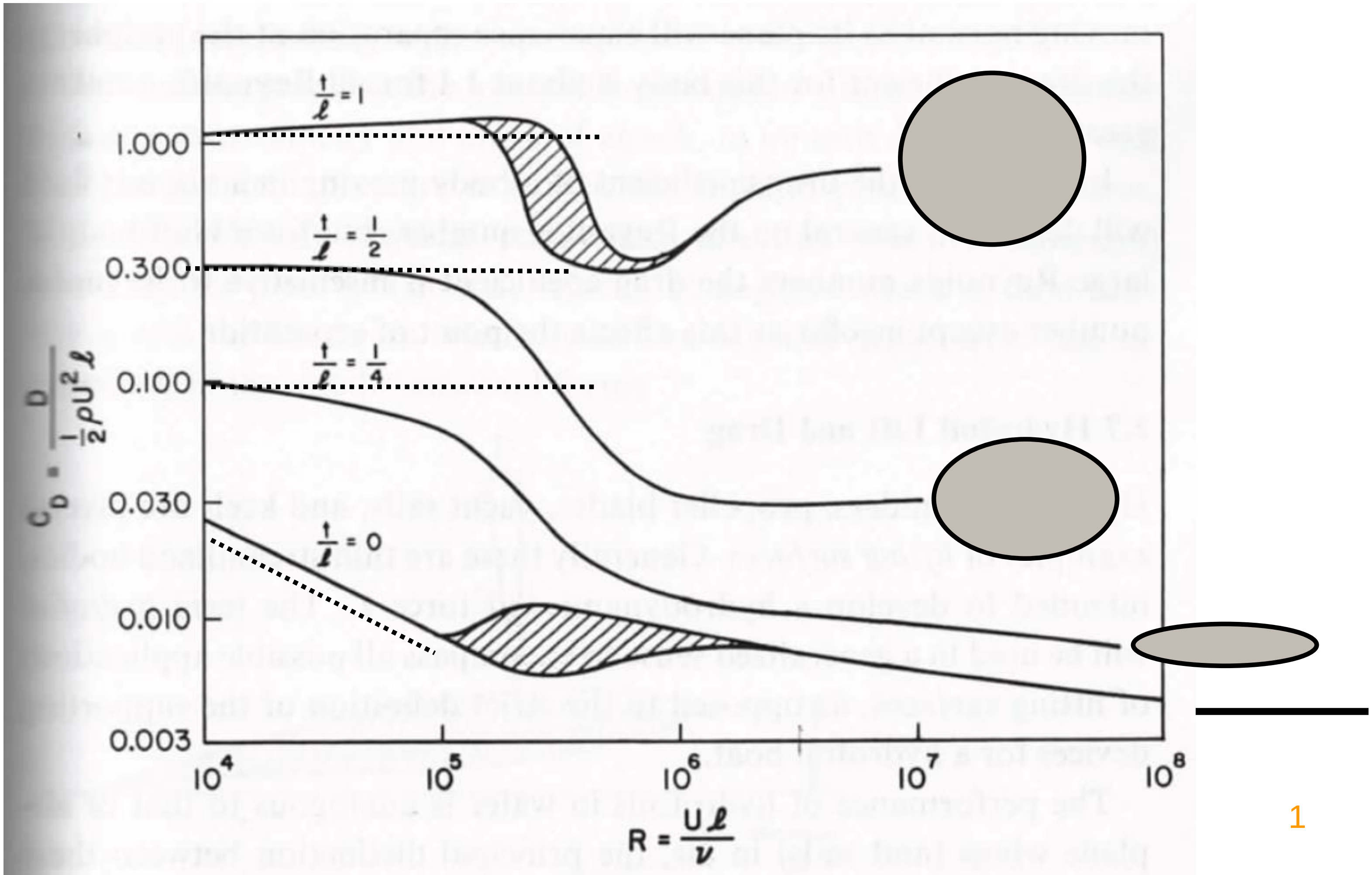
But this does still not explain the aerodynamic drag scaling:

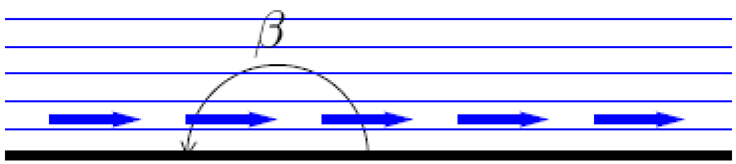
$$\frac{1}{2}\rho_\infty U_\infty{}^2 S$$



Pressure gradient effect

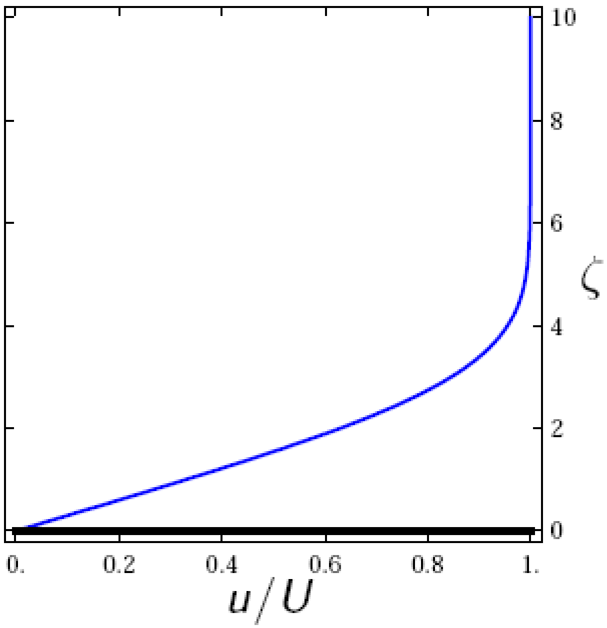
Consider the flow along an angle $\beta = \pi/(m+1) = \pi$ i.e. $m = 0$

This is the flow along a flat plate



Uniform flow- no pressure gradient

$\vec{\nabla} p$ =0

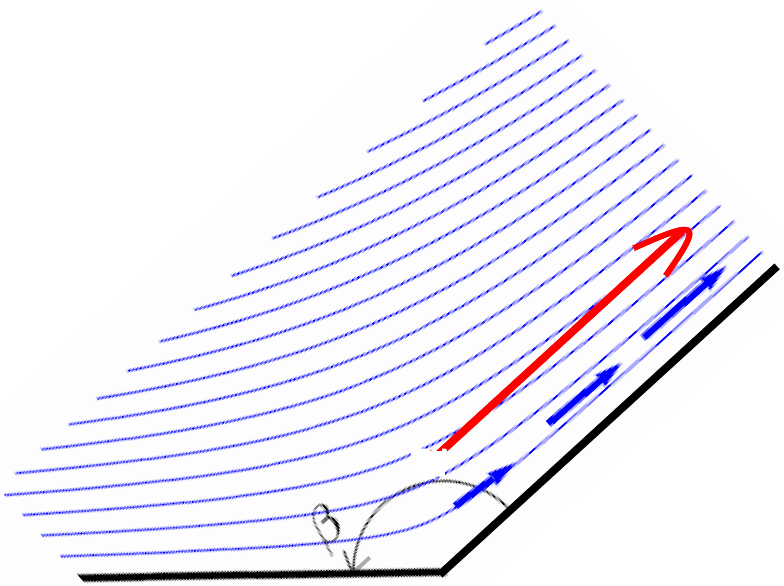


Blasius boundary layer

Pressure gradient effect

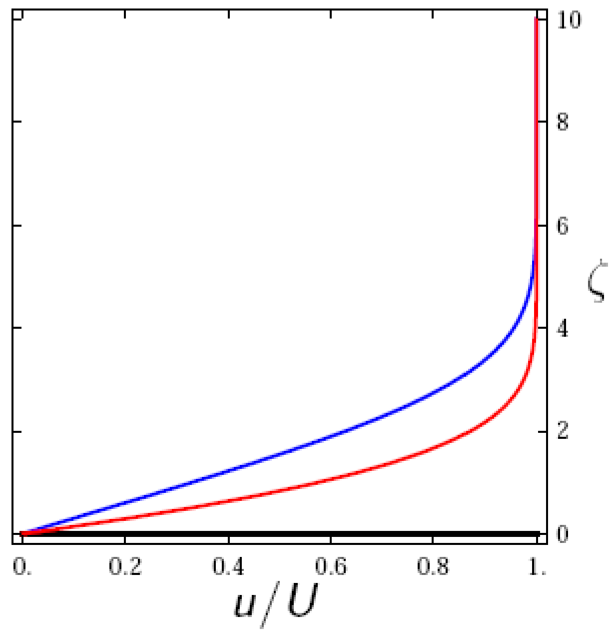
Consider the flow along an angle $\beta = \pi/(m+1) < \pi$ i.e. $m > 0$

This is the flow along a « forward wedge »



Accelerated flow
favorable pressure gradient

$\overline{\nabla} p > 0$

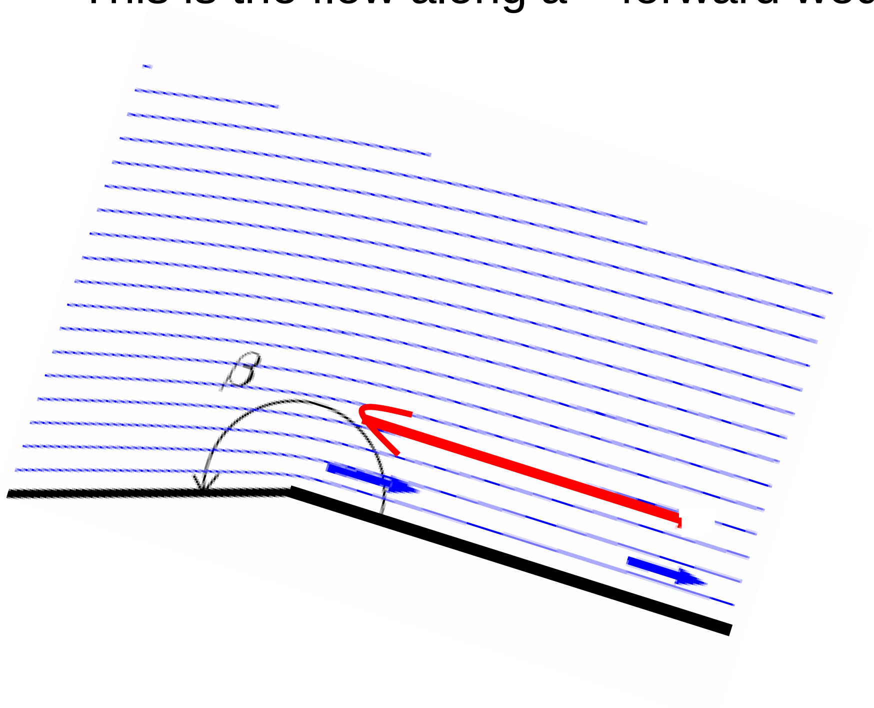


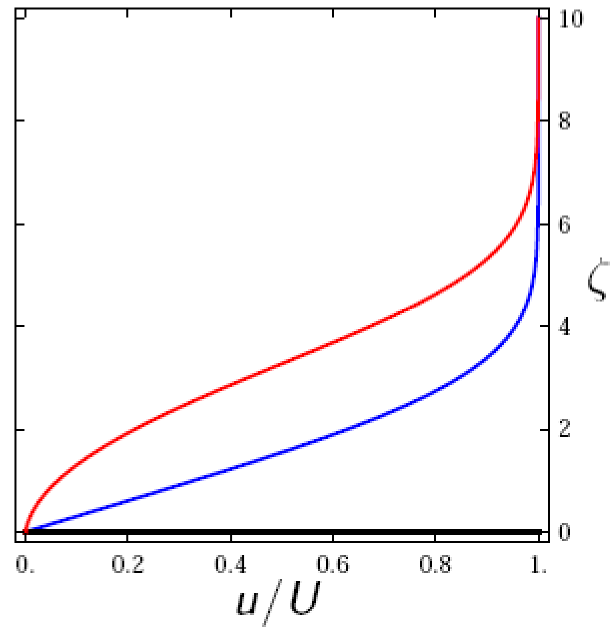
Thinner boundary layer

Pressure gradient effect

Consider the flow along an angle $\beta = \pi/(m+1) > \pi$ i.e. $m < 0$

This is the flow along a « forward wedge »





