Universidade de São Paulo
Escola de Engenharia de São Carlos

SEM0551 Fenômenos de Transporte

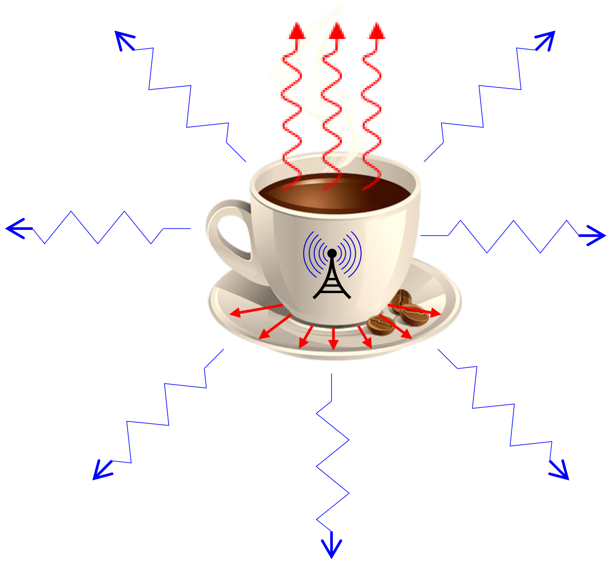
ESCOAMENTOS E CONVECÇÃO DE CALOR

Paulo Seleghim Jr.
Universidade de São Paulo

ANTES PORÉM:

RESISTÊNCIA TÉRMICA...

DEFINIÇÃO DE UMA RESISTÊNCIA TÉRMICA → CIRCUITOS TÉRMICOS EQUIVALENTES



Condução de calor: lei de Fourier

$$Q = k \cdot A \cdot \Delta T / L$$

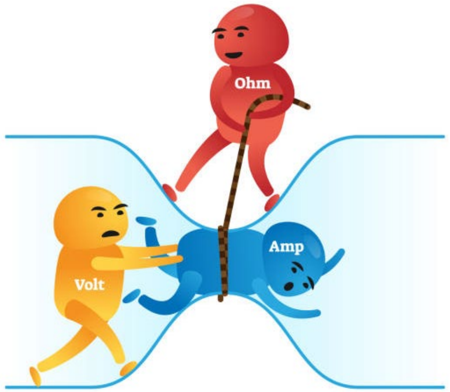
Convecção de calor: lei de Newton

$$Q = h \cdot A \cdot \Delta T$$

Radiação de calor: lei de Stefan–Boltzmann

$$Q = \sigma \cdot A \cdot \Sigma(T^4 - T_\infty^4) \rightarrow Q = \bar{h}_{rad} \cdot A \cdot \Delta T$$

DEFINIÇÃO DE UMA RESISTÊNCIA TÉRMICA → CIRCUITOS TÉRMICOS EQUIVALENTES



$$R_{elec} = \frac{\Delta V}{i}$$

$$\boxed{R_{term} = \frac{\Delta T}{Q}}$$

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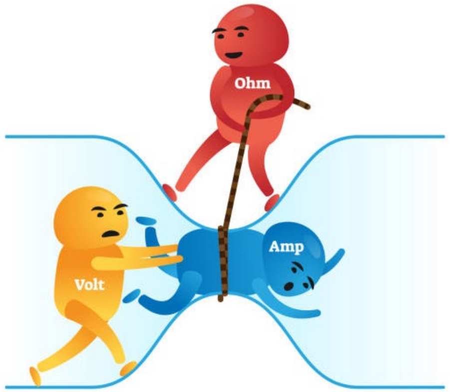

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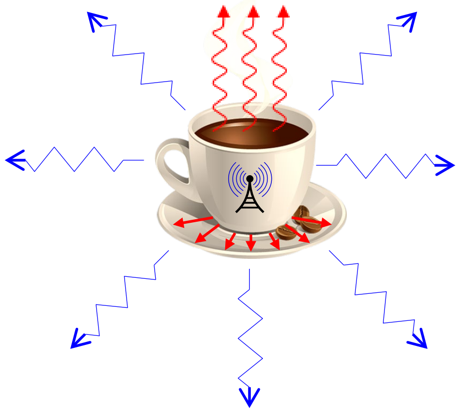

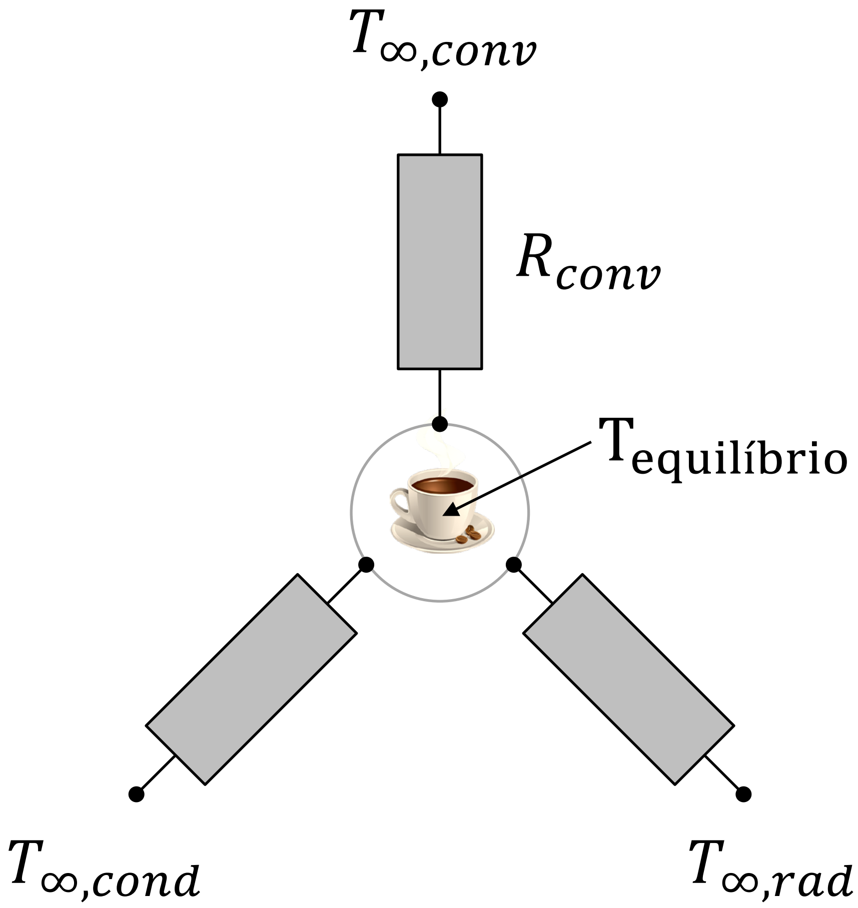

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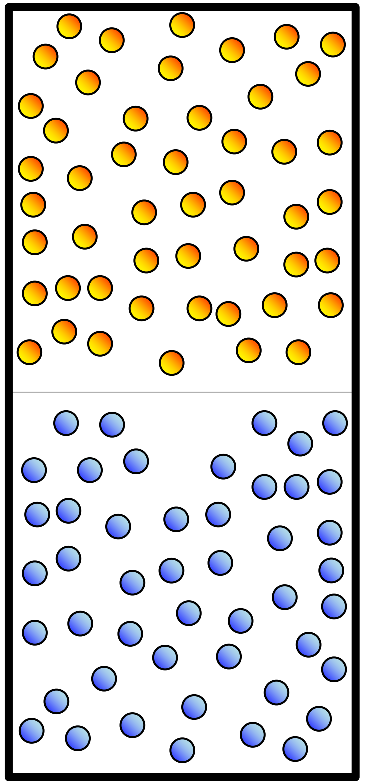
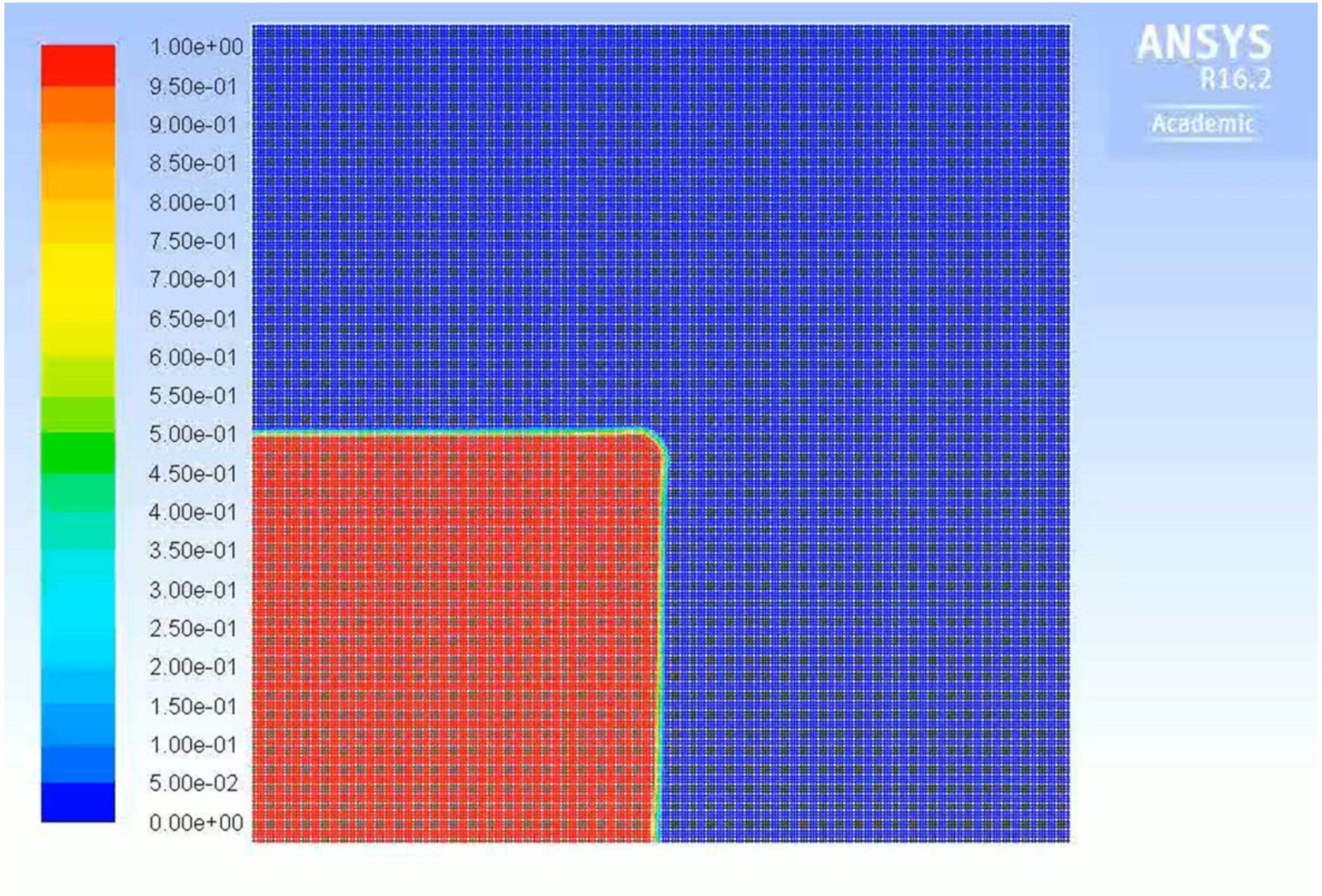
CONVECÇÃO NATURAL × CONVECÇÃO FORÇADA...

movimentação do fluido ↔ transporte de energia térmica

difusão



convecção



Contours of Volume fraction (phase-2) (Time=5.0000e-02) Mar 07, 2016
ANSYS Fluent Release 16.2 (2d, dp, pbns, vof, lam, transient)

Jingwei Zhu
26 subscribers

Oil-red; water-blue
Software: ANSYS Fluent
Oil density: 900kg/m3; viscosity: 0.1kg/m-s
Water density: 1000kg/m3; viscosity: 0.005kg/m-s

https://youtu.be/kNiUPuRLCXw

YouTube
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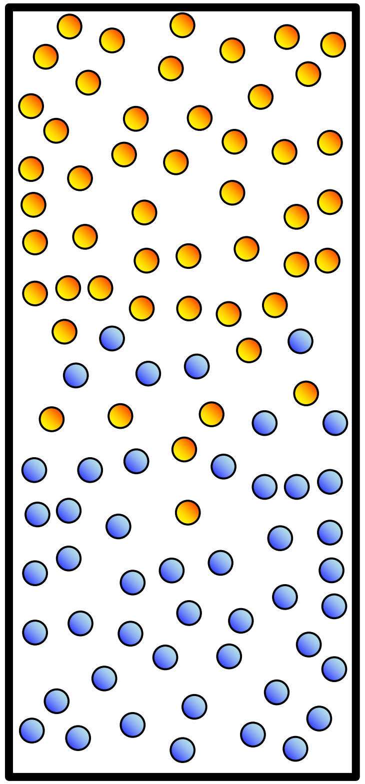
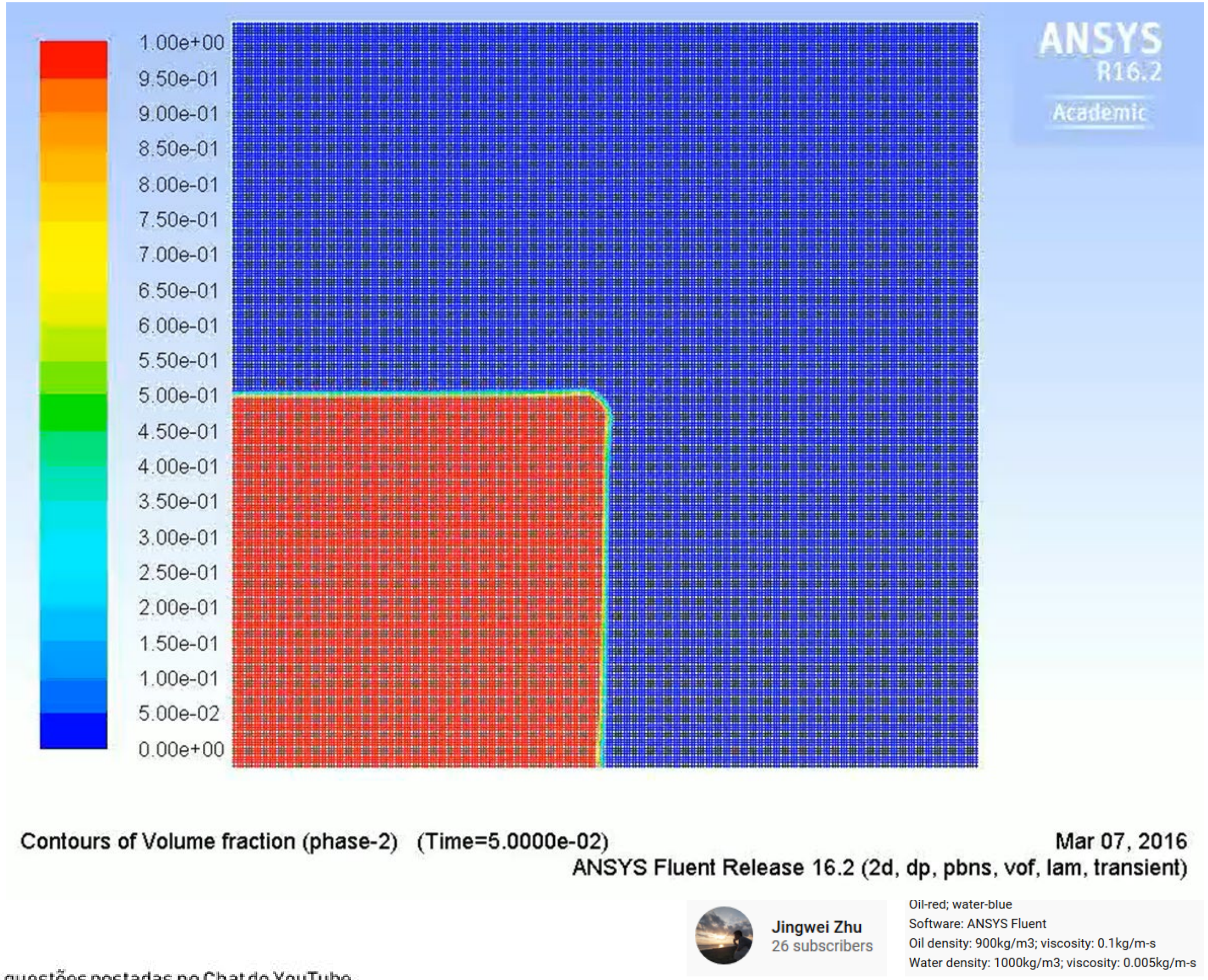
difusão



convecção



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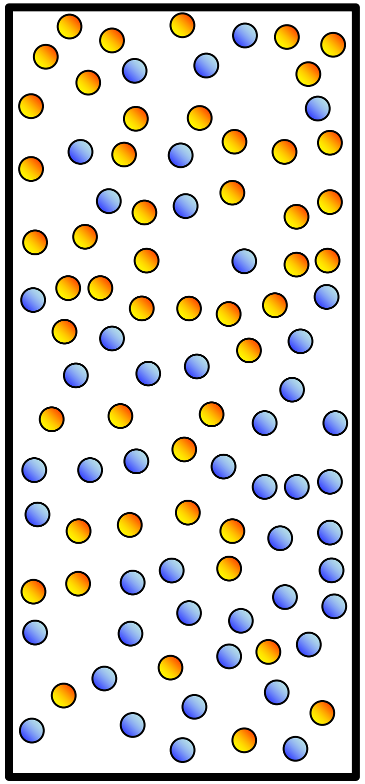
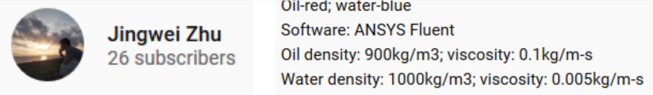


convecção

$$FM = -D\vec{\nabla}C$$

lei de Fick:



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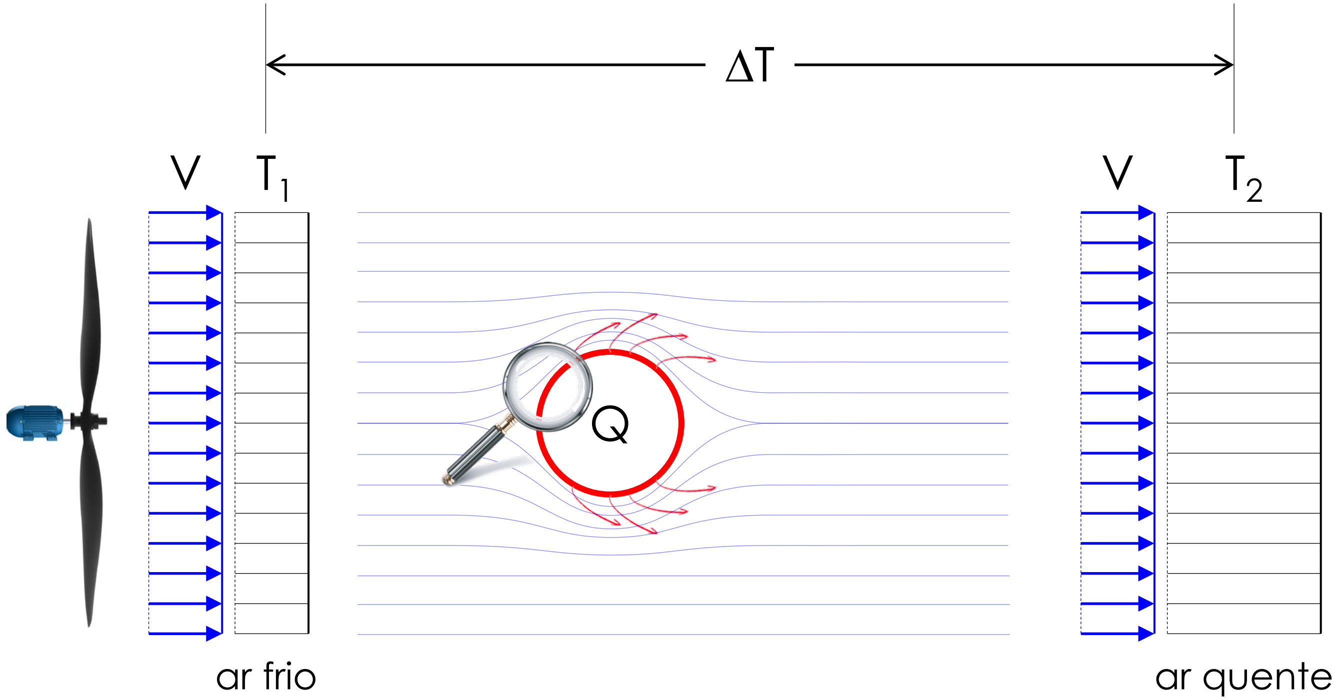
Convecção natural × convecção forçada...

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



Estes são os efeitos globais. Qual é o mecanismo de transferência de calor da resistência para o ar ? (Efeitos locais)

$$\Delta E_{Cin} = 0$$

$$\Delta E_{Ter} = Q \;= \dot{m}_{ar} C_{P,ar} \Delta T$$

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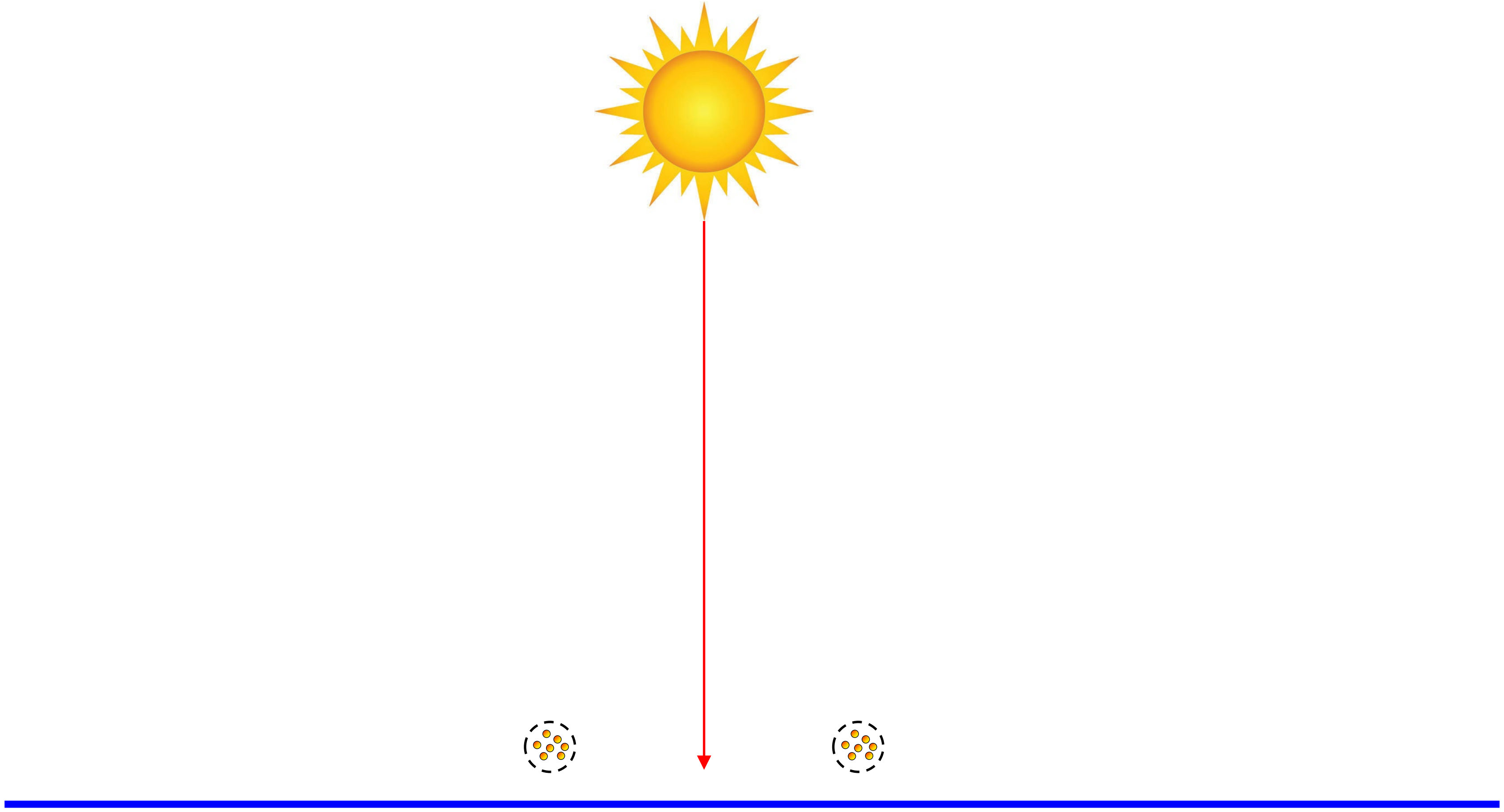
Convecção natural × convecção forçada...

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



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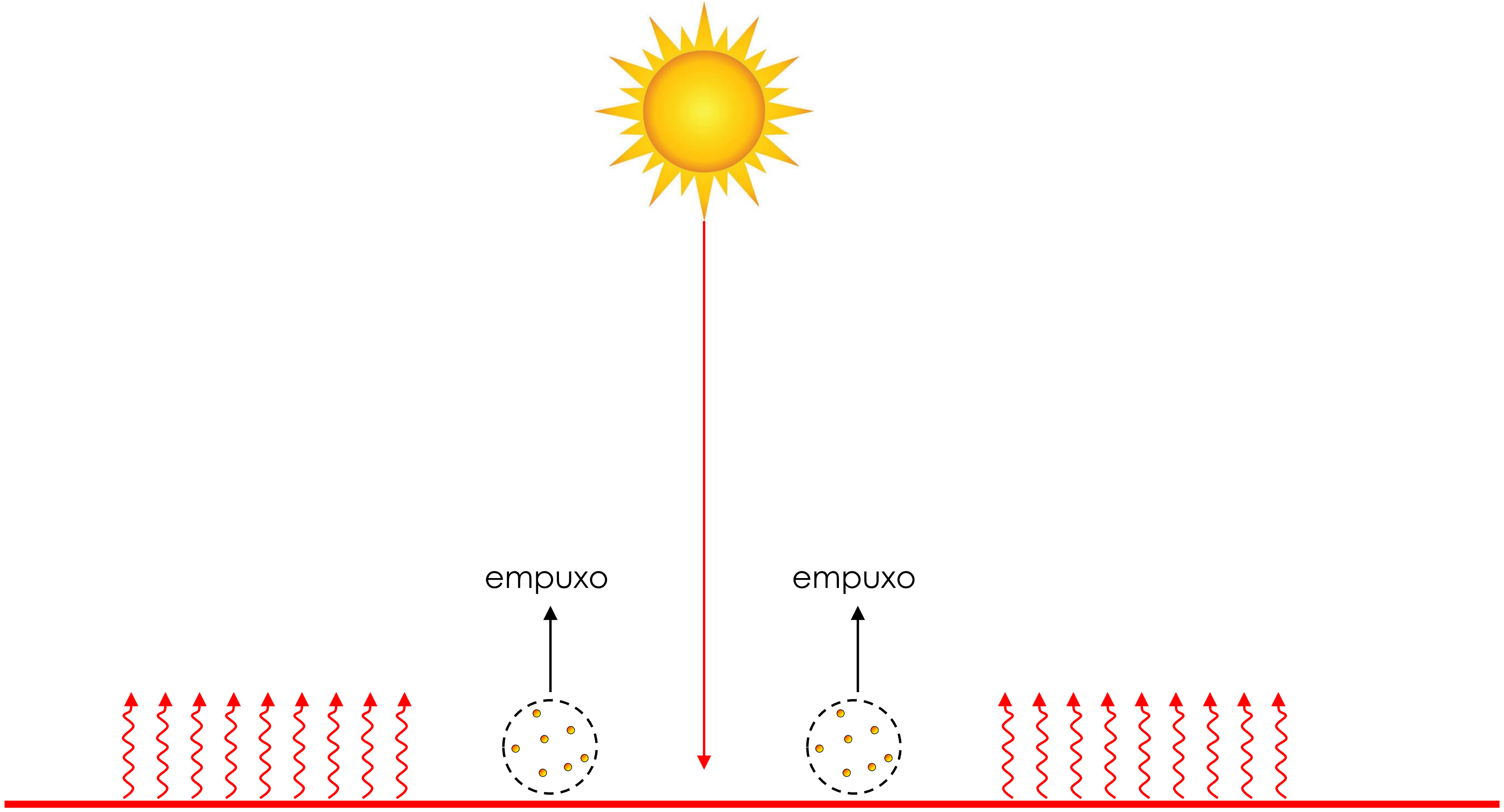

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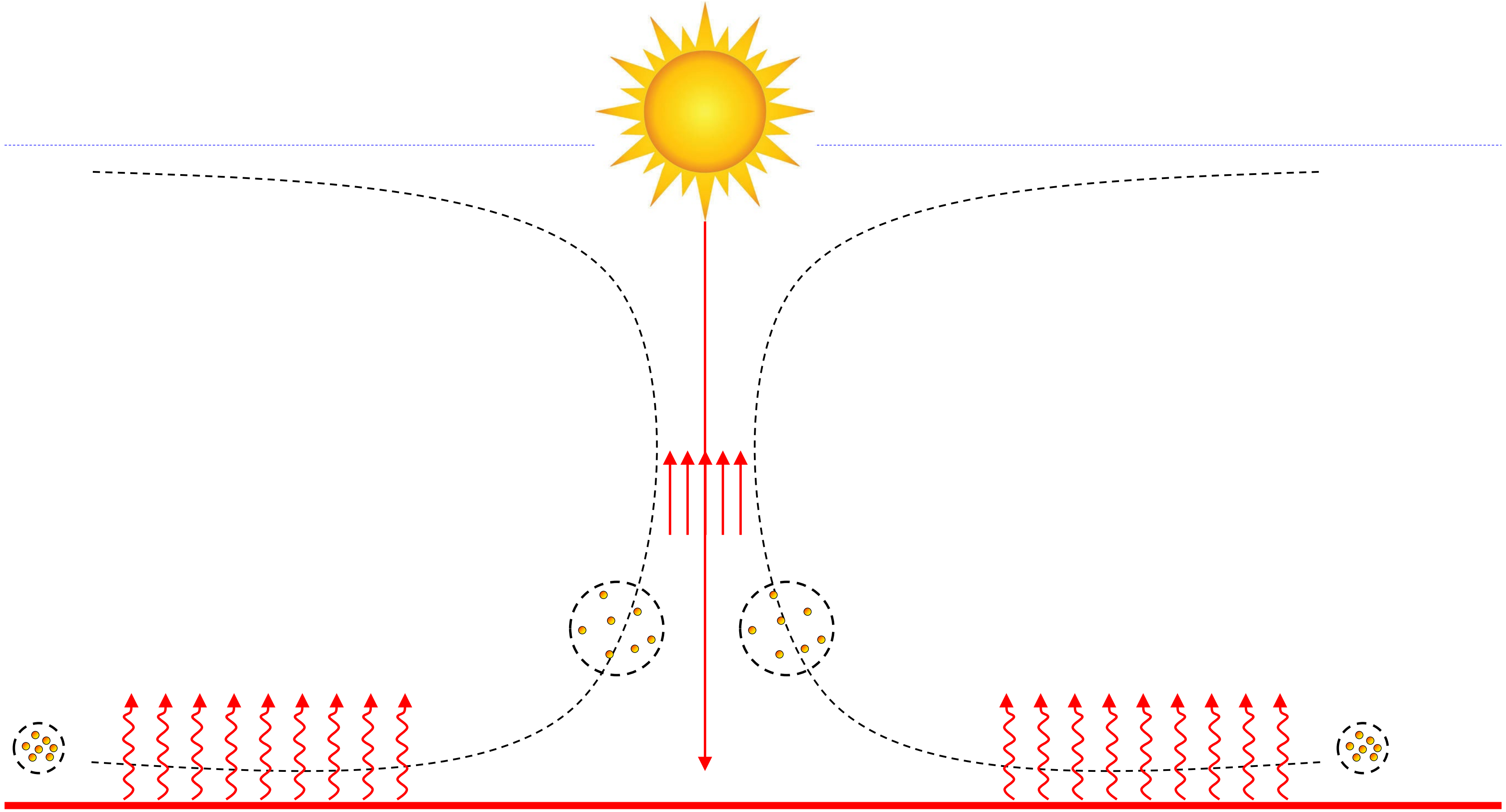

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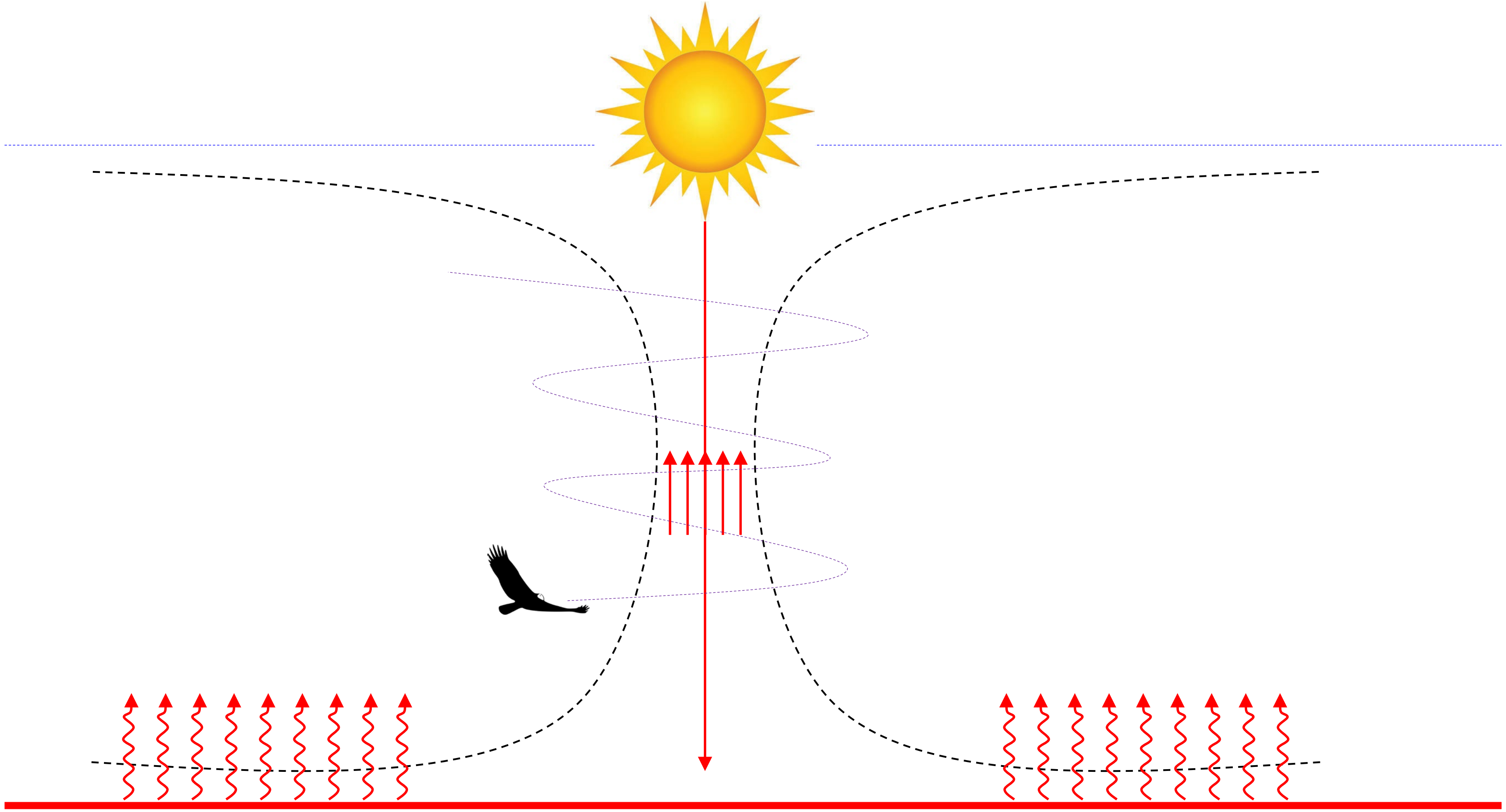

