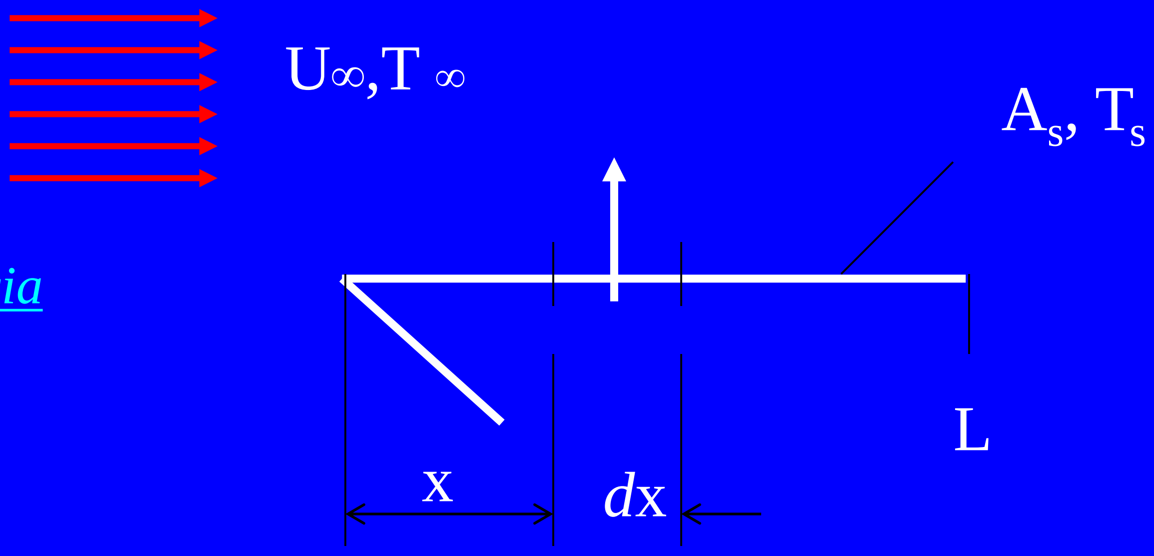
Definição do problema

Fluxo de calor local

$$q'' = h(T_s - T_\infty)$$



Taxa total de transferência de calor

$$q = \int_{A_s} q''\, dA_s$$

Coeficiente médio de convecção

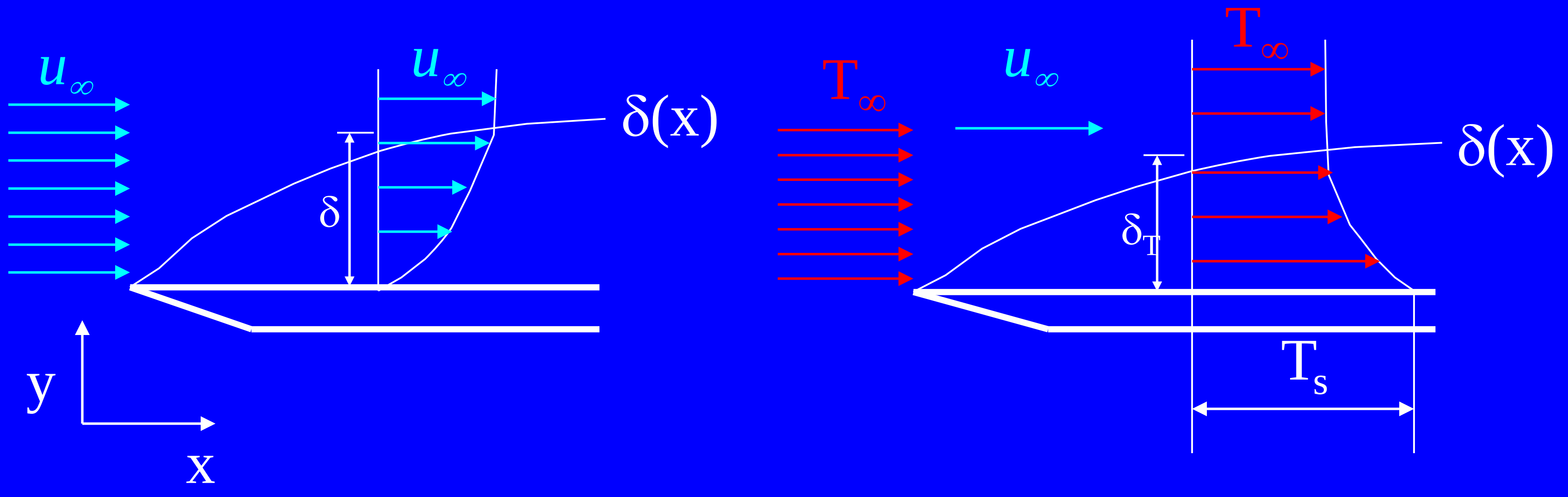
$$\bar{h} = \frac{1}{A_s} \int_{A_s} h\, dA_s$$

$$q = \bar{h} A_s (T_s - T_\infty)$$

Camadas Limites da Convecção

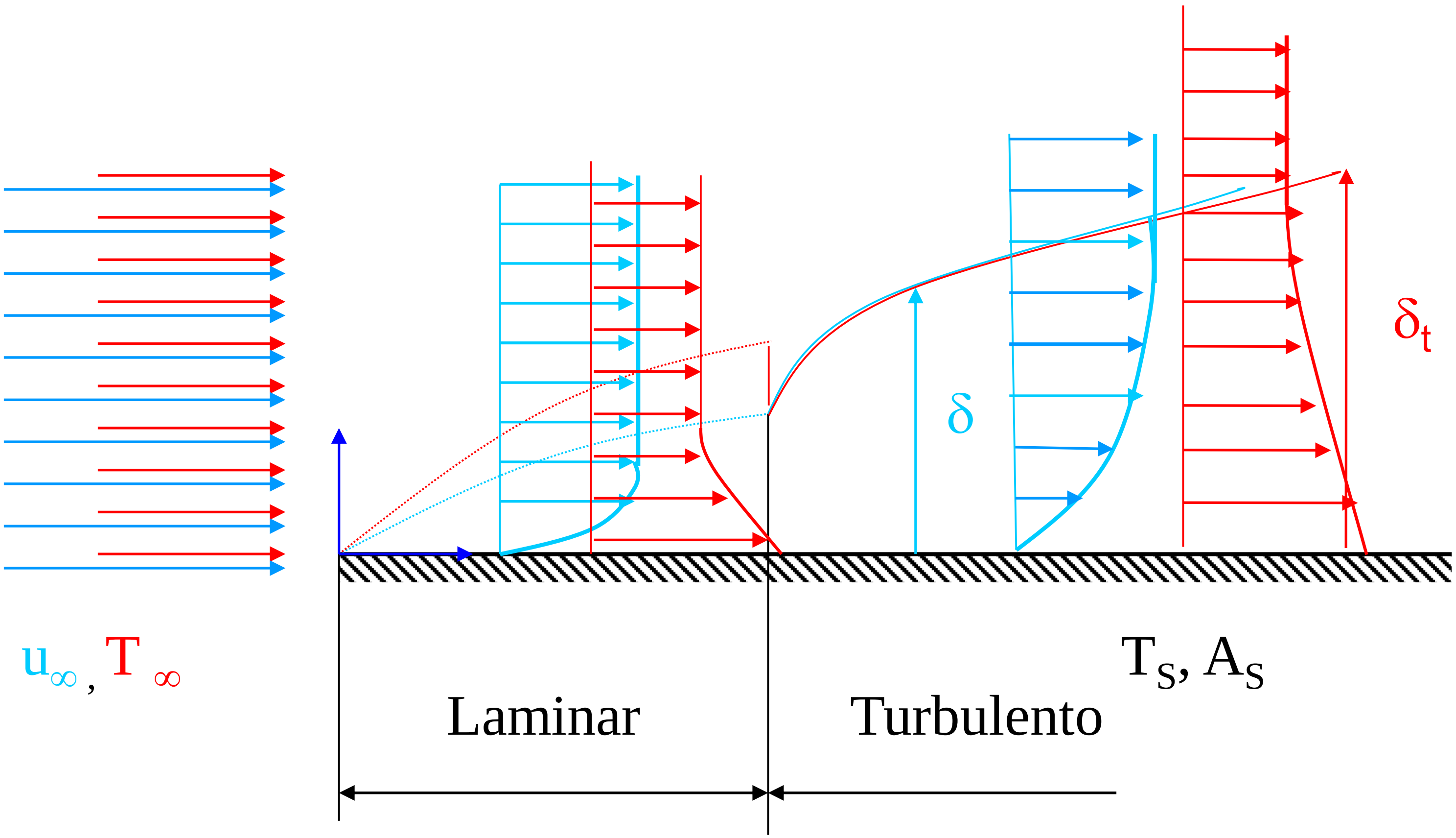
Camada limite hidrodinâmica

Camada limite térmica

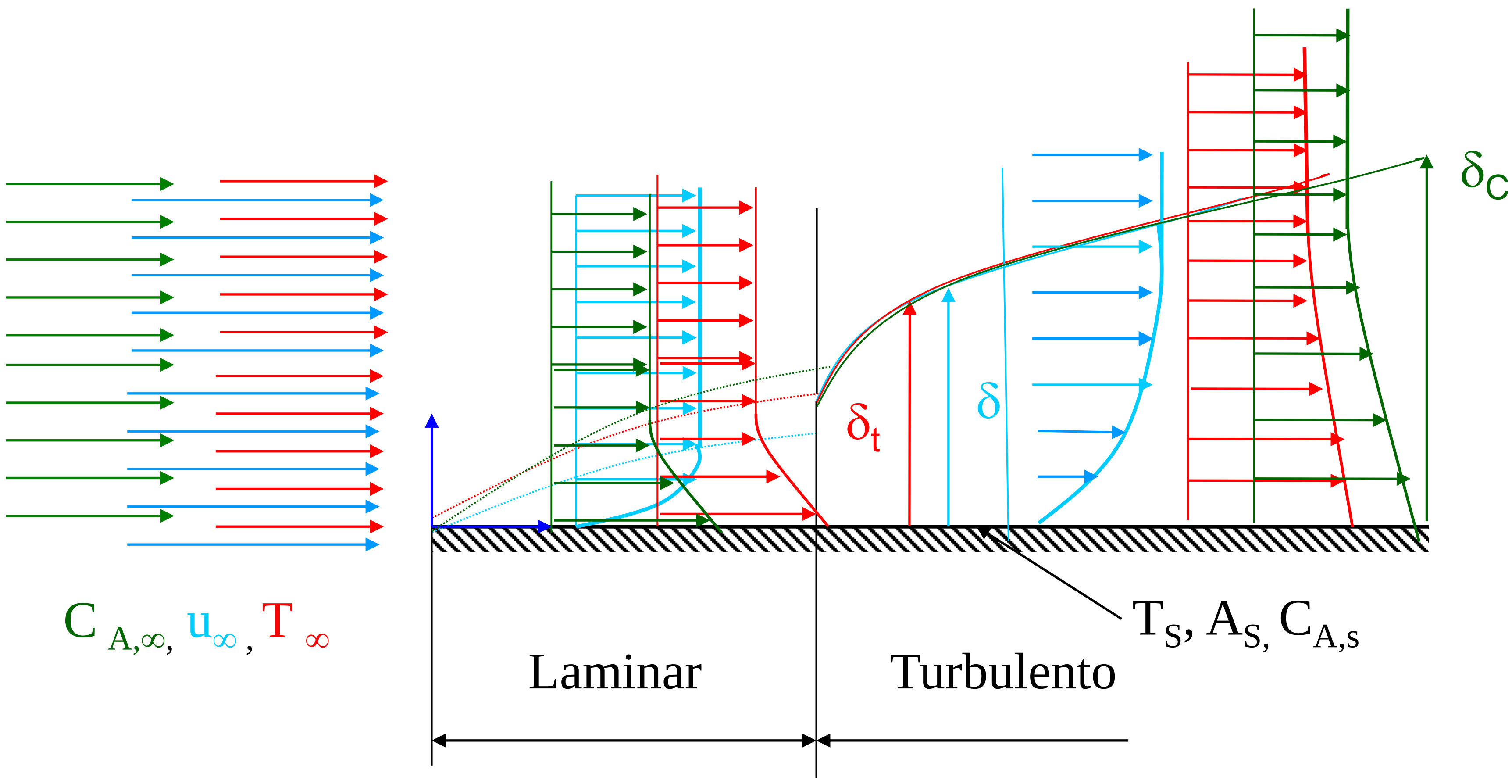


Transferência de Calor por Convecção

- Térmica



Transferência de massa convectiva



Transferência de Calor por Convecção

- Fluxo de Calor local: $q'' = h(T_S - T_\infty)$ [W/m²]

  - h: Coeficiente de convecção local ou coeficiente de película local [W/m²K]

