

# **EM 524 - FENÔMENOS DE TRANSPORTE**

## **Aula 16**

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# EM 524 - FENÔMENOS DE TRANSPORTE

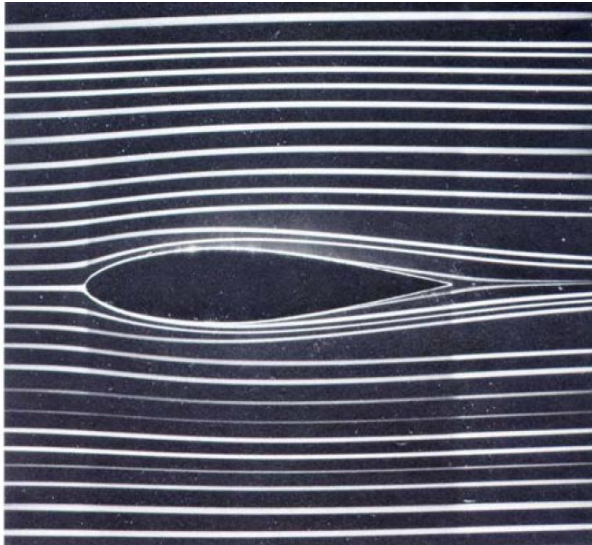
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*As informações abaixo têm como objetivo auxiliar o aluno quanto à organização dos tópicos principais abordados em sala e não excluem a necessidade de estudo e de complementação de conhecimentos através das referências indicadas na Agenda da Aula ou no Programa do curso.*

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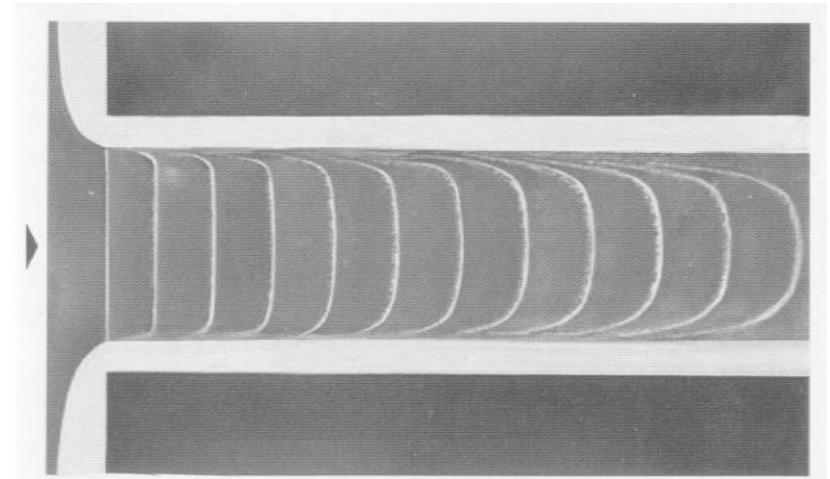
**Tópicos da aula (Cap. 6-Itens 6.1 a 6.5)**

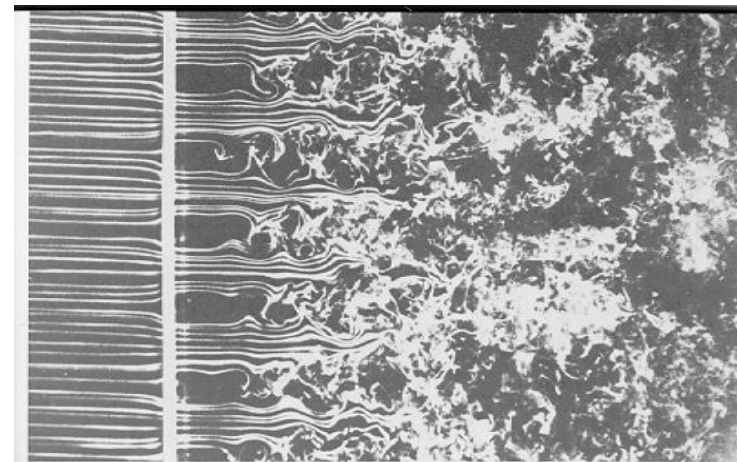
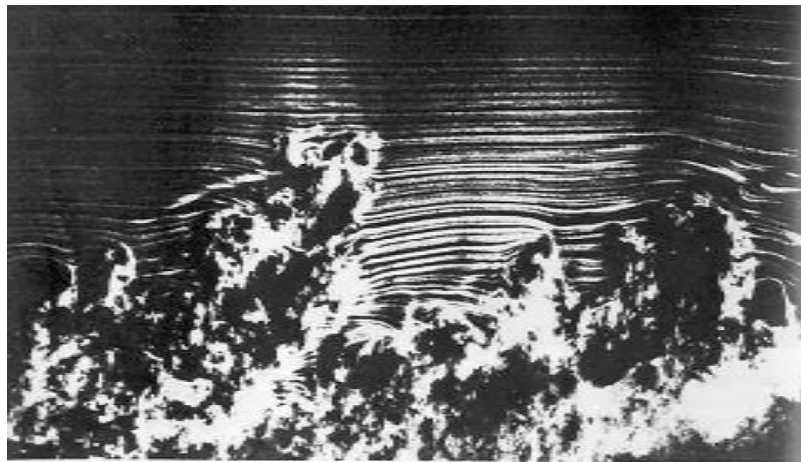
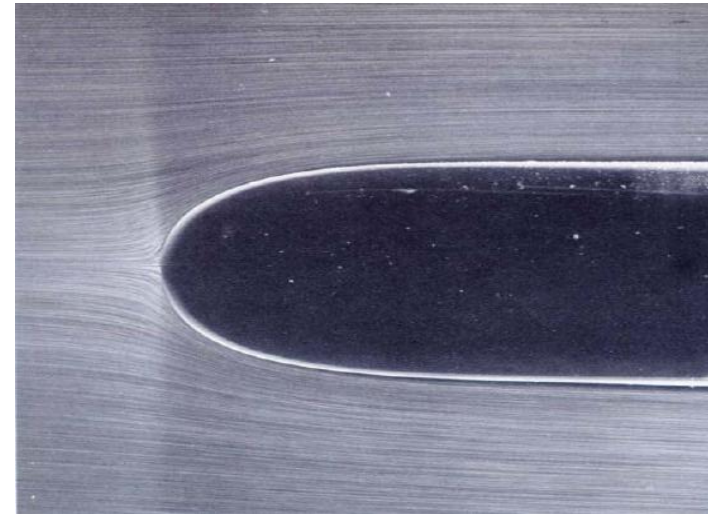
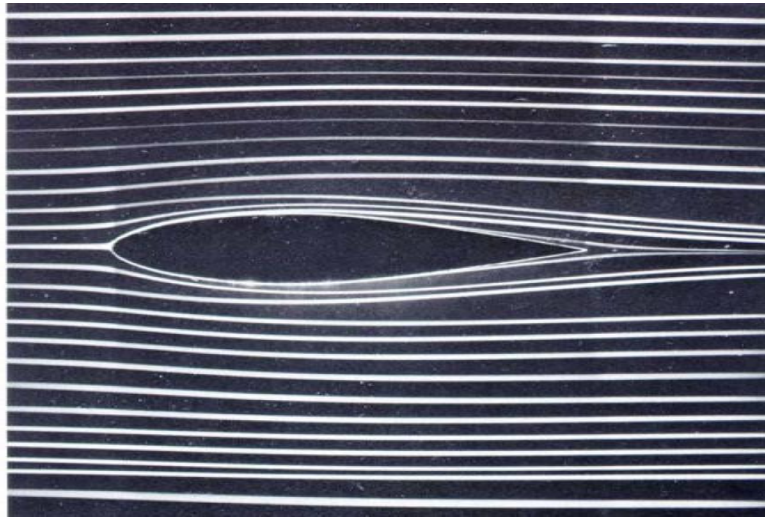
- **Escoamento Externo**
- **Perfil de Velocidades e a lei de não deslizamento**
- **Tensão de cisalhamento e a Lei de Newton**
- **Características da Camada Limite**
- **Regime de Escoamento: Laminar e Turbulento**
- **Arrasto Viscoso**
- **Efeitos do Gradiente de Pressão**
- **Arrasto de Forma**



Escoamentos **externos** não são confinados por paredes .

Escoamentos **internos** possuem fronteiras que limitam ou restringem o campo de escoamento





152. Generation of turbulence by a grid. Smoke wires show a uniform laminar stream passing through a  $\frac{1}{16}$ -inch plate with  $\frac{3}{16}$ -inch square perforations. The Reynolds number

is 1500 based on the 1-inch mesh size. Instability of the shear layers leads to turbulent flow downstream. Photograph by Thomas Corke and Hassan Nagib

- **Escoamento Laminar** – escoamento altamente ordenado, no qual uma molécula se desloca de maneira suave em relação às outras.
- **Escoamento turbulento** – Escoamento desordenado onde as posições das moléculas não são facilmente previsíveis. O escoamento ocorre de uma maneira caótica.

Condições **Laminares** ou **turbulentas** afetam enormemente a potência de bombeio requerida e as taxas de transferência de calor

- Escoamento onde as variações de densidade são negligenciáveis são chamados **Incompressíveis**

*Um fluido move-se por força ou naturalmente.*

- Em um **escoamento forçado (convecção forçada)**, energia é adicionada ao escoamento por um ventilador ou uma bomba ou um compressor, que força o escoamento.
- Em um **escoamento natural (convecção natural)** forças tais como a gravidade ou empuxo que fazem o fluido mover-se.





Fig. 21. Velocity profile in the laminar boundary layer (0.01% salt water, free stream velocity 0.6 cm/s, distance from the leading edge 200 mm,  $Re = 1.2 \times 10^3$ , hydrogen bubble method).



Fig. 21. Velocity profile in the laminar boundary layer (0.01% salt water, free stream velocity 0.6 cm/s, distance from the leading edge 200 mm,  $Re = 1.2 \times 10^3$ , hydrogen bubble method).