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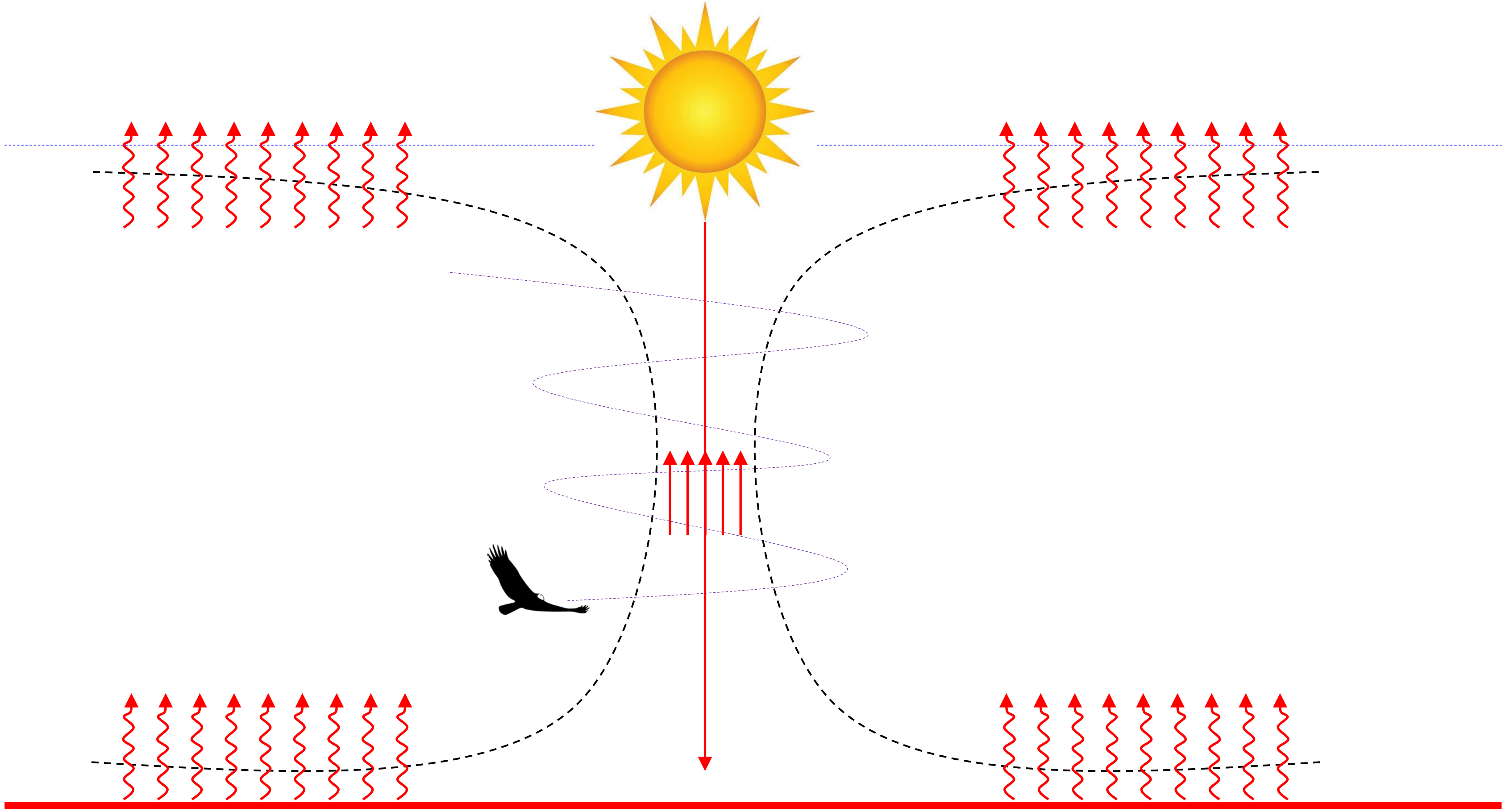

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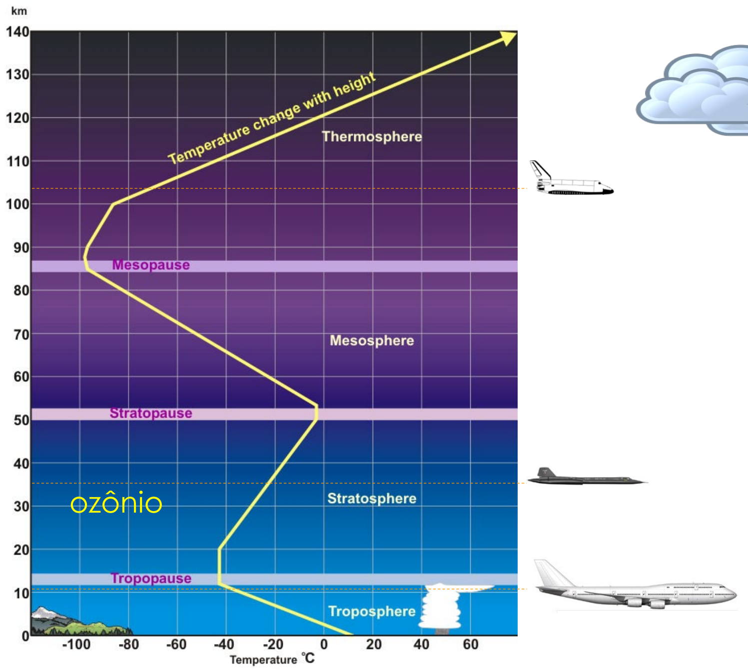

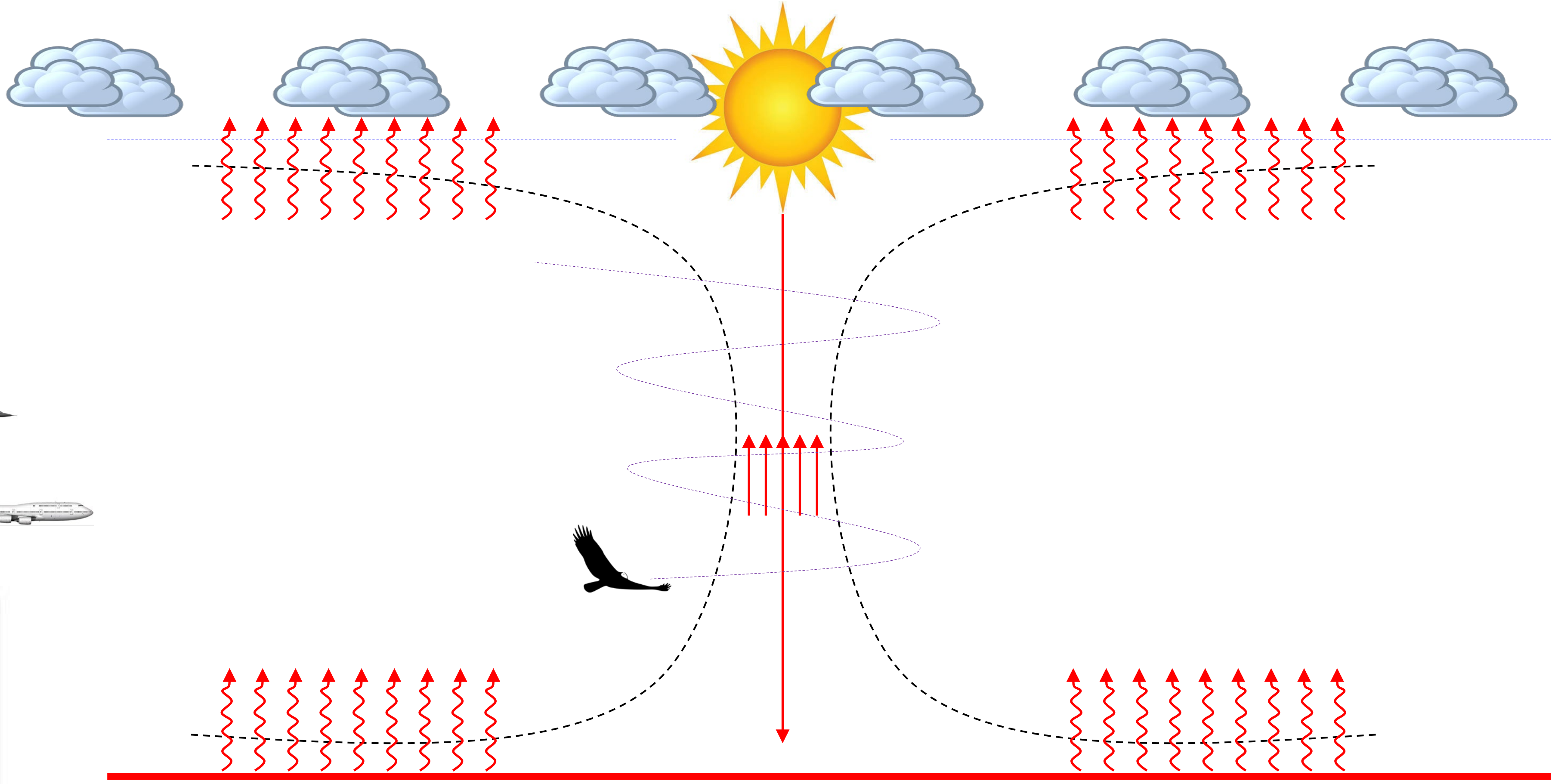

Cumulonimbus !

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Santiago Borja Lopez

Santiago Borja Lopez

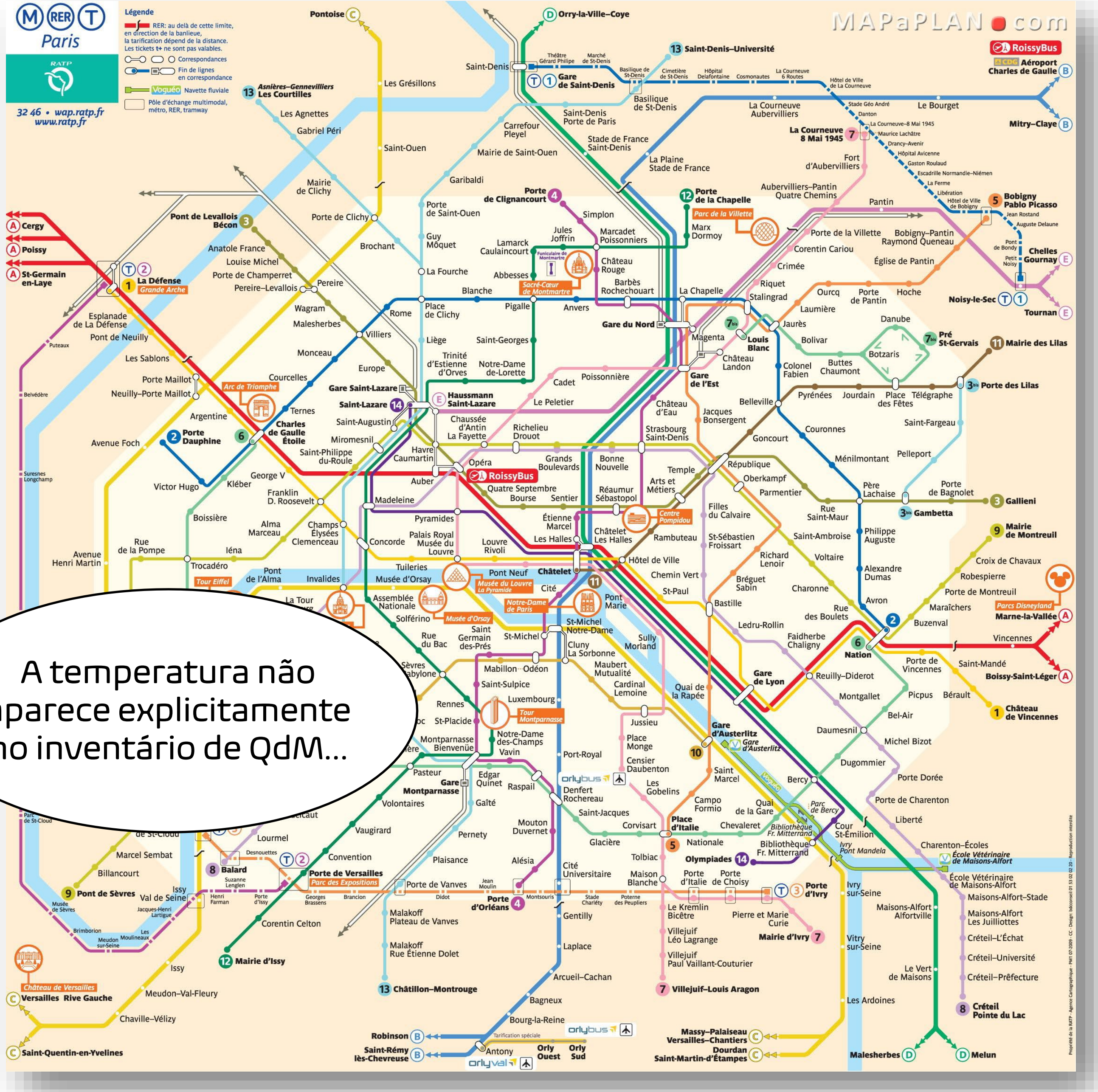
A CONVECÇÃO DE CALOR É UM FENÔMENO ACOPLADO...

movimentação do fluido ↔ transporte de energia térmica

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

$$\left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \vec{\nabla} \vec{u}\right) = -\vec{\nabla} P + \frac{1}{Re} \nabla^2 \vec{u} + \Sigma \frac{1}{R_k} F_k$$

$$\left(\frac{\partial T}{\partial t} + \vec{u} \cdot \vec{\nabla} T\right) = \frac{1}{Re\,Pr} \vec{\nabla} \cdot (k \vec{\nabla} T) + \frac{Ec}{Re} \Phi(\vec{u})$$



A temperatura não aparece explicitamente no inventário de QdM...

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Escoamento incidindo sobre uma placa plana... CAMADA LIMITE

As questões postadas no Chat do YouTube serão respondidas ao final da aula.

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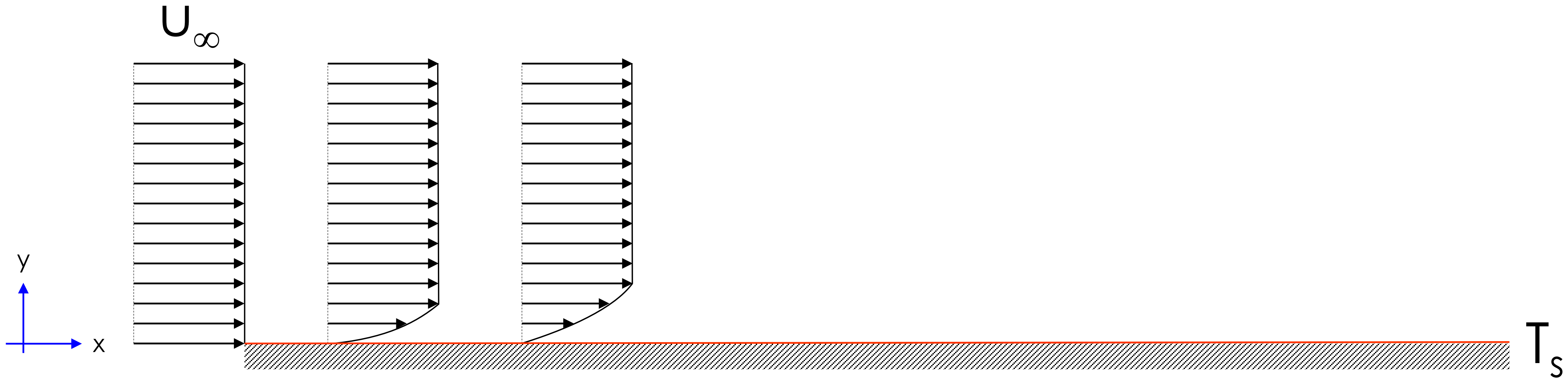

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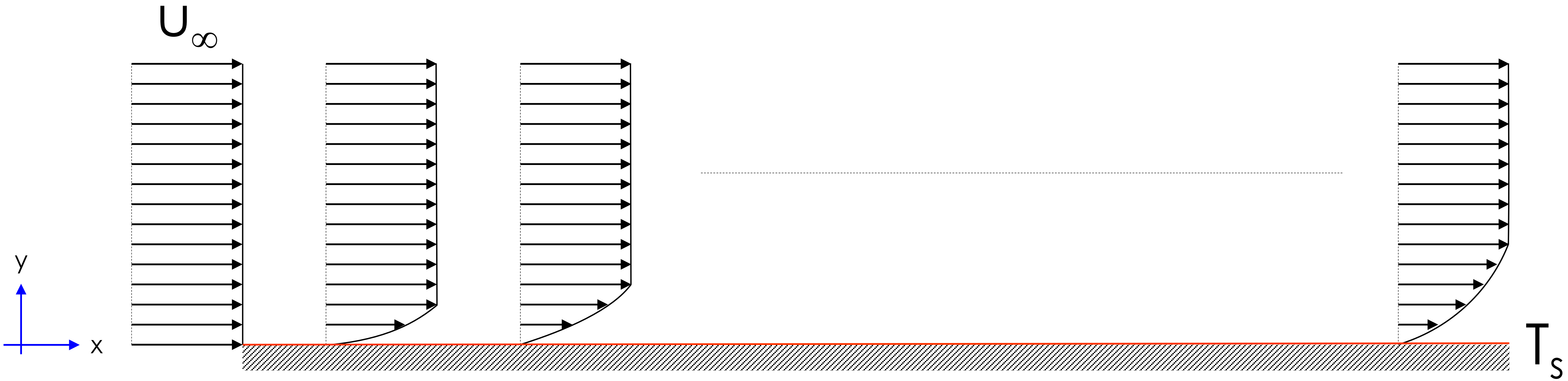

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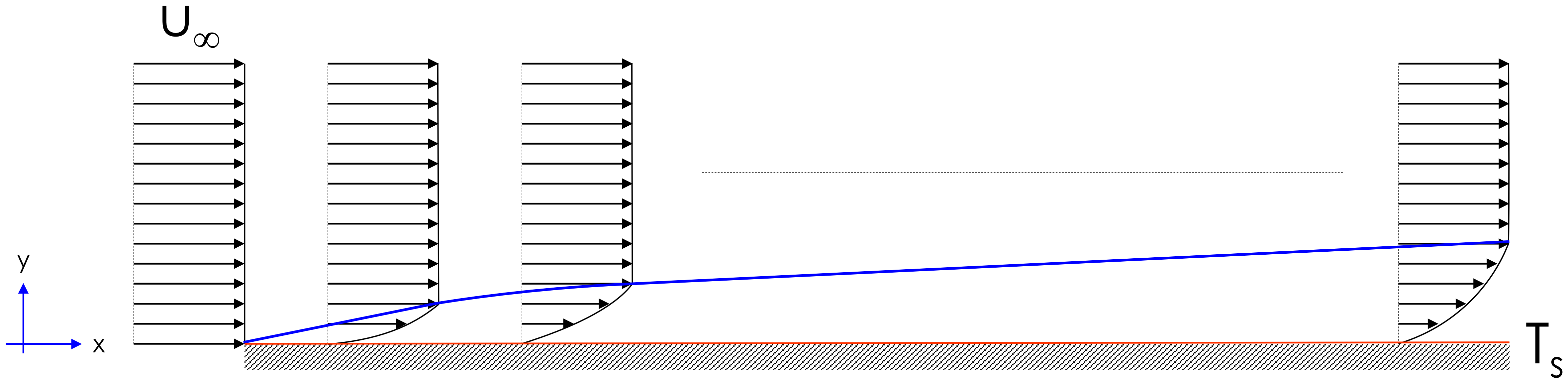

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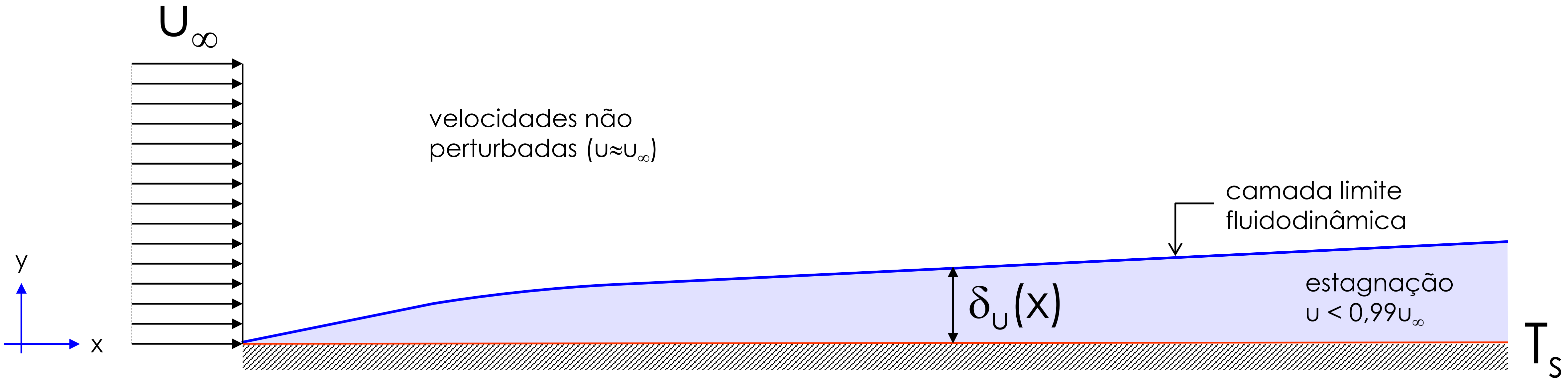


U_∞

velocidades não
perturbadas ($u \approx u_\infty$)

camada limite
fluidodinâmica

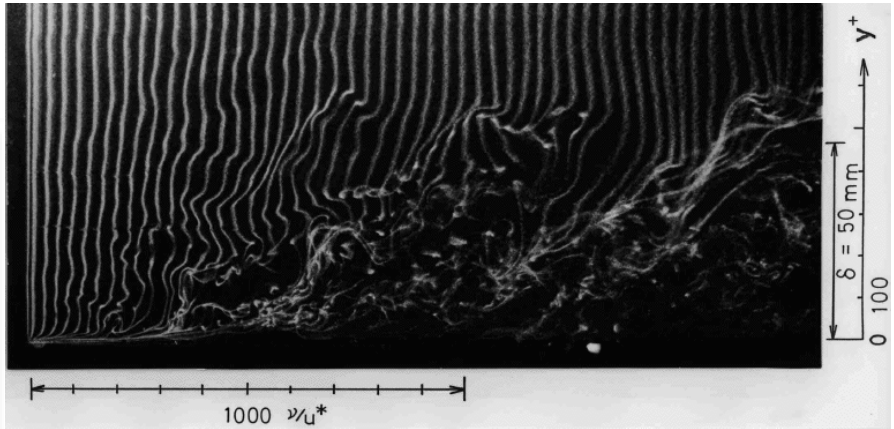
$\delta_u(x)$

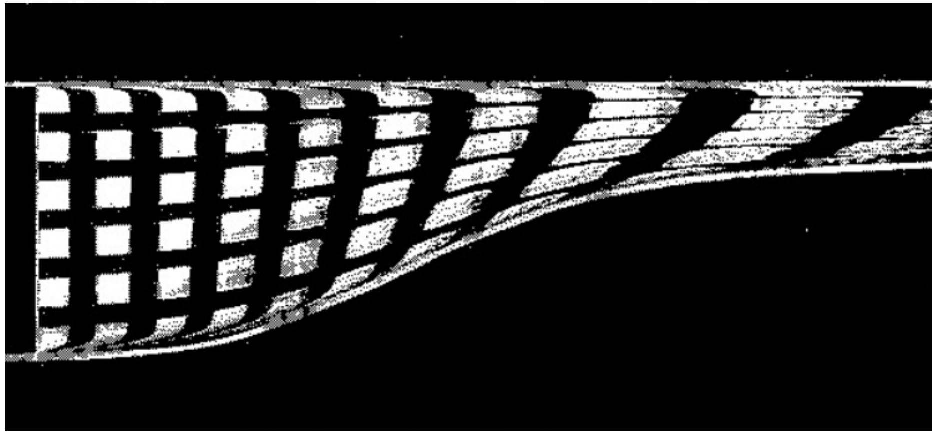
estagnação
$u < 0{,}99u_\infty$

T_s

y

x





Y. IRITANI, N. KASAGI and M. HIRATA

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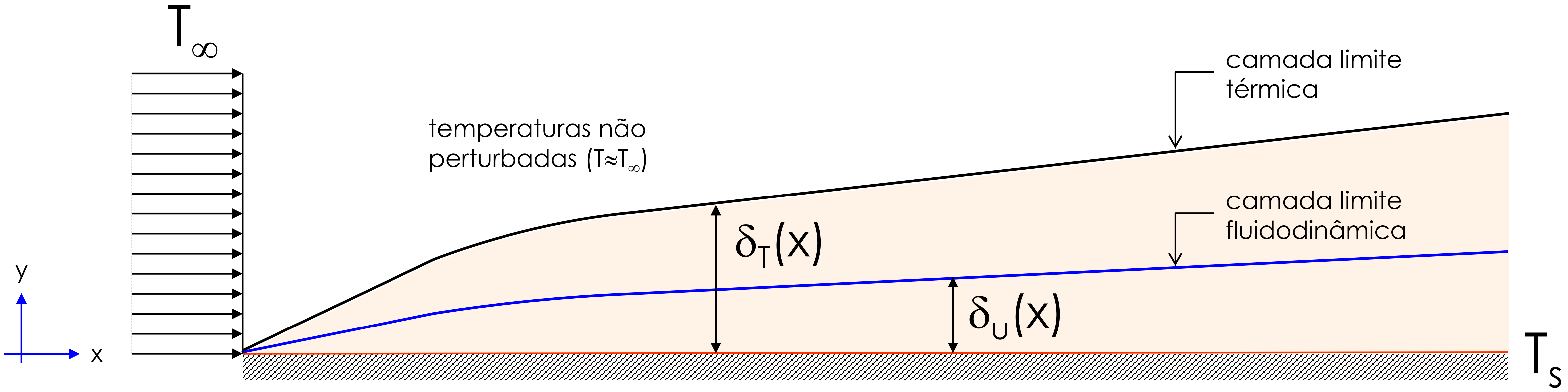
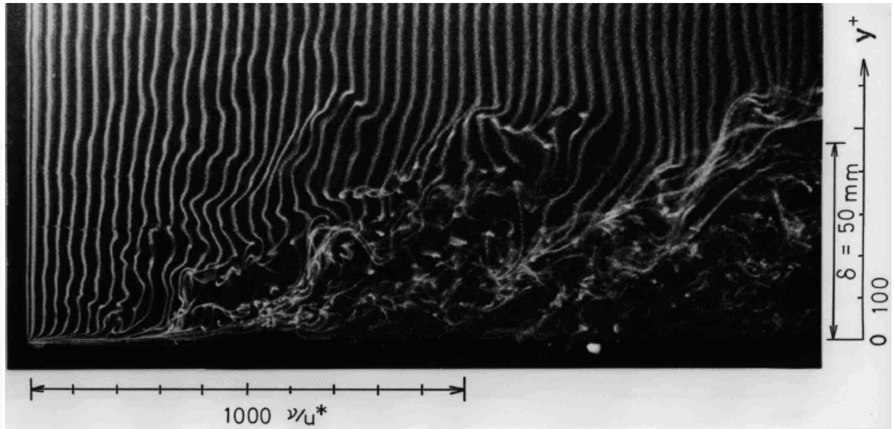
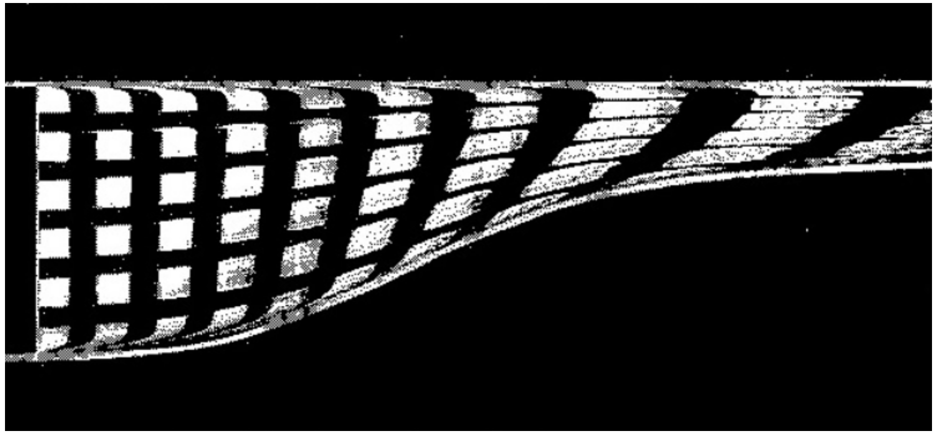
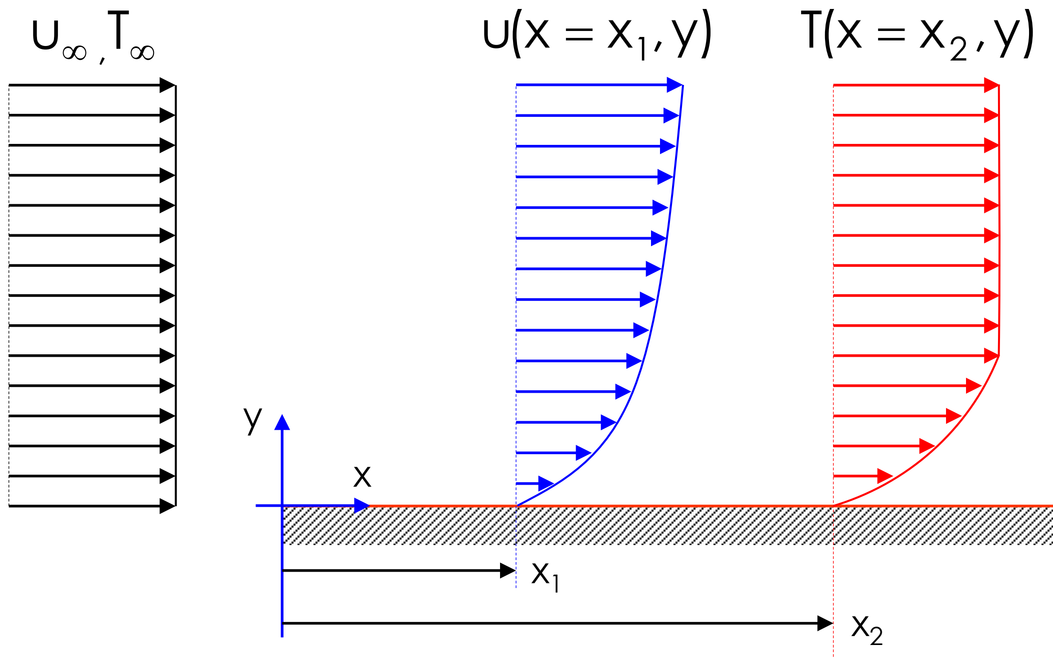






Y. IRITANI, N. KASAGI and M. HIRATA

Cálculo das camadas limites hidrodinâmica e térmica...



the following slides are

ANTI-EDUCATIONAL

Mind the logical sequence not necessarily the mathematical manipulation...

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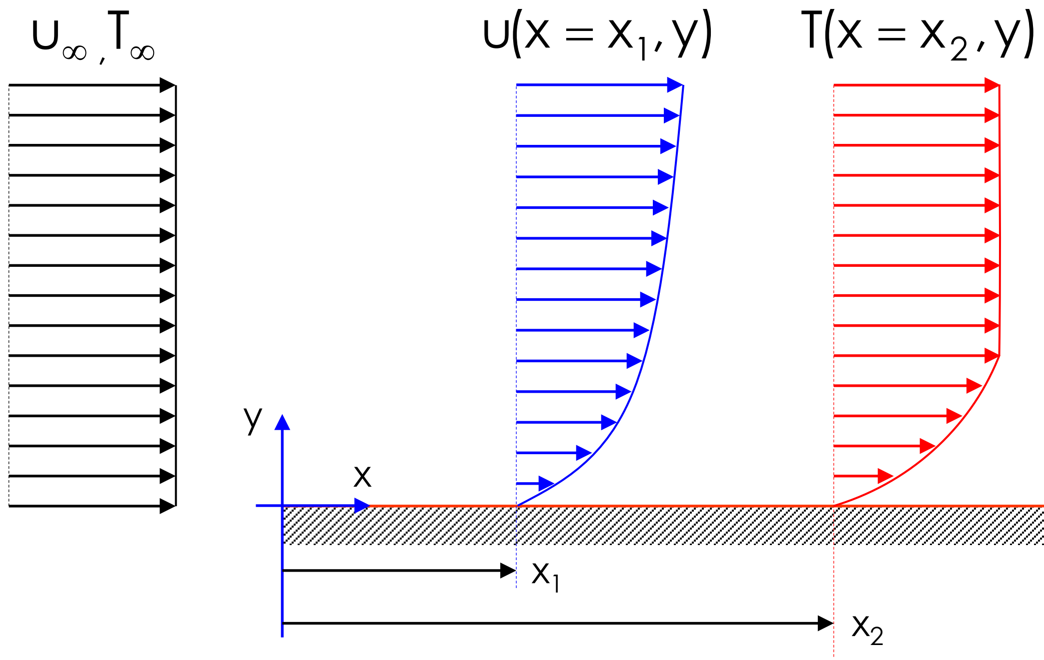
Cálculo das camadas limites hidrodinâmica e térmica...