- Fluxo de Calor total: [W]

$$q = \int_{A_s} q''\, dA_s$$

$$q = \left(T_S - T_\infty\right) \int_{A_s} h\, dA_s$$

Transferência de Calor por Convecção

$$\bar{h} = \frac{1}{A_S} \int_{A_s} h \, dA_s$$

$$q = \bar{h} A_S \left(T_S - T_\infty \right)$$

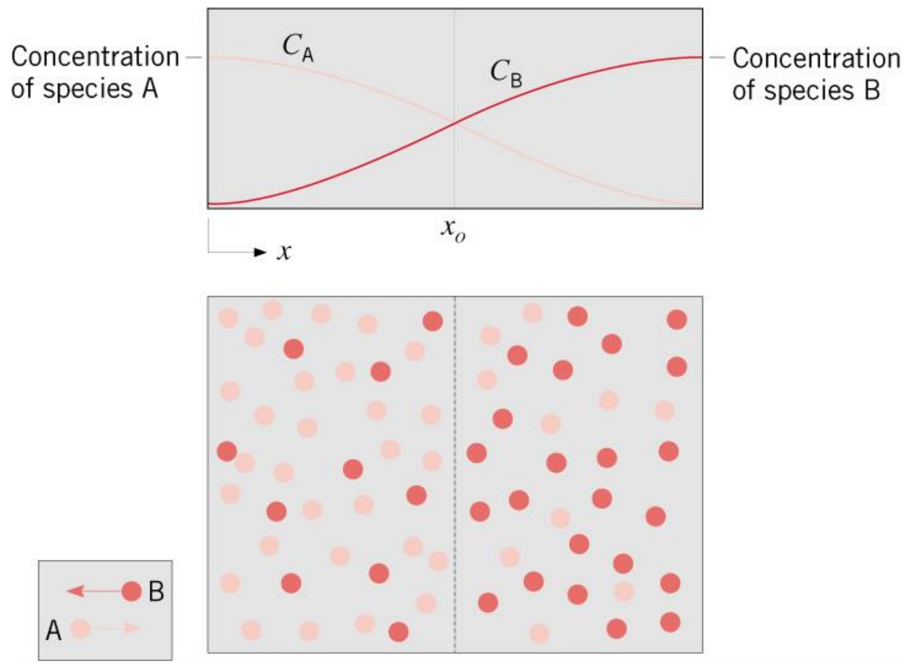
- $\bar{h}$: Coeficiente de convecção médio ou coeficiente de película médio [W/m^{2}K]

Transferência de Calor por Convecção

- Para uma placa plana

$$\bar{h} = \frac{1}{wL}\int_0^L hw\,dx = \frac{1}{L}\int_0^L h\,dx$$

Transferência de Massa: Difusão

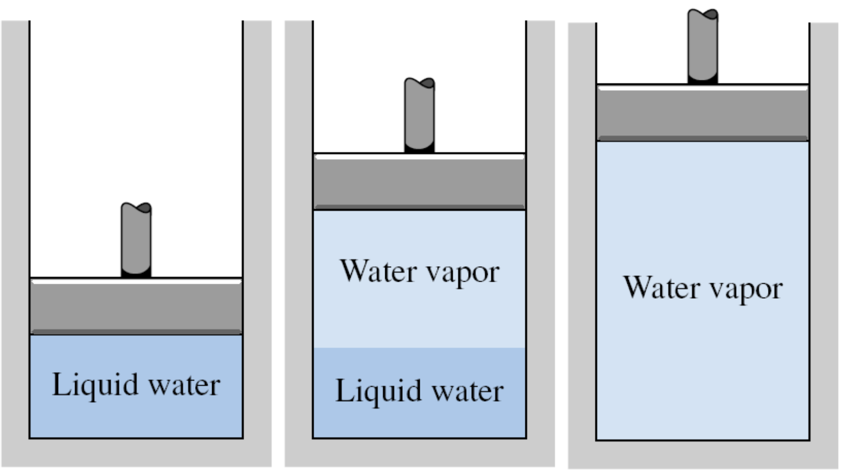


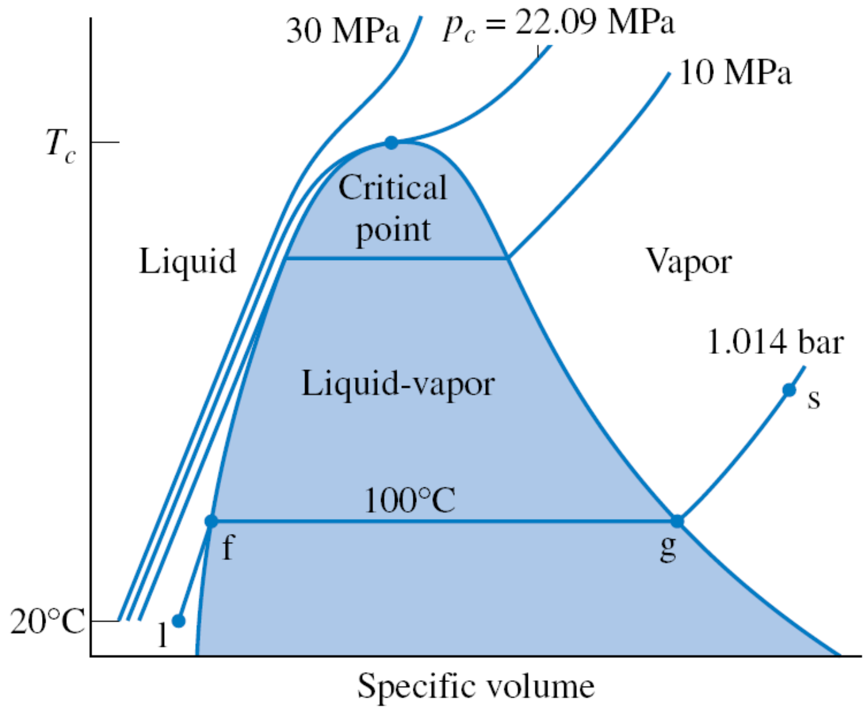
- From Fick's law (mass transfer analog to Fourier's law):

$$J_A^* = -CD_{AB}\nabla x_A$$

→ Binary diffusion coefficient or mass diffusivity (m^2/s)

Ebulição: água

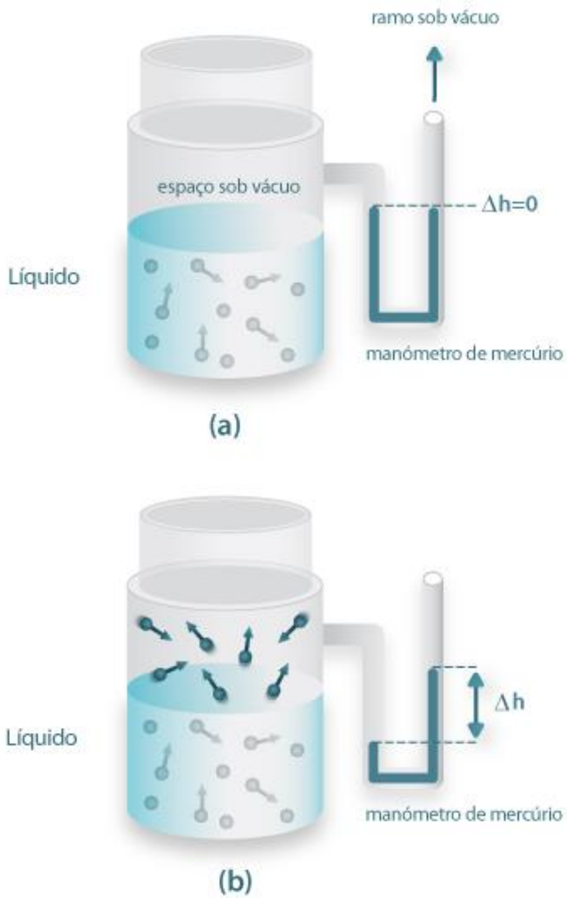


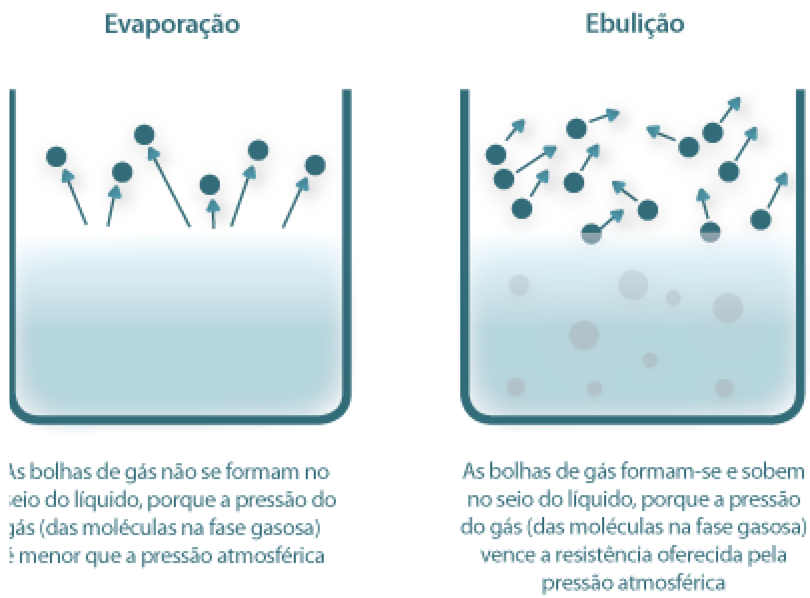


Evaporação: água

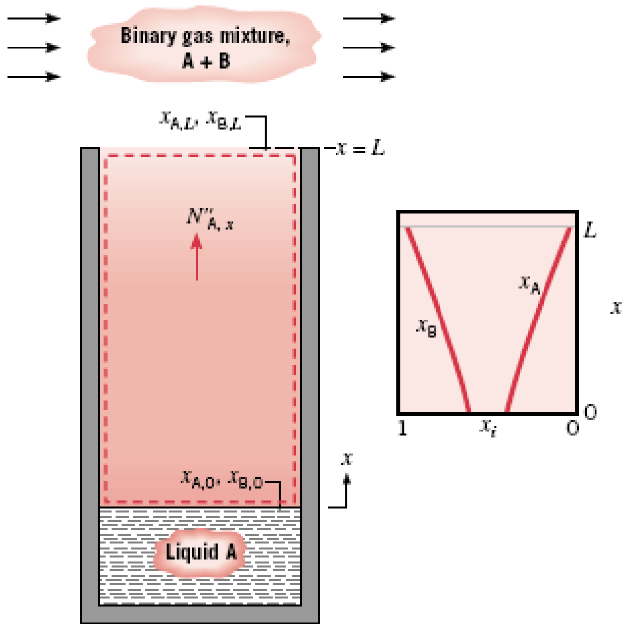
POSITIVE PROOF OF GLOBAL WARMING

Evaporação: água





Evaporation in a Column: A Nonstationary Medium



- Species Diffusion Equation on a Molar Basis:

$$\frac{\partial^2 C_A}{\partial x^2} + \frac{\partial^2 C_A}{\partial y^2} + \frac{\partial^2 C_A}{\partial z^2} + \frac{\dot{N}_A}{D_{AB}} = \frac{1}{D_{AB}} \frac{\partial C_A}{\partial t}$$

- Species Diffusion Equation on a Mass Basis:

$$\frac{\partial^2 \rho_A}{\partial x^2} + \frac{\partial^2 \rho_A}{\partial y^2} + \frac{\partial^2 \rho_A}{\partial z^2} + \frac{\dot{n}_A}{D_{AB}} = \frac{1}{D_{AB}} \frac{\partial \rho_A}{\partial t}$$

Transferência de Massa por Convecção

- Fluxo Molar da espécie a local: $N_A{}'' = h_m(C_{A,S} - C_{A,\infty})$
  $[kmol/sm^2] = [m/s].[kmol/m^3]$
  - h_m: Coeficiente de transferência de massa por convecção local [m/s]
- Taxa de transferência molar total:
  [kmol/sm]

$$N_A = \int_{A_s} N_A{}'' dA_s$$

$$N_A = \left(C_{A,S} - C_{A,\infty}\right) \int_{A_s} h_m dA_s$$

$$N_A = \bar{h}_m A_s \left(C_{A,S} - C_{A,\infty}\right)$$

Transferência de Massa por Convecção

$$\bar{h}_m = \frac{1}{A_S} \int_{A_s} h_m \, dA_s$$

$$N_A = \bar{h}_m A_S \left(C_{A,S} - C_{A,\infty} \right)$$

- $\bar{h}_m$: Coeficiente de transferência de massa por convecção médio [m/s]

Transferência de Massa por Convecção

- Para uma placa plana

$$\overline{h}_m = \frac{1}{wL}\int_0^L h_m w\,dx = \frac{1}{L}\int_0^L h_m\,dx$$

Transferência de Massa

- Fluxo de massa

$$C = \frac{\rho}{M_{molecular\,A}}$$

$$N''_A . M_{molecular\,A} = n''_A = h_m(\rho_{A,S} - \rho_{A,\infty}) \qquad [kg/sm^2]$$

$$N_A . M_{molecular\,A} = n_A = n''_A A_s = h_m A_s(\rho_{A,S} - \rho_{A,\infty}) \qquad [kg/s]$$

