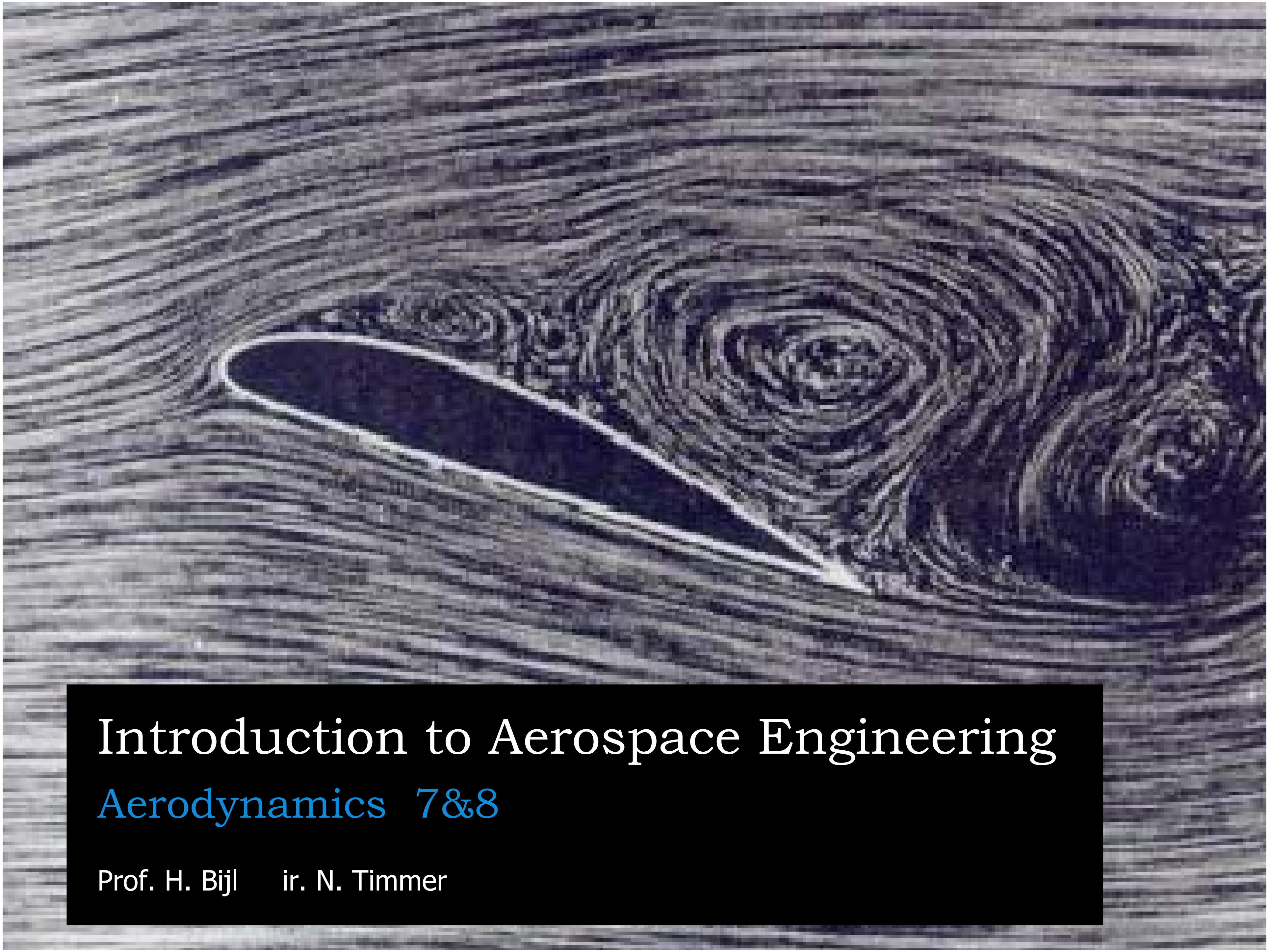
# Introduction to Aerospace Engineering

## Lecture slides



# Introduction to Aerospace Engineering

## Aerodynamics 7&8

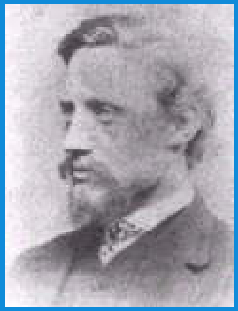
Prof. H. Bijl    ir. N. Timmer

# 7 & 8.

## *Laminar and turbulent flows*

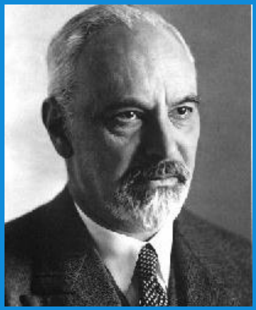
*Anderson 4.15 - end of chapter 4.*

Osborne Reynolds



1842-1912

Ludwig Prandtl



1874-1953

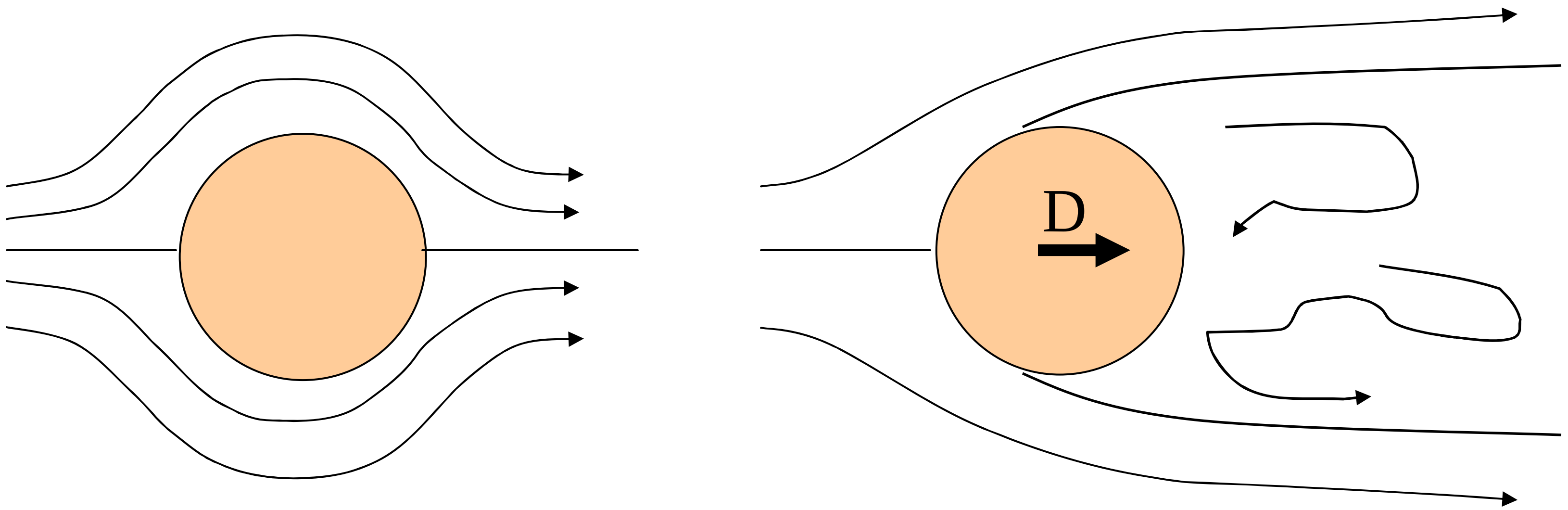
# Subjects lecture 7 & 8

- Viscous flows
- Laminar boundary layers
- Turbulent boundary layers
- Transition
- Separation

# Viscous flow

Up till now we have only dealt with <u>frictionless flow</u>.

What is the effect of friction ? ….




Inviscid flow (No friction)
NO DRAG

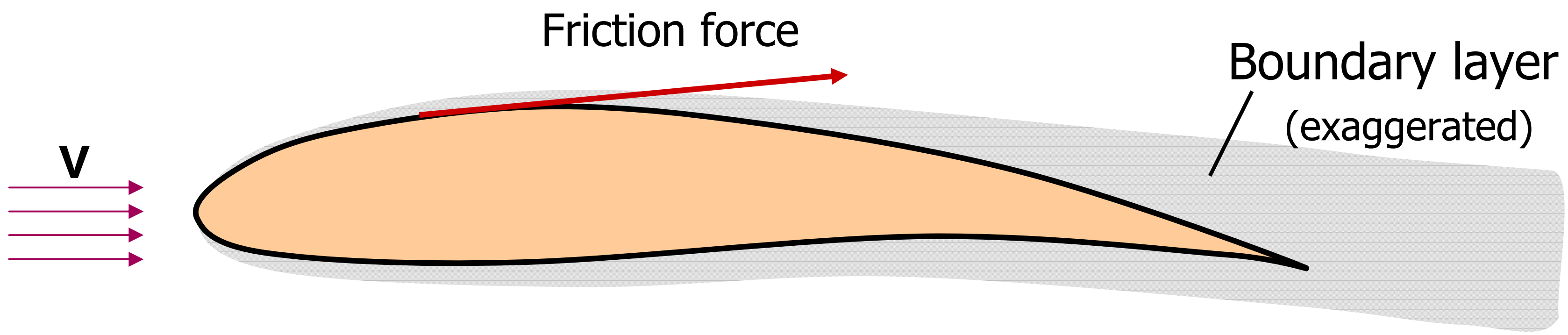
Viscous flow (friction)
FINITE DRAG

# Viscous flow

In real life the flow at the surface adheres to the surface because of friction between the gas and the solid material:

- Right at the surface the velocity is zero

# Boundary layer




- In the vicinity of the surface there is a thin region of retarded flow: the boundary layer
- The pressure through the boundary layer in a direction perpendicular to the surface is constant

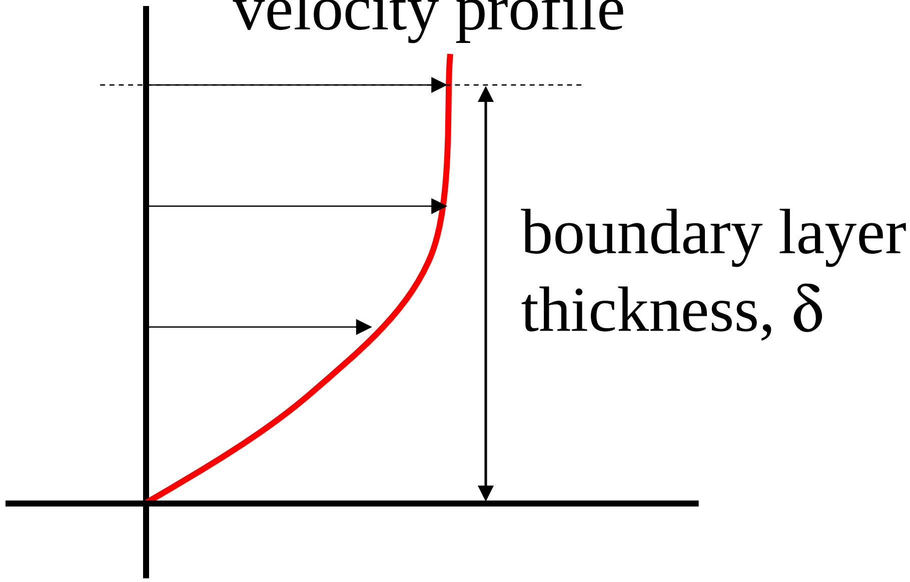
# Viscous flow

Inside the boundary layer

Bernoulli's law is not valid!!!!!!

# Viscous flows

Boundary layer
velocity profile



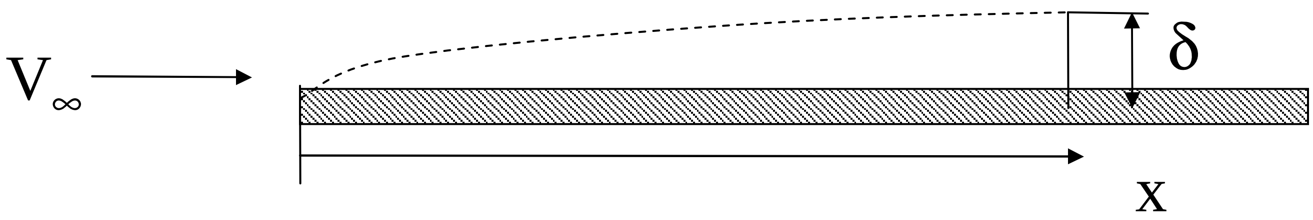

Shear stress can be written as :

$$\tau_w = \mu \left( \frac{dU}{dy} \right)_{y=0}$$

shear stress, $\tau w$
(schuifspanning)
⇒ skin friction drag

μ = absolute viscosity coefficient or viscosity
Air at standard sea level : $\mu = 1.789 * 10^{-5}$ kg/ms)

# Viscous flows, some definitions




Reynolds number :

$$Re_x = \frac{\rho_\infty V_\infty x}{\mu_\infty} = \frac{V_\infty x}{\nu_\infty}$$

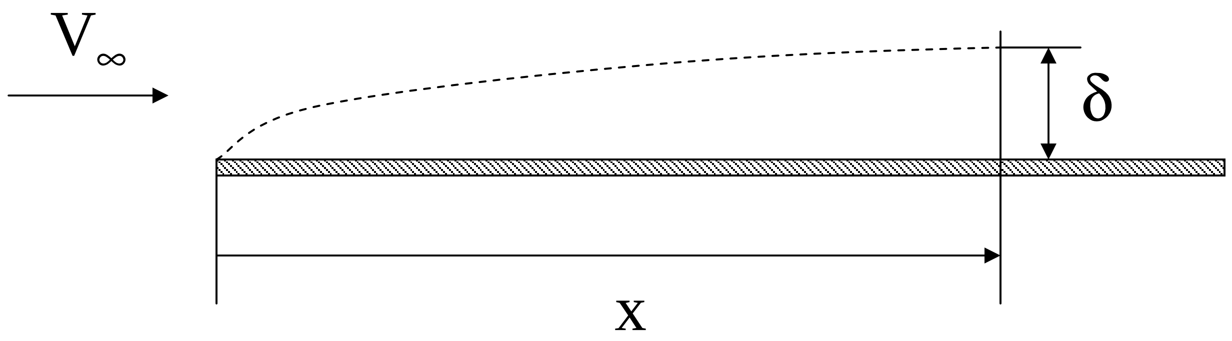
dimensionless, and varies linearly with x

Laminar flow : streamlines are smooth and regular and a fluid element moves smoothly along a streamline

Turbulent flow : streamlines break up and a fluid element moves in a random irregular way

# Laminar boundary layer, boundary layer thickness

Consider flat plate flow. What is boundary layer thickness $\delta$ and skin friction drag $D_f$ at location x?