Decelerated flow
unfavorable (adverse) pressure gradient

$\overline{\nabla} p < 0$

Thicker boundary layer

Pressure gradient effect

Adverse pressure gradient : $\frac{\partial p}{\partial x} > 0$

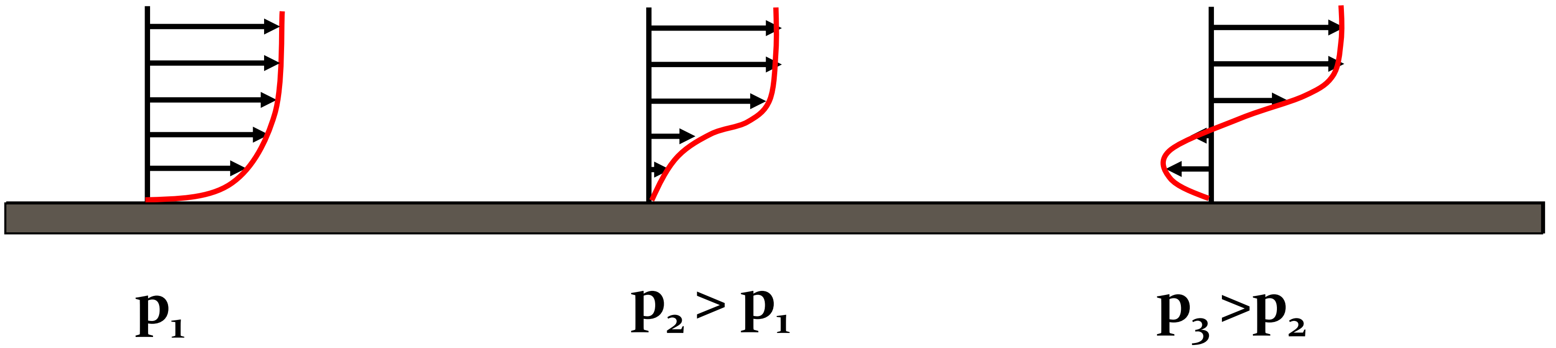
p_1 $p_2 > p_1$ $p_3 > p_2$

$p(x)$ $p(x+dx)$

Resulting pressure force

Pressure gradient effect

Adverse pressure gradient : $\frac{\partial p}{\partial x} > 0$

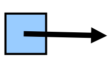


Close to the wall, the viscous effects dominate
The pressure gradient further decreases the velocity
⇨Detachement

Pressure gradient effect

Favorable pressure gradient: $\frac{\partial p}{\partial x} < 0$

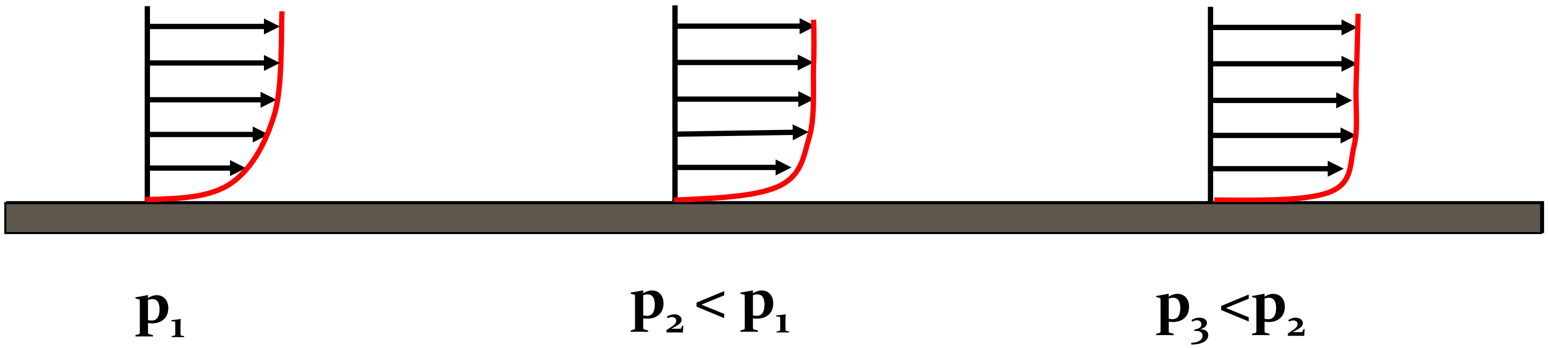
p_1 $p_2 < p_1$ $p_3 < p_2$

$p(x)$  $p(x+dx)$

Resulting pressure force

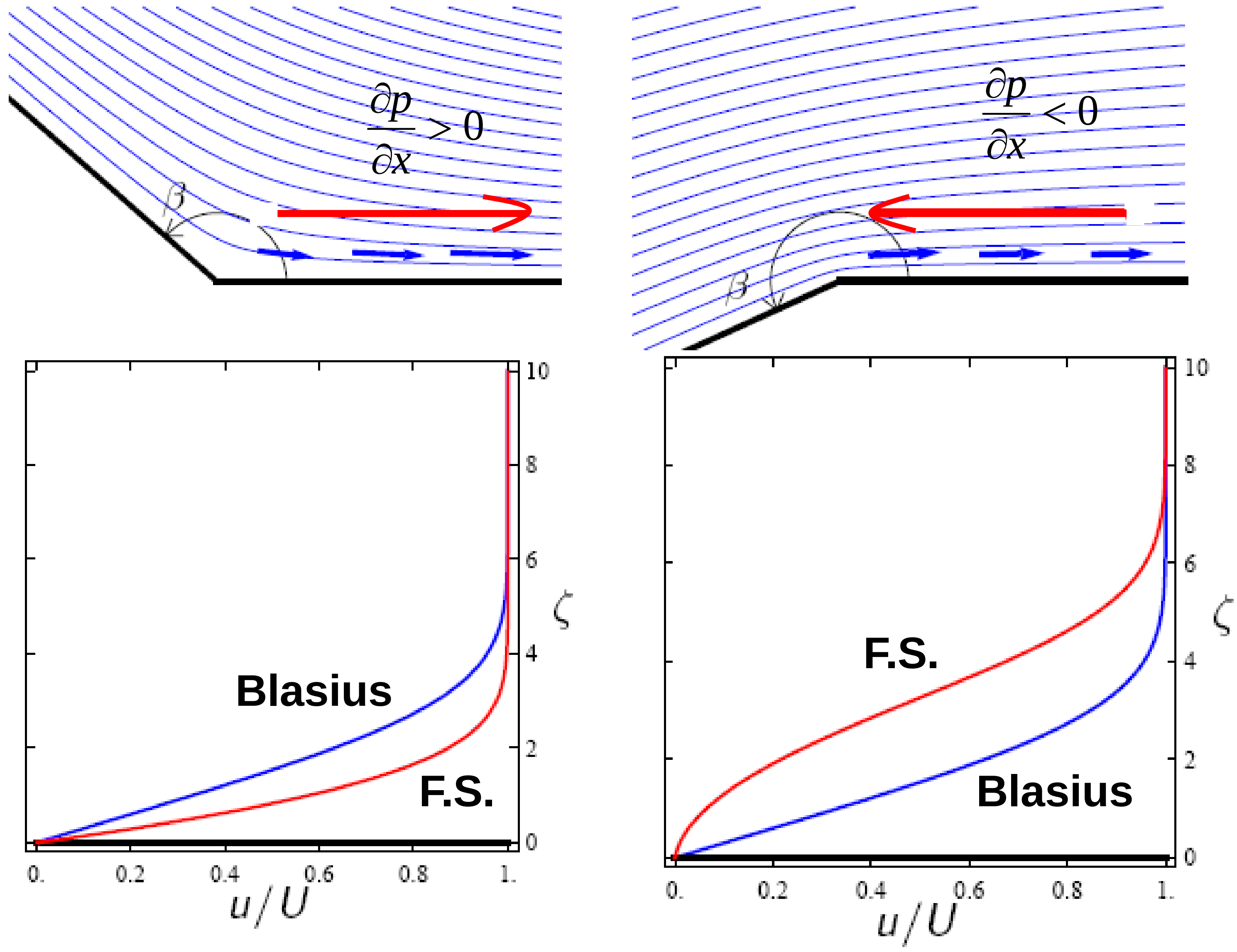
Pressure gradient effect

Favorable pressure gradient: $\frac{\partial p}{\partial x} < 0$



Close to the wall, the pressure gradient further increases the velocity of the flow ⇨ no detachement

Pressure gradient effect



Falkner-Skan solutions

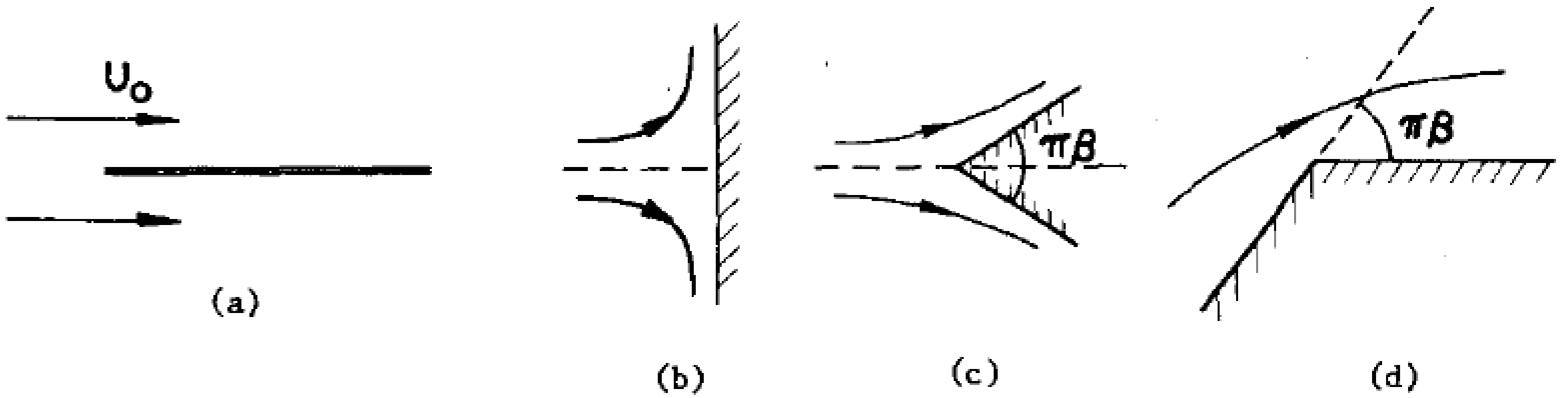
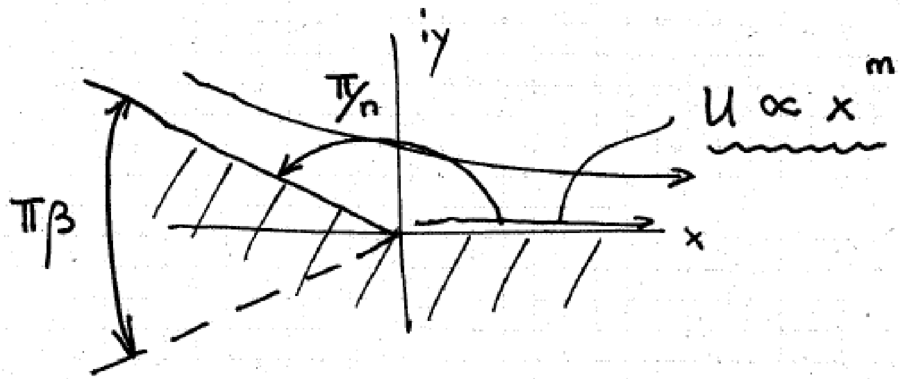