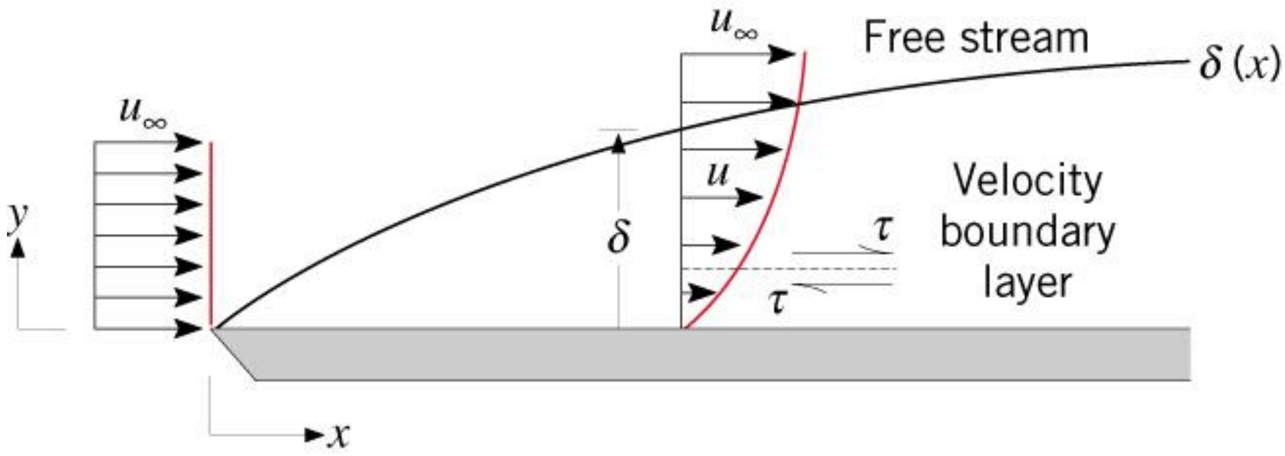
OBS: para determinar $C_{A,S}$ ou $\rho_{A,S}$ considera-se vapor saturado na temperatura T_S ou por aproximação de gás ideal:

$$C_{A,S} = \frac{\rho}{M_{molecular\,A}} = \frac{p_{sat}(T_S)}{\bar{R}T}$$

Ex 6.2 – Naftalina (sublimação) - Entregar

Camadas Limites

- Camada Limite Hidrodinâmica



$$\delta \rightarrow \frac{u(y)}{u_\infty} = 0.99$$

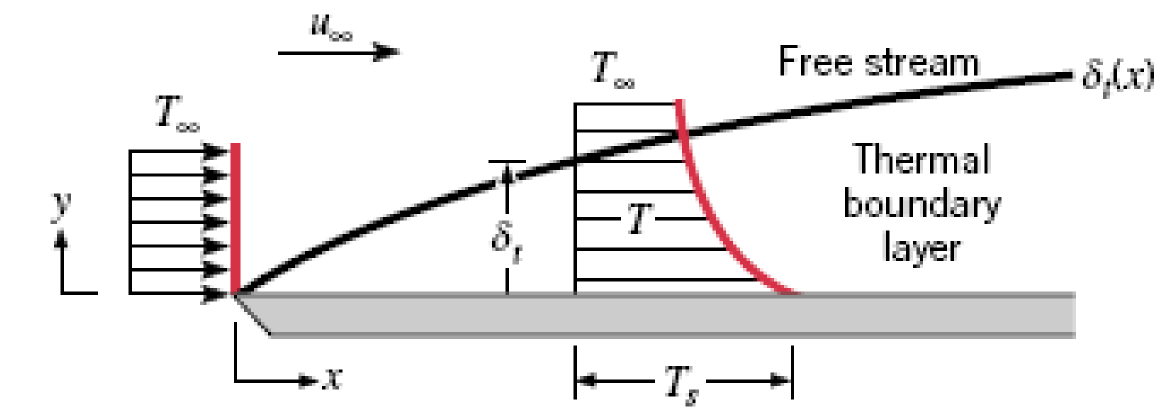
$$\tau_s = \mu \frac{\partial u}{\partial y}\bigg|_{y=0}$$

$$F_D = \int_{A_S} \tau_s dA_s$$

Coeficiente de atrito:

$$C_f = \frac{\tau_s}{\rho u_\infty^2 / 2}$$

- Camada Limite Térmica



$$\delta_t \rightarrow \frac{T_s - T(y)}{T_s - T_\infty} = 0.99$$

$$q_s'' = -k_f \left. \frac{\partial T}{\partial y} \right|_{y=0}$$

$$h \equiv \frac{-k_f \partial T / \partial y|_{y=0}}{T_s - T_\infty}$$

- Camada Limite de Concentração

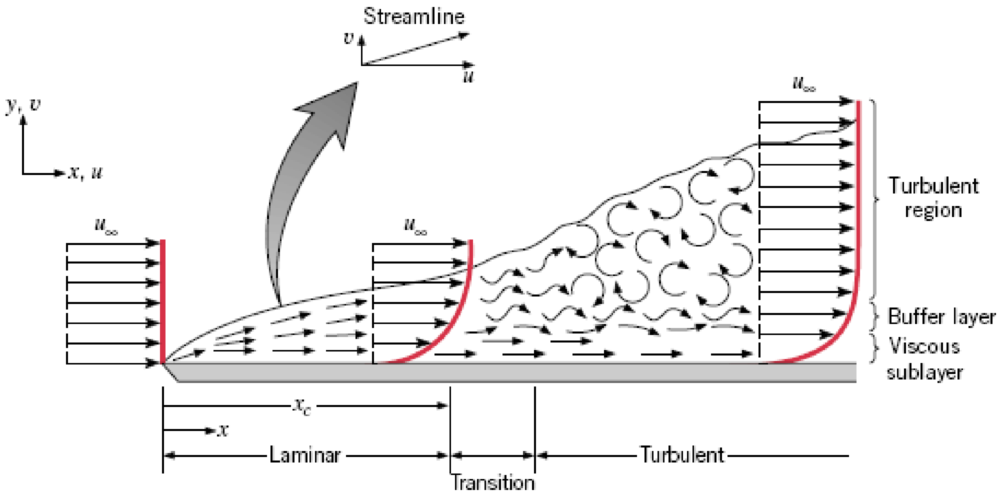
$$\delta_t \longrightarrow \delta_c$$
$$q \longrightarrow N$$
$$h \longrightarrow h_m$$

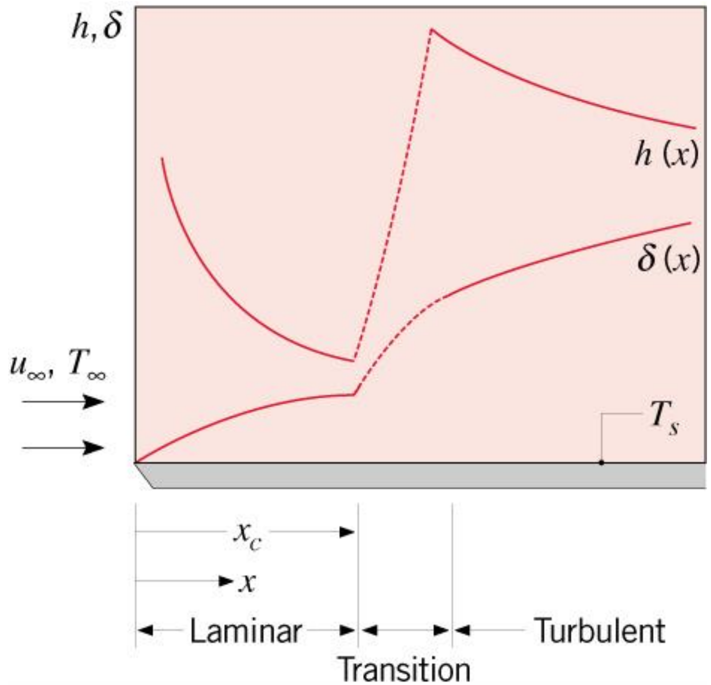
$$N_A'' = -D_{AB} \left. \frac{\partial C_A}{\partial y} \right|_{y=0} = h_m \left(C_{A,S} - C_{A,\infty} \right) \quad h_m = \frac{-D_{AB} \left. \partial C_A / \partial y \right|_{y=0}}{C_{A,S} - C_{A,\infty}} = \frac{-D_{AB} \left. \partial \rho_A / \partial y \right|_{y=0}}{\rho_{A,S} - \rho_{A,\infty}}$$

- Coeficiente de Difusão Binária
  para um gás ideal

$$D_{AB} \propto p^{-1} T^{3/2}$$

Laminar/Turbulento





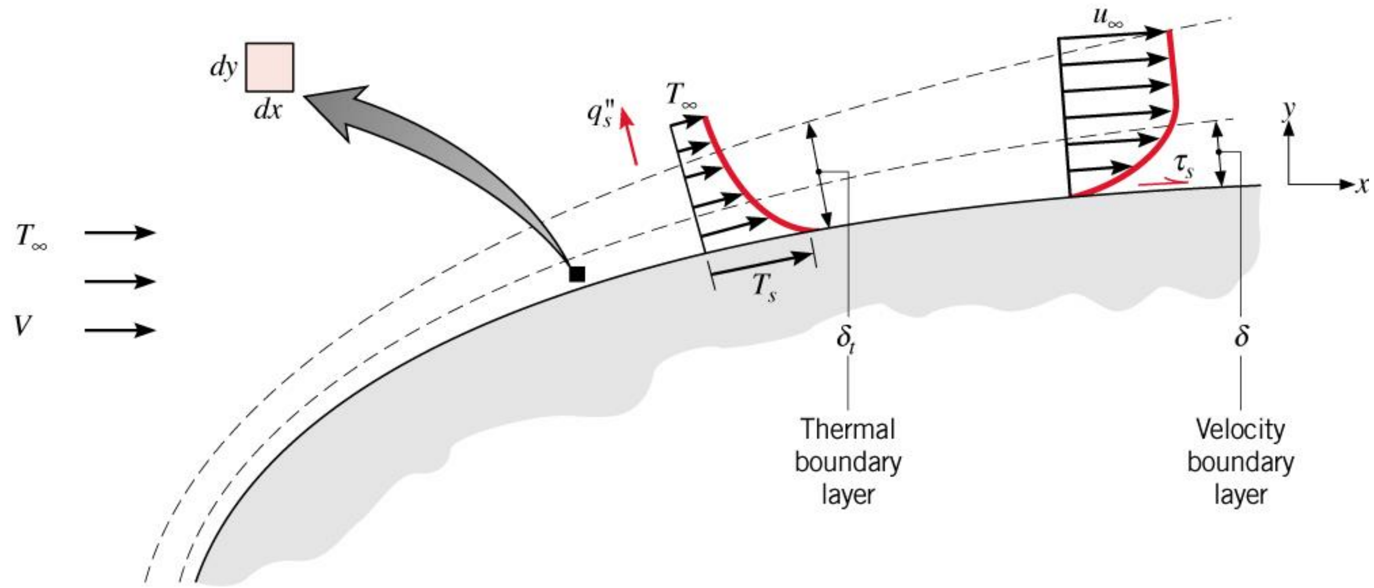
$$\mathrm{Re}_{x,c} \equiv \frac{\rho u_\infty x_c}{\mu} \rightarrow \text{ critical Reynolds number}$$

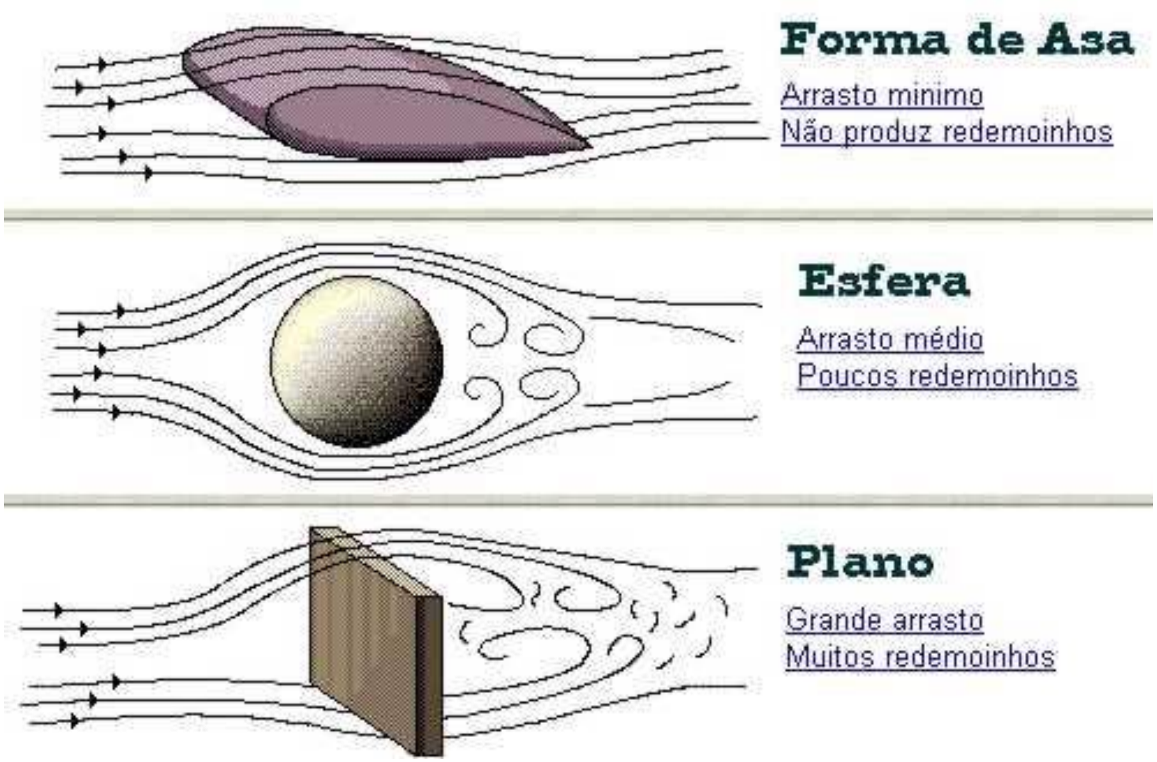
$x_c \rightarrow$ location at which transition to turbulence begins

