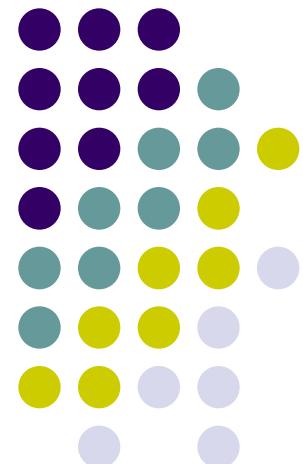
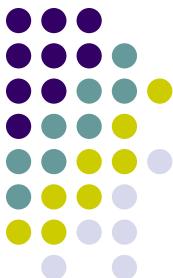


Escoamentos Complexos na Engenharia e Natureza

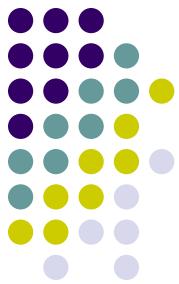
**Atila P. Silva Freire
PEM/COPPE/UFRJ**



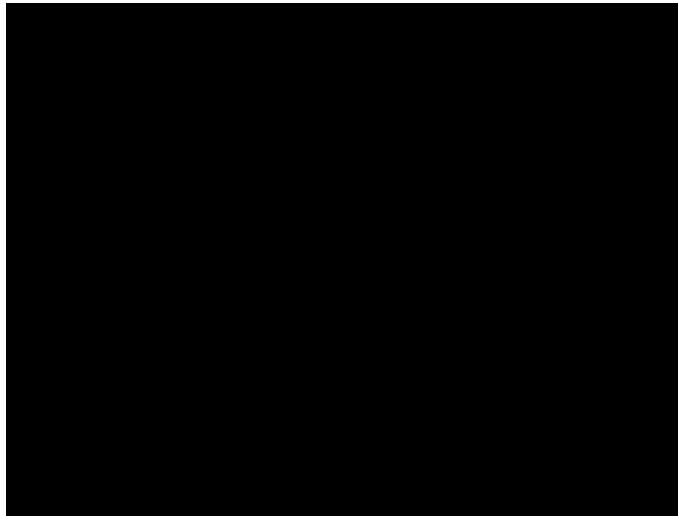


Plano da Apresentação

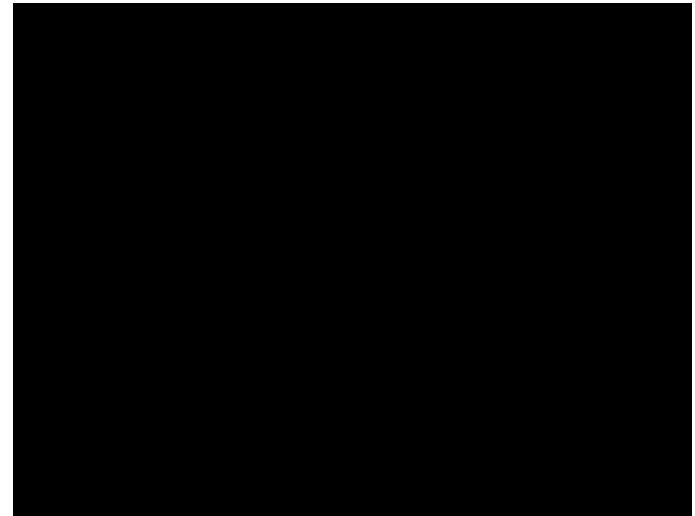
- Caracterização da Turbulência
- Caso 1.
 - Um caso real: ruas de Von Karman
 - A ponte sobre o rio Tacoma
 - Anemometria térmica
- Caso 2.
 - Escoamentos sobre elevações
 - Anemometria laser Doppler
 - CFD
- Caso 3.
 - Escoamentos em micro-canais
 - CFD
 - Experimentos básicos
- Palavras finais



Turbulência



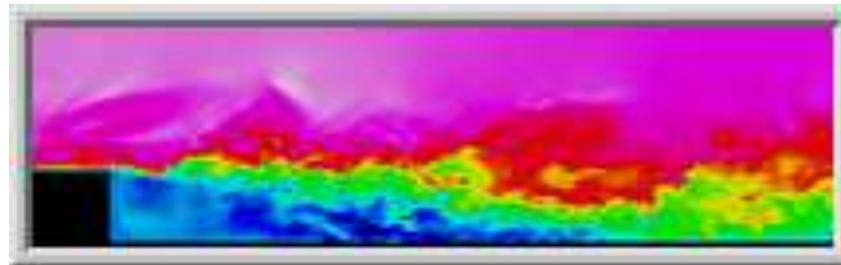
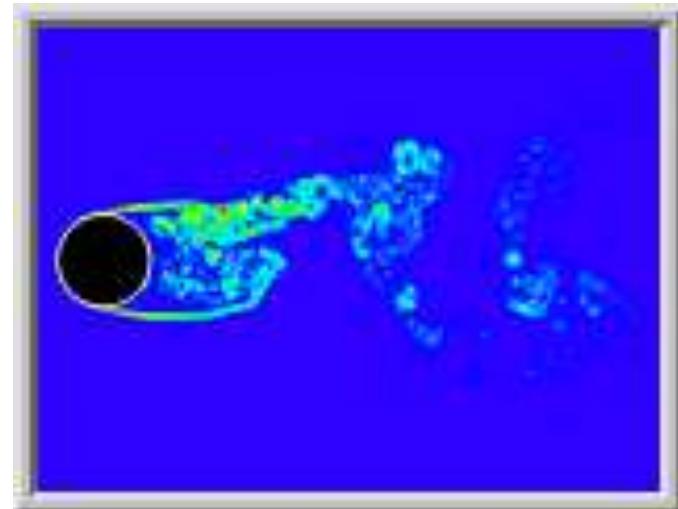
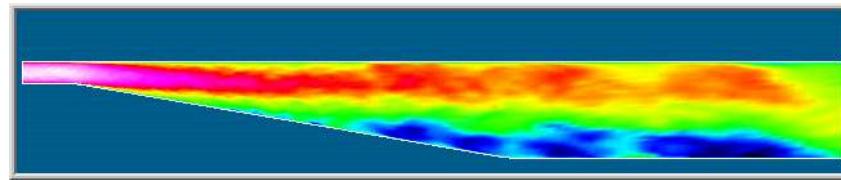
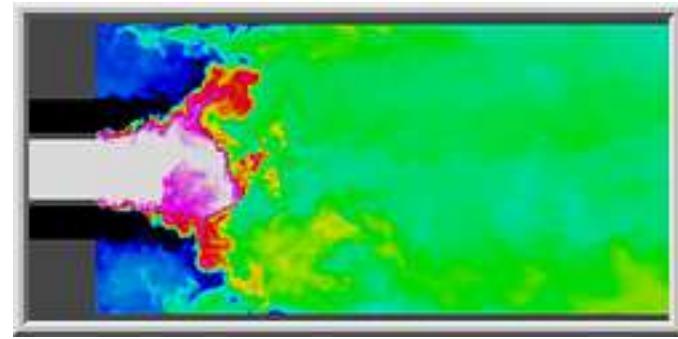
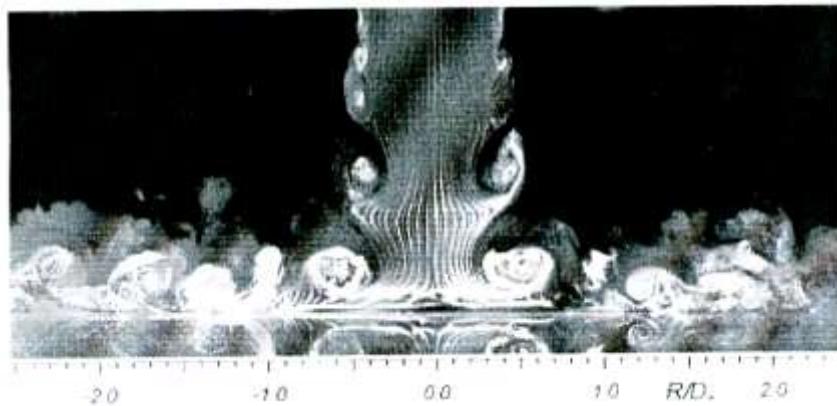
**Escoamento no bordo
de ataque de uma
placa plana**



Camada Limite Turbulenta



Turbulência: Vários exemplos.



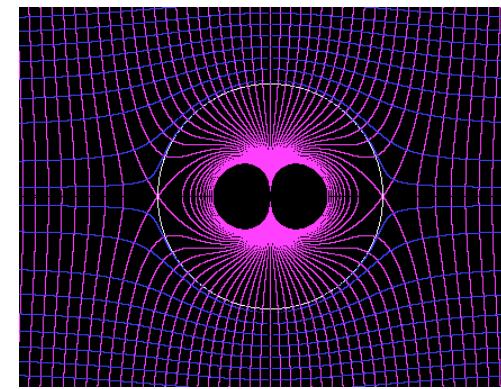
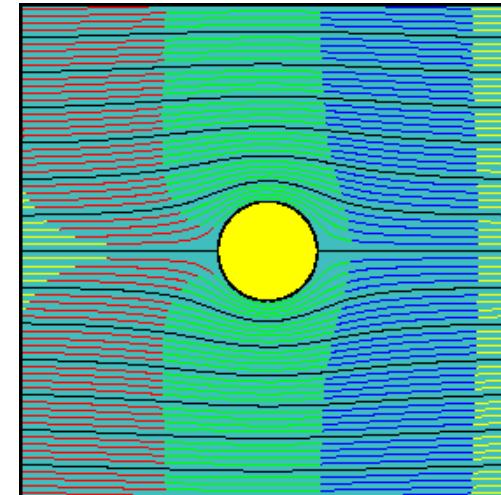
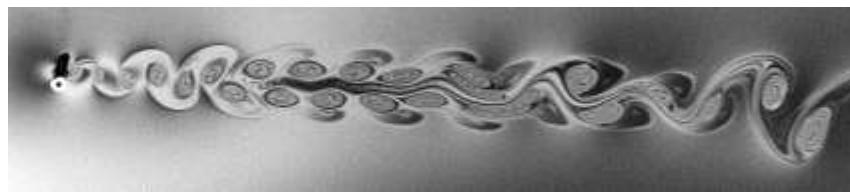
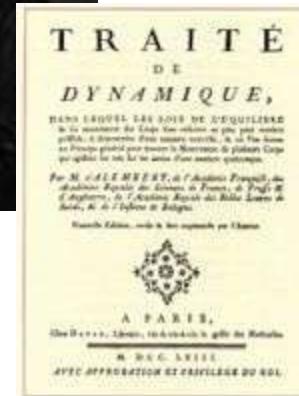