Figure 5.2 Boundary layer flows represented by solutions of the Falkner-Skan equation for different values of the parameter m: (a) $m = 0$; (b) $m = 1$; (c) $0 < m < 1$; (d) $-1/2 < m < 0$

Falkner-Skan far field solutions

pot. complexe

$$F(z) = C z^n$$



$$\frac{dF}{dz} = C n z^{n-1} = v_x - i v_y \longrightarrow \boxed{n = 1 + m}$$

$$\frac{\pi}{n} + \frac{\pi\beta}{2} = \pi \longrightarrow \frac{1}{1+m} + \frac{\beta}{2} = 1$$

$$\boxed{\beta = \frac{2m}{1+m}}$$

Falkner-Skan boundary layer equations

1. Prandtl equations

$$\hat{\psi}_{\hat{y}}\,\hat{\psi}_{x\hat{y}} - \hat{\psi}_x\,\hat{\psi}_{\hat{y}\hat{y}} = U\frac{\mathrm{d}U}{\mathrm{d}x} + \hat{\psi}_{\hat{y}\hat{y}\hat{y}},$$

$$\hat{\psi} = \hat{\psi}_{\hat{y}} = 0 \text{ on } \hat{y} = 0, \quad \hat{\psi}_{\hat{y}} \to U(x) \text{ as } \hat{y} \to \infty.$$

Falkner-Skan boundary layer equations

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2. Self-similar solution

$$\hat{\psi}(x, \hat{y}) = (Ax^{m+1})^{1/2} f(\eta) \text{ where } \eta = \hat{y}(Ax^{m-1})^{1/2}.$$

Falkner-Skan boundary layer equations

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$$\hat{\psi}(x, \hat{y}) = (Ax^{m+1})^{1/2} f(\eta) \text{ where } \eta = \hat{y}(Ax^{m-1})^{1/2}.$$

3. Falkner-Skan equation

$$f''' + \tfrac{1}{2}(m+1)\, ff'' + m(1 - f'^2) = 0$$

$$f(0) = f'(0) = 0, \quad f'(\infty) = 1$$

Falkner-Skan boundary layer solutions

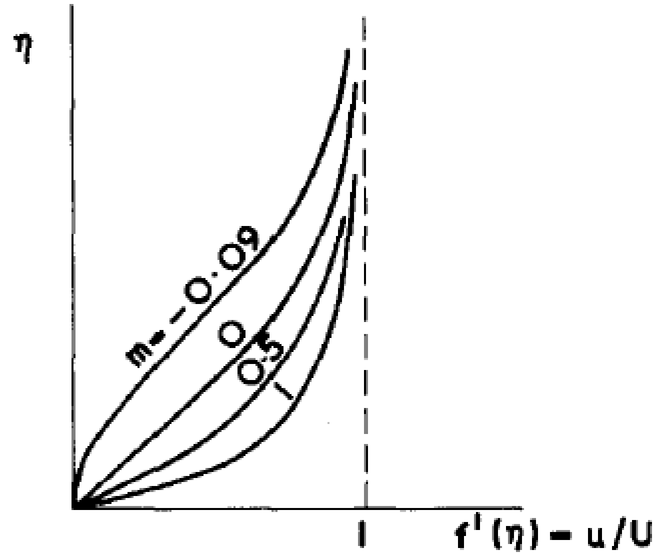
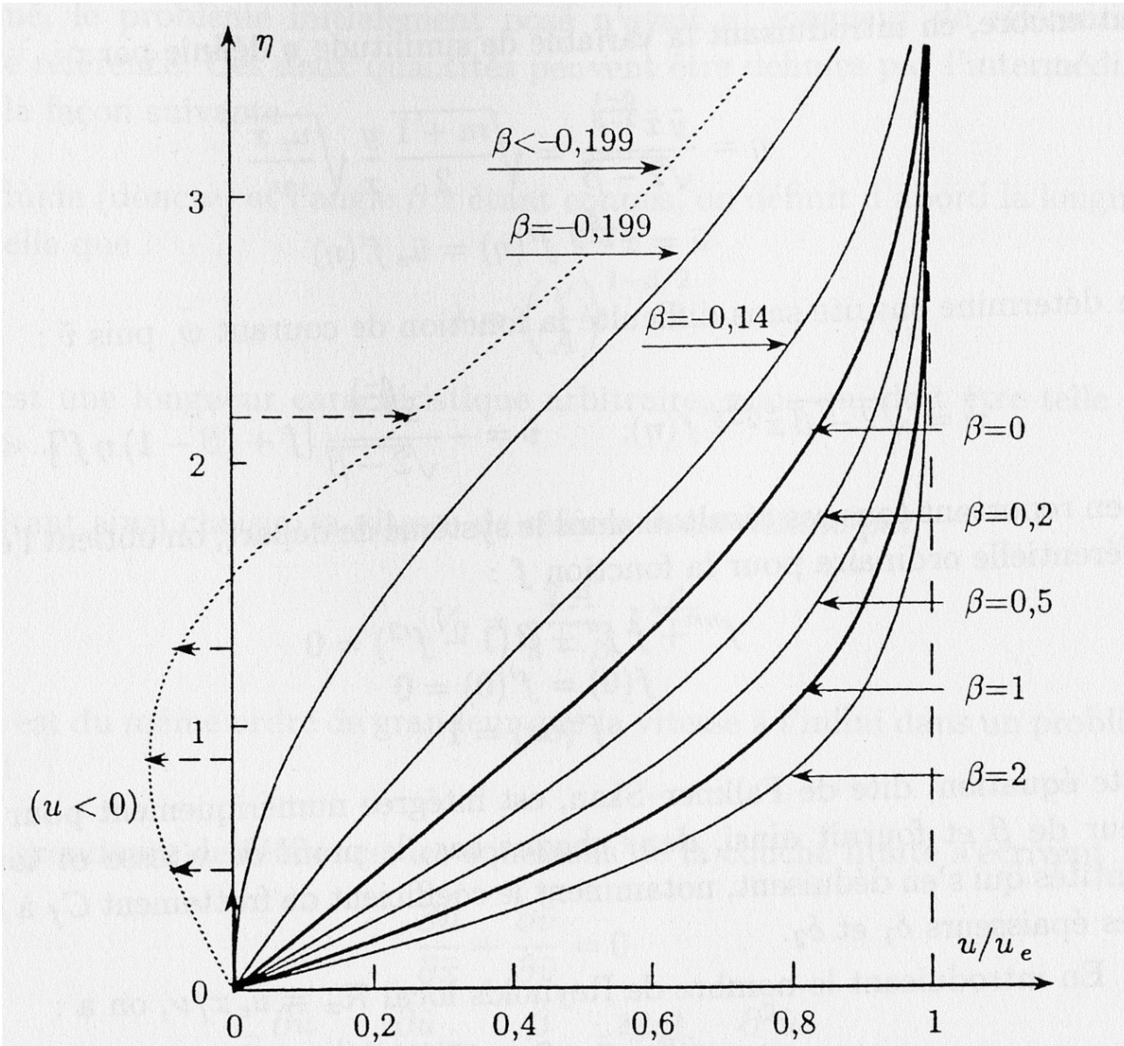
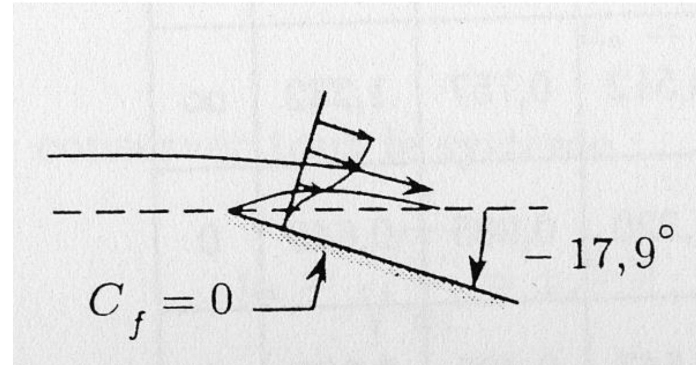
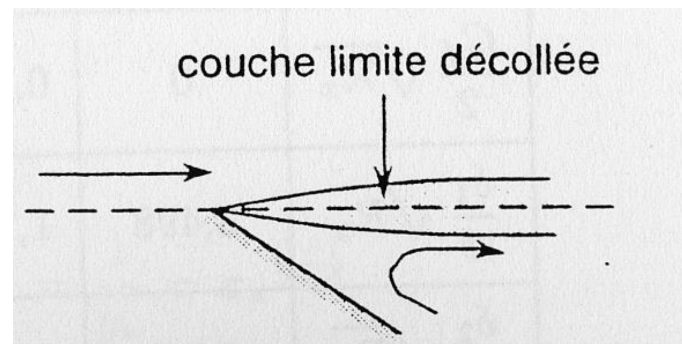


Figure 5.3 Sketch of velocity profiles given by solutions of the Falkner–Skan equation

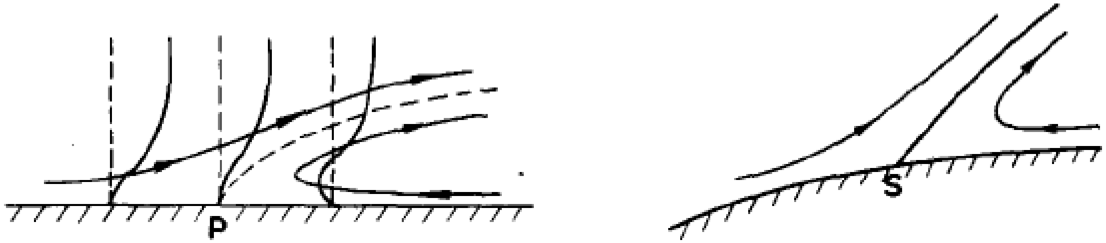
Falkner-Skan boundary layer solutions





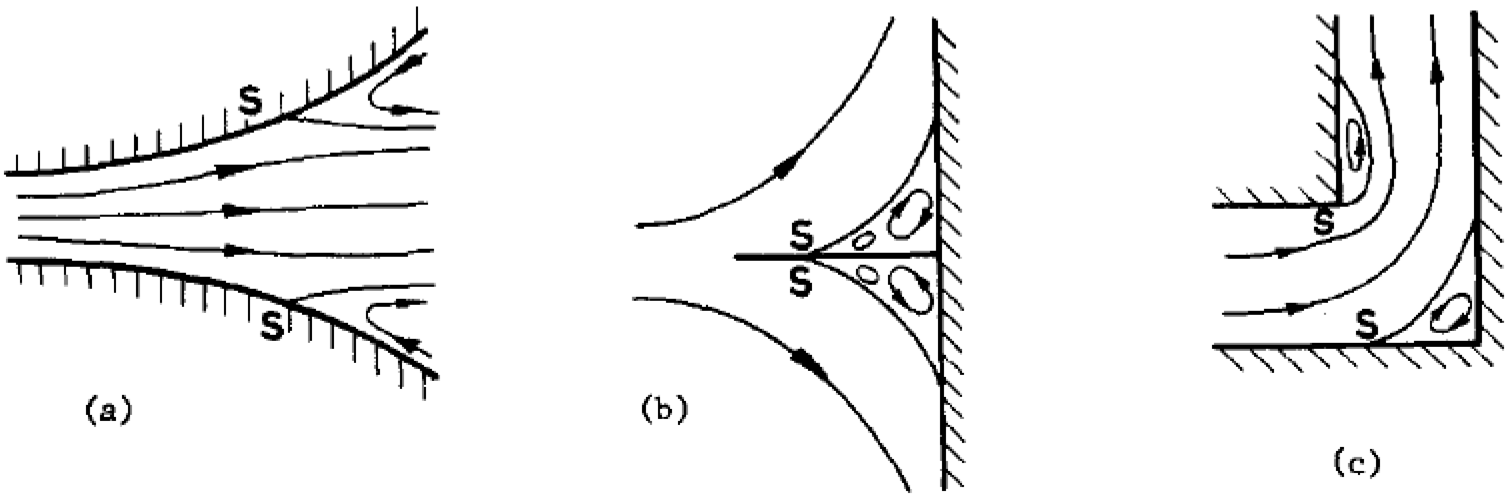


Boundary layer separation



$$\hat{\psi} \sim (x - x_S)^{1/2}, \quad \text{so that } \frac{\partial \hat{\psi}}{\partial x} \sim (x - x_S)^{-1/2} \text{ as } x \to x_S.$$

