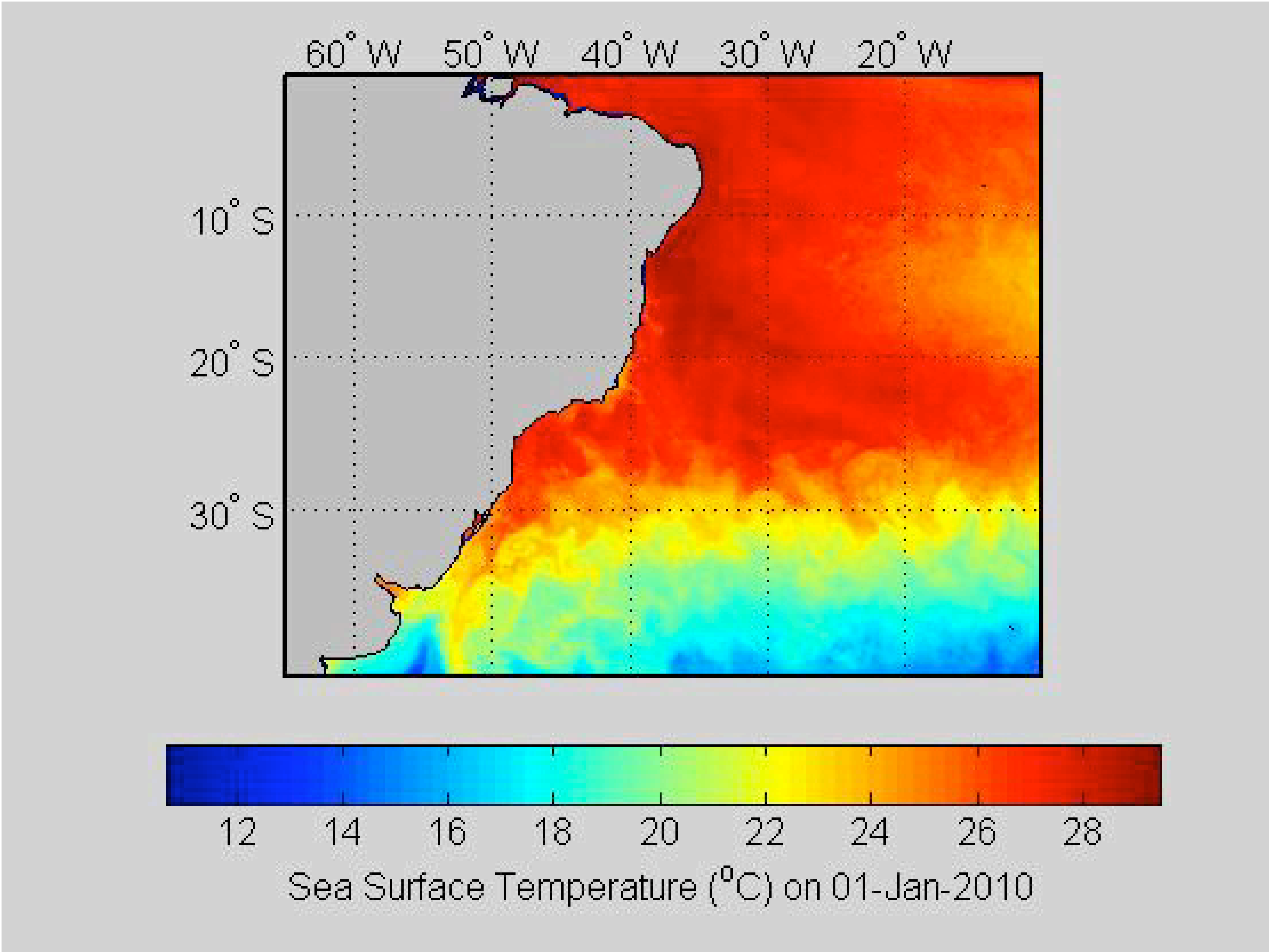
# The great, unsolved problem of turbulence and the need for wind tunnels

# Turbulence

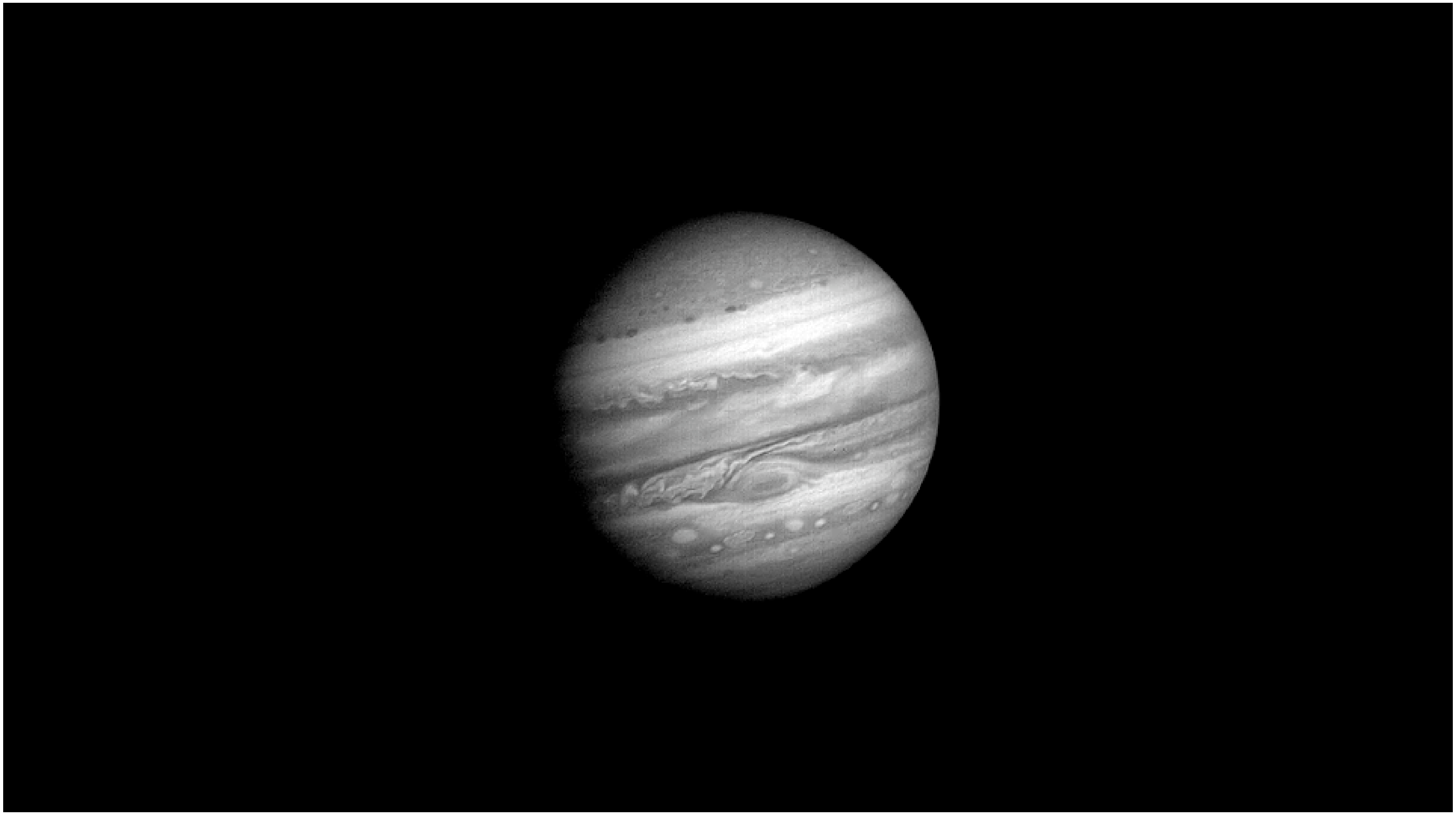
- Most important unsolved problem in classical physics
- Much harder than relativity or quantum mechanics
- Ubiquitous

NASA, Apollo 17




http://oceancurrents.rsmas.miami.edu/atlantic/img_artg.php

NASA Voyager 1



# Turbulence models

- **Singular perturbation problem at large Re**
- **Eddy diffusivity**
- **“Reynolds-averaged Navier-Stokes”**
- **Large eddy simulations**
- **Adjustable constants**
- **French curve**

# Direct numerical simulation

- Turbulent eddy spectrum
- Number of degrees of freedom $n = Re^{9/4}$
- At flight Reynolds numbers, $n = 10^{18}$
- Moore’s law

# Examples of surprises

- **Rectangular cylinder**
- **Stationary vortices**
- **Mixing and two-phase flows**

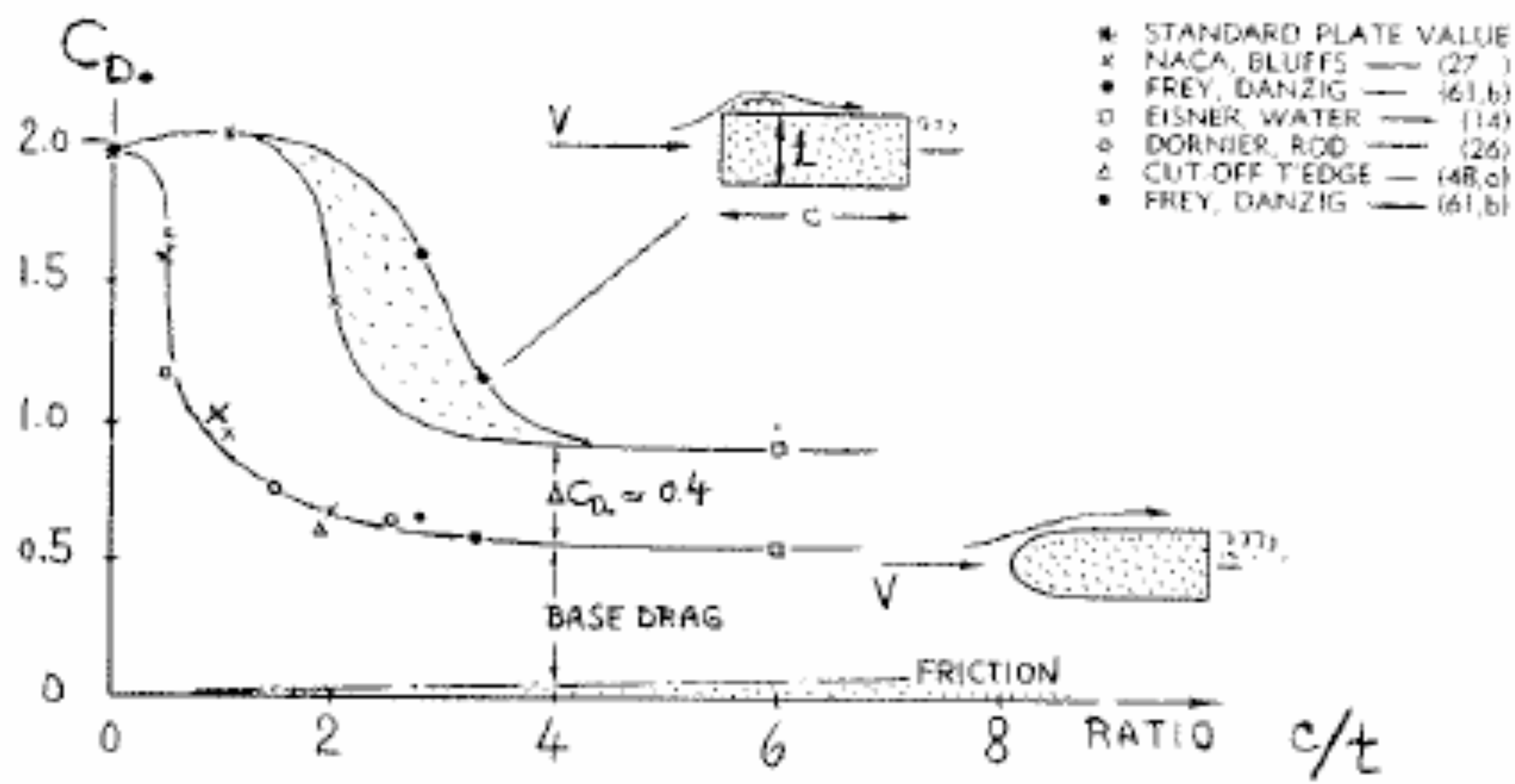
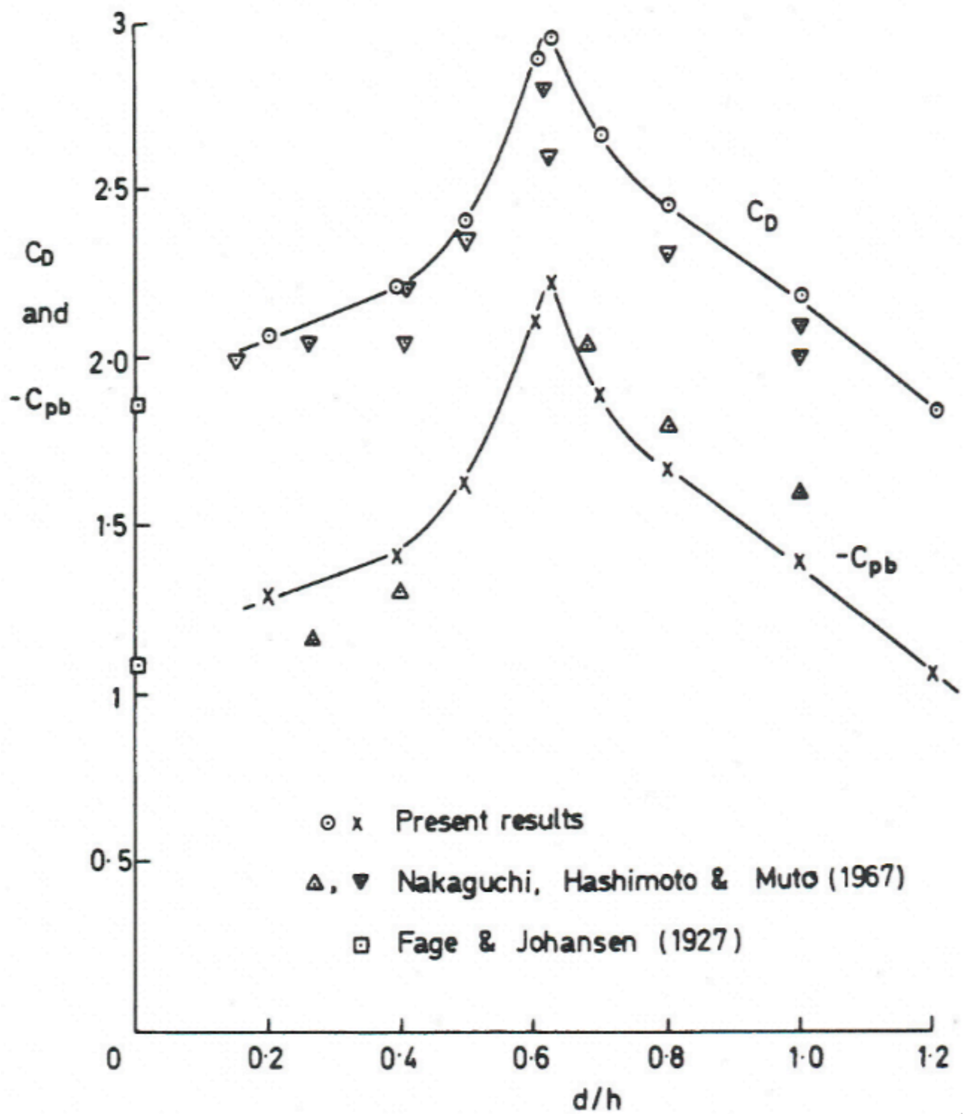
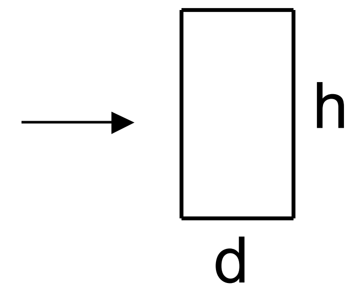



Figure 22. Drag coefficient of "rectangular" sections (tested <u>between walls</u>) with blunt leading edge (upper part) and with rounded shape (lower part), against length ratio.