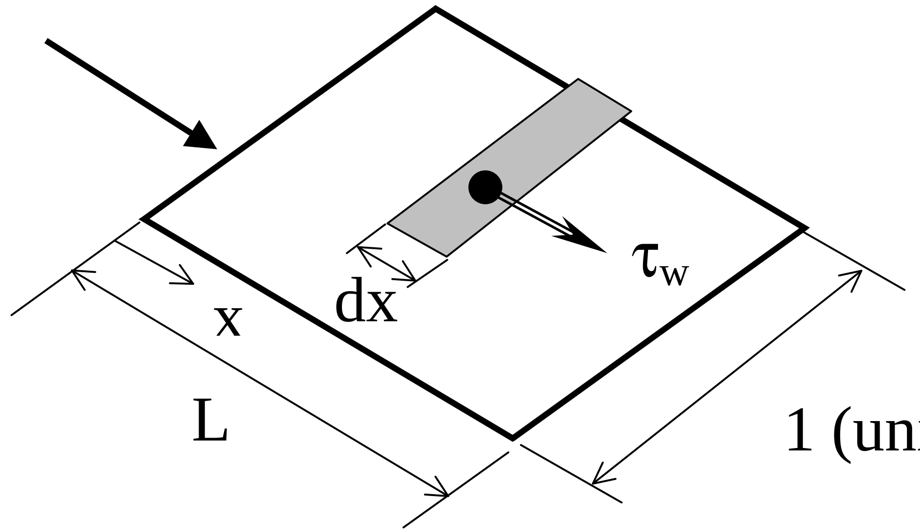



From **laminar** boundary layer theory :

$$\delta = \frac{5.2\ x}{\sqrt{Re_x}}$$

Thus $\delta$ is proportional to : $\sqrt{x}$ (parabolically)

# Laminar boundary layer, skin friction drag




Total force = total pressure force + total friction force

Total friction force on element dx is: $\tau_w(x)\cdot dx\cdot 1=\tau_w(x)dx$

Total skin friction drag is: $$D_f = \int_o^L \tau_w \, dx$$

# Laminar boundary layer, skin friction drag

For the skin friction coefficient we find from laminar boundary layer theory :

$$c_{f_x} = \frac{\tau_w}{\frac{1}{2}\rho_\infty V_\infty^2} = \frac{\tau_w}{q_\infty} = \frac{0.664}{\sqrt{Re_x}}$$

Thus $c_{f_x}$ and $\tau_w$ decrease as $\sqrt{x}$ increases

The skin friction at the beginning of the plate is larger than near the trailing edge.

To calculate the total aerodynamic force we must **integrate**!

# Laminar boundary layer, skin friction drag

$$D_f = \int_o^L c_{f_x} \cdot q_\infty \, dx = 0.664\, q_\infty \int_o^L \frac{dx}{\sqrt{Re_x}} = \frac{0.664 \;\; q_\infty}{\sqrt{V_\infty / \nu}} \int_o^L \frac{dx}{\sqrt{x}}$$

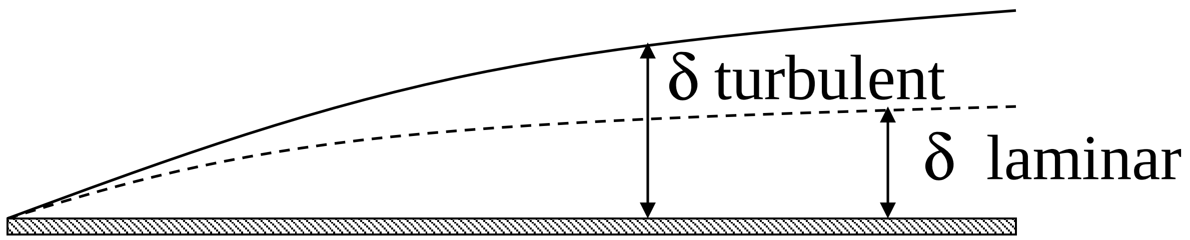
$$\int \frac{dx}{\sqrt{x}} = \int x^{-1/2} = 2\sqrt{x}$$

$$D_f = \frac{0.664\, q_\infty}{\sqrt{V_\infty / \nu_\infty}} 2\sqrt{L} = \frac{1.328 q_\infty L}{\sqrt{V_\infty L / \nu_\infty}}$$

Define total skin friction drag coefficient as $C_f = \dfrac{D_f}{q_\infty S}$

$$C_f = \frac{1.328}{\sqrt{Re_L}} \frac{L}{S} = \frac{1.328.L}{\sqrt{Re_L}\, L \cdot 1} \quad \Rightarrow \quad C_f = \frac{1.328}{\sqrt{Re_L}}$$

# Results for a turbulent boundary layer




Due to the action of **turbulence** :

no exact solution for turbulent boundary layers !

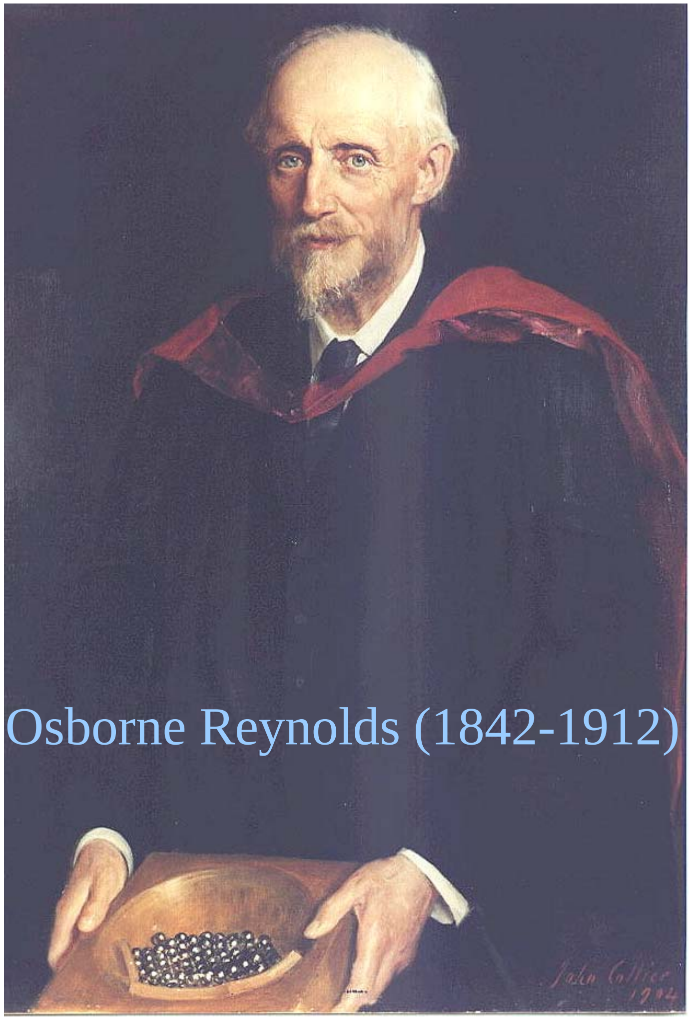
From experiments :

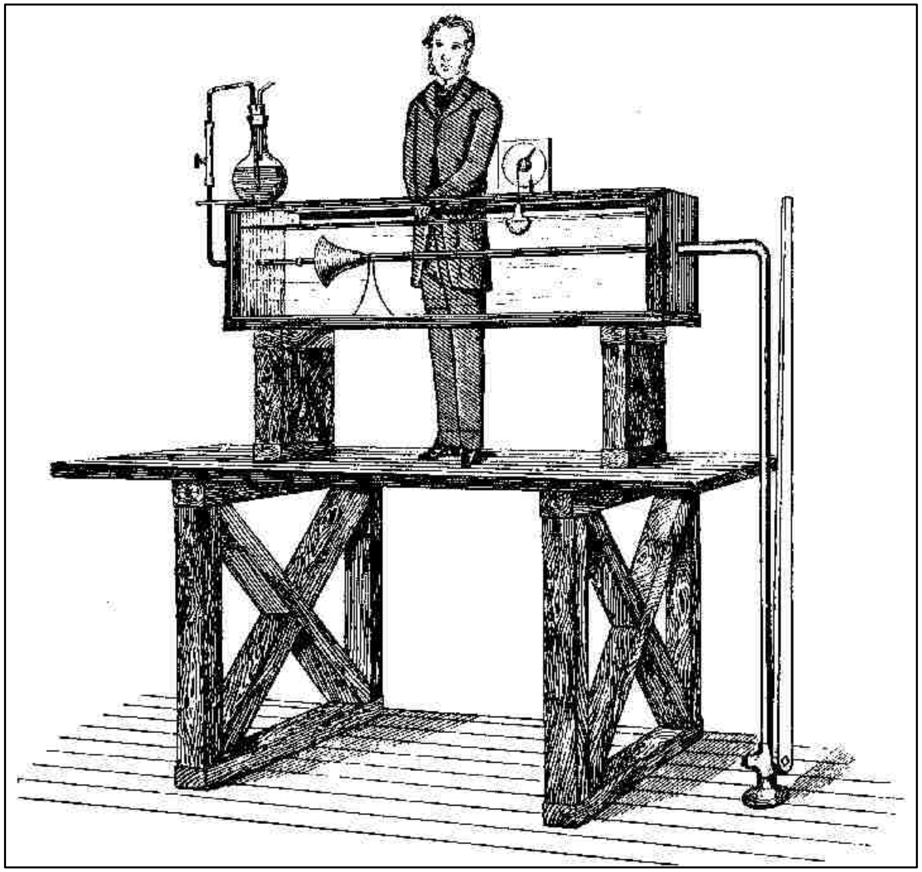
$$\delta = \frac{0.37x}{Re_x^{0.2}}$$

$$C_f = \frac{0.074}{Re_L^{0.2}}$$

Note : $C_f$ varies as $L^{-1/5}$ for turbulent flow while it changes as $L^{-1/2}$ for laminar flow. Thus the friction in a turbulent boundary layer is larger than in a laminar flow