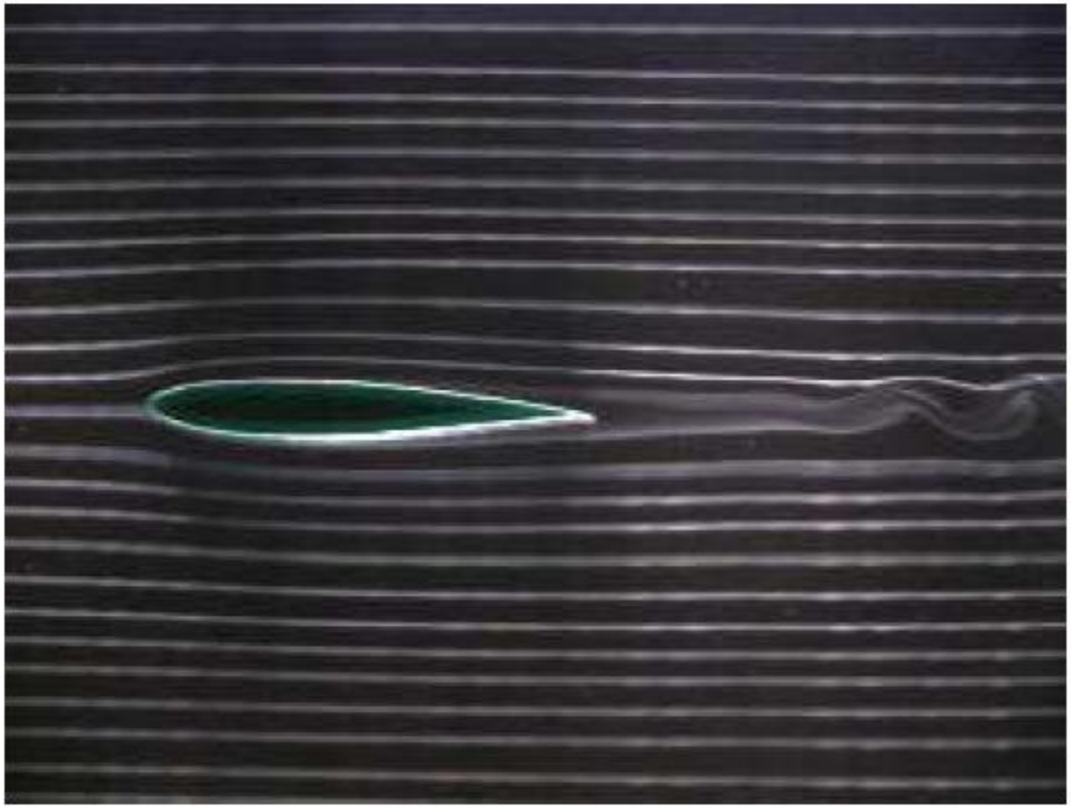
Boundary layer separation



Decollement sur un profil d'aile

Expériences en soufflerie menées à l'université de Stanford, l'écoulement est visualisé grâce à des fumées :

angle d'incidence $\boxed{\gamma = 0°}$:

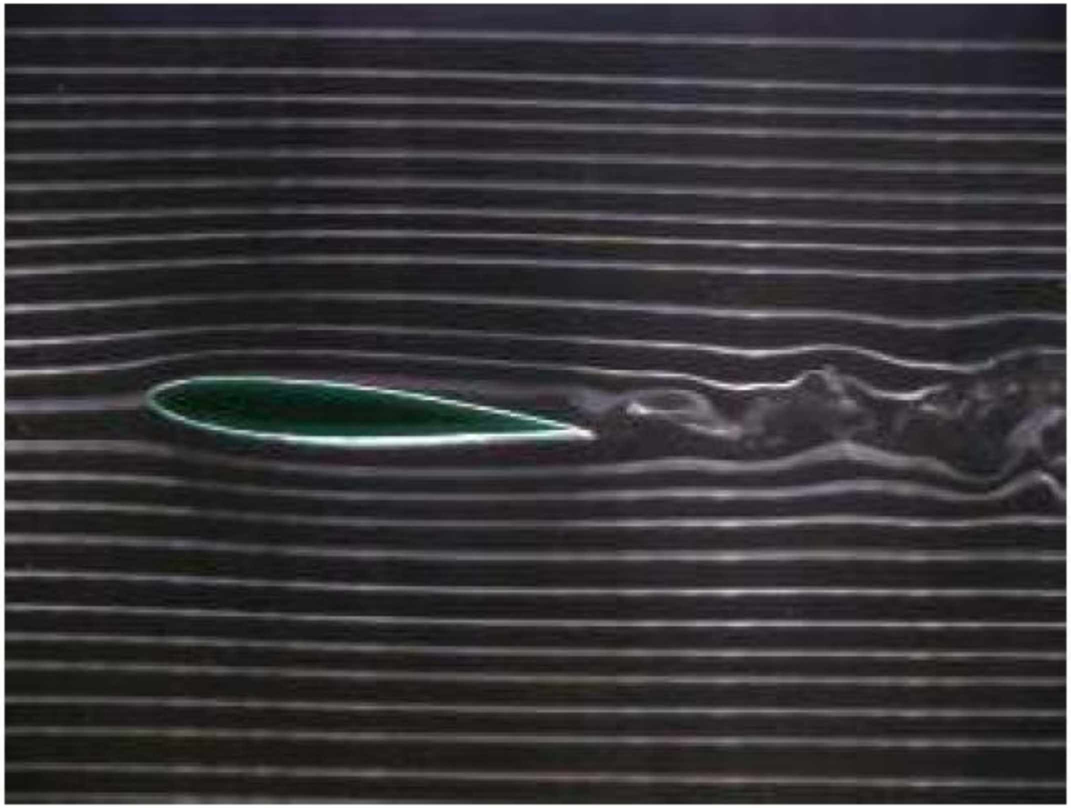


[DVD 'Multimedia Fluid Mechanics', Homsy et al. 2004, Cambridge University Press]

Décollement sur un profil d'aile

Expériences en soufflerie menées à l'université de Stanford, l'écoulement est visualisé grâce à des fumées :

angle d'incidence $\boxed{\gamma = 5°}$:

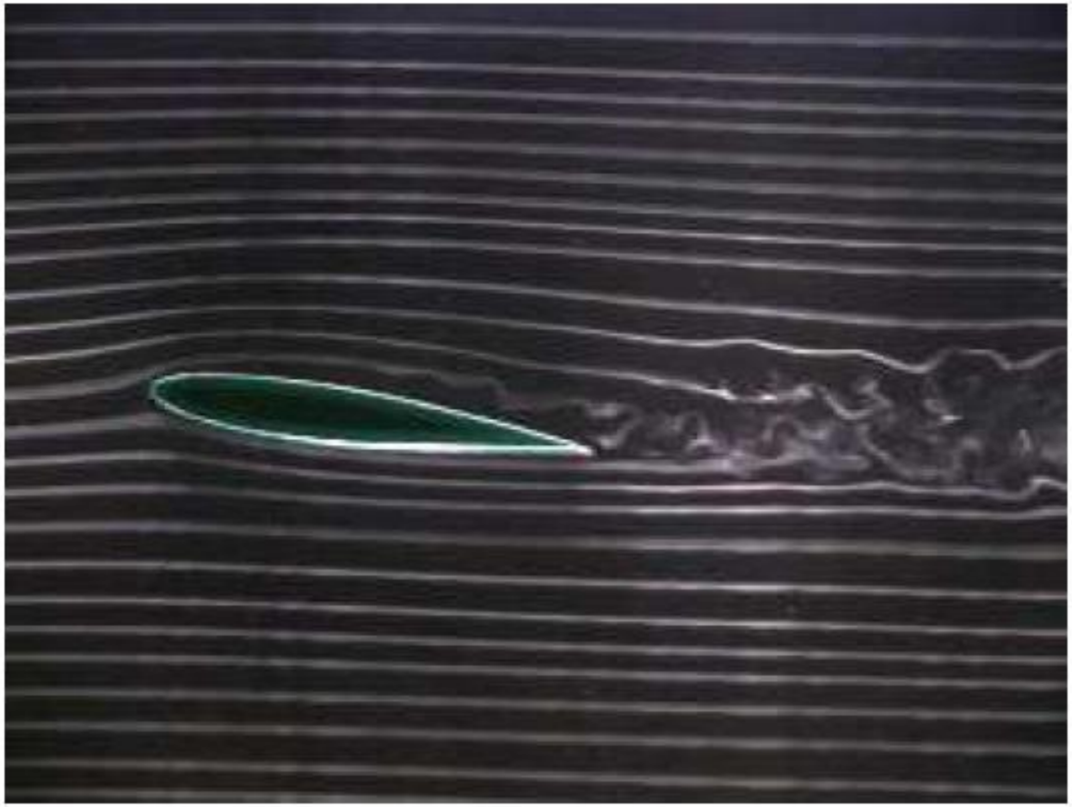


[DVD 'Multimedia Fluid Mechanics', Homsy et al. 2004, Cambridge University Press]

Décollement sur un profil d'aile

Expériences en soufflerie menées à l'université de Stanford, l'écoulement est visualisé grâce à des fumées :

angle d'incidence $\boxed{\gamma = 10^\circ}$:

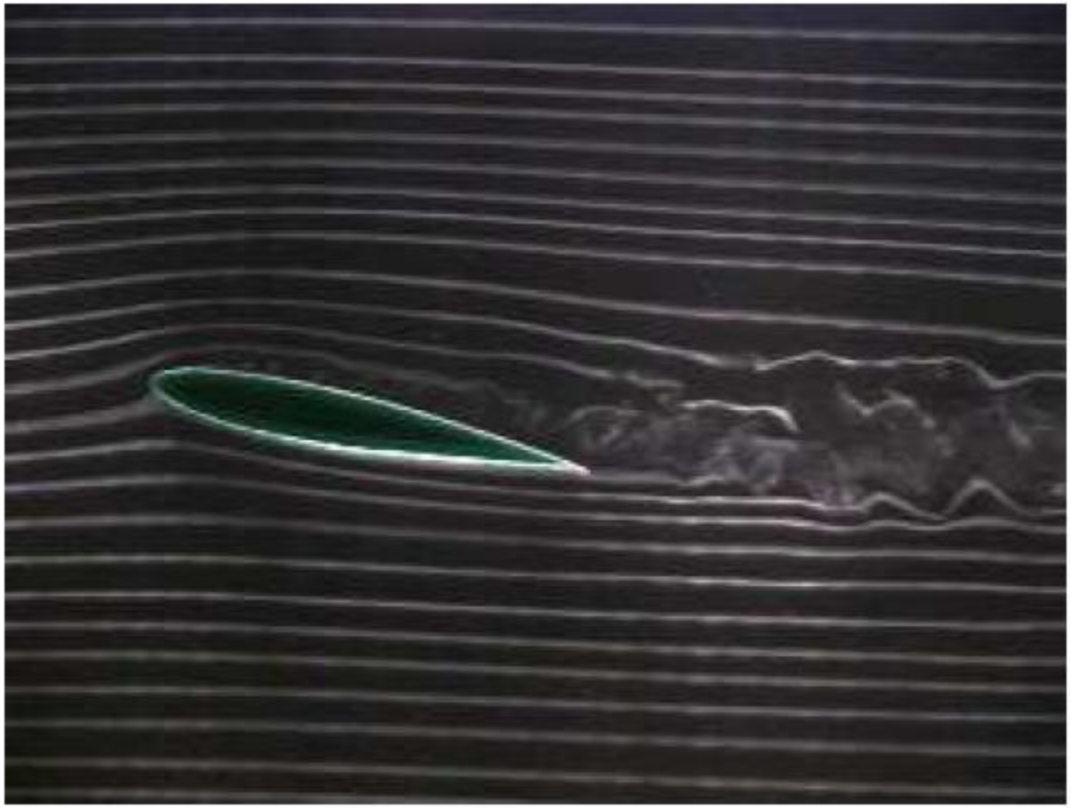


[DVD 'Multimedia Fluid Mechanics', Homsy et al. 2004, Cambridge University Press]