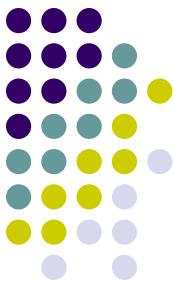
Caos





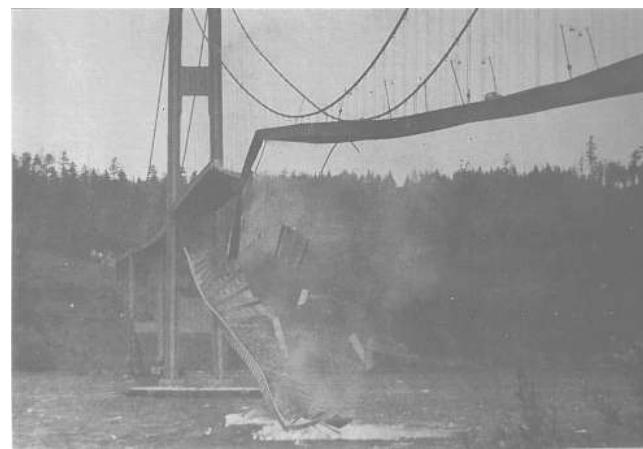
O paradoxo de d'Alembert





Caso 1.
Um caso real:

Ruas de Von Karman.
(A ponte sobre o rio Tacoma)





Um caso real:

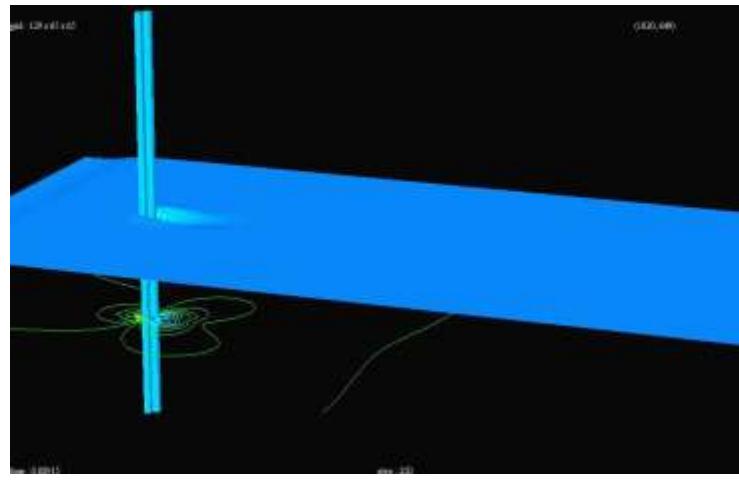
ruas de Von Karman
(A ponte de Tacoma)





Um caso real:

ruas de Von Karman
(A ponte de Tacoma)



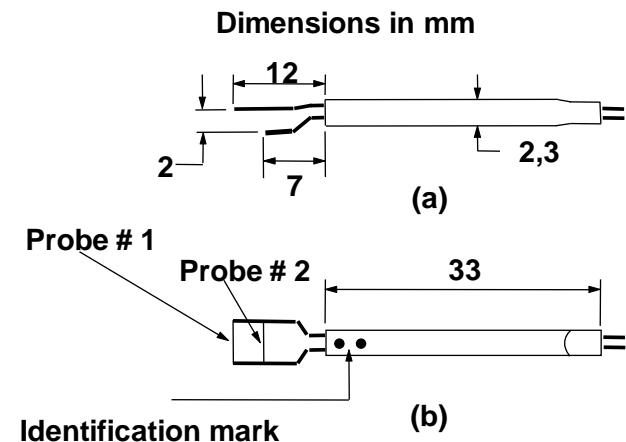
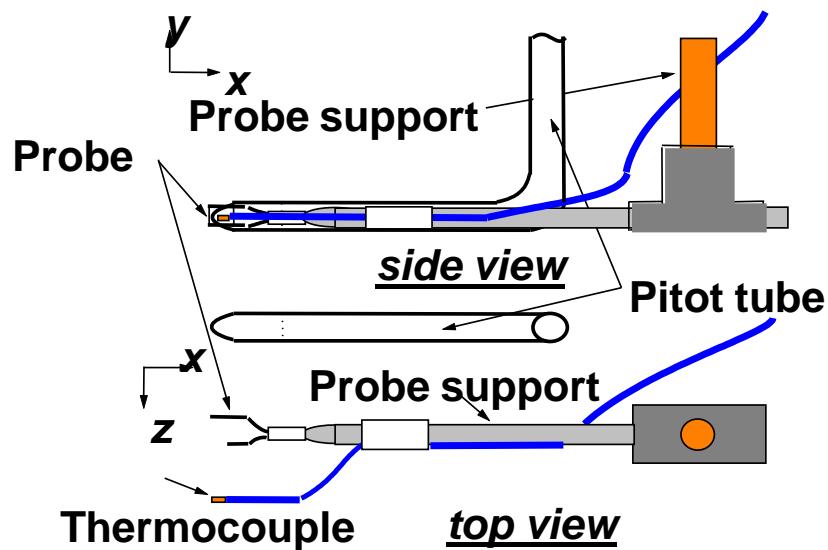


Túnel de vento



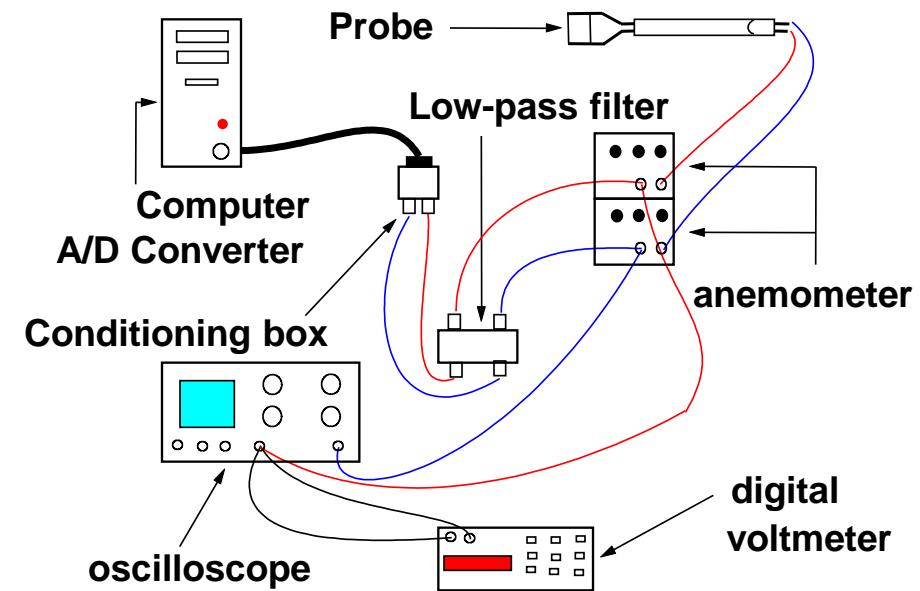


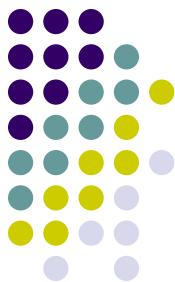
Anemometria térmica





Anemometria Térmica





Caso 1. Um caso real:

ruas de Von Karman
(A ponte sobre o rio Tacoma)

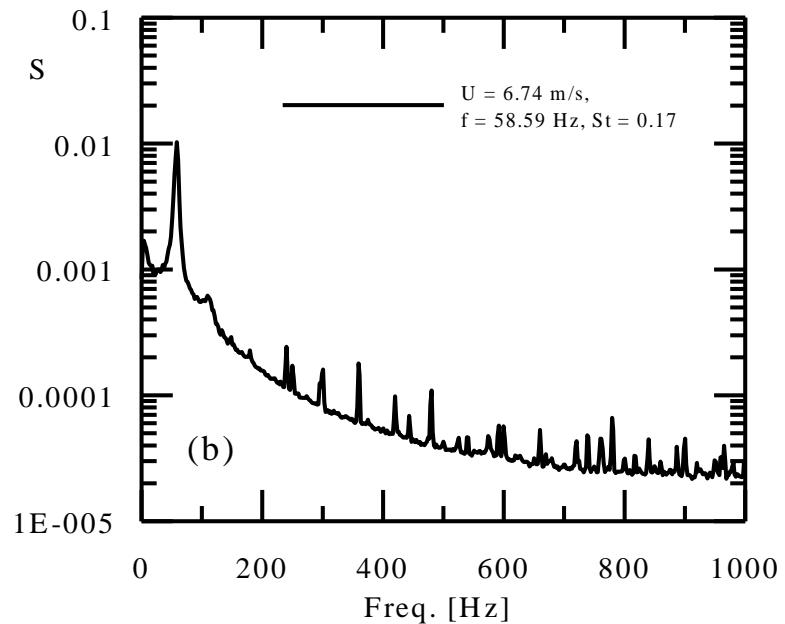
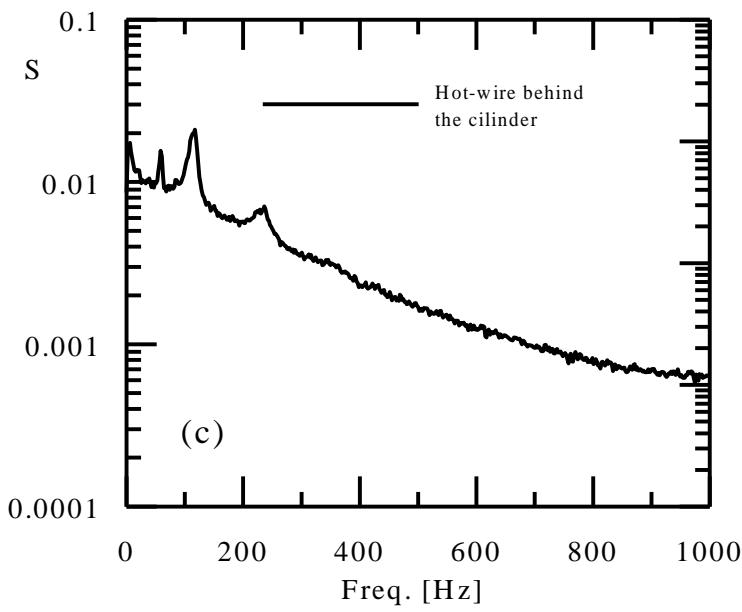




Caso 1.