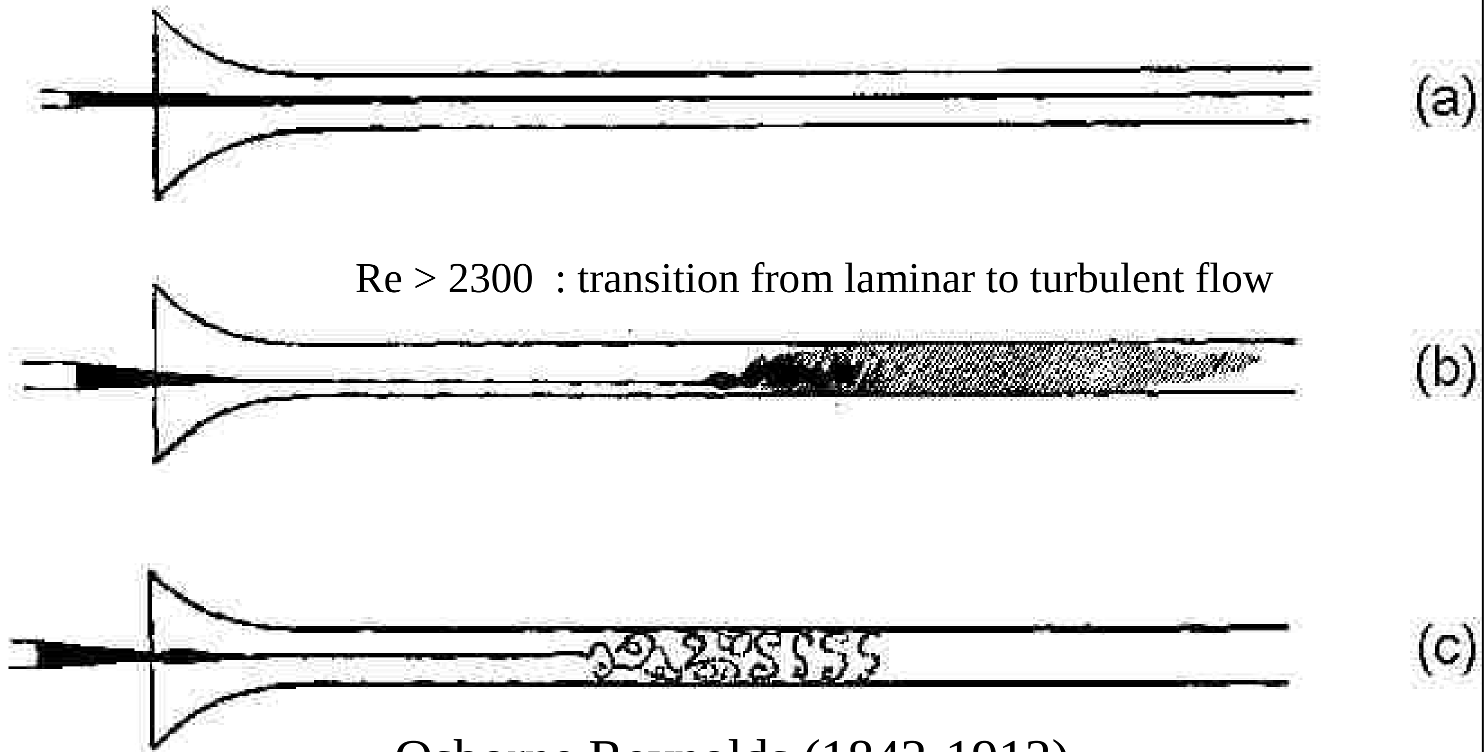
# Transition



Pipe flow experiment

# Transition

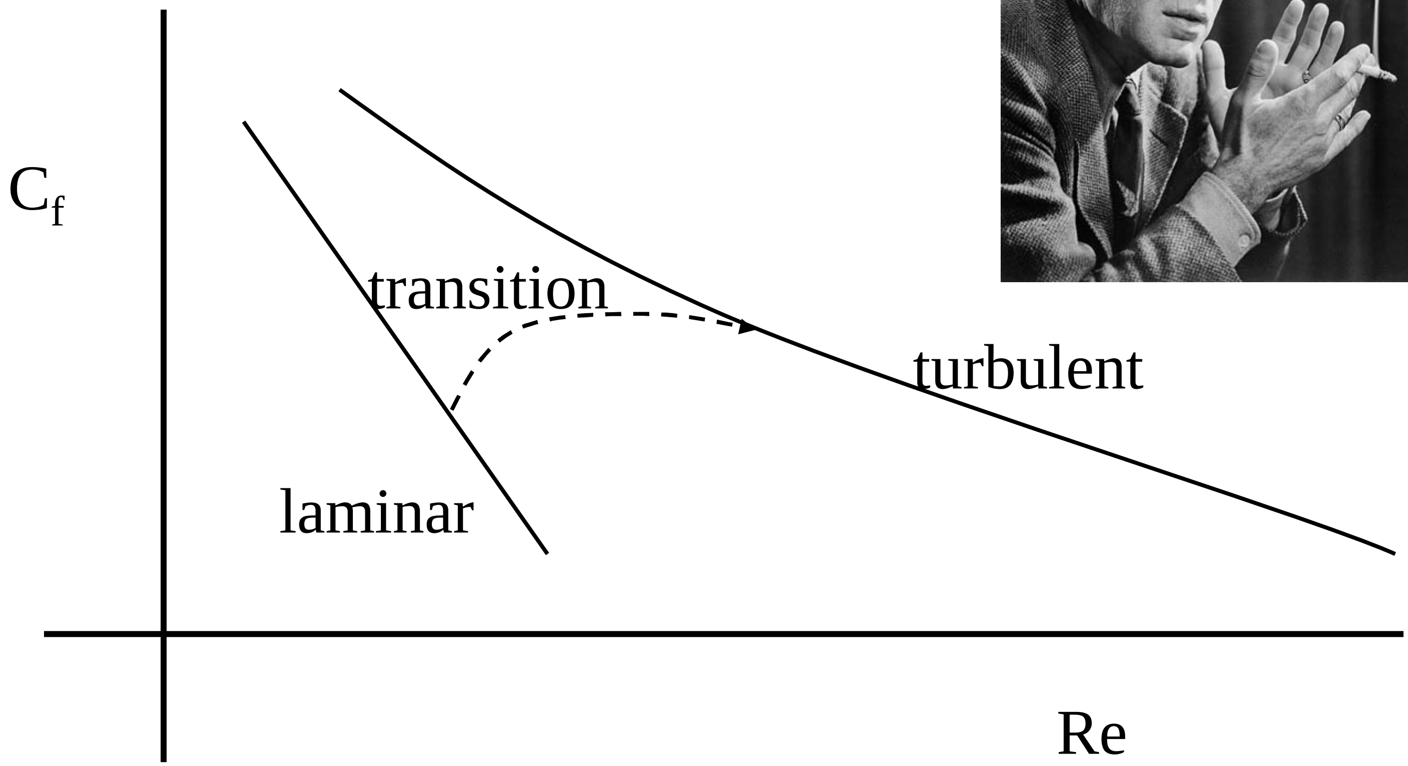



Re > 2300 : transition from laminar to turbulent flow

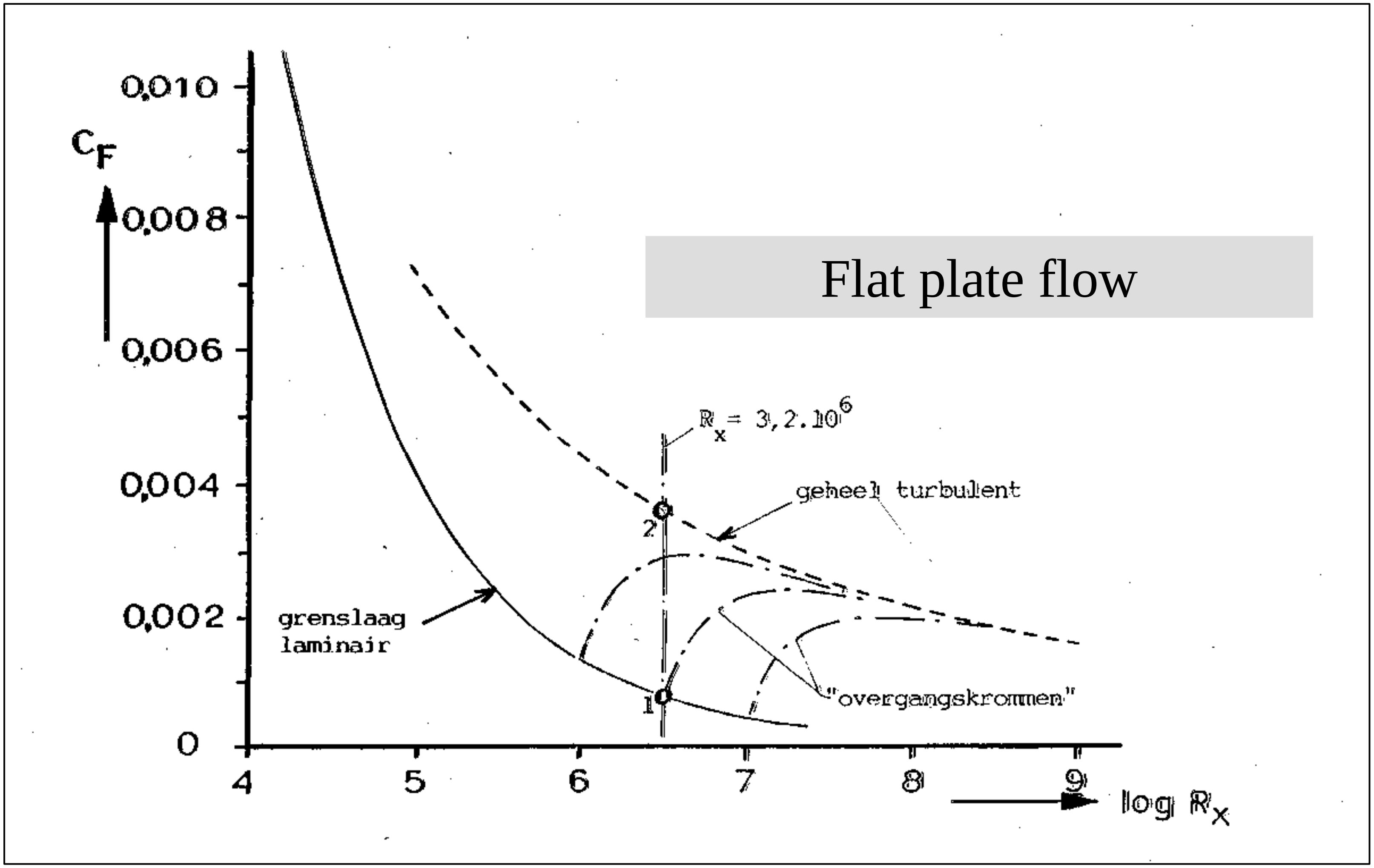
Osborne Reynolds (1842-1912)

Development of turbulent flow in pipes observed and sketched by Reynolds
(from his original paper)

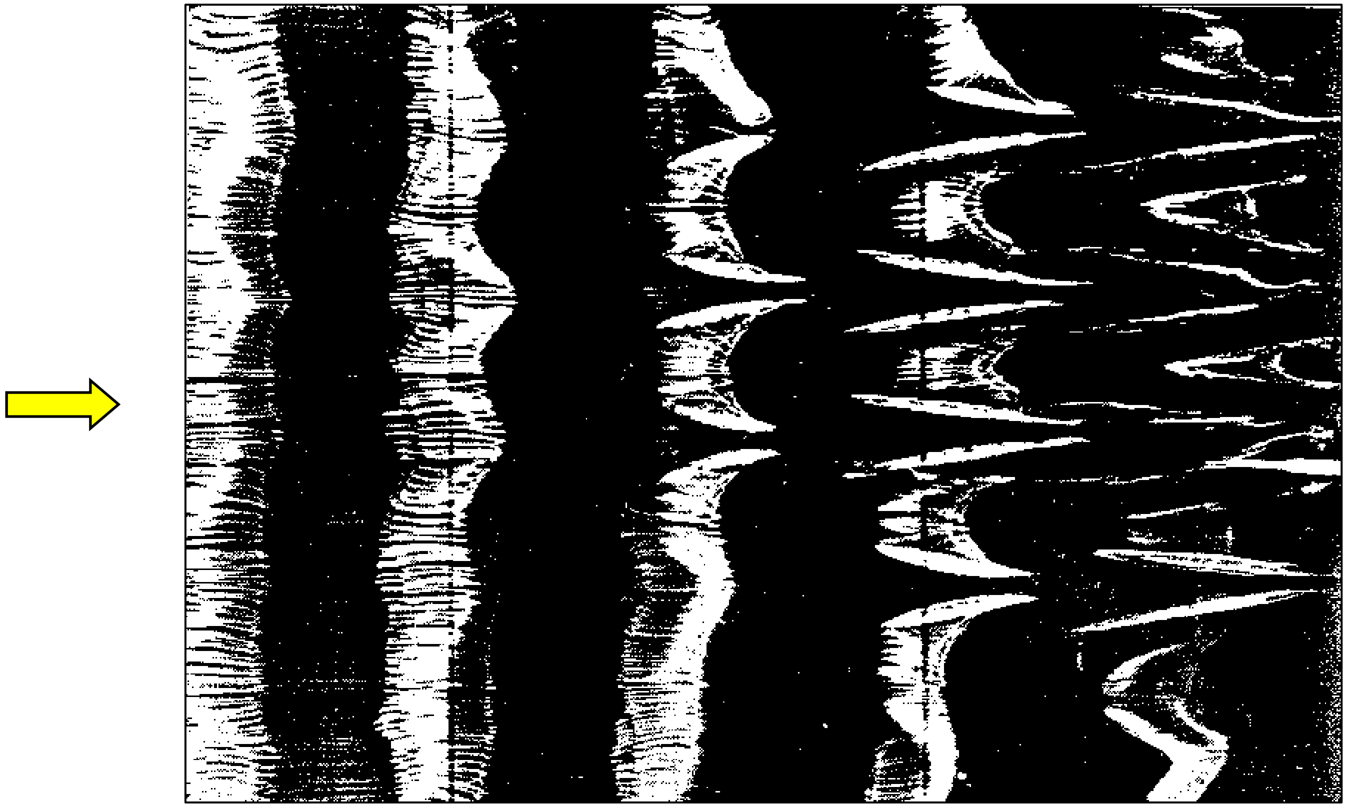
# Transition




# Transition

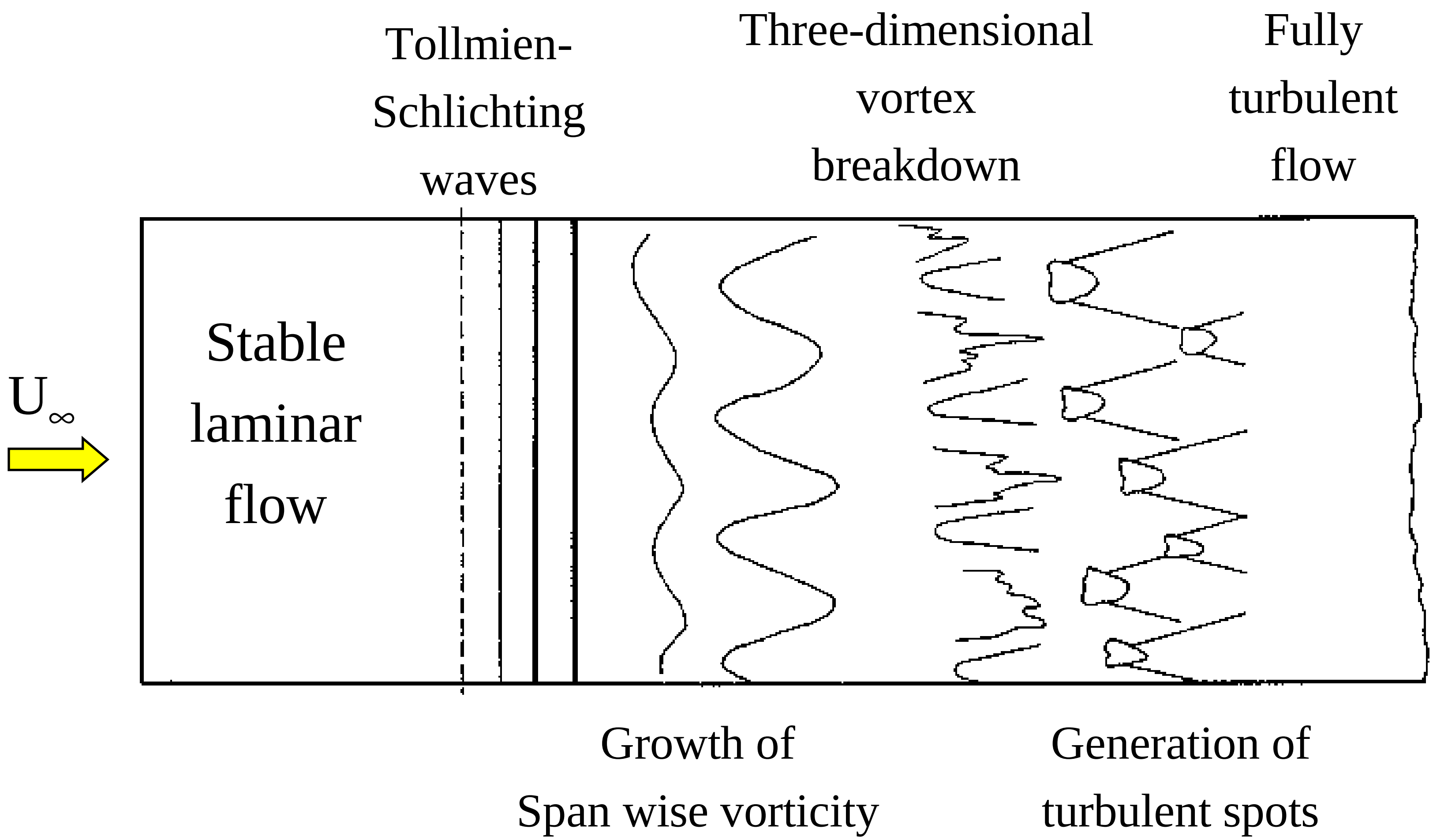

Flat plate flow
$c_F$
0,010
0,008
0,006
0,004
0,002
0
4
5
6
7
8
9
log $R_x$
$R_x = 3,2.10^6$
geheel turbulent
grenslaag
laminair
"overgangskrommen"
1
2

