|---------|---------|---------|--------------|---------|---------|---------|---------|---------|---------|---------|-------------|---------|---|
| 1 | P | 1 bar | | | posição | x | Tj | ρ | U (m/s) | μ (Pa.s) | kar | Cp | Re | Pr | Nu | hi | U | $\alpha(T)$ | Tj+1 | |
| 2 | ho | 1500 W/m2/K | | | 0 | 0 | 29 | 1,15301 | 1,41471 | 1,8683E-05 | 0,02615 | 1006,69 | 13096,2 | 0,71934 | 40,9754 | 7,14239 | 4,92177 | 0,07993 | 28,3574 | |
| 3 | k | 0,15 W/m/K | | | 1 | 0,67 | 28,3574 | 1,15548 | 1,41169 | 1,8652E-05 | 0,0261 | 1006,66 | 13117,9 | 0,71942 | 41,0312 | 7,13928 | 4,92029 | 0,0799 | 27,7494 | |
| 4 | Di | 0,15 m | | | 2 | 1,34 | 27,7494 | 1,15782 | 1,40884 | 1,8623E-05 | 0,02606 | 1006,64 | 13138,6 | 0,71949 | 41,0842 | 7,13634 | 4,9189 | 0,07988 | 27,174 | |
| 5 | Do | 0,17 m | | | 3 | 2,01 | 27,174 | 1,16004 | 1,40614 | 1,8595E-05 | 0,02601 | 1006,62 | 13158,2 | 0,71957 | 41,1345 | 7,13355 | 4,91757 | 0,07986 | 26,6296 | |
| 6 | Tinf | 17 oC | | | 4 | 2,68 | 26,6296 | 1,16215 | 1,40358 | 1,8569E-05 | 0,02597 | 1006,6 | 13176,8 | 0,71964 | 41,1823 | 7,13091 | 4,91631 | 0,07985 | 26,1145 | |
| 7 | Tmi | 29 oC | | | 5 | 3,35 | 26,1145 | 1,16416 | 1,40117 | 1,8544E-05 | 0,02594 | 1006,58 | 13194,5 | 0,7197 | 41,2276 | 7,1284 | 4,91512 | 0,07983 | 25,627 | |
| 8 | Vz @ i | 0,025 m3/s | | | 6 | 4,02 | 25,627 | 1,16606 | 1,39888 | 1,852E-05 | 0,0259 | 1006,56 | 13211,3 | 0,71977 | 41,2707 | 7,12603 | 4,91399 | 0,07981 | 25,1657 | |
| 9 | VzM @ i | 0,02883 kg/s | | | 7 | 4,69 | 25,1657 | 1,16787 | 1,39671 | 1,8498E-05 | 0,02587 | 1006,55 | 13227,2 | 0,71983 | 41,3116 | 7,12378 | 4,91292 | 0,07979 | 24,7291 | |
| 10 | | | | | 8 | 5,36 | 24,7291 | 1,16959 | 1,39466 | 1,8477E-05 | 0,02583 | 1006,53 | 13242,4 | 0,71989 | 41,3504 | 7,12164 | 4,91191 | 0,07978 | 24,316 | |
| 11 | | | | | 9 | 6,03 | 24,316 | 1,17122 | 1,39272 | 1,8457E-05 | 0,0258 | 1006,52 | 13256,7 | 0,71994 | 41,3872 | 7,11962 | 4,91095 | 0,07976 | 23,925 | |
| 12 | Tmo | 21 oC | | | 10 | 6,7 | 23,925 | 1,17276 | 1,39089 | 1,8438E-05 | 0,02578 | 1006,5 | 13270,4 | 0,71999 | 41,4221 | 7,11771 | 4,91004 | 0,07975 | 23,555 | |
| 13 | L | 13,4 m | | | 11 | 7,37 | 23,555 | 1,17423 | 1,38915 | 1,842E-05 | 0,02575 | 1006,49 | 13283,3 | 0,72004 | 41,4553 | 7,1159 | 4,90917 | 0,07974 | 23,2048 | |
| 14 | N | 20 nd | | | 12 | 8,04 | 23,2048 | 1,17562 | 1,38751 | 1,8403E-05 | 0,02572 | 1006,48 | 13295,6 | 0,72009 | 41,4867 | 7,11418 | 4,90836 | 0,07973 | 22,8733 | |
| 15 | dx | 0,67 m | | | 13 | 8,71 | 22,8733 | 1,17694 | 1,38595 | 1,8387E-05 | 0,0257 | 1006,47 | 13307,2 | 0,72013 | 41,5165 | 7,11255 | 4,90758 | 0,07971 | 22,5597 | |
| 16 | | | | | 14 | 9,38 | 22,5597 | 1,17819 | 1,38448 | 1,8372E-05 | 0,02567 | 1006,46 | 13318,2 | 0,72017 | 41,5448 | 7,11101 | 4,90685 | 0,0797 | 22,2628 | |
| 17 | | | | | 15 | 10,05 | 22,2628 | 1,17938 | 1,38308 | 1,8357E-05 | 0,02565 | 1006,45 | 13328,7 | 0,72021 | 41,5716 | 7,10955 | 4,90615 | 0,07969 | 21,9818 | |
| 18 | | | | | 16 | 10,72 | 21,9818 | 1,18051 | 1,38176 | 1,8343E-05 | 0,02563 | 1006,44 | 13338,6 | 0,72025 | 41,597 | 7,10817 | 4,9055 | 0,07968 | 21,7158 | |
| 19 | | | | | 17 | 11,39 | 21,7158 | 1,18157 | 1,38051 | 1,8331E-05 | 0,02561 | 1006,43 | 13348,1 | 0,72029 | 41,6211 | 7,10686 | 4,90487 | 0,07967 | 21,4641 | |
| 20 | | | | | 18 | 12,06 | 21,4641 | 1,18259 | 1,37933 | 1,8318E-05 | 0,02559 | 1006,42 | 13357 | 0,72032 | 41,644 | 7,10562 | 4,90428 | 0,07966 | 21,2258 | |
| 21 | | | | | 19 | 12,73 | 21,2258 | 1,18355 | 1,37821 | 1,8307E-05 | 0,02558 | 1006,42 | 13365,4 | 0,72035 | 41,6656 | 7,10444 | 4,90372 | 0,07966 | 21,0003 | |
| 22 | | | | | 20 | 13,4 | 21,0003 | 1,18446 | 1,37716 | 1,8296E-05 | 0,02556 | 1006,41 | 13373,5 | 0,72038 | 41,6861 | 7,10333 | 4,90319 | 0,07965 | 20,7868 | |
| 23 | | | | | | | | | | | | | | | | | | | | |
| 24 | | | | | | | | | | | | | | | | | | | | |
| 25 | | | | | | | | | | | | | | | | | | | | |
| 26 | | | | | | | | | | | | | | | | | | | | |