Um caso real:

ruas de Von Karman
(A ponte sobre o rio Tacoma)

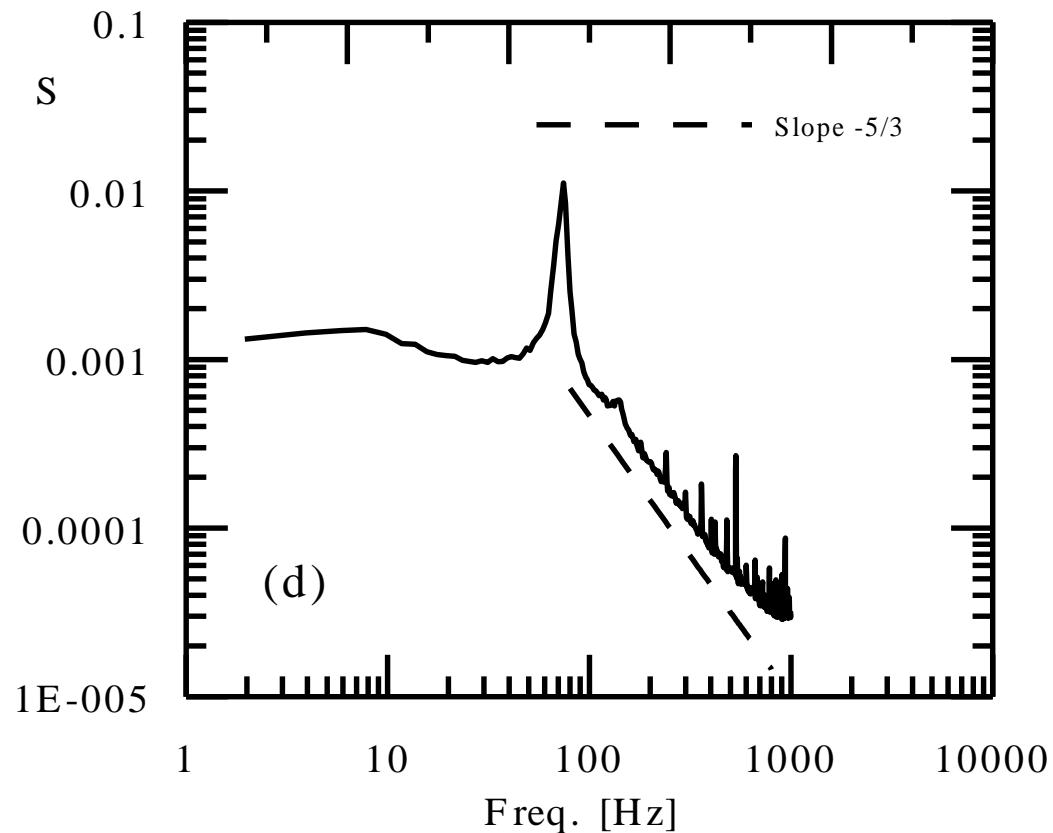
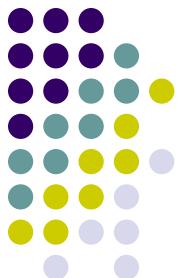




Caso 1.

Um caso real:

ruas de Von Karman
(A ponte sobre o rio Tacoma)





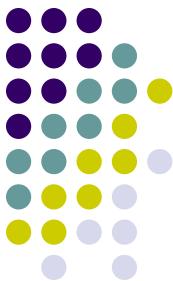
Anemômetros de Fio-quente

- Comprados no exterior (2 fabricantes mundiais)
 - US\$ 12,000.00 (por canal de medição)
 - Dependência tecnológica
 - Dificuldades de aperfeiçoamento e manutenção
- Construídos no Brasil
 - Aproximadamente R\$ 1.100,00
 - Domínio tecnológico
 - Possibilidades de aperfeiçoamento e customização



Oportunidades

- Aplicações para a anemometria térmica
 - Engenharias aeronáutica e civil
 - Ensaios em túnel de vento
 - Desenvolvimento de aerofólios
 - Aeroelasticidade
 - Meio Ambiente
 - Efeito estufa (floresta amazônica)
 - Previsões atmosféricas
 - Engenharia Offshore
 - Plataformas
 - Dutos
 - Risers
 - Etc, etc, etc ...



Riqueza em escalas, alto grau de mistura, caos no tempo e no espaço, a cascata de energia

Richardson

(1922)



Kolmogorov

(1941)

Picture of
Turbulence

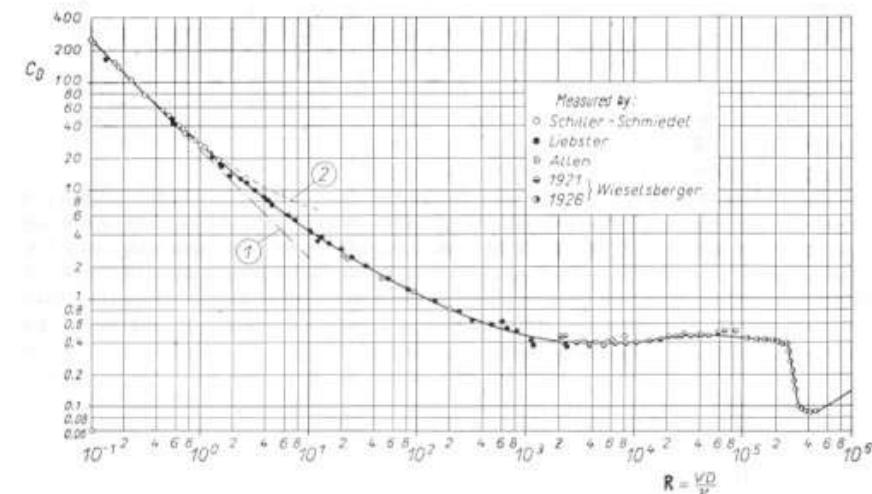
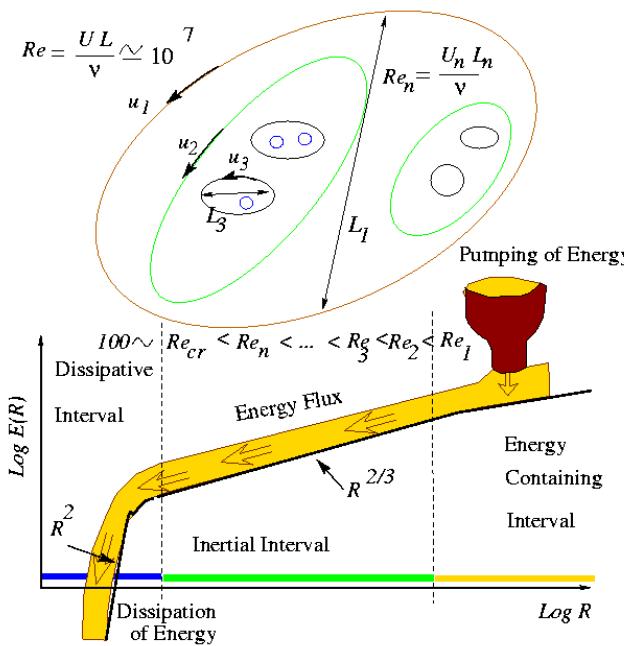
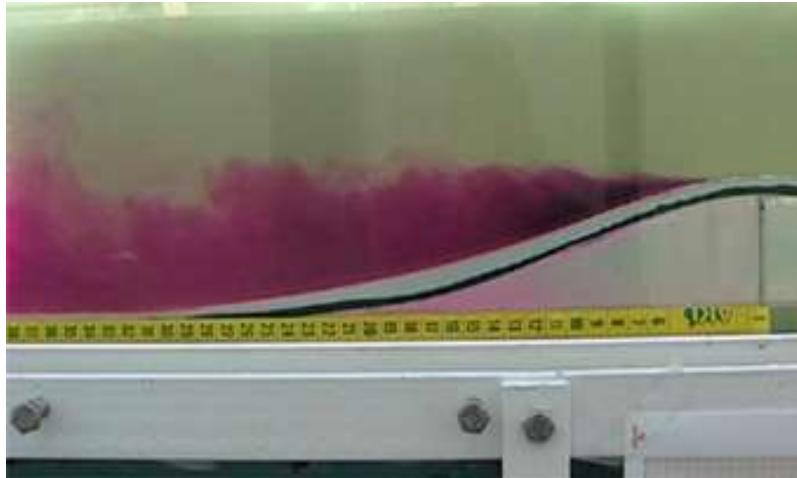


Fig. 1.5. Drag coefficient for spheres as a function of the Reynolds number
Curve (1): Stokes' theory, eqn. (6.10); curve (2): Oseen's theory, eqn. (6.13)

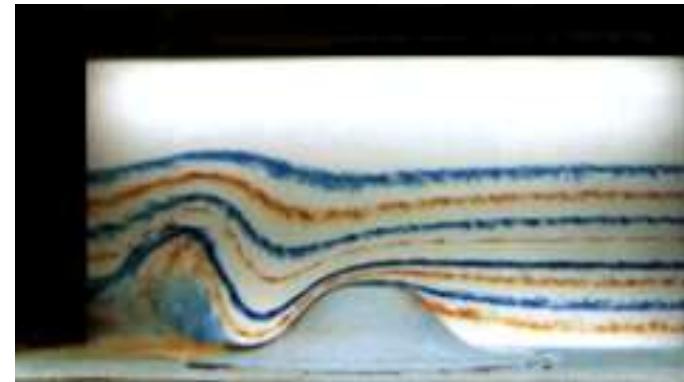


Caso 2. Escoamento sobre elevações.