Décollement sur un profil d'aile

Expériences en soufflerie menées à l'université de Stanford, l'écoulement est visualisé grâce à des fumées :

angle d'incidence $\boxed{\gamma = 15^\circ}$:

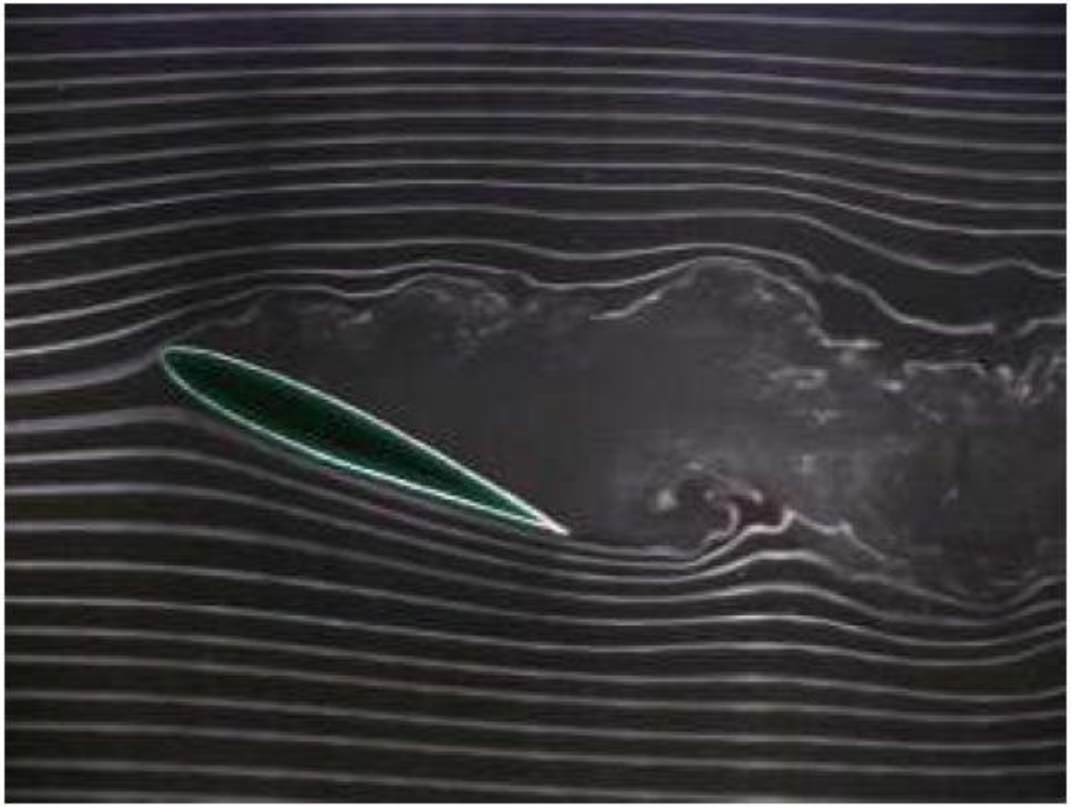


[DVD 'Multimedia Fluid Mechanics', Homsy et al. 2004, Cambridge University Press]

Décollement sur un profil d'aile

Expériences en soufflerie menées à l'université de Stanford, l'écoulement est visualisé grâce à des fumées :

angle d'incidence $\boxed{\gamma = 25^\circ}$:



[DVD 'Multimedia Fluid Mechanics', Homsy et al. 2004, Cambridge University Press]

Décollement sur un profil d'aile

Expériences en soufflerie menées à l'université de Stanford, l'écoulement est visualisé grâce à des fumées :

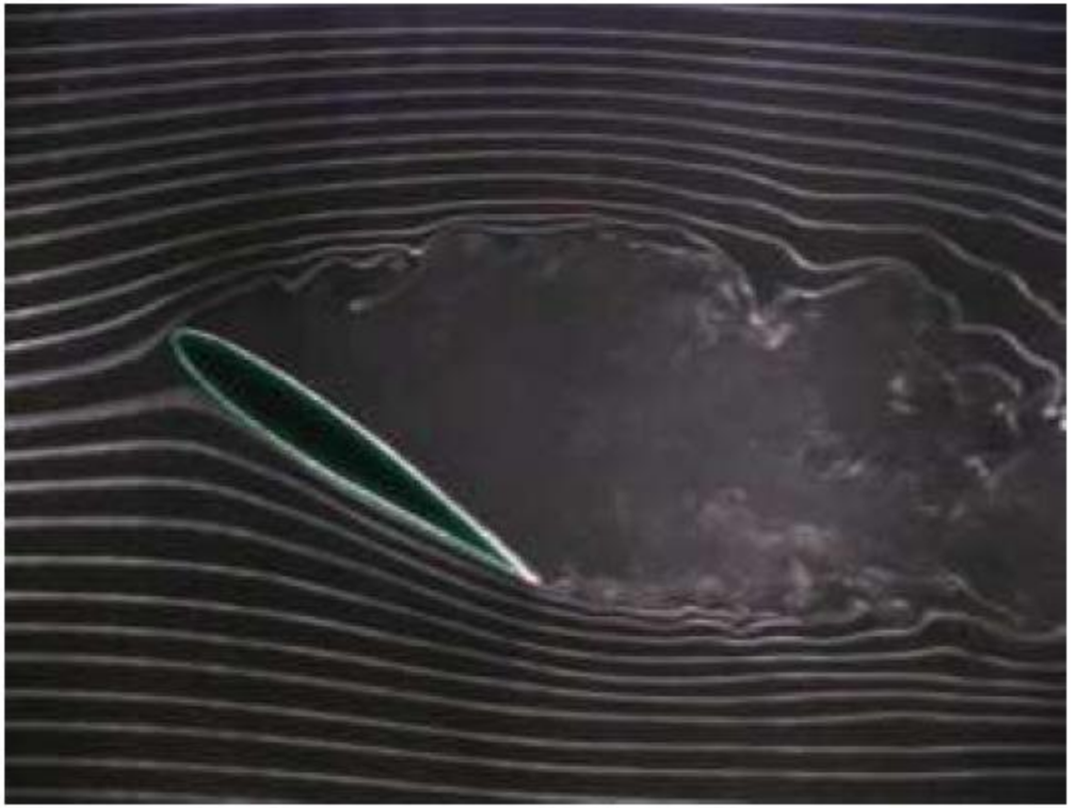
angle d'incidence $\boxed{\gamma = 30^\circ}$:

[DVD 'Multimedia Fluid Mechanics', Homsy et al. 2004, Cambridge University Press]

Décollement sur un profil d'aile

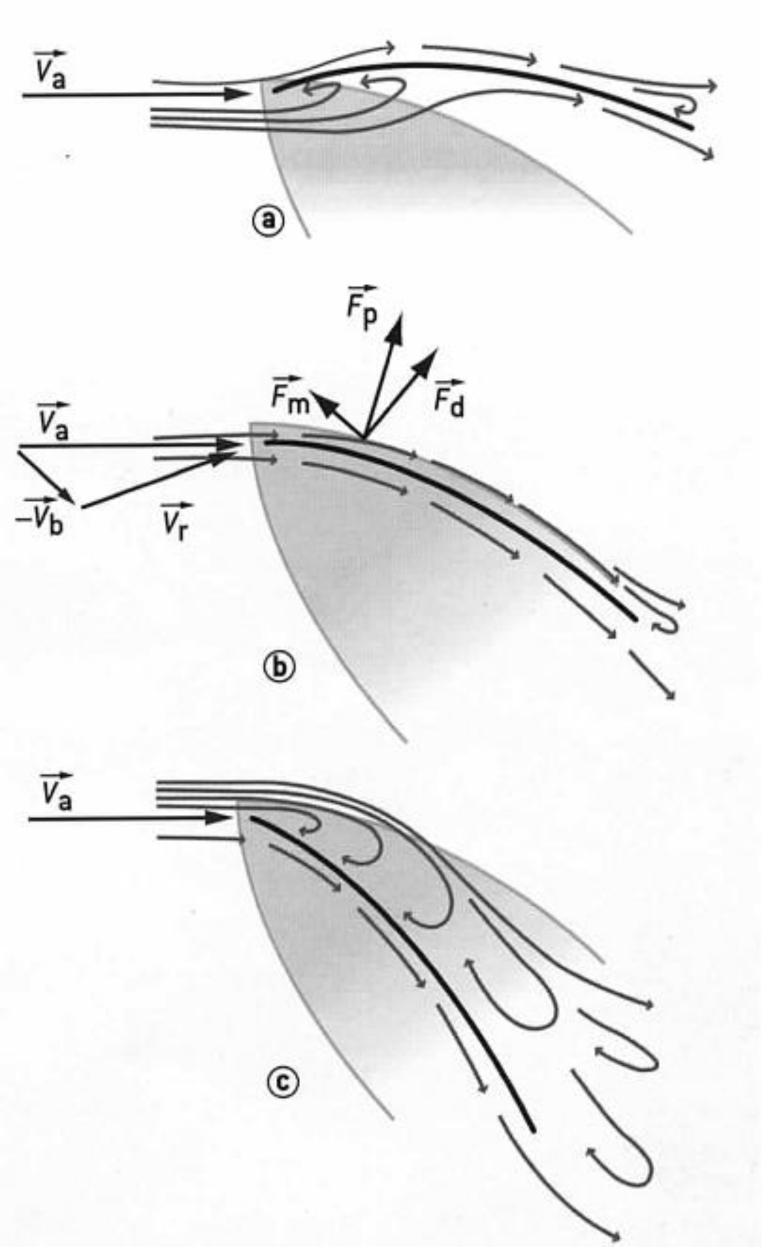
Expériences en soufflerie menées à l'université de Stanford, l'écoulement est visualisé grâce à des fumées :

angle d'incidence $\boxed{\gamma = 35^{\circ}}$:



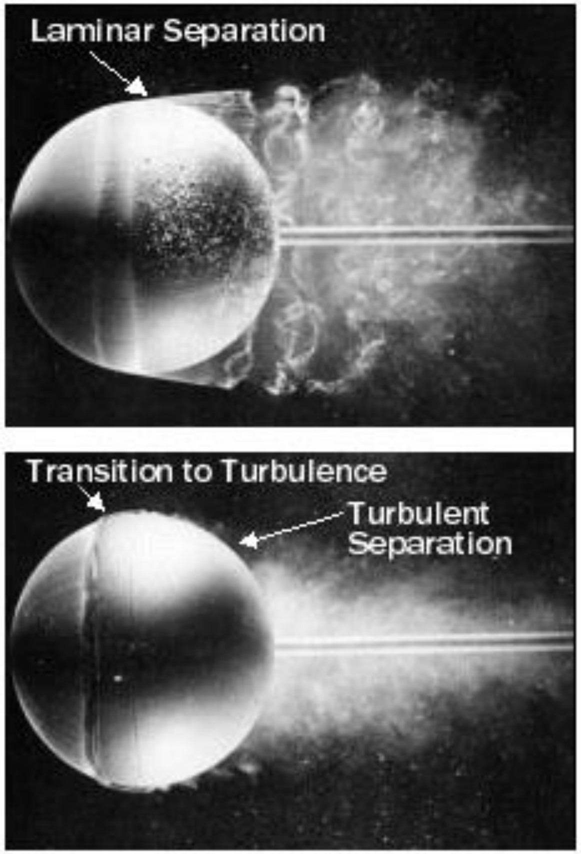
[DVD 'Multimedia Fluid Mechanics', Homsy et al. 2004, Cambridge University Press]