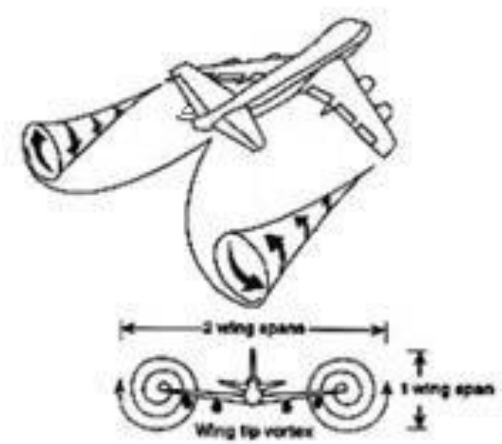
$$10^5 \lesssim \mathrm{Re}_{x,c} \lesssim 3 \text{ x } 10^6$$

Adotado: $\mathrm{Re}_{xc}=5 \times 10^5$

Resolução Formal das Equações




Forma de Asa
Arrasto minimo
Não produz redemoinhos
Esfera
Arrasto médio
Poucos redemoinhos
Plano
Grande arrasto
Muitos redemoinhos



Wake Vortex Study at Wallops Island
NASA Langley Research Center 5/4/1990 Image # EL-1996-00130

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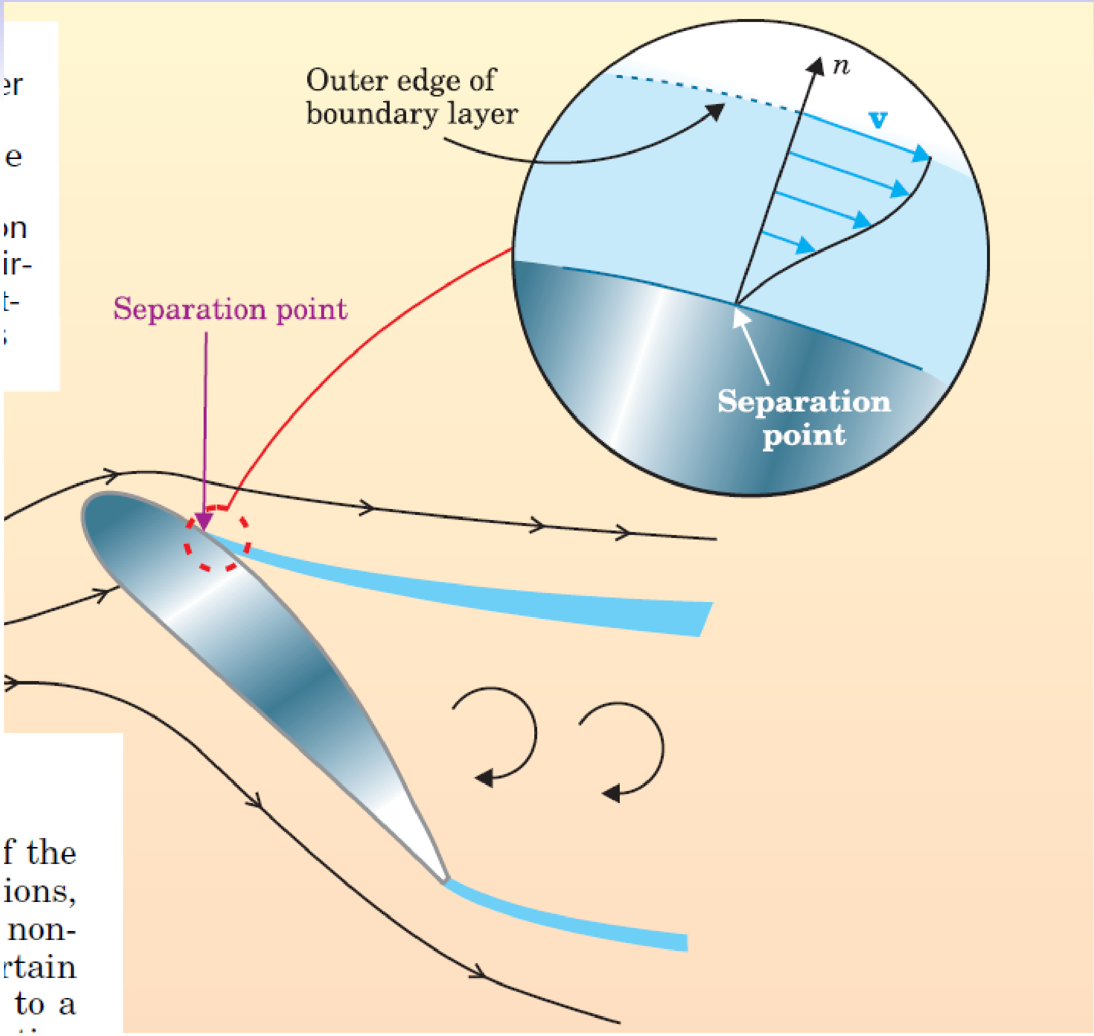

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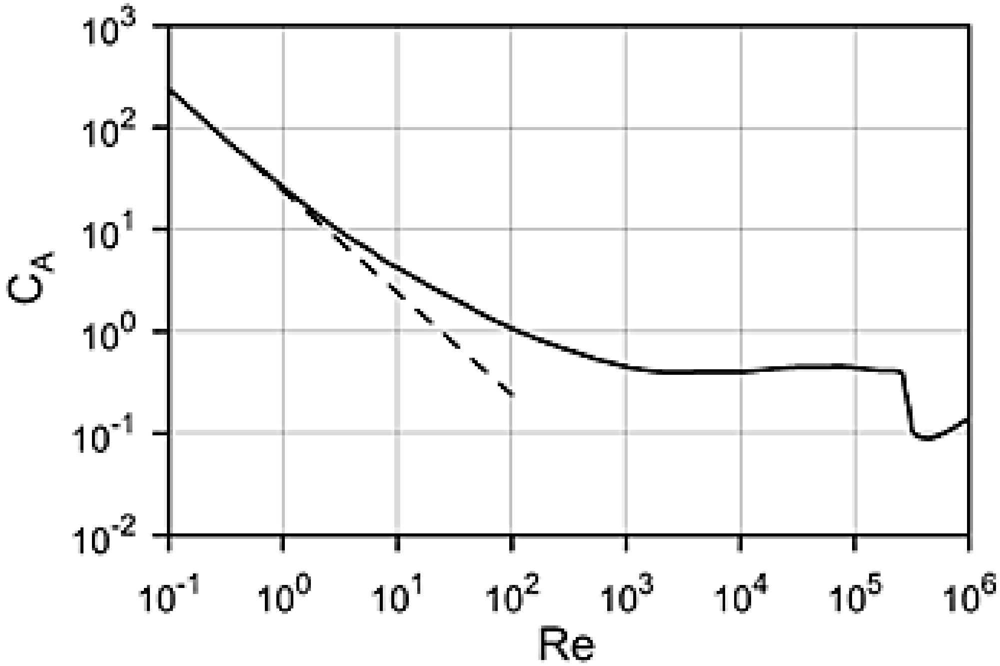
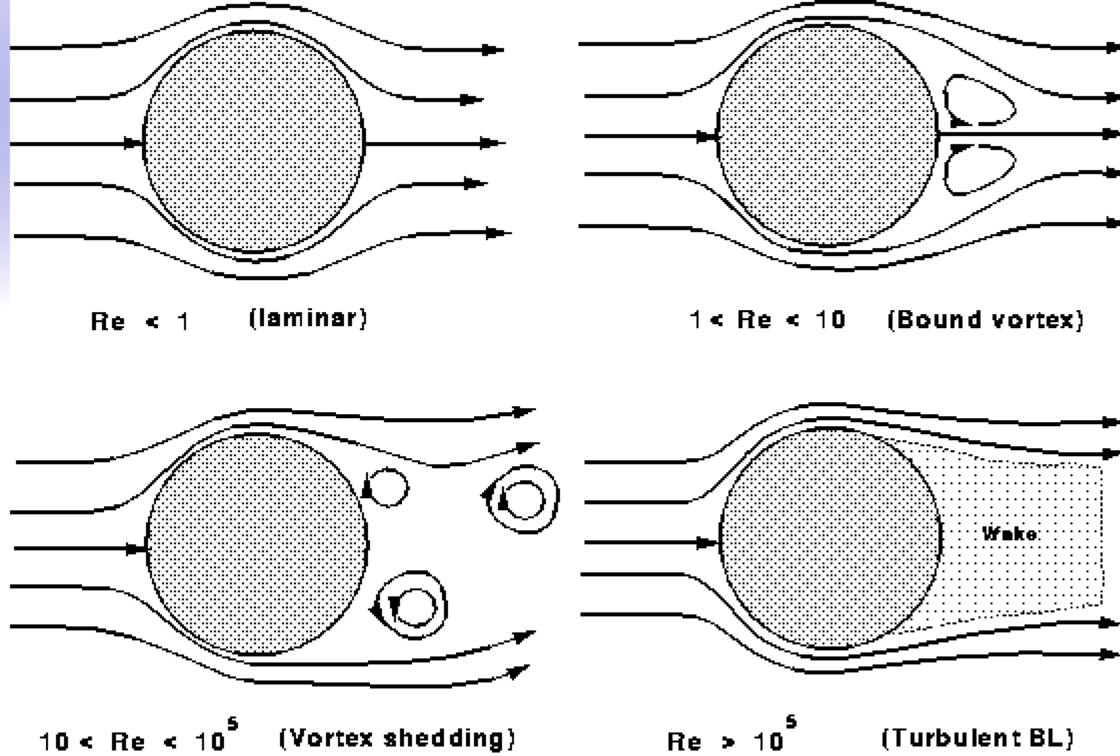
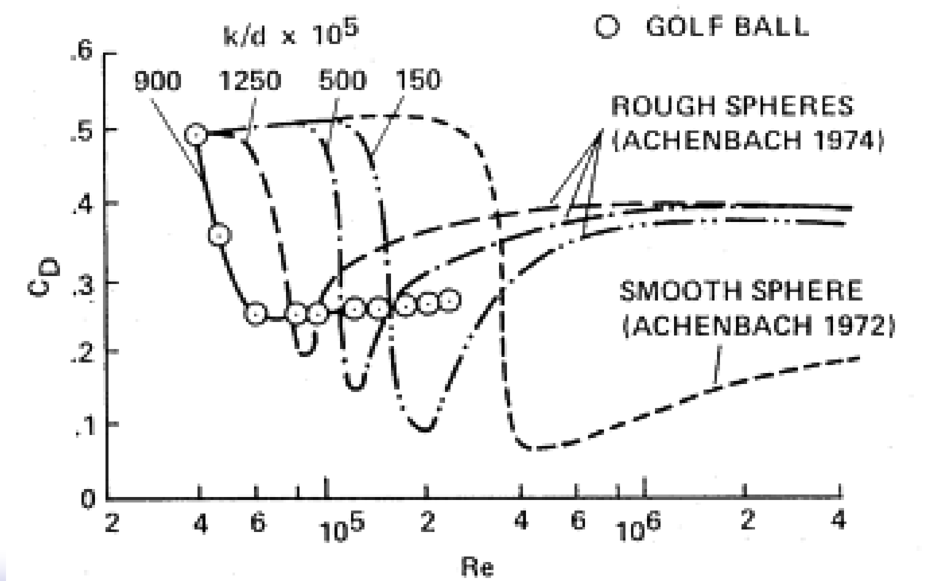
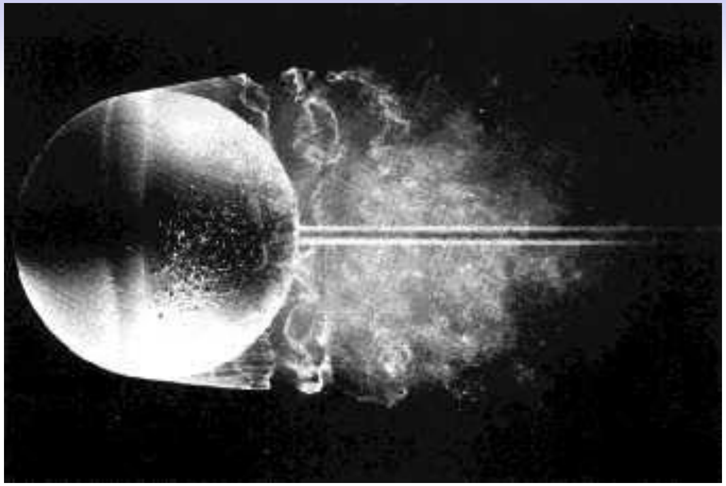
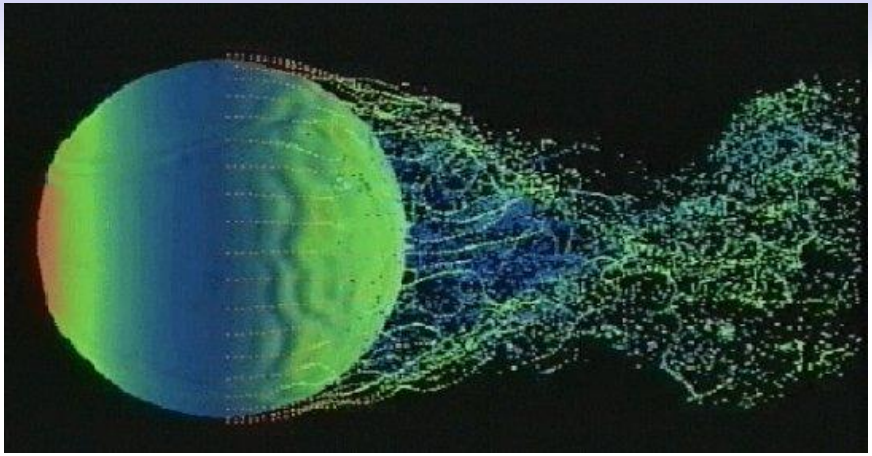
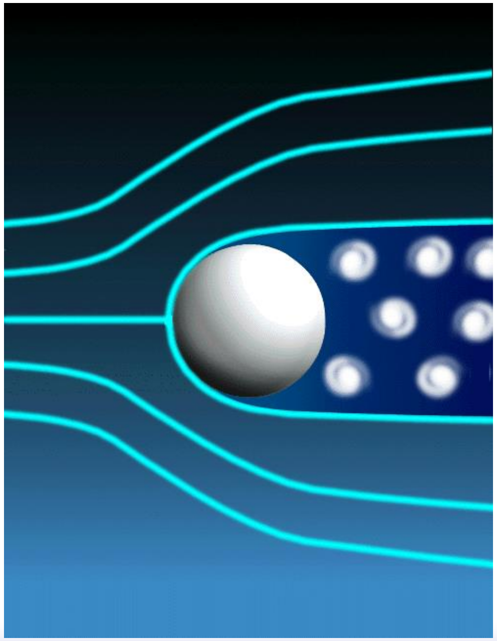
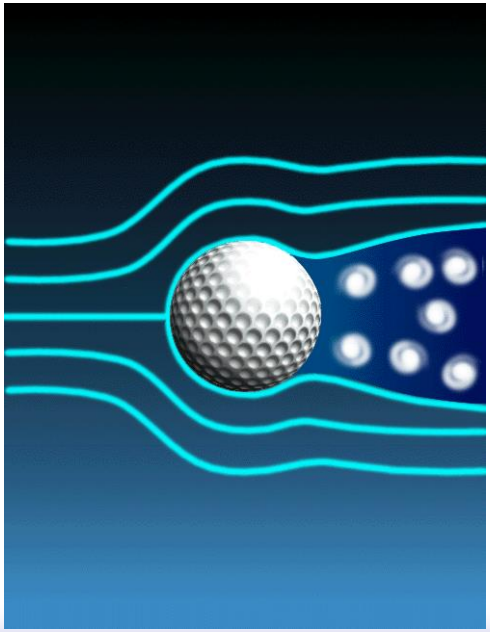