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

← 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

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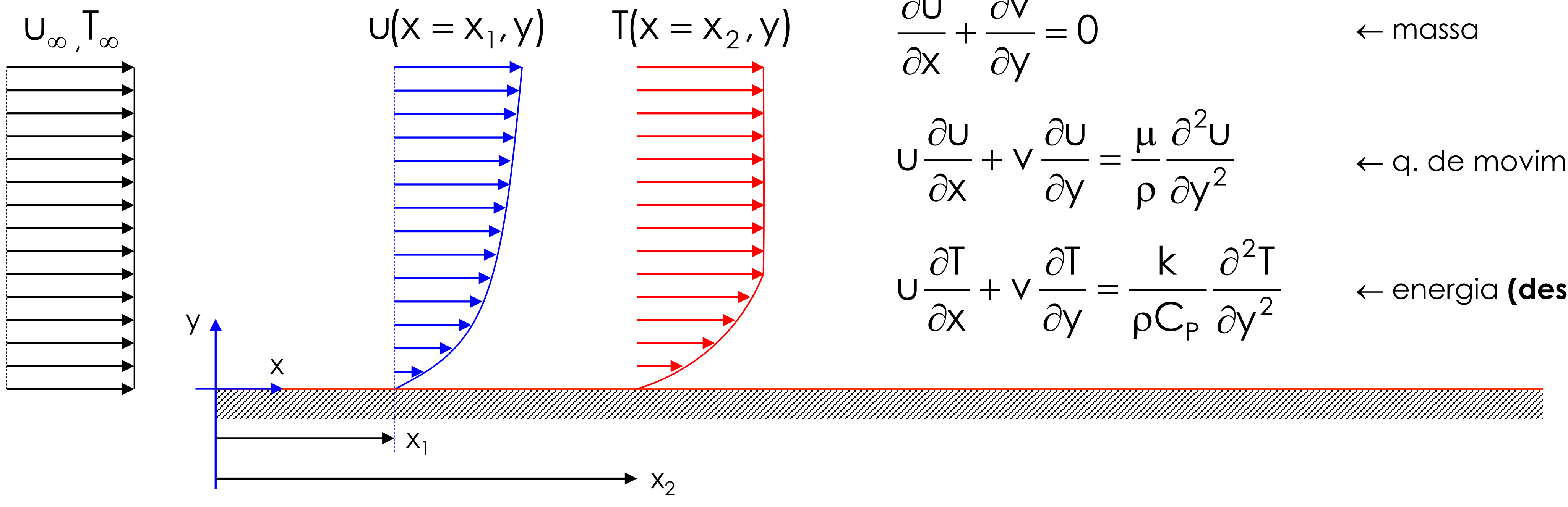
Cálculo das camadas limites hidrodinâmica e térmica...



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

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

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

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

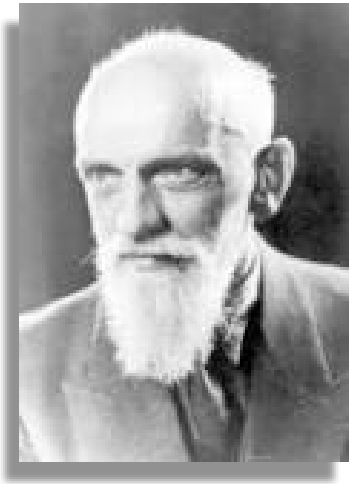
Solução de Blasius (1908)... **velocidades**

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

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

$$\xrightarrow{\text{transformação}}$$

$$a_0 \cdot f(\eta) + a_1\frac{f(\eta)}{d\eta} + a_2\frac{f^2(\eta)}{d\eta^2} + a_3\frac{f^3(\eta)}{d\eta^3} + ...$$



Paul R.H. Blasius
(1883 – 1970)

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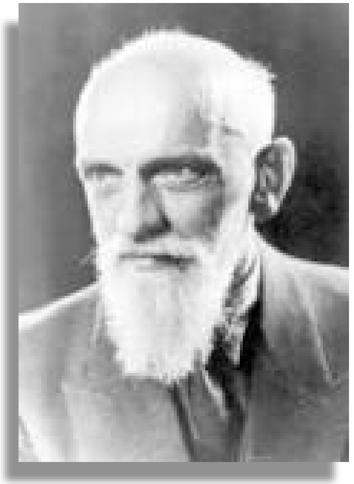
transformação

$$a_0\cdot f(\eta)+a_1\frac{f(\eta)}{d\eta}+a_2\frac{f^2(\eta)}{d\eta^2}+a_3\frac{f^3(\eta)}{d\eta^3}+....$$



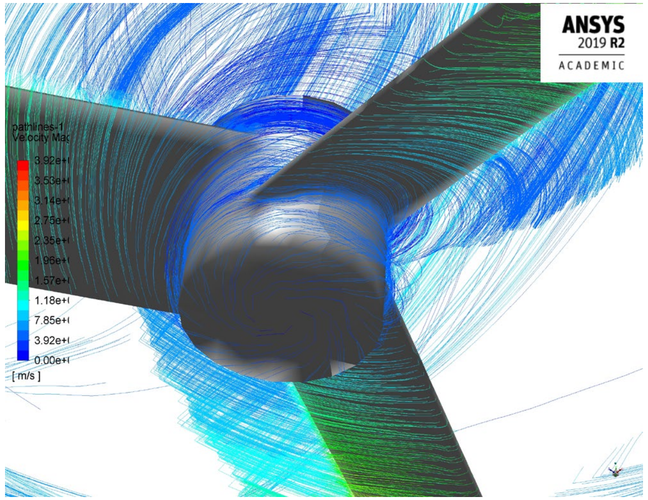
Paul R.H. Blasius
(1883 – 1970)

variável de similaridade

$$\eta \overset{def}{=} y\cdot\sqrt{\frac{U_\infty}{x\cdot\mu/\rho}}$$

$$f(\eta) \overset{def}{=} \frac{\psi}{U_\infty\cdot\sqrt{\frac{x\cdot\mu/\rho}{U_\infty}}}$$

ψ = função de corrente



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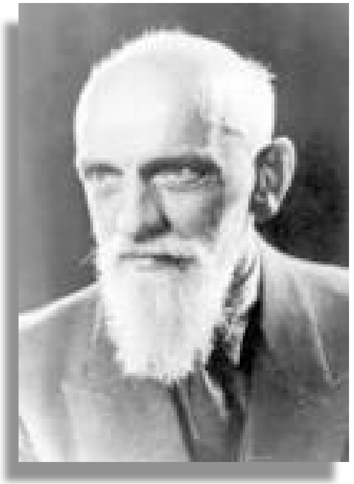
Solução de Blasius (1908)... **velocidades**

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

$$\psi(x,y) \overset{\text{def}}{=} \begin{cases} u = +\dfrac{\partial \psi}{\partial y} \\ v = -\dfrac{\partial \psi}{\partial x} \end{cases} \Rightarrow \text{🙊} \equiv 0$$

função de corrente



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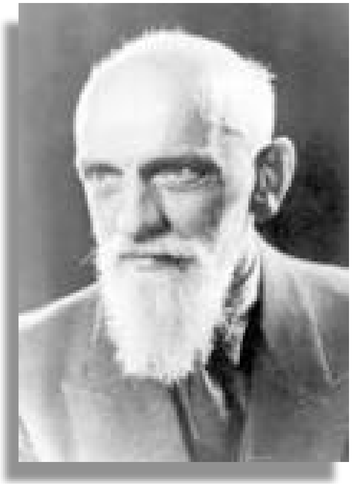

Paul R.H. Blasius
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$$\underset{\text{função de corrente}}{\psi(x,y)} \overset{\text{def}}{=} \begin{cases} u = +\dfrac{\partial \psi}{\partial y} \\ v = -\dfrac{\partial \psi}{\partial x} \end{cases} \Rightarrow$$ 🙊 $\equiv 0$

As componentes da velocidade se escrevem então como:

$$\eta = y \cdot \sqrt{\frac{U_\infty}{x \cdot \rho / \mu}}$$

$$\psi = U_\infty \sqrt{x \cdot \frac{\mu / \rho}{U_\infty}} \cdot f(\eta)$$

$$u = +\frac{\partial \psi}{\partial y} = +\left(\frac{\partial \psi}{\partial \eta}\right) \cdot \left(\frac{\partial \eta}{\partial y}\right) = \left(U_\infty \sqrt{\frac{x\nu}{U_\infty}} \cdot \frac{df}{d\eta}\right) \cdot \left(\sqrt{\frac{U_\infty}{x\nu}}\right) = U_\infty \frac{df}{d\eta}$$

$$\nu = \mu / \rho$$

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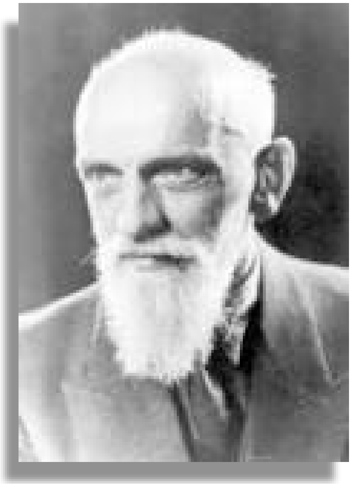
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$$u = +\frac{\partial\psi}{\partial y} = +\left(\frac{\partial\psi}{\partial\eta}\right)\cdot\left(\frac{\partial\eta}{\partial y}\right) = \left(U_\infty\sqrt{\frac{x\nu}{U_\infty}}\cdot\frac{df}{d\eta}\right)\cdot\left(\sqrt{\frac{U_\infty}{x\nu}}\right) = U_\infty\frac{df}{d\eta}$$

$$v = -\frac{\partial\psi}{\partial x} = -U_\infty\sqrt{\frac{\nu}{U_\infty}}\cdot f(\eta)\cdot\left(\frac{x^{-1/2}}{2}\right) - \left(U_\infty\sqrt{x\cdot\frac{\nu}{U_\infty}}\cdot\frac{\partial f}{\partial x}\right) = \frac{1}{2}\sqrt{\frac{U_\infty\nu}{x}}\cdot\left(\eta\frac{df}{d\eta} - f\right)$$

$$\nu = \mu / \rho$$

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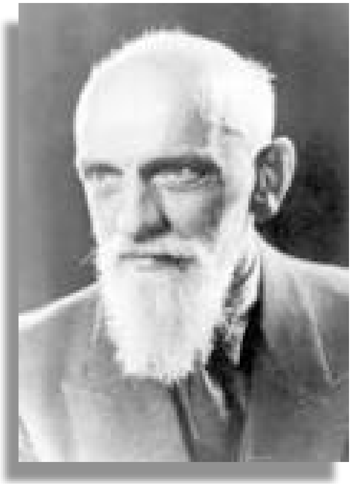
Solução de Blasius (1908)... **velocidades**



Paul R.H. Blasius
(1883 – 1970)

$$\psi(x,y) \overset{\text{def}}{=} \begin{cases} u = +\dfrac{\partial \psi}{\partial y} \\ v = -\dfrac{\partial \psi}{\partial x} \end{cases} \Rightarrow 🙊 \equiv 0$$

função de corrente

As componentes da velocidade se escrevem então como:

$$\eta = y \cdot \sqrt{\frac{U_\infty}{x \cdot \rho / \mu}}$$

$$\psi = U_\infty \sqrt{x \cdot \frac{\mu/\rho}{U_\infty}} \cdot f(\eta)$$

$$u = +\frac{\partial \psi}{\partial y} = +\left(\frac{\partial \psi}{\partial \eta}\right) \cdot \left(\frac{\partial \eta}{\partial y}\right) = \left(U_\infty \sqrt{\frac{x\nu}{U_\infty}} \cdot \frac{df}{d\eta}\right) \cdot \left(\sqrt{\frac{U_\infty}{x\nu}}\right) = U_\infty \frac{df}{d\eta}$$

$$v = -\frac{\partial \psi}{\partial x} = -U_\infty \sqrt{\frac{\nu}{U_\infty}} \cdot f(\eta) \cdot \left(\frac{x^{-1/2}}{2}\right) - \left(U_\infty \sqrt{x \cdot \frac{\nu}{U_\infty}} \cdot \frac{\partial f}{\partial x}\right) = \frac{1}{2} \sqrt{\frac{U_\infty \nu}{x}} \cdot \left(\eta \frac{df}{d\eta} - f\right)$$

$$\nu = \mu / \rho$$

$$\begin{matrix} u = \ldots \\ v = \ldots \end{matrix} \Rightarrow u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \frac{\mu}{\rho} \frac{\partial^2 u}{\partial y^2}$$ 🙈

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

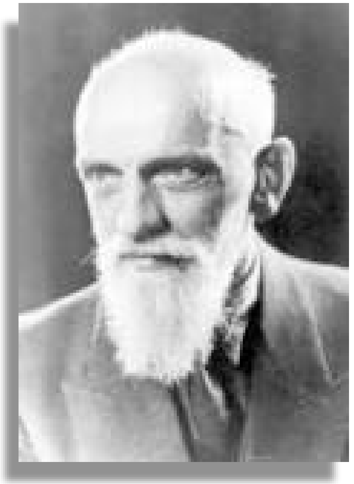
$$\frac{\partial u}{\partial x} = -\frac{u_\infty}{2x}\eta\frac{d^2f}{d\eta^2}$$

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

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

🙈

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



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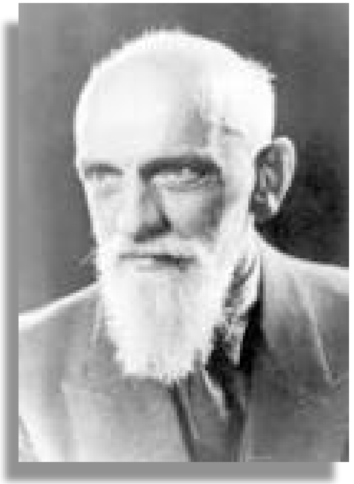
Solução de Blasius (1908)... **velocidades**



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

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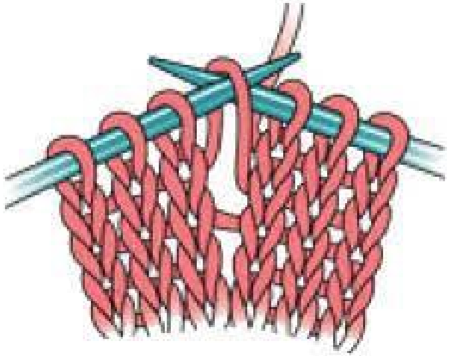
$$\frac{\partial^2 u}{\partial y^2} = \frac{U_\infty^2}{\nu x}\frac{d^3f}{d\eta^3}$$

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

$$\Rightarrow \quad \boxed{2\frac{d^3f}{d\eta^3} + f\frac{d^2f}{d\eta^2} = 0} \quad \Leftarrow$$

DIFERENÇAS FINITAS



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

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

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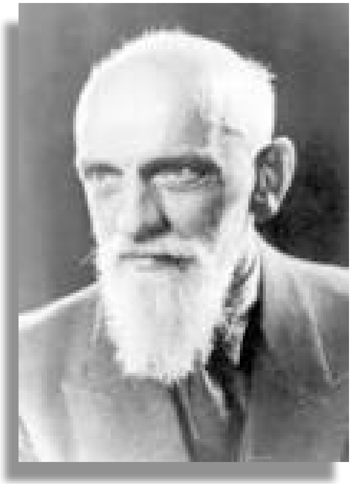

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$$\Rightarrow \quad \boxed{2\frac{d^3f}{d\eta^3} + f\frac{d^2f}{d\eta^2} = 0} \quad \Leftarrow$$

DIFERENÇAS FINITAS

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

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

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

$$\Rightarrow$$

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

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

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

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

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

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
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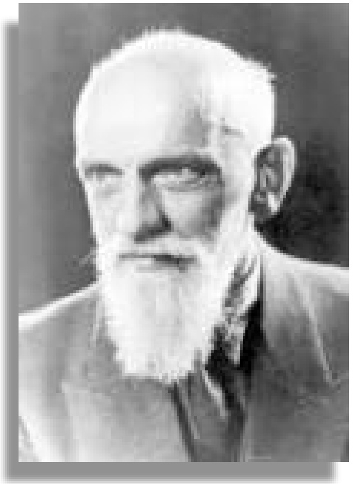

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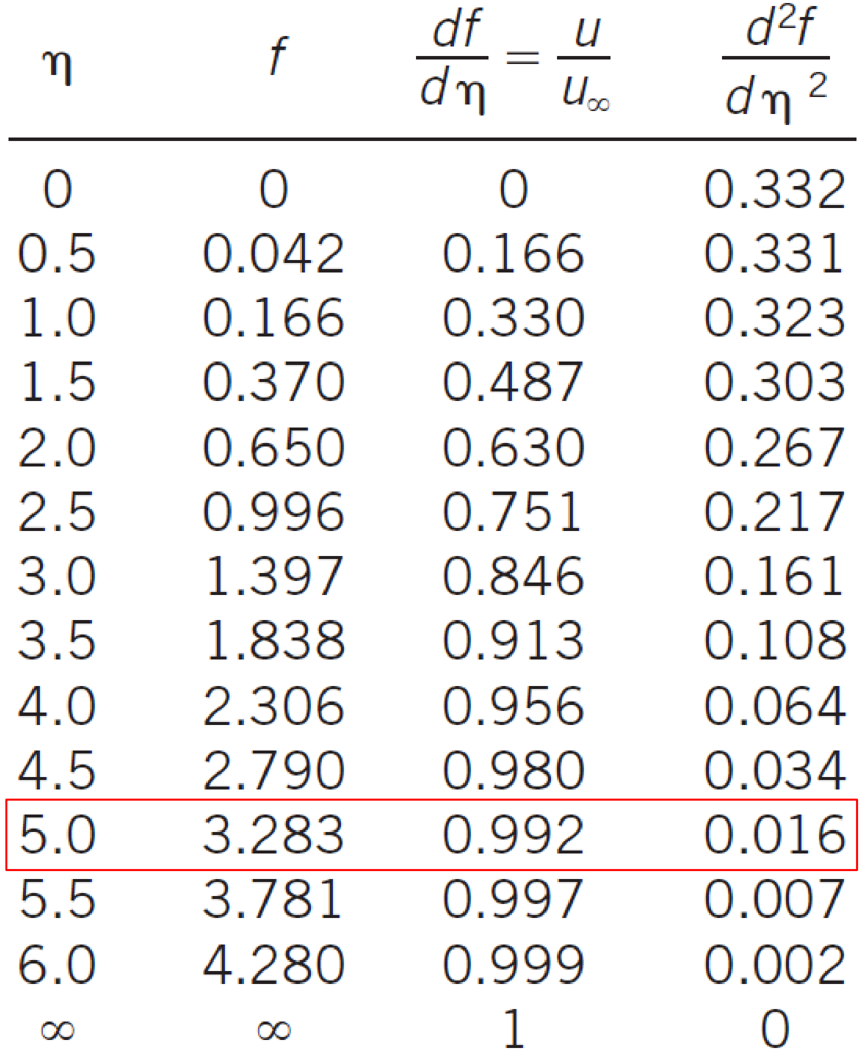
Solução de Blasius (1908)... **c. limite fluidodinâmica**

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

$$\delta \Rightarrow u/u_\infty = 0.99 \quad \Rightarrow \eta = 5.0$$



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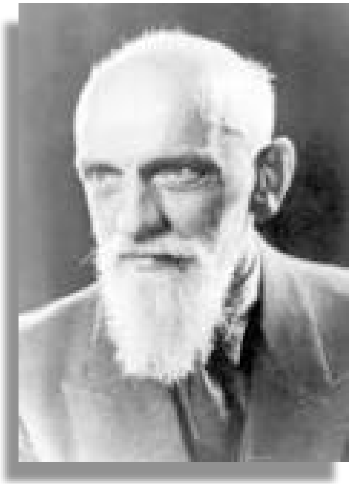

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$$\eta = y\cdot\sqrt{\frac{u_\infty}{x\nu}} \Rightarrow \quad \delta = 5.0\cdot\sqrt{\frac{x\nu}{u_\infty}}$$

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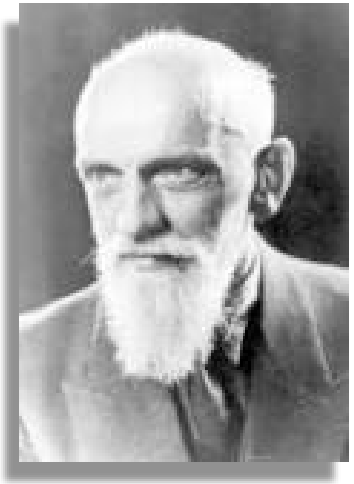

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$$\eta = y\cdot\sqrt{\frac{u_\infty}{x\nu}} \Rightarrow \quad \delta = 5.0\cdot\sqrt{\frac{x\nu}{u_\infty}}$$

⇨ $$\delta = \frac{5.0\cdot x}{\sqrt{Re_x}} \qquad Re = \frac{\rho u_\infty x}{\mu}$$

η	f	$\frac{df}{d\eta}=\frac{u}{u_\infty}$	$\frac{d^2f}{d\eta^2}$
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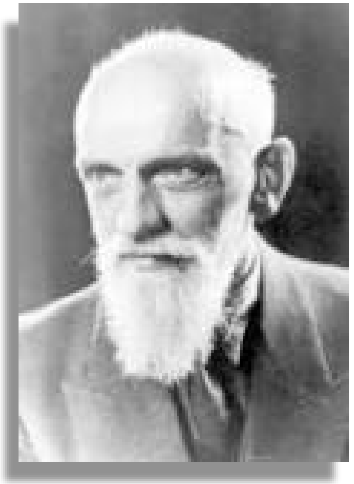

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Solução de Blasius (1908)... **tensões de cisalhamento**

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

$$\tau_x=\mu\frac{\partial u}{\partial y}\bigg|_{y=0}=\mu u_\infty\sqrt{\frac{u_\infty}{\nu x}}\frac{d^2f}{d\nu^2}\bigg|_{\eta=0}$$

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

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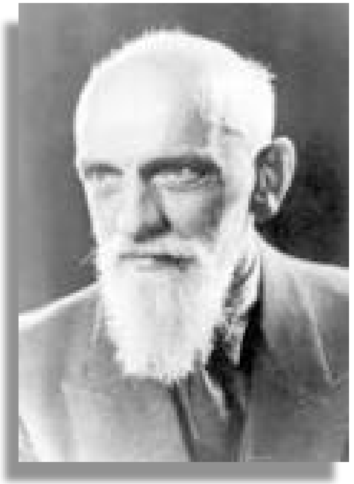

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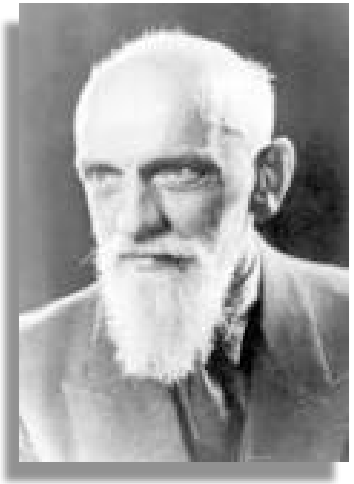
Solução de Blasius (1908)... **c. limite térmica**

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



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$$\psi = U_\infty \cdot \sqrt{\frac{x \cdot \mu / \rho}{U_\infty}} \cdot f(\eta)$$

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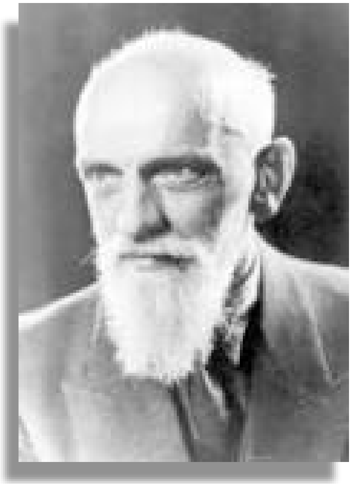
Solução de Blasius (1908)... **c. limite térmica**

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

$$\psi(x,y)\overset{\text{def}}{=}\begin{cases}u=+\dfrac{\partial\psi}{\partial y}\\[2ex] v=-\dfrac{\partial\psi}{\partial x}\end{cases}$$

🙊



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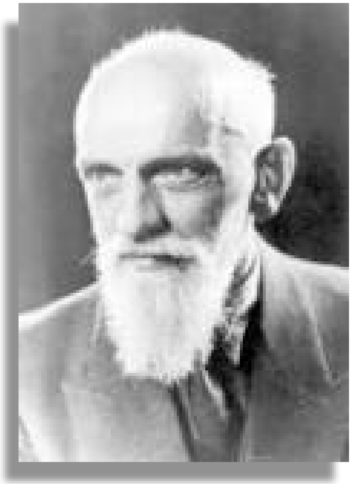

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$$\theta(x,y)\overset{\text{def}}{=}\frac{T(x,y)-T_s}{T_\infty-T_s}\Leftarrow$$

$$\psi=u_\infty\cdot\sqrt{\frac{x\cdot\mu/\rho}{u_\infty}}\cdot f(\eta)$$

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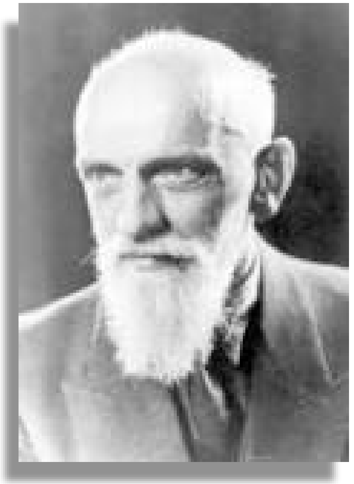

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$$\psi=u_\infty\cdot\sqrt{\frac{x\cdot\mu/\rho}{u_\infty}}\cdot f(\eta)$$

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

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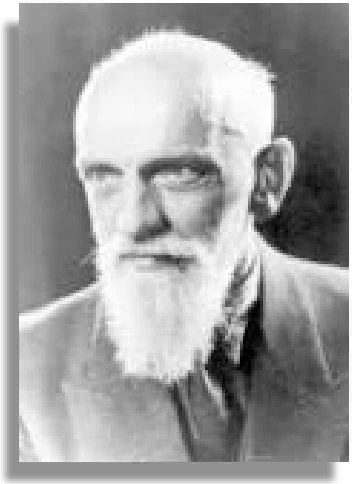
Solução de Blasius (1908)... **c. limite térmica**

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

$$\vdots$$

$$\Pr = \frac{\mu}{k/C_P} \Rightarrow \boxed{2\frac{d^2\theta}{d\eta^2} + \Pr\cdot f\frac{d\theta}{d\eta} = 0}$$

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



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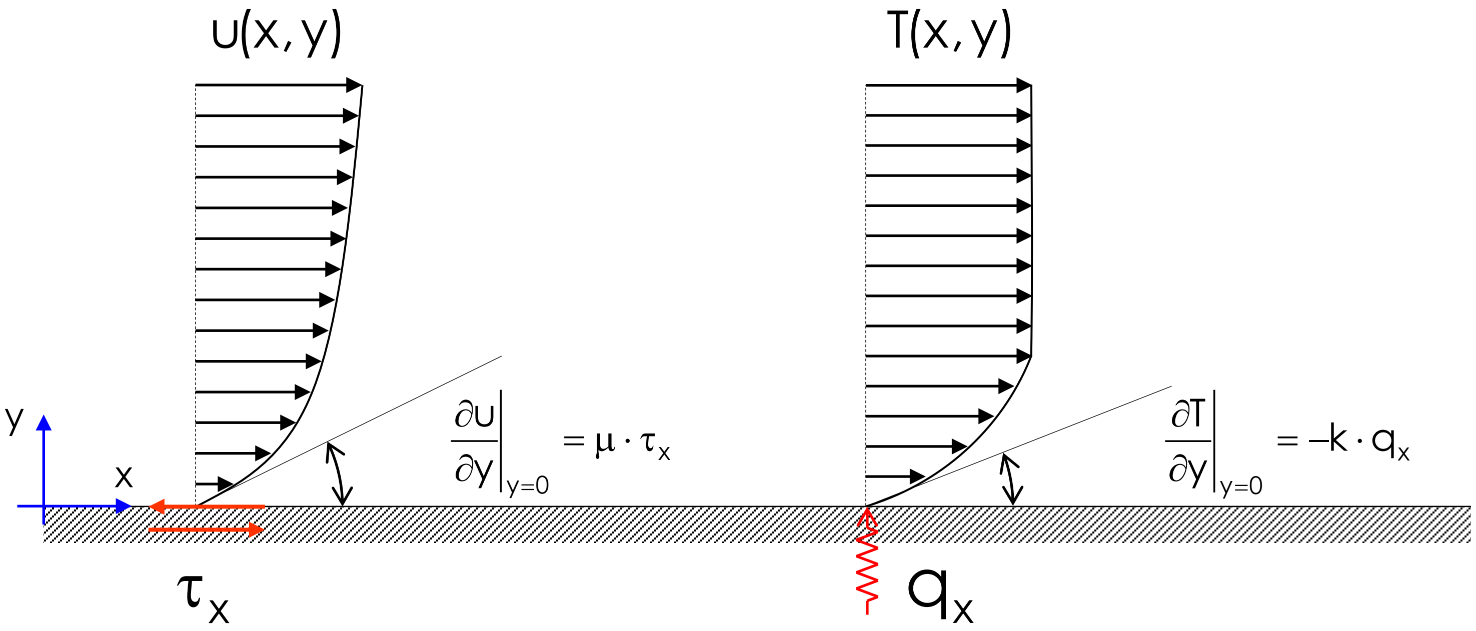
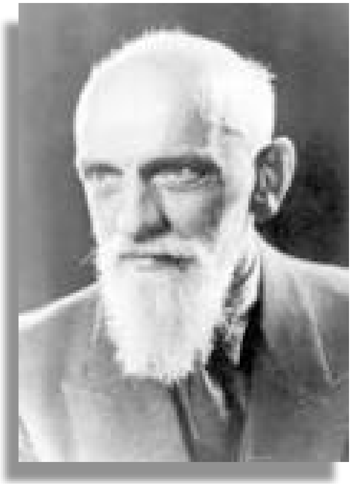
Solução de Blasius (1908)... **c. limite térmica**



$$\left.\frac{\partial u}{\partial y}\right|_{y=0} = \mu \cdot \tau_x$$

$$\left.\frac{\partial T}{\partial y}\right|_{y=0} = -k \cdot q_x$$



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

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

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

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

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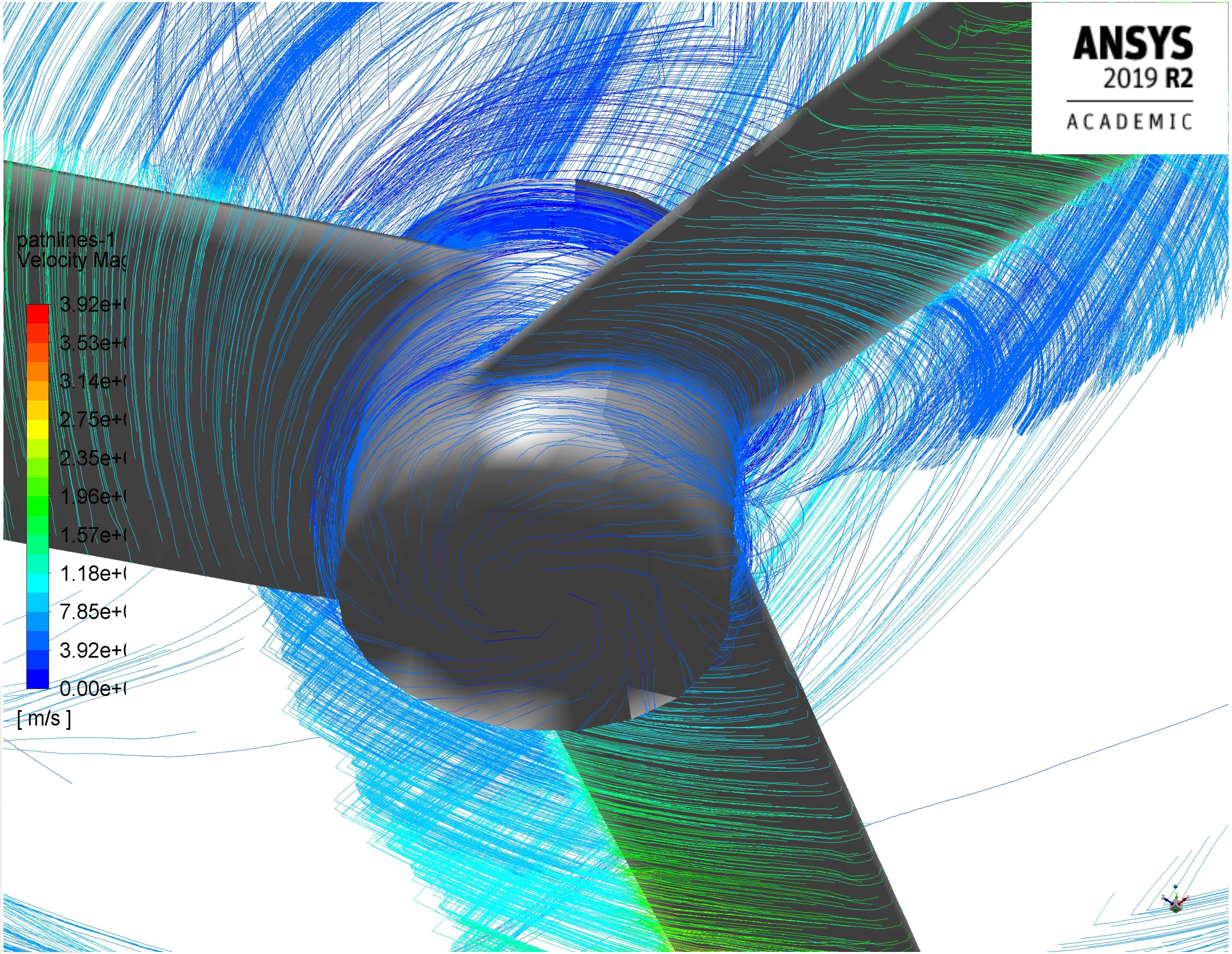
MÉTODOS DE SOLUÇÃO