Application to sailing

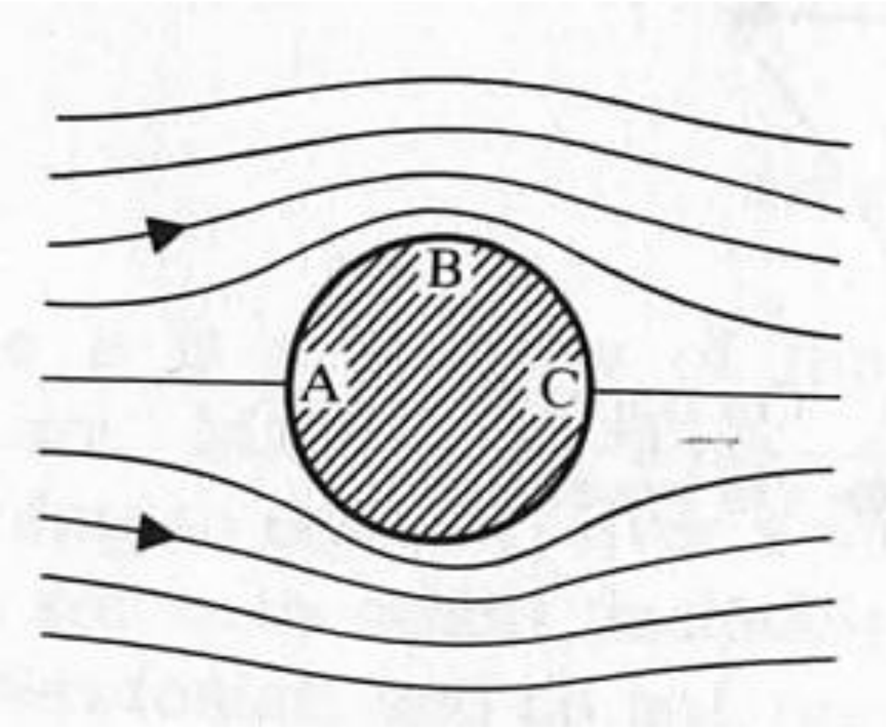


Application to sailing

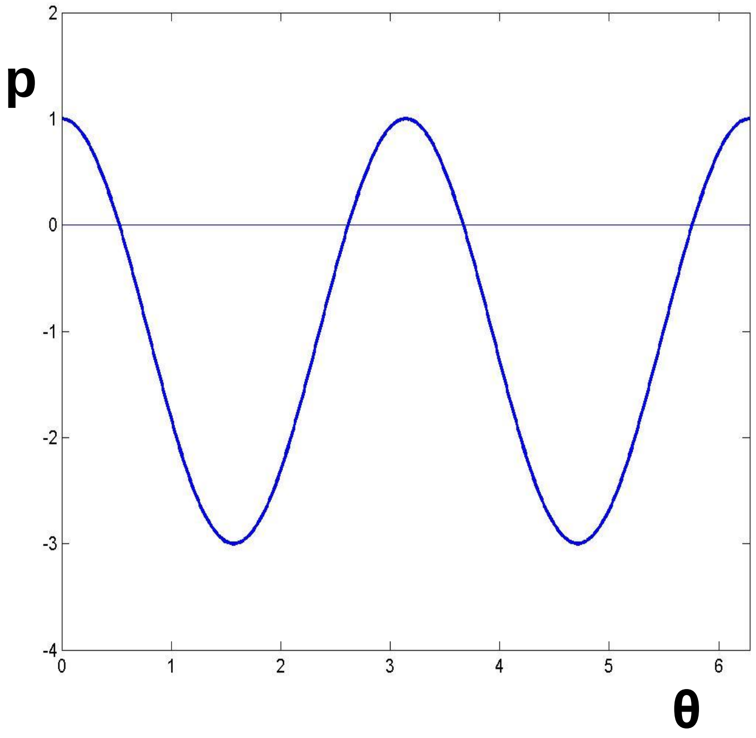
Example: Flow around a sphere



Flow around a cylinder



$$p(a,\theta) = \frac{1}{2}\rho U_\infty^2 (1 - 4\sin\theta^2)$$



Flow around a cylinder

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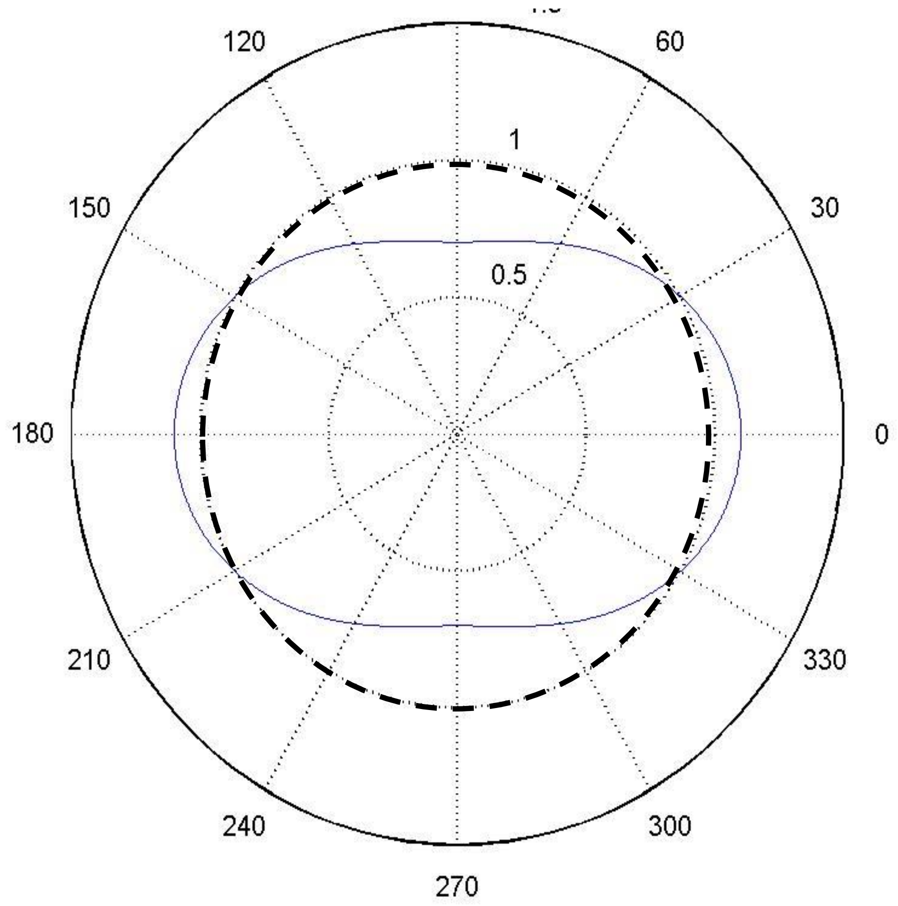
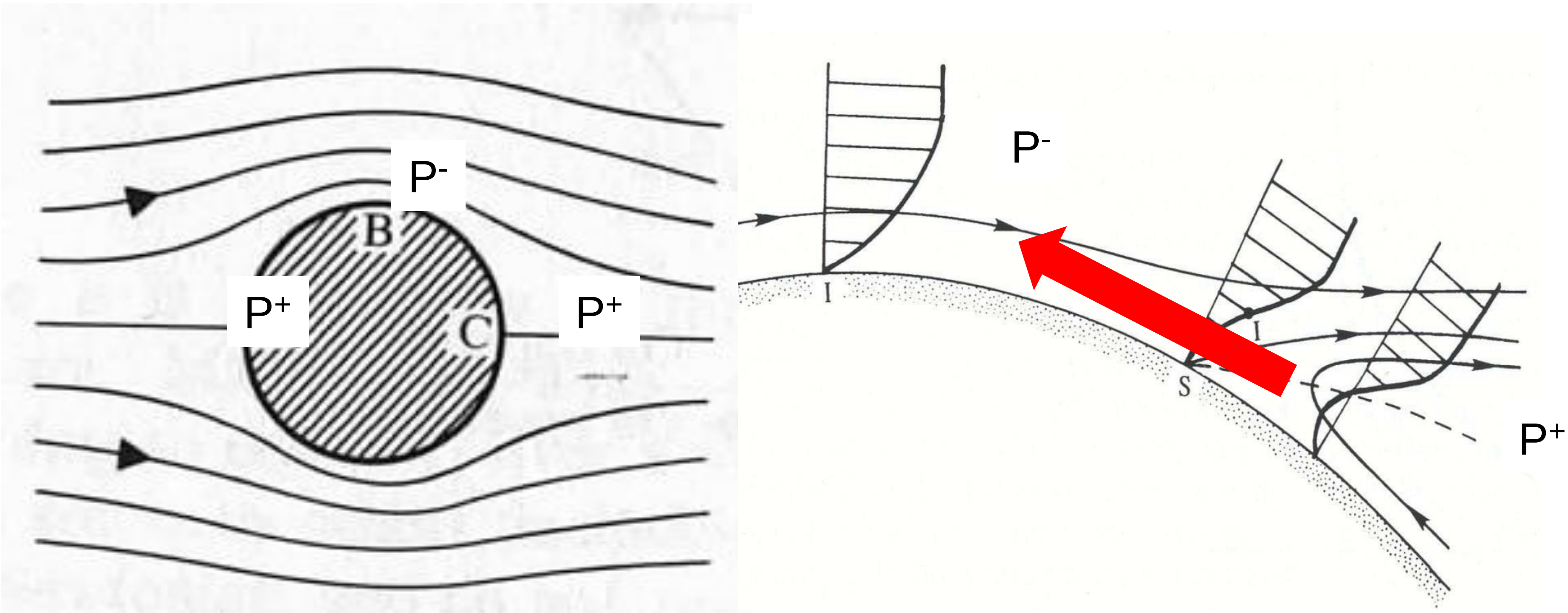
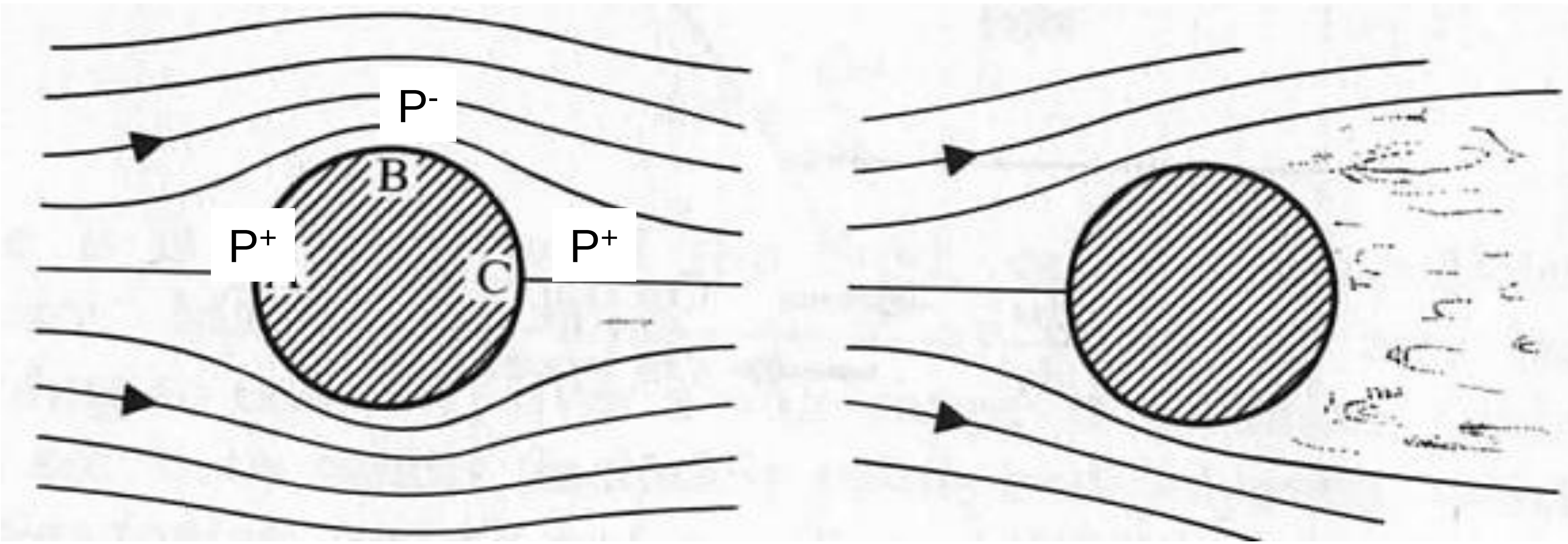