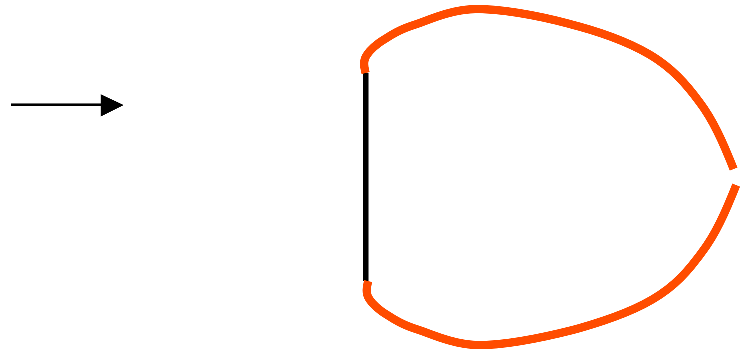
Hoerner 1965

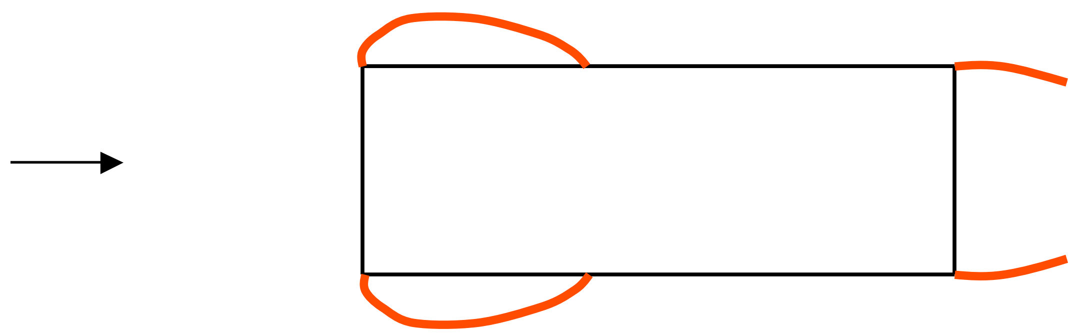



Bearman & Trueman 1972

# Topology changes





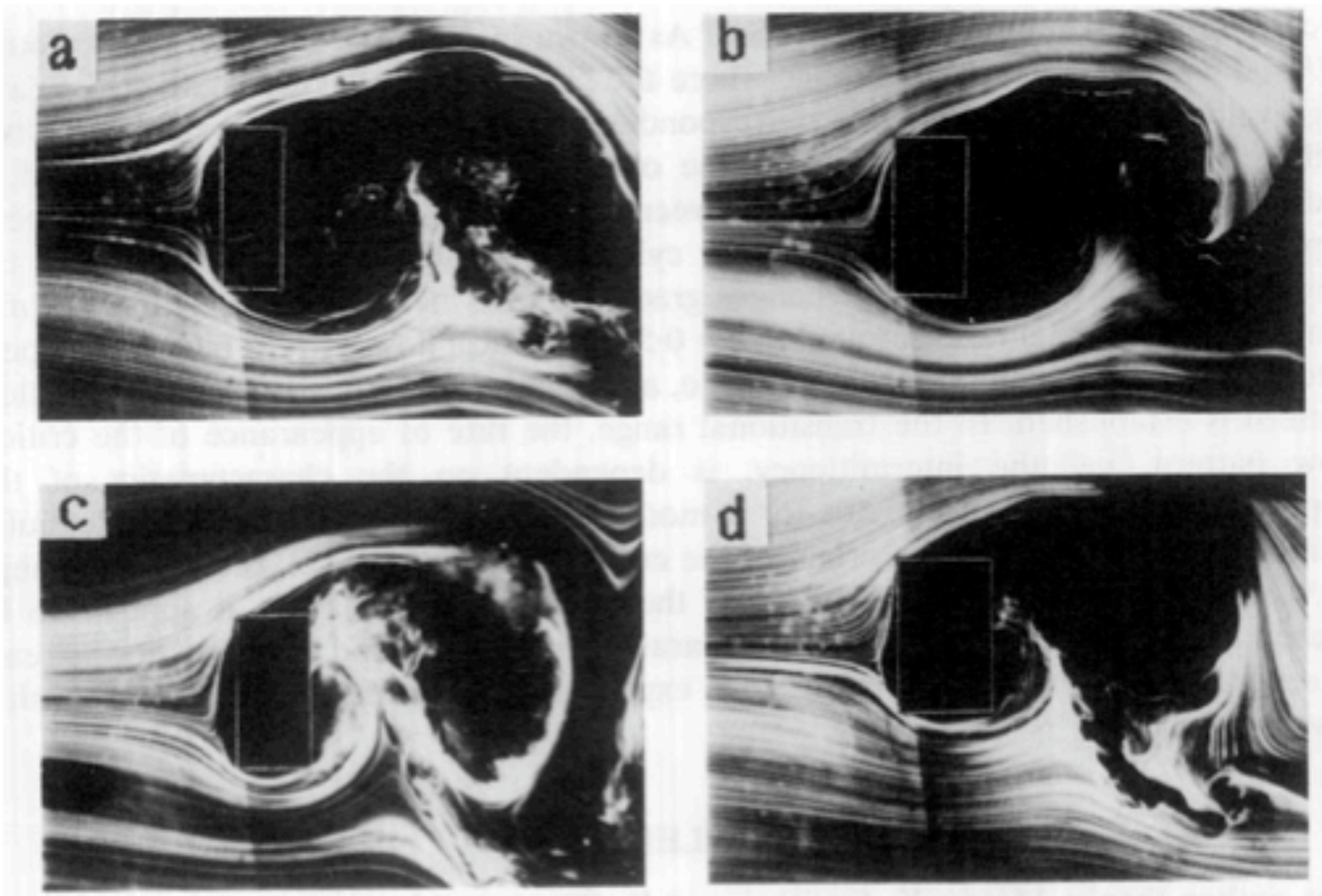
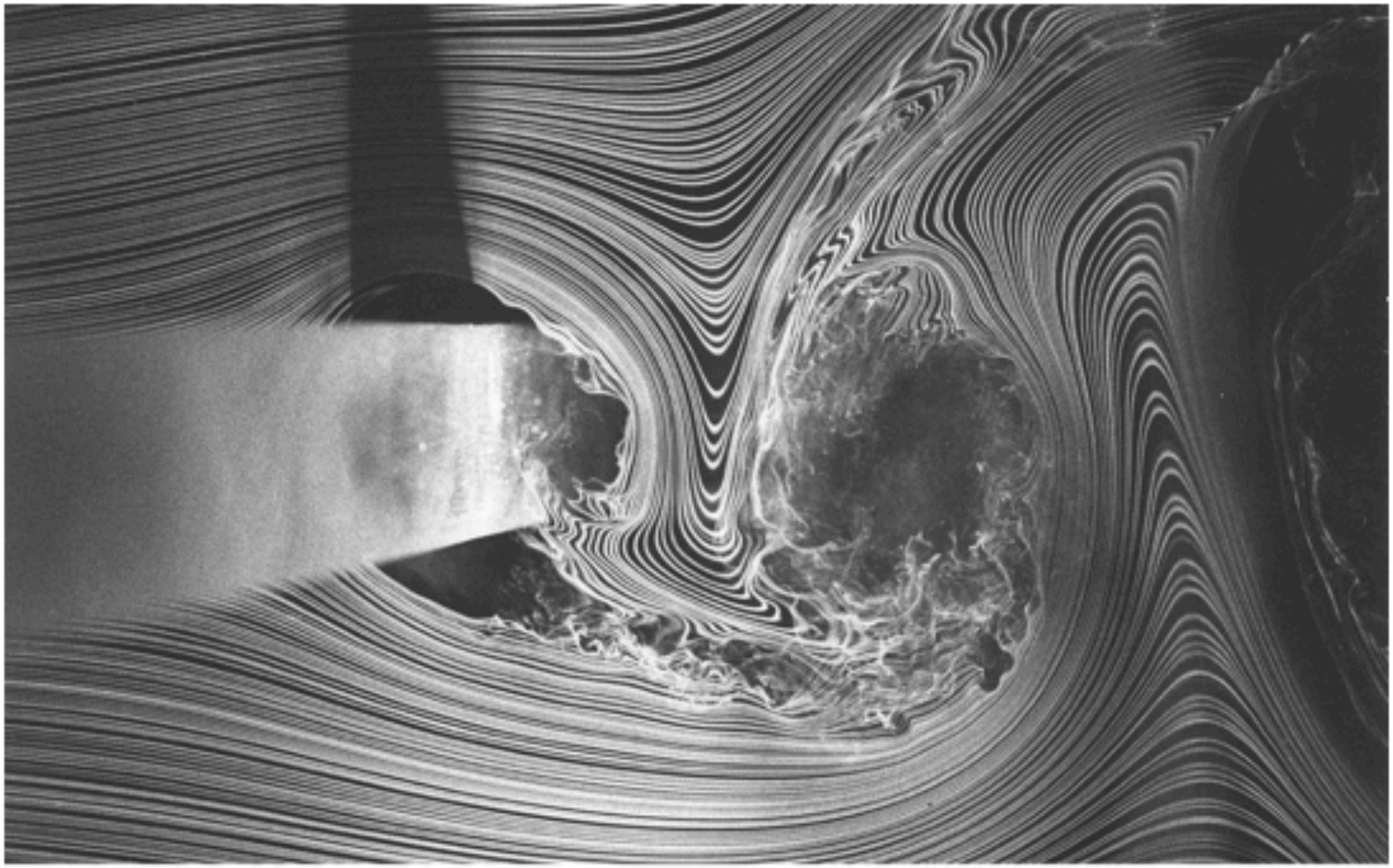



Figure 4. Flow around rectangular cylinders. $h = 10\,\text{cm}$, $U = 1\,\text{m/s}$, Re = 6700: (a) $d/h = 0{\cdot}4$; (b) $d/h = 0{\cdot}5$ at high base pressure; (c) $d/h = 0{\cdot}5$ at low base pressure; (d) $d/h = 0{\cdot}6$.

Bearman & Trueman 1972



$c/d = 0.62$, $\mathrm{Re} = 8\times10^3$

Norberg 1993

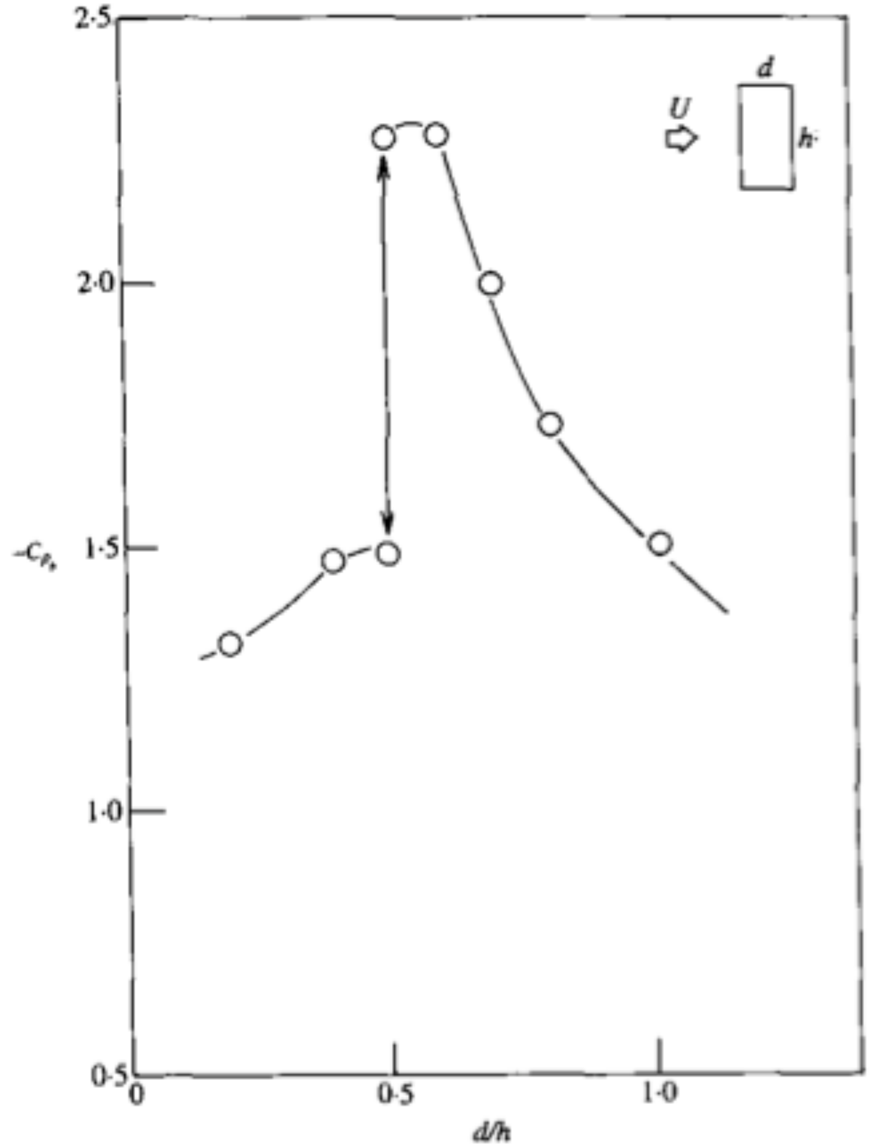
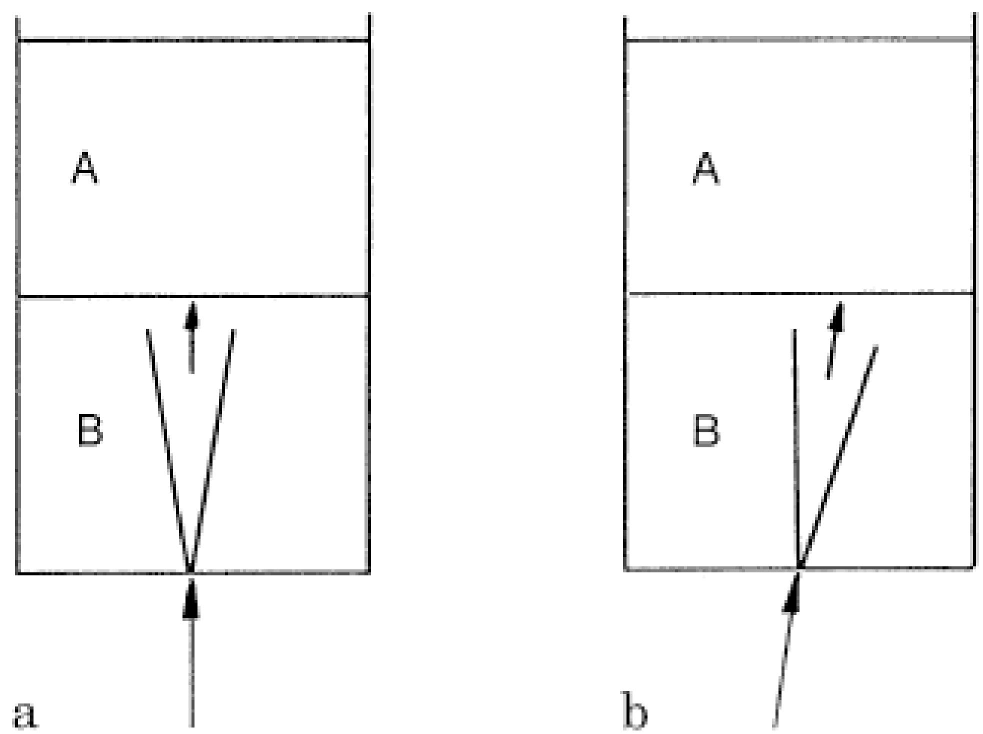



Figure 5. Base pressure coefficient variation with side ratio.