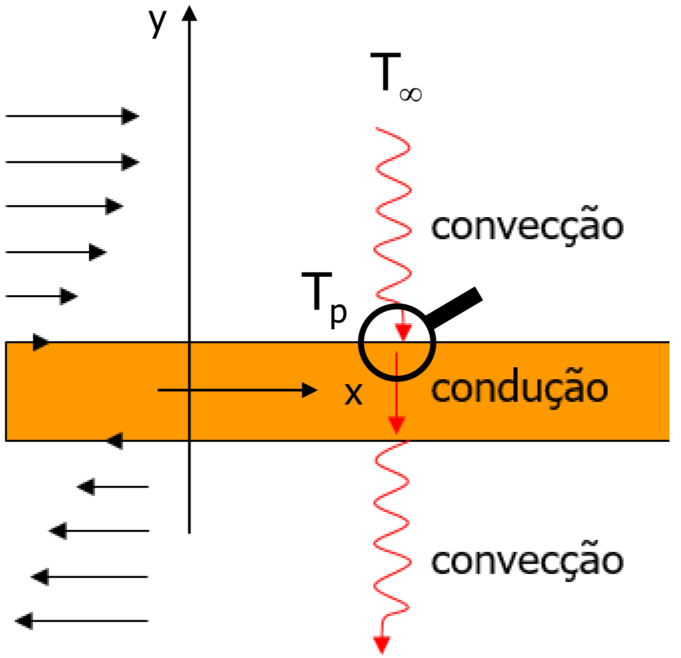
empíricos

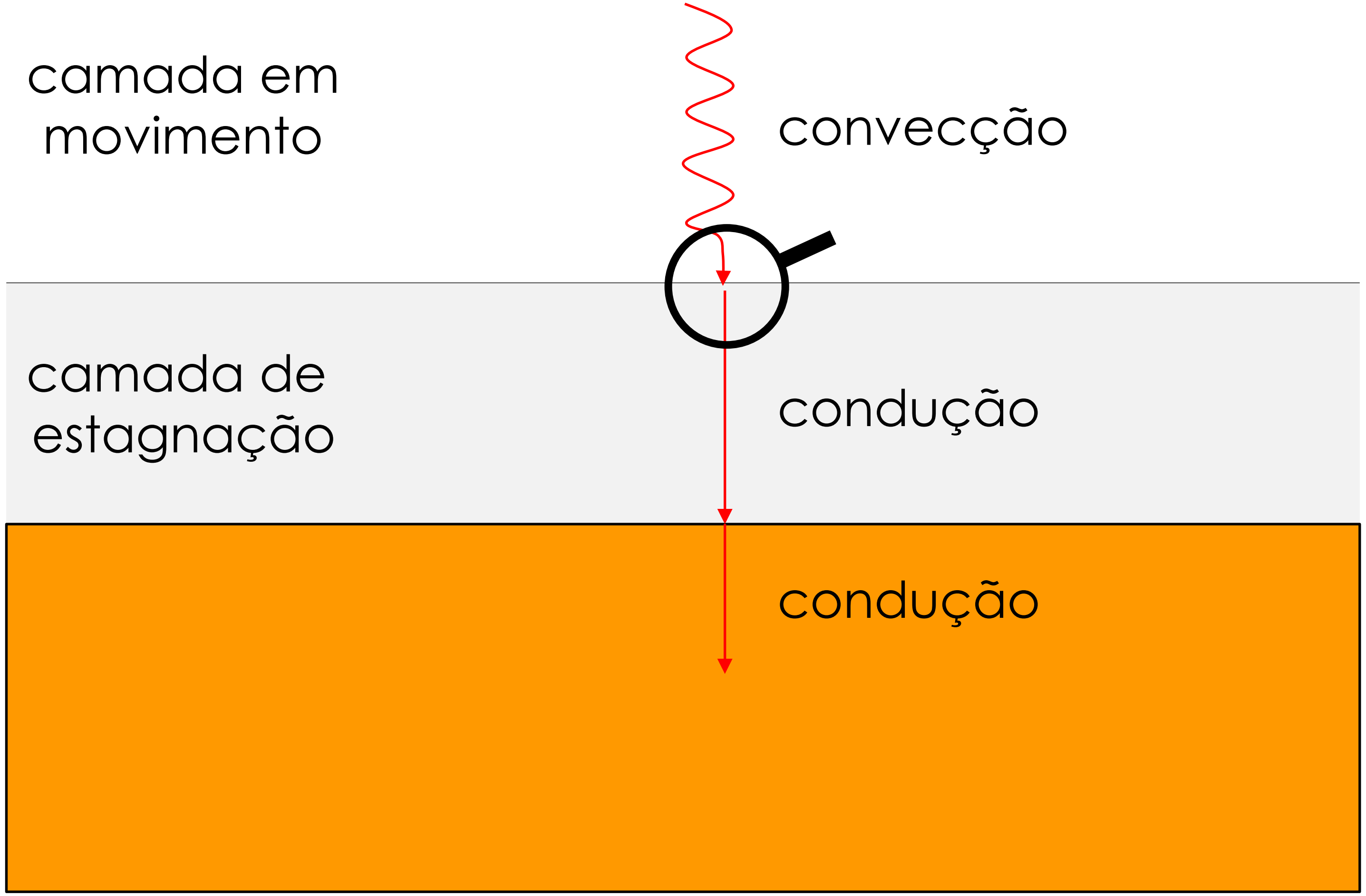
computacionais



A CONVECÇÃO DE CALOR – ABORDAGEM EMPÍRICA...

movimentação do fluido ↔ transporte de energia térmica





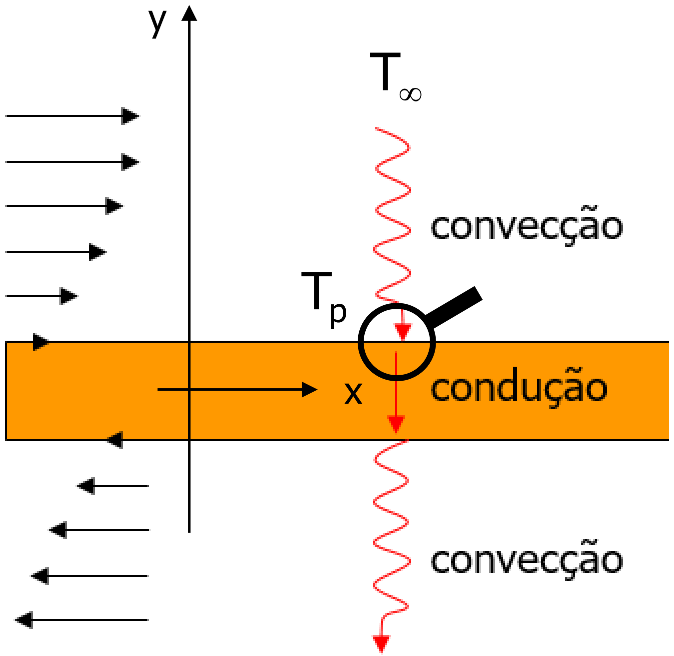
camada em movimento

convecção

camada de estagnação

condução

condução



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

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

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

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

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

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

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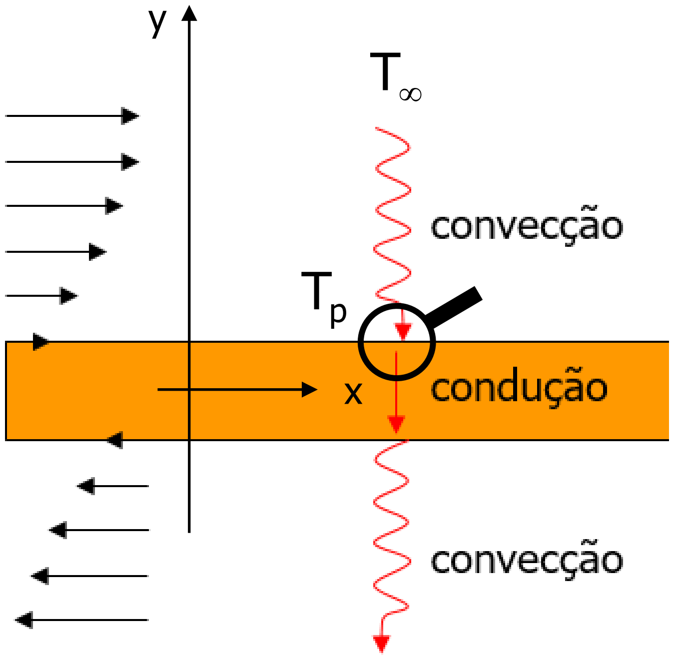
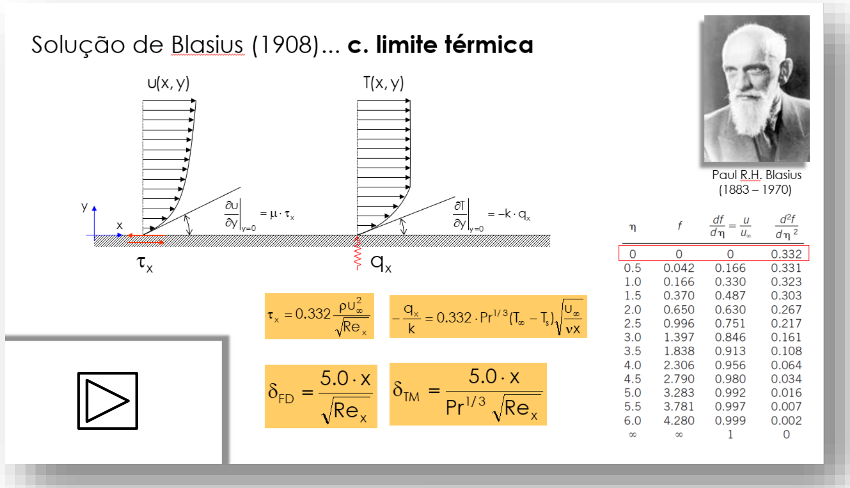


$$Nu \overset{def}{=} \frac{h_q}{k/D}$$

As equações diferenciais de balanço indicam que:



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

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

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

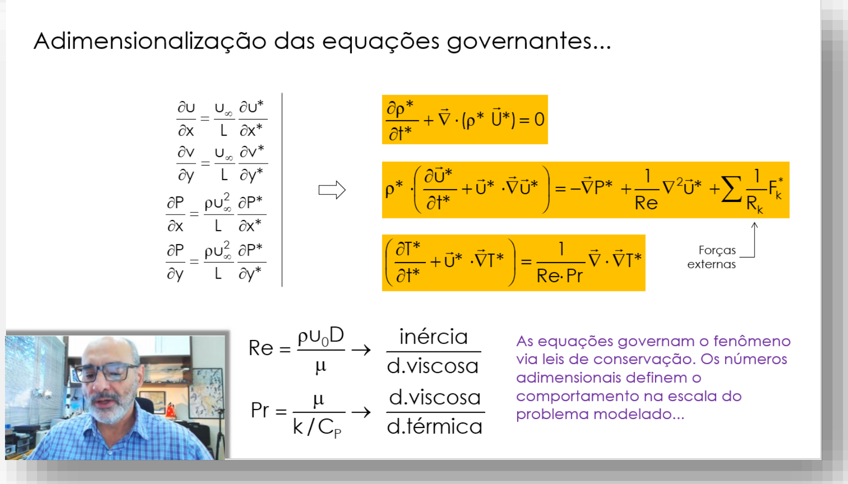
$$\delta_{FD} = \frac{5.0 \cdot x}{\sqrt{Re_x}}$$

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

Paul R.H. Blasius
(1883 – 1970)

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
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

aula MF2



Adimensionalização das equações governantes...

$$\frac{\partial u}{\partial x} = \frac{u_\infty}{L}\frac{\partial u^*}{\partial x^*}$$

$$\frac{\partial v}{\partial y} = \frac{u_\infty}{L}\frac{\partial v^*}{\partial y^*}$$

$$\frac{\partial P}{\partial x} = \frac{\rho u_\infty^2}{L}\frac{\partial P^*}{\partial x^*}$$

$$\frac{\partial P}{\partial y} = \frac{\rho u_\infty^2}{L}\frac{\partial P^*}{\partial y^*}$$

$$\Rightarrow$$

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

$$\rho^* \cdot \left(\frac{\partial \vec{U}^*}{\partial t^*} + \vec{U}^* \cdot \vec{\nabla}\vec{U}^*\right) = -\vec{\nabla}P^* + \frac{1}{Re}\nabla^2\vec{U}^* + \sum \frac{1}{R_k}F_k^*$$

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

Forças externas

$$Re = \frac{\rho u_0 D}{\mu} \rightarrow \frac{\text{inércia}}{\text{d.viscosa}}$$

$$Pr = \frac{\mu}{k/C_P} \rightarrow \frac{\text{d.viscosa}}{\text{d.térmica}}$$

As equações governam o fenômeno via leis de conservação. Os números adimensionais definem o comportamento na escala do problema modelado...

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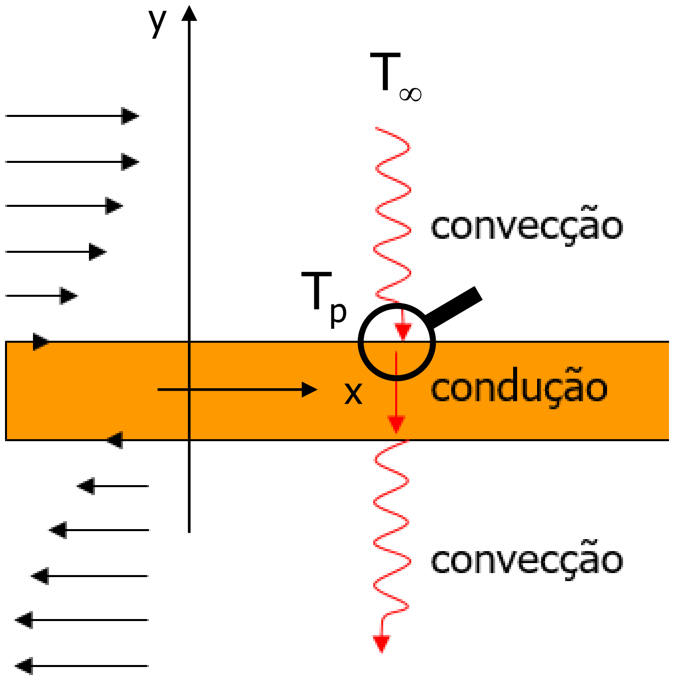


$$Nu \overset{def}{=} \frac{h_q}{k/D}$$

As equações diferenciais de balanço indicam que:

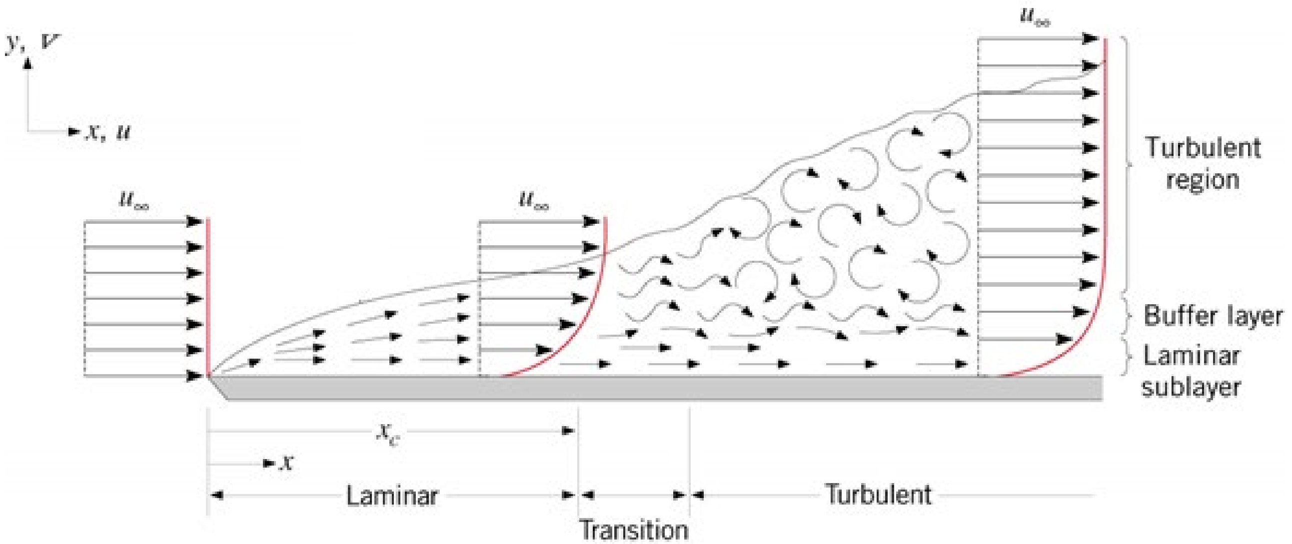
$$Nu = f\left(Re\,,Pr\right)$$

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

caracteriza o escoamento

caracteriza o fluido

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



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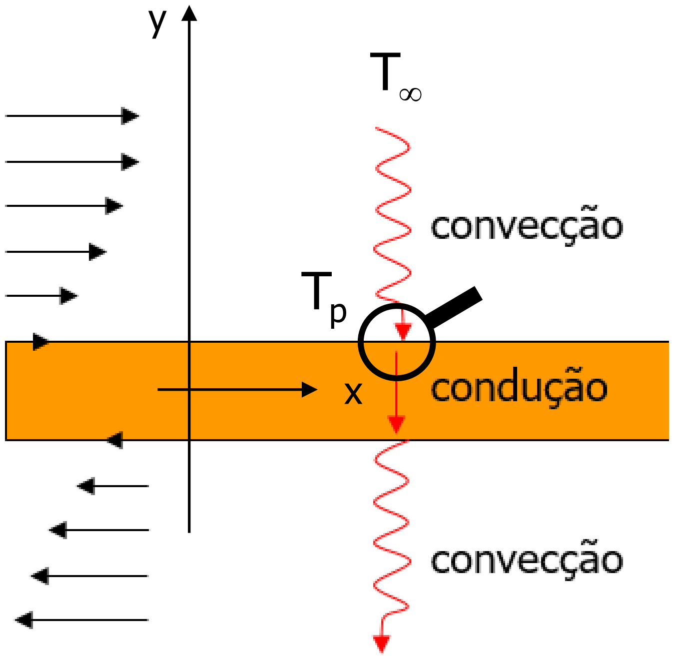
$$Nu \overset{def}{=} \frac{h_q}{k/D}$$

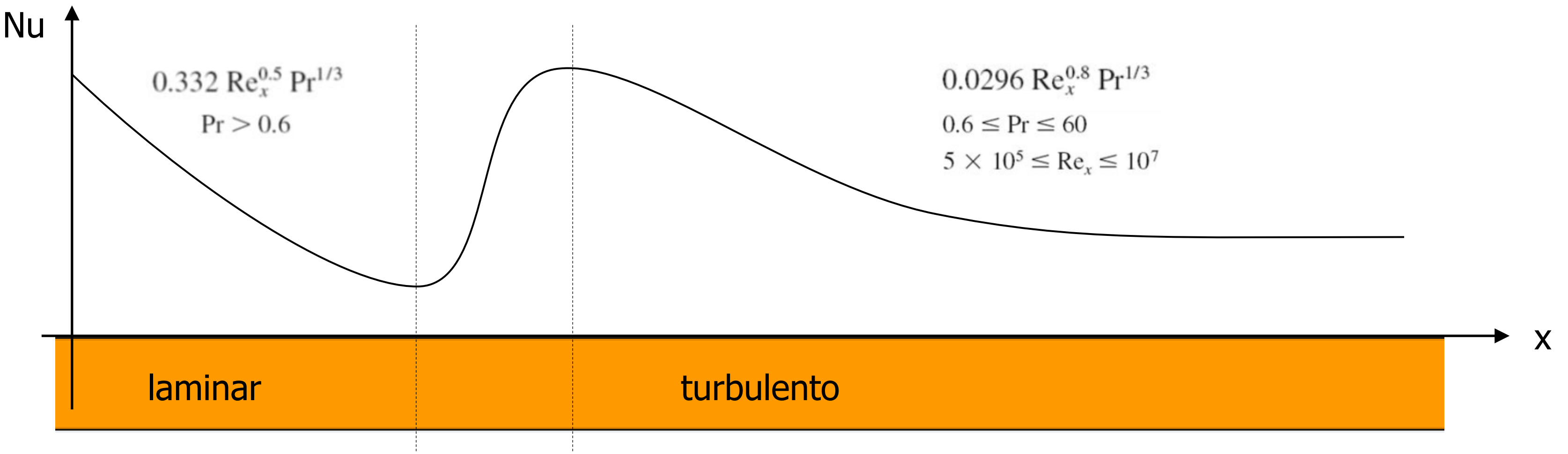


As equações diferenciais de balanço indicam que:

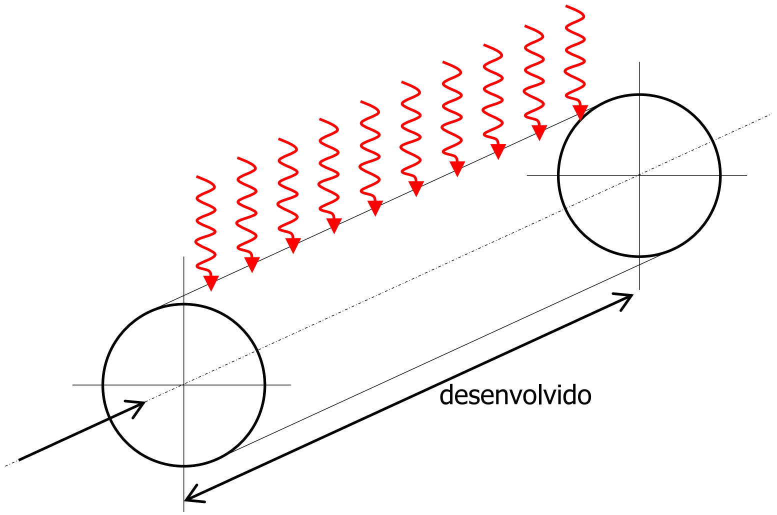
$$Nu = f(Re, Pr)$$

$$Re = \frac{\rho u_0 D}{\mu}$$ caracteriza o escoamento

caracteriza o fluido $$Pr = \frac{C_p \mu}{k}$$



Correlações para escoamentos internos...



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

Escoamento laminar:

Fluxo de calor constante: $Nu = 4.36$

Temperatura constante: $Nu = 3.66$

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

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

(Dittus-Boelter)

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

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

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

HOMEM DE FERRO

Avaliação P2

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

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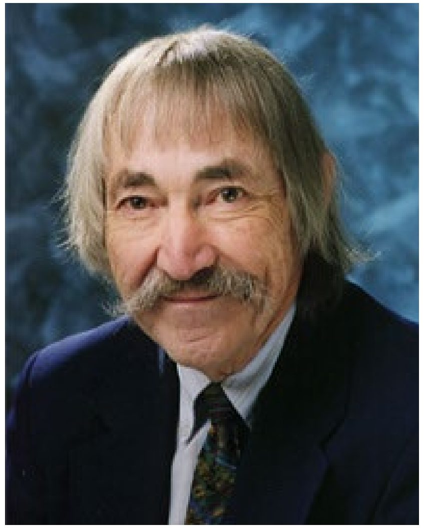
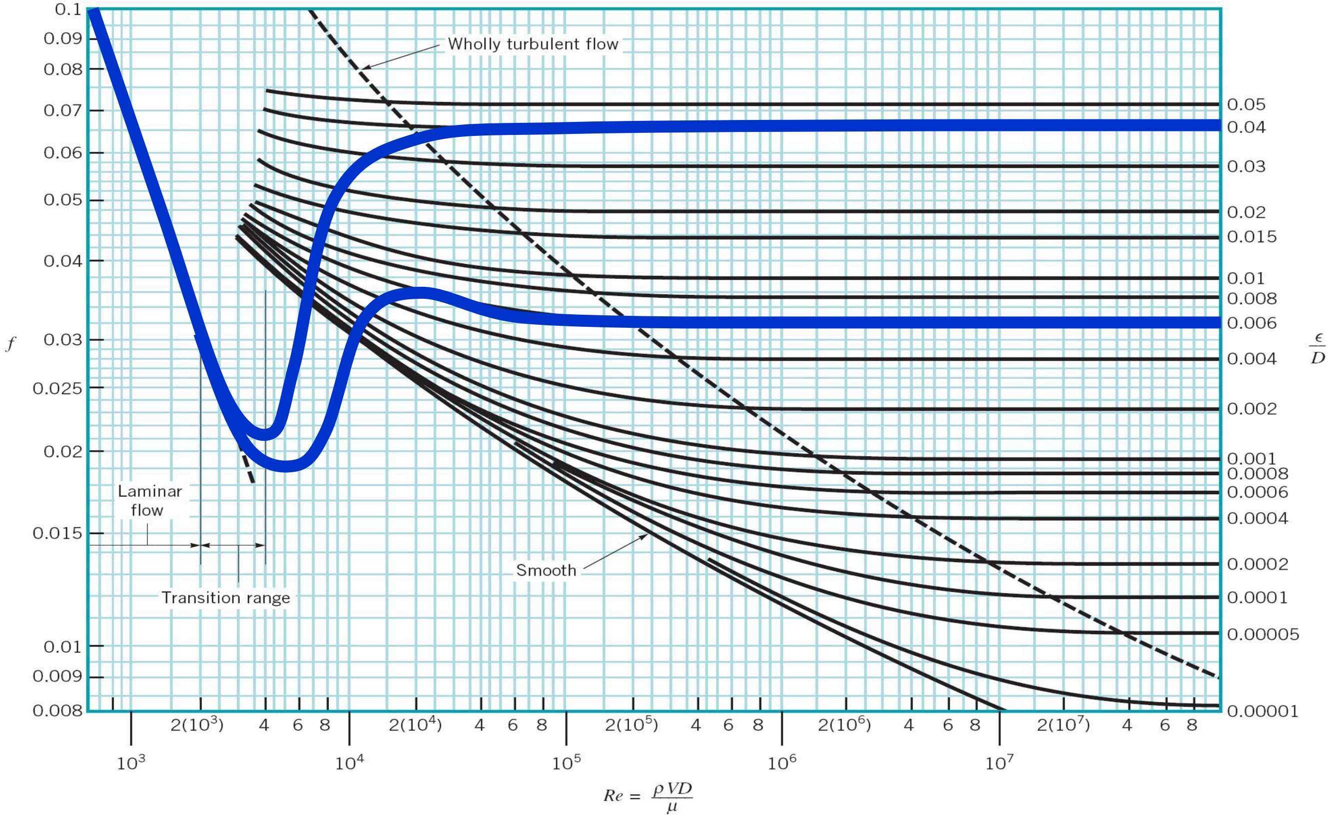
A equação de Darcy e cálculo do fator de atrito...

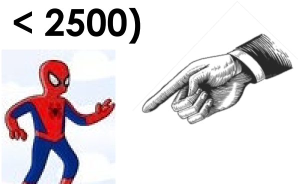


Stuart W. Churchill



Laminar (Re < 2500)

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



HOMEM ARANHA

Turbulento (Re > 4000)

Colebrook-White

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

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

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

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

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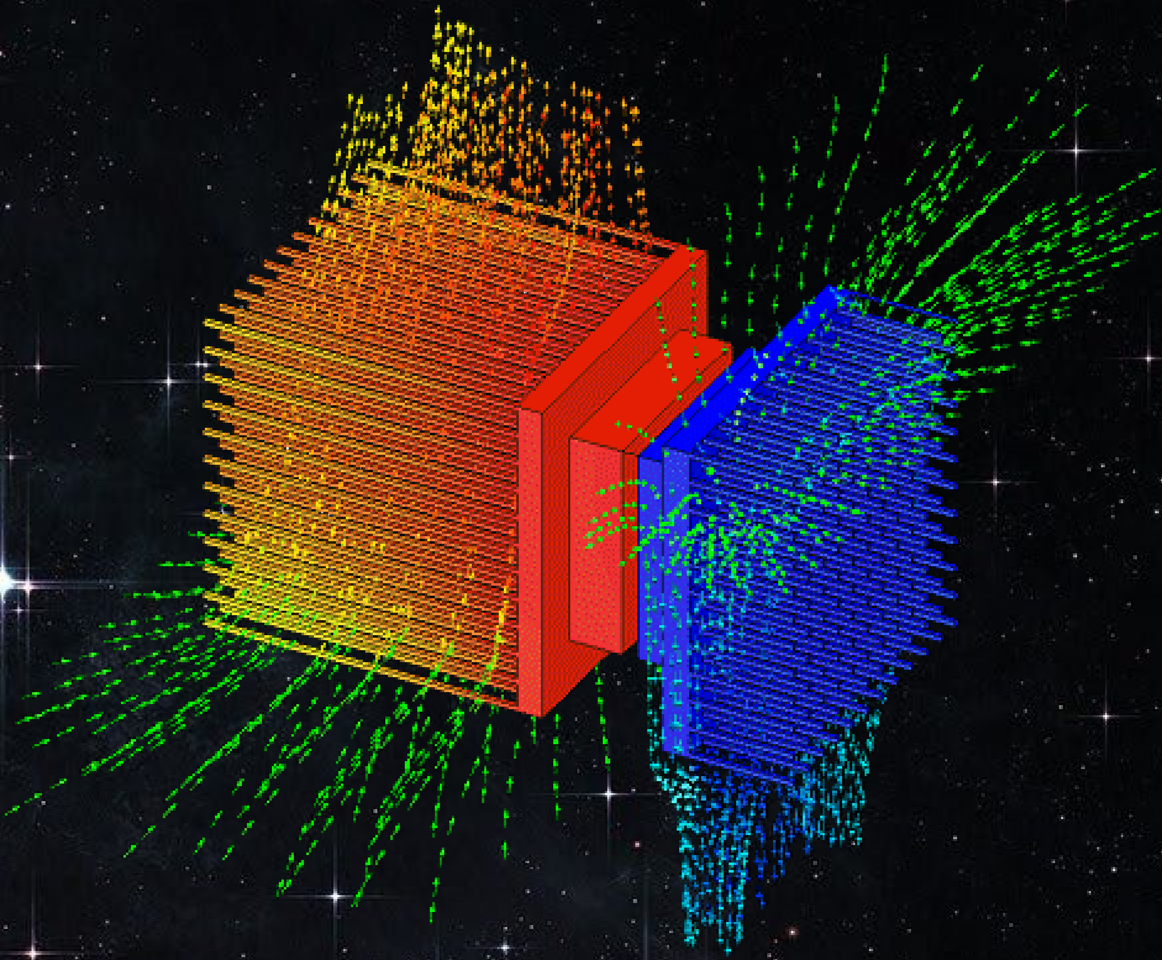
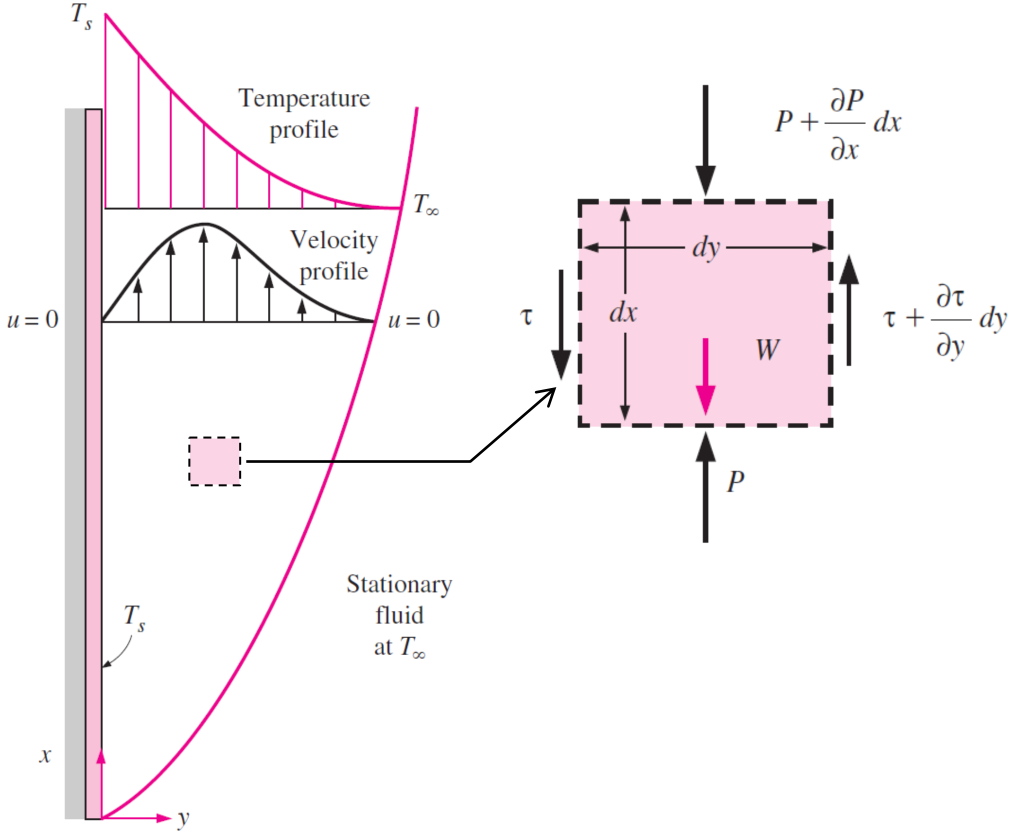
Convecção natural / escoamentos externos



Convecção natural: equações governantes e o número de Grashof...



$$F_x = a_x \cdot dm$$

$$a_x = \frac{du}{dt} = \frac{\partial u}{\partial x}\frac{dx}{dt} + \frac{\partial u}{\partial y}\frac{dy}{dt} = u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}$$

$$\frac{\partial P}{\partial y} = 0 \rightarrow \Downarrow \leftarrow \frac{\partial P}{\partial x} = -\rho_\infty g$$

$$\rightarrow \rho \cdot \left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} \right) = \mu \frac{\partial^2 u}{\partial y^2} + (\rho_\infty - \rho) g$$

$$\Downarrow \leftarrow \Delta\rho = \rho \cdot \beta \cdot \Delta T$$

Coef. expansão volumétrica

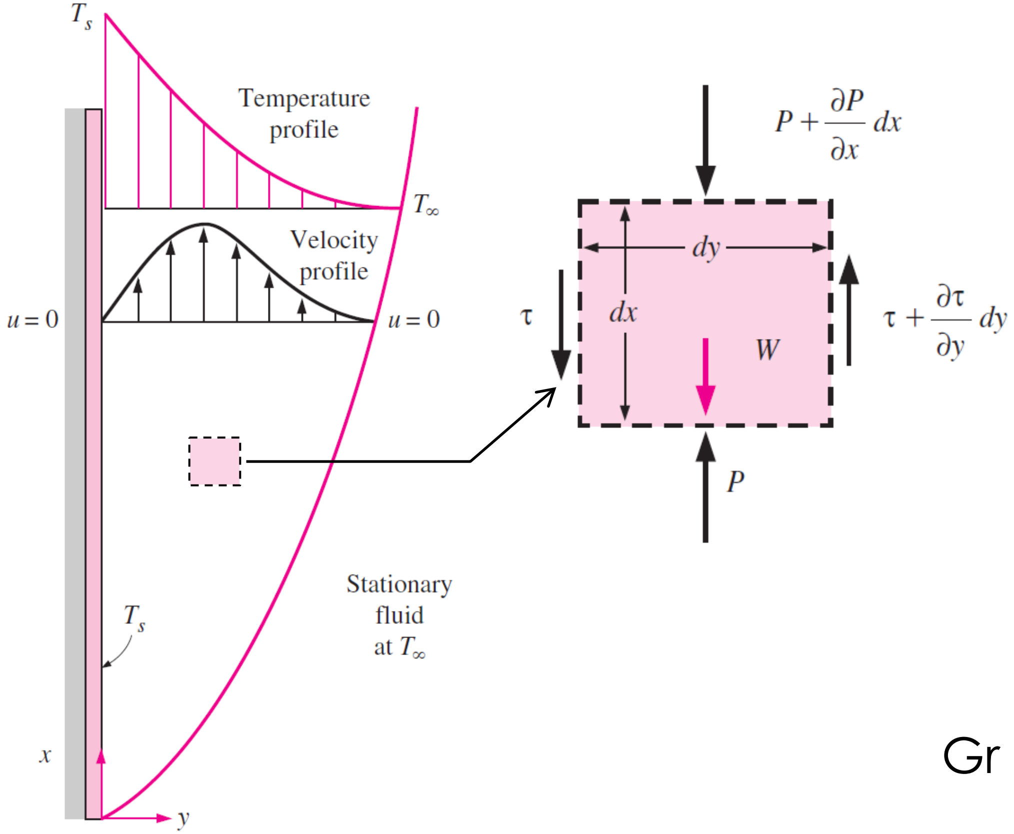
$$\rightarrow \rho \cdot \left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} \right) = \mu \frac{\partial^2 u}{\partial y^2} + g\beta \cdot (T - T_\infty)$$

Força de empuxo dependente da temperatura

p/ eq. convecção forçada

As questões postadas no Chat do YouTube serão respondidas ao final da aula.