Perfil 'médio' de  
Velocidade  
p/ regime  
Turbulento



O fluido adere à parede sólida. A velocidade do fluido junto à parede é igual à velocidade da parede sólida. *No-Slip Movie*

## Definição de um fluido

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- Qual é a diferença entre um **fluido** e um **sólido**?
- Um **fluido** deforma-se continuamente quando sujeito a uma tensão de cisalhamento (tangencial), mesmo que esta seja pequena (Filme: *Flow element deformation*)

Cisalhamento de um **Sólido** (a) e de um **Fluido** (b)

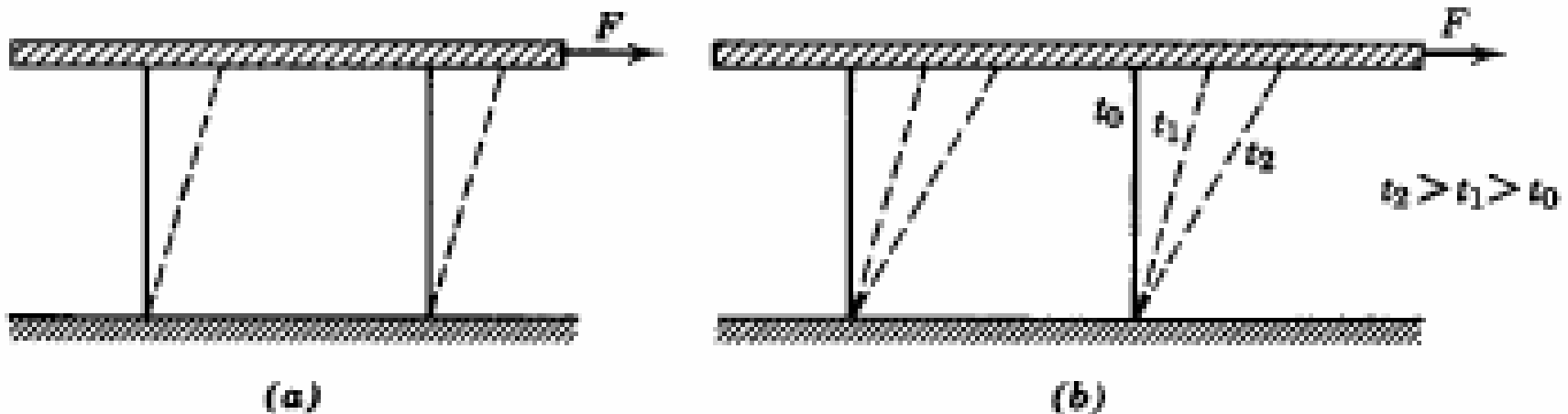


Fig. 1.1 Behavior of (a) solid and (b) fluid, under the action of a constant shear force.



- Pode ser mostrado que a tensão de cisalhamento é dada por:

$$\tau = \mu \frac{du}{dy}$$

→ Gradiente de velocidade (1/s)

→ **Viscosidade dinâmica** (Pa.s)

→ Tensão de cisalhamento (N/m<sup>2</sup>)

- A maioria dos fluidos usados em engenharia são Newtonianos.  
Ex: água, refrigerantes, hidrocarbonetos (por ex. Propano).
- Exemplos de fluidos não-Newtonianos: tintas, pasta de dentes, mel, etc...)

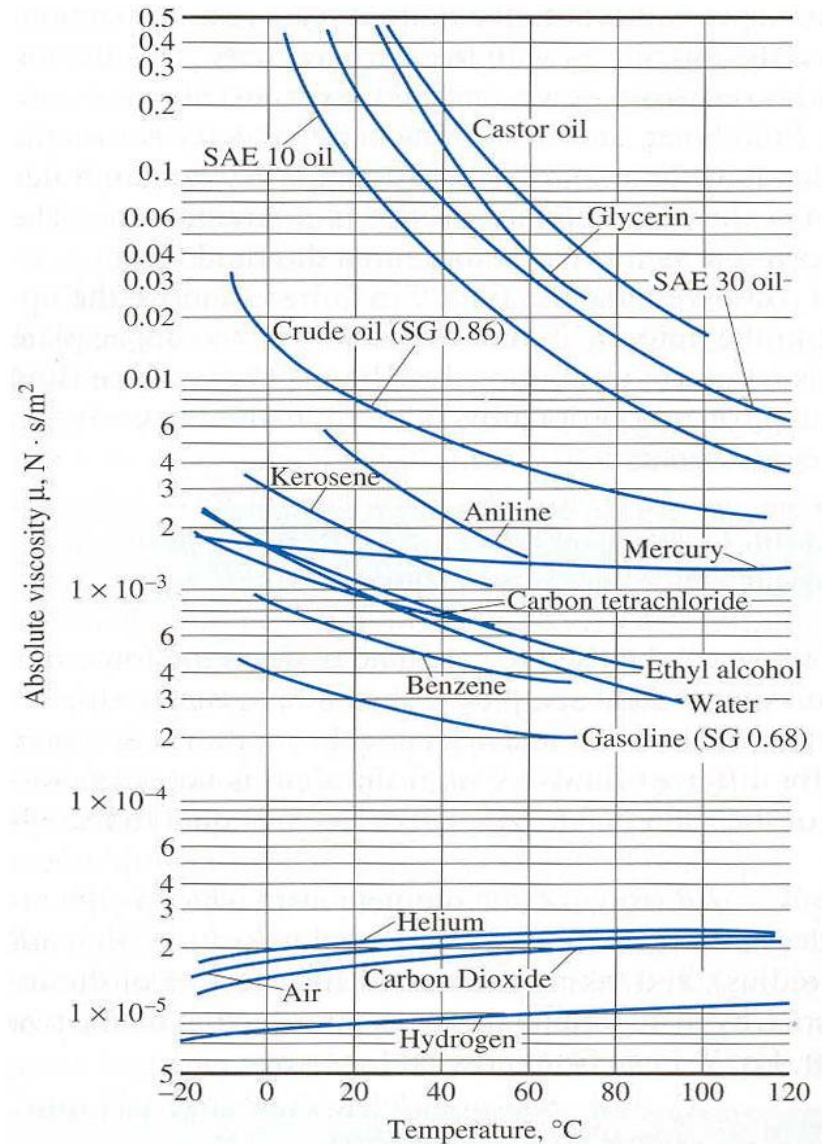
## Viscosidade Dinâmica

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- Propriedade intensiva
- Depende de ambos **temperatura** e **pressão** para um substância simples compressível.
- A dependência em relação à **pressão** é fraca,
- Mas a dependência em relação à **temperatura** é importante

Filme:

Viscosidad Dinâmica  
para fluidos comuns



## Características da Camada Limite

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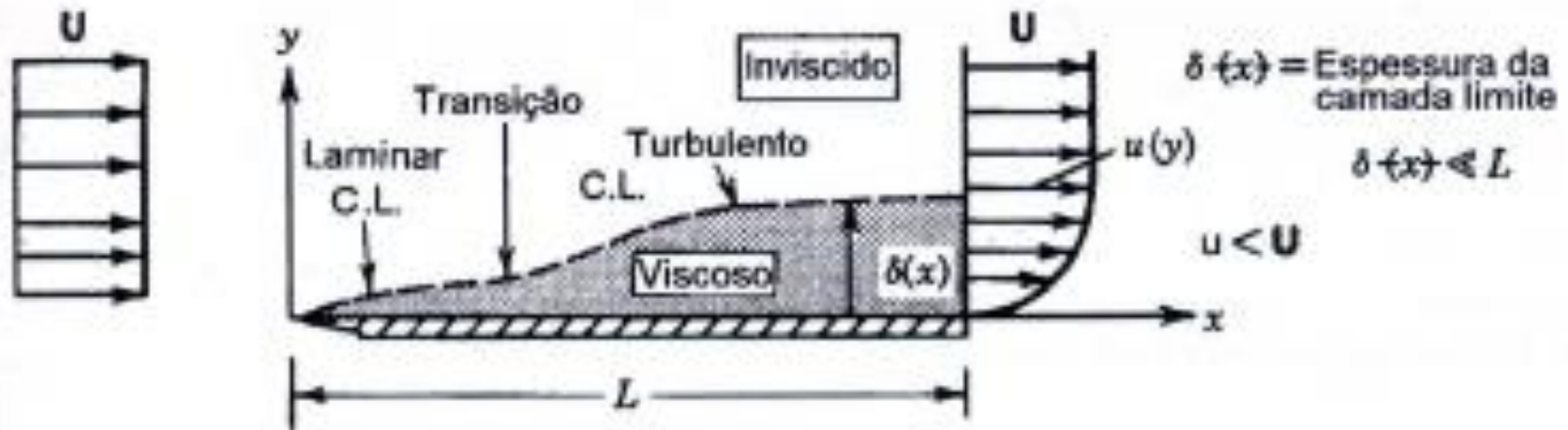


Figura 6.2 Camada limite hidrodinâmica sobre uma placa plana.

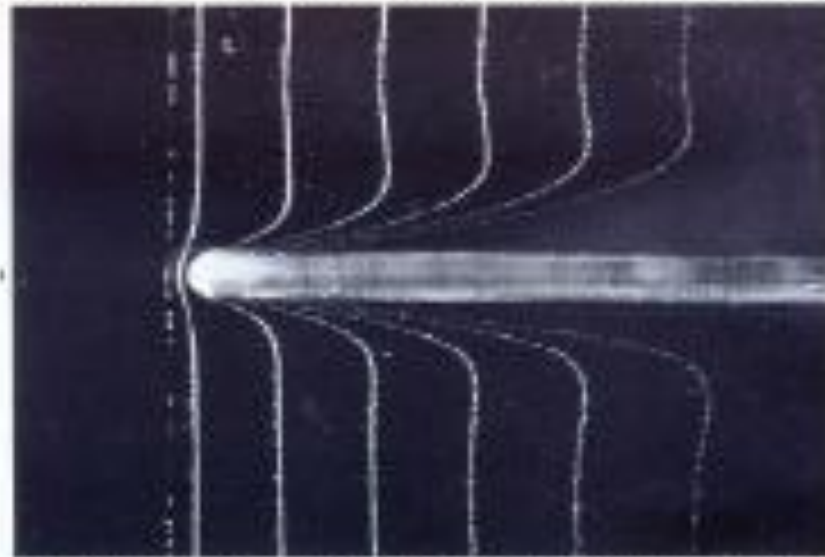


Fig. 6.2. Development of laminar boundary layer (Schlichting and Gersten, 1982).

## Características da Camada Limite

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- Ocorre para  $Re$  elevados,  $Re \gg 1$
- Perfil velocidades atinge  $U_{ext}$  para uma distância  $\delta$  da parede, onde  $\delta$  é a espessura da camada limite,  $\delta/L \ll 1$ ,
- A C.L. é uma região de alto gradiente de velocidade confinada próxima a parede sólida
- Externamente à C.L.,  $U_{ext}$  é governada por Bernoulli, efeitos viscosos ficam confinados na C.L.
- A C.L. pode ser Laminar ou Turbulenta.