# Which has the greater entrainment rate?

(Redekopp)



# Vertical impinging jet (Cotel)

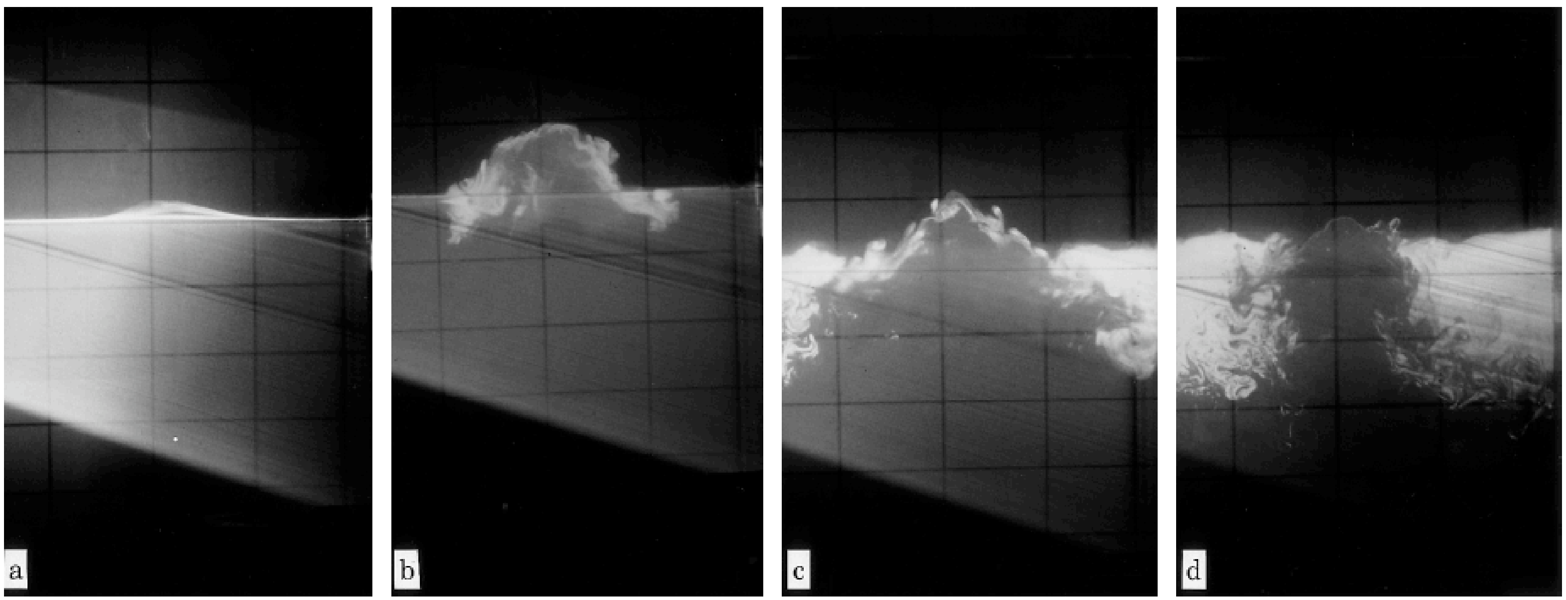



**Fig. 2a–d.** Time sequence photographs of the vertical jet impinging on the interface with $Ri = 5.3$ and $Re = 6900$ initially. **a** $t = 2$ s; **b** $t = 5$ s; **c** $t = 13$ s; **d** $t = 30$ s

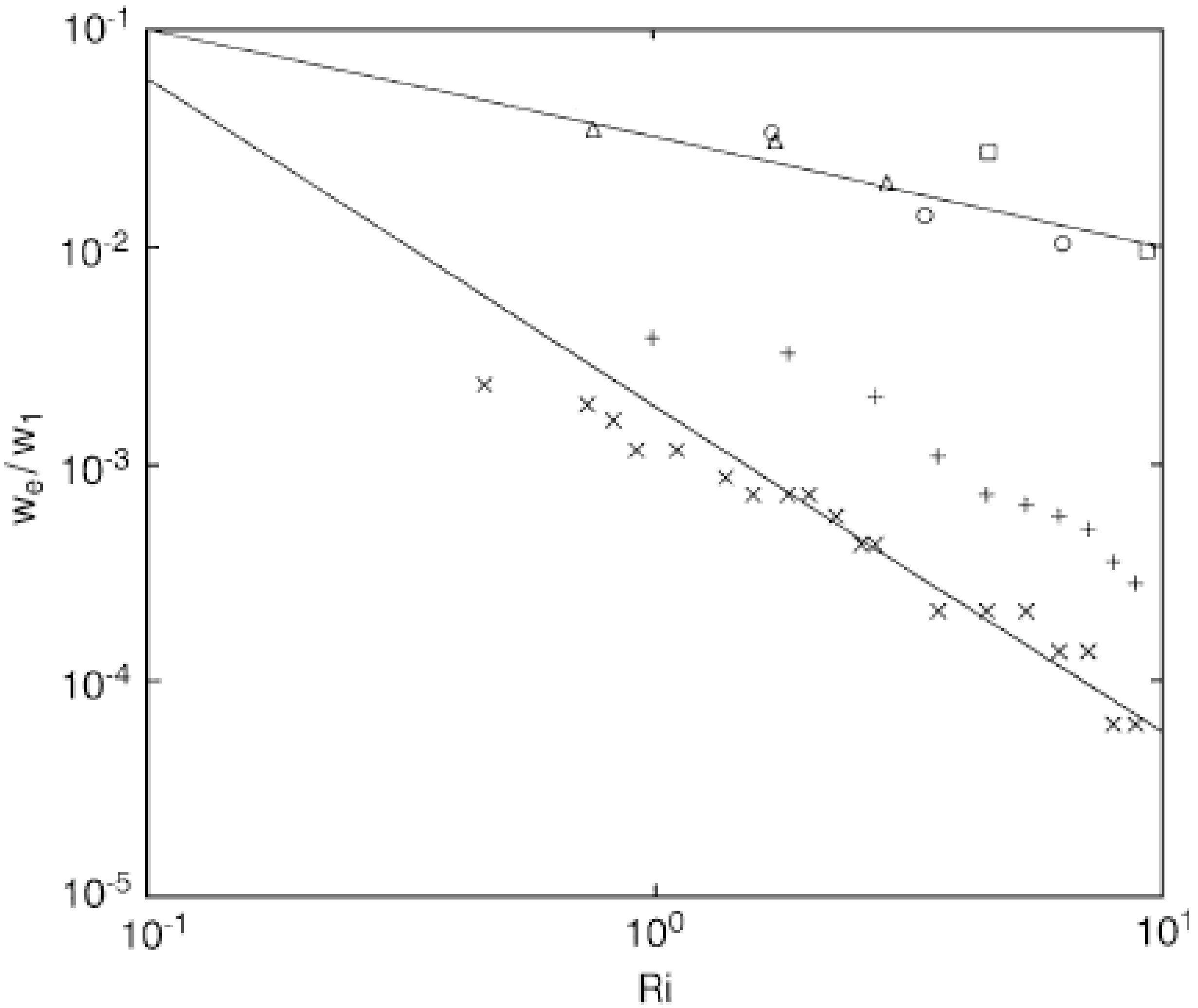
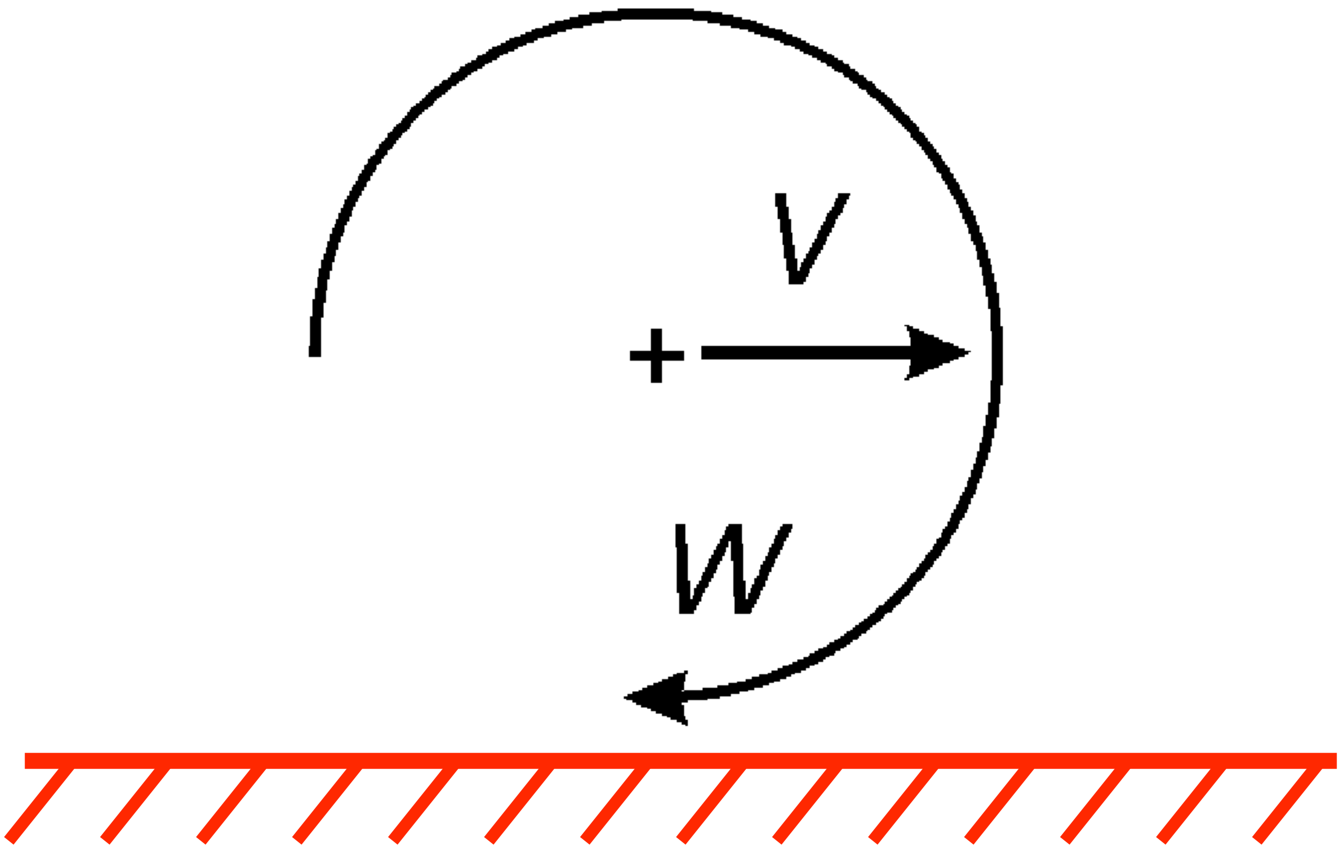


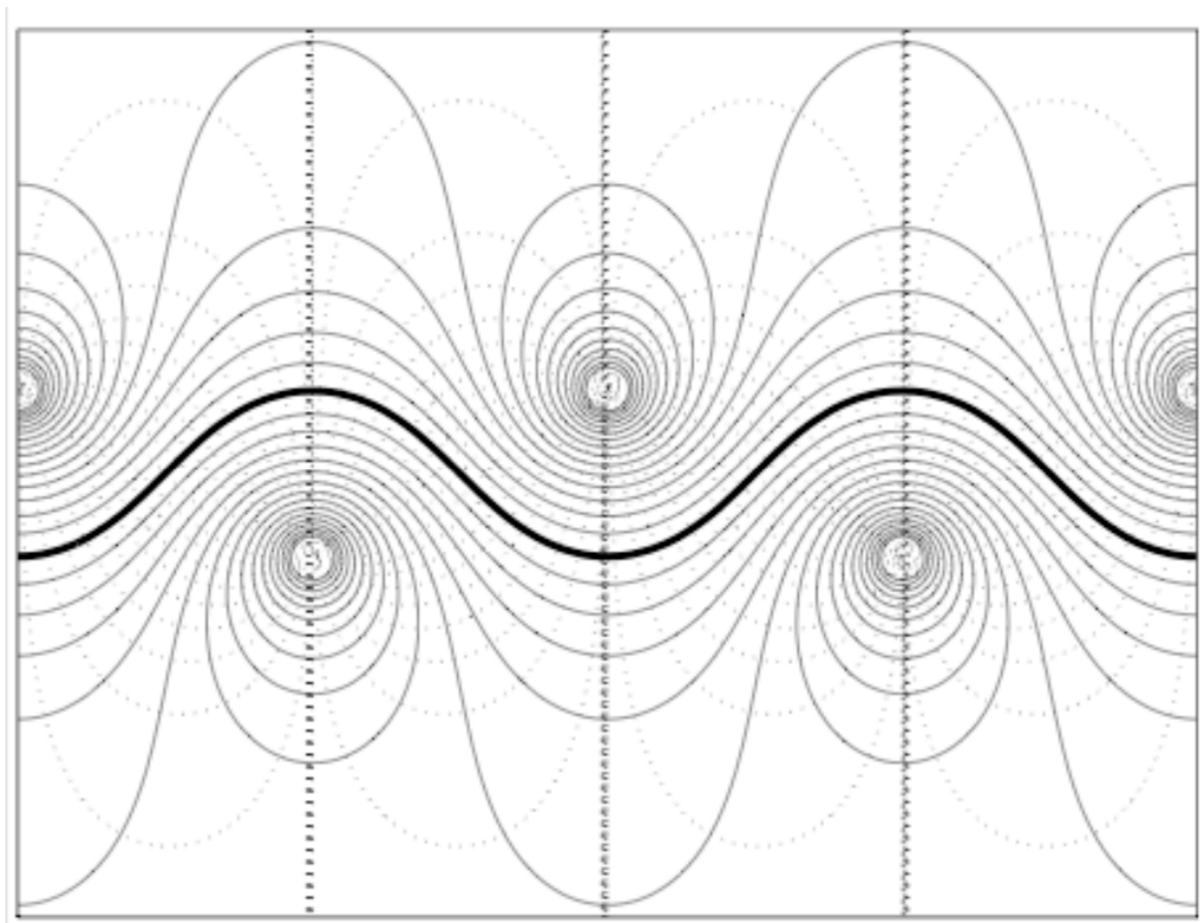

**Fig. 5.** Comparison of the entrainment rates for vertical and tilted jets. The slopes of the upper and lower lines are $-1/2$ and $-3/2$, respectively. The symbols for the vertical jet are as in Fig. 4. $\times$ Precessing, tilted jet; $+$ non-precessing, tilted jet

Cotel et al.