Convecção natural: equações governantes e o número de Grashof...



$$x^* = \frac{x}{L}, \quad y^* = \frac{y}{L}, \quad u^* = \frac{u}{U}, \quad v^* = \frac{v}{U}, \quad T^* = \frac{T - T_\infty}{T_s - T_\infty}$$

$$\Big\Downarrow \text{ adimensionalização}$$

$$u^* \frac{\partial u^*}{\partial x^*} + v^* \frac{\partial u^*}{\partial y^*} = \frac{1}{Re} \frac{\partial^2 u^*}{\partial y^{*2}} + \left(\frac{g\beta(T_s - T_\infty)L^3}{\nu^2} \right) \cdot \frac{1}{Re} T^*$$

$$Gr = \frac{g\beta(T_s - T_\infty)L^3}{\nu^2} = \frac{\text{força de empuxo}}{\text{dissipação viscosa}}$$

Análogo de Reynolds para convecção natural...

$$Ra = Gr \cdot Pr$$

Forma genérica para o Nr. Nusselt:

$$Nu = C \cdot (Gr \cdot Pr)^n = C \cdot Ra^n$$

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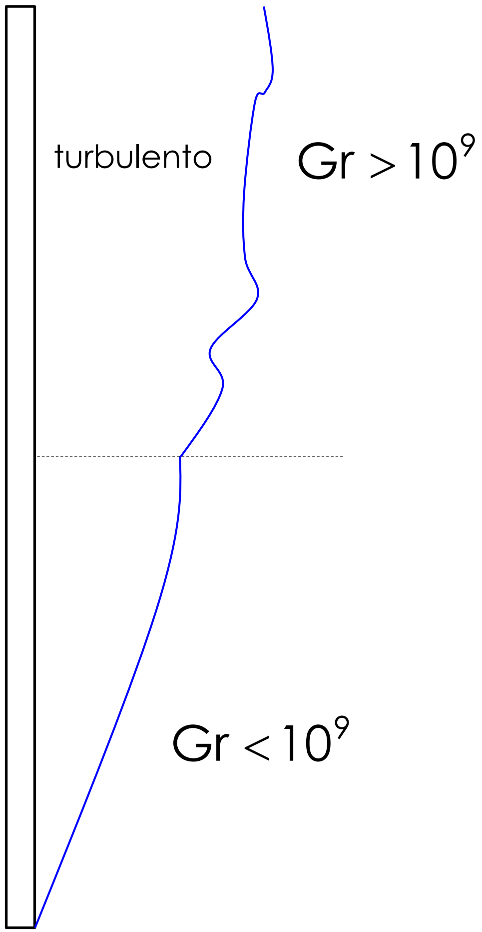
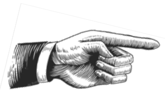
HE-MAN



Avaliação P2



MULHER-MARAVILHA

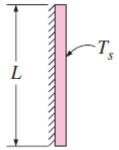
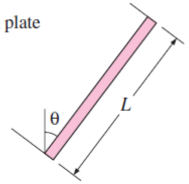
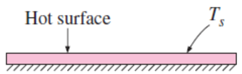
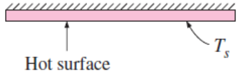
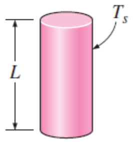
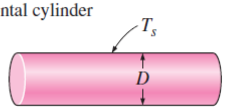
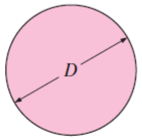
$$Q = hA_{lateral} \cdot (T - T_\infty)$$

$$Nu = C \cdot Ra^n$$

$$\text{properties @ } T_{fluid} = \left(\frac{T_s + T_\infty}{2}\right)$$

As questões postadas no Chat do YouTube serão respondidas ao final da aula.

Empirical correlations for the average Nusselt number for natural convection over surfaces

Geometry	Characteristic length L_c	Range of Ra	Nu
Vertical plate 	L	10^4–10^9 10^9–10^{13} Entire range	$Nu = 0.59Ra_L^{1/4}$ (9-19) $Nu = 0.1Ra_L^{1/3}$ (9-20) $Nu = \left\{0.825 + \frac{0.387Ra_L^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}}\right\}^2$ (9-21) (complex but more accurate)
Inclined plate 	L		Use vertical plate equations for the upper surface of a cold plate and the lower surface of a hot plate Replace g by $g\cos\theta$ for $Ra < 10^9$
Horiontal plate (Surface area A and perimeter p) (*a*) Upper surface of a hot plate (or lower surface of a cold plate)  (*b*) Lower surface of a hot plate (or upper surface of a cold plate) 	A_s/p	10^4–10^7 10^7–10^{11} 10^5–10^{11}	$Nu = 0.54Ra_L^{1/4}$ (9-22) $Nu = 0.15Ra_L^{1/3}$ (9-23) $Nu = 0.27Ra_L^{1/4}$ (9-24)
Vertical cylinder 	L		A vertical cylinder can be treated as a vertical plate when $D \geq \frac{35L}{Gr_L^{1/4}}$
Horizontal cylinder 	D	$Ra_D \leq 10^{12}$	$Nu = \left\{0.6 + \frac{0.387Ra_D^{1/6}}{[1 + (0.559/Pr)^{9/16}]^{8/27}}\right\}^2$ (9-25)
Sphere 	D	$Ra_D \leq 10^{11}$ $(Pr \geq 0.7)$	$Nu = 2 + \frac{0.589Ra_D^{1/4}}{[1 + (0.469/Pr)^{9/16}]^{4/9}}$ (9-26)

A CONVECÇÃO DE CALOR – ABORDAGEM NUMÉRICA...

movimentação do fluido ↔ transporte de energia térmica

TUTORIAL CFD ANSYS/FLUENT: PROJETO DE UM AQUECEDOR DE AR

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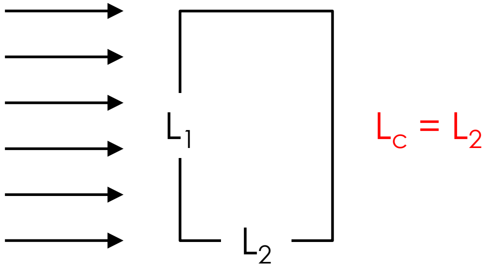
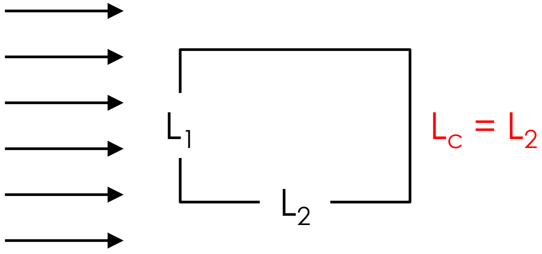
Avaliação P2





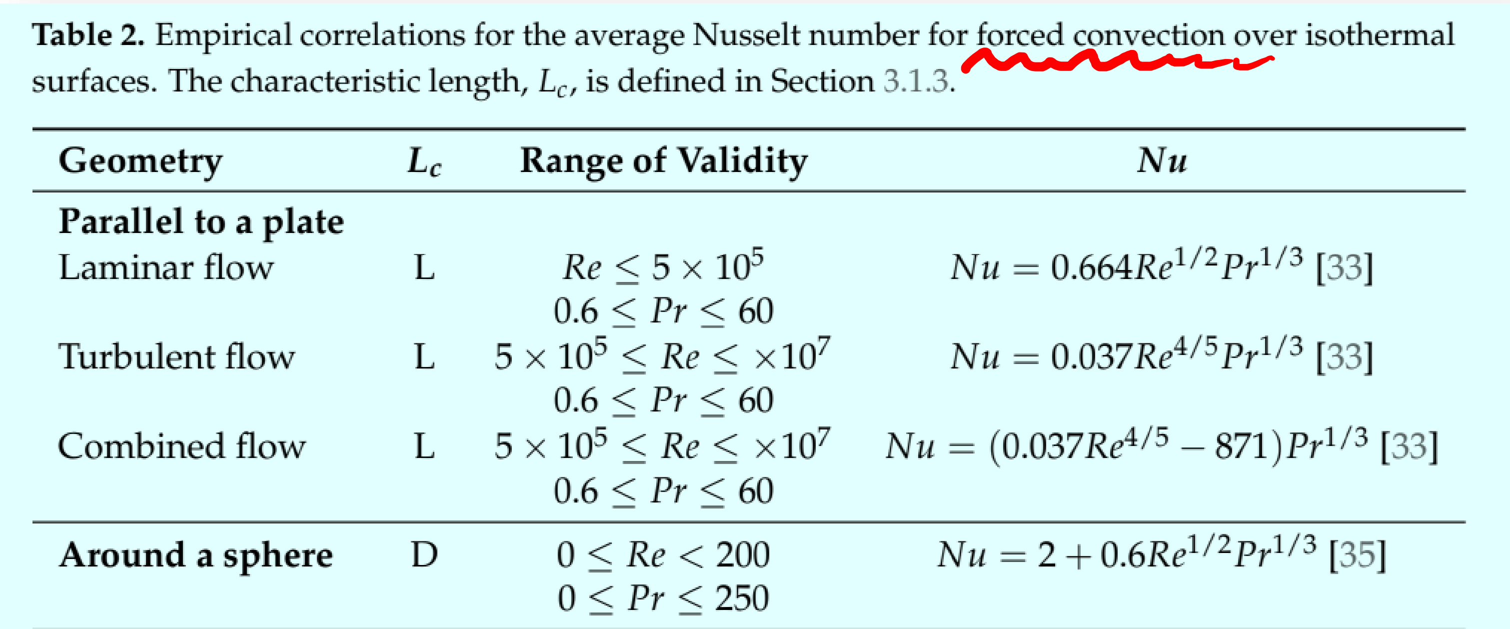


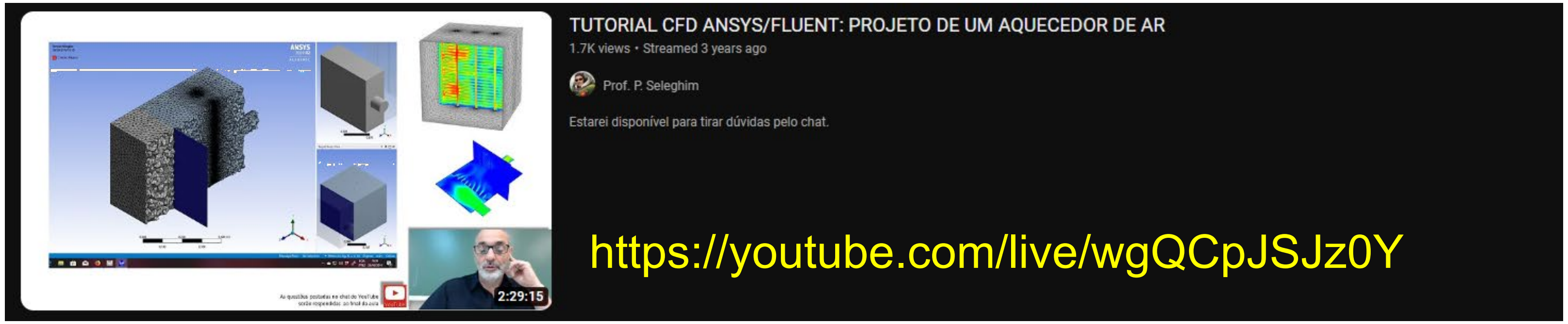
Table 2. Empirical correlations for the average Nusselt number for forced convection over isothermal surfaces. The characteristic length, L_c, is defined in Section 3.1.3.

Geometry	L_c	Range of Validity	Nu
Parallel to a plate			
Laminar flow	L	$Re \leq 5 \times 10^5$ $0.6 \leq Pr \leq 60$	$Nu = 0.664 Re^{1/2} Pr^{1/3}$ [33]
Turbulent flow	L	$5 \times 10^5 \leq Re \leq \times 10^7$ $0.6 \leq Pr \leq 60$	$Nu = 0.037 Re^{4/5} Pr^{1/3}$ [33]
Combined flow	L	$5 \times 10^5 \leq Re \leq \times 10^7$ $0.6 \leq Pr \leq 60$	$Nu = (0.037 Re^{4/5} - 871) Pr^{1/3}$ [33]
Around a sphere	D	$0 \leq Re < 200$ $0 \leq Pr \leq 250$	$Nu = 2 + 0.6 Re^{1/2} Pr^{1/3}$ [35]

[33] Welty, J.; Rorrer, G.L.; Foster, D.G. Fundamentals of Momentum, Heat and Mass Transfer; John Wiley & Sons: New York, NY, USA, 2014.

[35] Ranz, W.E.; Marshall, W.R. Evaporation from Drops. Chem. Eng. Prog. 1952, 48, 141–146.

Maragkos, Georgios, and Tarek Beji. "Review of convective heat transfer modelling in CFD simulations of fire-Driven Flows." *Applied Sciences* 11.11 (2021): 5240.



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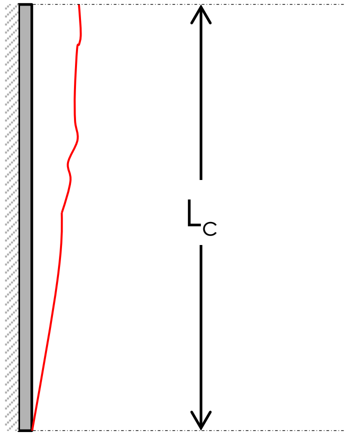
Avaliação P2

CAPITÃO
AMÉRICA



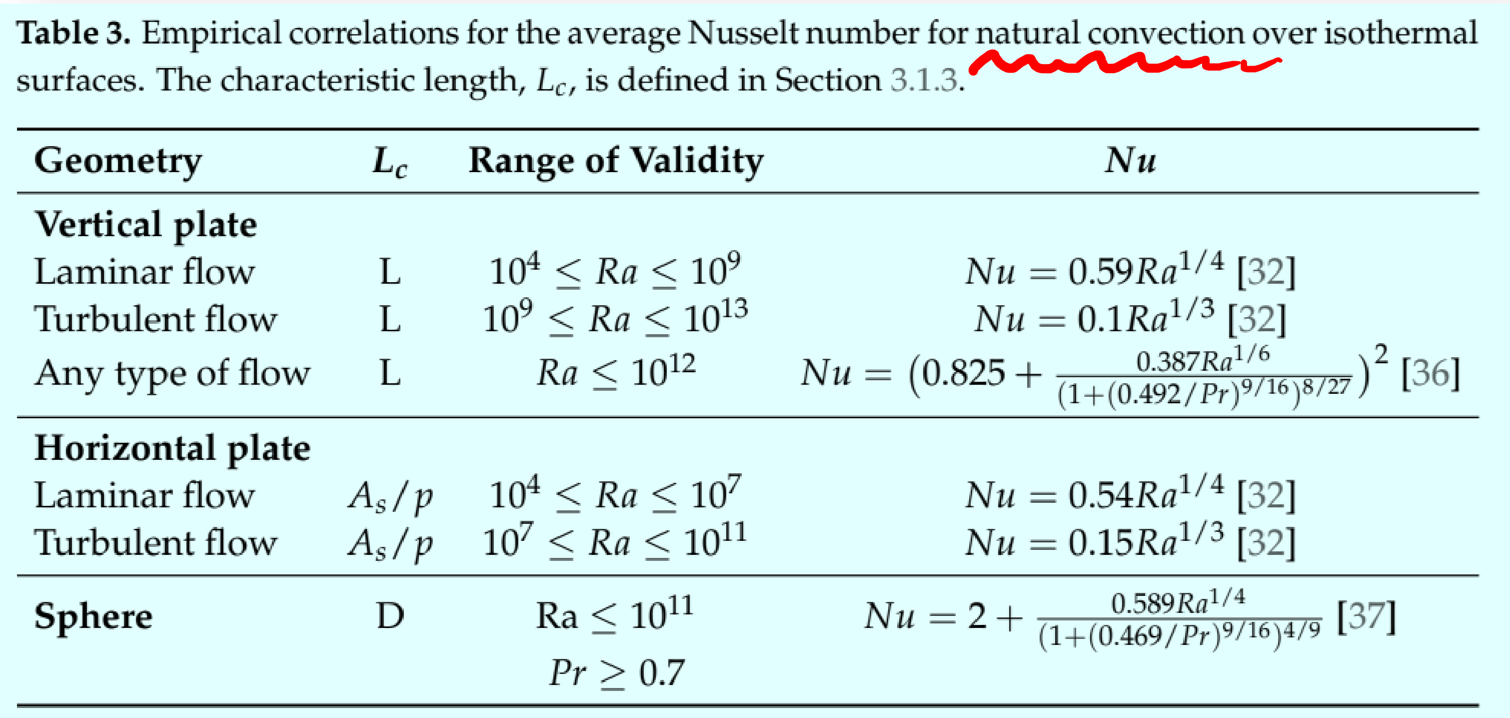
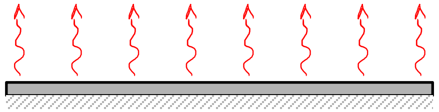


Table 3. Empirical correlations for the average Nusselt number for natural convection over isothermal surfaces. The characteristic length, L_c, is defined in Section 3.1.3.

Geometry	L_c	Range of Validity	Nu
Vertical plate			
Laminar flow	L	$10^4 \leq Ra \leq 10^9$	$Nu = 0.59Ra^{1/4}$ [32]
Turbulent flow	L	$10^9 \leq Ra \leq 10^{13}$	$Nu = 0.1Ra^{1/3}$ [32]
Any type of flow	L	$Ra \leq 10^{12}$	$Nu = \left(0.825 + \frac{0.387Ra^{1/6}}{(1+(0.492/Pr)^{9/16})^{8/27}}\right)^2$ [36]
Horizontal plate			
Laminar flow	A_s/p	$10^4 \leq Ra \leq 10^7$	$Nu = 0.54Ra^{1/4}$ [32]
Turbulent flow	A_s/p	$10^7 \leq Ra \leq 10^{11}$	$Nu = 0.15Ra^{1/3}$ [32]
Sphere	D	Ra $\leq 10^{11}$ $Pr \geq 0.7$	$Nu = 2 + \frac{0.589Ra^{1/4}}{(1+(0.469/Pr)^{9/16})^{4/9}}$ [37]



L_C = Area/perímetro

[32] McAdams, W.H. Heat Transmission; McGraw-Hill Book Company: New York, NY, USA, 1957.

[36] Churchill, S.W.; Chu, H.H.S. Correlating Equations for Laminar and Turbulent Free Convection from a Vertical Plate. Int. J. Heat Mass Transf. 1975, 18, 1323–1329. [CrossRef]

[37] Churchill, S.W. Free Convection around Immersed Bodies. In Heat Exchanger Design Handbook; Hemisphere Publishing: New York, NY, USA, 1983.

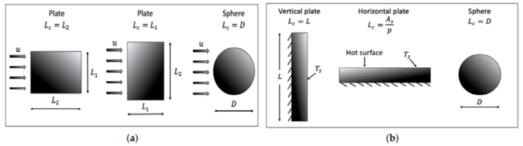


Figure 1. Characteristic length, L_c, for (**a**) forced and (**b**) natural convection scenarios. A_s and p are the surface area and perimeter of the plate, respectively.

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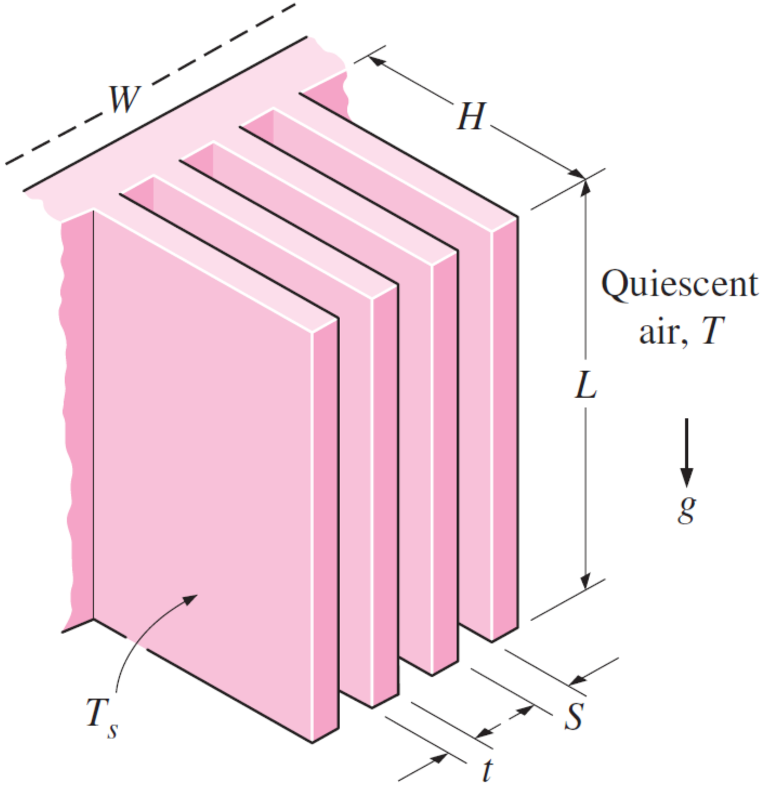
Convecção natural em superfícies aletadas @ T_s = cte ...



$$Ra_S = \frac{g\beta(T_s - T_\infty)\cdot S^3}{\nu^2}Pr \quad ou \quad Ra_L = \frac{g\beta(T_s - T_\infty)\cdot L^3}{\nu^2}Pr$$

$$Nu = \frac{hS_{opt}}{k} = \left[\frac{576}{(Ra_S \cdot S/L)^2} + \frac{2.873}{(Ra_S \cdot S/L)^{0.5}}\right]^{-0.5}$$

Avaliação P2

Bar-Cohen and Rohsenow

AQUAMAN

Espaçamento ótimo (trade-off área x vazão):

$$@\ T_s = cte \ \rightarrow\ S_{opt} = 2.714\frac{L}{Ra_L^{0.25}} \rightarrow Nu = 1.307$$

$$Q = h\cdot(2nLH)\cdot(T_s - T_\infty) \quad \leftarrow \ t << S$$

$$properties\ @\ T_{avg} = (T_s + T_\infty)/2$$

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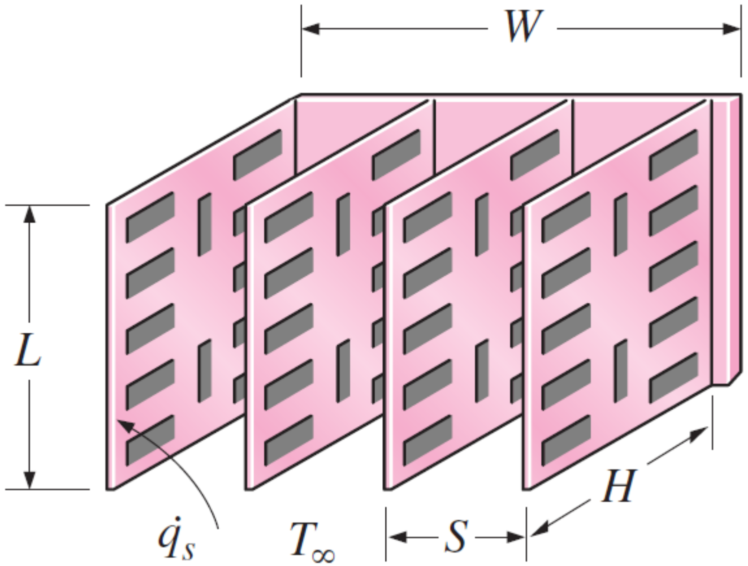
Convecção natural em superfícies aletadas @ q_s = cte ...



$$Ra_S = \frac{g\beta q_s \cdot S^4}{k\nu^2} Pr$$

$$Nu = \frac{hL}{k} = \left[\frac{48}{Ra_S \cdot S/L} + \frac{2.51}{(Ra_S \cdot S/L)^{0.4}} \right]^{-0.5}$$

Avaliação P2

Bar-Cohen and Rohsenow

TARTARUGA NINJA

Espaçamento ótimo (trade-off área x vazão):

$$@\ q_s = cte \ \rightarrow \ S_{opt} = 2.12 \cdot \left(\frac{S^4 L}{Ra_S} \right)^{0.2}$$

$$Q = q_s \cdot (2nLH) \quad \leftarrow \ t \ll S$$

$$\text{properties } @\ T_{avg} = (T_L + T_\infty)/2 \quad \leftarrow T_L = T_\infty + q_s / h$$

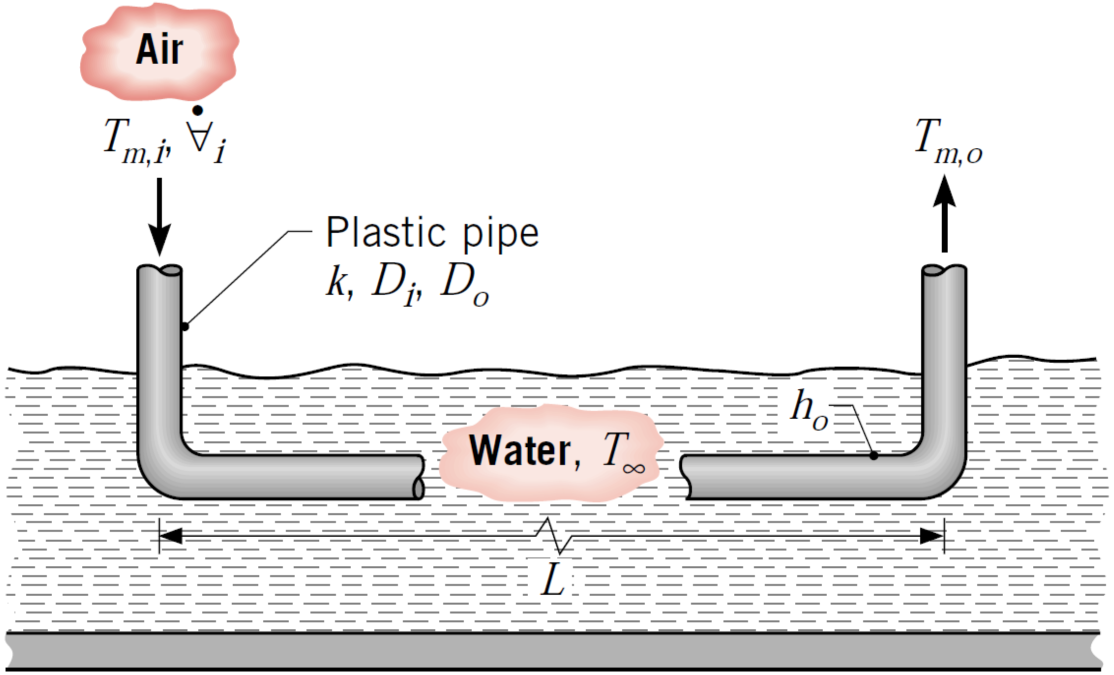
temperatura crítica ocorrendo na borda superior

As questões postadas no Chat do YouTube serão respondidas ao final da aula.

A CONVECÇÃO DE CALOR – ABORDAGEM EMPÍRICA...

exercício resolvido – tutorial excel

8.31: Para resfriar uma casa de verão sem uso de um ciclo frigorífico, ar é encaminhado através de uma tubulação de plástico ($k=0.15W/m/K$, $D_i=0.15m$, $D_0=0.17m$) submersa em um corpo d’água adjacente. A temperatura da água é normalmente de $T_\infty=17°C$, e o coeficiente de convecção é mantido em $h_o=1500\ W/m^2/K$ na superfície externa da tubulação. Se ar proveniente da casa entra no tubo a uma temperatura de $T_{m,i}=29°C$ e uma vazão volumétrica de $V_i=0.025m^3/s$, qual extensão L é necessária para que a temperatura na saída seja de $T_{m,o}=21°C$?



Próxima aula ?

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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 ($k=0.15 W/m/K$, $D_i=0.15m$, $D_0=0.17m$) submersa em um corpo d'água adjacente. A temperatura da água é normalmente de $T_\infty=17°C$, e o coeficiente de convecção é mantido em $h_o=1500\ W/m^2/K$ na superfície externa da tubulação. Se ar proveniente da casa entra no tubo a uma temperatura de $T_{m,i}=29°C$ e uma vazão volumétrica de $V_i=0.025m^3/s$, qual extensão L é necessária para que a temperatura na saída seja de $T_{m,o}=21°C$?

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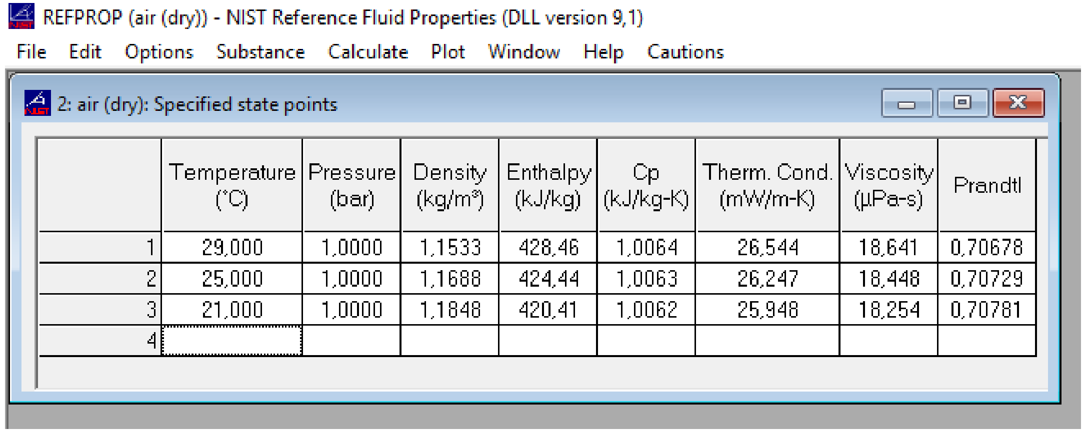

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Cp (kJ/kg-K)	Therm. Cond. (mW/m-K)	Viscosity (μPa-s)	Prandtl
1	29,000	1,0000	1,1533	428,46	1,0064	26,544	18,641	0,70678
2	25,000	1,0000	1,1688	424,44	1,0063	26,247	18,448	0,70729
3	21,000	1,0000	1,1848	420,41	1,0062	25,948	18,254	0,70781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

$$Q = \dot{m} \cdot (\hbar_i - \hbar_o) = \rho_i V_i \cdot (\hbar_i - \hbar_o)$$

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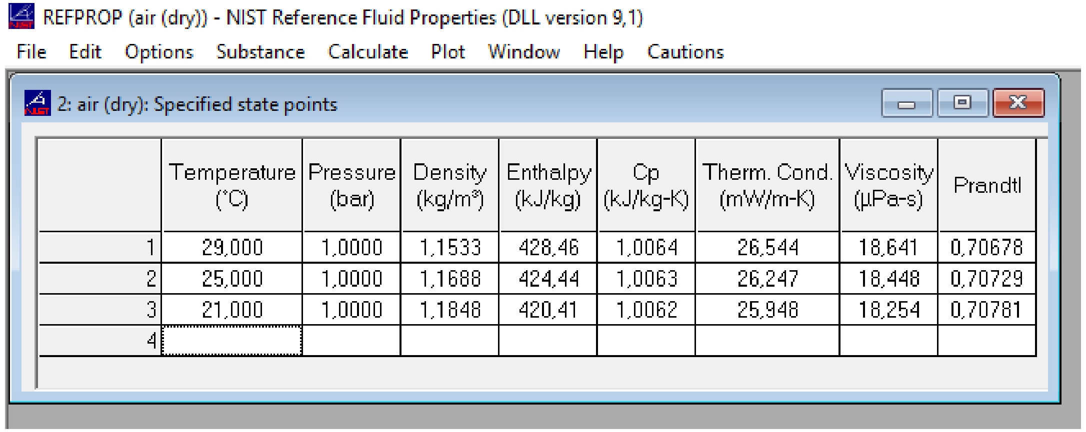

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$$Q = 1.1533 \frac{kg}{m^3} 0.025 \frac{m^3}{s} \cdot (428.46 - 420.41) \frac{kJ}{kg}$$

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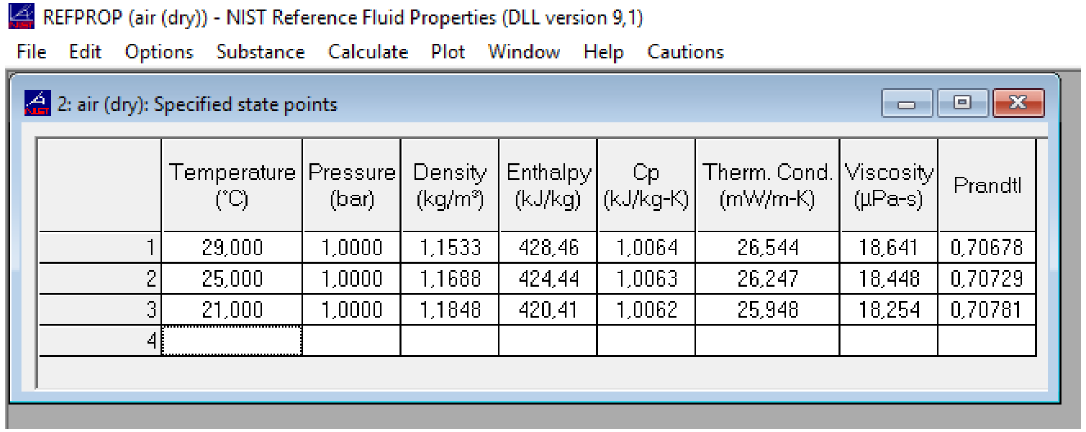

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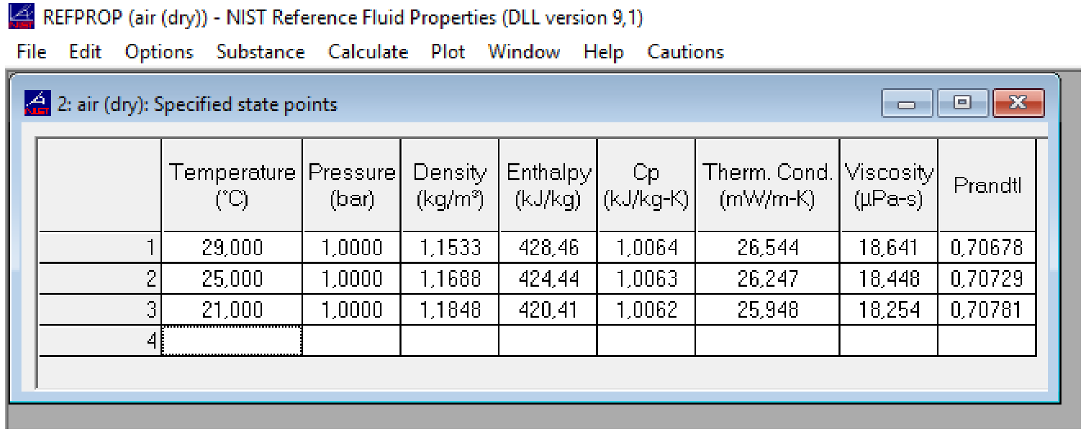
$$Q = \dot{m} \cdot (\hbar_i - \hbar_o) = \rho_i V_i \cdot (\hbar_i - \hbar_o)$$

$$Q = \underbrace{1.1533 \frac{kg}{m^3} 0.025 \frac{m^3}{s}}_{\dot{m} = 0.02883 kg/s} \cdot (428.46 - 420.41) \frac{kJ}{kg}$$

8.31: Para resfriar uma casa de verão sem uso de um ciclo frigorífico, ar é encaminhado através de uma tubulação de plástico (k=0.15W/m/K, D_i=0.15m, D_0=0.17m) submersa em um corpo d'água adjacente. A temperatura da água é normalmente de T_∞=17°C, e o coeficiente de convecção é mantido em h_o=1500 W/m²/K na superfície externa da tubulação. Se ar proveniente da casa entra no tubo a uma temperatura de $T_{m,i}$=29°C e uma vazão volumétrica de V_i=0.025m³/s, qual extensão L é necessária para que a temperatura na saída seja de $T_{m,o}$=21°C ?