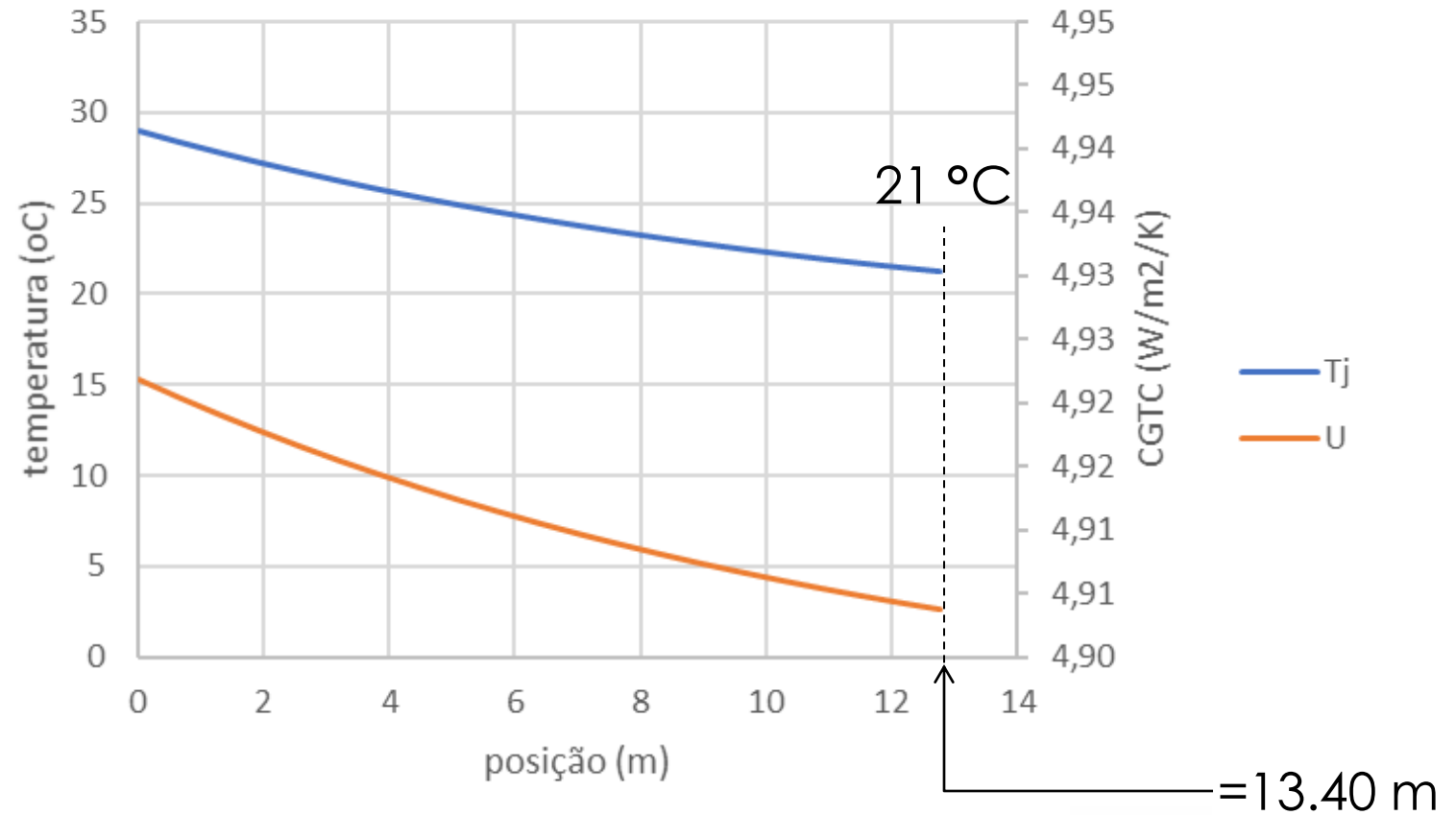




Tutorial: montagem da planilha de simulação...



Tutorial: montagem da planilha de simulação...



=13.88 m



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