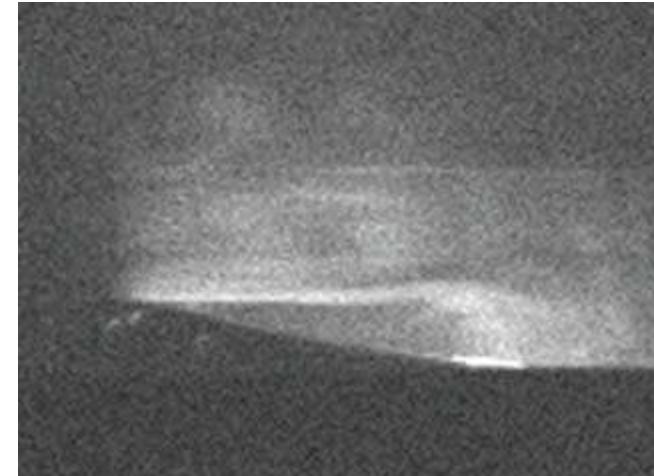
Escoamento da direita para a esquerda



Escoamento da direita para a esquerda



Escoamento da direita para a esquerda



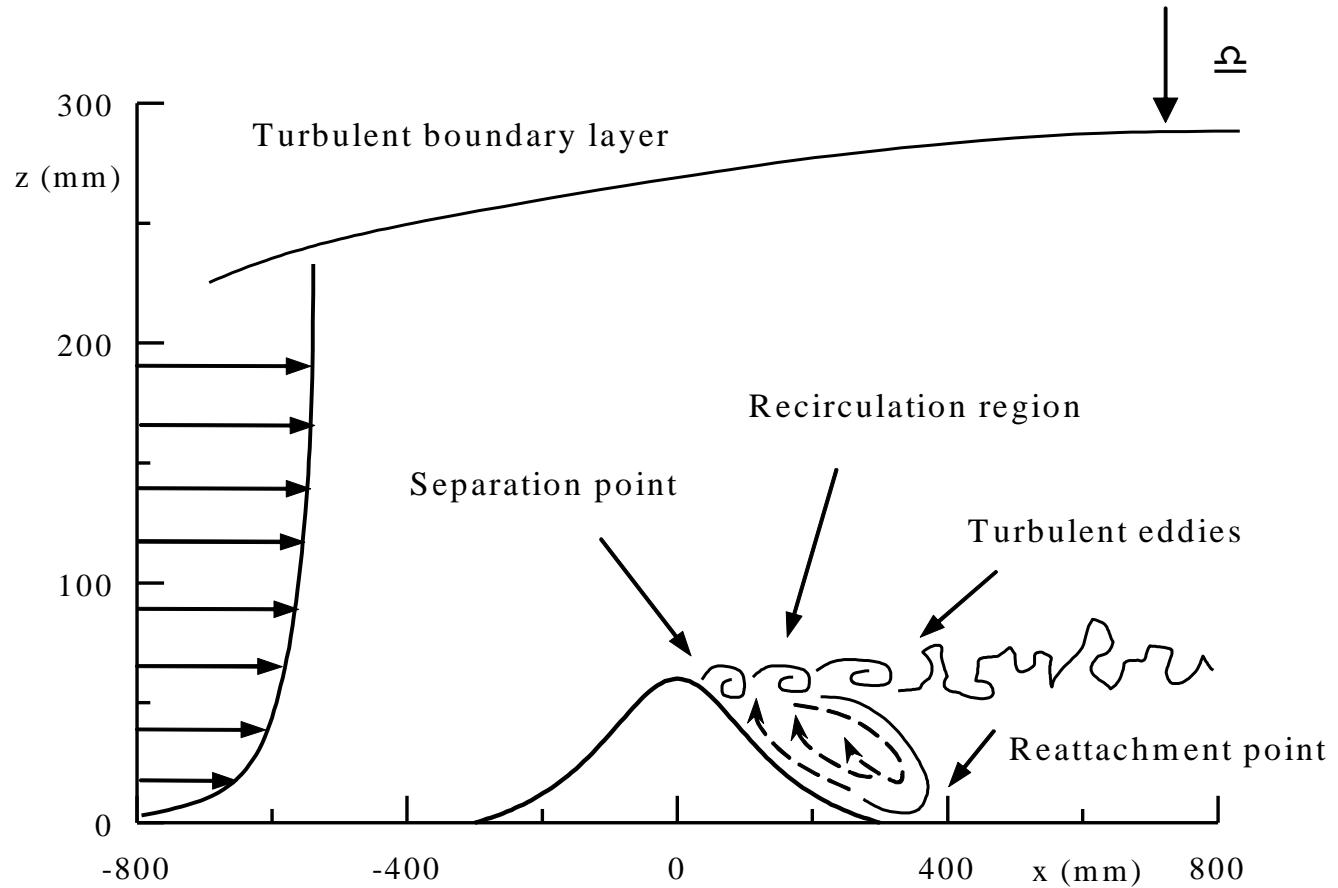


Escoamento sobre elevações



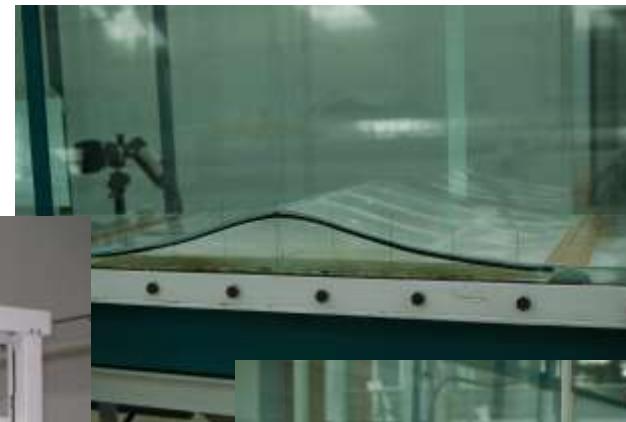


Experimentos



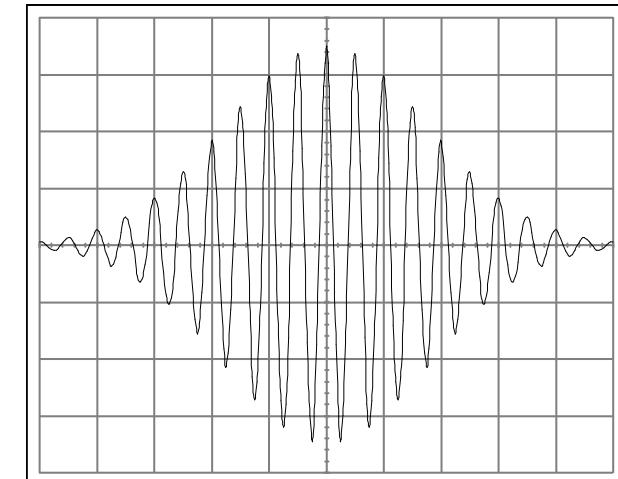
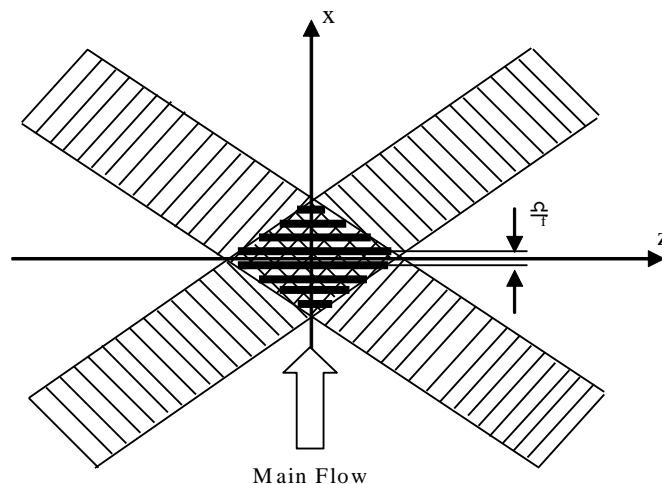
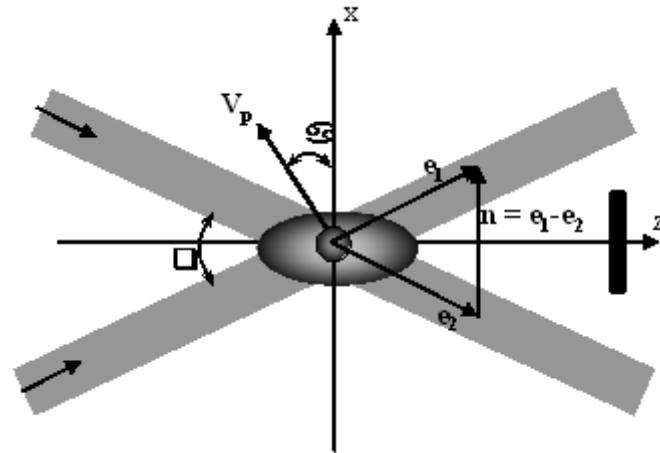
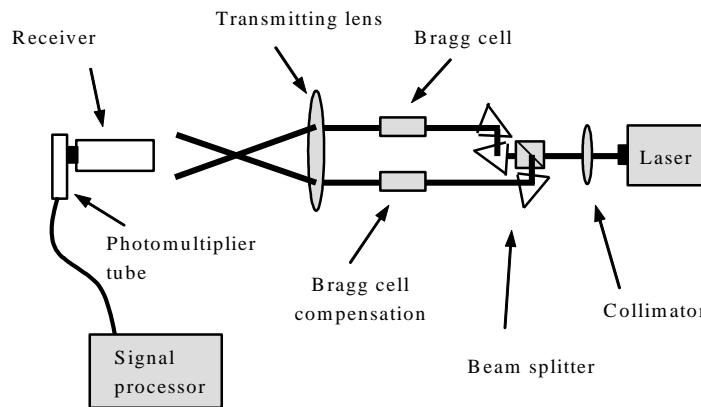


Tanque d'água e modelo da colina



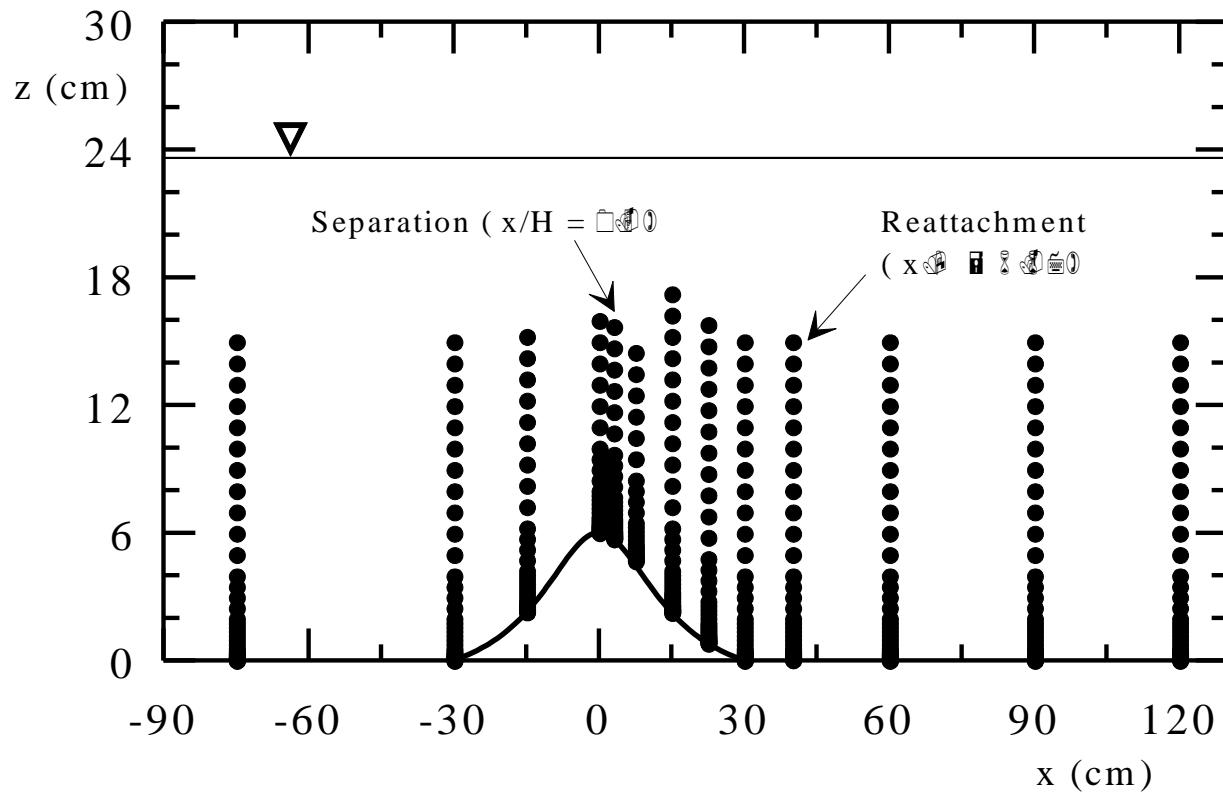


Anemometria laser Doppler





Estações de medições





Promediação das ENS (EPNS)

Equações do Movimento

- $u = U + u'$
- Média temporal, média espacial, esperança matemática.