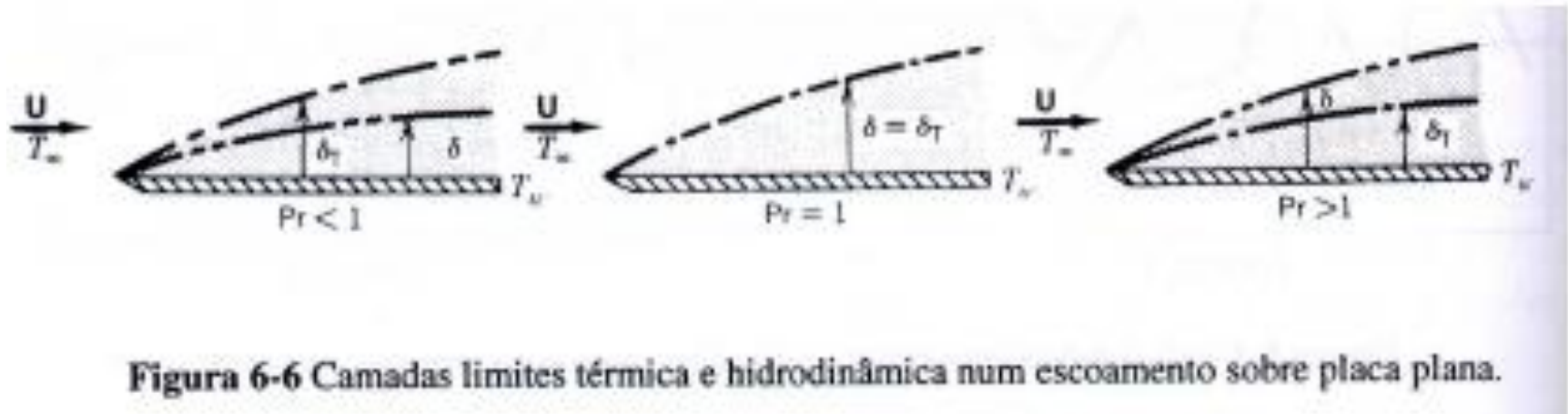


Figura 6-6 Camadas limites térmica e hidrodinâmica num escoamento sobre placa plana.

## Características da Camada Limite

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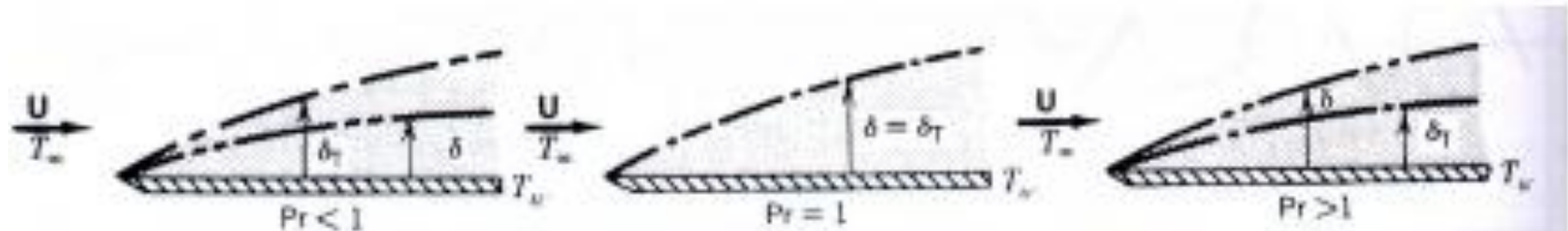


Figura 6-6 Camadas limites térmica e hidrodinâmica num escoamento sobre placa plana.

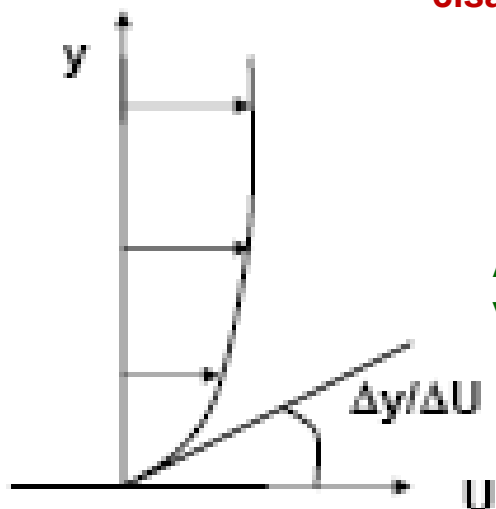
N. Prandtl,  $Pr$

$$Pr = \frac{\nu}{\alpha} = \frac{\delta}{\delta_T}$$

Onde  $\nu$  é a viscosidade cinemática e  $\alpha$  é a difusividade térmica.

O  $Pr$  pode ser interpretado como a razão entre as espessuras das C.L. Hidrodinâmica e térmica.

- O **arrasto viscoso** é devido exclusivamente às forças viscosas que atuam nas paredes sólidas.
- A **tensão de cisalhamento** na parede é uma força localizada. Ela é avaliada pelo produto entre o gradiente de velocidade na parede e a viscosidade dinâmica do fluido.
- Frequentemente ela é expressa por meio do **Coefficiente de Atrito**,  $C_f$ , de Fanno:



**Tensão de cisalhamento**

$$\tau_w = \mu \left. \frac{dU}{dy} \right|_{\text{parede}}$$

**Coefficiente de Atrito**

$$C_f = \frac{\tau_w}{(1/2)\rho U_{\text{ext}}^2}$$

**Arrasto viscoso**

$$D = \frac{1}{2} \rho U_{\text{ext}}^2 \cdot C_f \cdot [\text{Área Molhada Corpo}]$$

- A força de **arrasto viscoso total** num corpo, é avaliada a partir da integração do arrasto localizado ao longo do corpo.
- É frequentemente expressa em termos do **coeficiente de atrito médio**

Coeficiente de  
Atrito médio ↘

$$\bar{C}_f = \frac{1}{(1/2)\rho U_{\text{ext}}^2} \frac{\int_A \tau_w \cdot dA}{A}$$

Arrasto  
viscoso  
total ↗

$$\bar{D} = \frac{1}{2} \rho U_{\text{ext}}^2 \cdot \bar{C}_f \cdot A$$

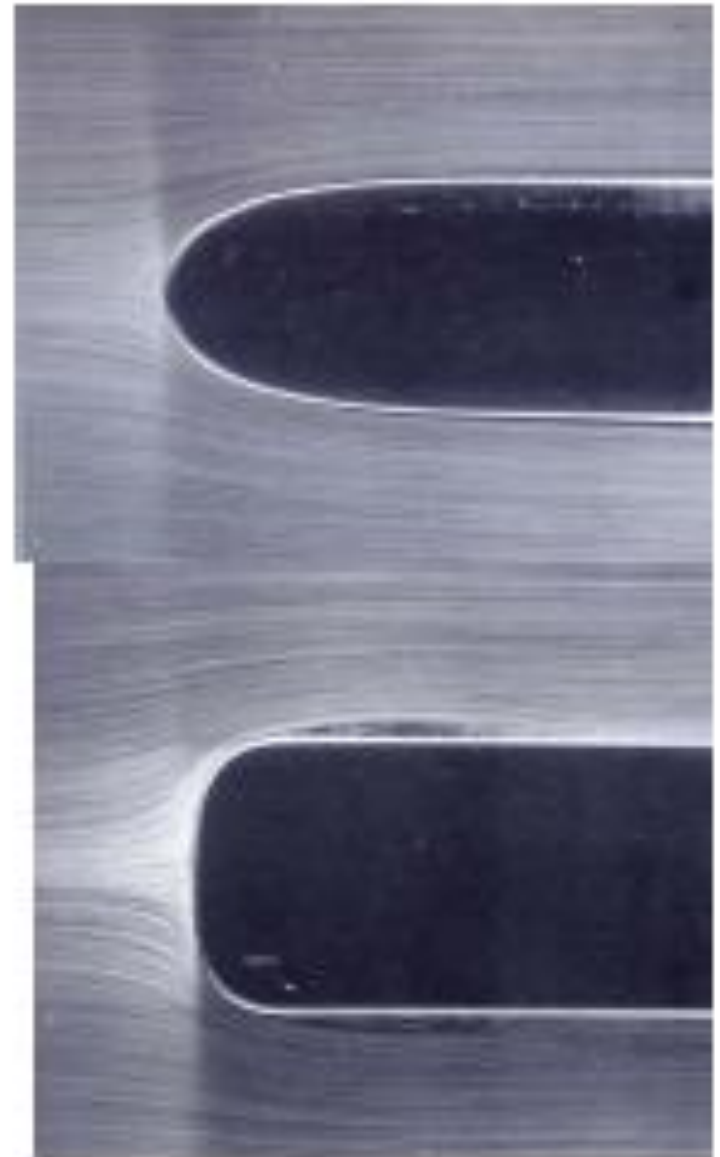
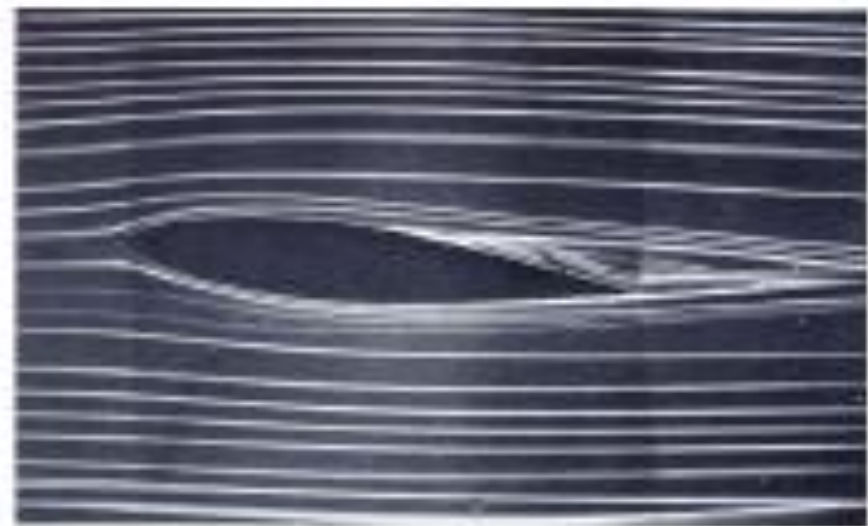
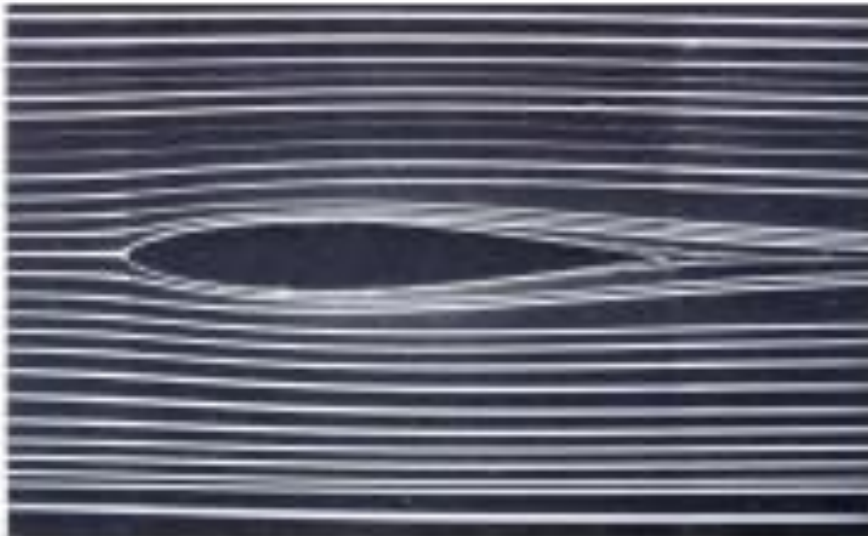


Arrasto viscoso em uma placa plana com ausência de gradiente de pressão:

Tabela 6-1 Resumo das relações da camada limite para uma placa plana lisa

| Laminar                                | $Re_x < 5 \times 10^5$        |
|--|-------------------------------|
| $u / U = f(y\sqrt{U / \nu x})$         | Veja Tabela 6-2               |
| $\delta / x = 5,0 Re_x^{-1/2}$         |                               |
| $\tau_w = 0,332 \rho U^2 Re_x^{-1/2}$  |                               |
| $C_{fx} = 0,664 Re_x^{-1/2}$           |                               |
| $\bar{C}_f = 1,328 Re_L^{-1/2}$        |                               |
| Turbulento                             | $5 \times 10^5 < Re_x < 10^7$ |
| $u / U \cong (y / \delta)^{1/7}$       |                               |
| $\delta / x = 0,371 Re_x^{-1/5}$       |                               |
| $\tau_w = 0,0296 \rho U^2 Re_x^{-1/5}$ |                               |
| $C_{fx} = 0,0592 Re_x^{-1/5}$          |                               |
| $\bar{C}_f = 0,074 Re_L^{-1/5}$        |                               |

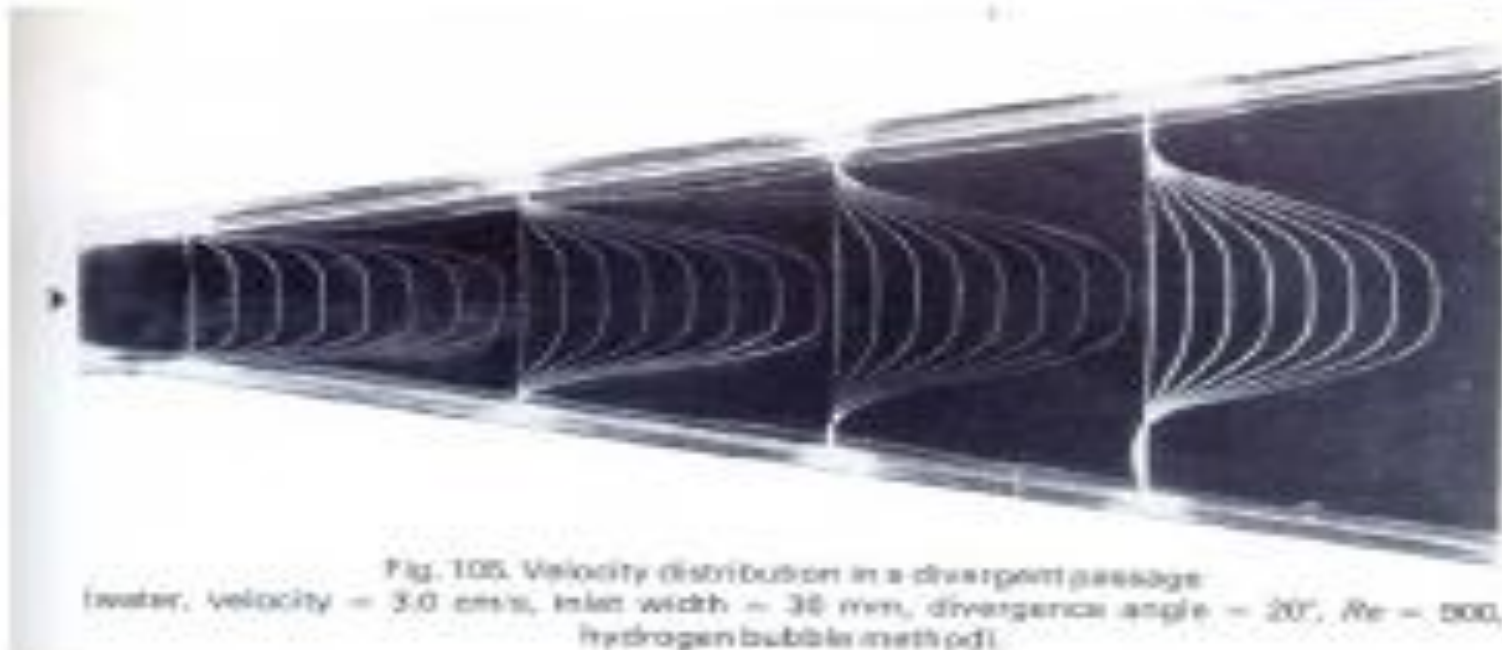
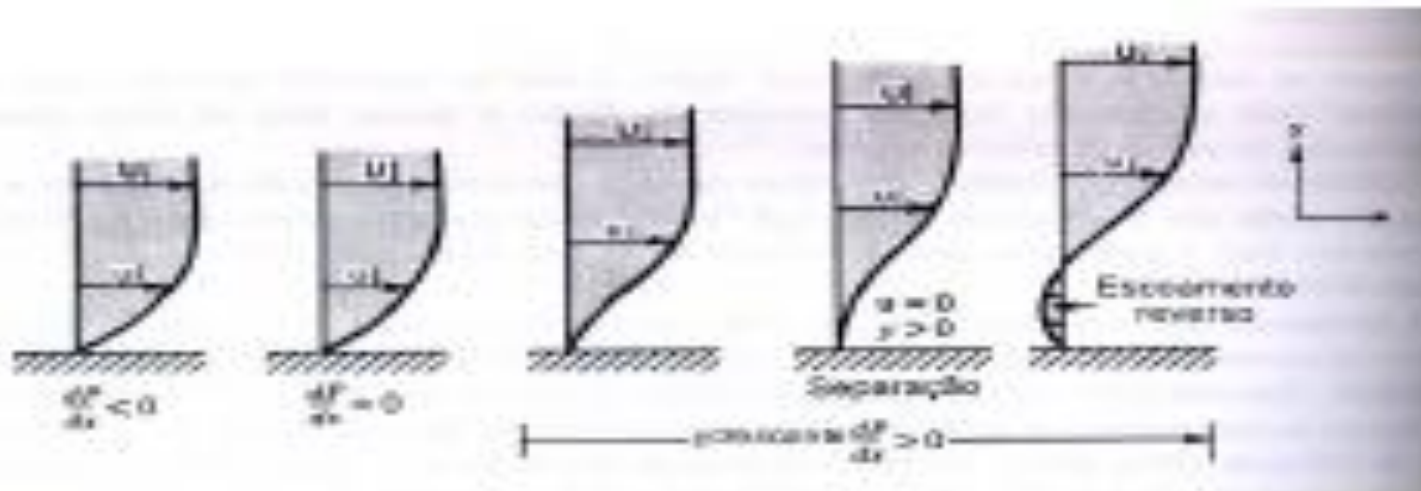
## Gradiente de Pressão & Separação



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## Gradiente de Pressão & Separação

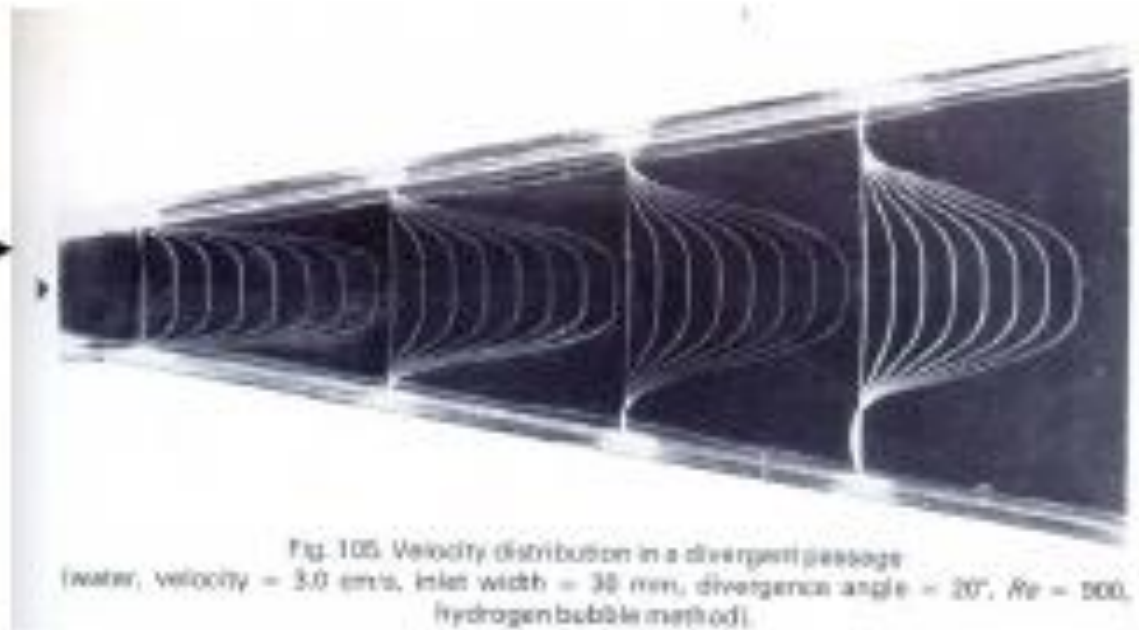
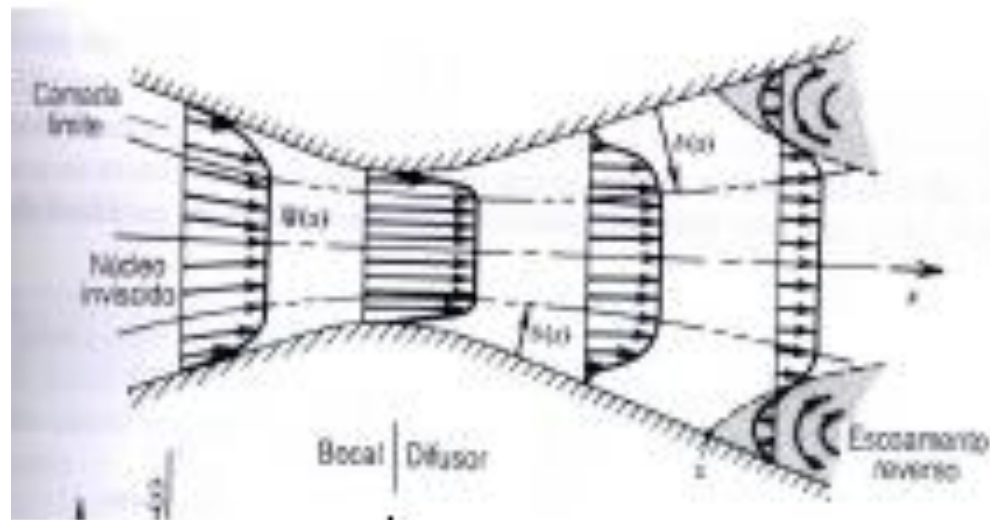
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## Gradiente de Pressão & Separação

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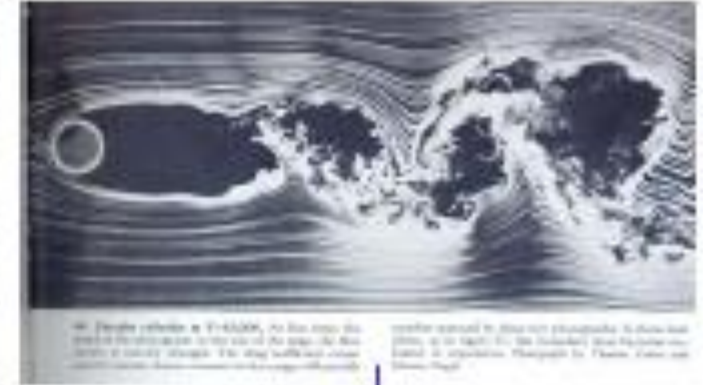


Fig. 5. Flow around a circular cylinder at  $Re = 55$  (water, flow velocity 0.95 cm/s, cylinder diameter 1.5 cm, aluminum powder method).