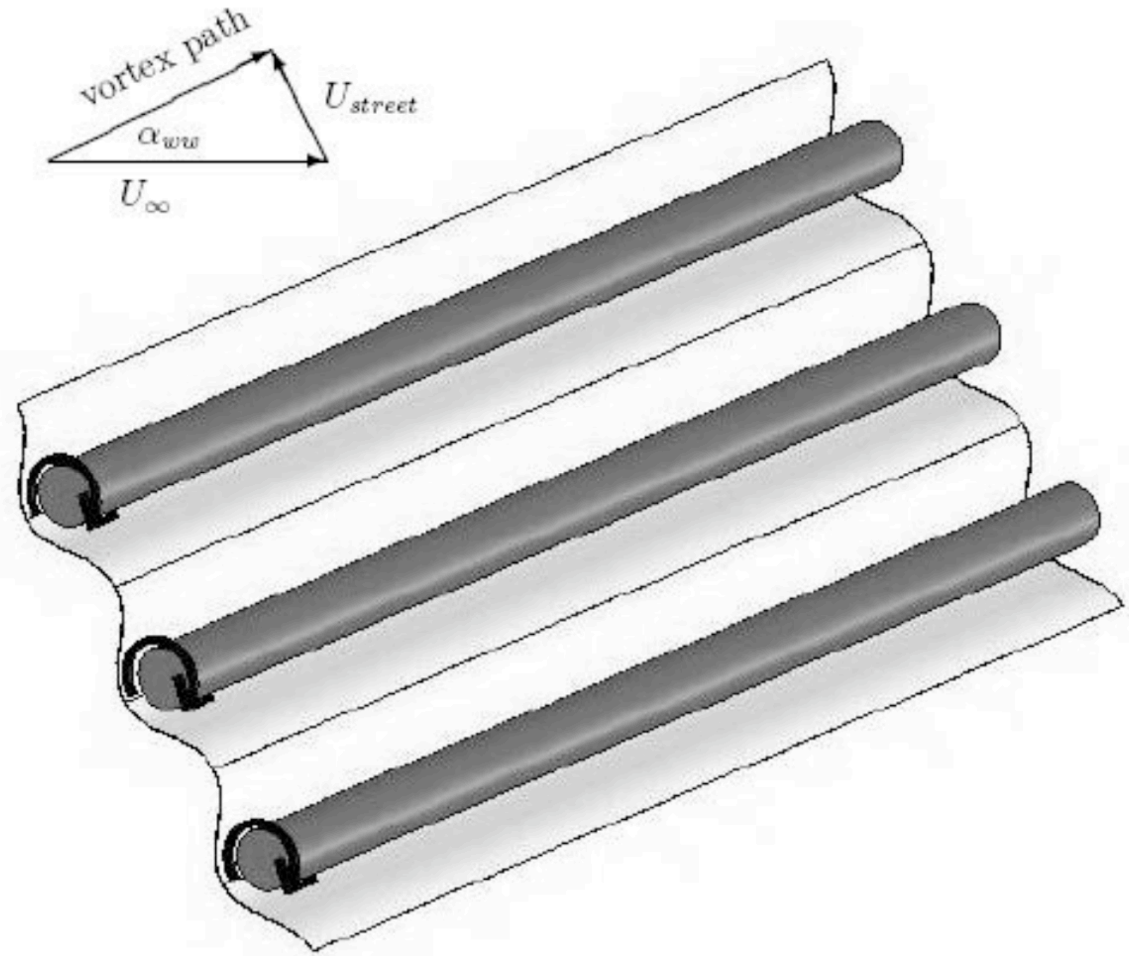
# What kind of surface?



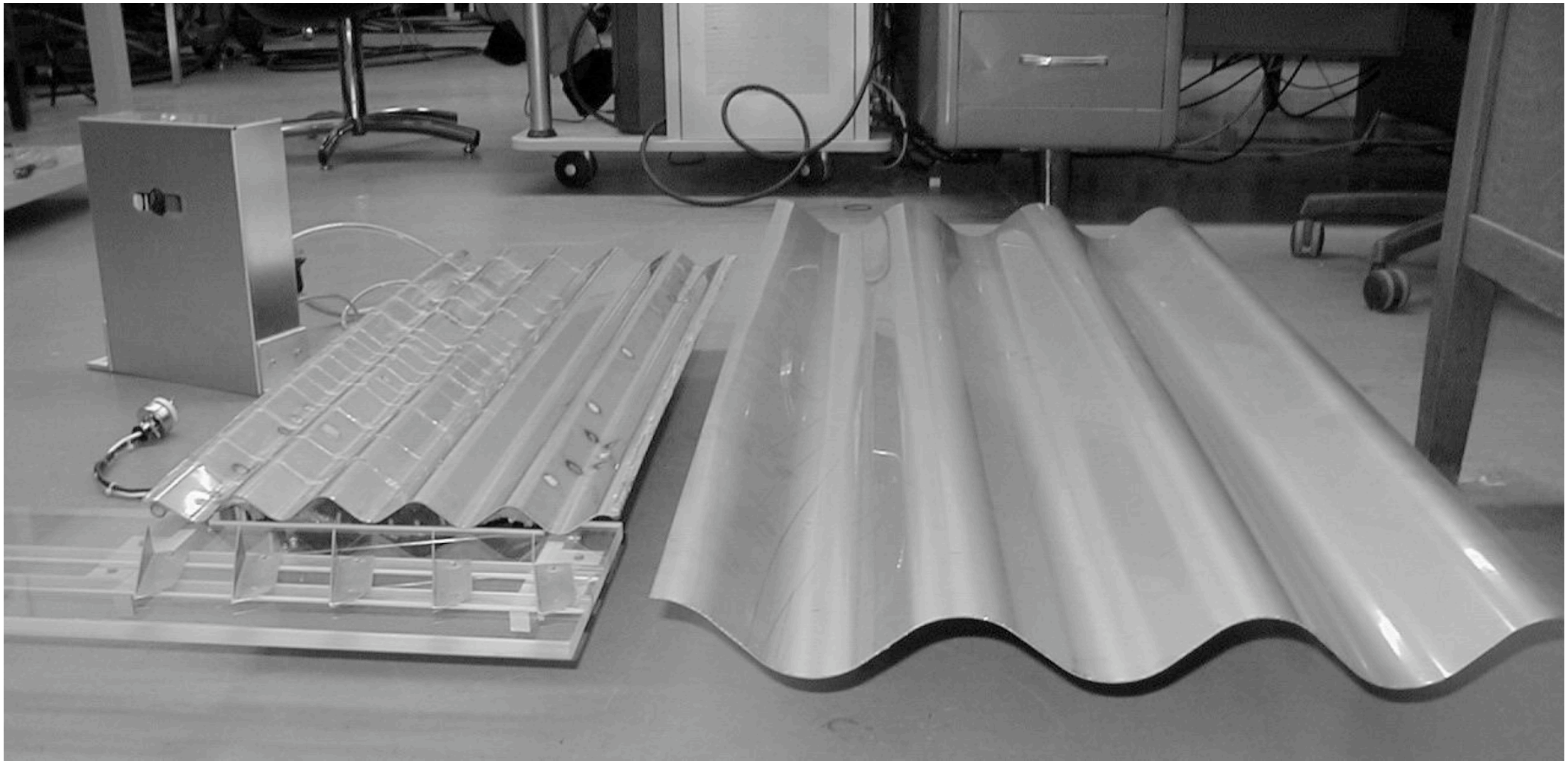
# von Karman wake (Balle)



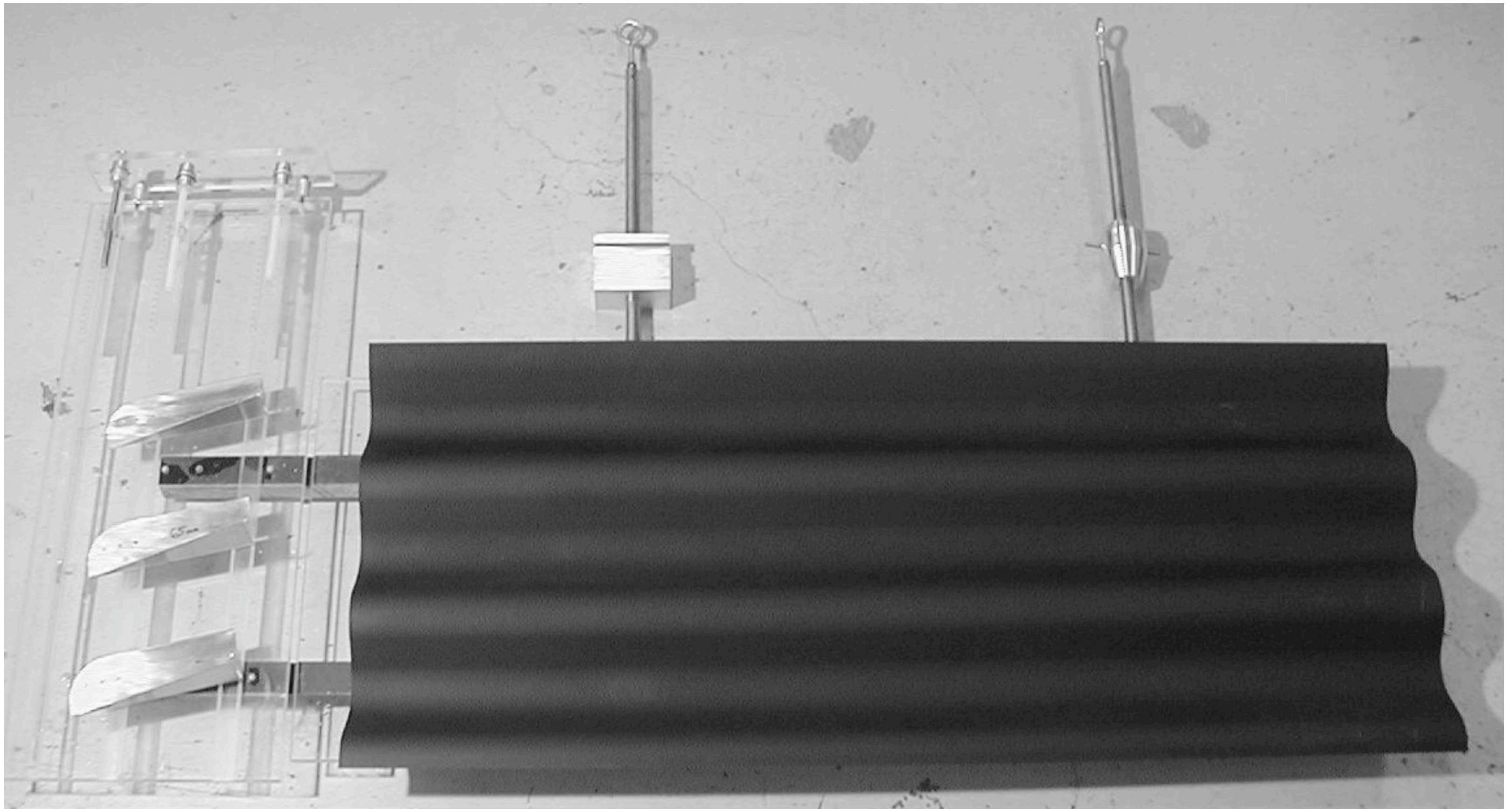
# (Nearly) streamwise vortices



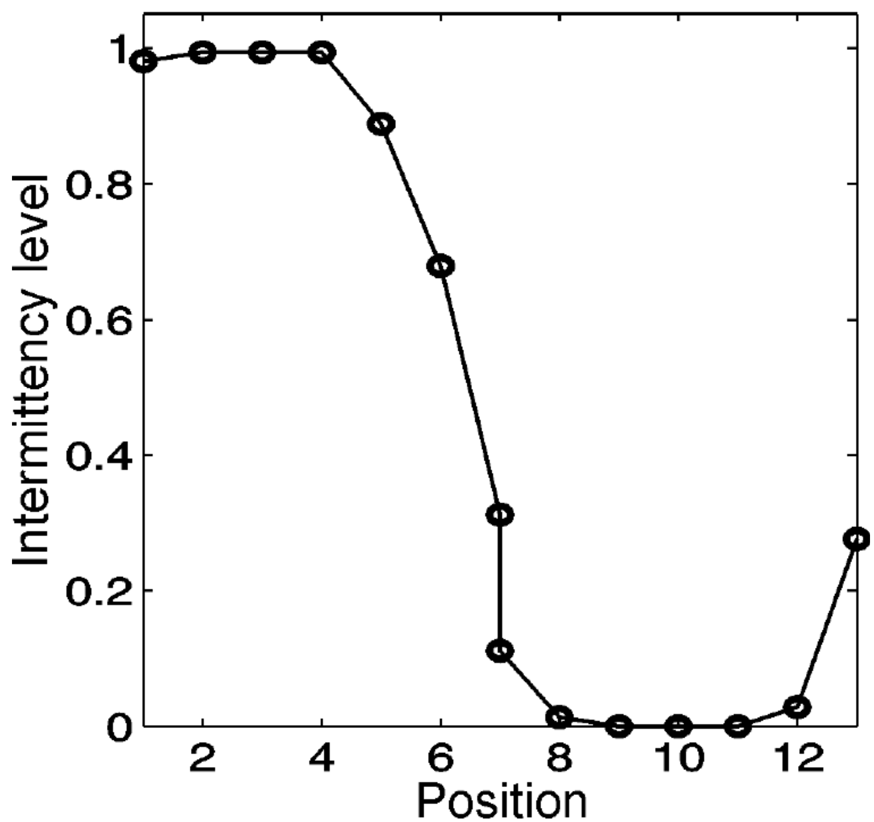
# wavy walls (Dawson)