Figura 1 - Coeficiente de arrasto de uma esfera lisa, em função do número de Reynolds. A linha cheia é o resultado de medidas realizadas em túneis de vento. A linha tracejada corresponde à fórmula de Stokes (força de arrasto proporcional a V)

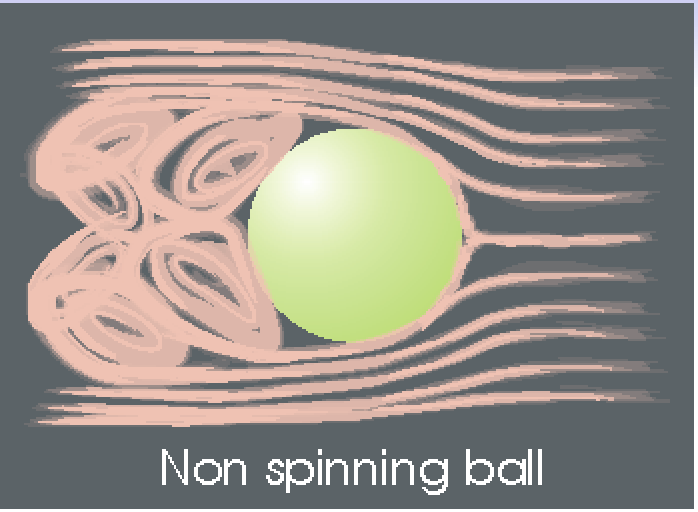
$$F_A = \frac{1}{2} C_A \rho A V^2$$

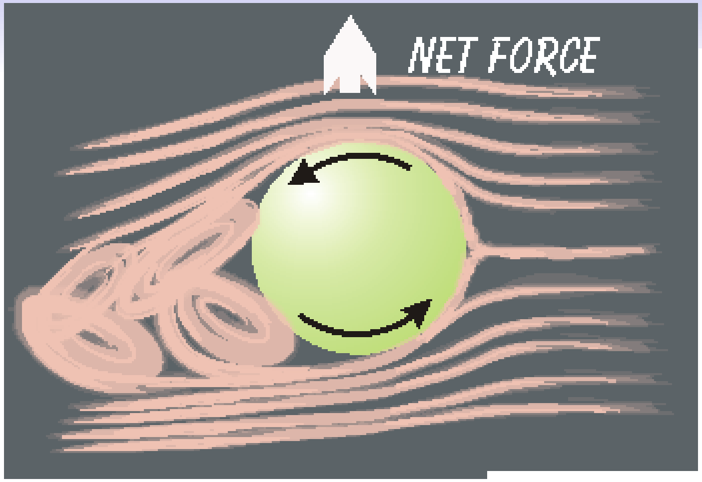

Re < 1 (laminar)
1 < Re < 10 (Bound vortex)
10 < Re < 10^5 (Vortex shedding)
Wake
Re > 10^5 (Turbulent BL)

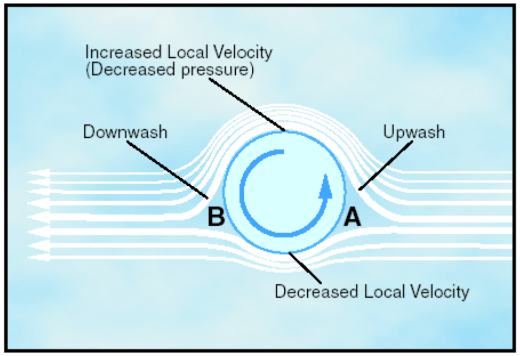

k/d × 10^5
900
1250
500
150
GOLF BALL
ROUGH SPHERES
(ACHENBACH 1974)
SMOOTH SPHERE
(ACHENBACH 1972)
C_D
Re
.6
.5
.4
.3
.2
.1
0
2
4
6
10^5
2
4
6
10^6
2
4

The Magnus Effect.







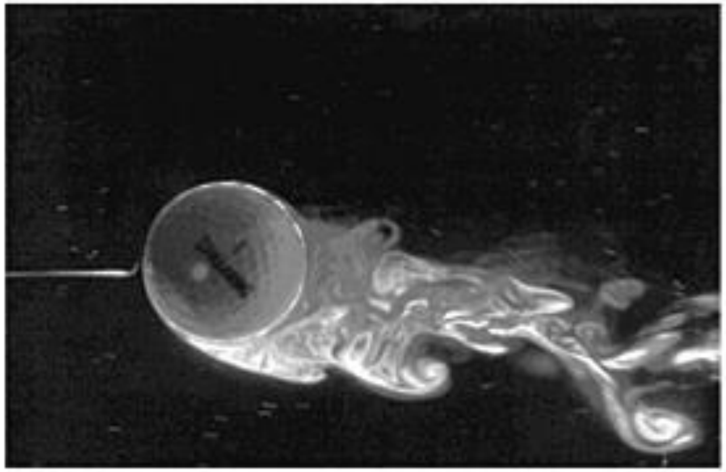
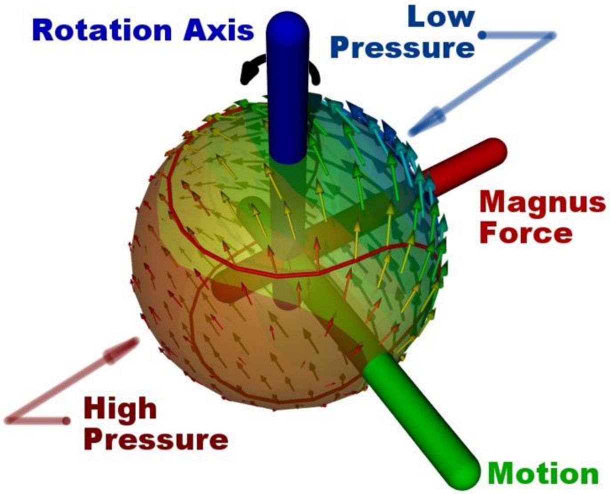
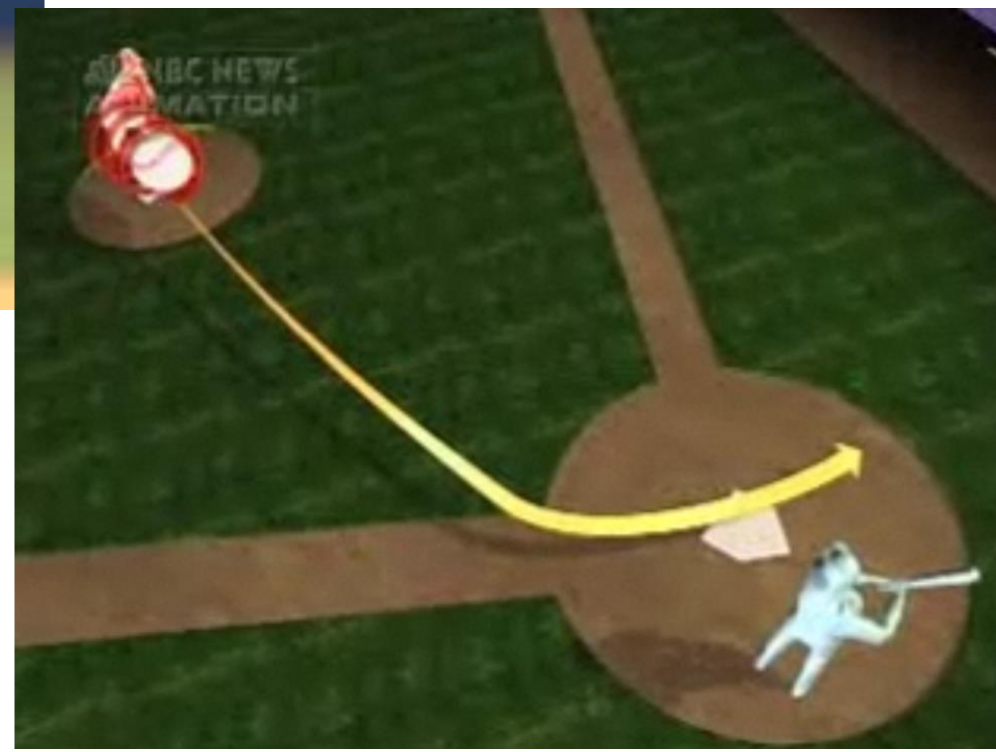
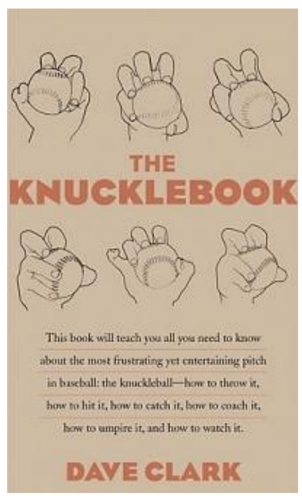


Figura 5 - Separação da camada limite em uma bola girando no sentido horário [17].

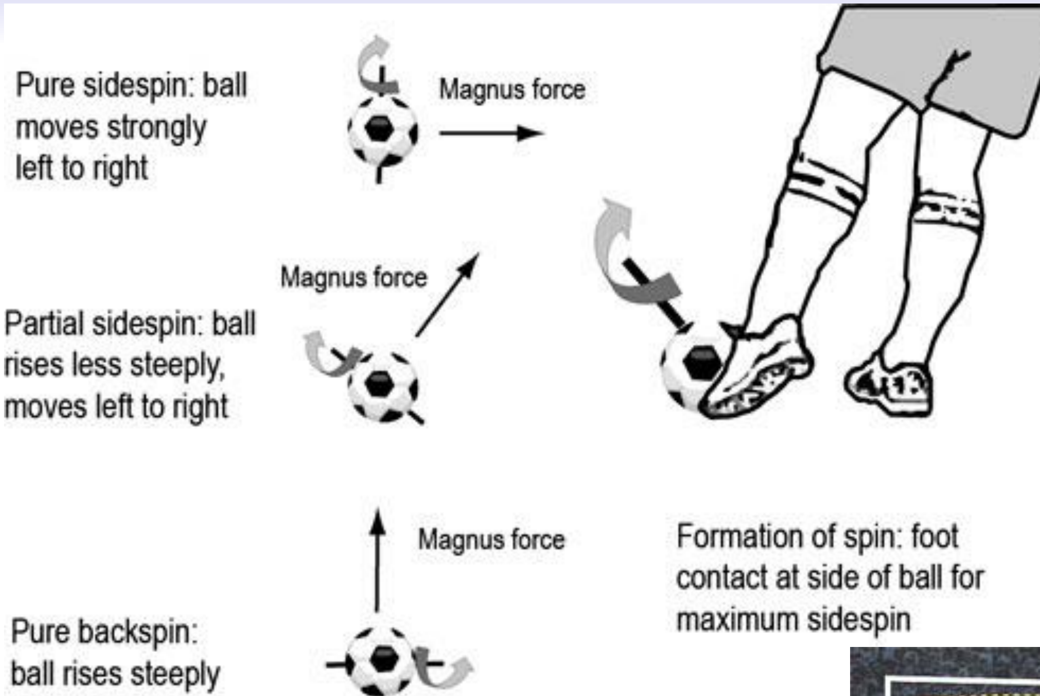


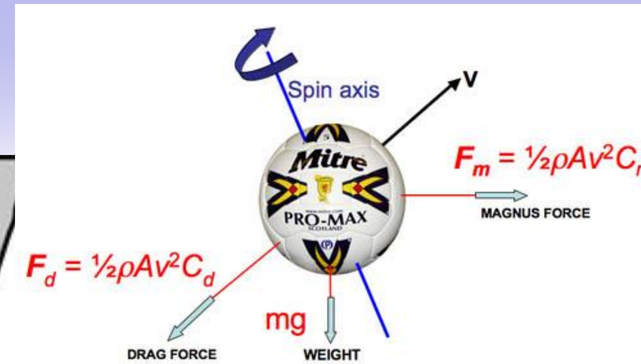
- Video: Daisuke Matsuzaka throws a gyroball