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

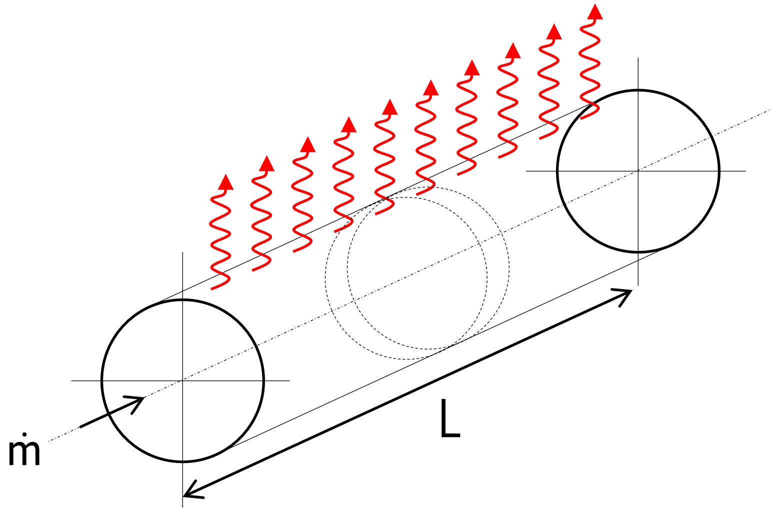
$$\dot{m} = 0.02883\,kg/s$$

$$\boxed{Q = 0.2321\,kW}$$

As questões postadas no Chat do YouTube serão respondidas ao final da aula.

Equação do decaimento da temperatura ao longo da tubulação

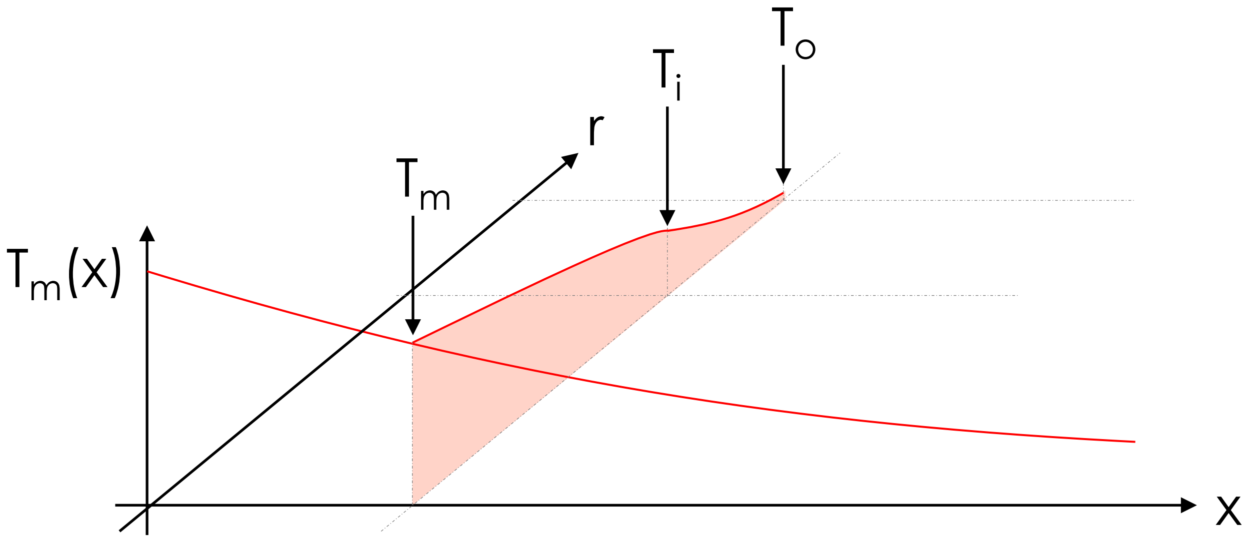
Balanço global de energia...



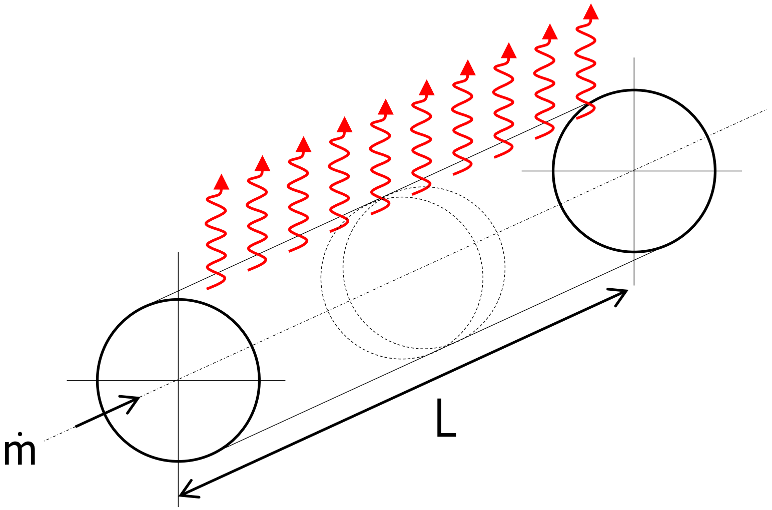
p = perímetro

$T_m(x)$ → perfil axial de temperaturas

$T_r(x)$ → perfil radial de temperaturas

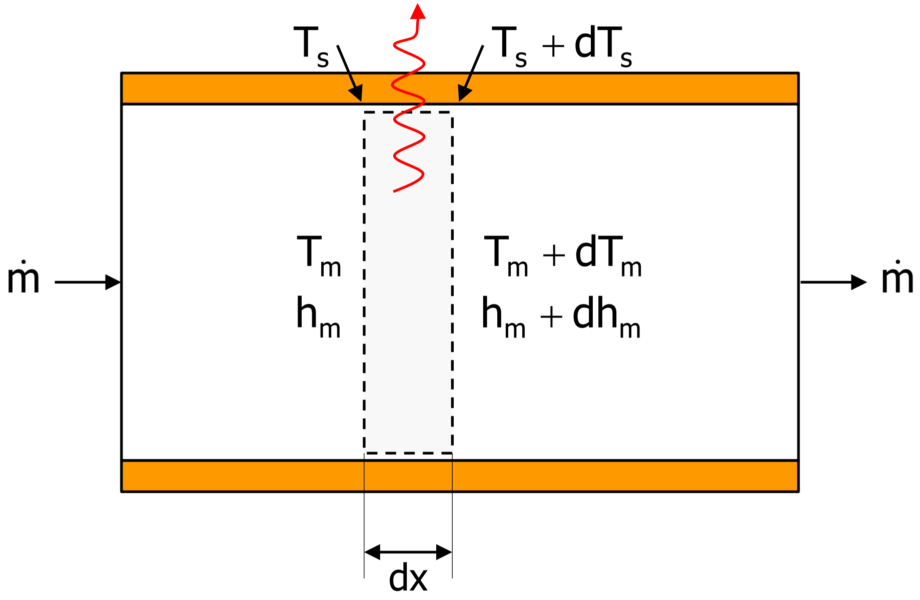


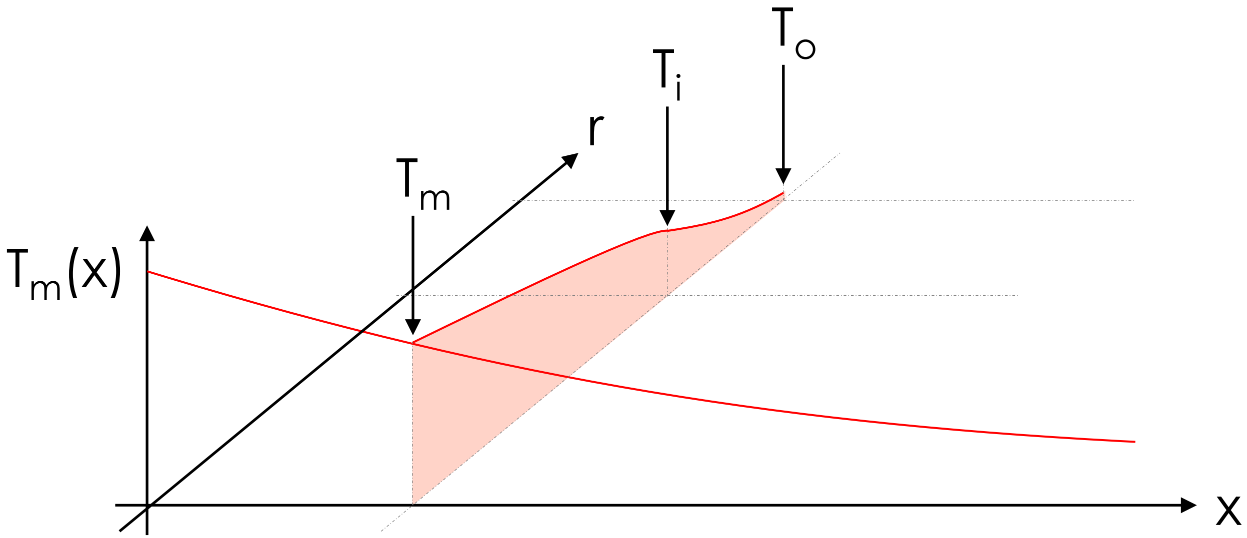
Balanço global de energia...



p = perímetro

$$dQ_{conv} = pdx \cdot q_{conv}$$





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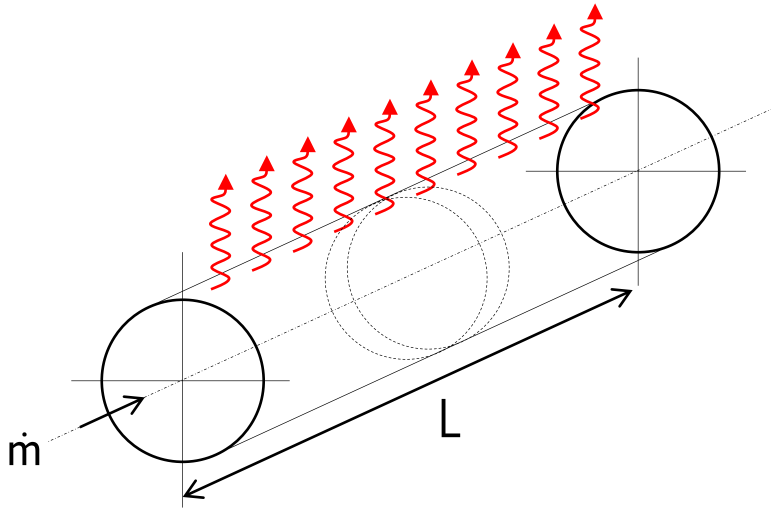
Balanço global de energia...



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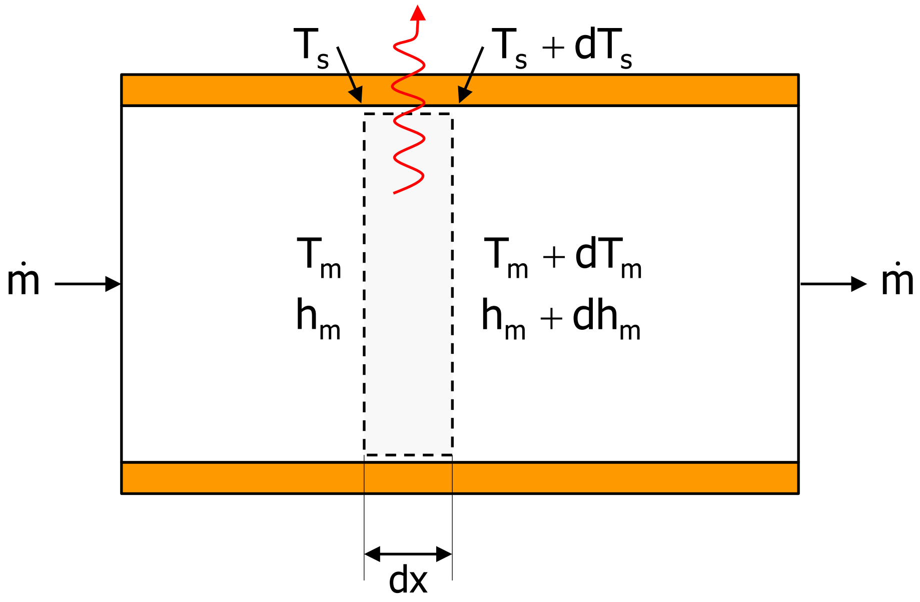

$$\dot{Q} - \dot{W} = \sum_{sai} \dot{m}_k \cdot \left(\hbar_k + \cancel{gz_k} + \cancel{V_k^2} / 2\right) - \sum_{entra} \dot{m}_k \cdot \left(\hbar_k + \cancel{gz_k} + \cancel{V_k^2} / 2\right)$$

$$pq_{conv}dx = \dot{m} \cdot (\cancel{\hbar_m} + d\hbar_m) - \dot{m} \cdot \cancel{\hbar_m}$$

$$q_{conv} = h_{conv} \cdot (T_s - T_m) \rightarrow \boxed{\dot{m} \cdot \frac{d\hbar_m}{dx} - ph_{conv} \cdot (T_s - T_m) = 0}$$

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Balanço global de energia...

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

Solução direta via método numérico de solução de equação diferencial

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

Implementação numérica...

As questões postadas no Chat do YouTube serão respondidas ao final da aula.

Balanço global de energia...

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

Solução direta via método numérico de solução de equação diferencial

$$\hbar = \hbar(P, T)$$

Implementação numérica...

Solução analítica a partir de hipóteses simplificadoras

$$\hbar = C_p \cdot T$$

gases perfeitos
“fluido incompressível” (C_p=C_v)

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

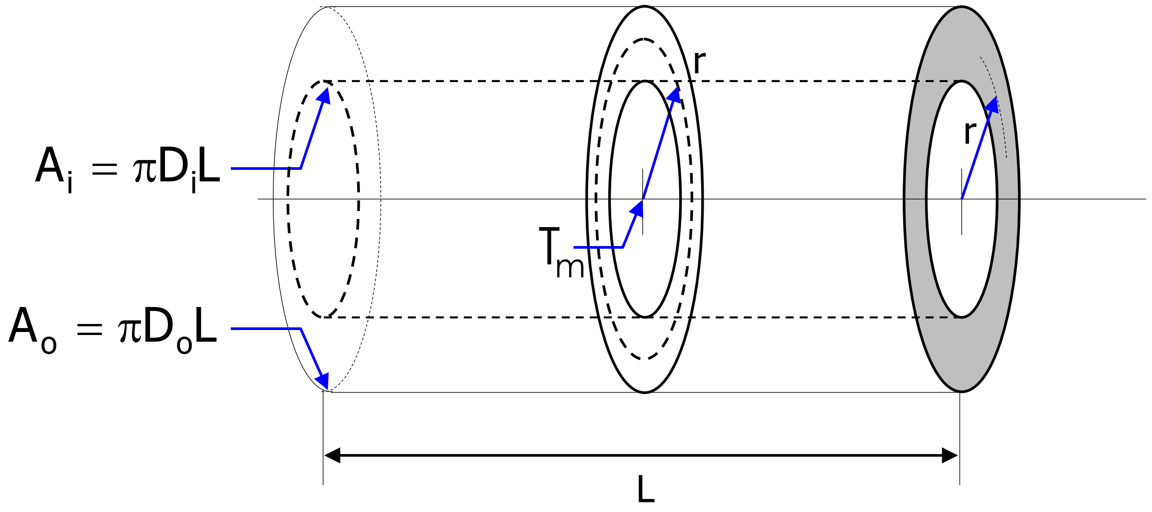
Fluxo de calor constante →

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

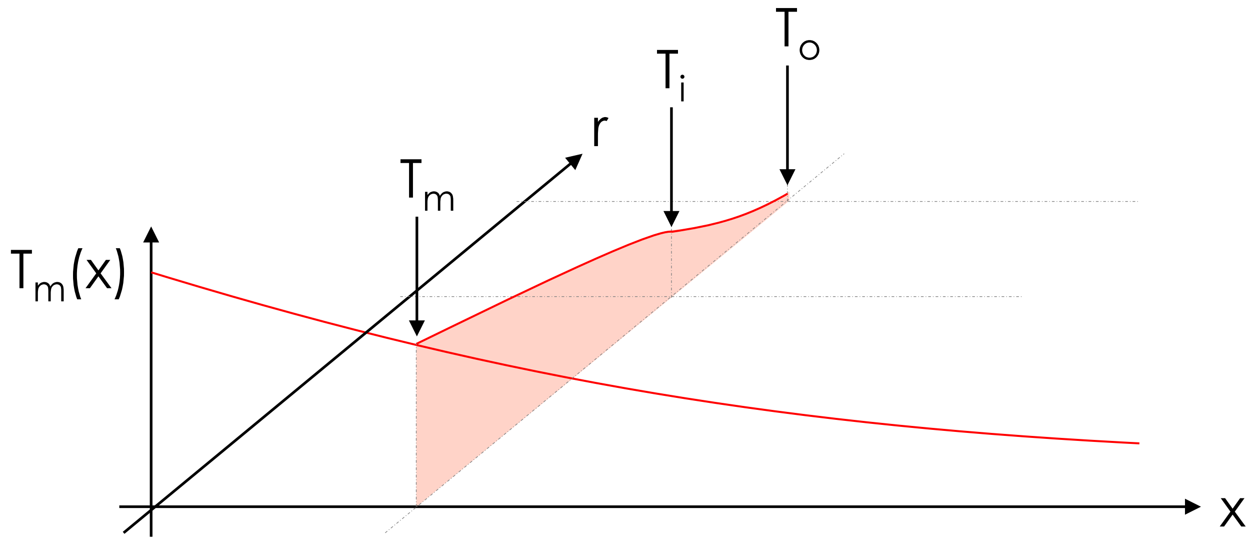
Temperatura superficial constante →

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

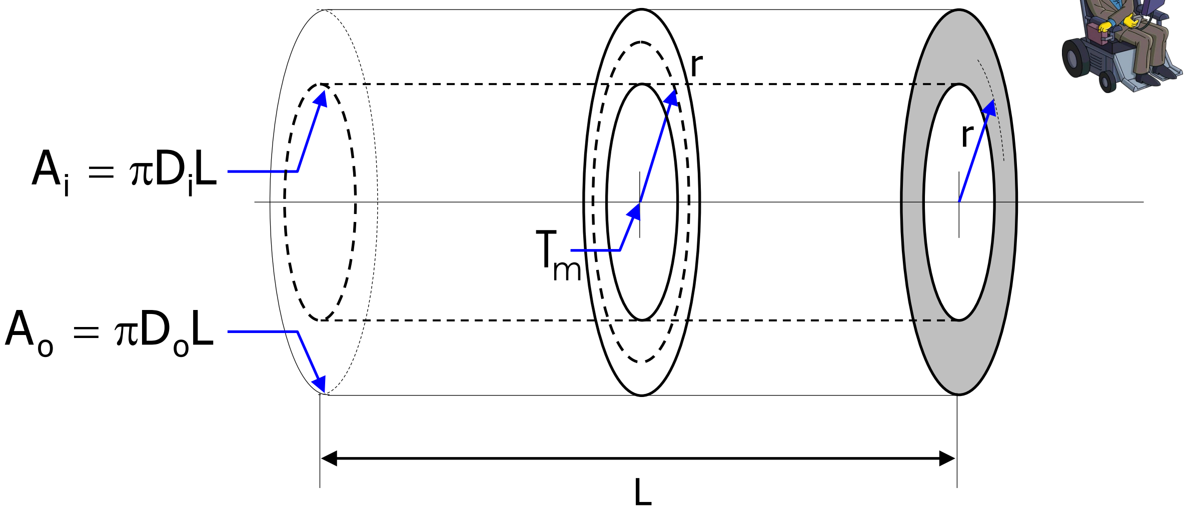
Geometria cilíndrica... **variação radial da temperatura**



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



Geometria cilíndrica... variação radial da temperatura



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

$$\rightarrow \frac{dT}{dr}=\cancel{C_1}+\frac{C_2}{r} \qquad \text{Obs.: } \lim_{r\rightarrow\infty}\frac{dT}{dr}=0$$

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

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

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

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

Equação do decaimento radial da temperatura

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

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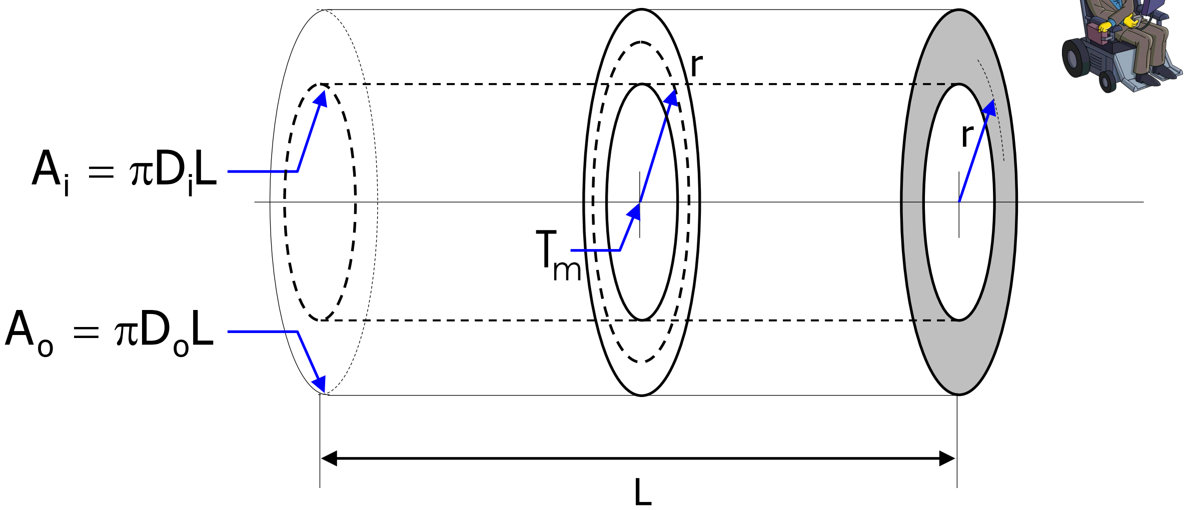
Geometria cilíndrica... variação radial da temperatura



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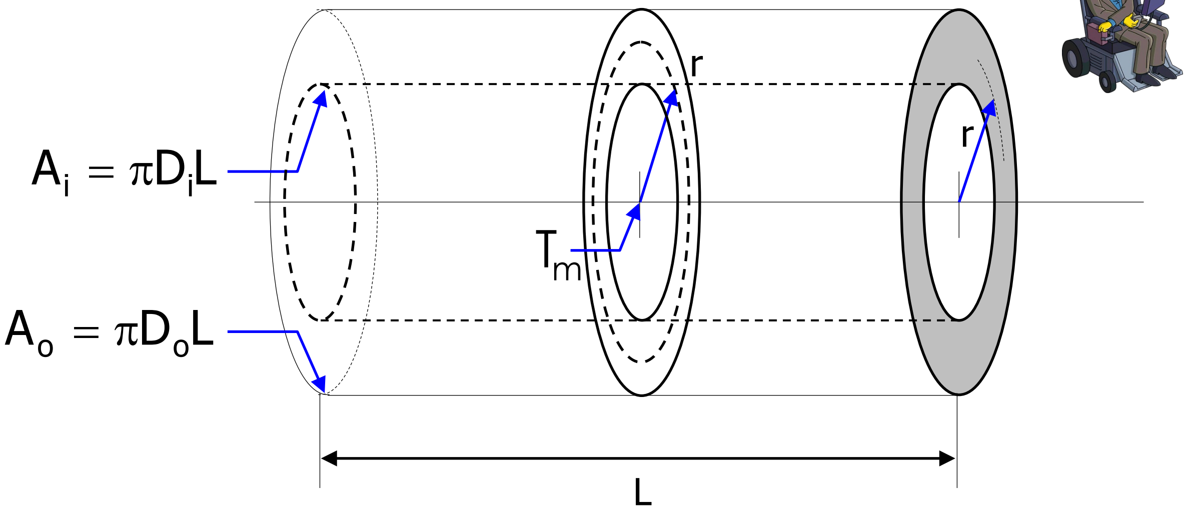

$$\vec{\nabla} \cdot (k\vec{\nabla}T) = 0 \rightarrow \quad \frac{d}{dr}\left(kr\frac{dT}{dr}\right) = 0$$

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

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

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

$$Q = h_i A_i (T_i - T_m) \rightarrow T_i = \frac{Q}{h_i A_i} + T_m$$

$$Q = h_o A_o (T_o - T_\infty) \rightarrow T_o = \frac{Q}{h_o A_o} - T_\infty$$

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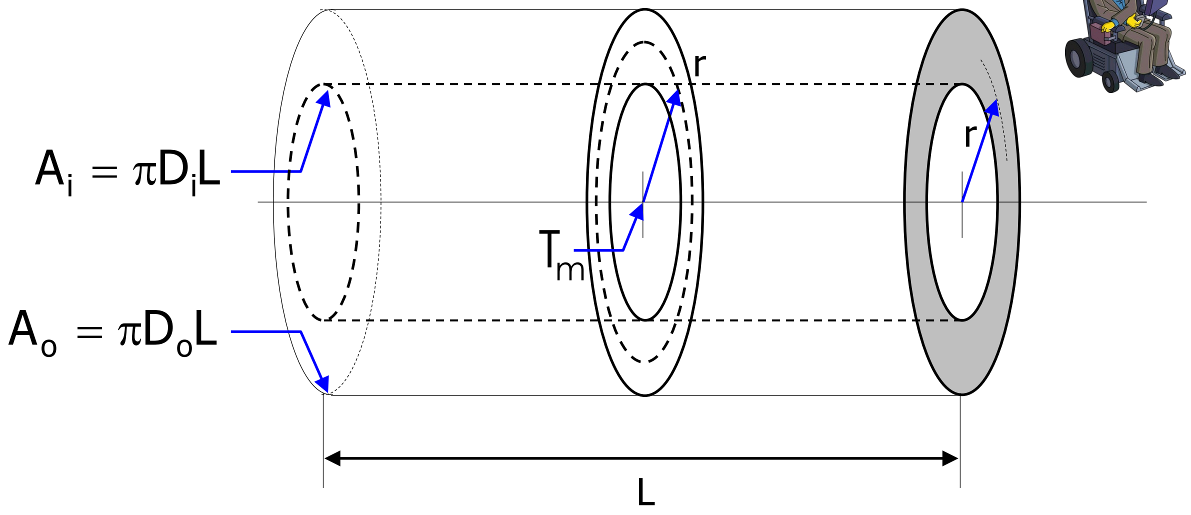
Geometria cilíndrica... variação radial da temperatura



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

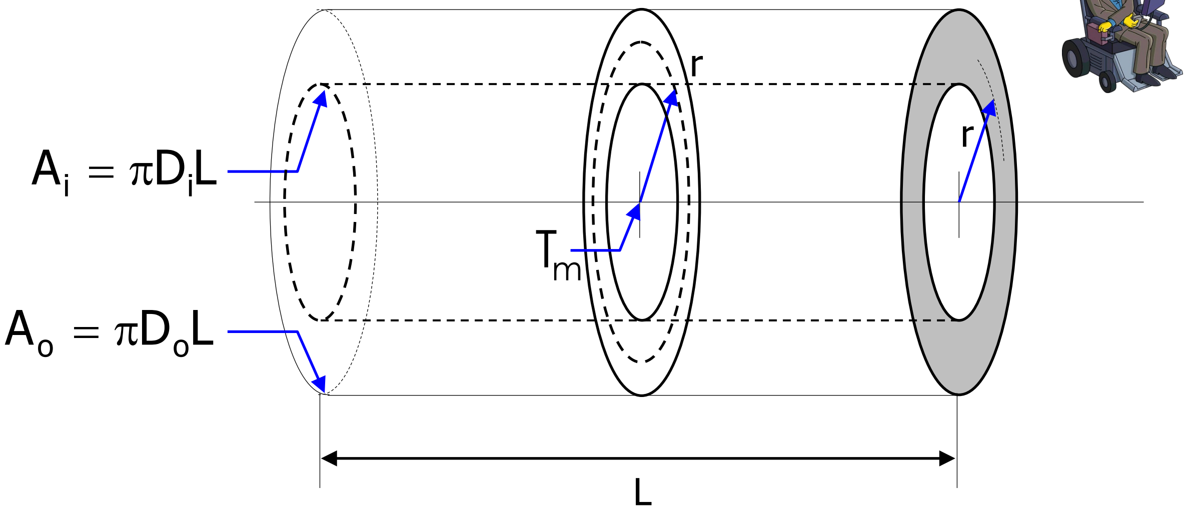
$$T(r)=T_i+\frac{T_o-T_i}{\ln(r_o/r_i)}\cdot\ln\left(\frac{r}{r_i}\right)$$

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

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

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

Geometria cilíndrica... variação radial da temperatura



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

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

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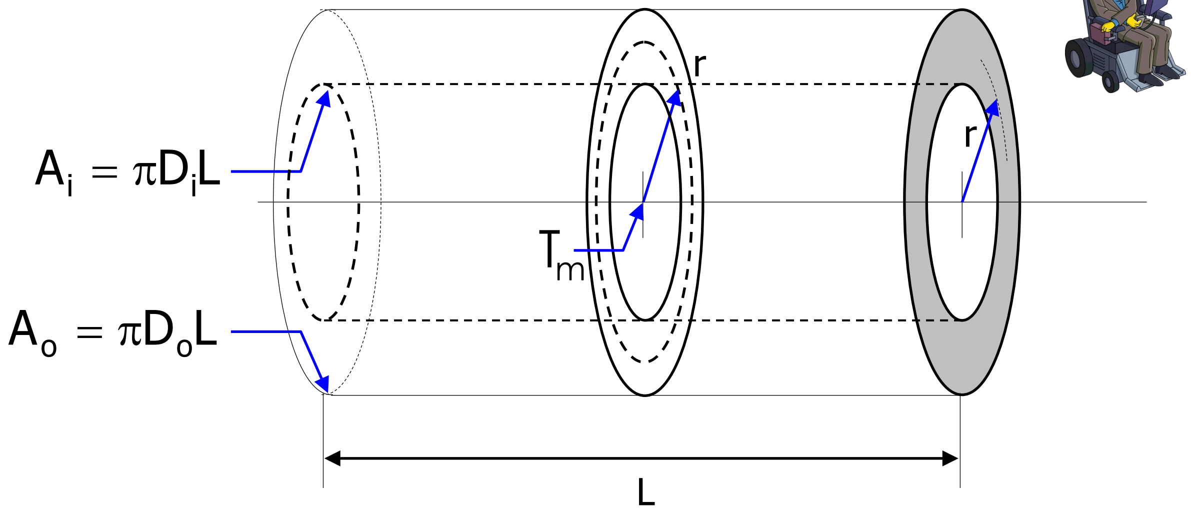
Geometria cilíndrica... variação radial da temperatura