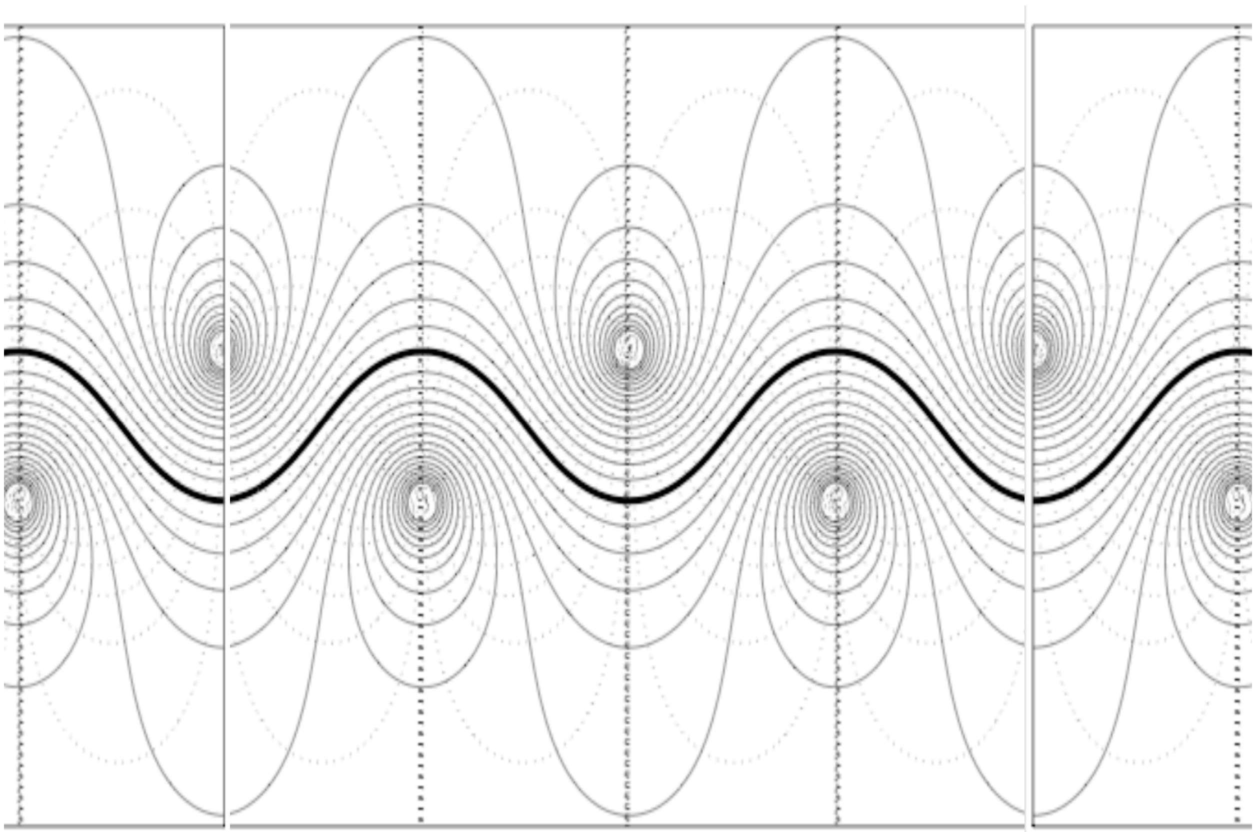
# upstream VG's



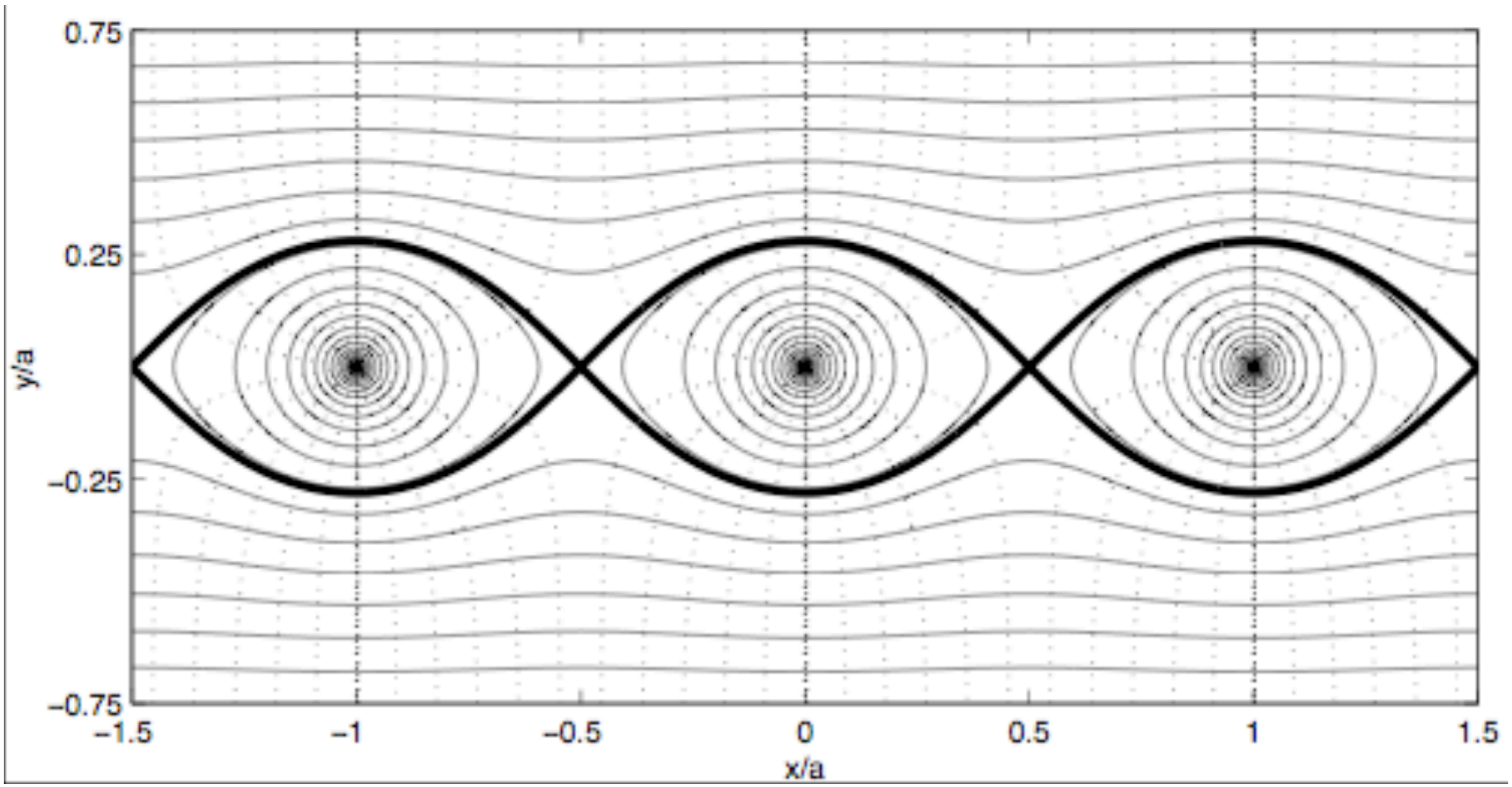
# Turbulent intermittency over one wavelength (Bauer)