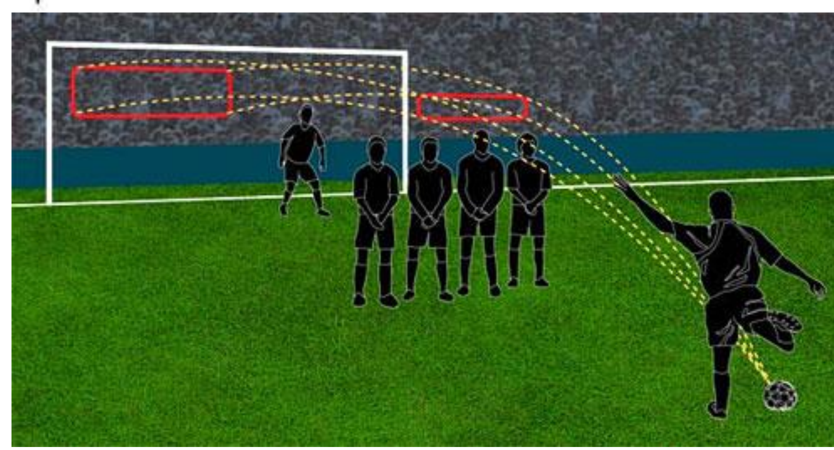




As Bert Blyleven, Three-Finger Mordecai Brown, and Joan Joyce (of the Stratford, nee Raybestos, Brakettes, maybe the best of this elite company) could tell you, a curveball is more than just the physics behind the Magnus


Pure sidespin: ball moves strongly left to right
Magnus force
Magnus force
Partial sidespin: ball rises less steeply, moves left to right
Magnus force
Pure backspin: ball rises steeply
Formation of spin: foot contact at side of ball for maximum sidespin


Spin axis
v
Mitre
PRO-MAX
$F_m = ½ρAv^2C_m$
MAGNUS FORCE
$F_d = ½ρAv^2C_d$
mg
DRAG FORCE
WEIGHT



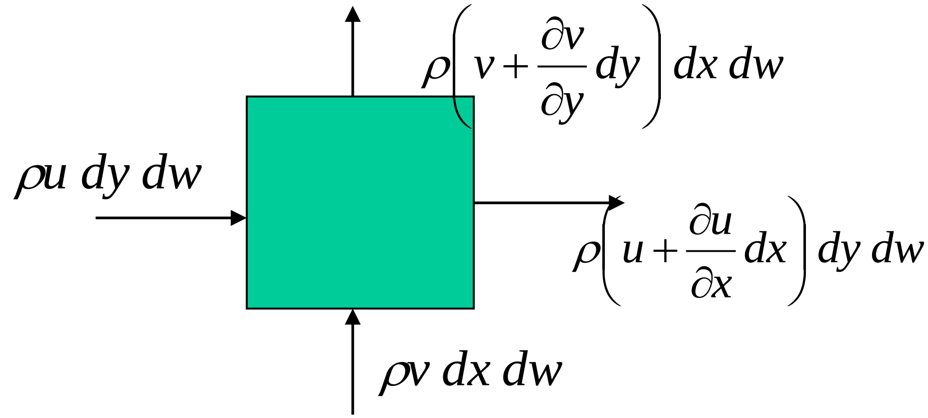
Resolução Formal das Equações

- Conservação da massa
- Energia
- 2º Lei de Newton
- Espécie Química
- 2º Lei da Termodinâmica

Para um escoamento 2-D estacionário, **incompressível** e com propriedades constantes

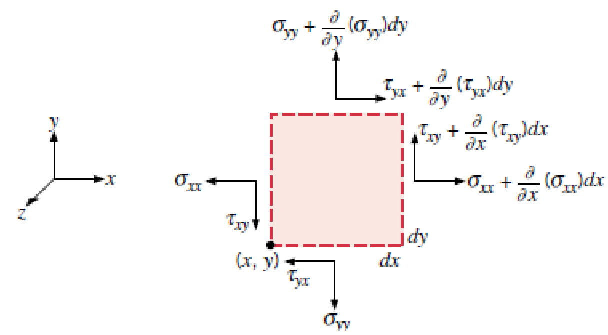
- Conservação da Massa

$$0 = \frac{\partial}{\partial t}\int_{VC} \rho d\forall + \int_{SC} \rho \vec{V} \cdot d\vec{A}$$



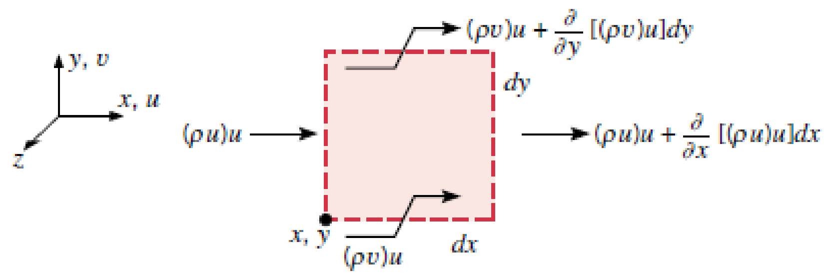
$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

- 2ª Lei de Newton



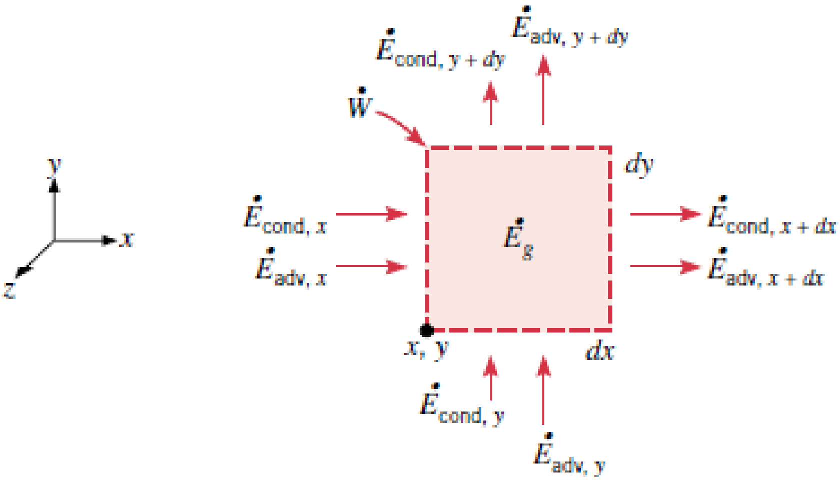
$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + \rho g_x$$

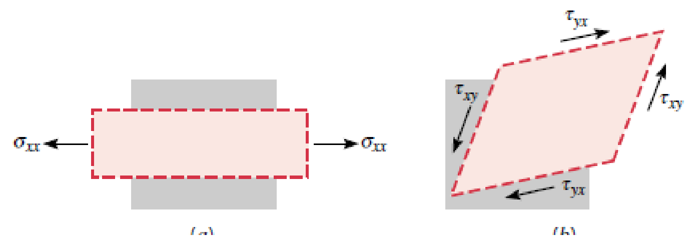
$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \rho g_y$$



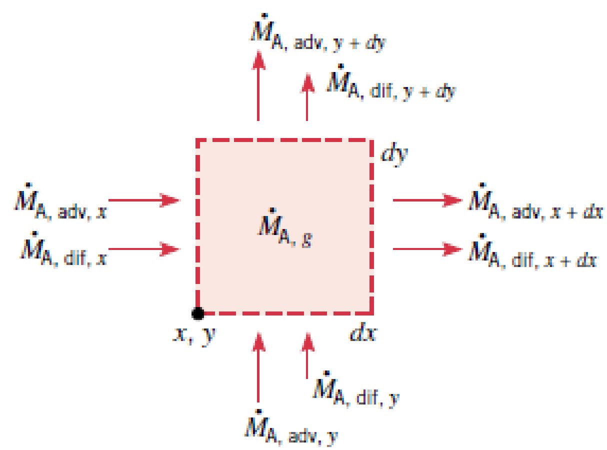
- Energia

$$\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\mu\left\{\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2+2\left[\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2\right]\right\}+\dot{q}$$





- Concentração



$$u\frac{\partial C_A}{\partial x}+v\frac{\partial C_A}{\partial y}=D_{AB}\left(\frac{\partial^2 C_A}{\partial x^2}+\frac{\partial^2 C_A}{\partial y^2}\right)+\dot{N}_A$$

Conjunto de Equações

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

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + \rho g_x$$

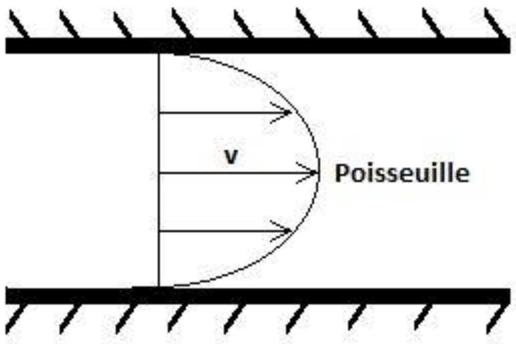
$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \rho g_y$$

$$\rho c_p\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \mu\left\{\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + 2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2\right]\right\} + \dot{q}$$

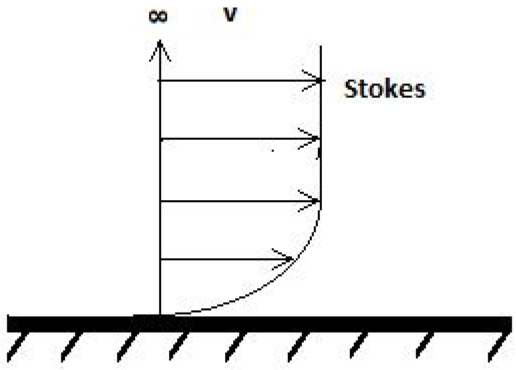
$$u\frac{\partial C_A}{\partial x} + v\frac{\partial C_A}{\partial y} = D_{AB}\left(\frac{\partial^2 C_A}{\partial x^2} + \frac{\partial^2 C_A}{\partial y^2}\right) + \dot{N}_A$$

Padrões de escoamento

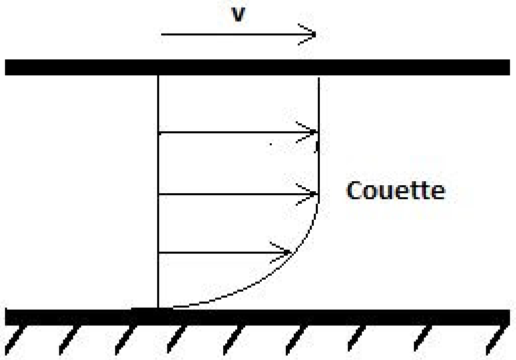
Escoamento de Poiseuille



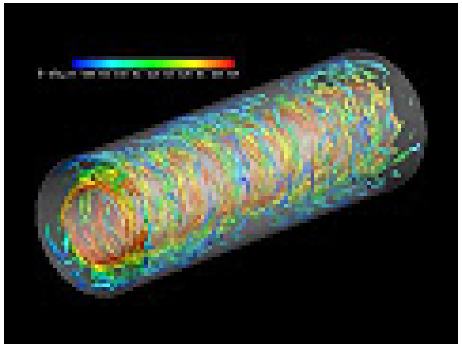
Escoamento de Stokes



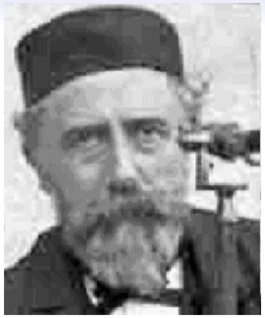
Escoamento de Couette

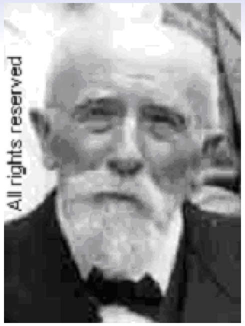


Escoamento de Taylor-Couette



Escoamento de Couette





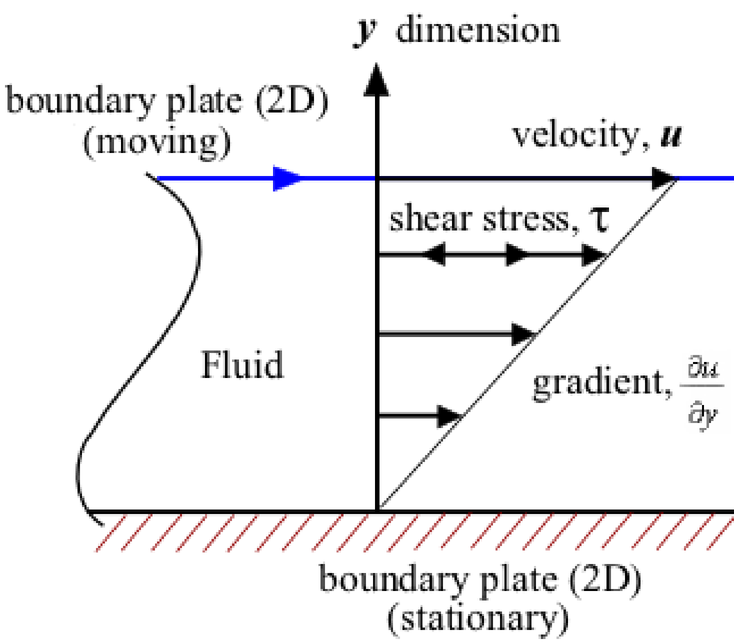
Maurice Marie Alfred Couette (1858 -1943)