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0$$

Equação da continuidade

$$\frac{\partial \bar{u}_j}{\partial t} + u_i \frac{\partial \bar{u}_j}{\partial x_i} = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial}{\partial x_j} \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \frac{\partial}{\partial x_j} (\bar{u}'_i \bar{u}'_j)$$

Equação da conservação
da taxa de variação da
quantidade de movimento

efeitos iniciais

efeitos viscosos

efeitos turbulentos

efeitos da pressão



Estratégias de modelagem, viscosidade turbulenta, modelo kappa-epsilom, RSM

I) Hipótese da viscosidade turbulenta

$$-\overline{\dot{u}_i \dot{u}_j} = \nu_t \left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} \right) - \frac{2}{3} \kappa \delta_{ij}$$

Termo a ser modelado

II) Modelo kappa-epsilom

$$\frac{\mu_t}{\rho} = \nu_t = C_\mu \frac{\kappa^2}{\varepsilon}$$
$$\frac{\partial (U_i \kappa)}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\frac{\nu_t}{\sigma_k} \frac{\partial \kappa}{\partial x_i} \right) - \overline{u_i u_j} S_{ij} - \varepsilon$$

Energia cinética turbulenta

$$\frac{\partial (U_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\frac{\nu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_i} \right) - \frac{\varepsilon}{\kappa} (C_1 \overline{u_i u_j} S_{ij} + C_2 \varepsilon)$$

Taxa de energia dissipada por unidade de massa

Grandezas flutuantes,
tensão turbulenta



Modelos do Tensor de Reynolds

III) RSM

Equação de transporte para os elementos do tensor de Reynolds

$$\frac{\partial \tau_{ij}}{\partial t} + \frac{\partial \bar{u}_k \tau_{ij}}{\partial x_k} = P_{ij} + \frac{2}{3} \beta' \omega \kappa \delta_{ij} + \frac{\partial}{\partial x_k} \left(\left(v + \frac{v_t}{\sigma^*} \right) \frac{\partial \tau_{ij}}{\partial x_k} \right)$$

Produção

$$P_k = -\bar{u}_i \bar{u}_j \frac{\partial u_j}{\partial x_i}$$

Grandezas transportáveis

$$\frac{\partial \omega}{\partial t} + \frac{\partial \bar{u}_k \omega}{\partial x_k} = \alpha_3 \frac{\omega}{\kappa} P_\kappa - \beta_3 \omega^2 + \frac{\partial}{\partial x_k} \left(\left(v + \frac{v_t}{\sigma_{\omega 3}} \right) \frac{\partial \omega}{\partial x_k} \right) + (1 - F_1)^2 \frac{1}{\sigma_2 \omega} \frac{\partial \kappa}{\partial x_k} \frac{\partial \omega}{\partial x_k}$$

Os modelos dependem da determinação experimental de muitos parâmetros



Formulação de lei da parede

- Mellor (1966)

$$u^+ = \xi_{p^+} + \frac{2}{\kappa} \left(\sqrt{1+p^+ z^+} - 1 \right) + \frac{1}{\kappa} \left(\frac{4z^+}{2+p^+ z^+ + 2\sqrt{1+p^+ z^+}} \right)$$

- Nakayana & Koyama (1984)

$$u^+ = \frac{2}{\kappa^+} \left[3(\zeta - \zeta_s) + \ln \left(\frac{\zeta_s + 1}{\zeta_s - 1} \frac{\zeta - 1}{\zeta + 1} \right) \right]$$

- Cruz and Silva Freire (1998, 2002)

$$u = \frac{\tau_w}{|\tau_w|} \frac{2}{\kappa} \sqrt{\frac{\tau_w}{\rho} + \frac{1}{\rho} \frac{dP_w}{dx} z} + \frac{\tau_w}{|\tau_w|} \frac{u_\tau}{\kappa} \ln \left(\frac{z}{L_c} \right)$$

$$L_c = \frac{\sqrt{\left(\frac{\tau_w}{\rho} \right)^2 + 2 \frac{\nu}{\rho} \frac{dP_w}{dx} u_R} - \frac{\tau_w}{\rho}}{\frac{1}{\rho} \frac{dP_w}{dx}}$$



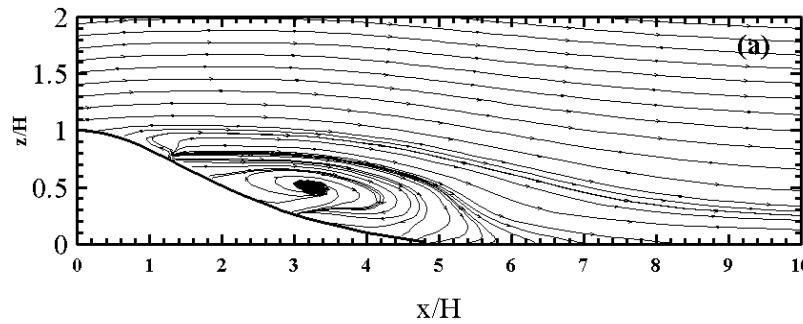
Configuração do Cluster

- Administrador:
 - Intel D875PBZ Motherboard (With on-board Gigabit Ethernet network interface)
 - Pentium 4, 3.0Gz, 1Mb Cache
 - 1 Gb DDR400 in dual mode (2 x 512 Mb)
 - 200 GB SATA HD
- Nós (4):
 - Intel D875PBZ Motherboard (With on-board Gigabit Ethernet network interface)
 - Pentium 4, 3.0Gz, 1Mb Cache
 - 1 Gb DDR400 in dual mode (2 x 512 Mb)
 - 40 GB ATA HD
- 3COM Gigabit Ethernet Switch 3C16478
- 2 “APC Back-UPS RS 1500” 1500 VA UPS

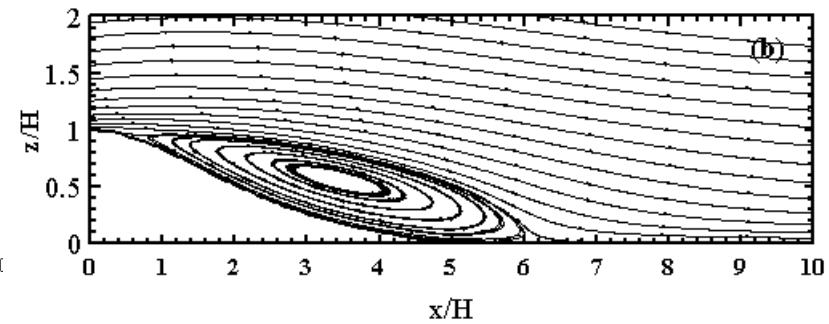




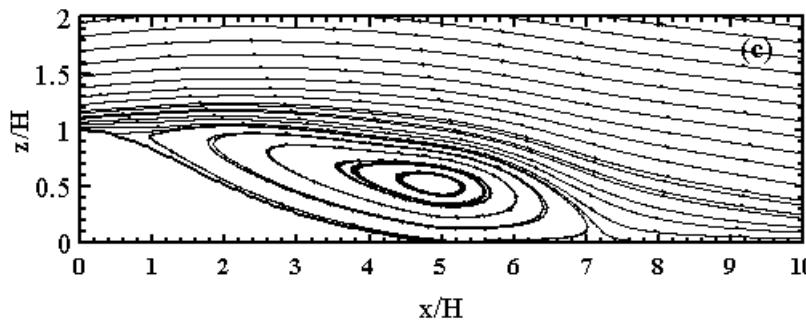
Comparação entre os experimentos e as simulações numéricas: região de separação



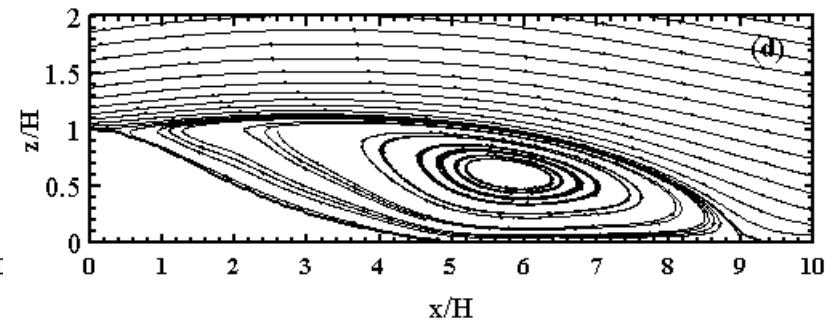
Experimentos: Loureiro (2004)



Cruz and Silva Freire (1998)



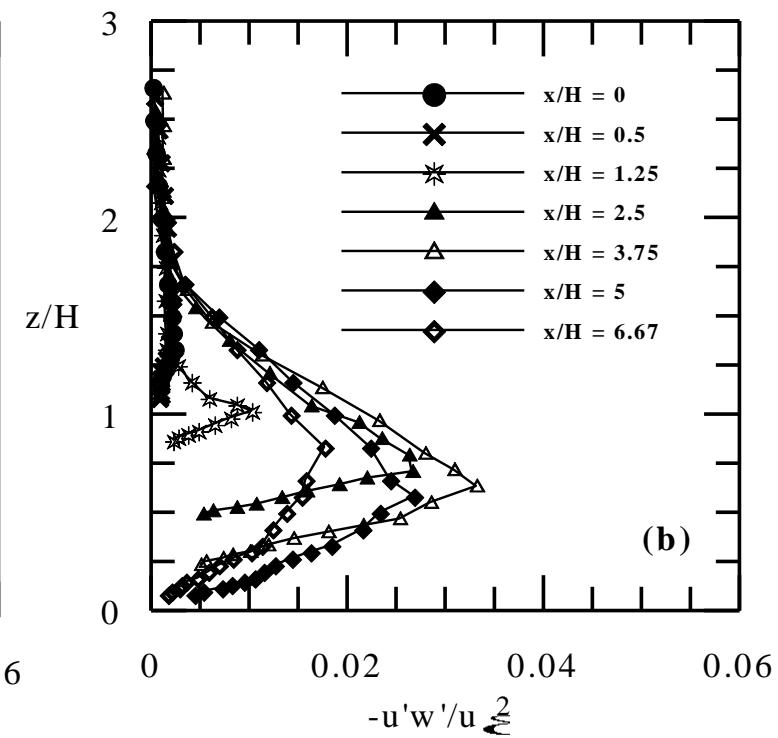
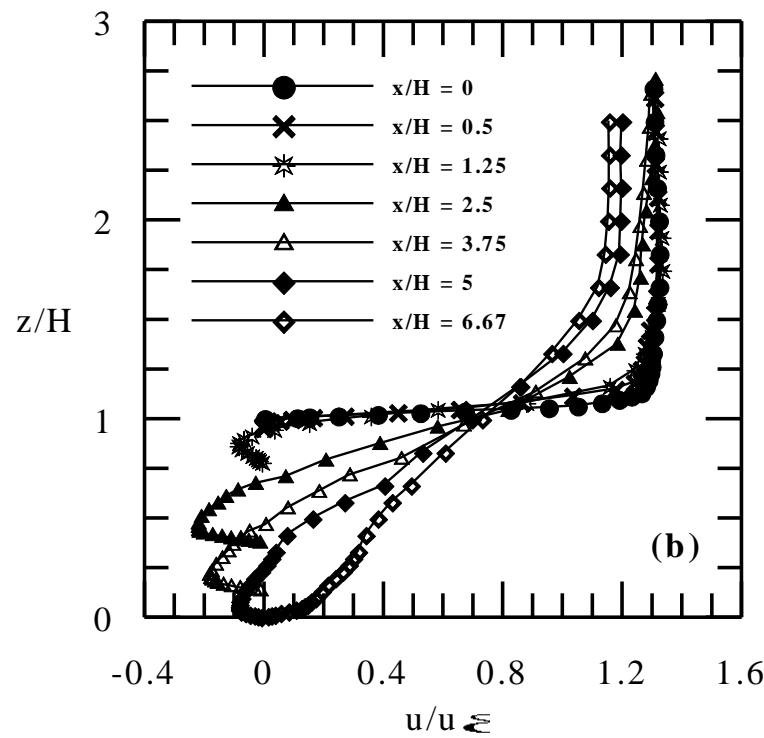
Mellor (1966)