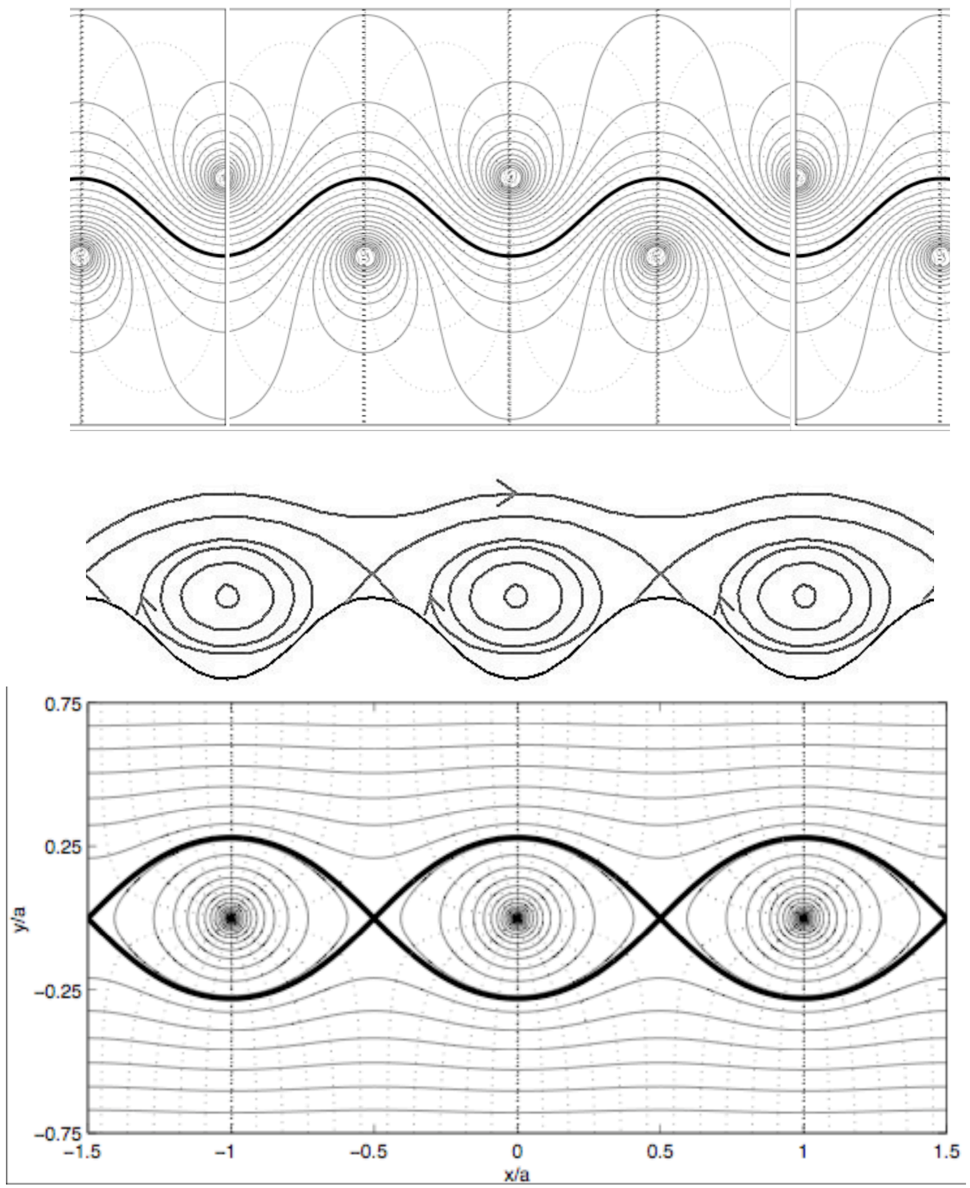
# von Karman wake



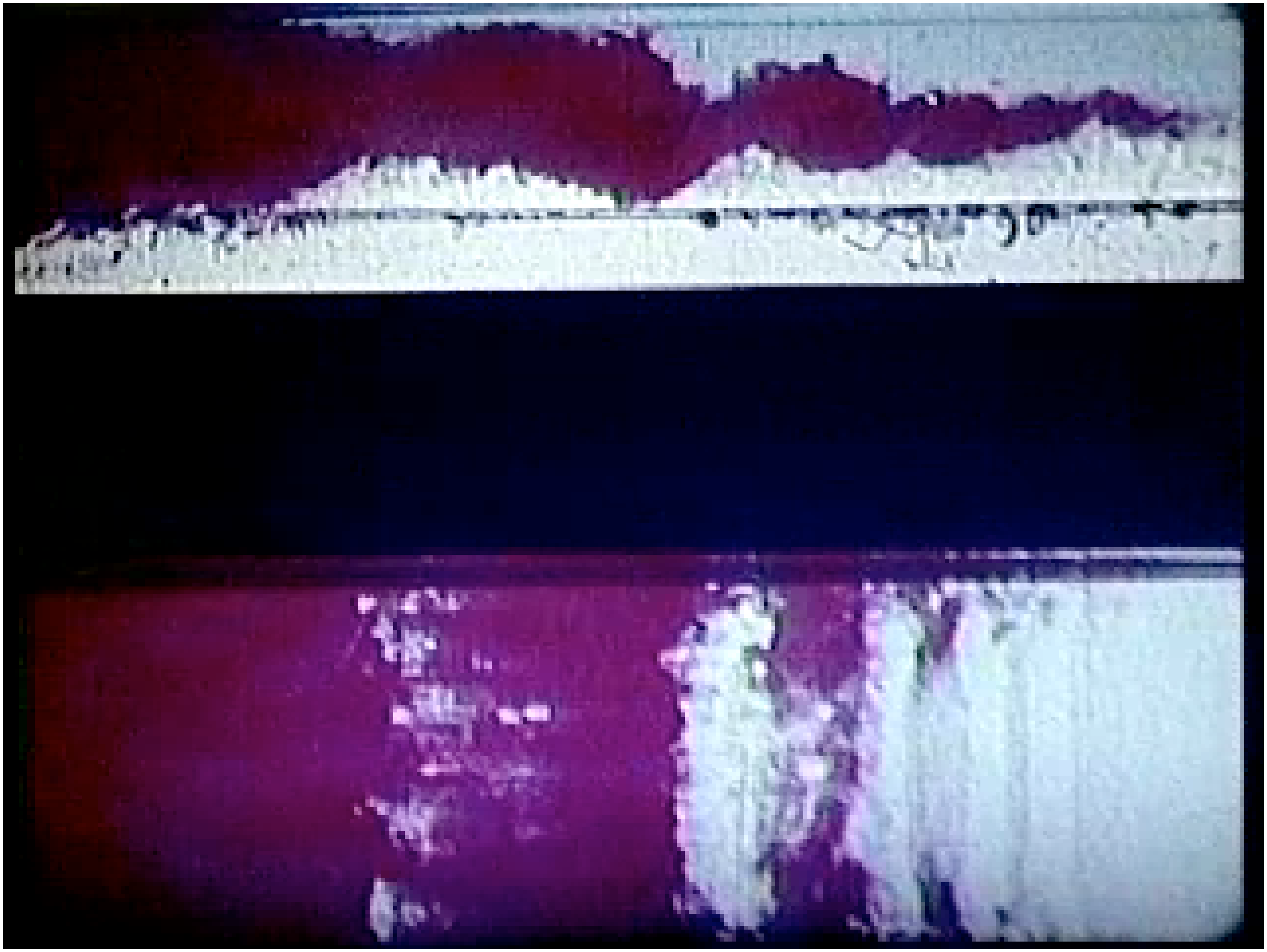
# Kelvin's cat's eyes

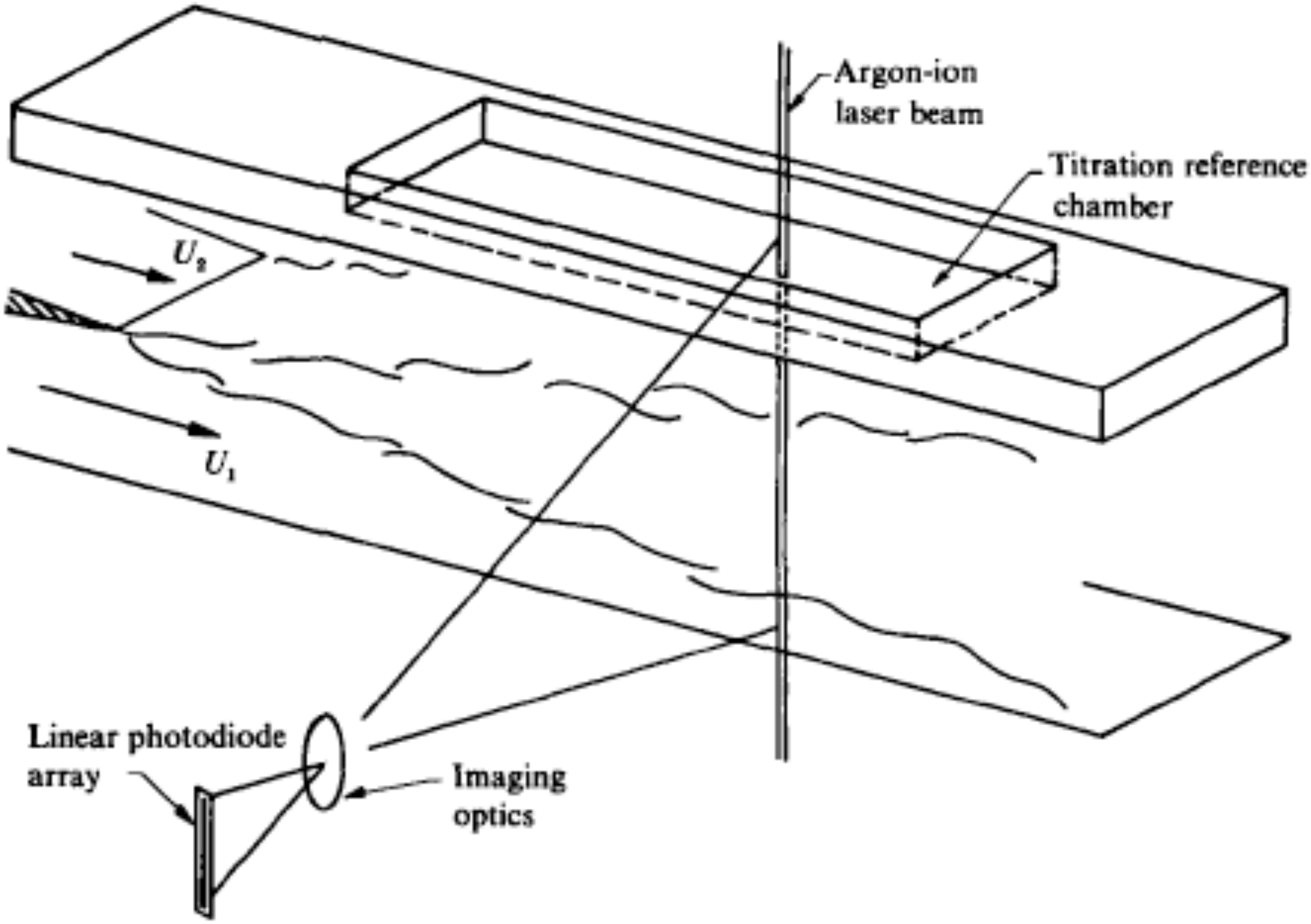



Miles


0.75
0.25
−0.25
−0.75
y/a
−1.5
−1
−0.5
0
0.5
1
1.5
x/a

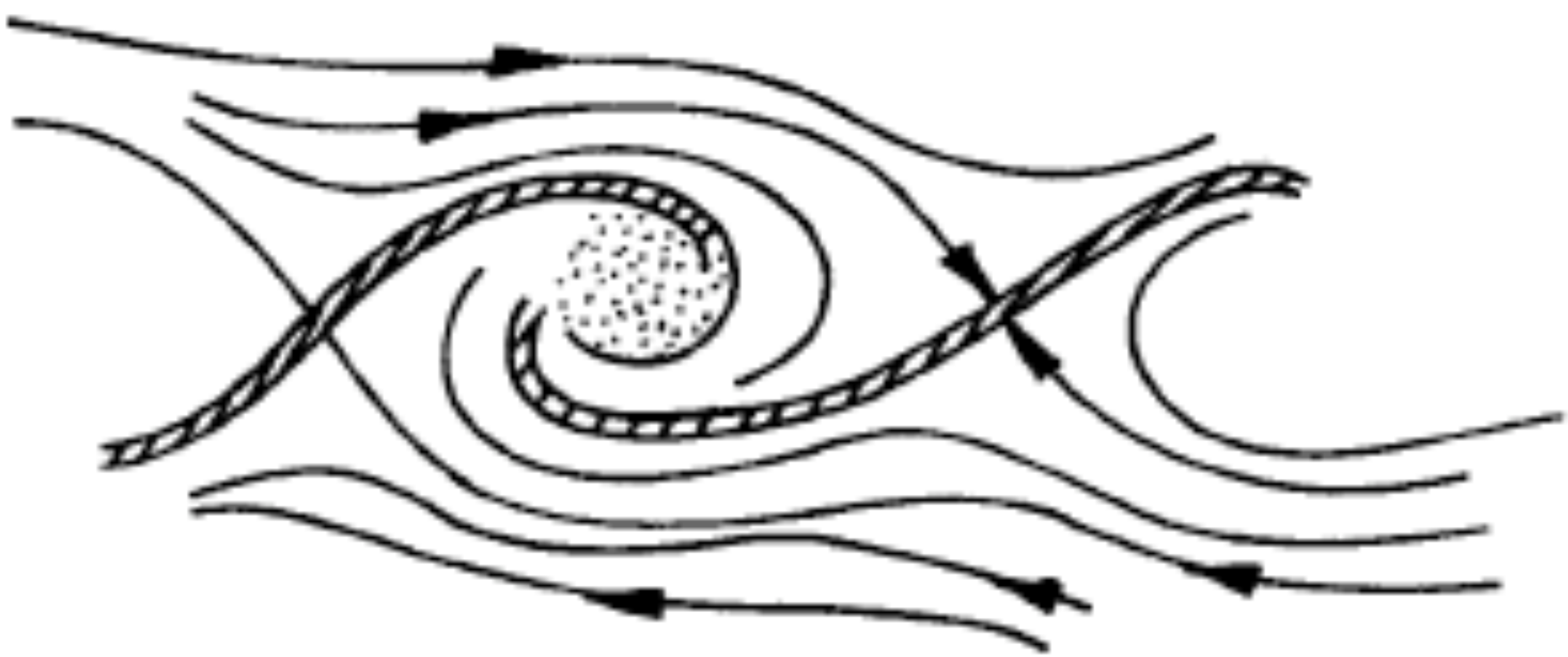
Brown & Roshko 1969





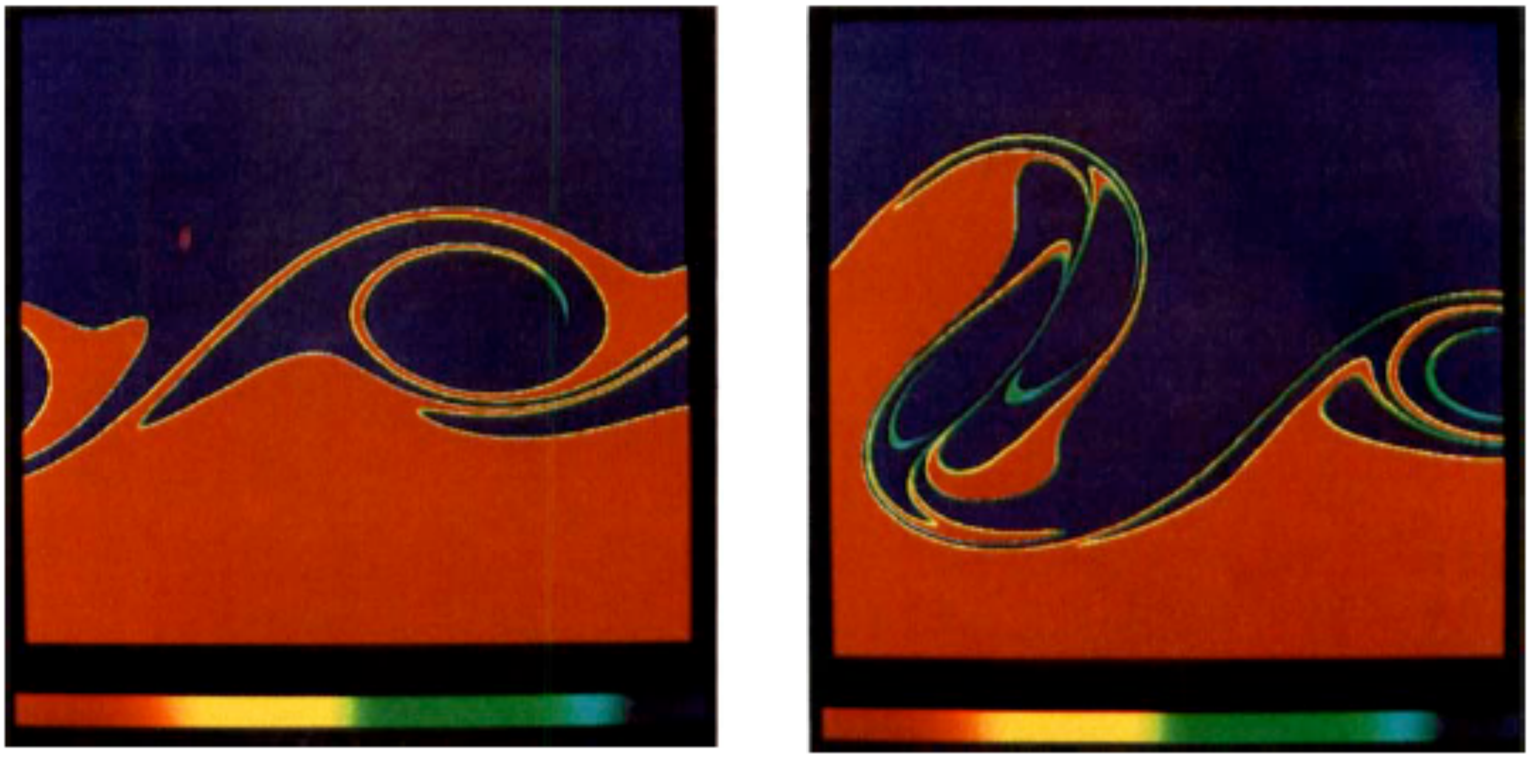

Koochesfahani & Dimotakis 1986

# Mixing model



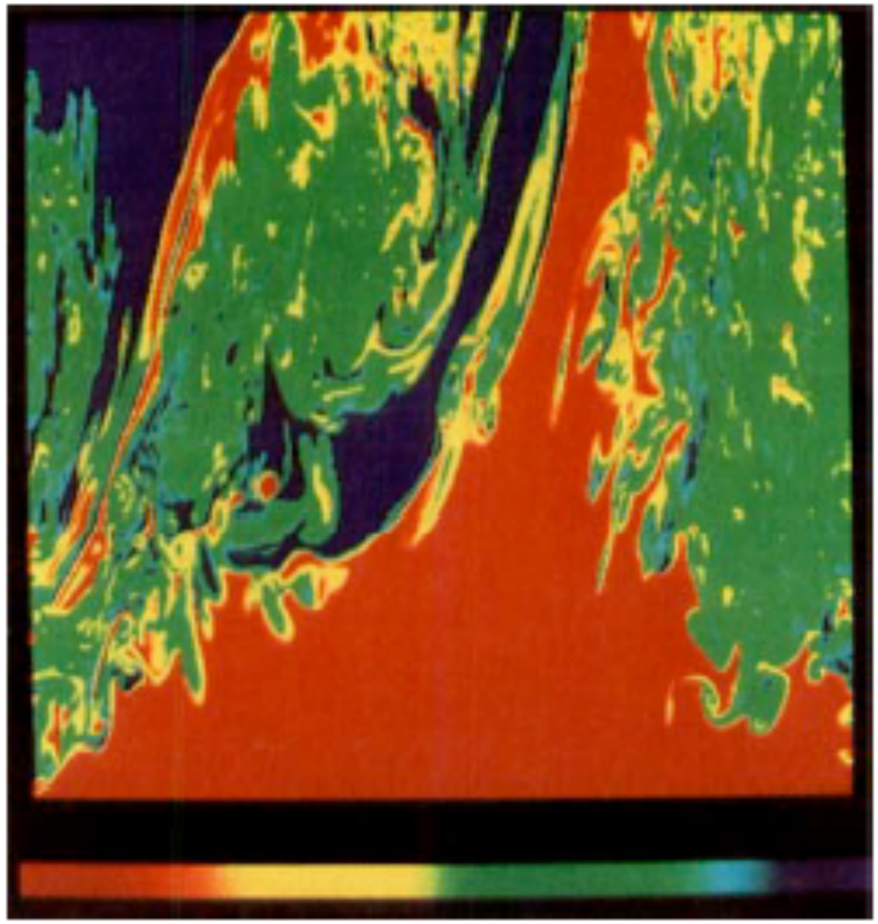
with Broadwell 1982

# Below the mixing transition



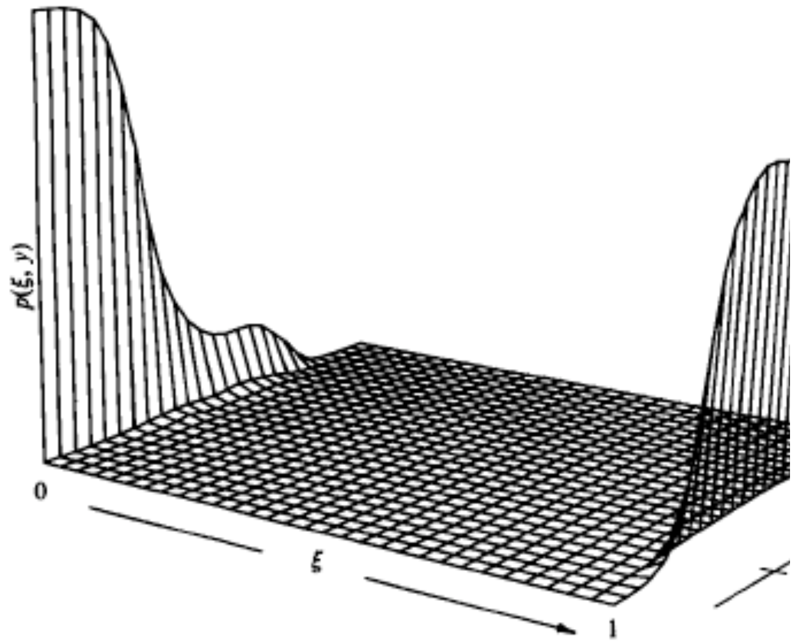
Koochesfahani & Dimotakis 1986

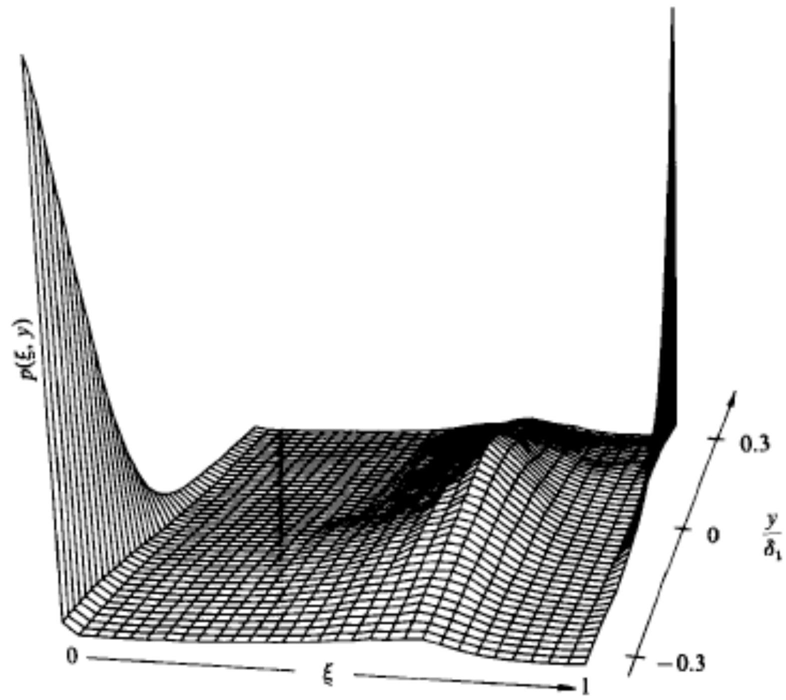
# Above the mixing transition



Koochesfahani & Dimotakis 1986

# Probability density function of scalar concentration




Koochesfahani & Dimotakis 1986