# Transition

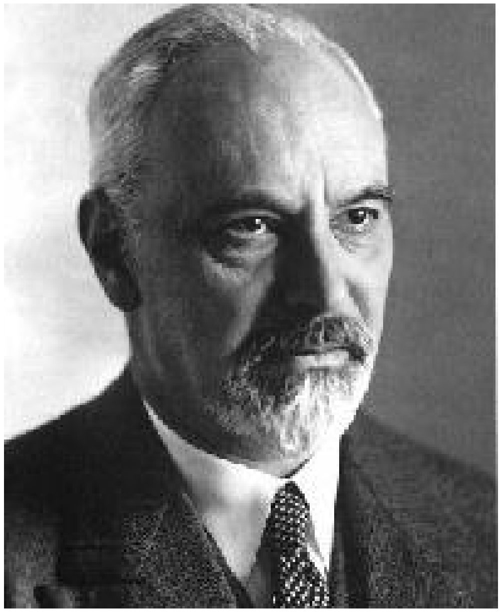


Flow visualization experiment

# Transition

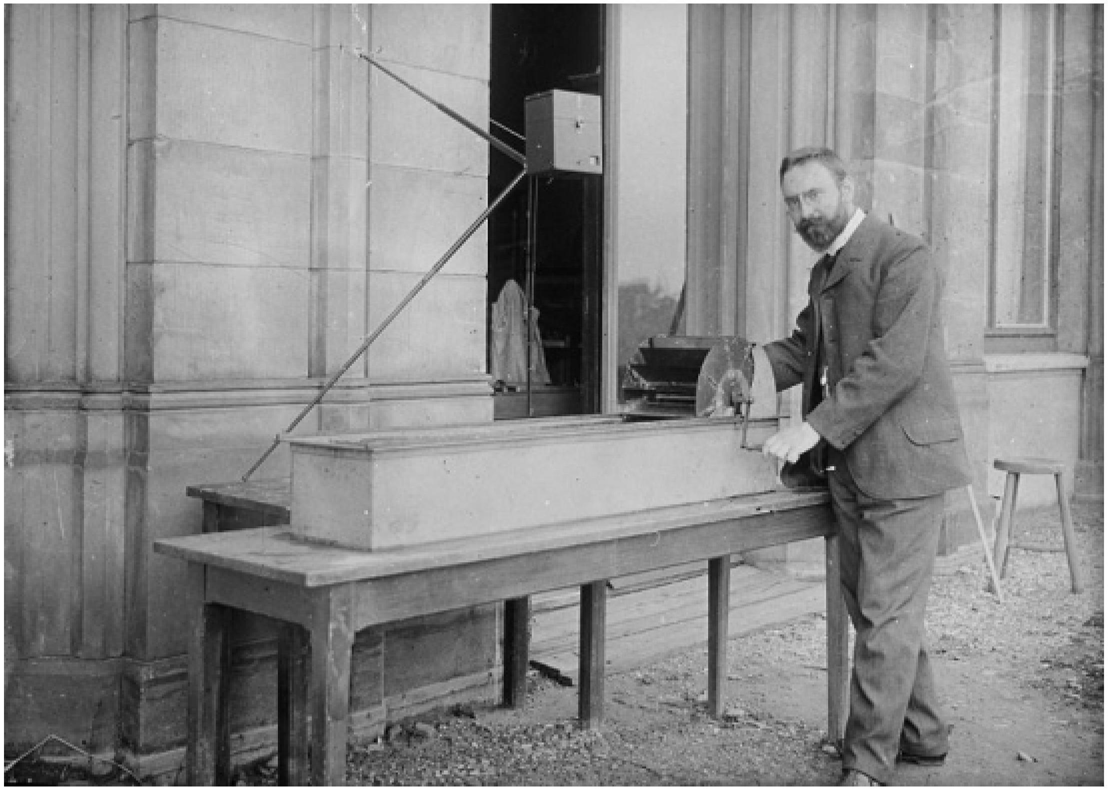

Tollmien-
Schlichting
waves
Three-dimensional
vortex
breakdown
Fully
turbulent
flow
$U_\infty$
Stable
laminar
flow
Growth of
Span wise vorticity
Generation of
turbulent spots

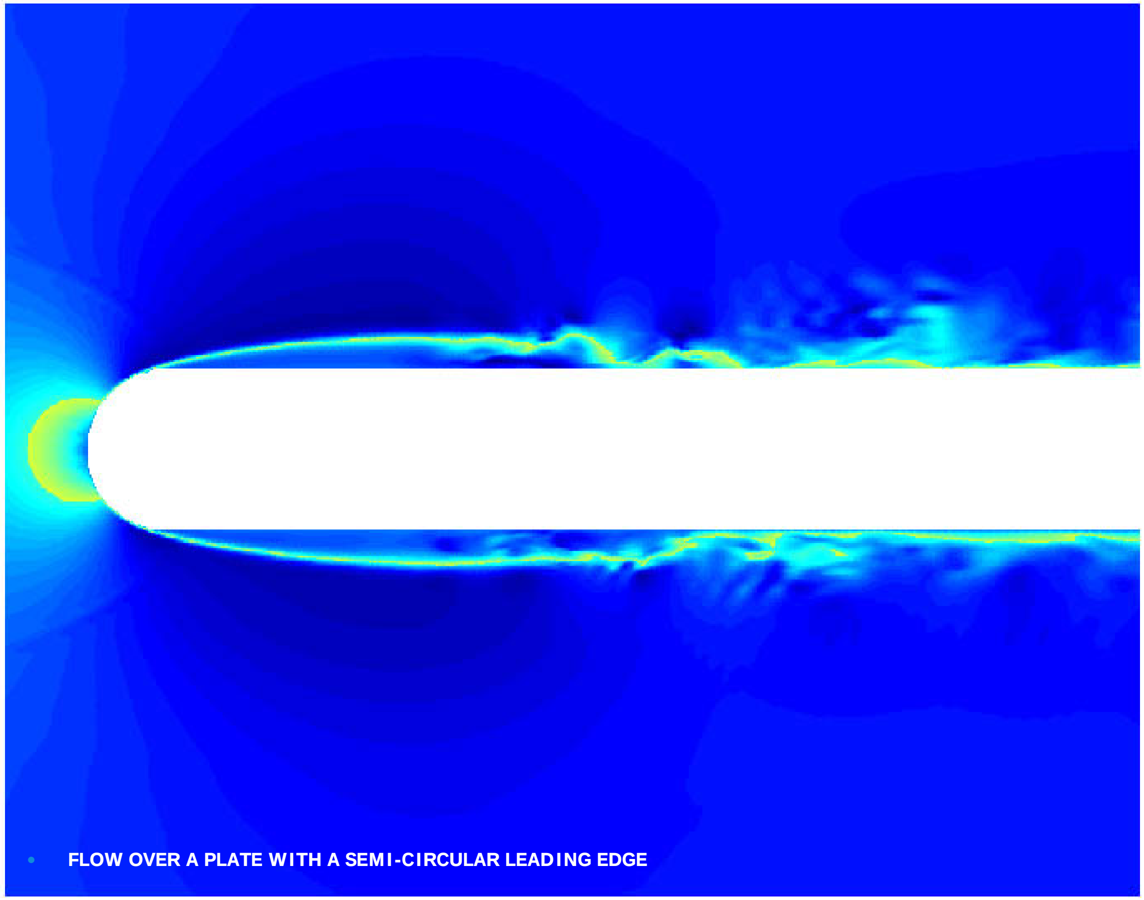
# Ludwig Prandtl (1875-1953)



- Boundary Layer theory (1904)
- Wing theory (1918 - 1919)
- Contributions to the theory of supersonic flow & turbulence
- Development of wind tunnels and other aerodynamic equipment
- Theory of plasticity and of meteorology.

- Prandtl and his water tunnel (TU Hannover 1904)





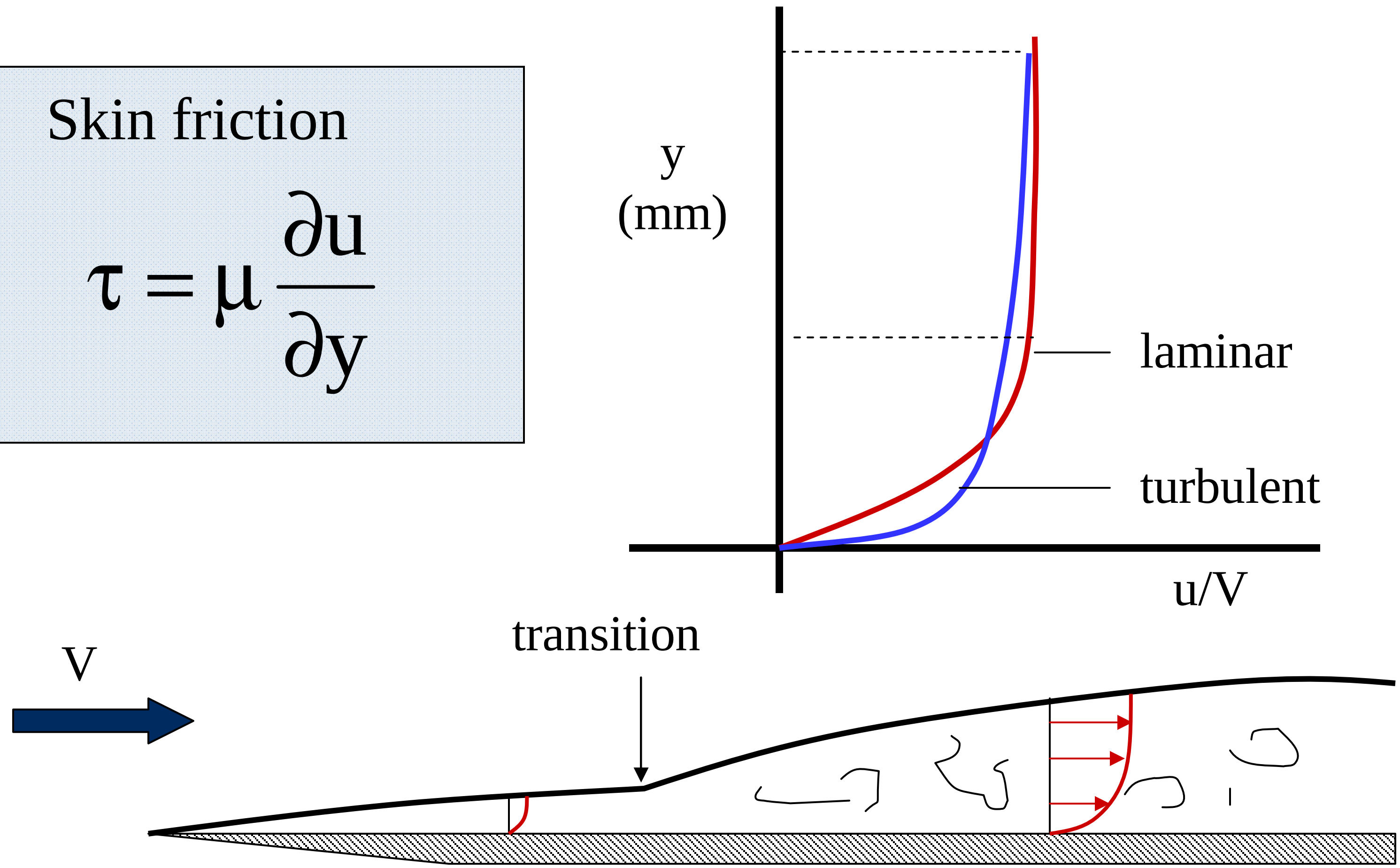

Zhiyin Yang and Peter Voke

***Fluids Research Center, University of Surrey, U.K.*** The image represents the results of a hybrid DNS/LES (by Zhiyin Yang and Peter Voke) computation of separation, transition and reattachment of the flow over a plate with a semicircular leading edge