Narayama & Koyama (1984)

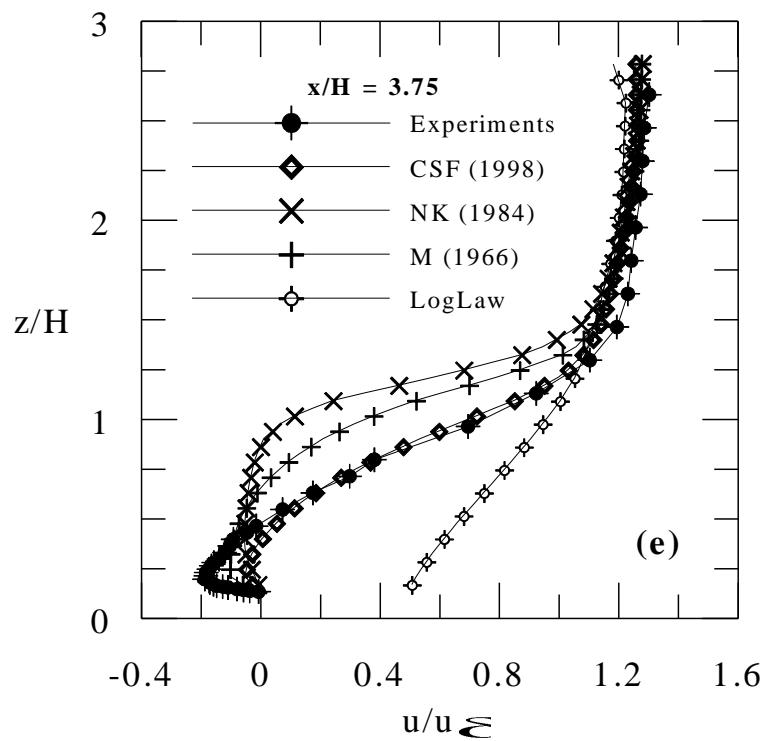
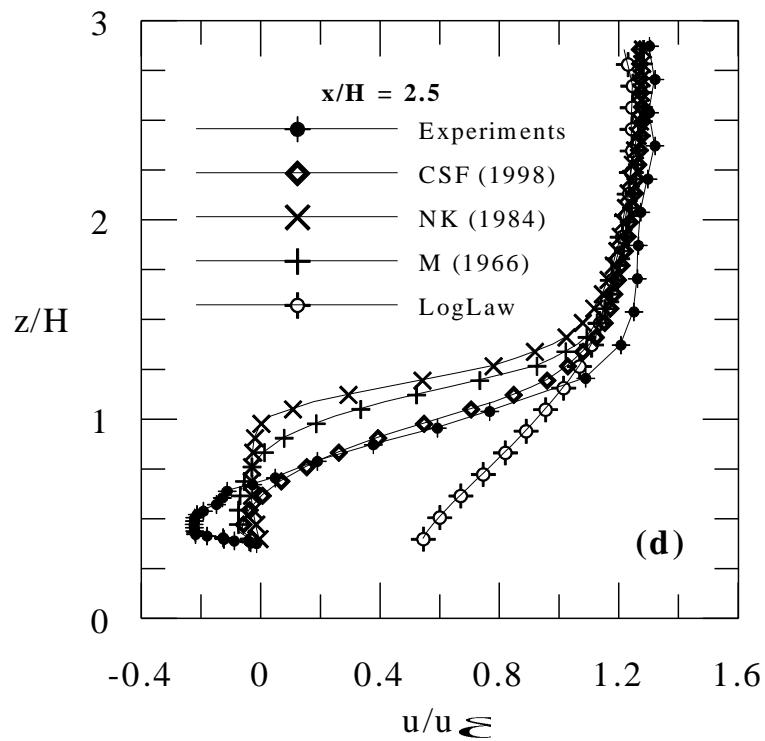


Experimentos: região de separação



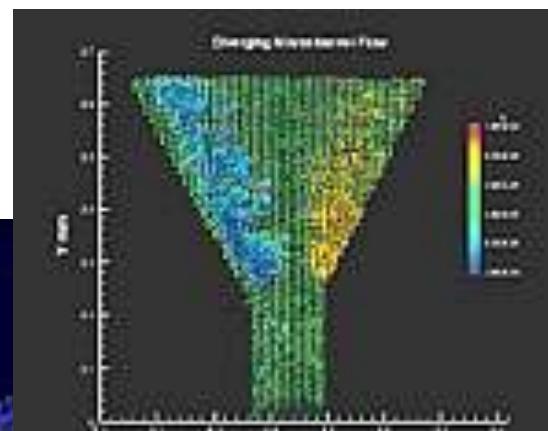
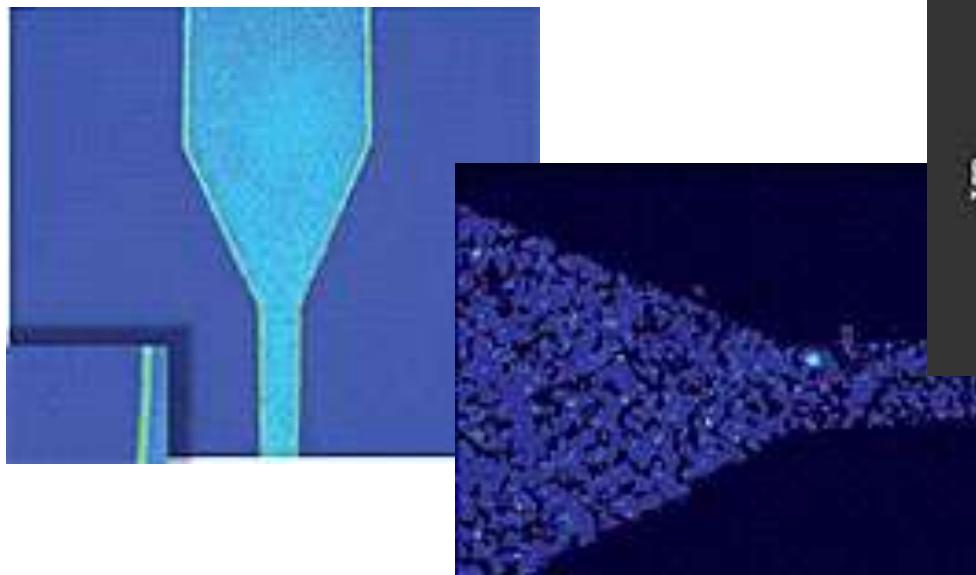


Simulações numéricas: região de separação





Caso 3: Escoamento sobre superfícies rugosas. Aplicações em MEMS.





Motivação. MEMS.

- Transição preceose.
 - Wu and Little (1983, Cryogenics, 23, 273-277), $R_c = 350$
 - Peng and Peterson (1996, IJHMT, 12, 2599-2608), $R_c = 300$
 - Mala and Li (1999, IJHFF, 20, 142-148), $R_c = 300, 900$ ($D = 50$ to $254 \mu\text{m}$), $f_R > HP$
 - Qu et al. (2000, IJHMT, 43, 353-364)
 - Guo and Li (2003, IJHMT, 46, 284-298), compressible flow, ($D = 80$ to $166 \mu\text{m}$).
 - Wu and Cheng (2003, IJHMT, 46, 2547-2556), $R_c = 1500$
- Predições convencionais.
 - Mala and Li (1999, IJHFF, 20, 142-148), $R_c = 300, 900$ ($D = 254 \mu\text{m}$)
 - Qu and Mudawar (2002, IJHMT, 45, 2549-2565)
 - Judy et al. (2002, IJHMT, 45, 3477-3489), $f_R = HP$
 - Sharp and Adrian (2004, Exp. Fluids, 36, 741-747), $D = 50$ to $247 \mu\text{m}$
 - Celata et al. (2004, ETFS, 28, 87-95), $R_c = 1900, 2500$ ($D = 130$),
 $f_R = HP$ ($R < 600$), $f_R > HP$ ($R > 600$), relative channel surface roughness = 2.65%
 - Li e Olsen (2006, IJHFF, 27, 123-134), $R_c = 1718, 1885$ ($D = 200$ a $640 \mu\text{m}$).



Motivação. MEMS.

It is well known that the surface roughness does not affect the laminar flow in macrochannels. However, as size decreases, surface roughness becomes important. K/D_h varies from 10-3 to 10-5.

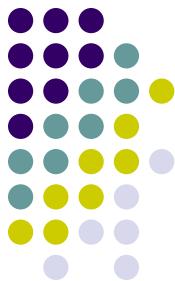
Wu and Cheng 2003 IJHMT 46 2547-2556

Causes of deviation from conventional macroscale results: wall slip effects (gas flow), surface roughness, viscous dissipation.

Koo and Kleinstreuer 2005 IJHMT 48 2625-2634

A common point in early studies is that researchers who found early laminar-trubulent transition concluded that the relative high surface roughness was one of the major reasons.

Li and Olsen 2006 IJHFF 27 123-134



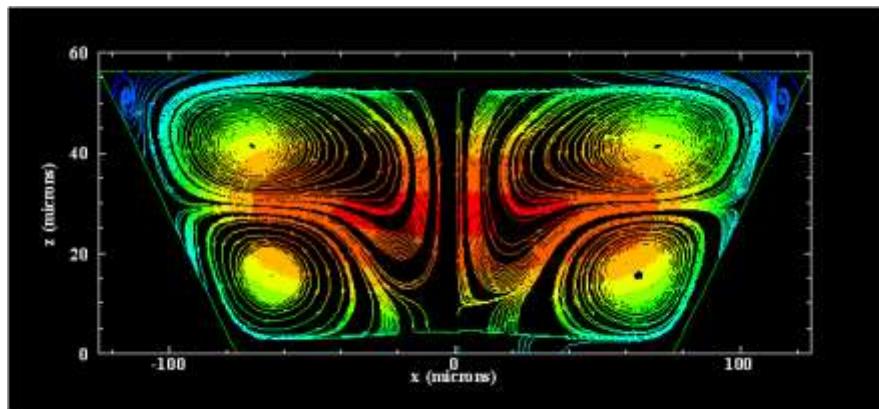
Detalhes da simulação

Determinação do comprimento rugoso efetivo

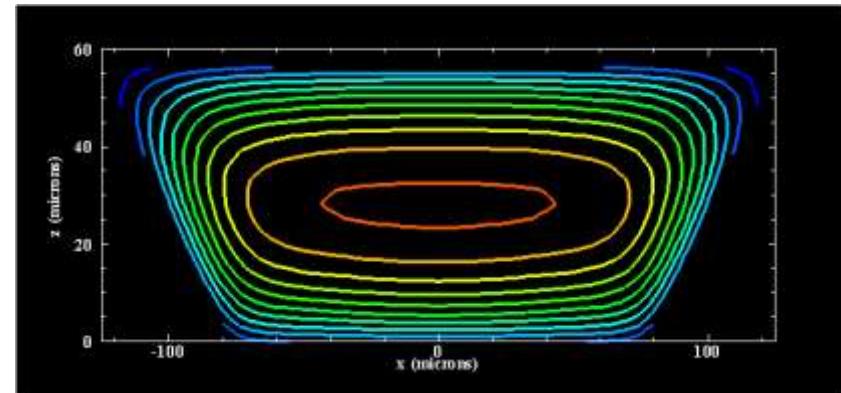
- Dica (Meteorology)
 - $K_0 = 1/10 K$
 - $K = 0.008 \text{ microns}$ (Li and Olsen, 2006)
 - $K = 0.003 \text{ microns}$ (Wu and Cheng, 2003, #8)
 - $K = 0.9 \text{ microns}$ (Wu and Cheng, 2003, #10)
- Cálculo de K_0 a partir de K_s
 - $K_s = 1/0.033 K_0$
 - $K_s = 0.024 \text{ microns}$ (Li and Olsen, 2006)
 - $K_s = 0.009 \text{ microns}$ (Wu and Cheng, 2003, #8)
 - $K_s = 2.728 \text{ microns}$ (Wu and Cheng, 2003, #10)



Resultados. BSL-RSM. Geometria #5, Re 600.