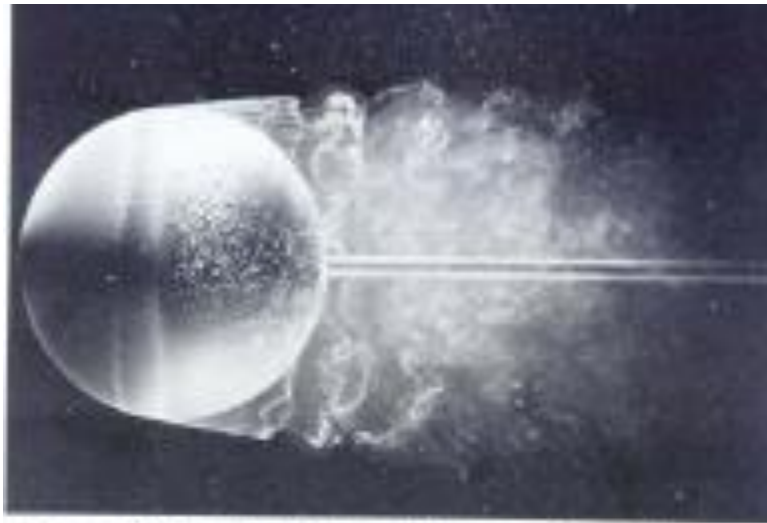
Fig. 22. Water, velocity of motion 2 cm/s, cylinder diameter 70 mm, photographed two seconds after the start of motion,  $Re = 1.2 \times 10^3$ , hydrogen bubble method.

**A Distribuição de Pressão no Corpo Causa uma Força Resultante Contrária ao Escoamento?**

**A Separação (Descolamento) do Escoamento Altera a Distribuição de Pressão no Corpo?**

**Ela Tem Influência na Força de Arrasto do Corpo?**





10. Flow visualization around a sphere at  $Re = 20000$ . The flow is turbulent and the boundary layer separates at a small angle of  $80^\circ$  from the stagnation point. The wake is narrow and contains a turbulent jet.

10. Flow visualization around a sphere at  $Re = 20000$ . The flow is turbulent and the boundary layer separates at a small angle of  $80^\circ$  from the stagnation point. The wake is narrow and contains a turbulent jet.



11. Flow visualization around a sphere at  $Re = 20000$ . The flow is laminar and the boundary layer separates at a large angle of  $120^\circ$  from the stagnation point. The wake is wide and contains a laminar jet.

11. Flow visualization around a sphere at  $Re = 20000$ . The flow is laminar and the boundary layer separates at a large angle of  $120^\circ$  from the stagnation point. The wake is wide and contains a laminar jet.

## Distribuição de Pressão Não Simétrica Em Cilindros

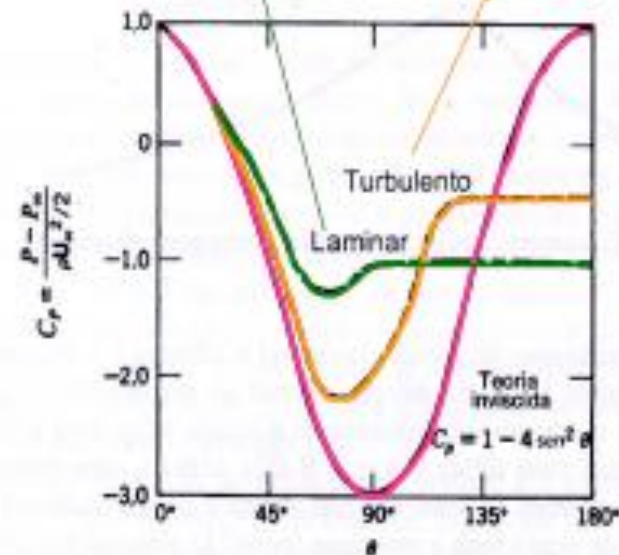
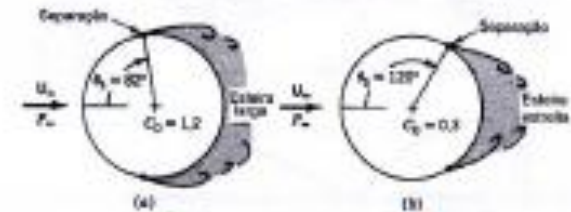
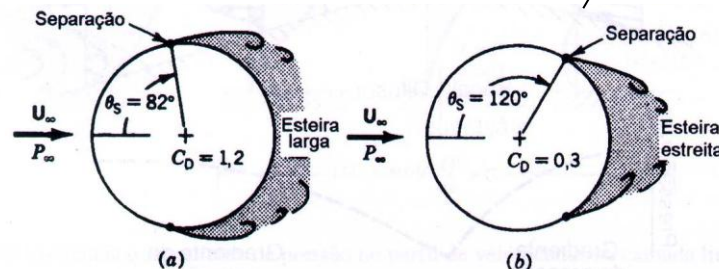
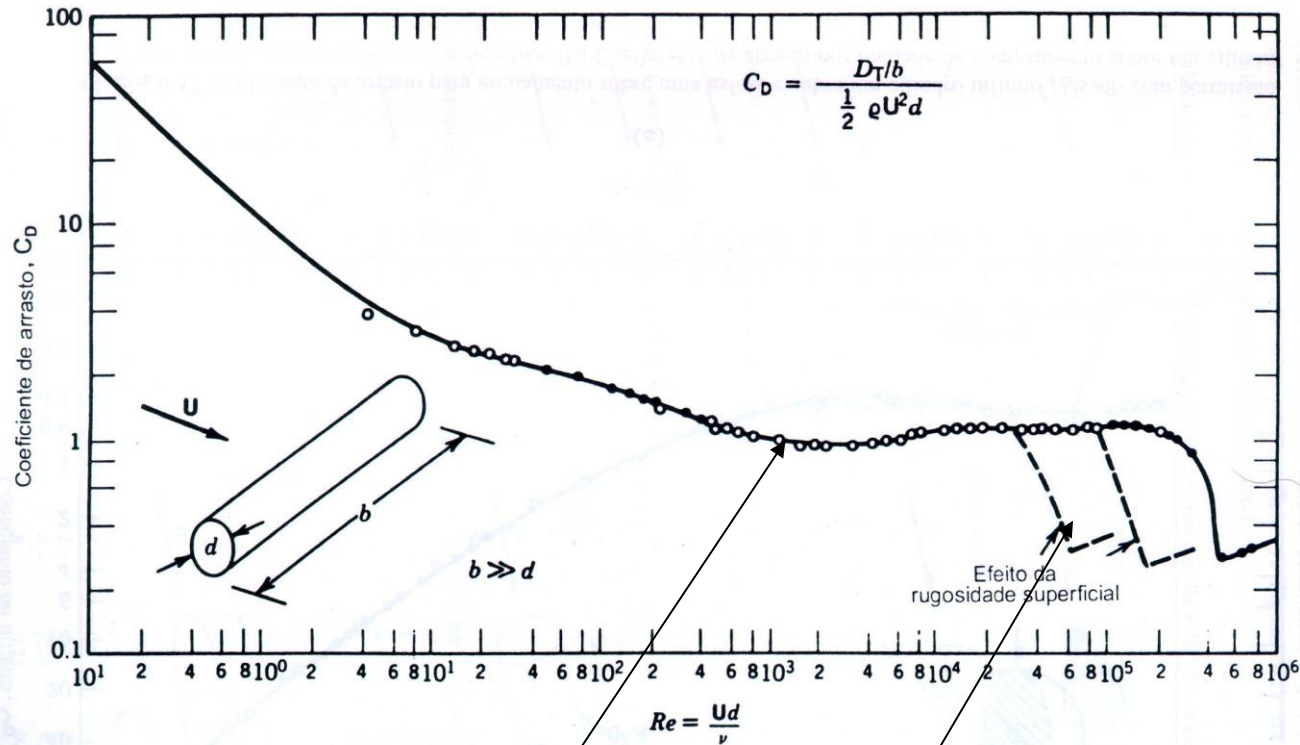


Figura 6-11 Pressão de escoamento e de superfície sobre um cilindro circular infinito normal ao escoamento. (a) Escoamento laminar, (b) Escoamento turbulento.

# Arrasto de forma (Distribuição de Pressão)



**Camada Limite**

**(a) Laminar & (b) Turbulento**

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$$F_{D, friction} = C_{D, friction} \times \frac{1}{2} \rho V^2 A$$

$$F_{D, pressure} = C_{D, pressure} \times \frac{1}{2} \rho V^2 A$$

$$F_{D, total} = F_{D, pressure} + F_{D, friction}$$

## Arrasto Total

$$\bar{D}_T = \bar{D}_p + \bar{D}_f$$

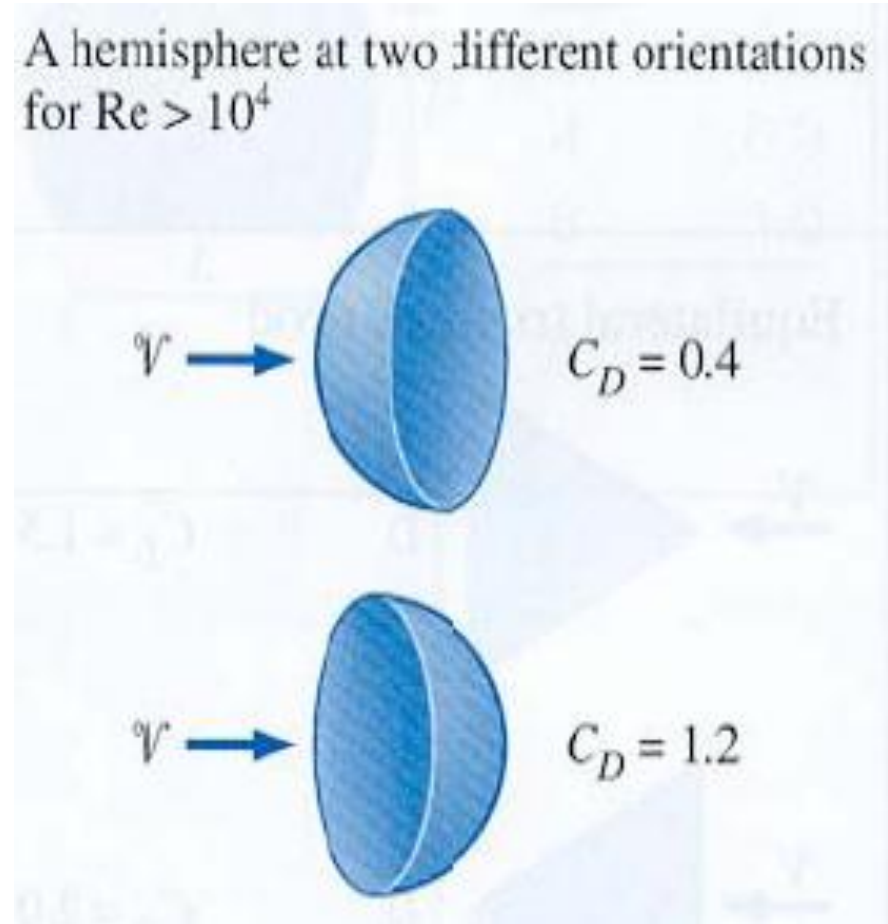
Arrasto  
TotalArrasto  
FormaArrasto  
Viscoso