# Transition

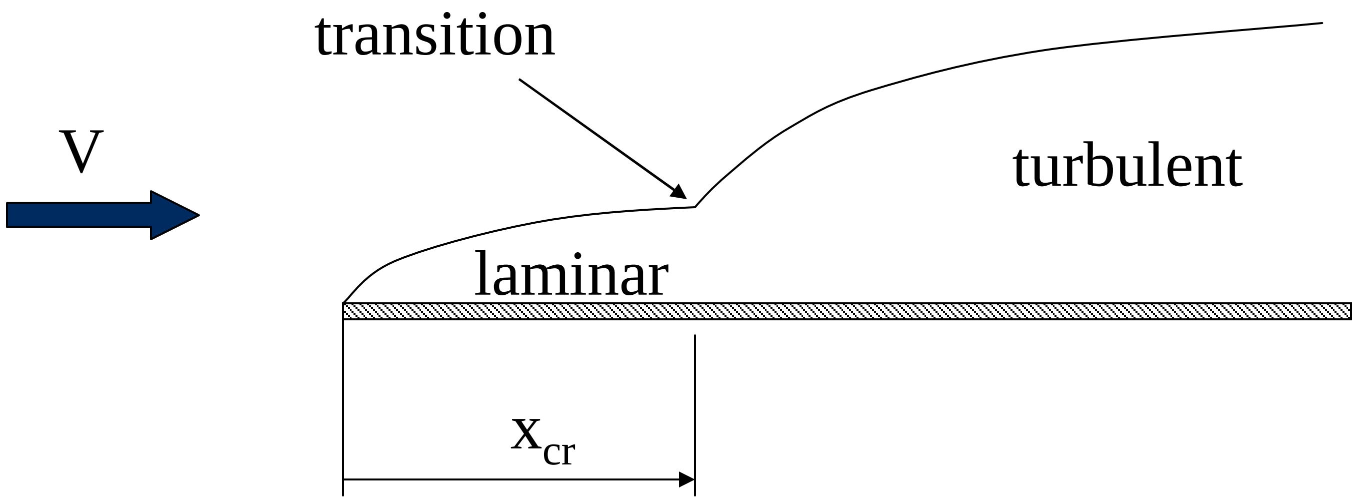
Skin friction

$$\tau = \mu \frac{\partial u}{\partial y}$$



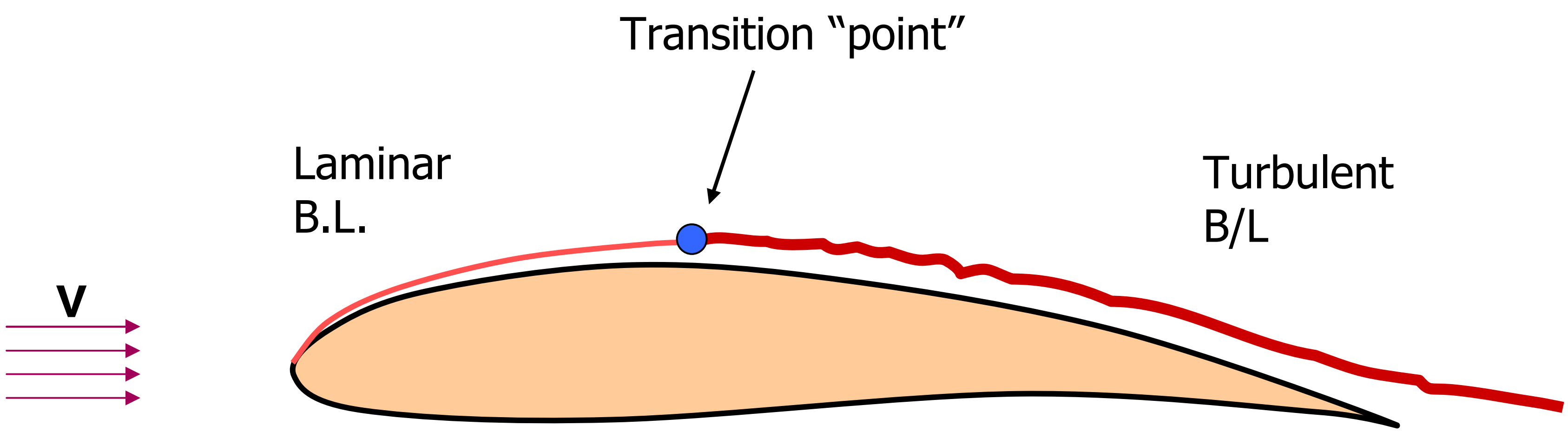

Flat plate flow

# Transition

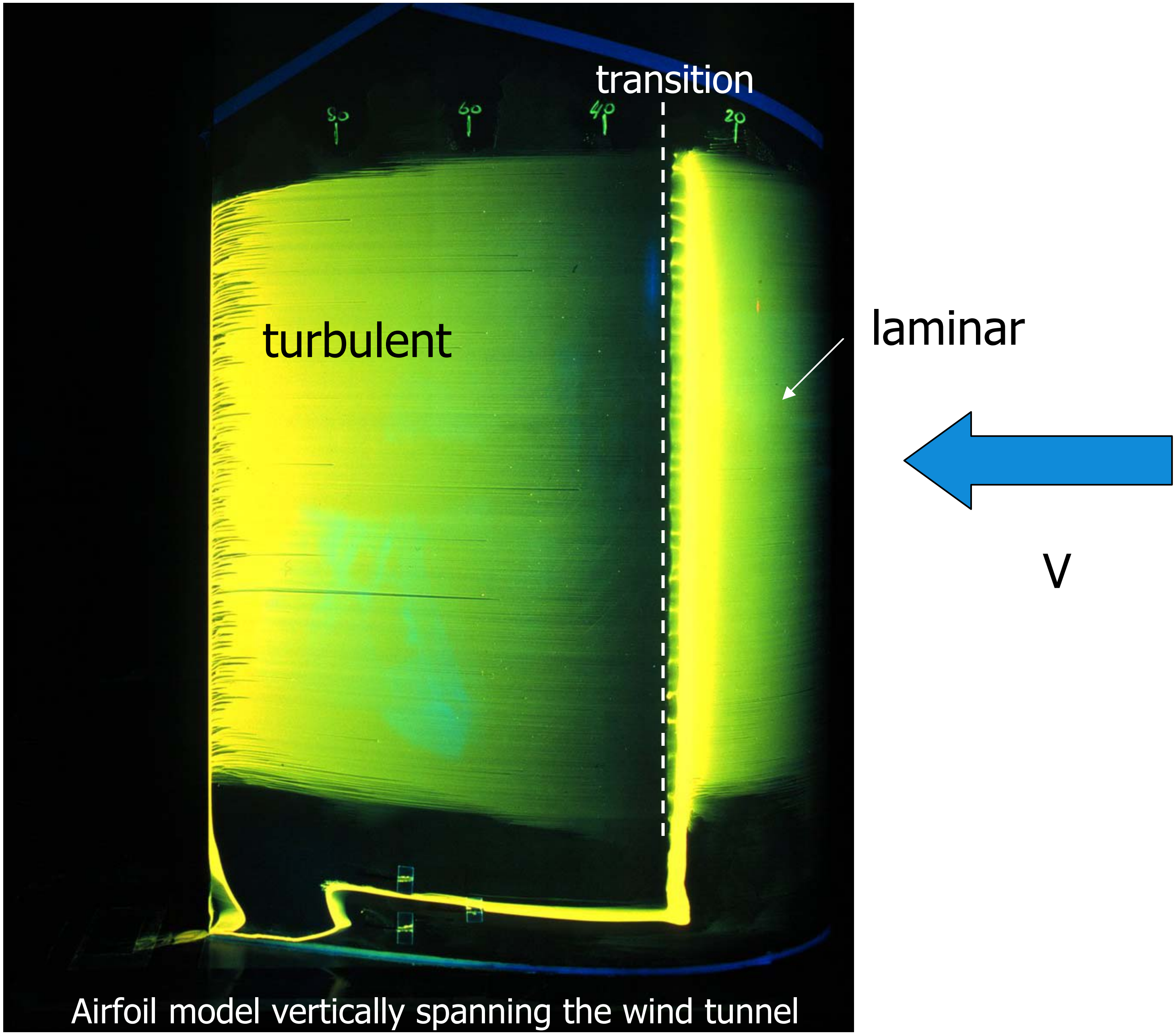



- The critical Reynolds number at which transition occurs is difficult to find.
- It should be found from experimental data applicable for the given problem

# Laminar-Turbulent Transition on airfoils



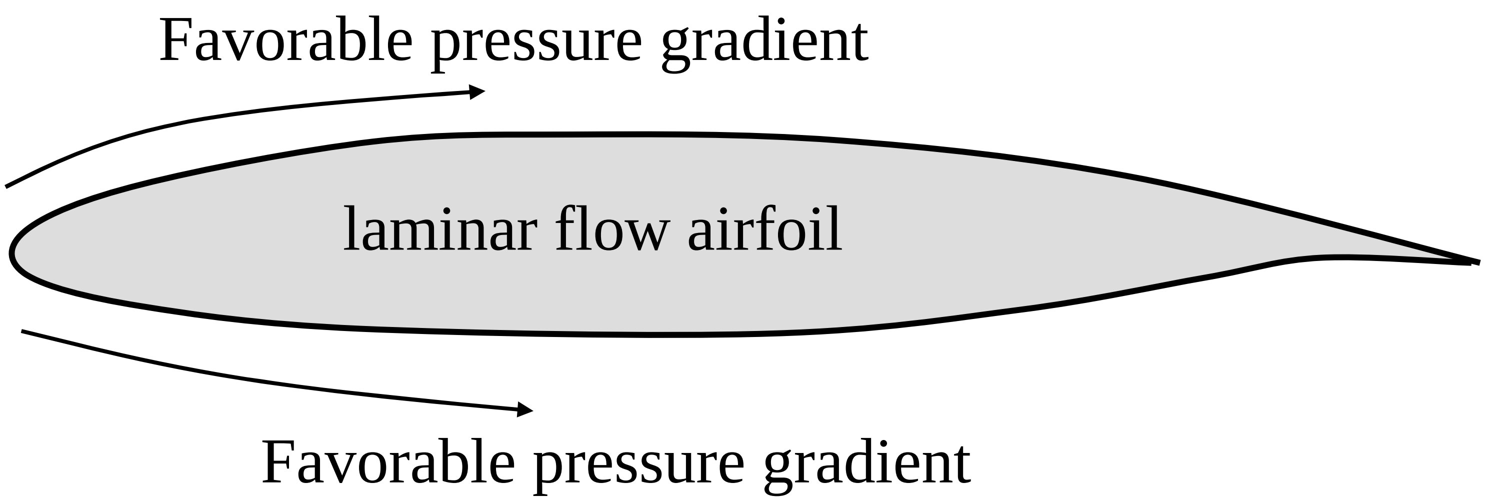

*Laminar* boundary layer: thin, low skin friction drag
*Turbulent* boundary layer: thick, high skin friction drag


transition
80
60
40
20
turbulent
laminar
V
Airfoil model vertically spanning the wind tunnel

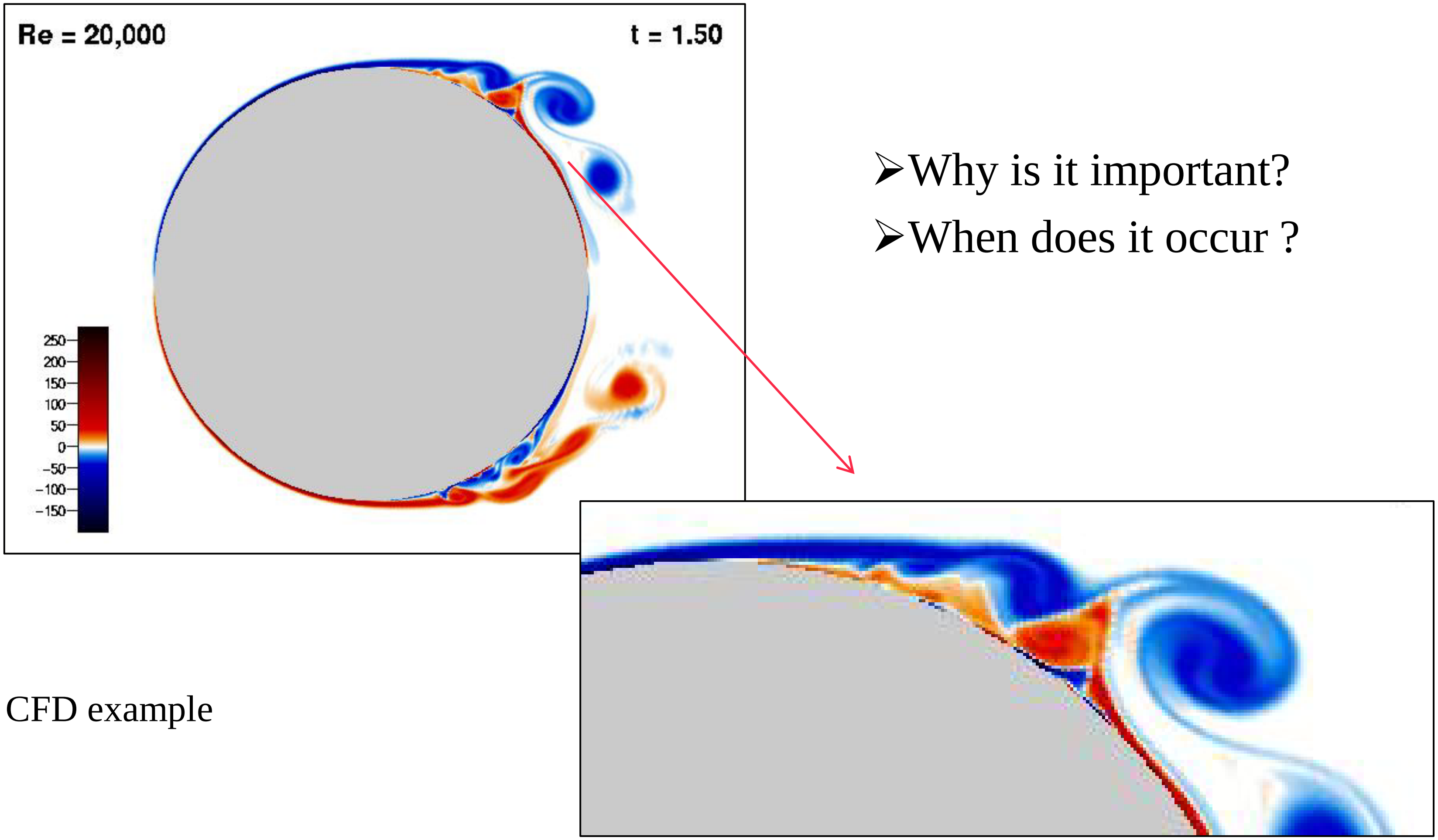
# Laminar flow favourable

We have seen that : $\tau_{w_{laminar}} < \tau_{w_{turbulent}}$

**Vast majority of flows is TURBULENT** ! =>
We may adapt the geometry of the airfoil such that it favors laminar flow. We then have **Laminar flow airfoils.**