Professor da Université Catholique de l'Ouest
Angers, France

Figure 2. Maurice Couette's concentric cylinder apparatus (viscometer) (1888)

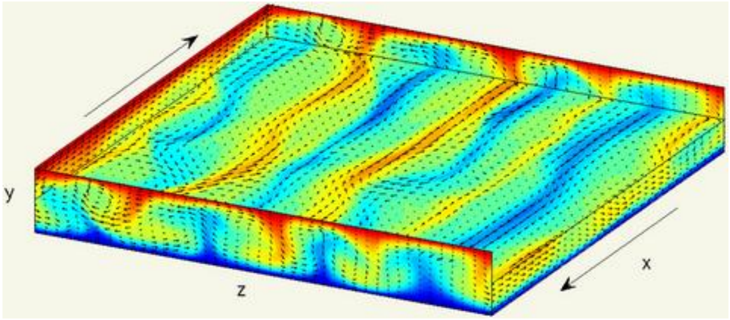
http://rheologie.ujf-grenoble.fr/Couette/gfr_Couettepiau.pdf

Escoamento de Couette



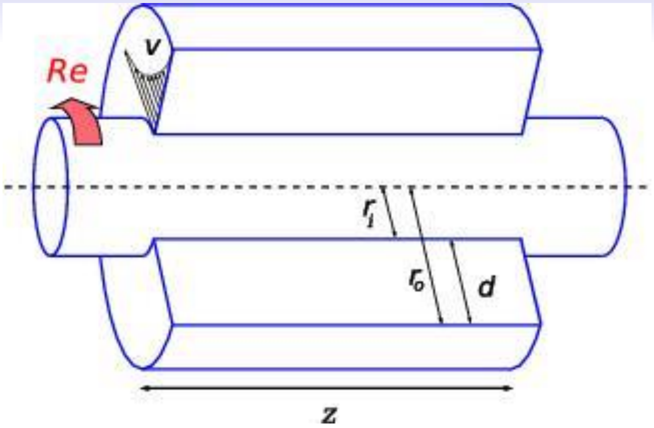
http://en.wikipedia.org/wiki/File:Laminar_shear.png

Plane Couette turbulence in a periodic cell with large aspect ratio

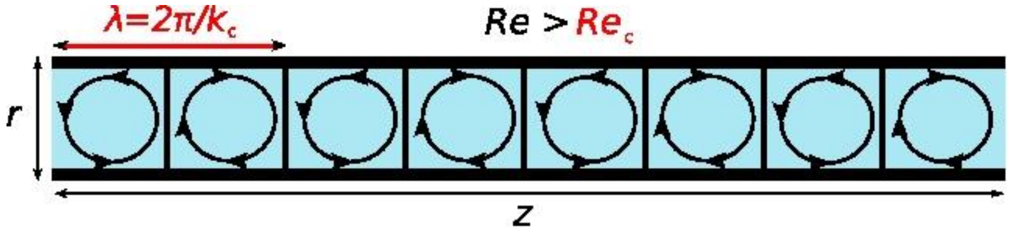


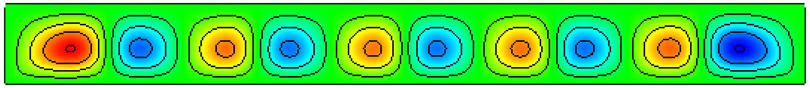
http://www.cns.gatech.edu/~gibson/PCF-movies/bigbox_rand.mp4