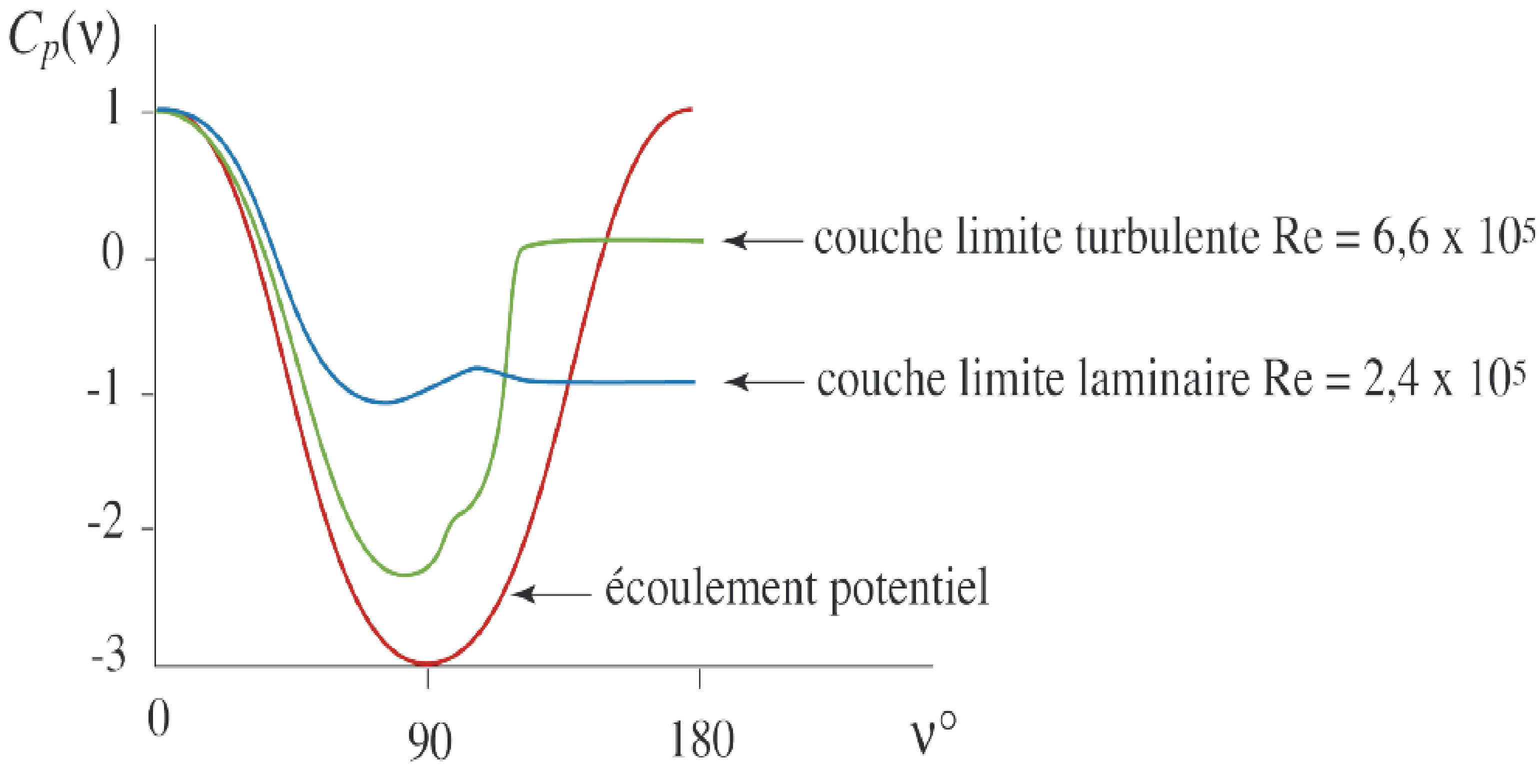
Origin of detachment: pressure gradient



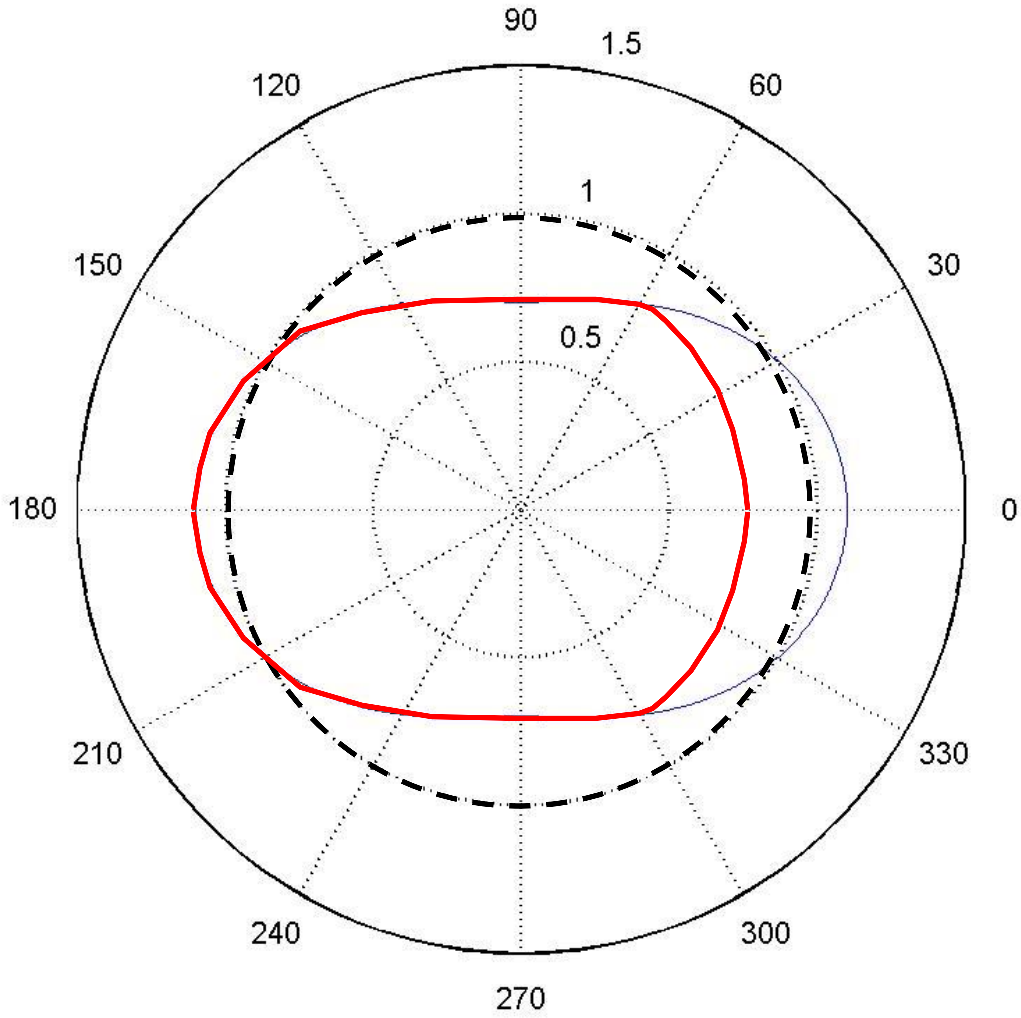
A viscous flow close to the wall opposes the free-stream


P-
B
P+
C
P+

Pressure coefficient

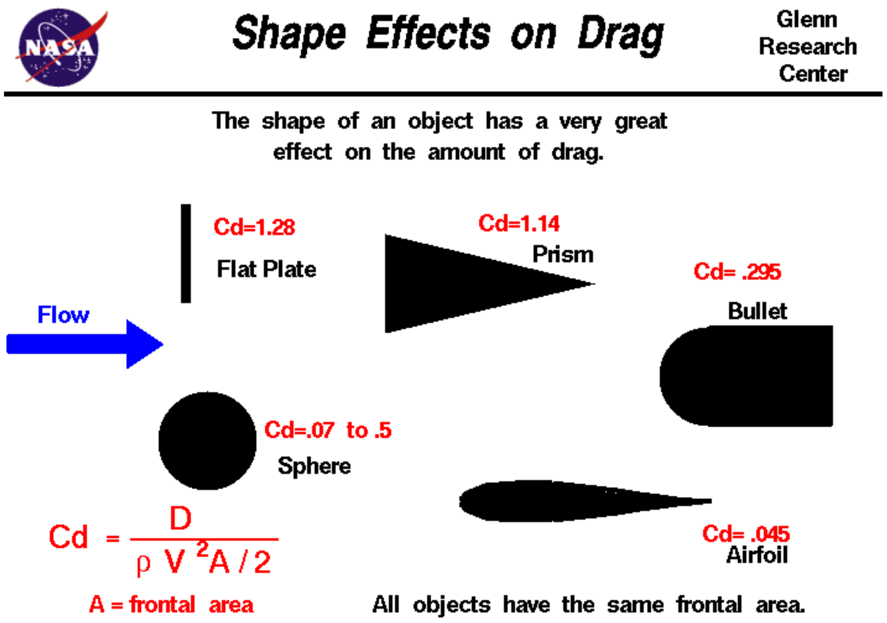


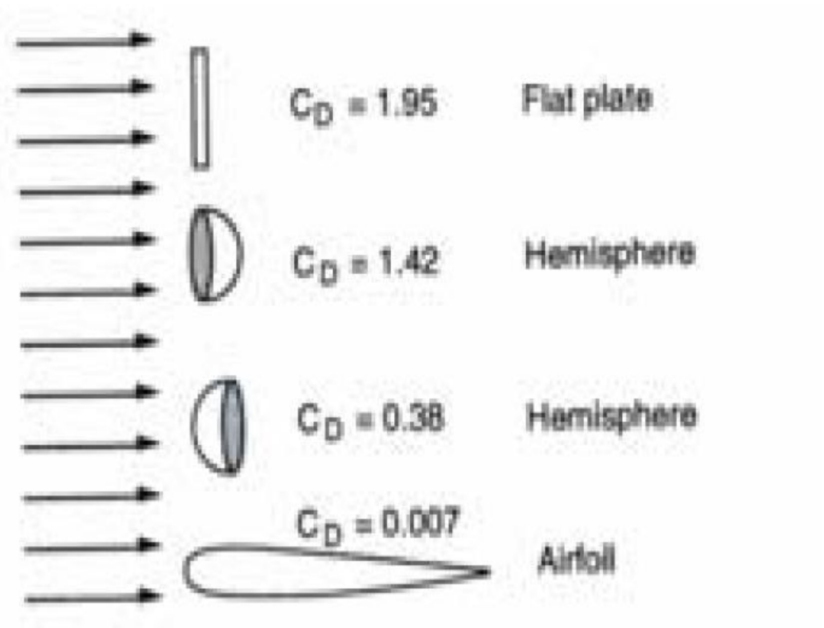
Form drag



Drag coefficient

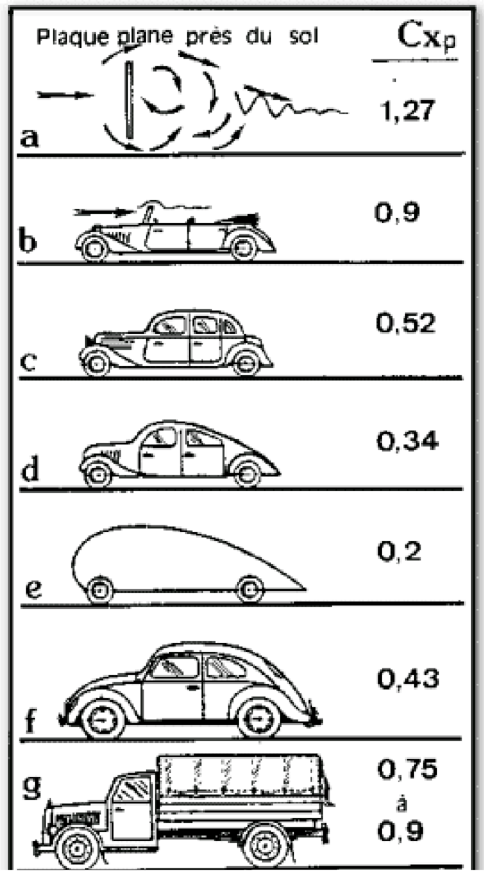
$$C_X = \frac{trainée}{\frac{1}{2}\rho U^2 A}$$