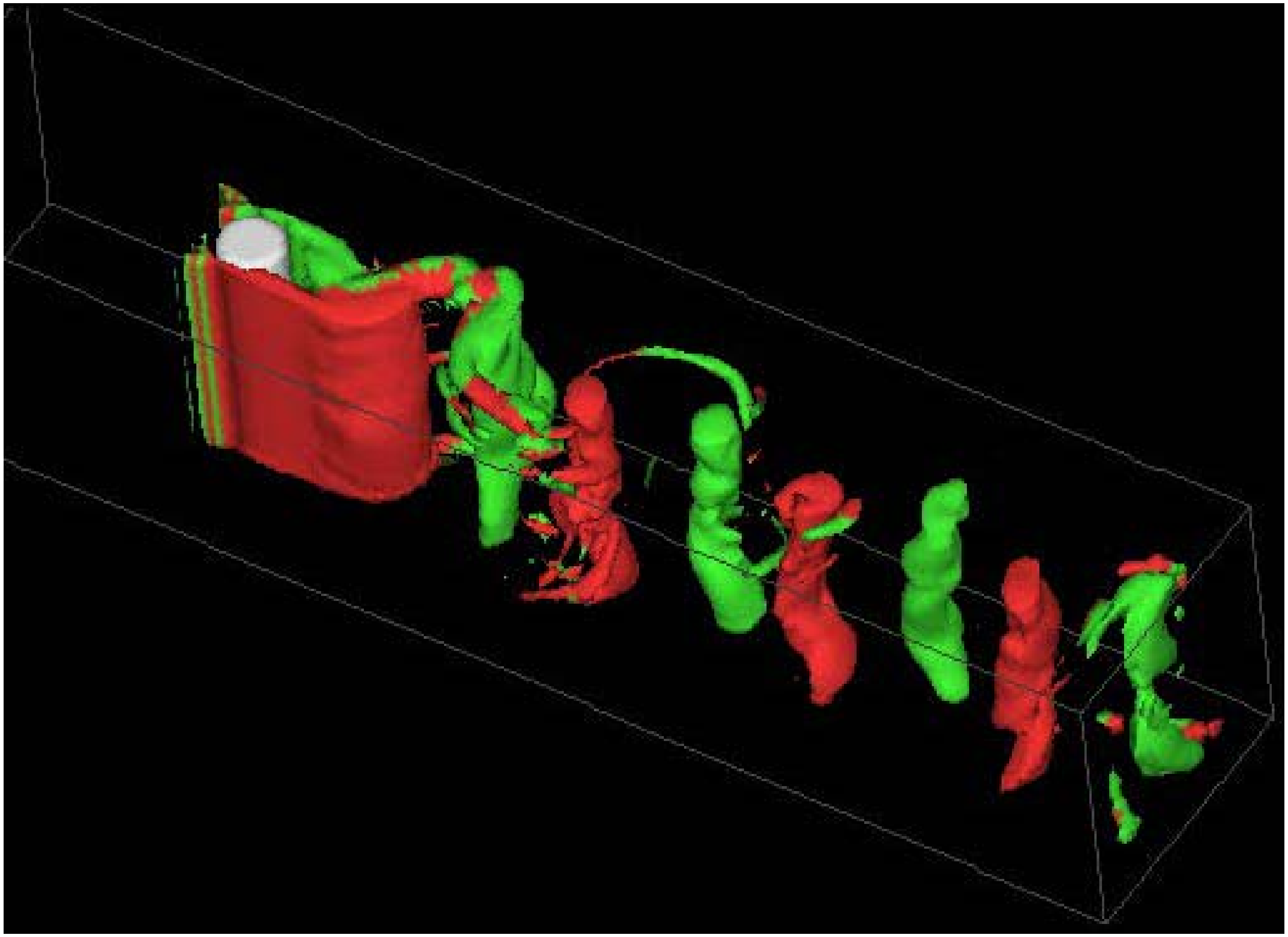
# Flow Separation



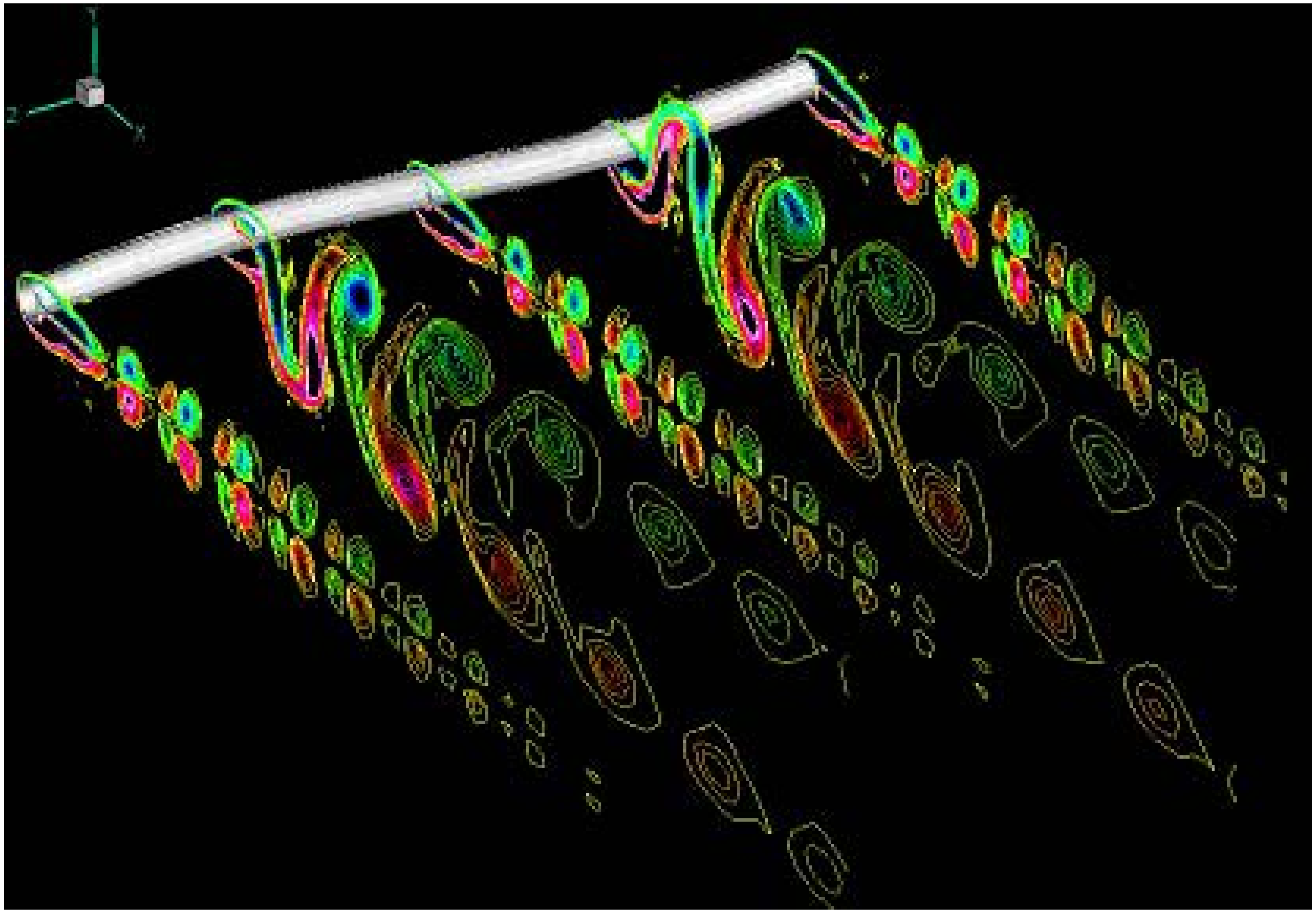

- Why is it important?
- When does it occur ?

CFD example

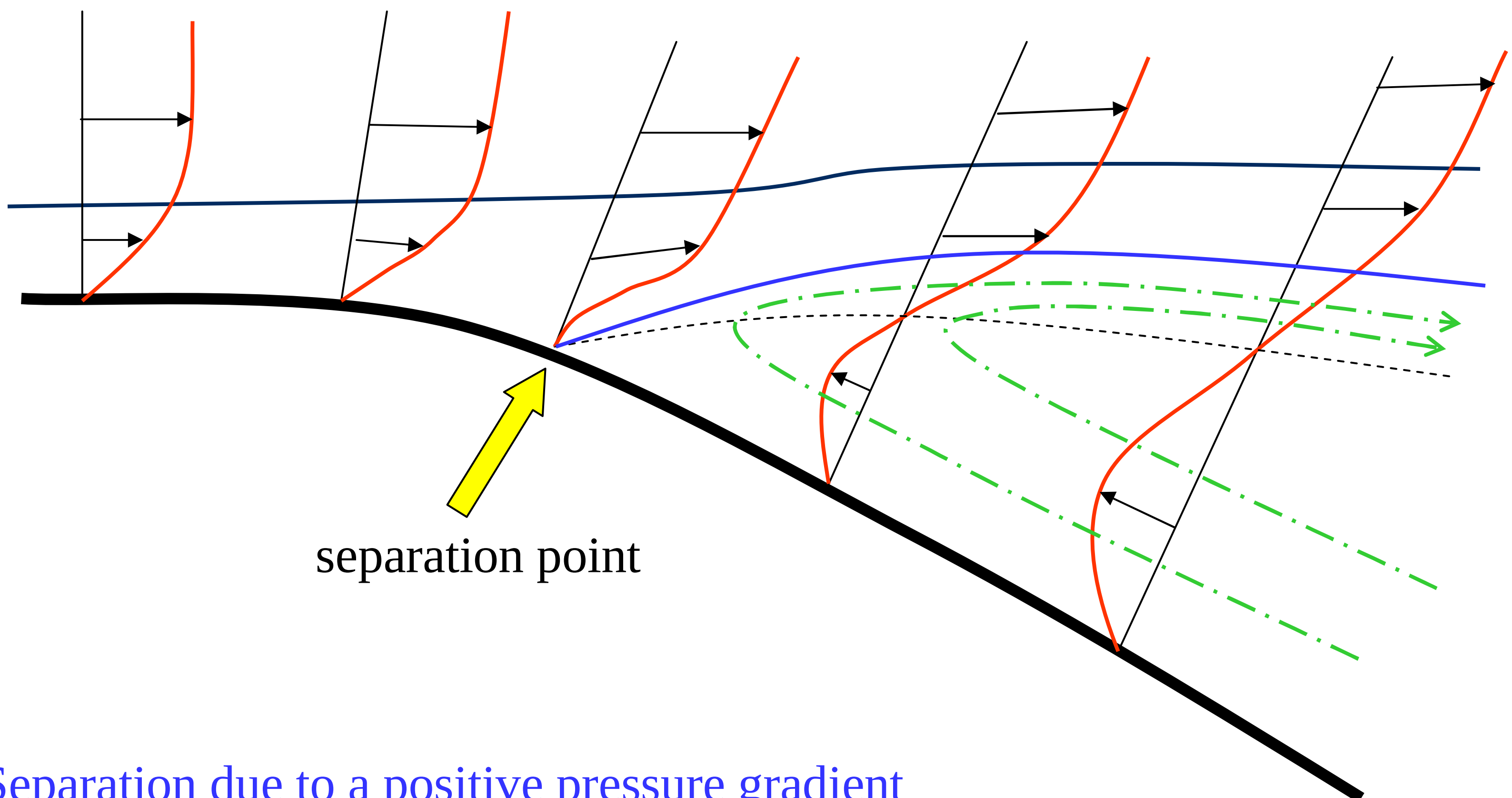
## Alternating separating vortices on a cilinder (Karman street)