$$C_D = \frac{\bar{D}_T}{(1/2) \rho U_{ext}^2 \cdot A}$$

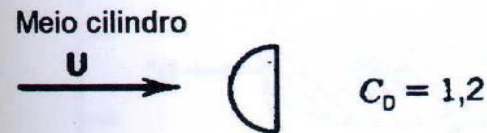
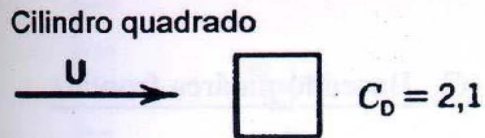
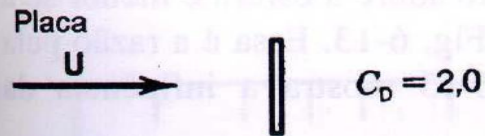
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- Arrastó é muito dependente da geometria
- Tabelas 6.3 e 6.4 do Livro-Texto apresentam coeficientes de arrasto para algumas formas
- Veja também tabelas a seguir.

Filme:



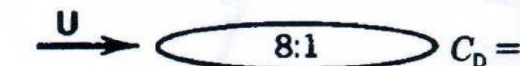
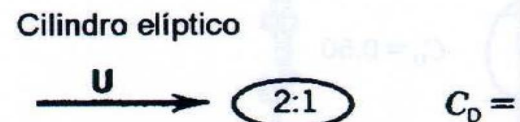
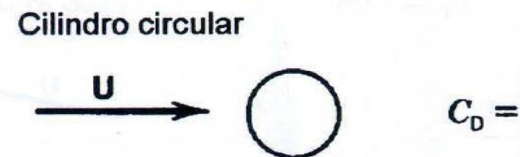
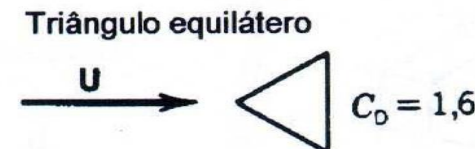
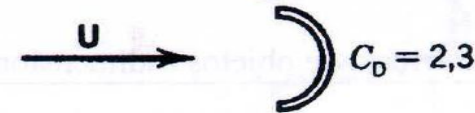
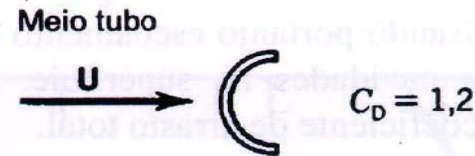
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Tabela 6-3 Coeficientes de arrasto de objetos bidimensionais para  $Re \approx 10^5$ 

$$C_D = \frac{\text{arrasto/ comprimento unitário}}{\frac{1}{2} \rho U^2 t}$$

$$Re = \frac{Ut}{\nu}$$

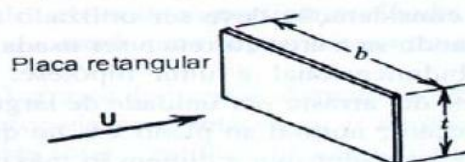
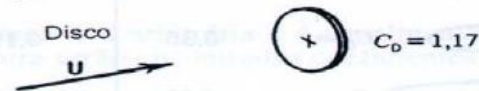
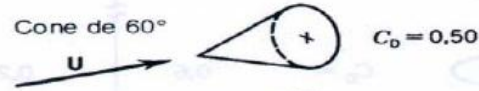
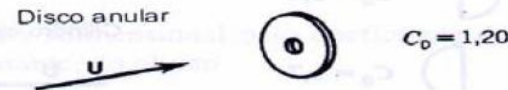
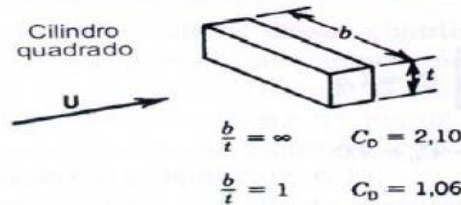
$t =$  Altura projetada normal a  $U$



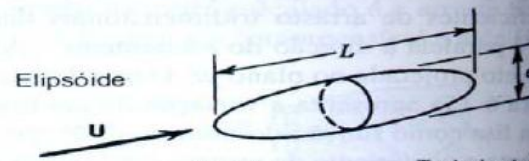
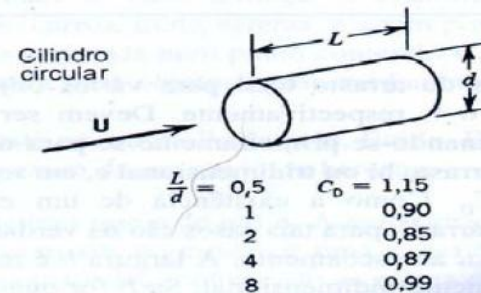
|  | Laminar | Turbulento |
|--|---------|------------|
|  | 1,1     | 0,3        |
|  | ~       |            |
|  | 0,6     | 0,2        |
|  | 0,35    | 0,15       |
|  | 0,25    | 0,1        |



**Tabela 6-4** Coeficiente de arrasto de objetos tridimensionais  $Re \approx 10^5$  ( $C_D$  Baseado na área frontal)



|                   |              |
|-------------------|--------------|
| $\frac{b}{t} = 1$ | $C_D = 1,18$ |
| 5                 | 1,20         |
| 10                | 1,30         |
| 20                | 1,50         |
| $\infty$          | 2,00         |



Laminar

|                   |              |
|-------------------|--------------|
| $\frac{L}{d} = 1$ | $C_D = 0,47$ |
| 2                 | 0,25         |
| 4                 | 0,20         |
| 8                 | 0,23         |



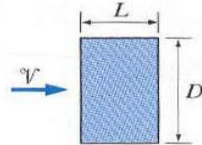
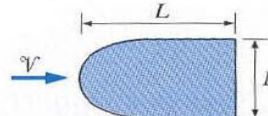
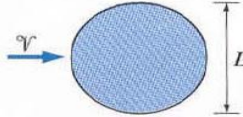
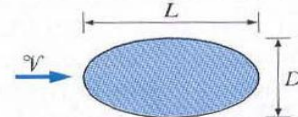
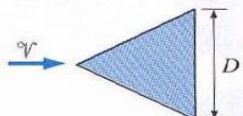
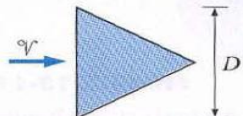

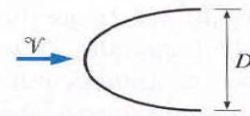

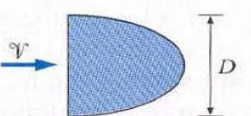
Turbulento<sup>3</sup>

| $Re \approx 10^6$ | $Re \approx 10^7$ |
|-------------------|-------------------|
| 0,100             | 0,090             |
| 0,055             | 0,040             |
| 0,065             | 0,041             |
| 0,100             | 0,078             |

Re baseado em  $L$  ou  $t$  a altura projetada normal a  $U$

TABLE 13-1

Drag coefficients  $C_D$  of various two-dimensional bodies for  $Re > 10^4$  based on the frontal area  $A = bD$ , where  $b$  is the length normal to the direction of the paper (for use in the drag force relation  $F_D = C_D A \rho V^2 / 2$  where  $V$  is the free-stream velocity away from the body)

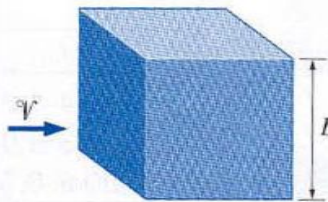
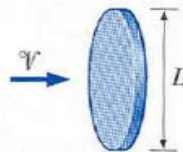
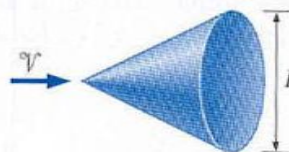