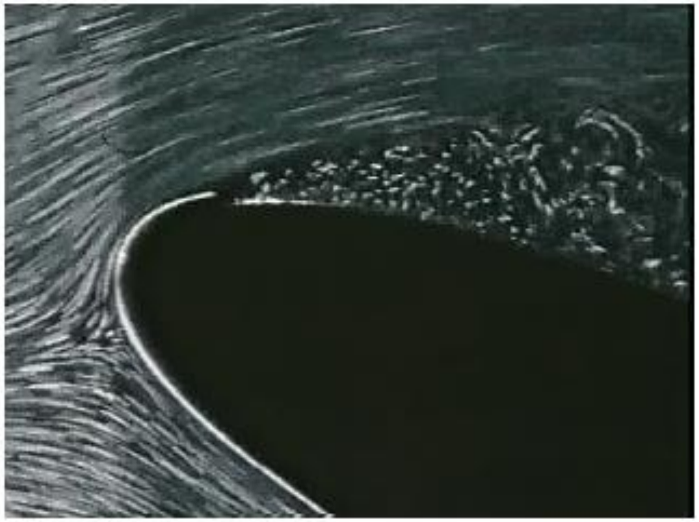


$$C_{\mathbf{x}} = \frac{\textbf{drag}}{\frac{1}{2}\rho U^2 A}$$

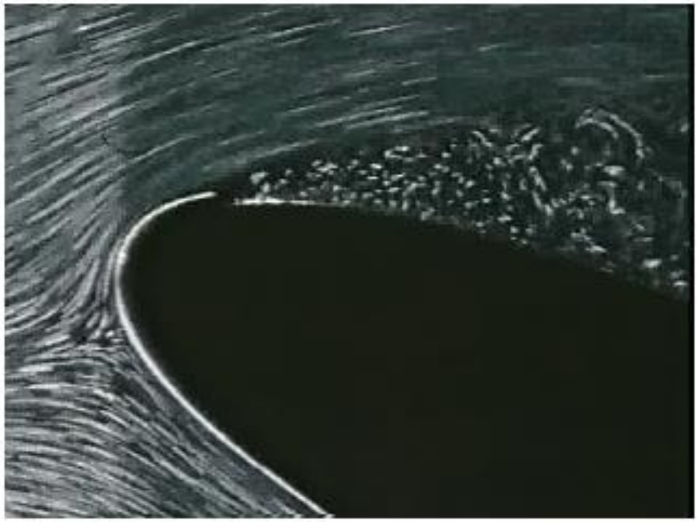
section, somewhat arbitrary…



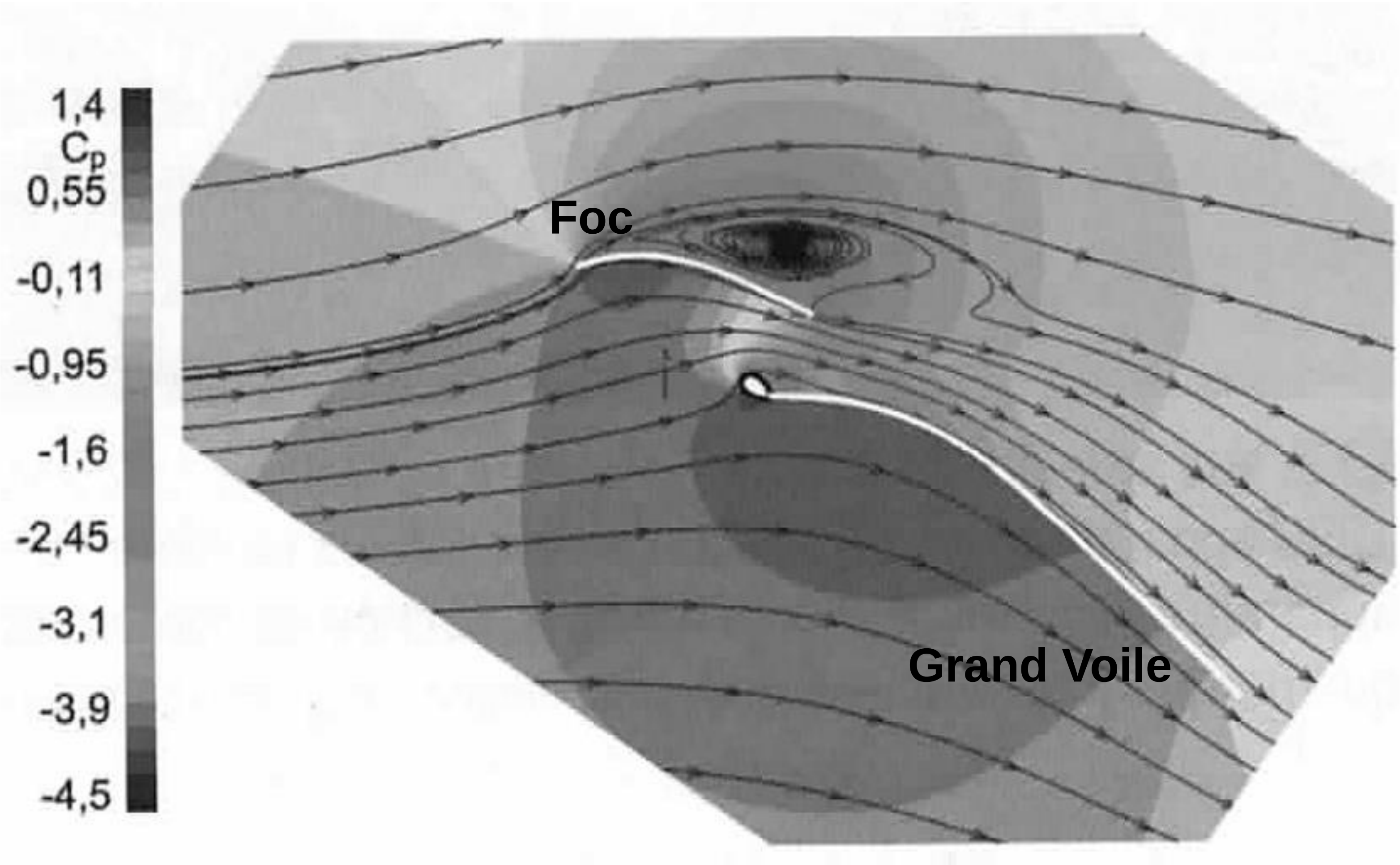
Separation control



Separation control



Application to sailing

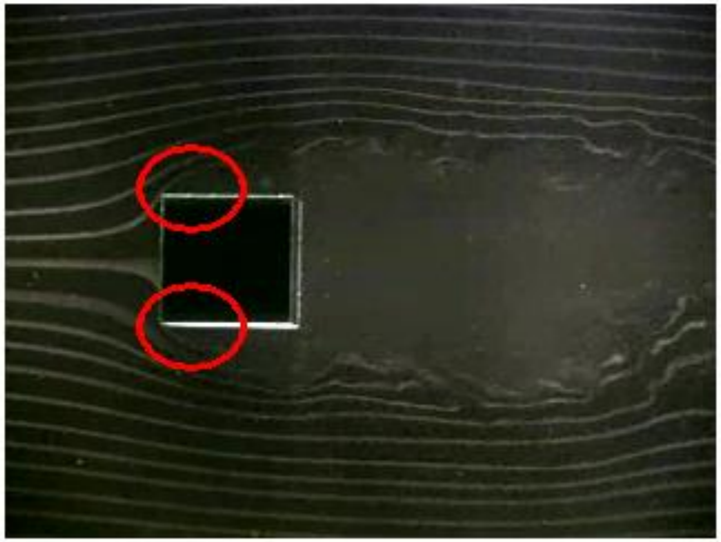


Thickness effect

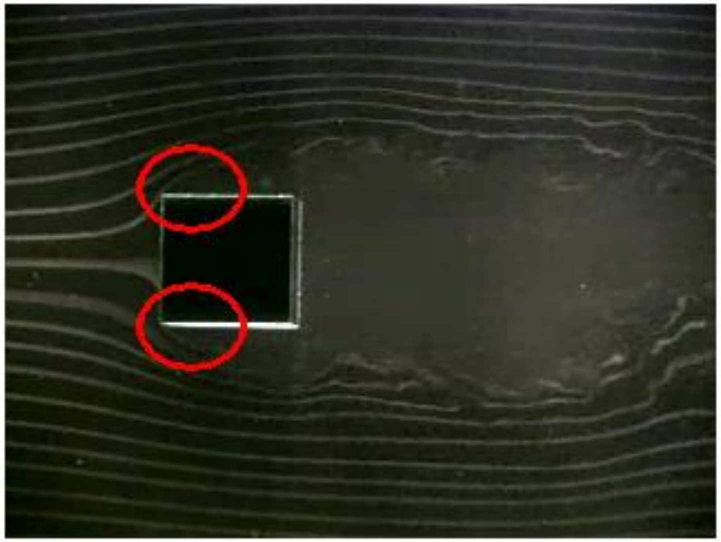
Attached

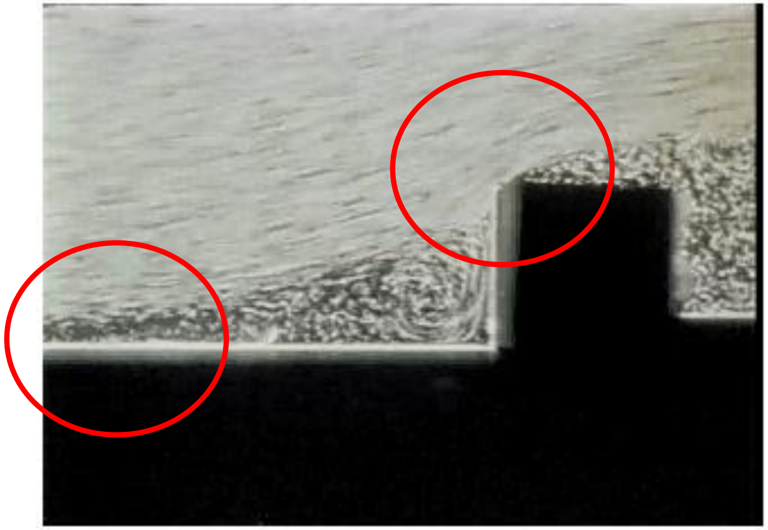
Detached

A gallery of detached flows



A gallery of detached flows





A gallery of detached flows