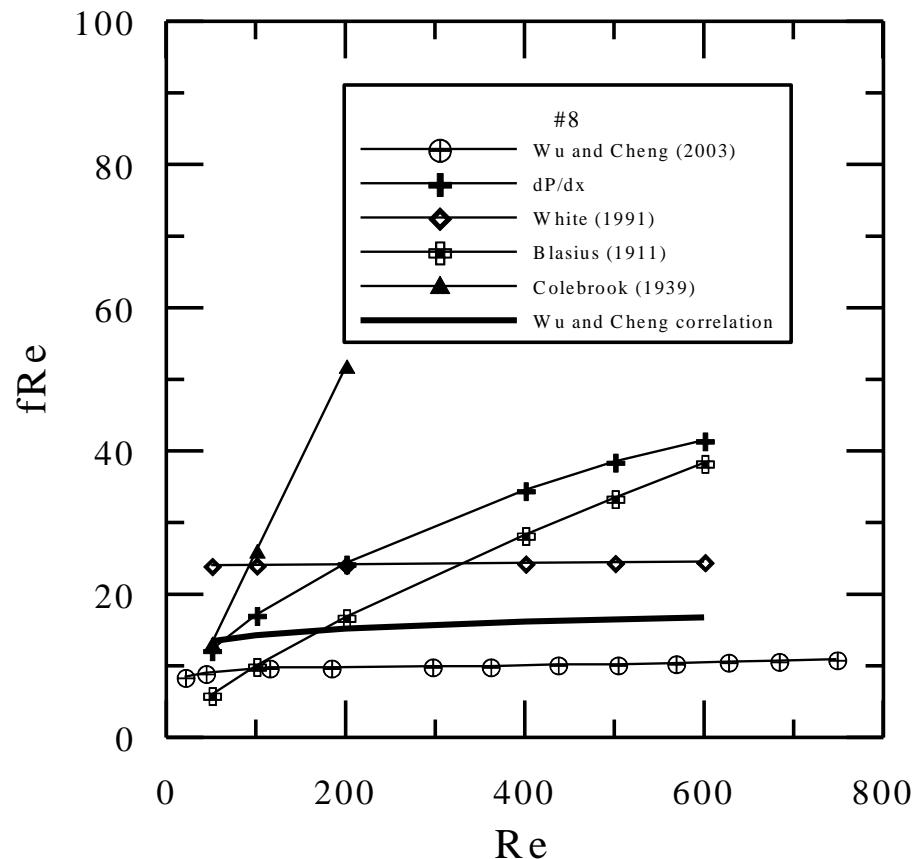
Linhos de corrente



LInhas de contorno

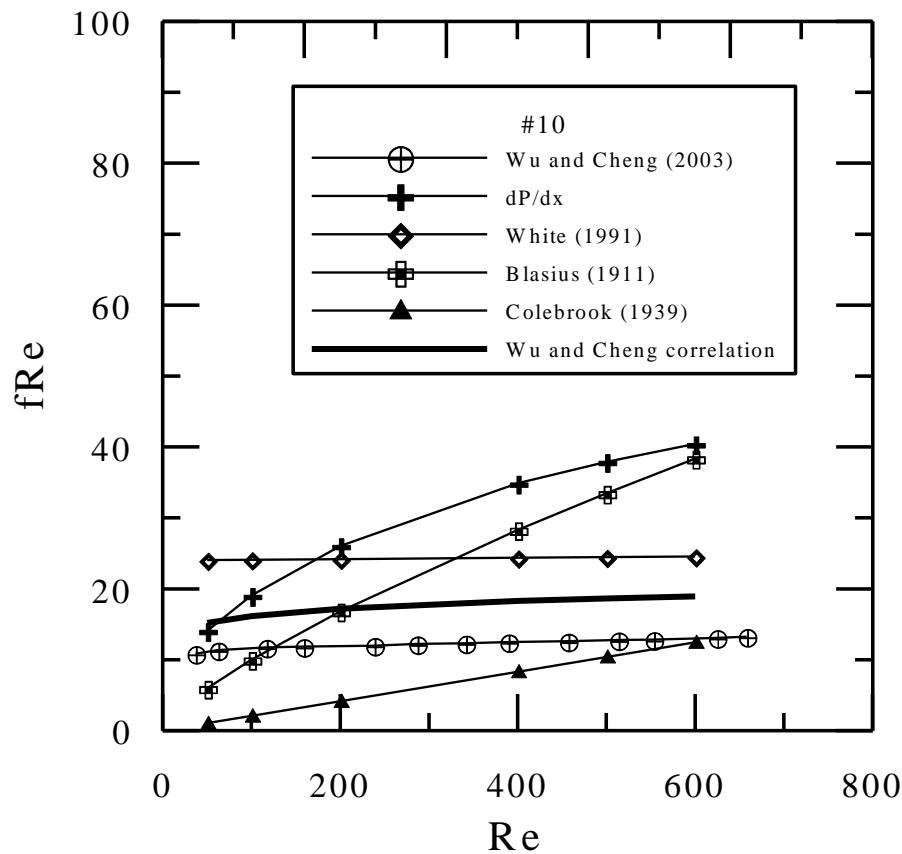


Resultados. BSL-RSM. Geometria #8.



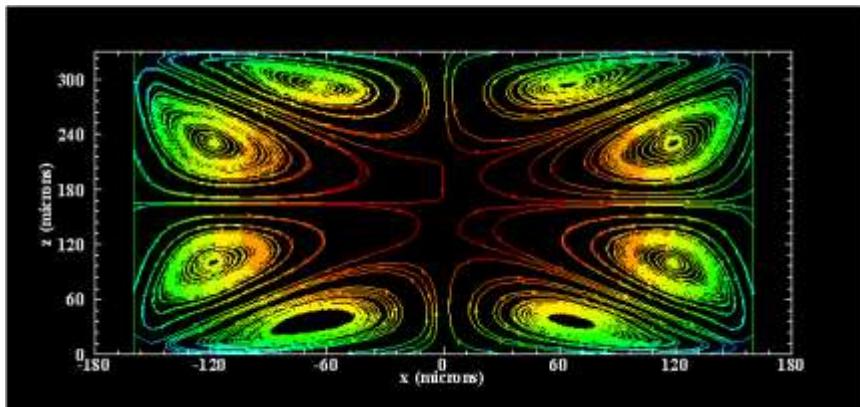


Resultados. BSL-RSM. Geometria #10.