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

$$\boxed{Q=\frac{T_m-T_\infty}{\frac{1}{2\pi r_iLh_i}+\frac{\ln(r_o/r_i)}{2\pi Lk}+\frac{1}{2\pi r_oLh_o}}}$$

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

$$A\overset{def}{=}\pi D_iL\rightarrow U=\left[\frac{1}{h_i}+\frac{r_i}{k}\ln\left(\frac{r_o}{r_i}\right)+\frac{1}{h_o}\cdot\frac{r_i}{r_o}\right]^{-1}$$

coeficiente global de transferência de calor (condutância)

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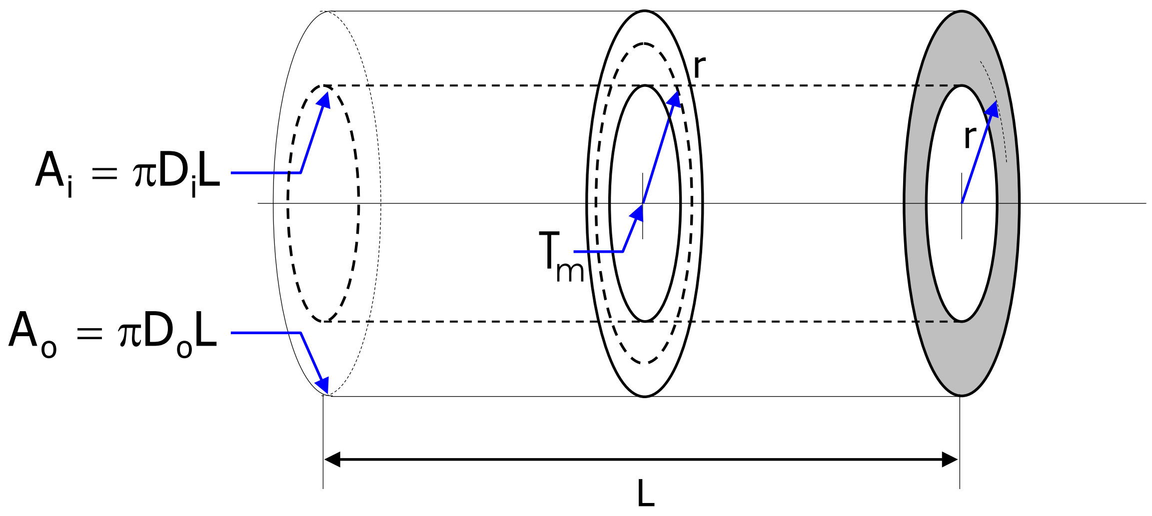
Geometria cilíndrica... variação radial da temperatura



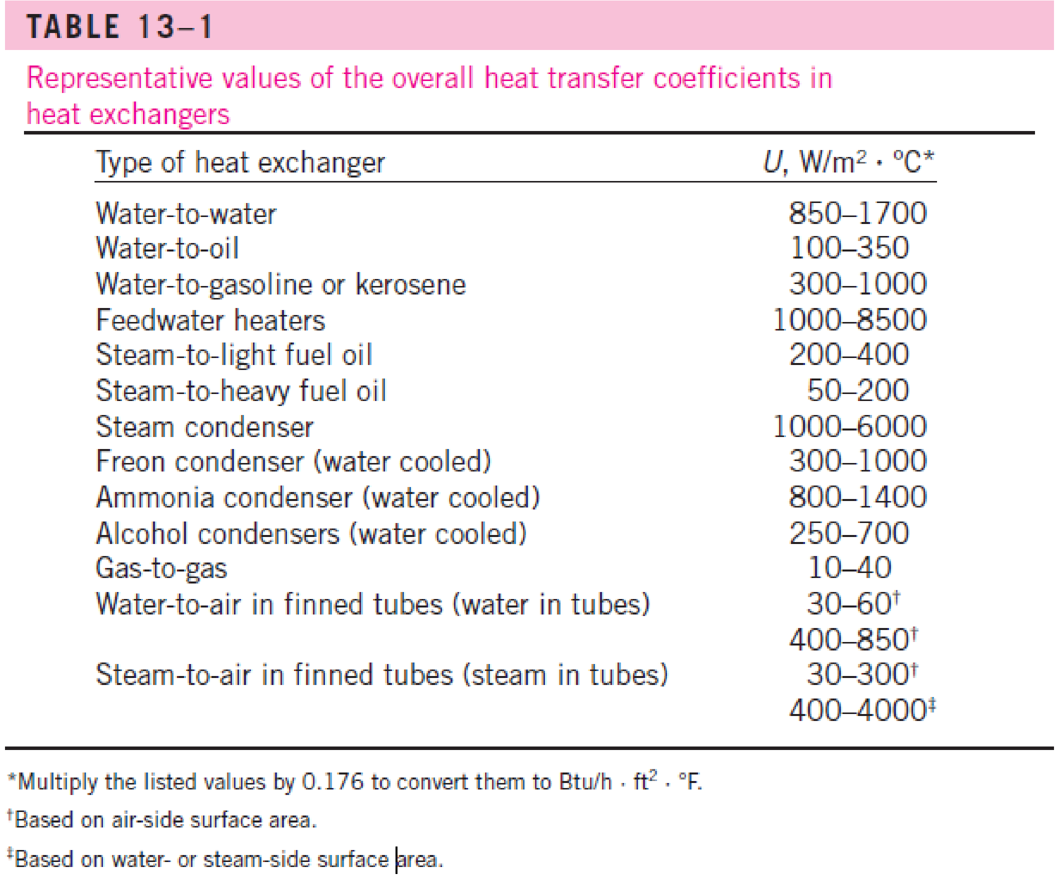


TABLE 13–1

Representative values of the overall heat transfer coefficients in heat exchangers

Type of heat exchanger	U, W/m² · °C*
Water-to-water	850–1700
Water-to-oil	100–350
Water-to-gasoline or kerosene	300–1000
Feedwater heaters	1000–8500
Steam-to-light fuel oil	200–400
Steam-to-heavy fuel oil	50–200
Steam condenser	1000–6000
Freon condenser (water cooled)	300–1000
Ammonia condenser (water cooled)	800–1400
Alcohol condensers (water cooled)	250–700
Gas-to-gas	10–40
Water-to-air in finned tubes (water in tubes)	30–60†
	400–850†
Steam-to-air in finned tubes (steam in tubes)	30–300†
	400–4000‡

*Multiply the listed values by 0.176 to convert them to Btu/h · ft² · °F.

†Based on air-side surface area.

‡Based on water- or steam-side surface area.

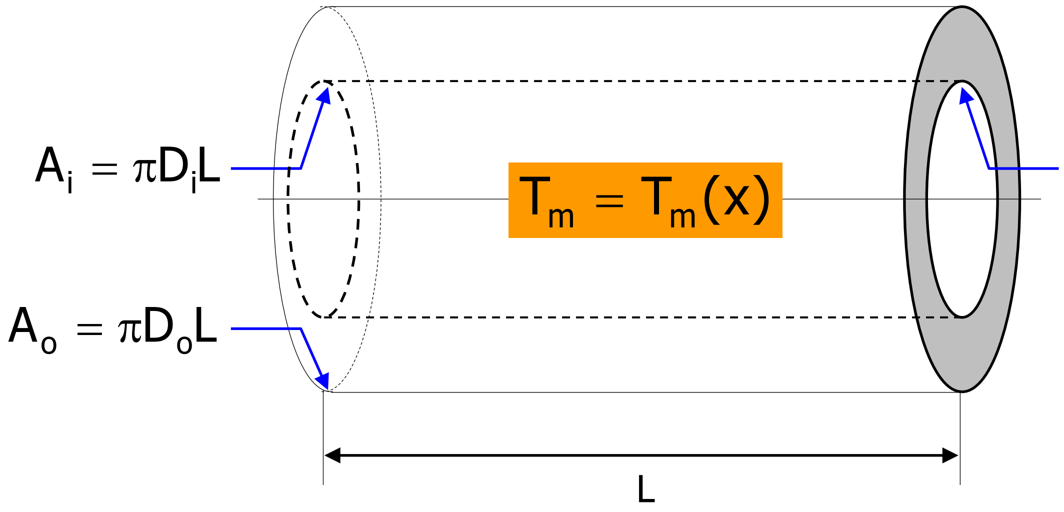
$$\text{Obs.:}\ Q = q_i \cdot A_i = q_o \cdot A_o$$

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

coeficiente global de transferência de calor (condutância)

Geometria cilíndrica... **variação axial da temperatura**

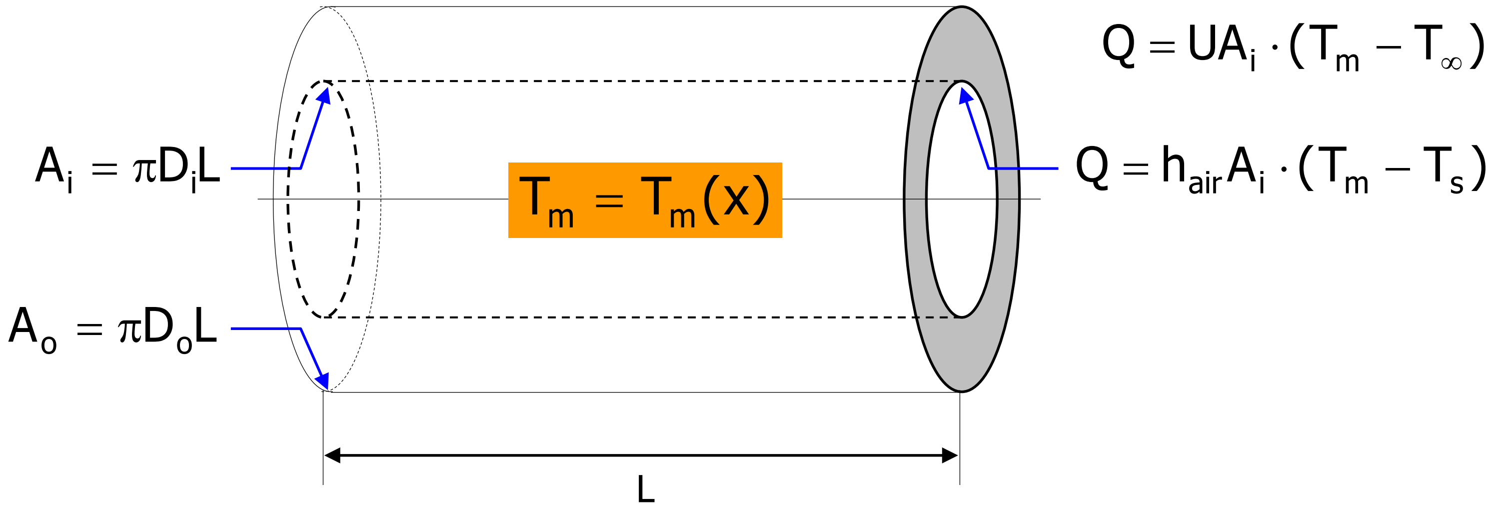
🙈 $\dot{m}\cdot\frac{dT_m}{dx}-\frac{ph_{conv}}{C_P}\cdot(T_s-T_m)=0$



Eliminando T_s do equacionamento

Geometria cilíndrica... variação axial da temperatura

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



$A_i = \pi D_i L$

$A_o = \pi D_o L$

$T_m = T_m(x)$

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

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

As questões postadas no Chat do YouTube serão respondidas ao final da aula.

Geometria cilíndrica... variação axial da temperatura

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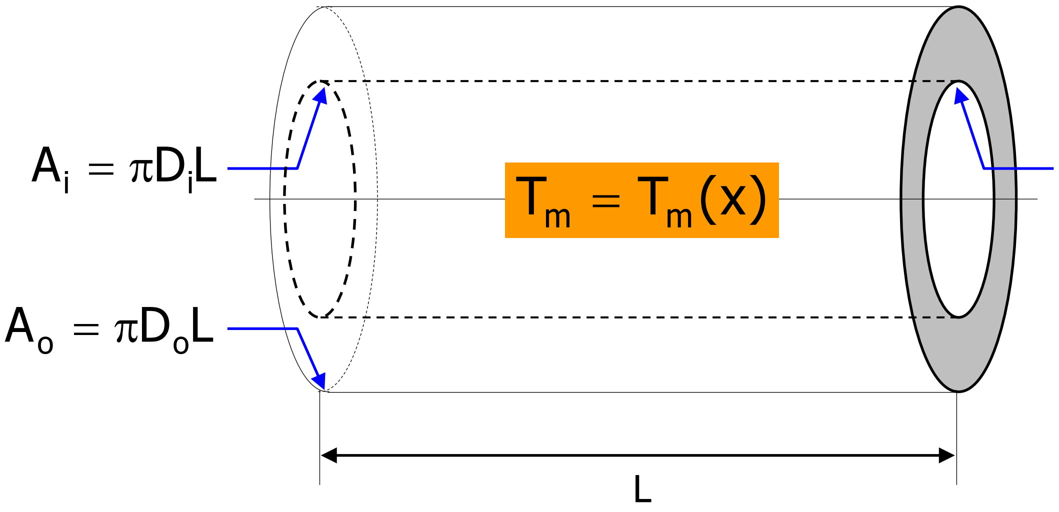

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L

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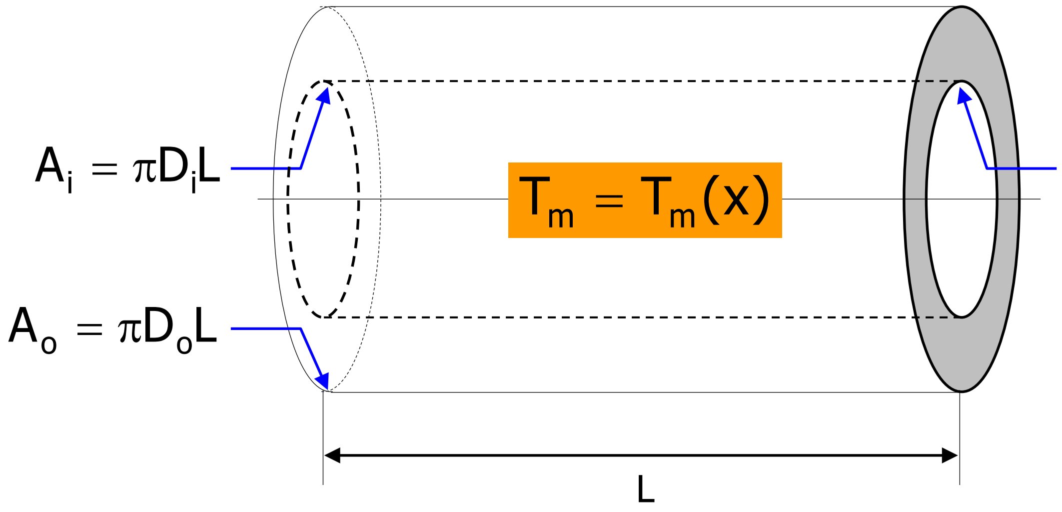

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equação do
balanço global
de energia

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

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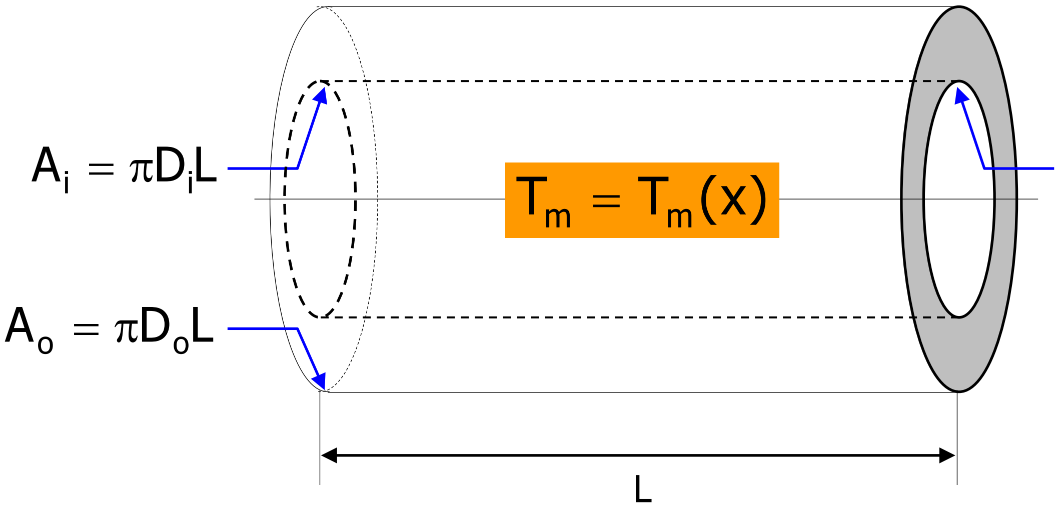

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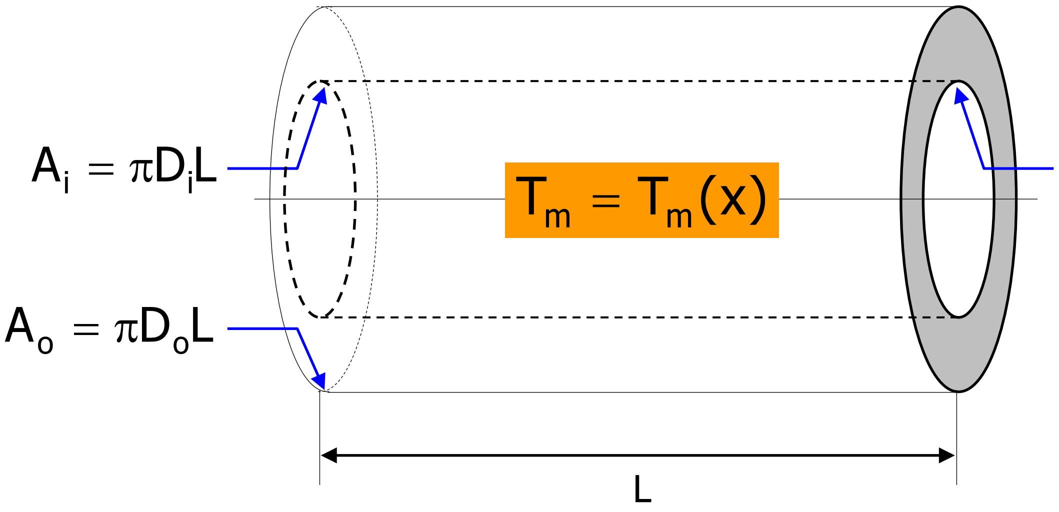

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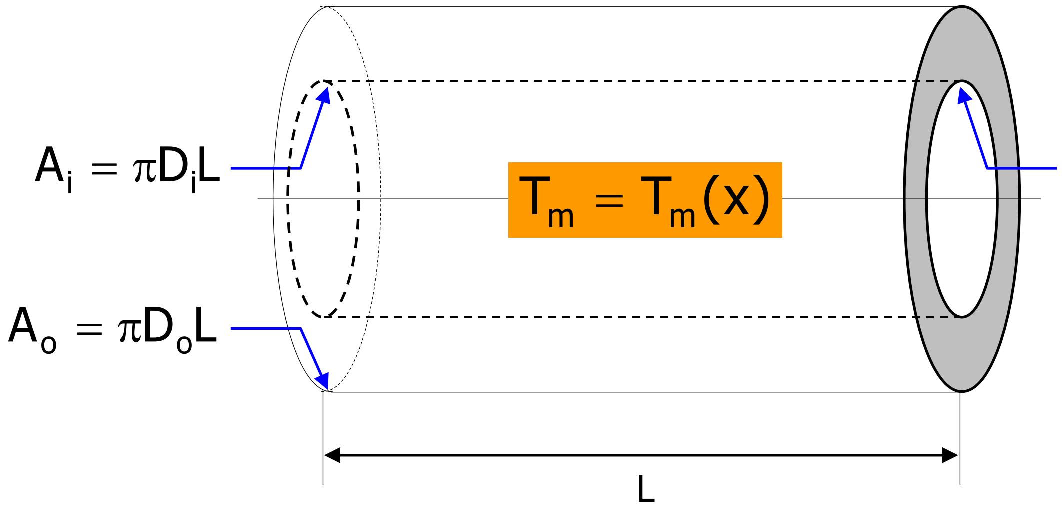

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equação do balanço global de energia

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

$$\downarrow$$

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

$$\downarrow$$

$$\dot{m}C_P\cdot\frac{dT_m}{dx} - ph_{air}\cdot\left[\left(T_m - \frac{U}{h_{air}}(T_m - T_\infty)\right) - T_m\right] = 0 \rightarrow$$

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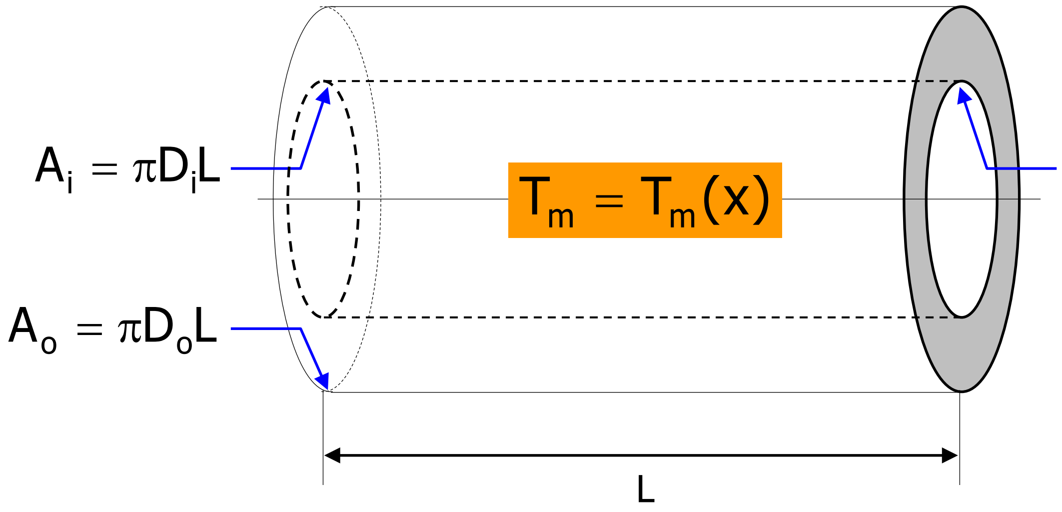

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equação do
balanço global
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$$\downarrow$$

$$\int_{T_{m,e}}^{T_{m,s}}\frac{d(T_m - T_\infty)}{T_m - T_\infty} = -\frac{pL}{\dot{m}C_P}\cdot\frac{1}{L}\int_0^L Udx$$

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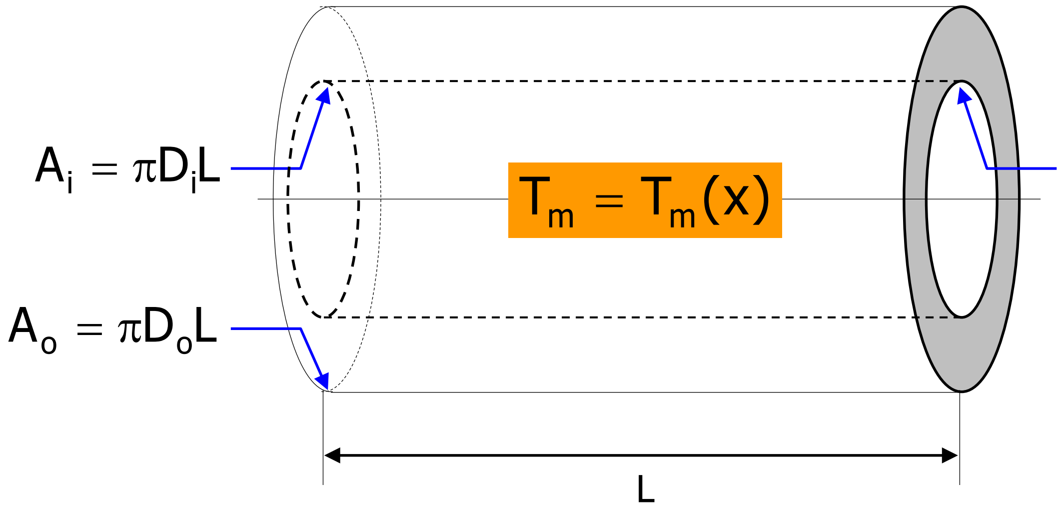

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$$\boxed{\frac{T_{m,s}-T_\infty}{T_{m,e}-T_\infty}=\exp\left(-\frac{\overline{U}A}{\dot{m}C_P}\right)}$$

... calculado @
temperatura axial
média

$$\frac{T_{m,s} - T_{\infty}}{T_{m,e} - T_{\infty}} = \exp\left(- \frac{\overline{U}A}{\dot{m}C_P} \right) \rightarrow \qquad \boxed{(\overline{U}A_i)^{-1} = \frac{1}{2\pi r_i L h_i} + \frac{\ln(r_o / r_i)}{2\pi L k} + \frac{1}{2\pi r_o L h_o}}$$

Dittus-Boelter ?

=cte

=cte

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=cte

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Escoamento turbulento desenvolvido (Re > 10^4):

Superfície lisa:

(Dittus-Boelter)

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

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

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

$$\begin{bmatrix} 0.7 \lesssim Pr \lesssim 160 \\ Re_D \gtrsim 10{,}000 \\ \dfrac{L}{D} \gtrsim 10 \end{bmatrix}$$

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$$\overline{T}=25°C \rightarrow \quad \rho = 1.1688\,kg/m^3 \quad \mu = 18.448\,\mu Pa\cdot s \quad C_P = 1.0063\,kJ/kg/K$$

$$k = 26.247\ mW/m/K \qquad Pr = 0.70729$$

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

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

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

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=cte

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

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

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

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

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$$7.035\ \frac{W}{m^2\,K} \qquad 0.15\ \frac{W}{mK} \qquad 1500\ \frac{W}{m^2\,K}$$

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

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$$7.035\ \frac{W}{m^2K} \qquad 0.15\ \frac{W}{mK} \qquad 1500\ \frac{W}{m^2K}$$

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

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

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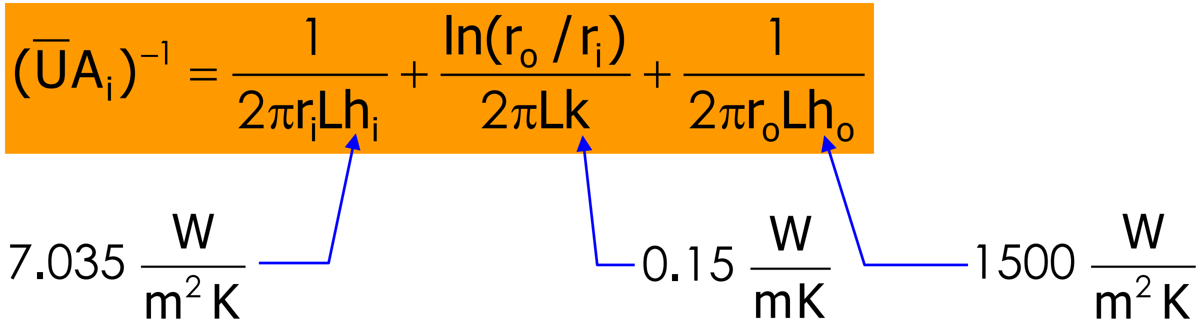
$$\frac{T_{m,s}-T_\infty}{T_{m,e}-T_\infty}=\exp\left(-\frac{\overline{U}A}{\dot{m}C_P}\right)\rightarrow\qquad \frac{21-17}{29-17}=\exp\left(-\frac{2.295\cdot L}{0.02883\cdot 1006.3}\right)$$

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



$$\boxed{(\bar{U}A_{i})^{-1}=\frac{1}{2\pi r_{i}Lh_{i}}+\frac{\ln(r_{o}/r_{i})}{2\pi Lk}+\frac{1}{2\pi r_{o}Lh_{o}}}$$

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

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$$\boxed{L=13.88\,m}$$

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Considerando propriedades termofísicas variáveis...

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

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

Balanço global de energia...

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

Solução direta via método numérico de solução de equação diferencial

$$\hbar = \hbar(P,T)\ \Big\downarrow$$

Implementação numérica...

Solução analítica a partir de hipóteses simplificadoras

$$\hbar = C_p \cdot T\ \Big\downarrow$$

gases perfeitos
“fluido incompressível” (C_p=C_v)

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

🙈

$$\mu = \mu(P,T),\ldots\ \Big\downarrow$$

Implementação numérica...

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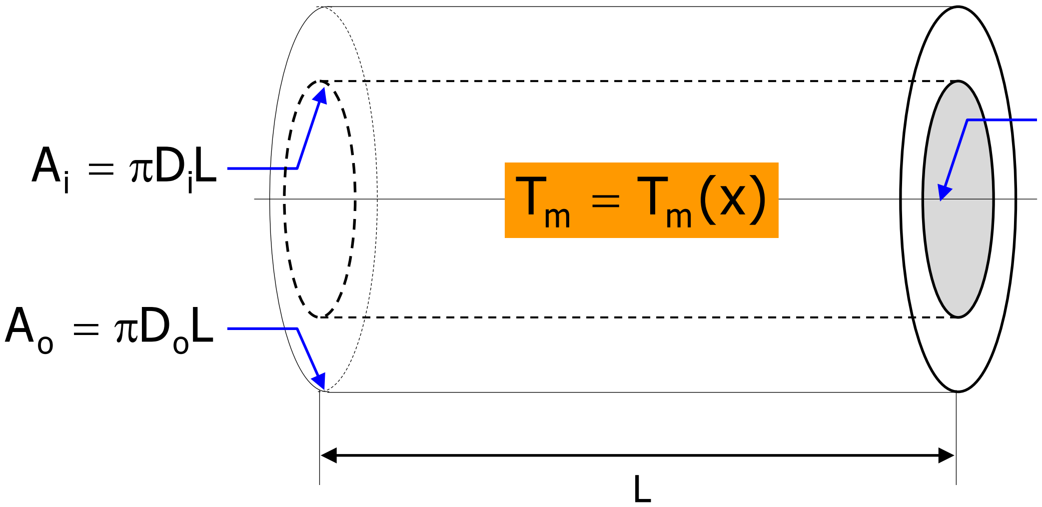
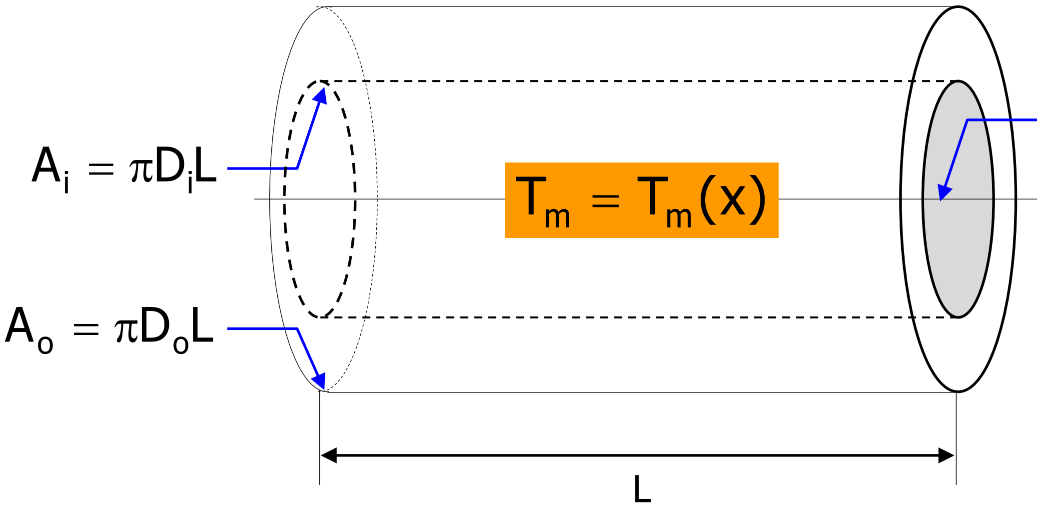
Geometria cilíndrica... variação axial da temperatura



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

🙉 Eliminada T_s da eq. 🙈

Geometria cilíndrica... variação axial da temperatura



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

$$U = \left[\frac{1}{h_i} + \frac{r_i}{k}\ln\left(\frac{r_o}{r_i}\right) + \frac{1}{h_o} \cdot \frac{r_i}{r_o}\right]^{-1}$$

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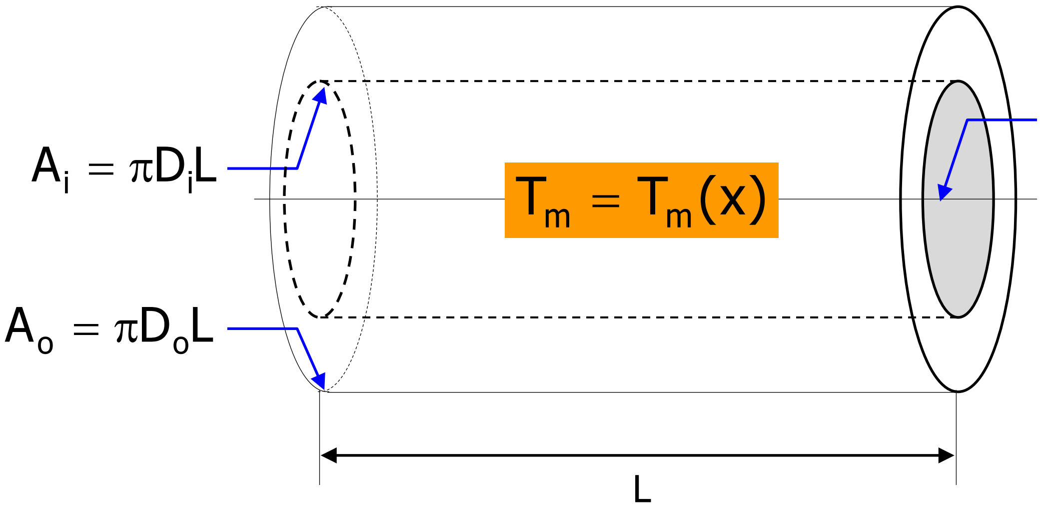