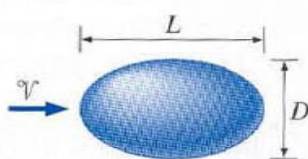
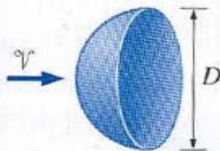
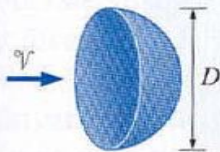
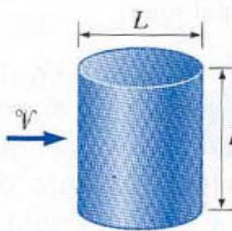
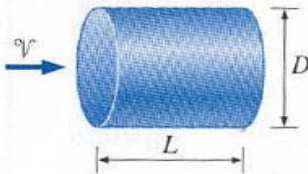
| <p>Square rod</p>  <p>Sharp corners:<br/><math>C_D = 2.2</math></p>  <p>Round corners<br/>(<math>r/D = 0.2</math>):<br/><math>C_D = 1.2</math></p> | <p>Rectangular rod</p>  <p>Sharp corners:</p>  <p>Round front edge:</p>                      | <table><tr><th><math>L/D</math></th><th><math>C_D</math></th></tr><tr><td>0.0*</td><td>1.9</td></tr><tr><td>0.1</td><td>1.9</td></tr><tr><td>0.5</td><td>2.5</td></tr><tr><td>1.0</td><td>2.2</td></tr><tr><td>2.0</td><td>1.7</td></tr><tr><td>3.0</td><td>1.3</td></tr></table> <p>*Corresponds to thin plate</p> <table><tr><th><math>L/D</math></th><th><math>C_D</math></th></tr><tr><td>0.5</td><td>1.2</td></tr><tr><td>1.0</td><td>0.9</td></tr><tr><td>2.0</td><td>0.7</td></tr><tr><td>4.0</td><td>0.7</td></tr></table> | $L/D$ | $C_D$ | 0.0* | 1.9     | 0.1       | 1.9 | 0.5  | 2.5  | 1.0 | 2.2  | 2.0  | 1.7 | 3.0  | 1.3  | $L/D$ | $C_D$ | 0.5 | 1.2 | 1.0 | 0.9 | 2.0 | 0.7 | 4.0 | 0.7 |
|--|---|--|-------|-------|------|---------|-----------|-----|------|------|-----|------|------|-----|------|------|-------|-------|-----|-----|-----|-----|-----|-----|-----|-----|
| $L/D$  | $C_D$   |  |       |       |      |         |           |     |      |      |     |      |      |     |      |      |       |       |     |     |     |     |     |     |     |     |
| 0.0*   | 1.9   |  |       |       |      |         |           |     |      |      |     |      |      |     |      |      |       |       |     |     |     |     |     |     |     |     |
| 0.1  | 1.9   |  |       |       |      |         |           |     |      |      |     |      |      |     |      |      |       |       |     |     |     |     |     |     |     |     |
| 0.5  | 2.5   |  |       |       |      |         |           |     |      |      |     |      |      |     |      |      |       |       |     |     |     |     |     |     |     |     |
| 1.0  | 2.2   |  |       |       |      |         |           |     |      |      |     |      |      |     |      |      |       |       |     |     |     |     |     |     |     |     |
| 2.0  | 1.7   |  |       |       |      |         |           |     |      |      |     |      |      |     |      |      |       |       |     |     |     |     |     |     |     |     |
| 3.0  | 1.3   |  |       |       |      |         |           |     |      |      |     |      |      |     |      |      |       |       |     |     |     |     |     |     |     |     |
| $L/D$  | $C_D$   |  |       |       |      |         |           |     |      |      |     |      |      |     |      |      |       |       |     |     |     |     |     |     |     |     |
| 0.5  | 1.2   |  |       |       |      |         |           |     |      |      |     |      |      |     |      |      |       |       |     |     |     |     |     |     |     |     |
| 1.0  | 0.9   |  |       |       |      |         |           |     |      |      |     |      |      |     |      |      |       |       |     |     |     |     |     |     |     |     |
| 2.0  | 0.7   |  |       |       |      |         |           |     |      |      |     |      |      |     |      |      |       |       |     |     |     |     |     |     |     |     |
| 4.0  | 0.7   |  |       |       |      |         |           |     |      |      |     |      |      |     |      |      |       |       |     |     |     |     |     |     |     |     |
| <p>Circular rod (cylinder)</p>  <p>Laminar:<br/><math>C_D = 1.2</math><br/>Turbulent:<br/><math>C_D = 0.3</math></p>  | <p>Elliptical rod</p>   | <table><tr><th rowspan="2"><math>L/D</math></th><th colspan="2"><math>C_D</math></th></tr><tr><th>Laminar</th><th>Turbulent</th></tr><tr><td>2</td><td>0.60</td><td>0.20</td></tr><tr><td>4</td><td>0.35</td><td>0.15</td></tr><tr><td>8</td><td>0.25</td><td>0.10</td></tr></table>   | $L/D$ | $C_D$ |      | Laminar | Turbulent | 2   | 0.60 | 0.20 | 4   | 0.35 | 0.15 | 8   | 0.25 | 0.10 |       |       |     |     |     |     |     |     |     |     |
| $L/D$  | $C_D$   |  |       |       |      |         |           |     |      |      |     |      |      |     |      |      |       |       |     |     |     |     |     |     |     |     |
|  | Laminar   | Turbulent  |       |       |      |         |           |     |      |      |     |      |      |     |      |      |       |       |     |     |     |     |     |     |     |     |
| 2  | 0.60  | 0.20   |       |       |      |         |           |     |      |      |     |      |      |     |      |      |       |       |     |     |     |     |     |     |     |     |
| 4  | 0.35  | 0.15   |       |       |      |         |           |     |      |      |     |      |      |     |      |      |       |       |     |     |     |     |     |     |     |     |
| 8  | 0.25  | 0.10   |       |       |      |         |           |     |      |      |     |      |      |     |      |      |       |       |     |     |     |     |     |     |     |     |
| <p>Equilateral triangular rod</p>  <p><math>C_D = 1.5</math></p>  <p><math>C_D = 2.0</math></p>  | <p>Semicircular shell</p>  <p><math>C_D = 1.2</math></p>  <p><math>C_D = 2.3</math></p> | <p>Semicircular rod</p>  <p><math>C_D = 1.2</math></p>  <p><math>C_D = 1.7</math></p>  |       |       |      |         |           |     |      |      |     |      |      |     |      |      |       |       |     |     |     |     |     |     |     |     |





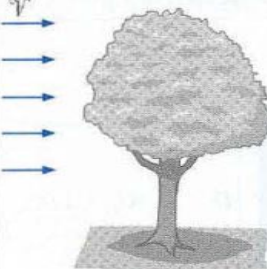








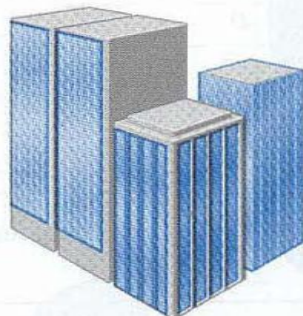
## Aula 16

TABLE 13-2

Representative drag coefficients  $C_D$  for various three-dimensional bodies for  $Re > 10^4$  based on the frontal area (for use in the drag force relation  $F_D = C_D A \rho V^2 / 2$  where  $V$  is the free-stream velocity away from the body)

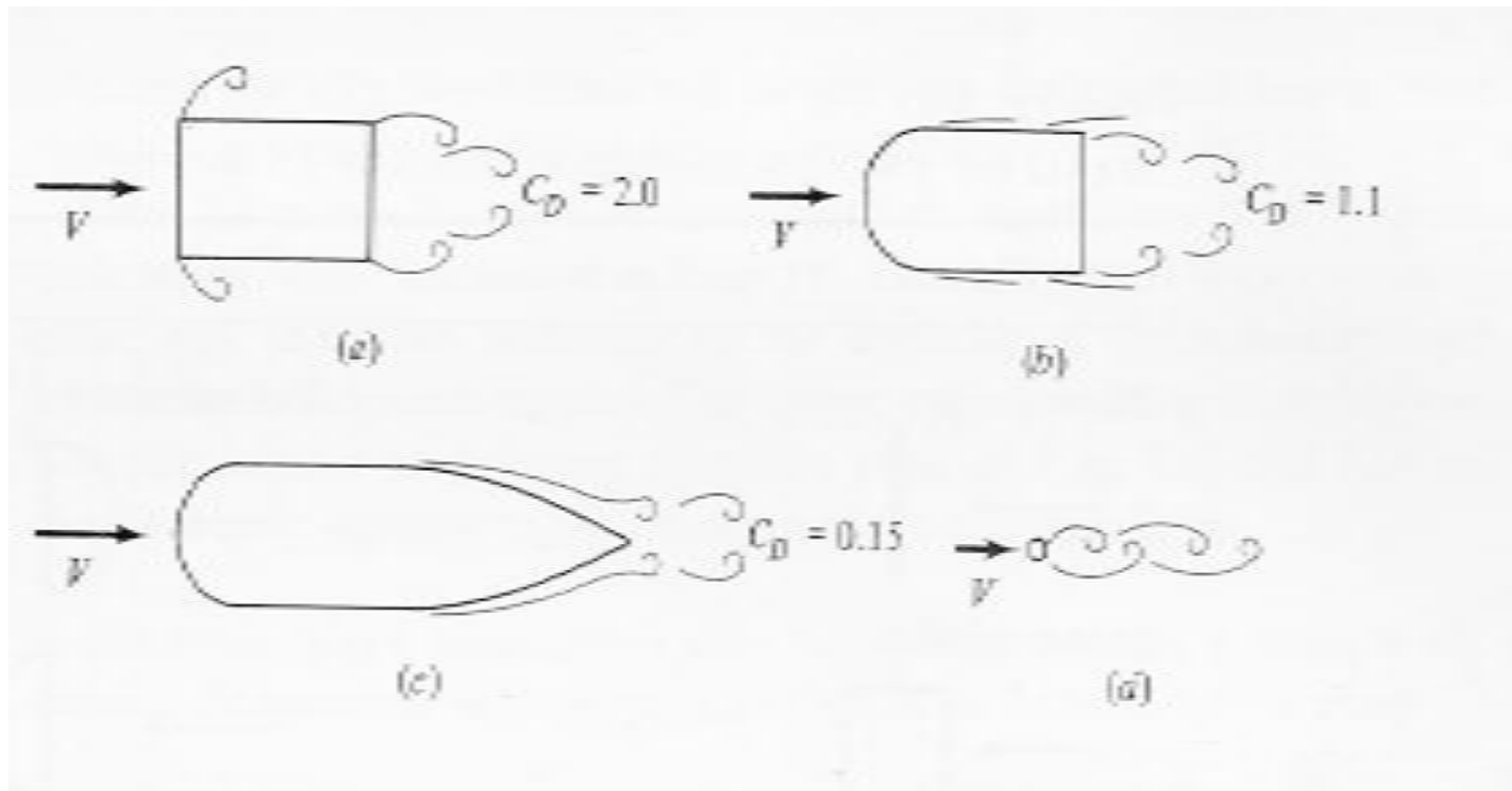
| <p>Cube, <math>A = D^2</math></p>  <p><math>C_D = 1.05</math></p>  | <p>Thin circular disk, <math>A = \pi D^2/4</math></p>  <p><math>C_D = 1.1</math></p>  | <p>Cone (for <math>\theta = 30^\circ</math>), <math>A = \pi D^2/4</math></p>  <p><math>C_D = 0.5</math></p>  |       |       |     |         |           |      |     |     |     |   |       |       |     |     |   |     |     |     |     |     |   |     |
|---|--|---|-------|-------|-----|---------|-----------|------|-----|-----|-----|---|-------|-------|-----|-----|---|-----|-----|-----|-----|-----|---|-----|
| <p>Sphere, <math>A = \pi D^2/4</math></p>  <p>Laminar:<br/><math>C_D = 0.5</math><br/>Turbulent:<br/><math>C_D = 0.2</math></p>  | <p>Ellipsoid, <math>A = \pi D^2/4</math></p>   | <table><tr><th rowspan="2"><math>L/D</math></th><th colspan="2"><math>C_D</math></th></tr><tr><th>Laminar</th><th>Turbulent</th></tr><tr><td>0.75</td><td>0.5</td><td>0.2</td></tr><tr><td>1</td><td>0.5</td><td>0.2</td></tr><tr><td>2</td><td>0.3</td><td>0.1</td></tr><tr><td>4</td><td>0.3</td><td>0.1</td></tr><tr><td>8</td><td>0.2</td><td>0.1</td></tr></table> | $L/D$ | $C_D$ |     | Laminar | Turbulent | 0.75 | 0.5 | 0.2 | 1   | 0.5   | 0.2   | 2     | 0.3 | 0.1 | 4 | 0.3 | 0.1 | 8   | 0.2 | 0.1 |   |     |
| $L/D$   | $C_D$  |   |       |       |     |         |           |      |     |     |     |   |       |       |     |     |   |     |     |     |     |     |   |     |
|   | Laminar  | Turbulent   |       |       |     |         |           |      |     |     |     |   |       |       |     |     |   |     |     |     |     |     |   |     |
| 0.75  | 0.5  | 0.2   |       |       |     |         |           |      |     |     |     |   |       |       |     |     |   |     |     |     |     |     |   |     |
| 1   | 0.5  | 0.2   |       |       |     |         |           |      |     |     |     |   |       |       |     |     |   |     |     |     |     |     |   |     |
| 2   | 0.3  | 0.1   |       |       |     |         |           |      |     |     |     |   |       |       |     |     |   |     |     |     |     |     |   |     |
| 4   | 0.3  | 0.1   |       |       |     |         |           |      |     |     |     |   |       |       |     |     |   |     |     |     |     |     |   |     |
| 8   | 0.2  | 0.1   |       |       |     |         |           |      |     |     |     |   |       |       |     |     |   |     |     |     |     |     |   |     |
| <p>Hemisphere, <math>A = \pi D^2/4</math></p>  <p><math>C_D = 0.4</math></p>  <p><math>C_D = 1.2</math></p> | <p>Short cylinder, vertical, <math>A = \pi D^2/4</math></p>  <table><tr><th><math>L/D</math></th><th><math>C_D</math></th></tr><tr><td>1</td><td>0.6</td></tr><tr><td>2</td><td>0.7</td></tr><tr><td>5</td><td>0.8</td></tr><tr><td>10</td><td>0.9</td></tr></table> | $L/D$   | $C_D$ | 1     | 0.6 | 2       | 0.7       | 5    | 0.8 | 10  | 0.9 | <p>Short cylinder, horizontal, <math>A = \pi D^2/4</math></p>  <table><tr><th><math>L/D</math></th><th><math>C_D</math></th></tr><tr><td>0.5</td><td>1.1</td></tr><tr><td>1</td><td>0.9</td></tr><tr><td>2</td><td>0.9</td></tr><tr><td>4</td><td>0.9</td></tr><tr><td>8</td><td>1.0</td></tr></table> | $L/D$ | $C_D$ | 0.5 | 1.1 | 1 | 0.9 | 2   | 0.9 | 4   | 0.9 | 8 | 1.0 |
| $L/D$   | $C_D$  |   |       |       |     |         |           |      |     |     |     |   |       |       |     |     |   |     |     |     |     |     |   |     |
| 1   | 0.6  |   |       |       |     |         |           |      |     |     |     |   |       |       |     |     |   |     |     |     |     |     |   |     |
| 2   | 0.7  |   |       |       |     |         |           |      |     |     |     |   |       |       |     |     |   |     |     |     |     |     |   |     |
| 5   | 0.8  |   |       |       |     |         |           |      |     |     |     |   |       |       |     |     |   |     |     |     |     |     |   |     |
| 10  | 0.9  |   |       |       |     |         |           |      |     |     |     |   |       |       |     |     |   |     |     |     |     |     |   |     |
| $L/D$   | $C_D$  |   |       |       |     |         |           |      |     |     |     |   |       |       |     |     |   |     |     |     |     |     |   |     |
| 0.5   | 1.1  |   |       |       |     |         |           |      |     |     |     |   |       |       |     |     |   |     |     |     |     |     |   |     |
| 1   | 0.9  |   |       |       |     |         |           |      |     |     |     |   |       |       |     |     |   |     |     |     |     |     |   |     |
| 2   | 0.9  |   |       |       |     |         |           |      |     |     |     |   |       |       |     |     |   |     |     |     |     |     |   |     |
| 4   | 0.9  |   |       |       |     |         |           |      |     |     |     |   |       |       |     |     |   |     |     |     |     |     |   |     |
| 8   | 1.0  |   |       |       |     |         |           |      |     |     |     |   |       |       |     |     |   |     |     |     |     |     |   |     |