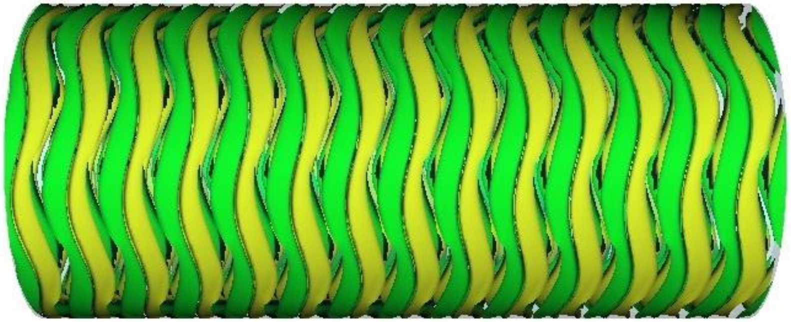
Escoamento de Taylor-Couette



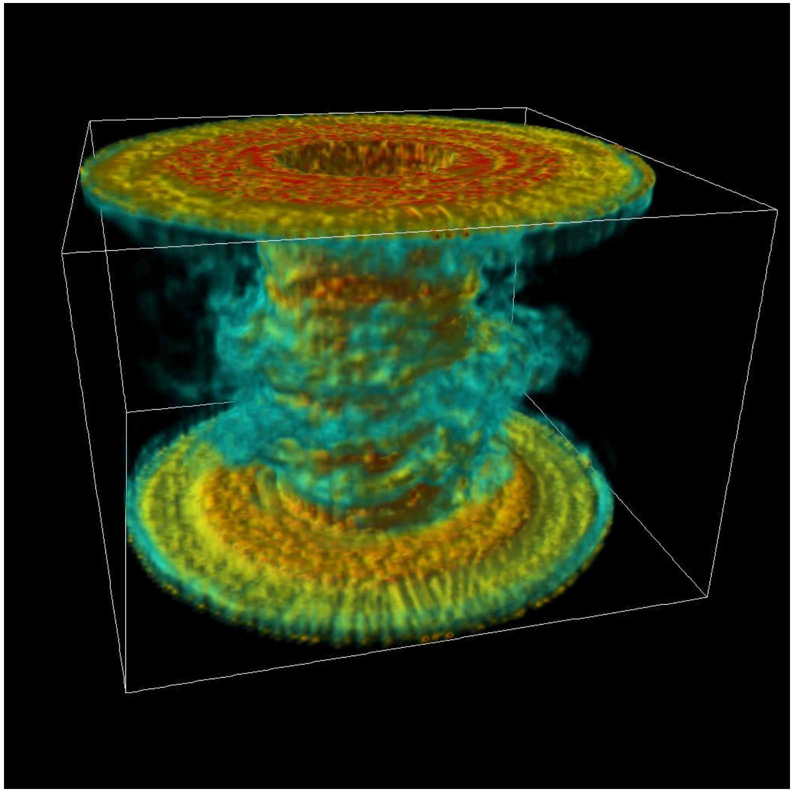
www-fa.upc.es/websfa/fluids/marc/img

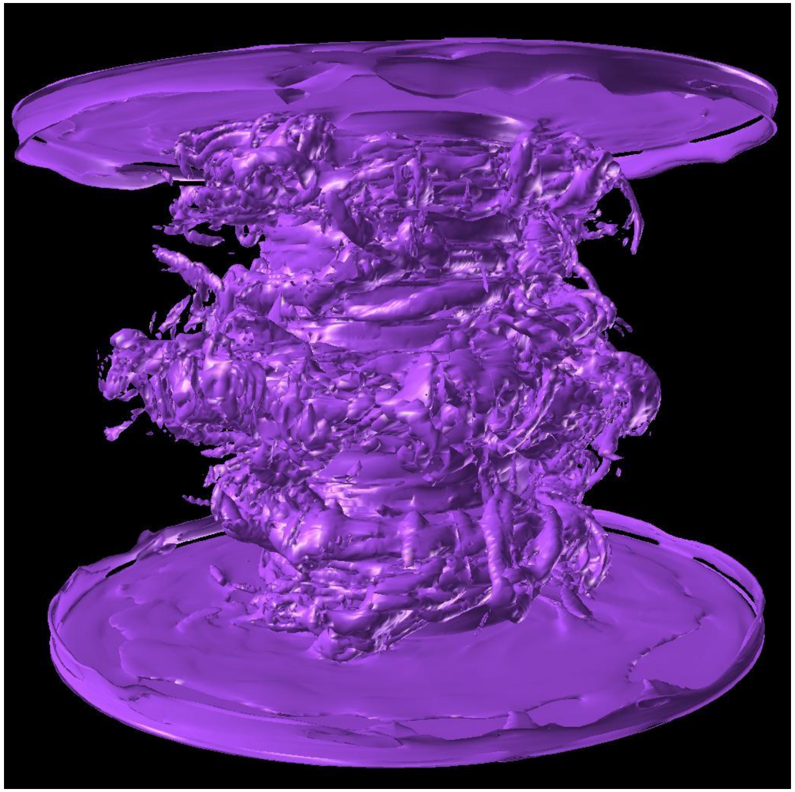






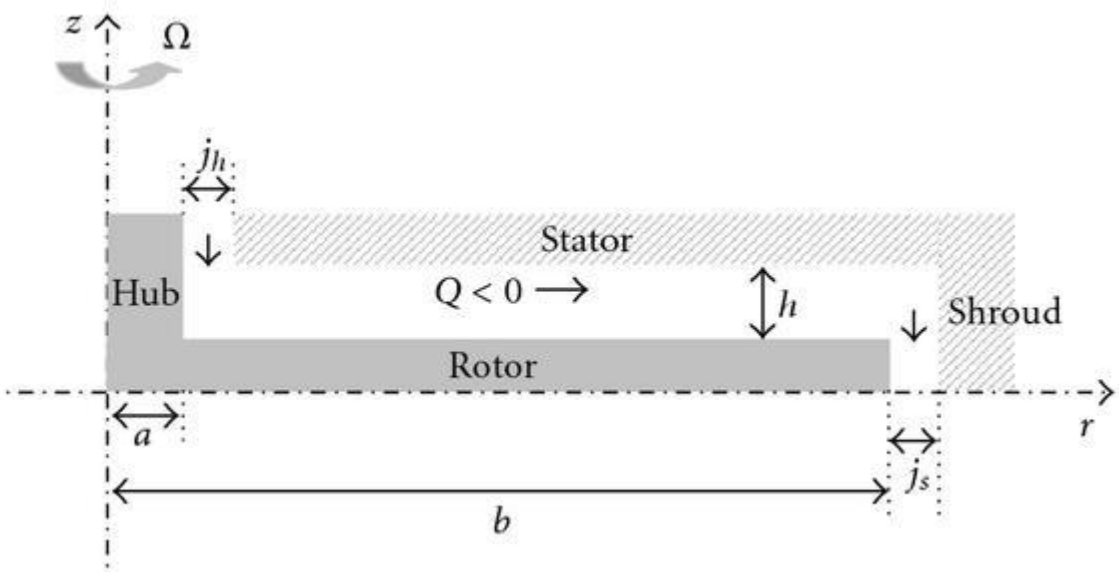
Exemplo - Escoamento de Taylor Couette

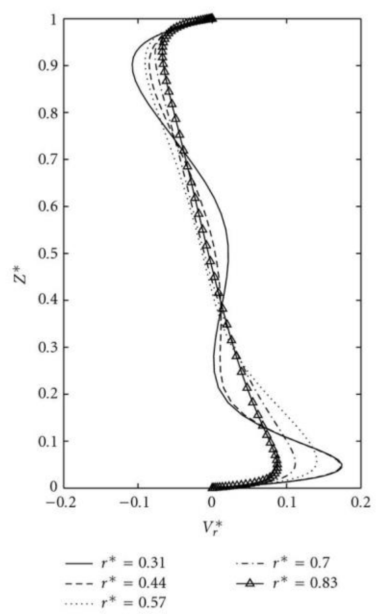


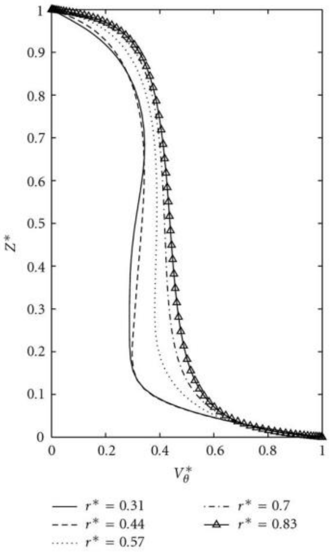


- http://flash.uchicago.edu/~cattaneo/Pages/image_gallery.htm

Aplicações

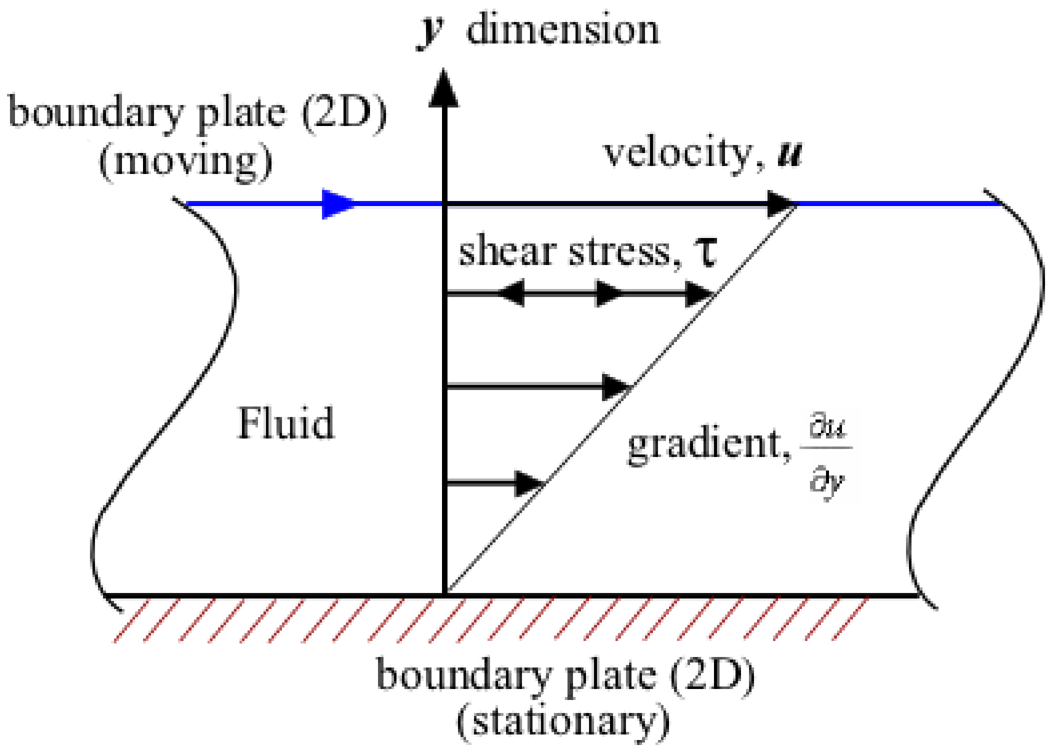






http://www.hindawi.com/journals/ijrm/2008/635138.fig2.html

Escoamento de Couette



Conjunto de Equações

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

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + \rho g_x$$

$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \rho g_y$$

$$\rho c_p\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \mu\left\{\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + 2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2\right]\right\} + \dot{q}$$

$$u\frac{\partial C_A}{\partial x} + v\frac{\partial C_A}{\partial y} = D_{AB}\left(\frac{\partial^2 C_A}{\partial x^2} + \frac{\partial^2 C_A}{\partial y^2}\right) + \dot{N}_A$$

Com as aproximações p/ escoamento de Couette

(ECD=Escoamento completamente desenvolvido)

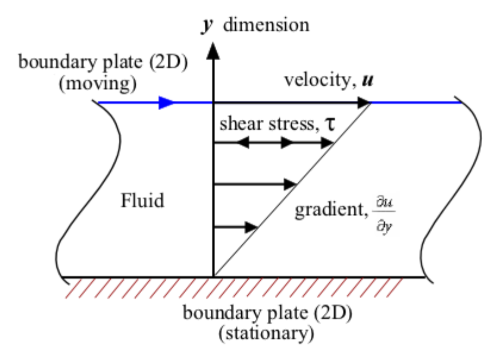
$$\frac{\partial u}{\partial x}+\overset{(v=0)}{\cancel{\frac{\partial v}{\partial y}}}=0$$

$$\rho\left(\overset{(CM,ECD)}{\cancel{u\frac{\partial u}{\partial x}}}+\overset{(v=0)}{\cancel{v\frac{\partial u}{\partial y}}}\right)=\overset{\text{sem }\nabla p}{\cancel{-\frac{\partial p}{\partial x}}}+\mu\left(\overset{(CM)}{\cancel{\frac{\partial^2 u}{\partial x^2}}}+\frac{\partial^2 u}{\partial y^2}\right)+\overset{\text{sem } F_{Bx}}{\cancel{\rho g_x}}$$

$$\rho\left(\overset{(v=0)}{\cancel{u\frac{\partial v}{\partial x}}}+\overset{(v=0)}{\cancel{v\frac{\partial v}{\partial y}}}\right)=-\frac{\partial p}{\partial y}+\mu\left(\overset{(v=0)}{\cancel{\frac{\partial^2 v}{\partial x^2}}}+\overset{(v=0)}{\cancel{\frac{\partial^2 v}{\partial y^2}}}\right)+\overset{\text{sem } F_{By}}{\cancel{\rho g_y}}$$

$$\rho c_p\left(\overset{(ECD)}{\cancel{u\frac{\partial T}{\partial x}}}+\overset{(v=0)}{\cancel{v\frac{\partial T}{\partial y}}}\right)=k\left(\overset{(ECD)}{\cancel{\frac{\partial^2 T}{\partial x^2}}}+\frac{\partial^2 T}{\partial y^2}\right)+\mu\left\{\left(\frac{\partial u}{\partial y}+\overset{(v=0)}{\cancel{\frac{\partial v}{\partial x}}}\right)^2+2\left[\left(\overset{(CM)}{\cancel{\frac{\partial u}{\partial x}}}\right)^2+\left(\overset{(v=0)}{\cancel{\frac{\partial v}{\partial y}}}\right)^2\right]\right\}+\overset{\text{sem geração de calor}}{\cancel{\dot{q}}}$$

$$\overset{(ECD)}{\cancel{u\frac{\partial C_A}{\partial x}}}+\overset{(v=0)}{\cancel{v\frac{\partial C_A}{\partial y}}}=D_{AB}\left(\overset{(ECD)}{\cancel{\frac{\partial^2 C_A}{\partial x^2}}}+\frac{\partial^2 C_A}{\partial y^2}\right)+\overset{\text{sem geração de M}}{\cancel{\dot{N}_A}}$$



Finalmente para o escoamento de Couette

$$\frac{\partial u}{\partial x} = 0$$

$$\mu\left(\frac{\partial^2 u}{\partial y^2}\right) = 0$$

$$\frac{\partial p}{\partial y} = 0$$

$$k\left(+\frac{\partial^2 T}{\partial y^2}\right) + \mu\left\{\left(\frac{\partial u}{\partial y}\right)^2\right\} = 0$$

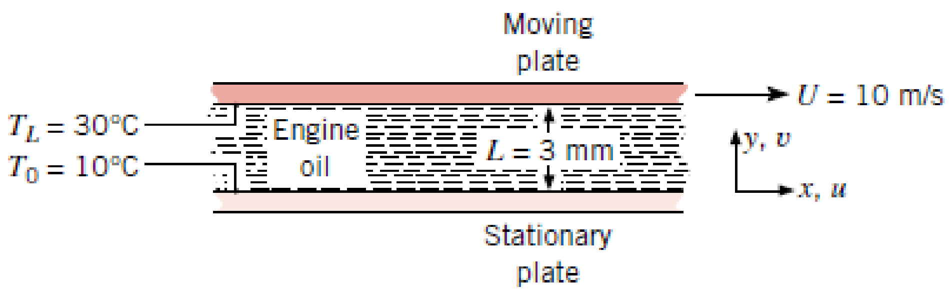
$$D_{AB}\left(+\frac{\partial^2 C_A}{\partial y^2}\right) = 0$$

Known: Couette flow with heat transfer.

Find:

1. Form of the continuity equation.
2. Velocity distribution.
3. Temperature distribution.
4. Surface heat fluxes and maximum temperature for prescribed conditions.

Schematic:



Assumptions:

1. Steady-state conditions.
2. Two-dimensional flow (no variations in z).
3. Incompressible fluid with constant properties.
4. No body forces.
5. No internal energy generation.

Properties: Table A.8, engine oil (20°C): $\rho = 888.2\ \mathrm{kg/m^3}$, $k = 0.145\ \mathrm{W/m \cdot K}$, $\nu = 900 \times 10^{-6}\ \mathrm{m^2/s}$, $\mu = \nu\rho = 0.799\ \mathrm{N \cdot s/m^2}$.

Analysis:

1. For an incompressible fluid (constant ρ) and parallel flow ($v = 0$), Equation D.1 reduces to

$$\frac{\partial u}{\partial x} = 0 \qquad \triangleleft$$

The important implication of this result is that, although depending on y, the x velocity component u is independent of x. It may then be said that the velocity field is *fully developed.*

2. For two-dimensional, steady-state conditions with $v = 0$, $(\partial u/\partial x) = 0$, and $X = 0$, Equation D.2 reduces to

$$0 = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial y^2}\right)$$

However, in Couette flow, motion of the fluid is not sustained by the pressure gradient, $\partial p/\partial x$, but by an external force that provides for motion of the top plate relative to the bottom plate. Hence $(\partial p/\partial x) = 0$. Accordingly, the x-momentum equation reduces to

$$\frac{\partial^2 u}{\partial y^2} = 0$$

The desired velocity distribution may be obtained by solving this equation. Integrating twice, we obtain

$$u(y) = C_1 y + C_2$$

where C_1 and C_2 are the constants of integration. Applying the boundary conditions

$$u(0) = 0 \quad u(L) = U$$

it follows that $C_2 = 0$ and $C_1 = U/L$. The velocity distribution is then

$$u(y) = \frac{y}{L} U \qquad \triangleleft$$

3. The energy equation (D.4) may be simplified for the prescribed conditions. In particular, with $v = 0$, $(\partial u/\partial x) = 0$, and $\dot{q} = 0$, it follows that

$$\rho c_p u \frac{\partial T}{\partial x} = k\frac{\partial^2 T}{\partial x^2} + k\frac{\partial^2 T}{\partial y^2} + \mu\left(\frac{\partial u}{\partial y}\right)^2$$

However, because the top and bottom plates are at uniform temperatures, the temperature field must also be fully developed, in which case $(\partial T/\partial x) = 0$. The appropriate form of the energy equation is then

$$0 = k\frac{\partial^2 T}{\partial y^2} + \mu\left(\frac{\partial u}{\partial y}\right)^2$$

The desired temperature distribution may be obtained by solving this equation. Rearranging and substituting for the velocity distribution,

$$k\frac{d^2T}{dy^2} = -\mu\left(\frac{du}{dy}\right)^2 = -\mu\left(\frac{U}{L}\right)^2$$

Integrating twice, we obtain

$$T(y) = -\frac{\mu}{2k}\left(\frac{U}{L}\right)^2 y^2 + C_3 y + C_4$$

The constants of integration may be obtained from the boundary conditions

$$T(0) = T_0 \qquad T(L) = T_L$$

in which case

$$C_4 = T_0 \qquad \text{and} \qquad C_3 = \frac{T_L - T_0}{L} + \frac{\mu}{2k}\frac{U^2}{L}$$

and

$$T(y) = T_0 + \frac{\mu}{2k}U^2\left[\frac{y}{L} - \left(\frac{y}{L}\right)^2\right] + (T_L - T_0)\frac{y}{L}$$

◁

4. Knowing the temperature distribution, the surface heat fluxes may be obtained by applying Fourier's law. Hence

$$q''_y = -k\frac{dT}{dy} = -k\left[\frac{\mu}{2k}U^2\left(\frac{1}{L} - \frac{2y}{L^2}\right) + \frac{T_L - T_0}{L}\right]$$

At the bottom and top surfaces, respectively, it follows that

$$q''_0 = -\frac{\mu U^2}{2L} - \frac{k}{L}(T_L - T_0) \qquad \text{and} \qquad q''_L = +\frac{\mu U^2}{2L} - \frac{k}{L}(T_L - T_0)$$

Hence, for the prescribed numerical values,

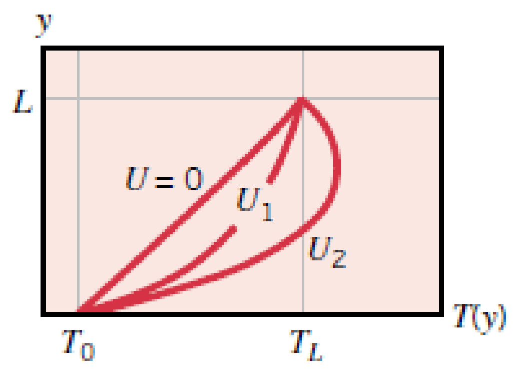
$$q''_0 = -\frac{0.799\ \text{N}\cdot\text{s/m}^2 \times 100\ \text{m}^2/\text{s}^2}{2 \times 3 \times 10^{-3}\text{m}} - \frac{0.145\ \text{W/m}\cdot\text{K}}{3 \times 10^{-3}\text{m}}(30 - 10)^\circ\text{C}$$

$$q''_0 = -13{,}315\ \text{W/m}^2 - 967\ \text{W/m}^2 = -14.3\ \text{kW/m}^2 \quad \triangleleft$$

$$q''_L = +13{,}315\ \text{W/m}^2 - 967\ \text{W/m}^2 = 12.3\ \text{kW/m}^2 \quad \triangleleft$$

The location of the maximum temperature in the oil may be found from the requirement that

$$\frac{dT}{dy} = \frac{\mu}{2k}U^2\left(\frac{1}{L} - \frac{2y}{L^2}\right) + \frac{T_L - T_0}{L} = 0$$



Solving for y, it follows that

$$y_{max} = \left[\frac{k}{\mu U^2}(T_L - T_0) + \frac{1}{2}\right]L$$