# Unsteady behavior of construction due to separation

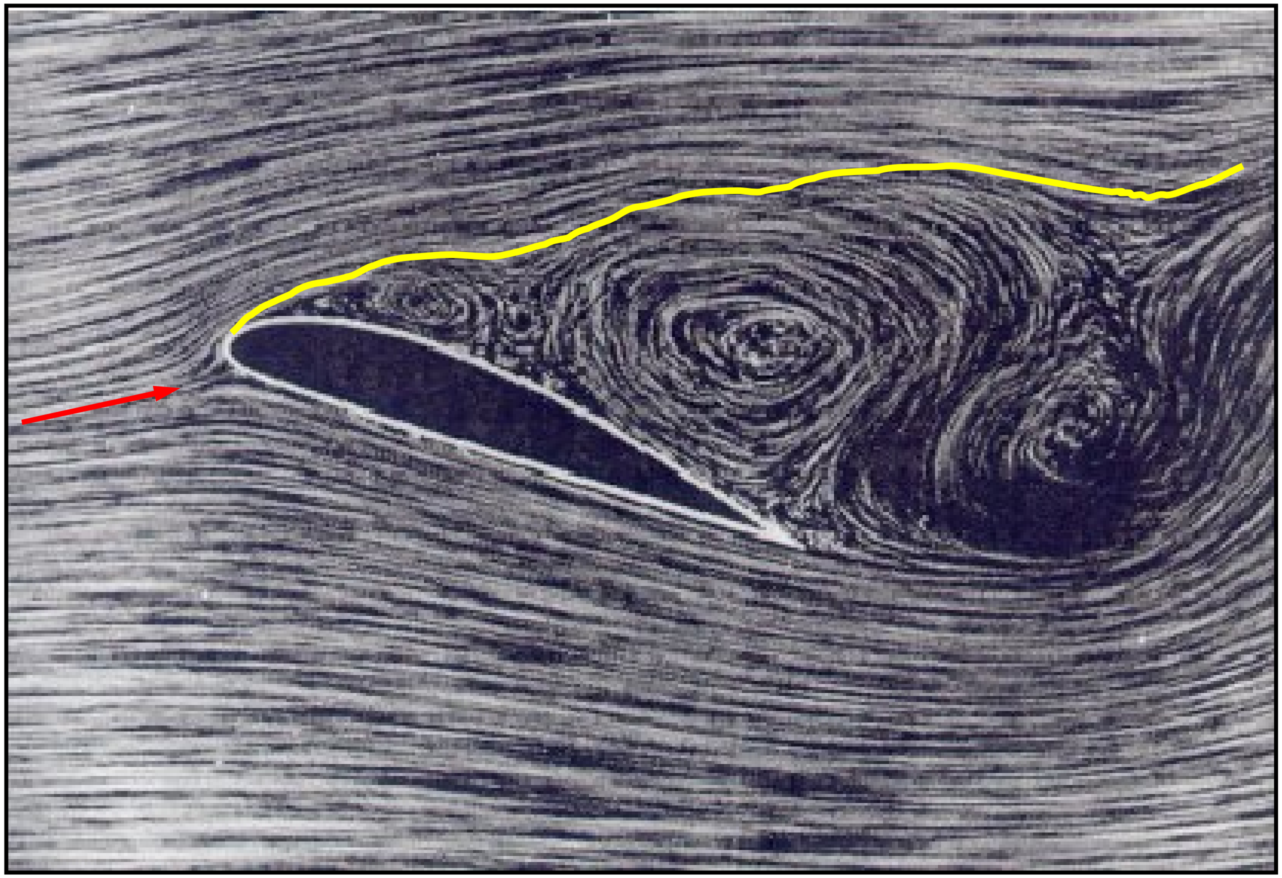


# Flow separation




Separation due to a positive pressure gradient

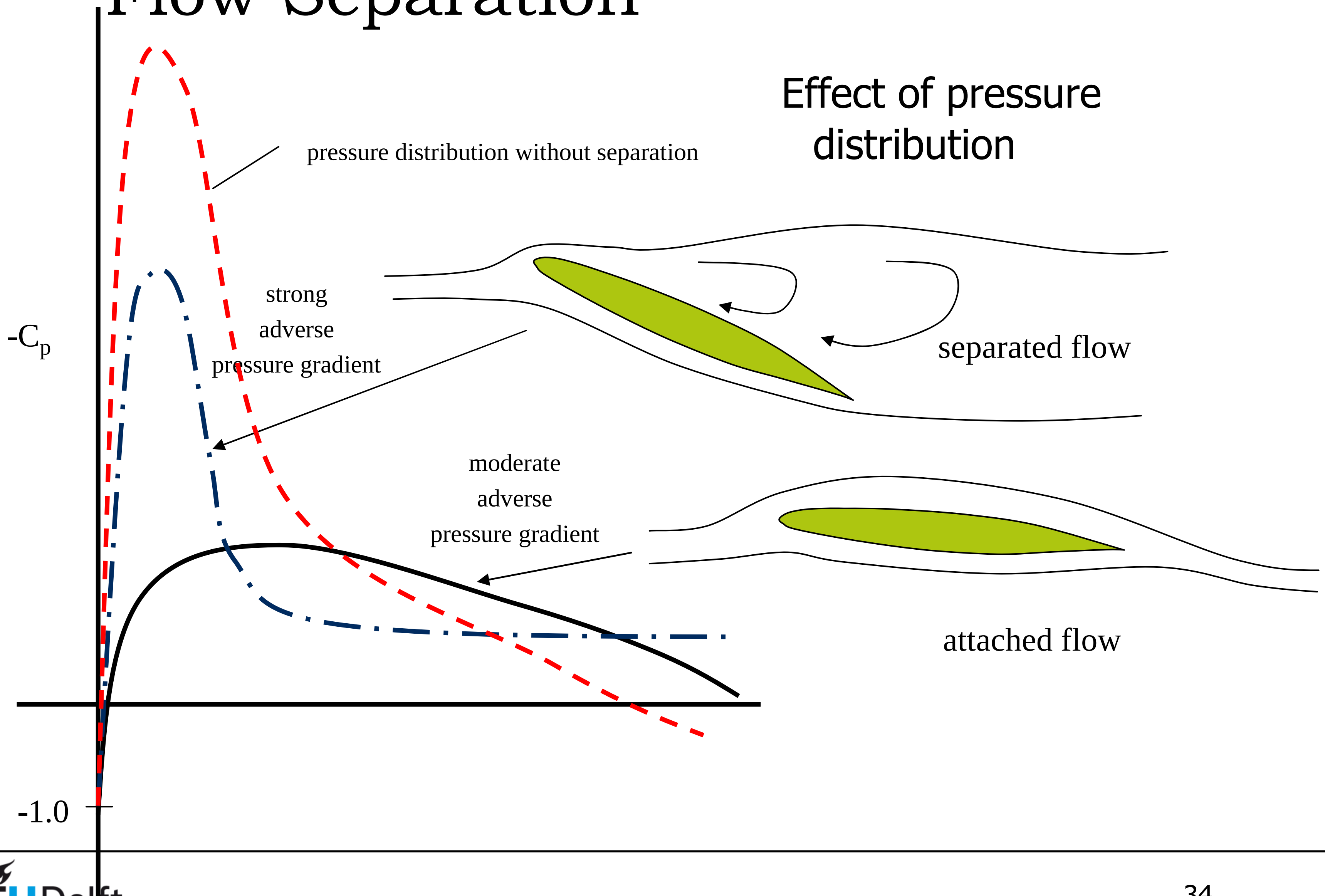
# Separation

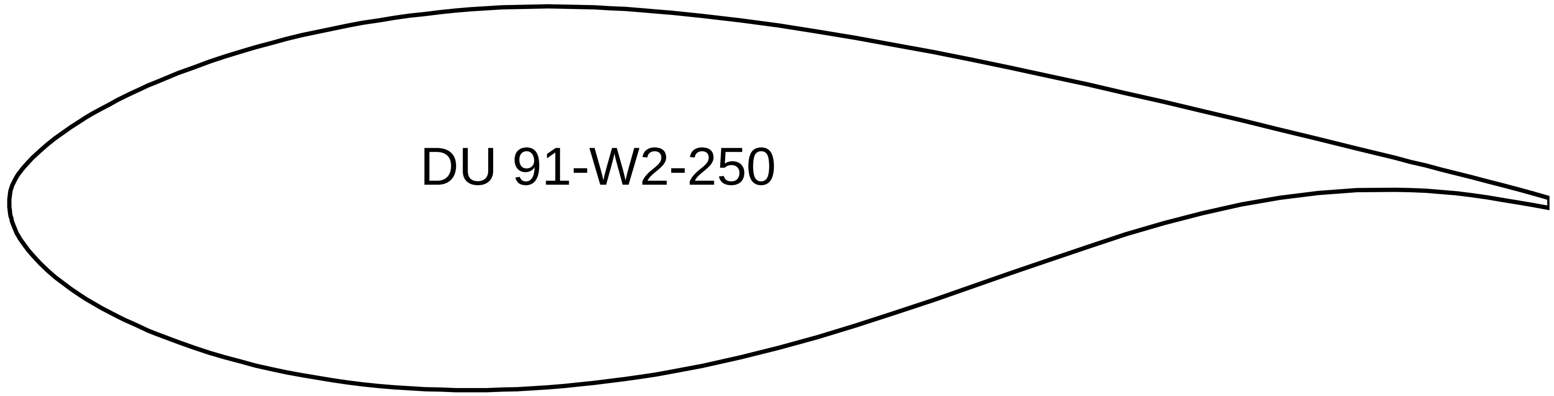


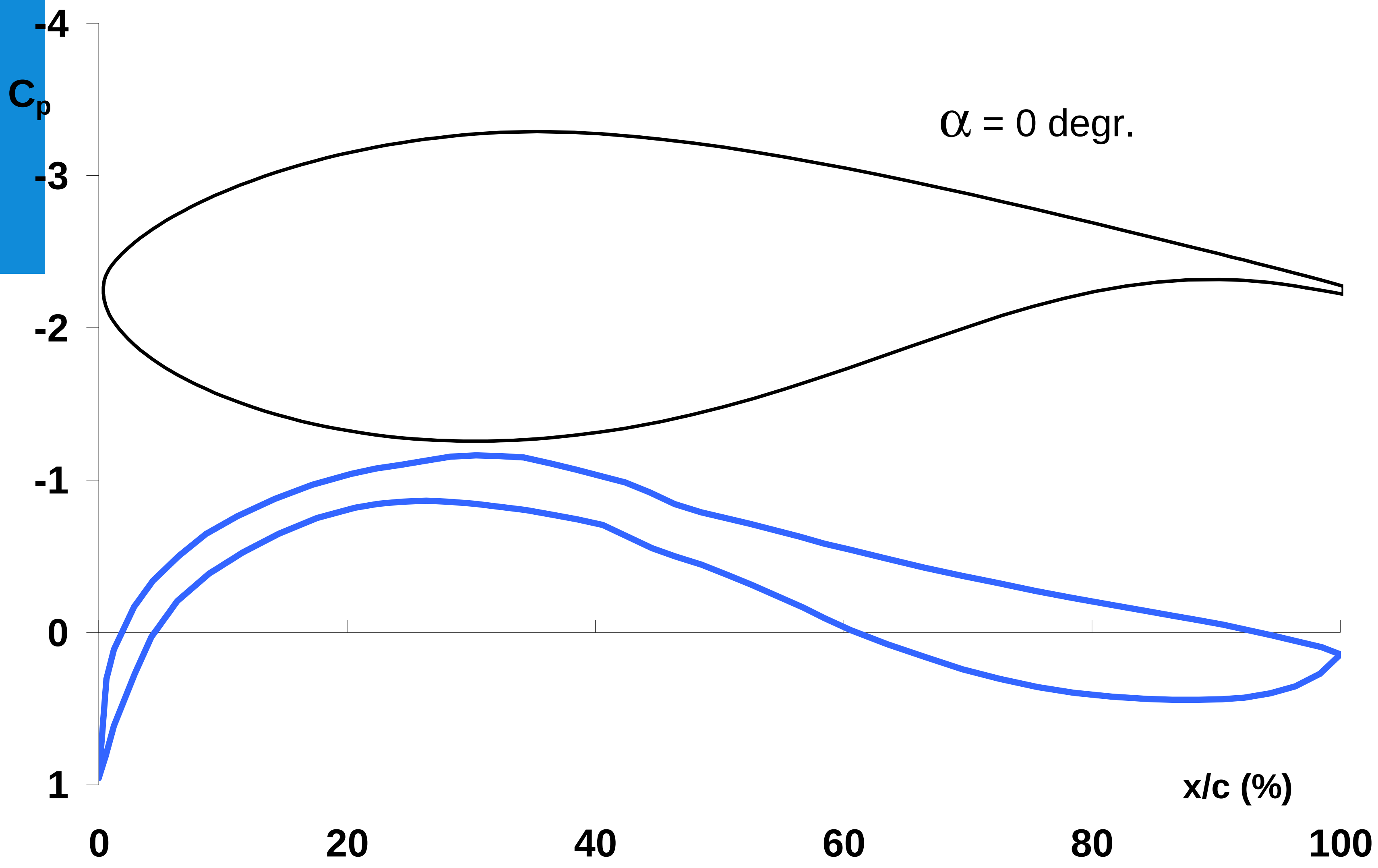
From:
Van Dyke:
*"An Album of fluid motion"*