**TABLE 13-2** (Concluded)

| <p>Streamlined body, <math>A = \pi D^2/4</math></p>  <p><math>C_D = 0.04</math></p>   | <p>Parachute, <math>A = \pi D^2/4</math></p>  <p><math>C_D = 1.3</math></p>  | <p>Tree, <math>A = \text{frontal area}</math></p>  <table border="1" data-bbox="1574 398 1825 564"> <thead> <tr> <th><math>V</math>, m/s</th> <th><math>C_D</math></th> </tr> </thead> <tbody> <tr> <td>10</td> <td>0.4–1.2</td> </tr> <tr> <td>20</td> <td>0.3–1.0</td> </tr> <tr> <td>30</td> <td>0.2–0.7</td> </tr> </tbody> </table> | $V$ , m/s | $C_D$ | 10 | 0.4–1.2 | 20 | 0.3–1.0 | 30 | 0.2–0.7 |
|--|---|---|-----------|-------|----|---------|----|---------|----|---------|
| $V$ , m/s  | $C_D$   |   |           |       |    |         |    |         |    |         |
| 10   | 0.4–1.2   |   |           |       |    |         |    |         |    |         |
| 20   | 0.3–1.0   |   |           |       |    |         |    |         |    |         |
| 30   | 0.2–0.7   |   |           |       |    |         |    |         |    |         |
| <p>Person (average)</p>  <p>Standing, <math>C_D A = 9 \text{ ft}^2 = 0.84 \text{ m}^2</math><br/>         Sitting, <math>C_D A = 6 \text{ ft}^2 = 0.56 \text{ m}^2</math></p> | <p>Bikes</p> <div style="display: flex; justify-content: space-around;"> <div data-bbox="732 669 1153 811">  <p>Upright:<br/> <math>A = 5.5 \text{ ft}^2 = 0.51 \text{ m}^2</math><br/> <math>C_D = 1.1</math></p> </div> <div data-bbox="1238 692 1808 811">  <p>Drafting:<br/> <math>A = 3.9 \text{ ft}^2 = 0.36 \text{ m}^2</math><br/> <math>C_D = 0.50</math></p> </div> </div> <div style="display: flex; justify-content: space-around; margin-top: 20px;"> <div data-bbox="732 863 1153 975">  <p>Racing:<br/> <math>A = 3.9 \text{ ft}^2 = 0.36 \text{ m}^2</math><br/> <math>C_D = 0.9</math></p> </div> <div data-bbox="1271 858 1808 975">  <p>With fairing:<br/> <math>A = 5.0 \text{ ft}^2 = 0.46 \text{ m}^2</math><br/> <math>C_D = 0.12</math></p> </div> </div> |   |           |       |    |         |    |         |    |         |
| <p>Semitruck, (<math>A = \text{frontal area}</math>)</p>  <p>Without fairing:<br/> <math>C_D = 0.96</math><br/>         With fairing:<br/> <math>C_D = 0.76</math></p>      | <p>Automotive (<math>A = \text{frontal area}</math>)</p> <div style="display: flex; justify-content: space-around;"> <div data-bbox="732 1046 1278 1163">  <p>Minivan,<br/> <math>C_D = 0.4</math></p> </div> <div data-bbox="732 1216 1278 1305">  <p>Passenger car,<br/> <math>C_D = 0.3</math></p> </div> </div>   | <p>High-rise buildings (<math>A = \text{frontal area}</math>)</p>  <p><math>C_D = 1.4</math></p>   |           |       |    |         |    |         |    |         |

## Aula 16

A importância da forma aerodinâmica na redução do arrasto,  $C_D$  baseado na área frontal do corpo. (a) cilindro retangular; (b) c/ nariz arredondado; (c) c/ nariz e cauda arredondados e; (d) cilindro circular com o mesmo arrasto do caso (c) !



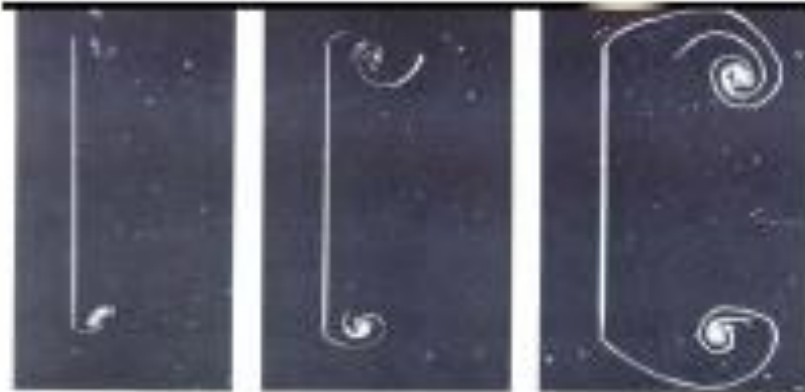


Fig. 2.12. Impulsive motion of a flat plate normal to flow. The Reynolds number is 50 based on leading edge. White dye present on the plate for duration of each phase.

great vortex sheet shed from each edge. The plate has normal 1075, 5.12, and 0.01 leading to vortex 0.11 and 0.11.

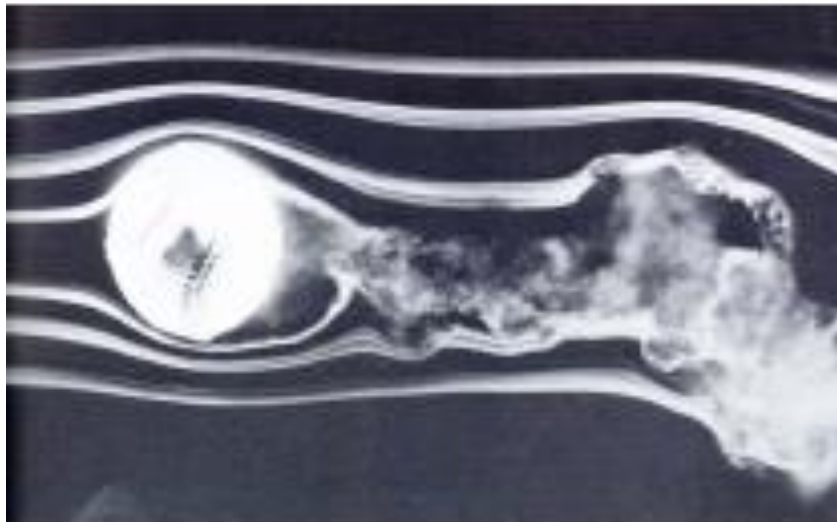


Fig. 2.12. Smoke flow around a road vehicle in a full-scale wind tunnel. (Courtesy of Volkswagen AG.)



## Aula 16

**Livro Texto:**

- Schmidt, F. W., Henderson, R. E., Wolgemuth, C. H., "Introduction to Thermal Sciences - Thermodynamics, Fluid Dynamics, Heat Transfer", John Wiley, 1993.
- Schmidt, F. W., Henderson, R. E., Wolgemuth, C. H., "Introdução às Ciências Térmicas", Editora Edgar Blücher Ltda, 1996. **Cap. 6. Itens 6.1 a 6.5.**

**Outros livros sobre o assunto:**

- Potter and Scott, "Ciências Térmicas: Termodinâmica, Mecânica dos Fluidos e Transmissão de Calor", Thomson, 2007
- Turner and Cengel, "Fundamentals of Thermal-Fluid Sciences", McGraw Hill, 2004
- Sissom and Pitts, "Fenômenos de Transporte", LTC, 1979
- Fox and McDonald, "Introdução à Mecânica dos Fluidos", 5ed, LTC editora, 1998.