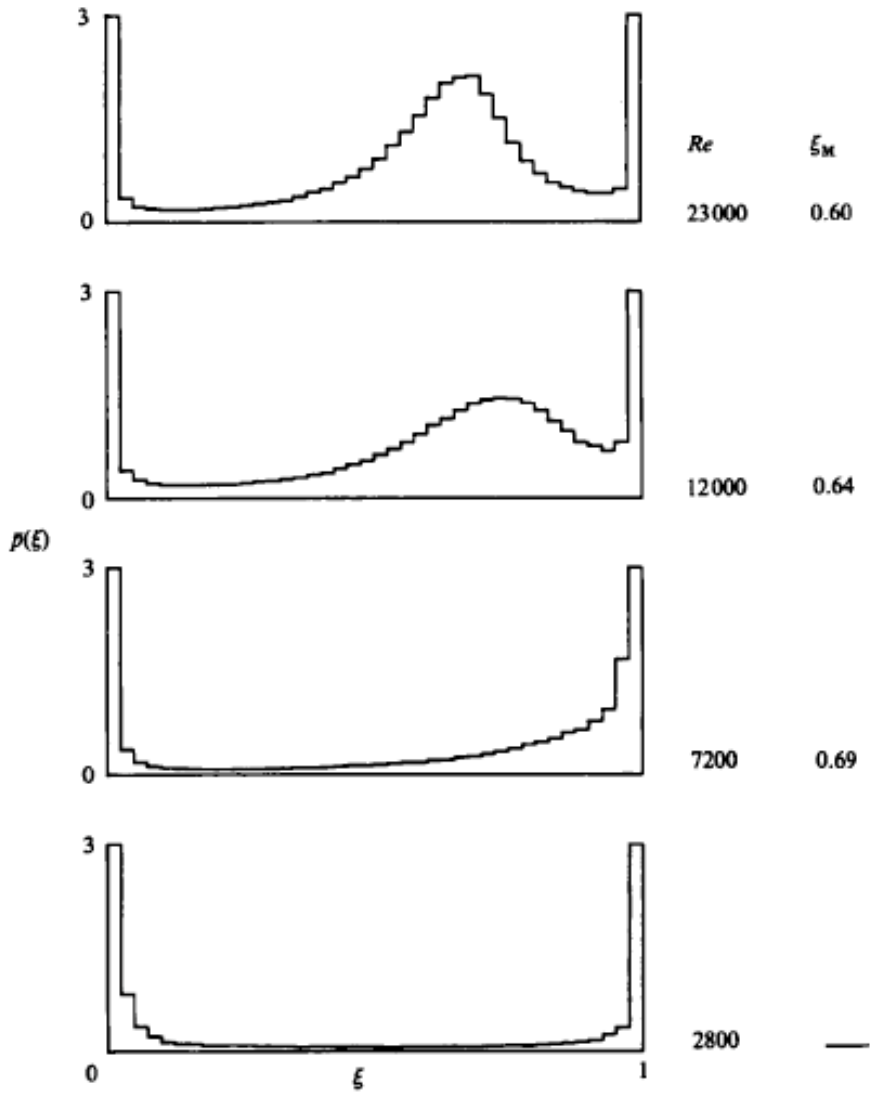
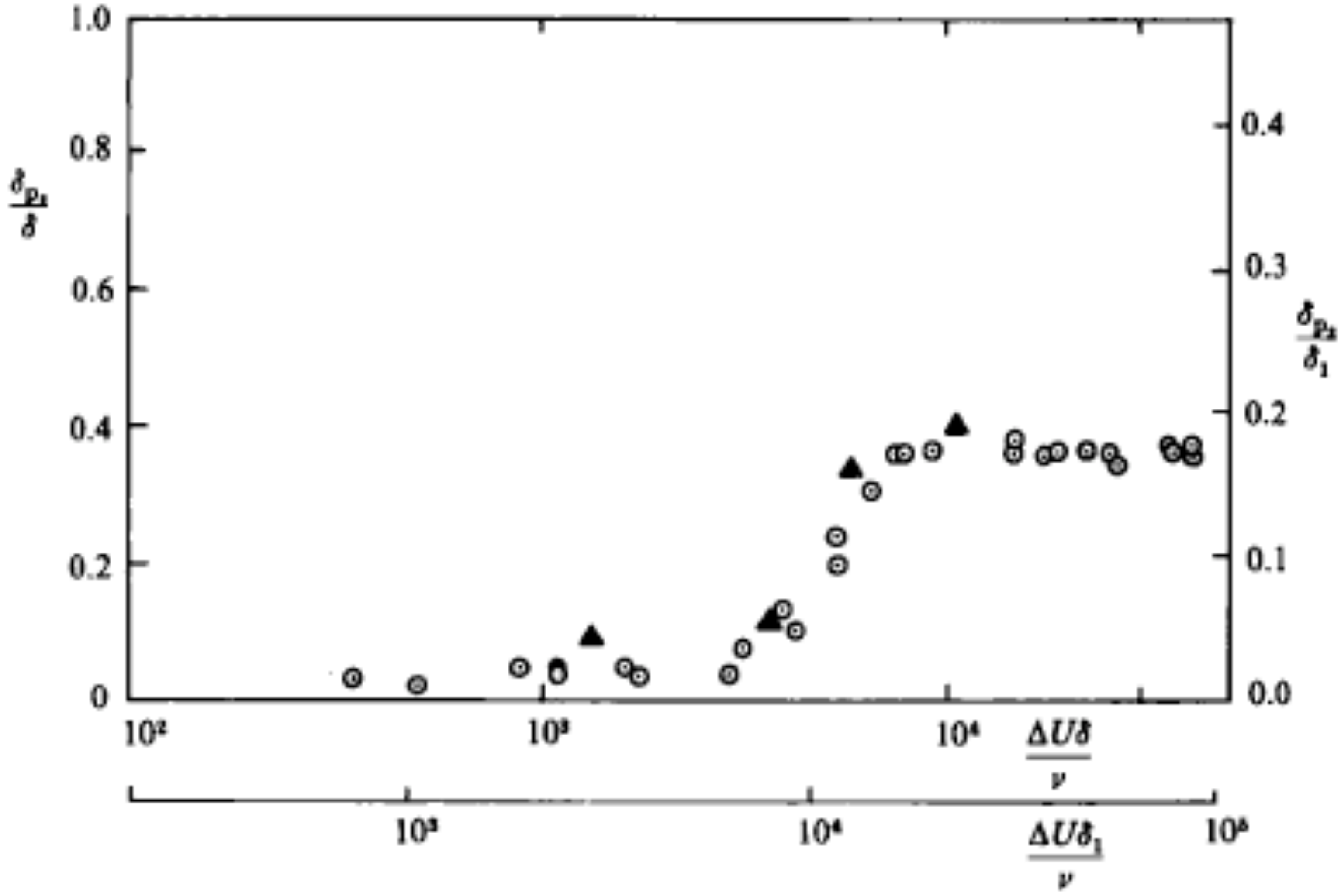



FIGURE 12. Evolution of the p.d.f. during the mixing transition.

Koochesfahani & Dimotakis 1986

# Mixing

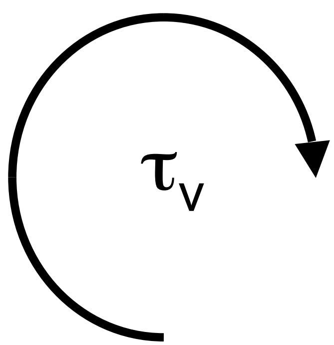


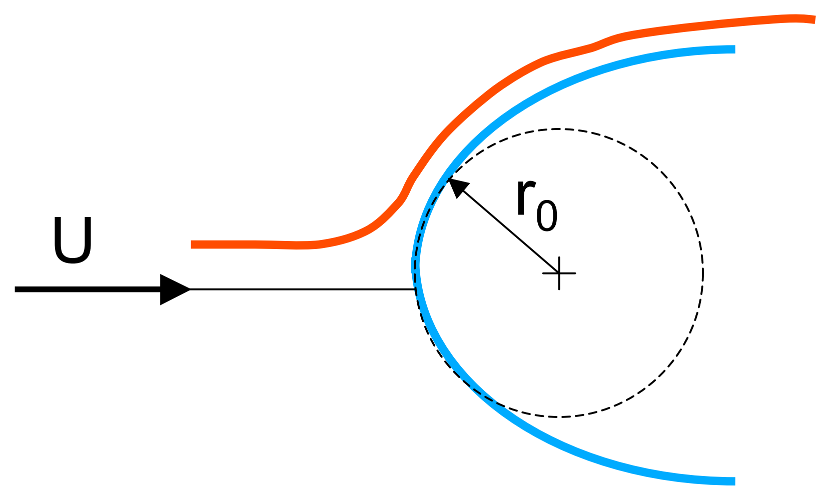
1.0
0.8
0.6
0.4
0.2
0
$\frac{\delta_{p_2}}{\delta}$
0.4
0.3
0.2
0.1
0.0
$\frac{\delta_{p_2}}{\delta_1}$
$10^2$
$10^3$
$10^4$
$\frac{\Delta U \delta}{\nu}$
$10^3$
$10^4$
$10^5$
$\frac{\Delta U \delta_1}{\nu}$

# Two-phase flow

St = particle time / flow acceleration time

$= \tau_p / \tau_a$




$\tau_a = \tau_v$

$\tau_a = r_0/U$

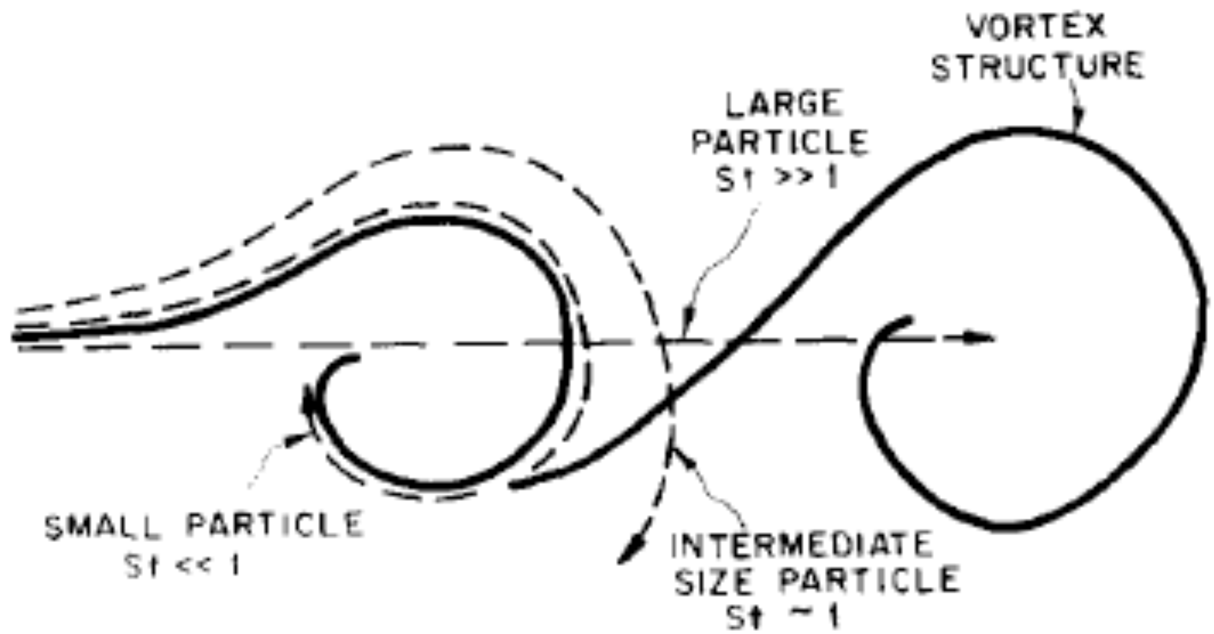



FIG. 2. Pictorial representation of the effect of Stokes number on particle dispersion in large-scale turbulent structures.