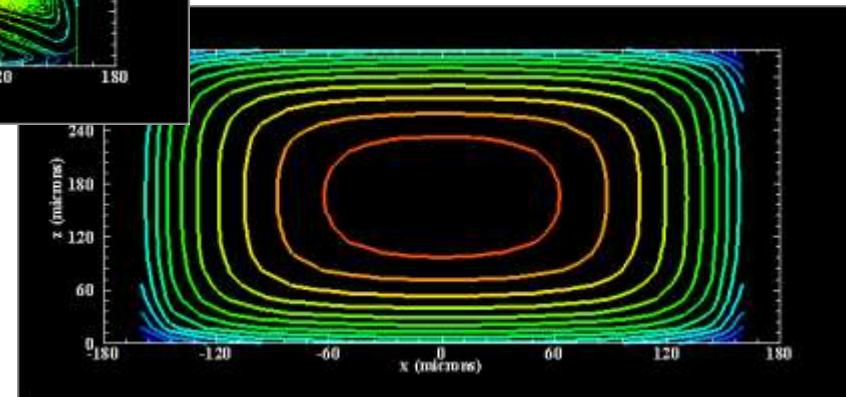




Resultados. BSL-RSM. Li and Olsen 2006 IJHFF 27 123-134



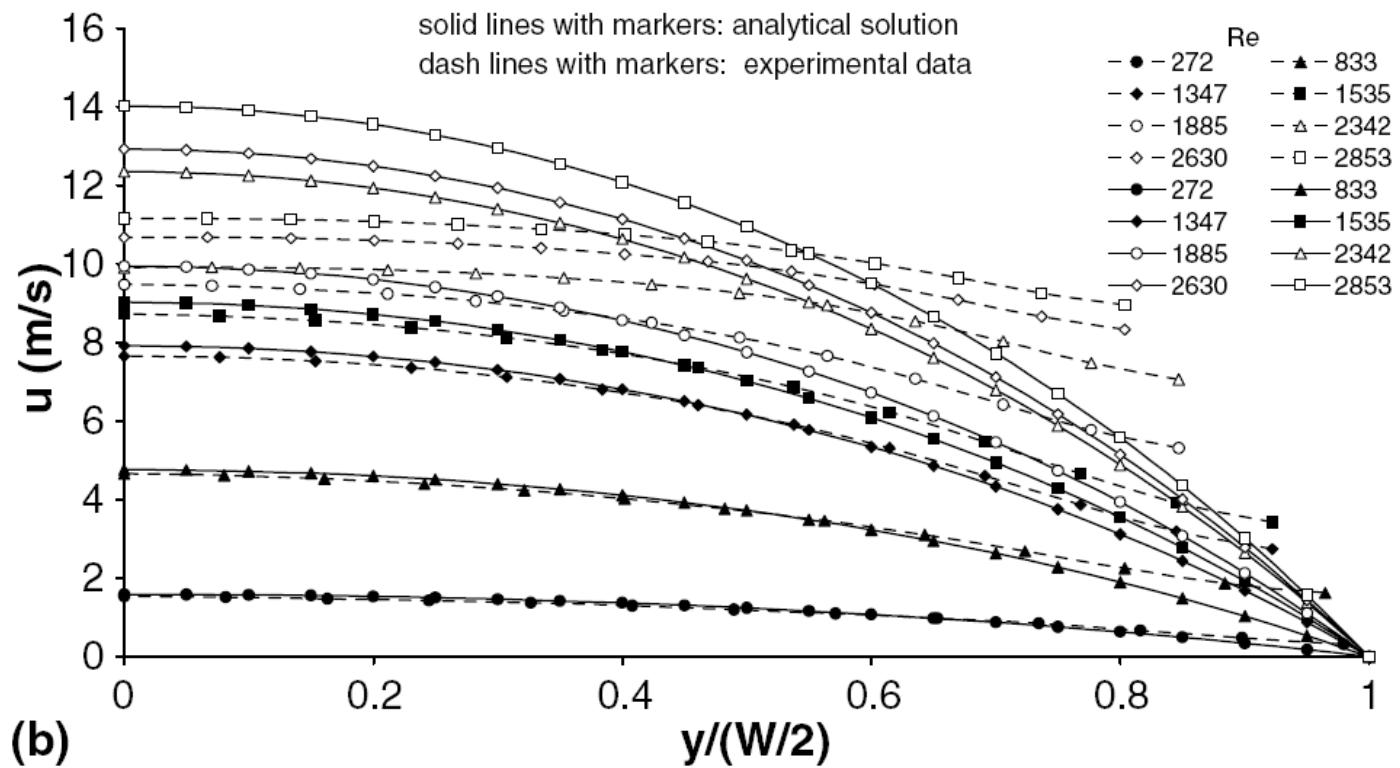
Linhas de Corrente



Linhas de Contorno

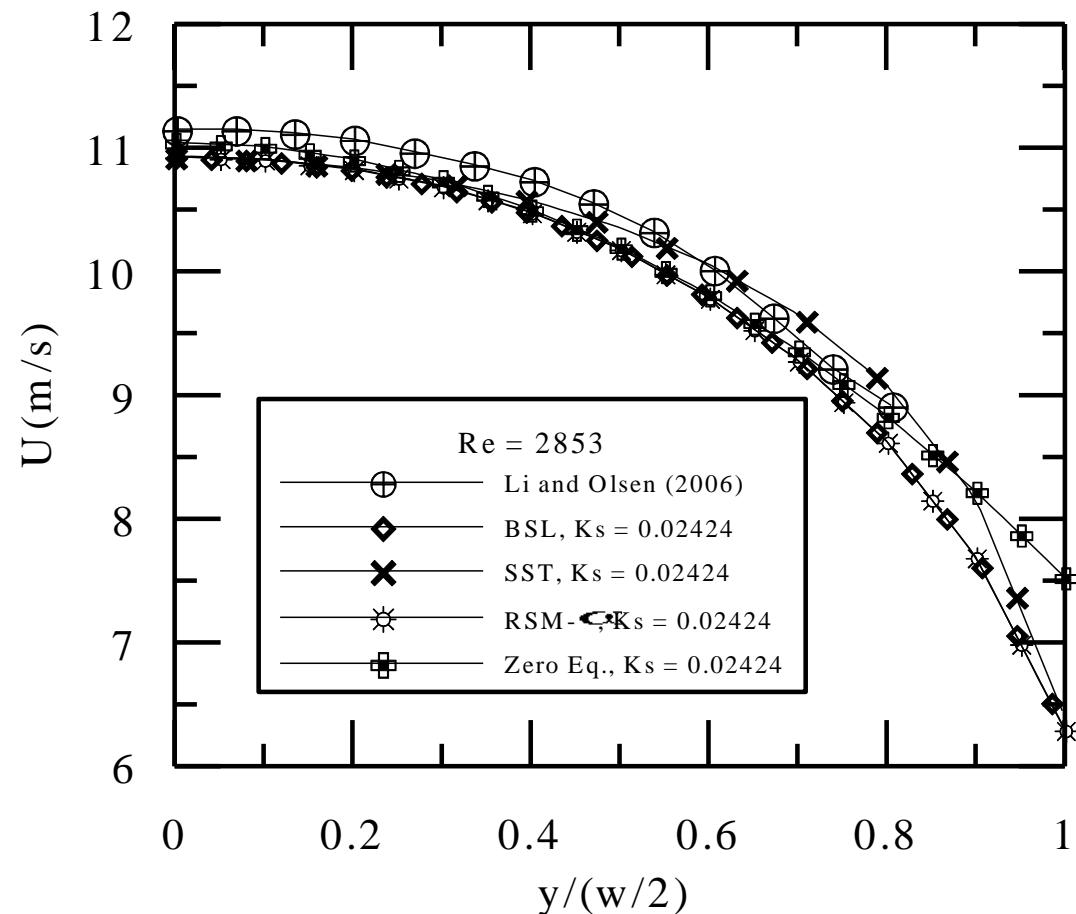


Resultados





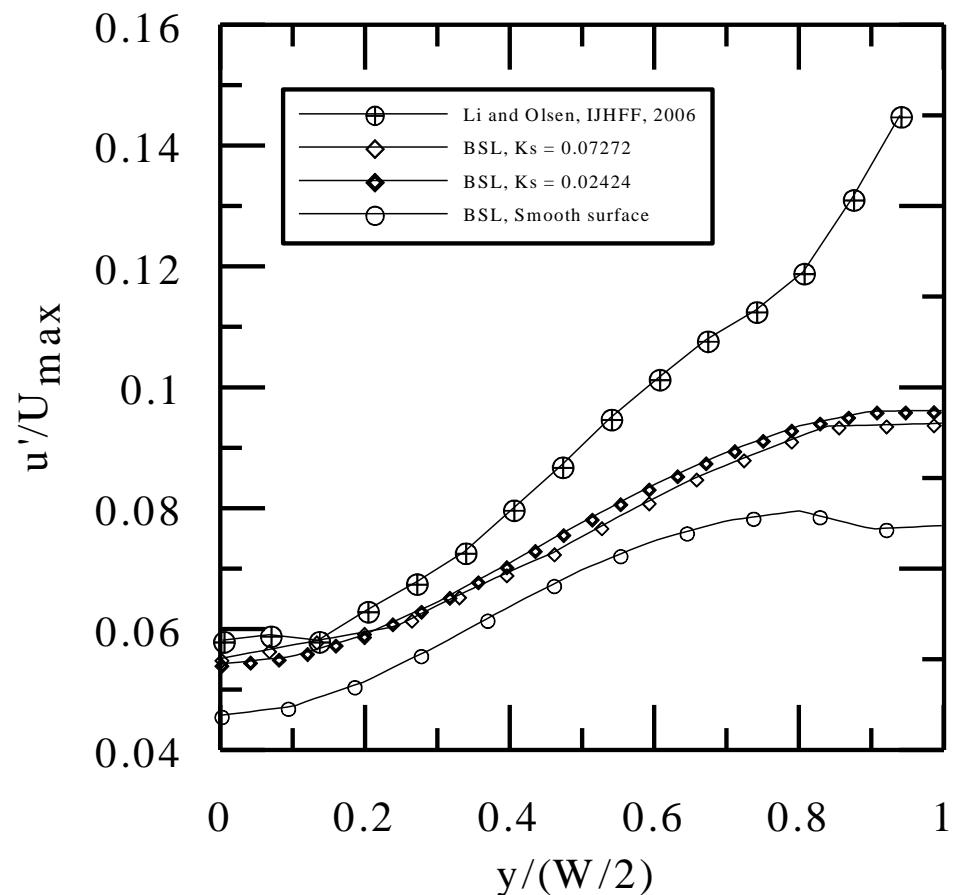
Resultados Diferentes modelos de turbulência, diferentes comprimentos de rugosidade.





Resultados

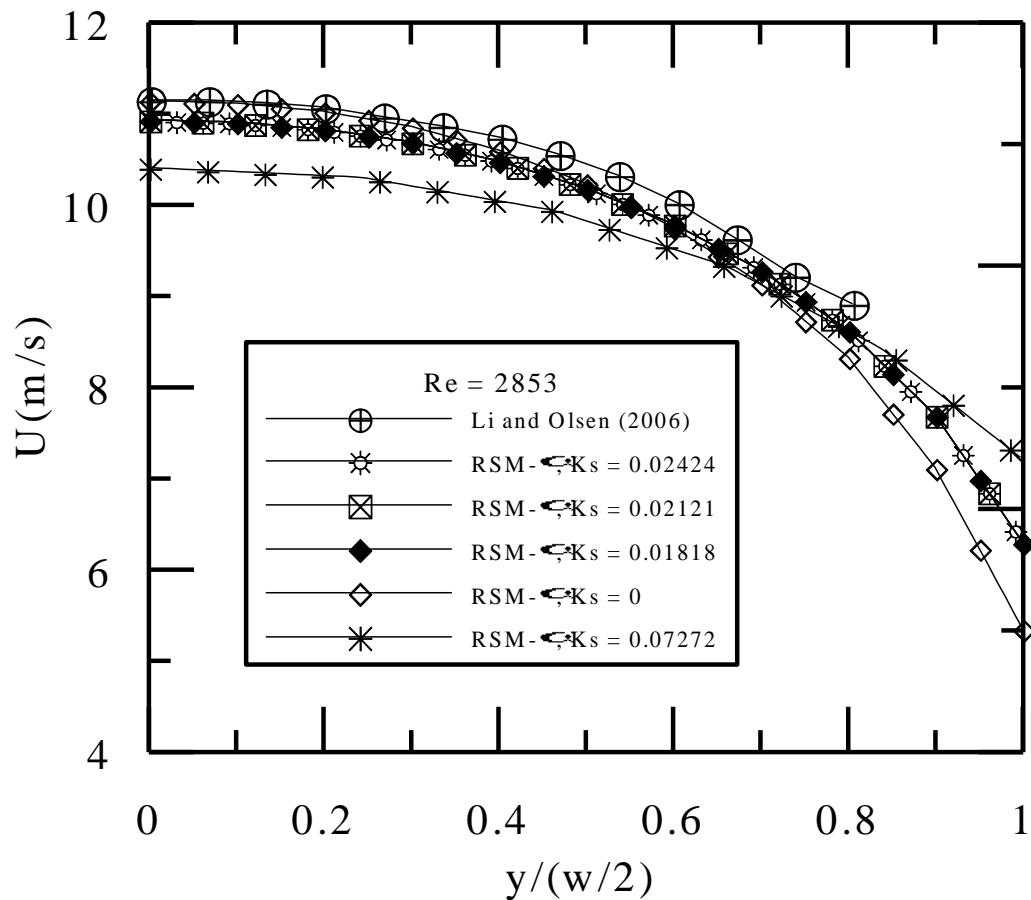
Modelo BSL-RSM, diferentes modelos de rugosidade.

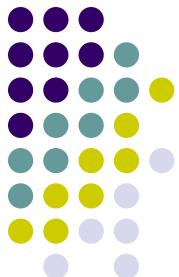




Resultados

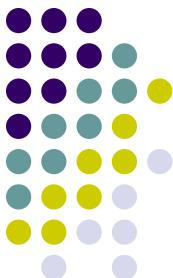
Modelos RSM-w, diferentes comprimentos de rugosidade.





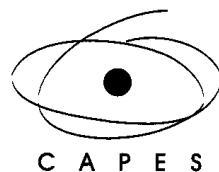
A importância dos escoamentos complexos

1. Todos os processos industriais que envolvam escoamento de fluidos
2. Processos geofísicos
3. Pesquisa fundamental.



Acknowledgements

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