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Dittus-Boelter

=cte

=cte

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

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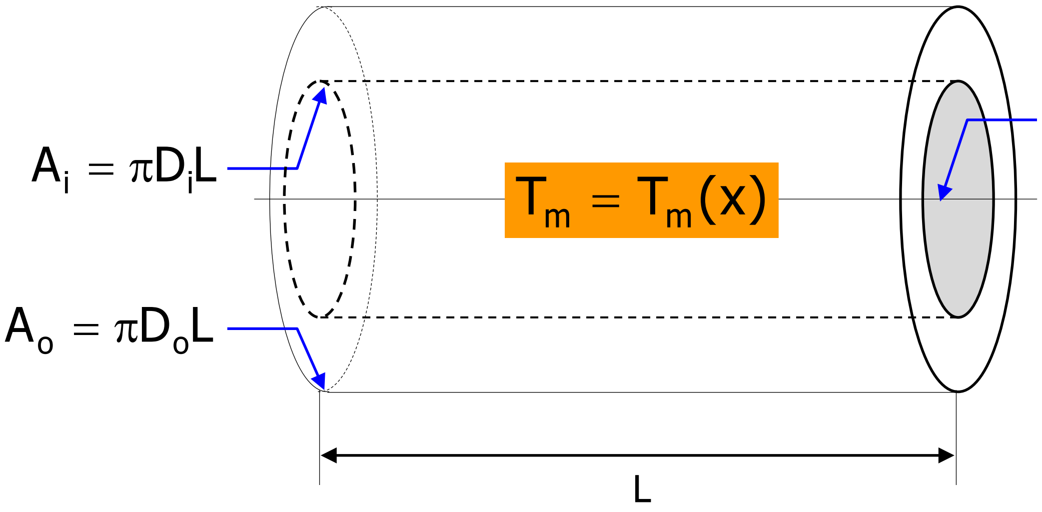


$A_i = \pi D_i L$

$A_o = \pi D_o L$

$T_m = T_m(x)$

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

$$U = \left[\frac{1}{h_i} + \frac{r_i}{k}\ln\left(\frac{r_o}{r_i}\right) + \frac{1}{h_o}\cdot\frac{r_i}{r_o}\right]^{-1}$$

Dittus-Boelter

=cte

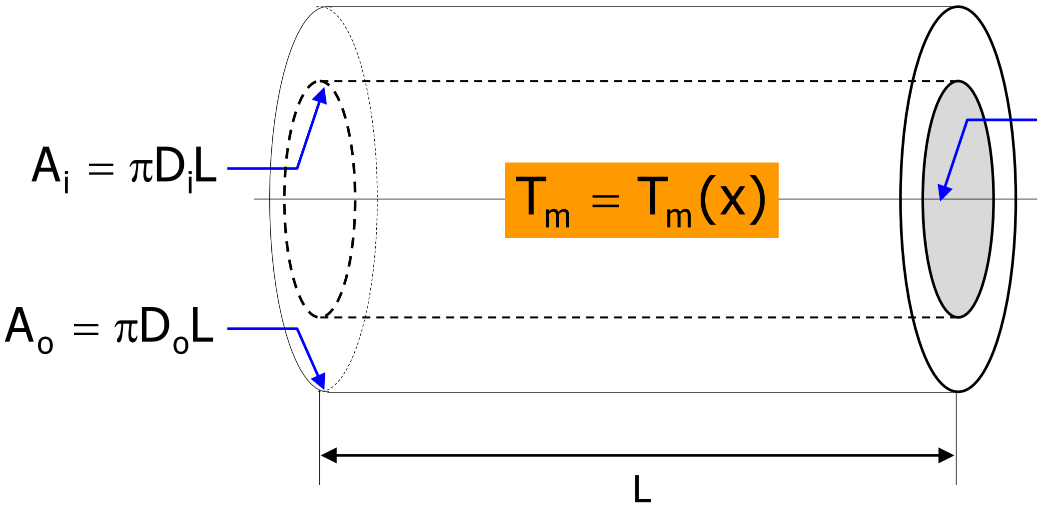
=cte

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

$$Re = \left.\frac{\rho u_0 D}{\mu}\right|_{T_m}$$

$$Pr = \left.\frac{C_p \mu}{k}\right|_{T_m}$$

Geometria cilíndrica... variação axial da temperatura



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

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

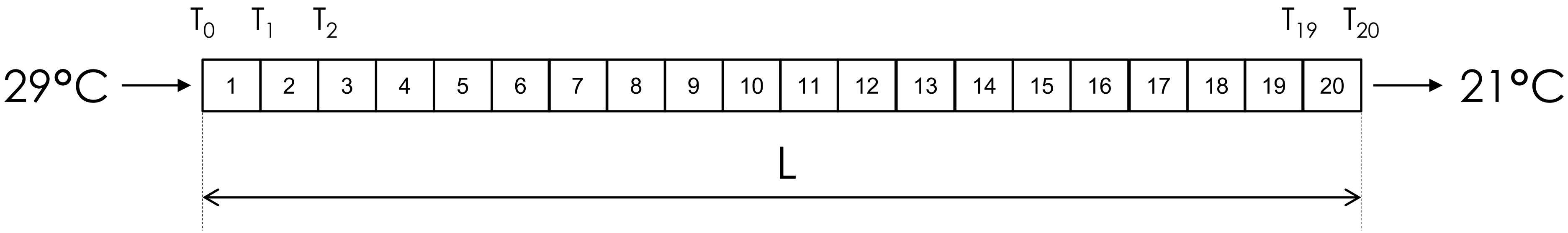
$$\frac{T_{m,j+1} - T_{m,j}}{dx} + \alpha_j \cdot (T_{m,j} - T_\infty) = 0$$

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

$$\alpha(T_m) = \frac{p}{\dot{m}}\frac{U(T_m)}{C_P(T_m)}$$

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

8.31: Para resfriar uma casa de verão sem uso de um ciclo frigorífico, ar é encaminhado através de uma tubulação de plástico (k=0.15W/m/K, D_i=0.15m, D_0=0.17m) submersa em um corpo d'água adjacente. A temperatura da água é normalmente de T_∞=17°C, e o coeficiente de convecção é mantido em h_o=1500 W/m^2/K na superfície externa da tubulação. Se ar proveniente da casa entra no tubo a uma temperatura de $T_{m,i}$=29°C e uma vazão volumétrica de V_i=0.025m^3/s, qual extensão L é necessária para que a temperatura na saída seja de $T_{m,o}$=21°C ?



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

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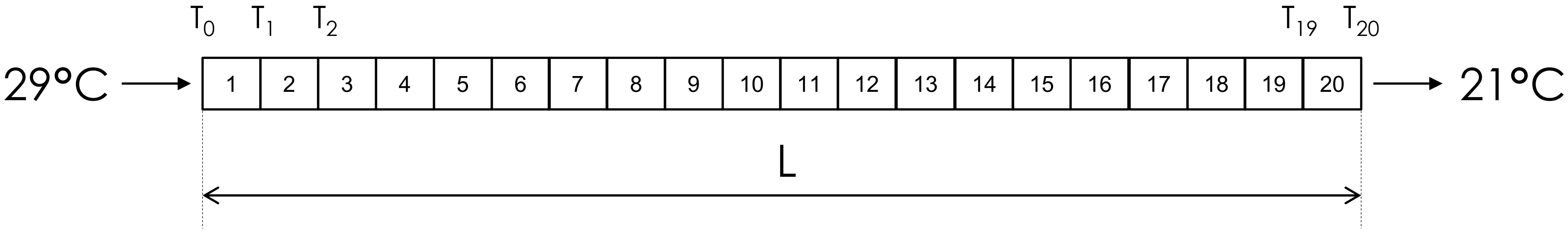
8.31: Para resfriar uma casa de verão sem uso de um ciclo frigorífico, ar é encaminhado através de uma tubulação de plástico (k=0.15W/m/K, D_i=0.15m, D_0=0.17m) submersa em um corpo d'água adjacente. A temperatura da água é normalmente de T_∞=17°C, e o coeficiente de convecção é mantido em h_o=1500 W/m²/K na superfície externa da tubulação. Se ar proveniente da casa entra no tubo a uma temperatura de $T_{m,i}$=29°C e uma vazão volumétrica de V_i=0.025m³/s, qual extensão L é necessária para que a temperatura na saída seja de $T_{m,o}$=21°C ?



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

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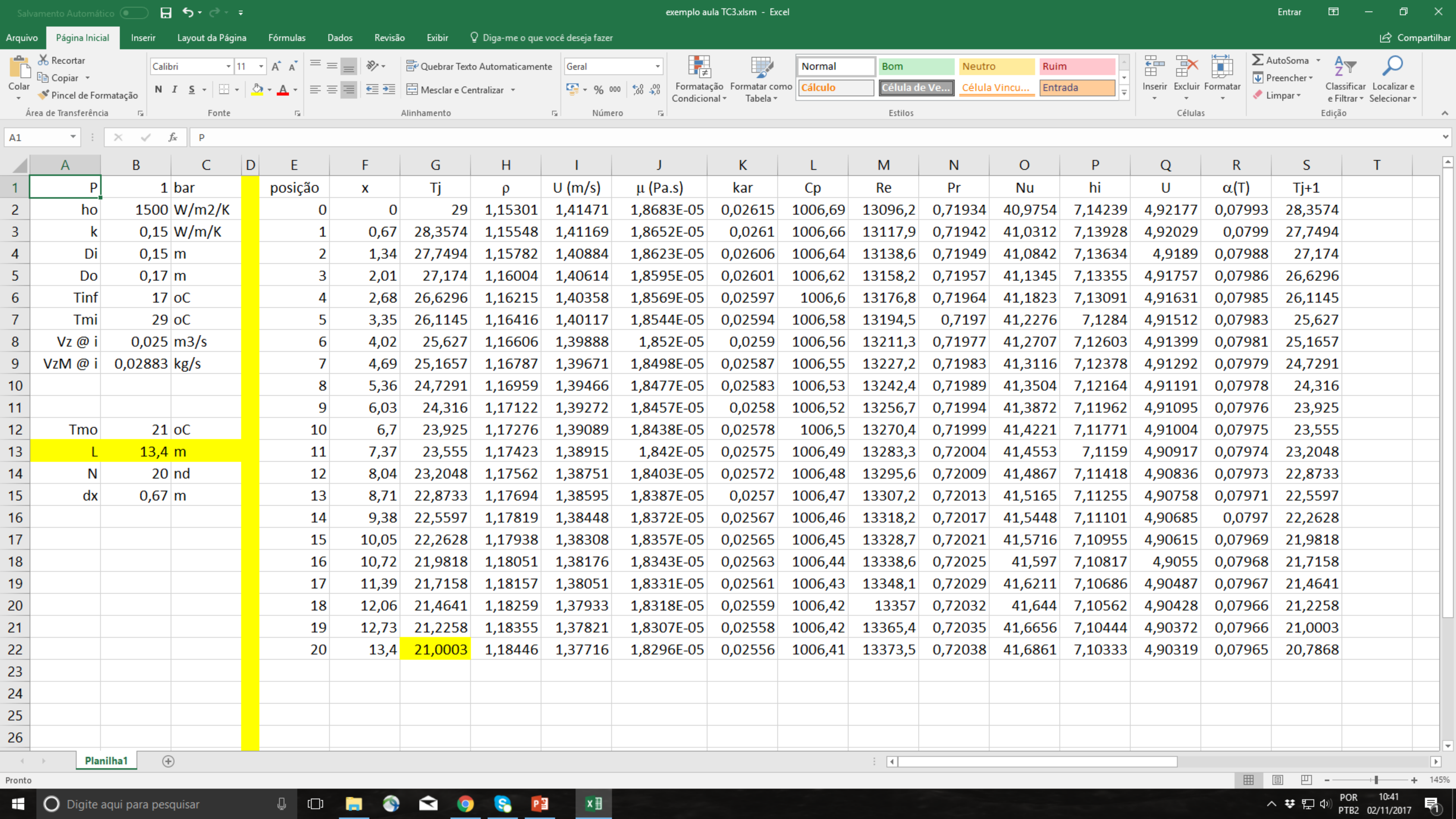
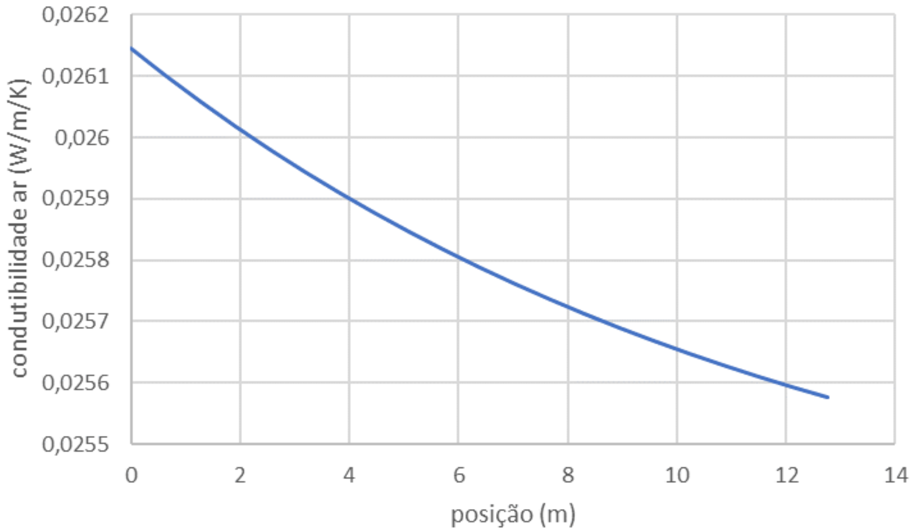
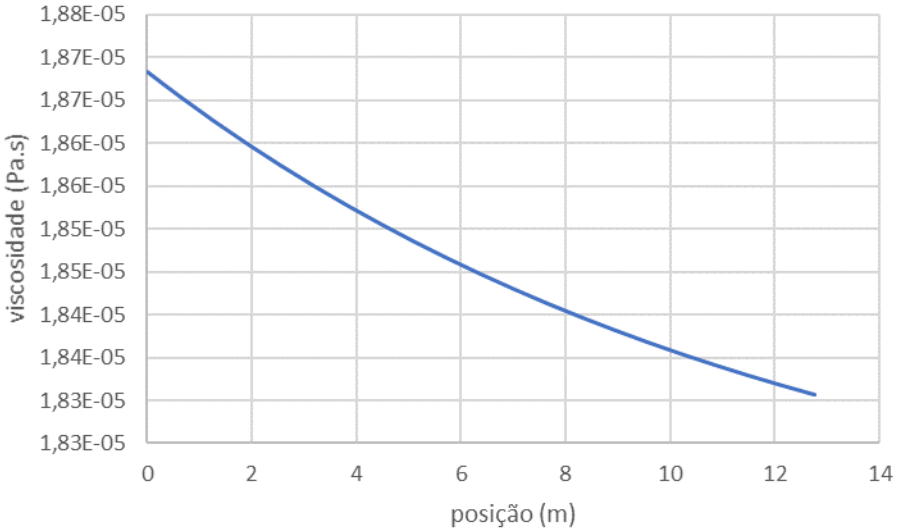
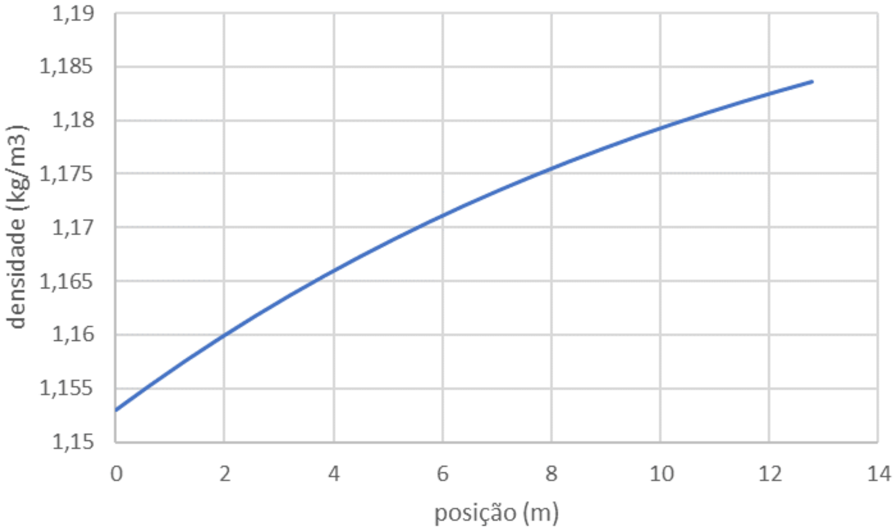
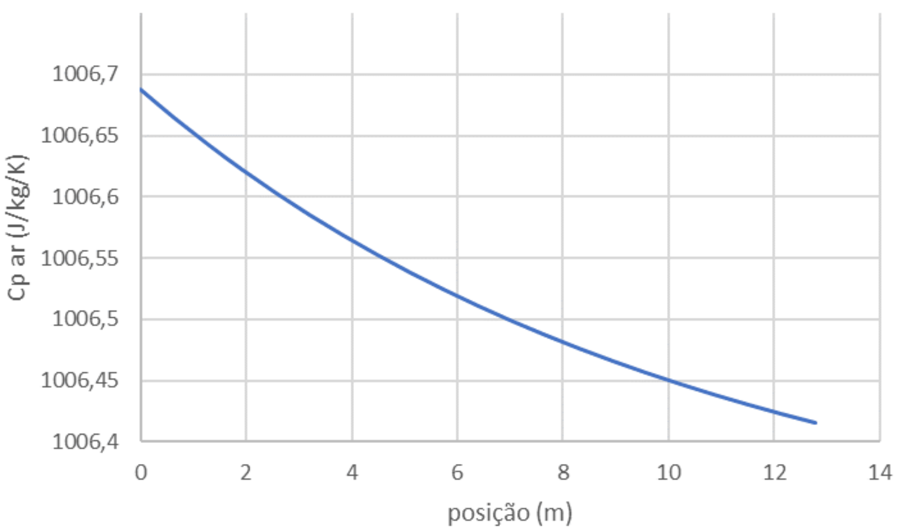


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	P	1	bar		posição	x	Tj	ρ	U (m/s)	µ (Pa.s)	kar	Cp	Re	Pr	Nu	hi	U	α(T)	Tj+1
2	ho	1500	W/m2/K		0	0	29	1,15301	1,41471	1,8683E-05	0,02615	1006,69	13096,2	0,71934	40,9754	7,14239	4,92177	0,07993	28,3574
3	k	0,15	W/m/K		1	0,67	28,3574	1,15548	1,41169	1,8652E-05	0,0261	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









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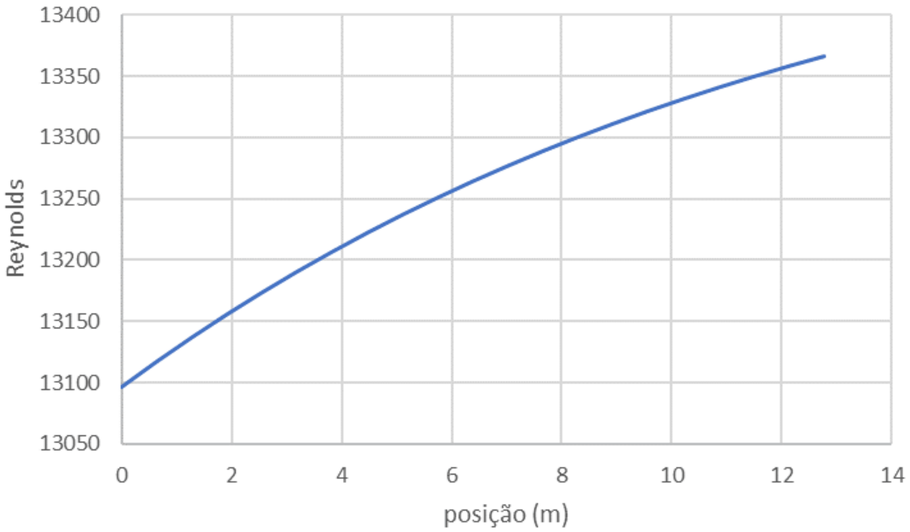

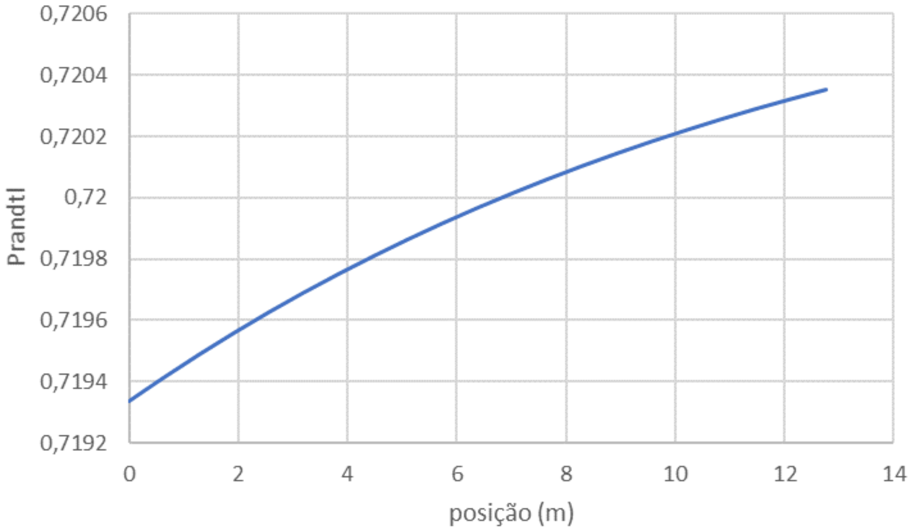

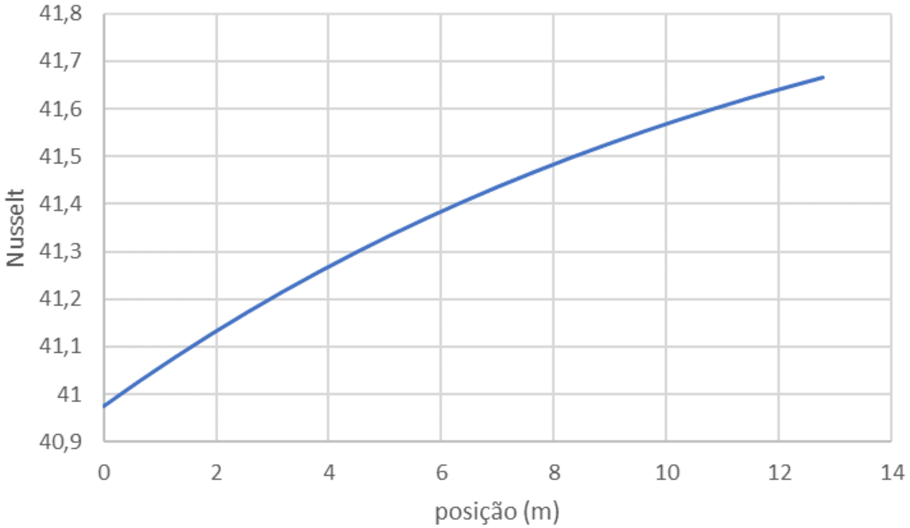

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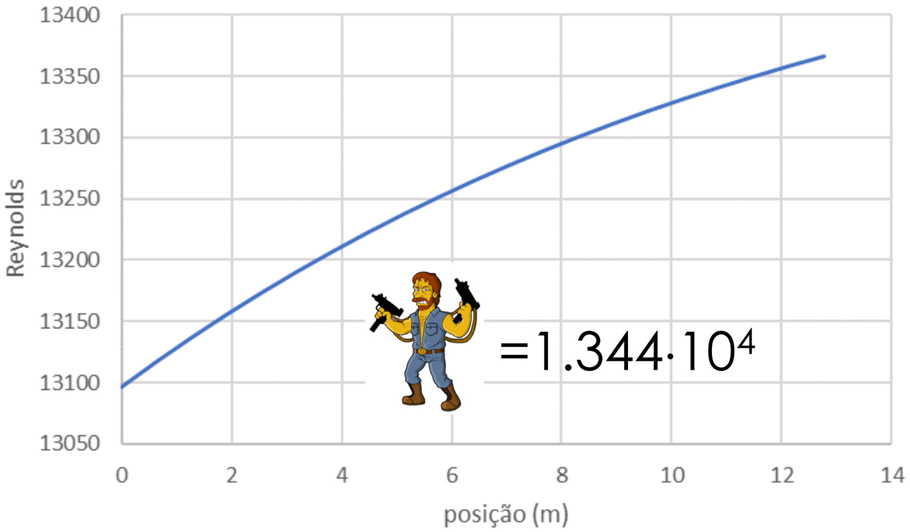
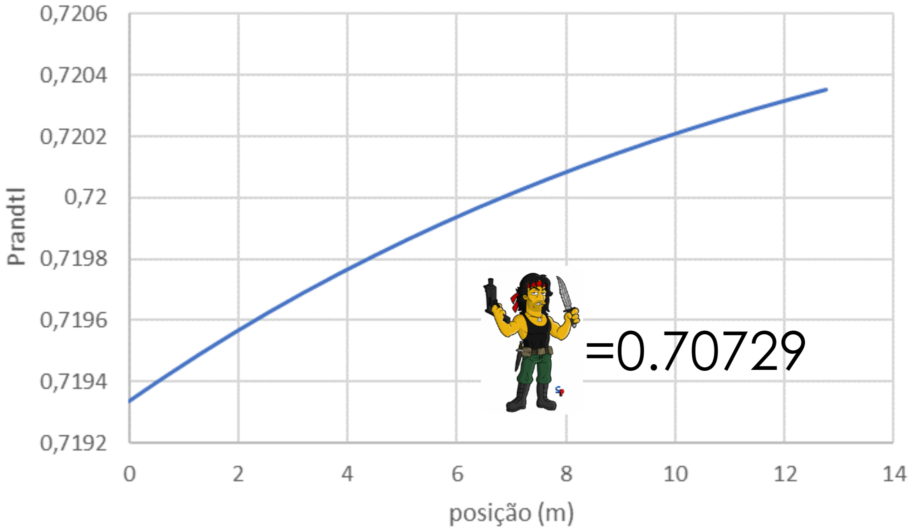
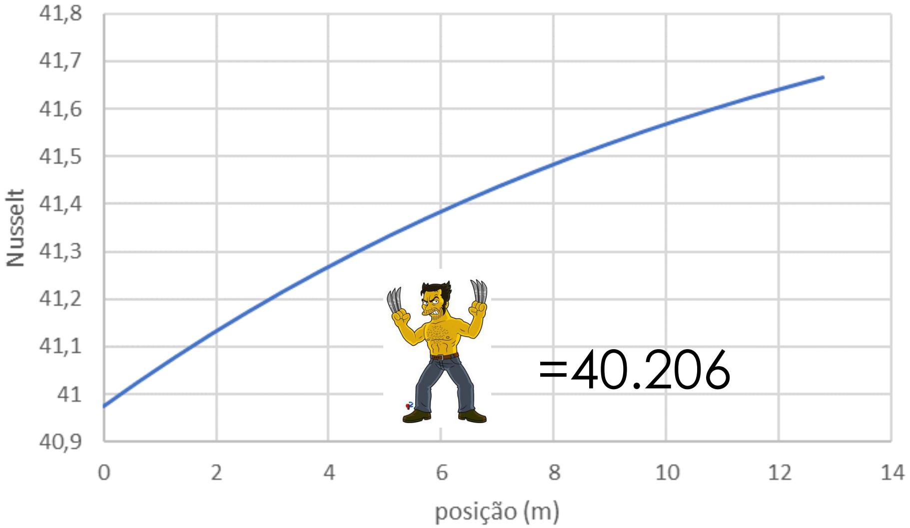


$=1.344 \cdot 10^4$



$=0.70729$



$=40.206$

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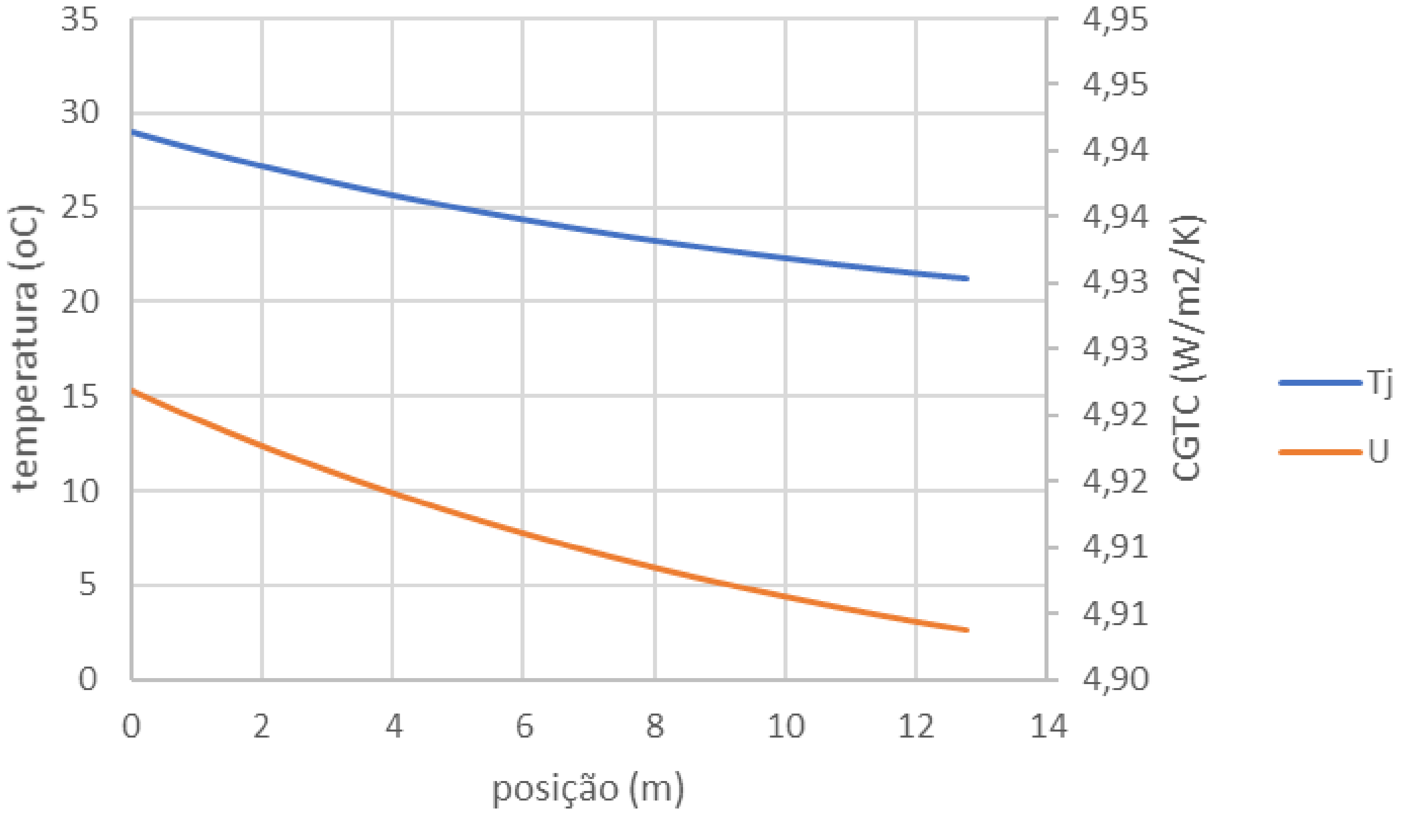
Tutorial: montagem da planilha de simulação...



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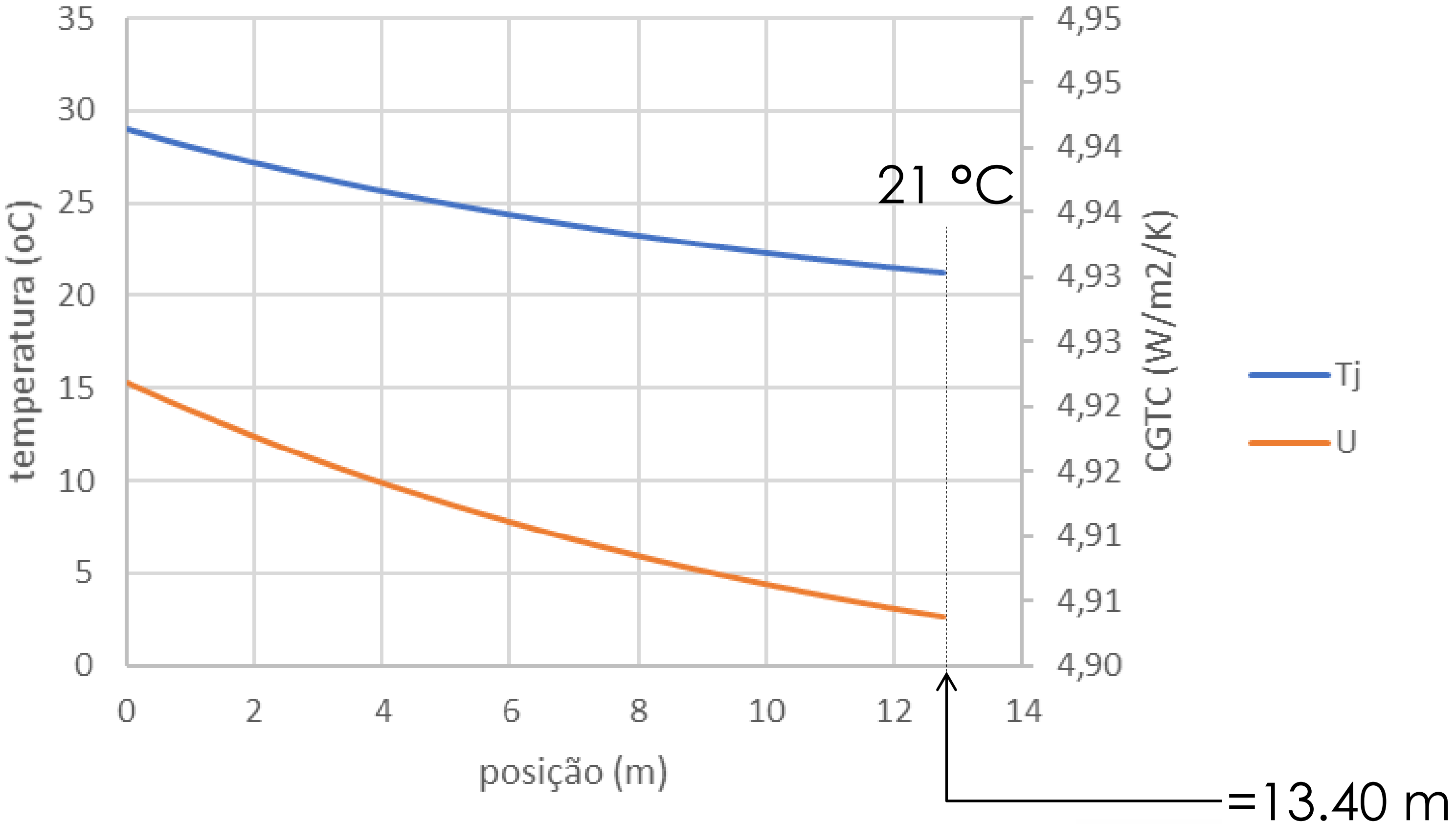
Tutorial: montagem da planilha de simulação...



=13.88 m

Dúvidas ?

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