Crow, Chung, & Troutt 1988

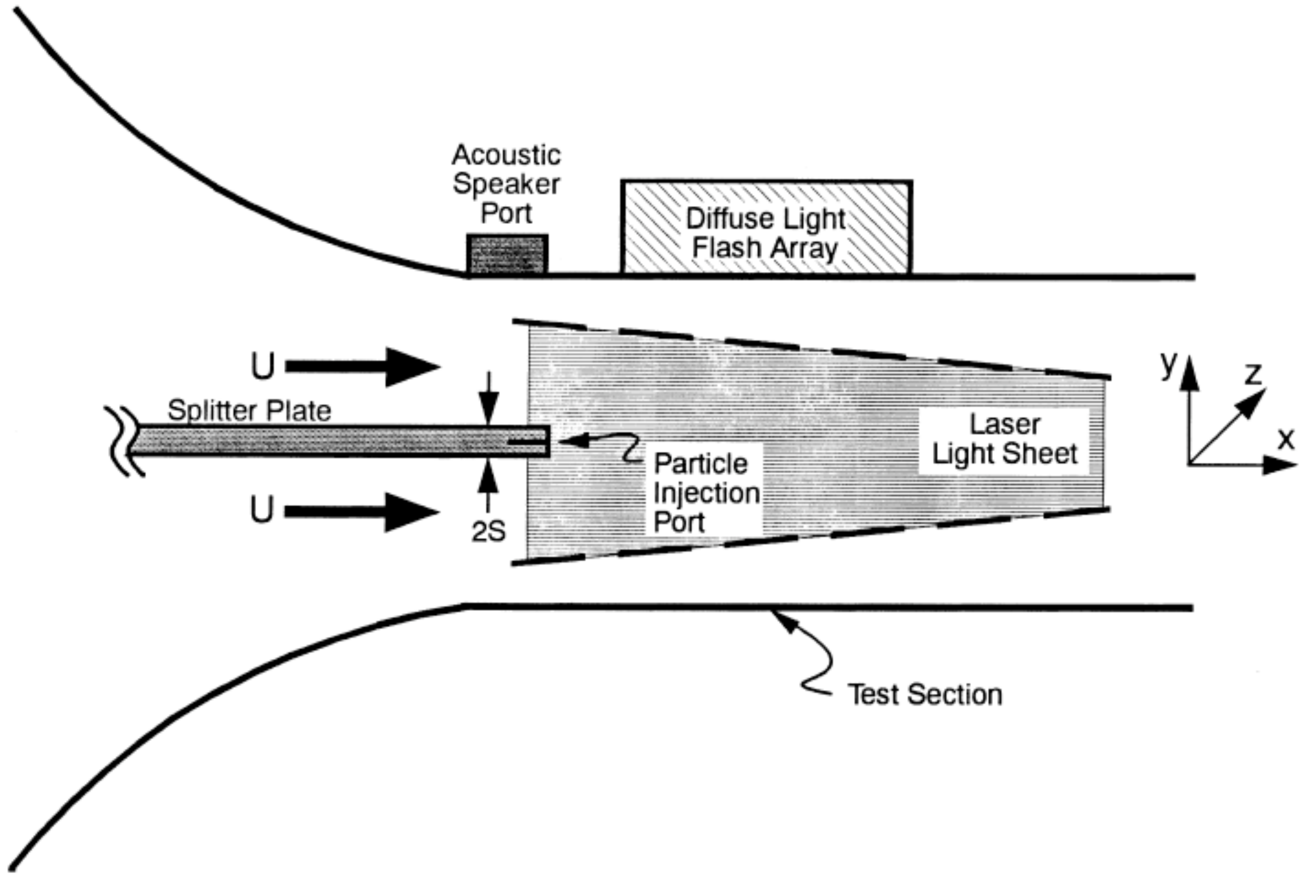
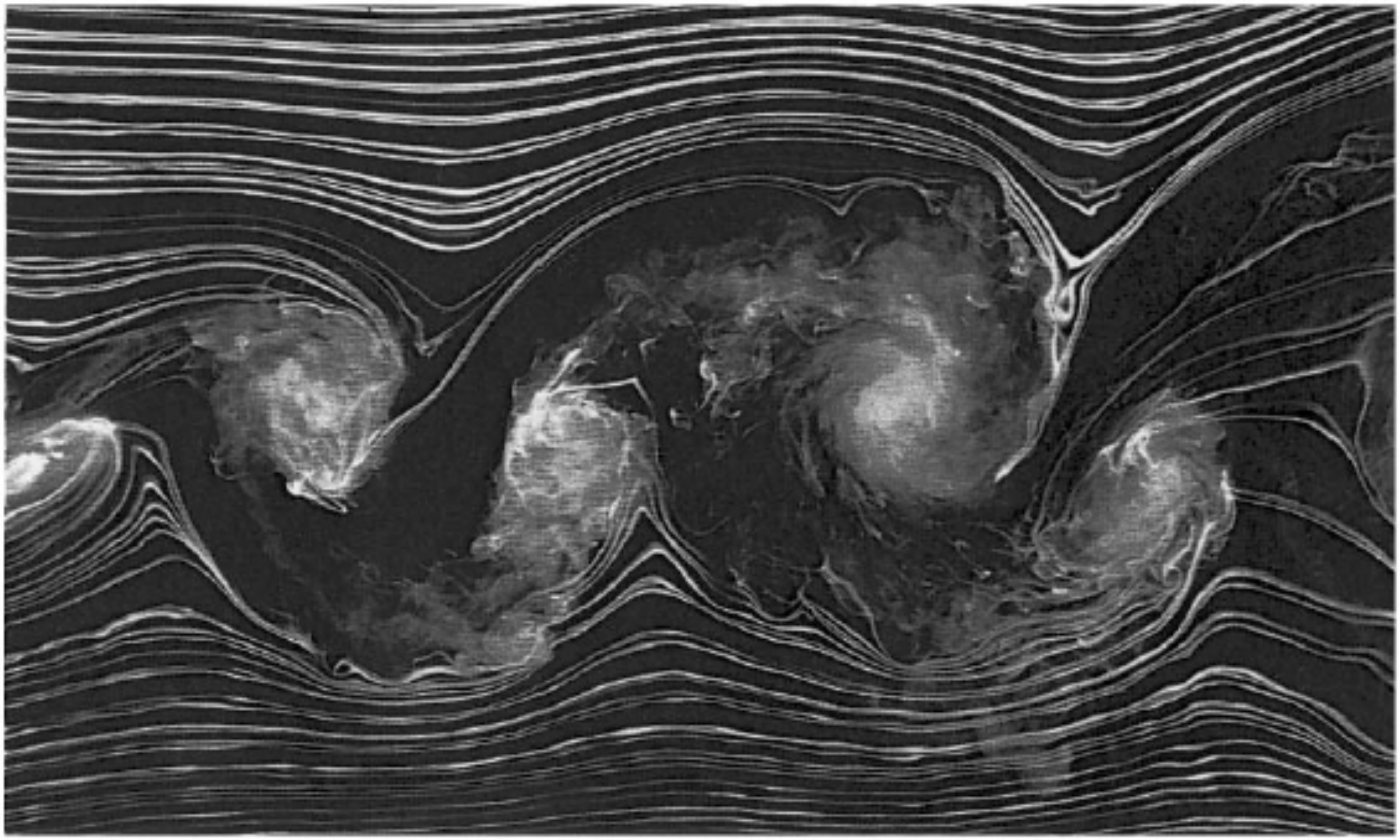


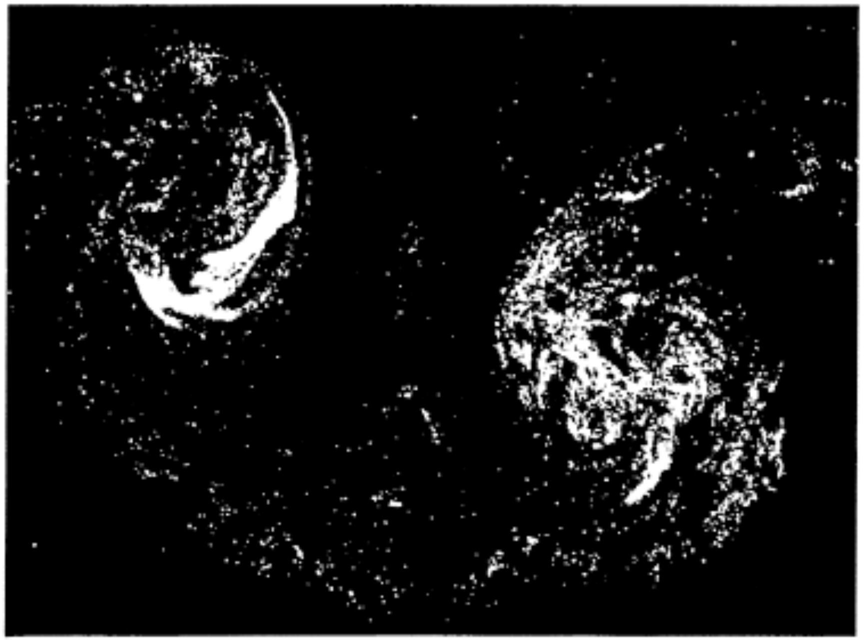

Fig. 1. Schematic of test facility.

Yang, Crow, Chung, & Troutt 2000

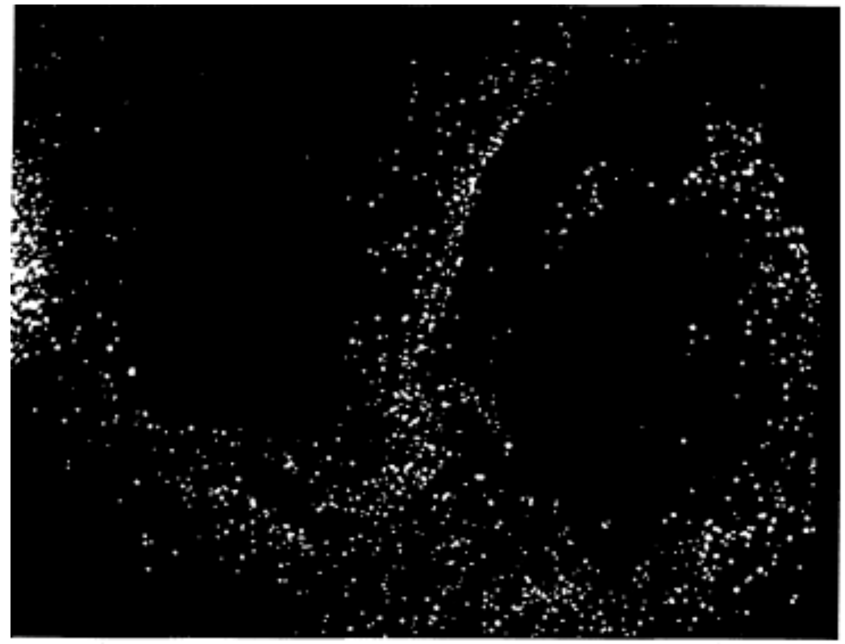


Yang, Crow, Chung, & Troutt 2000

# De-mixing



St = 0.15

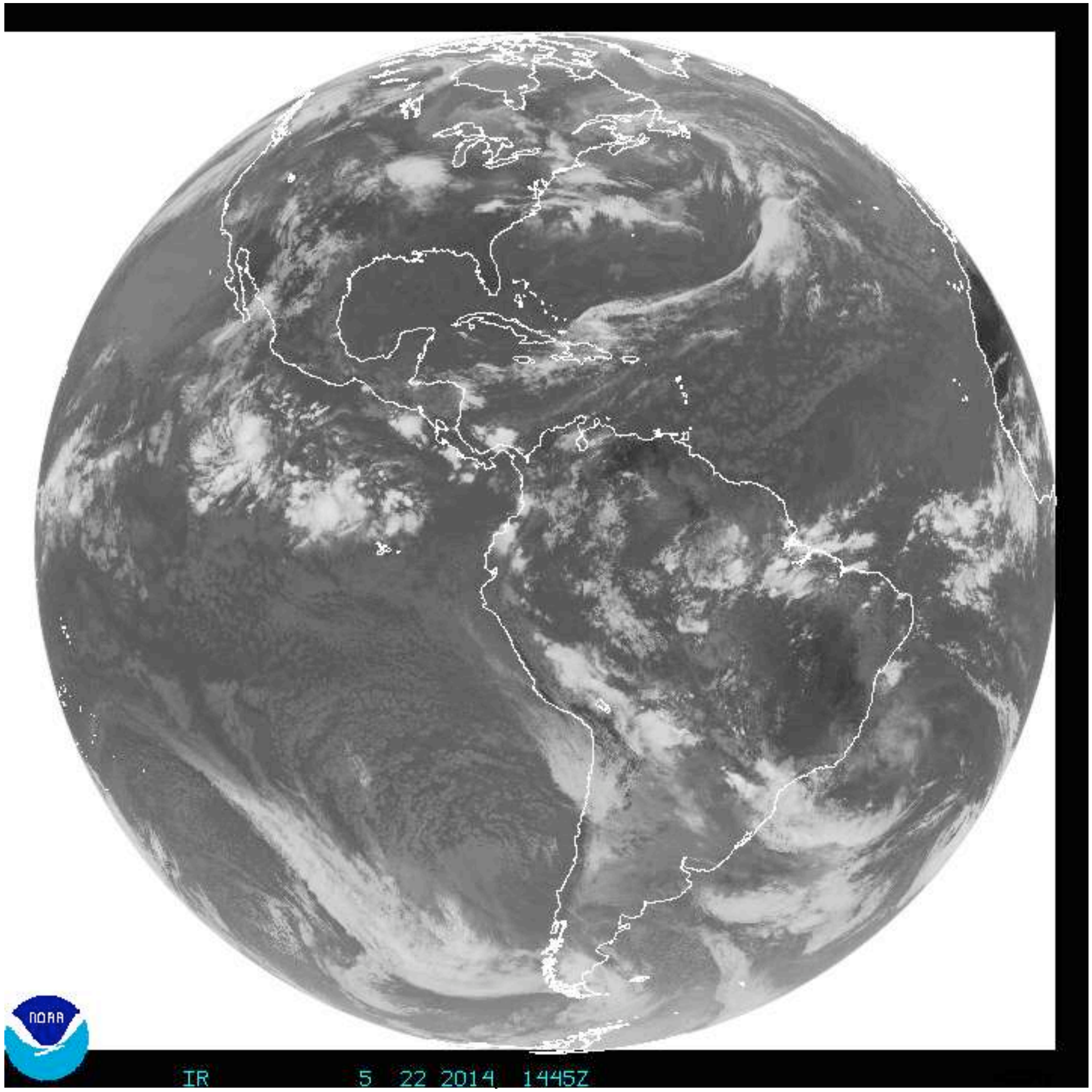


St = 1.4

Yang, Crow, Chung, & Troutt 2000

# Conclusions

- Turbulence: beautiful, everywhere, and hard
- Turbulence models based on wind tunnels
- Continuing need for wind tunnel experiments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