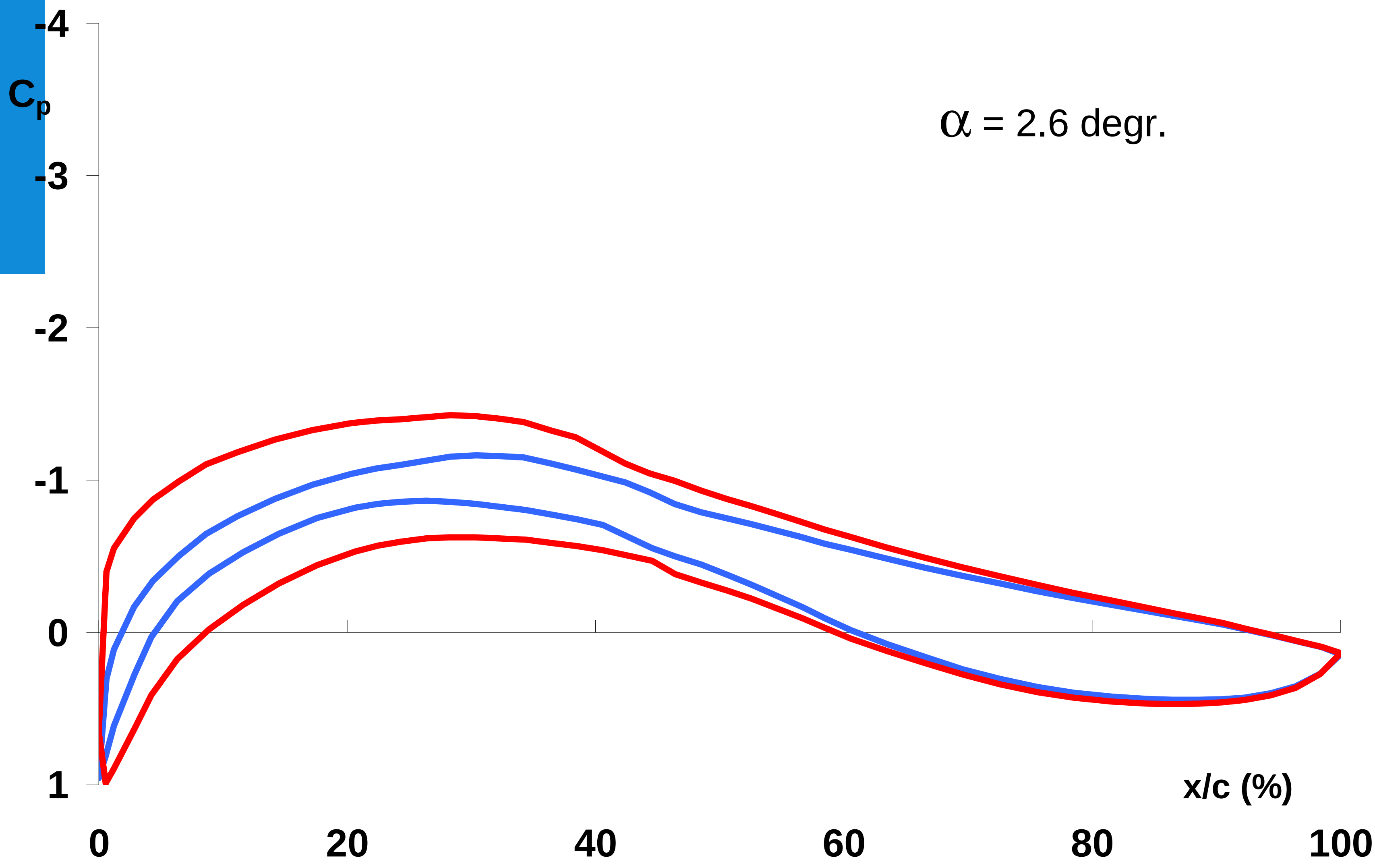
aluminum
powder
in water

# Flow Separation

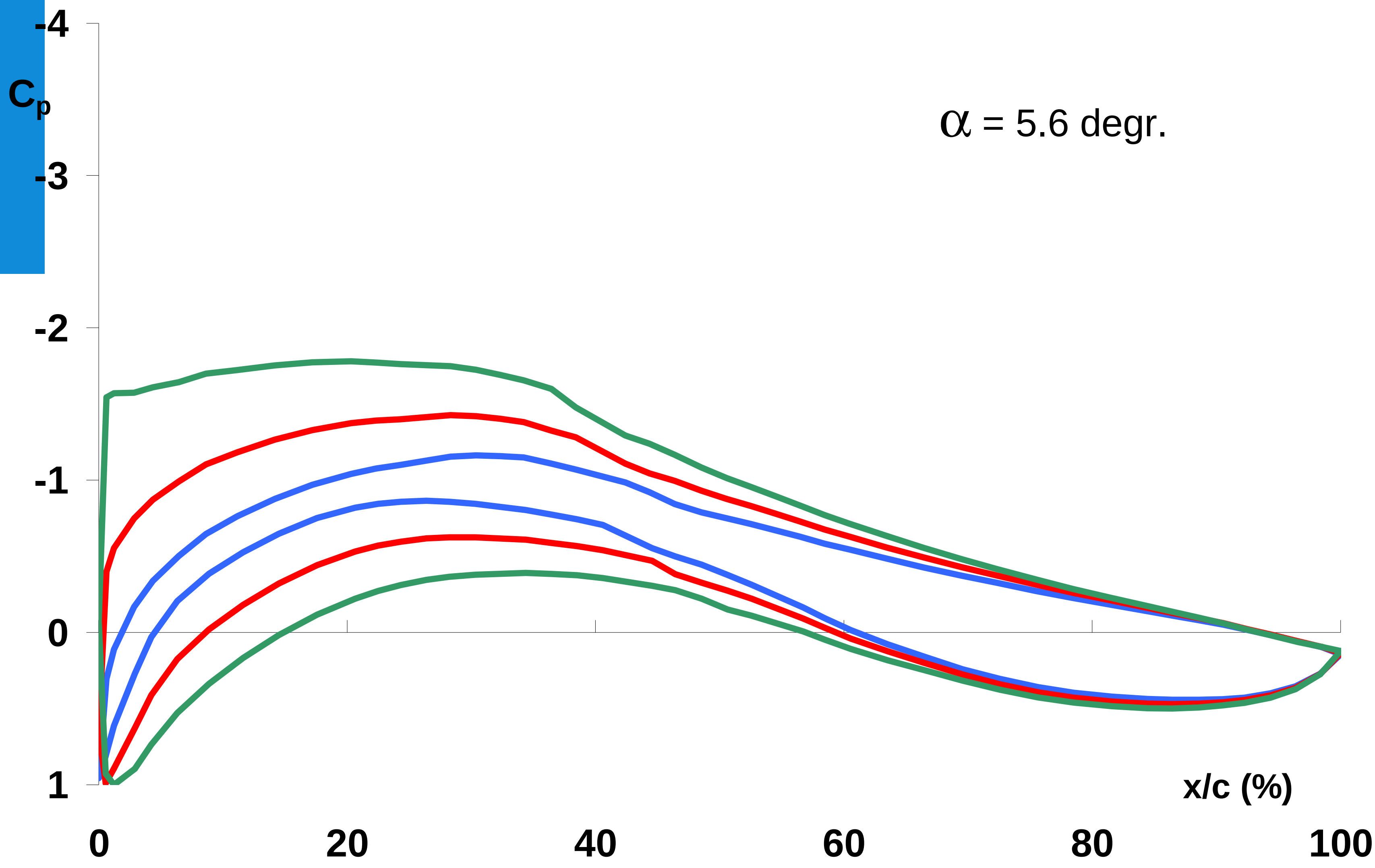



DU 91-W2-250

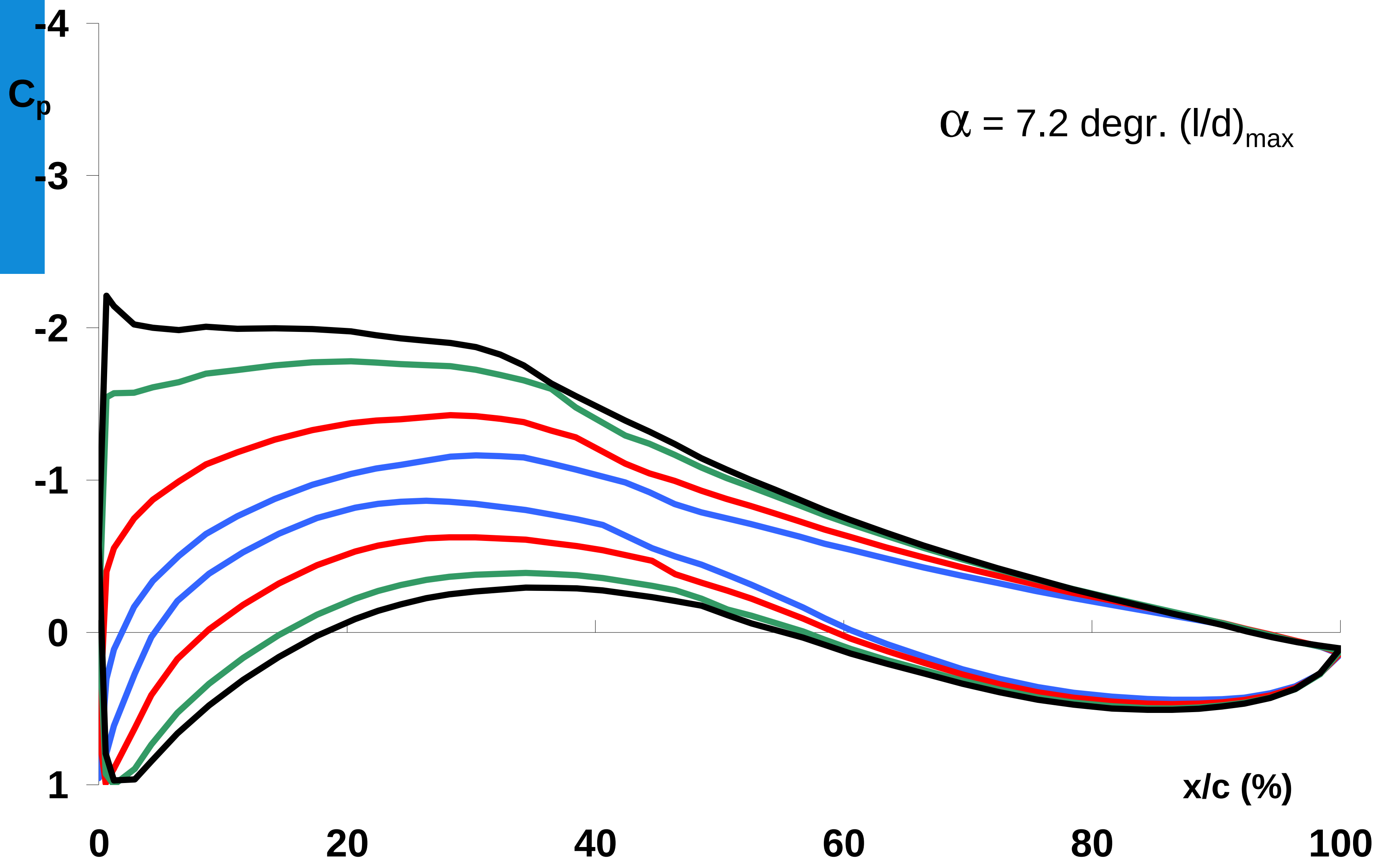

-4
Cp
-3
-2
-1
0
1
α = 0 degr.
x/c (%)
0
20
40
60
80
100

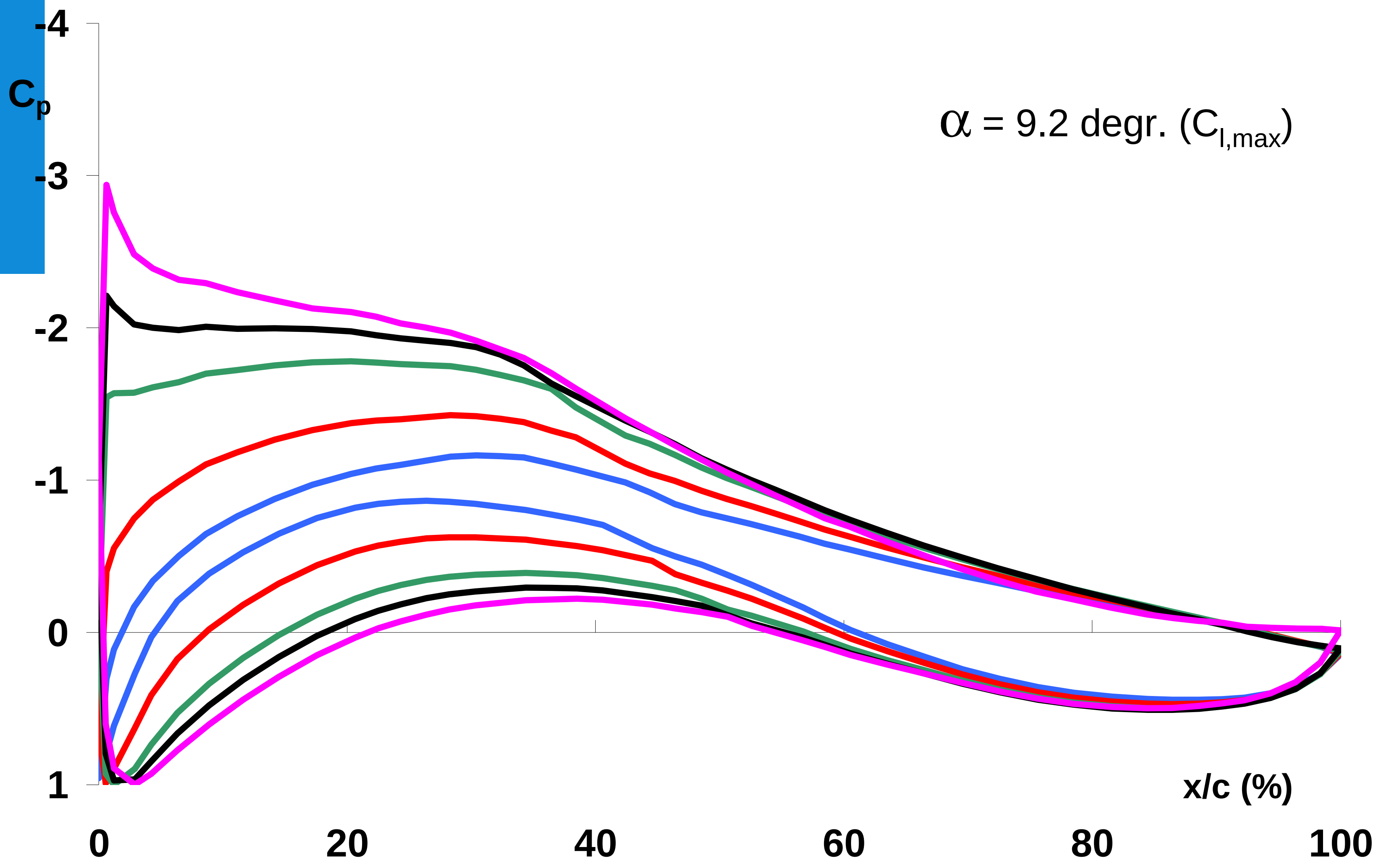


-4
Cp
-3
-2
-1
0
1
α = 2.6 degr.
x/c (%)
0
20
40
60
80
100

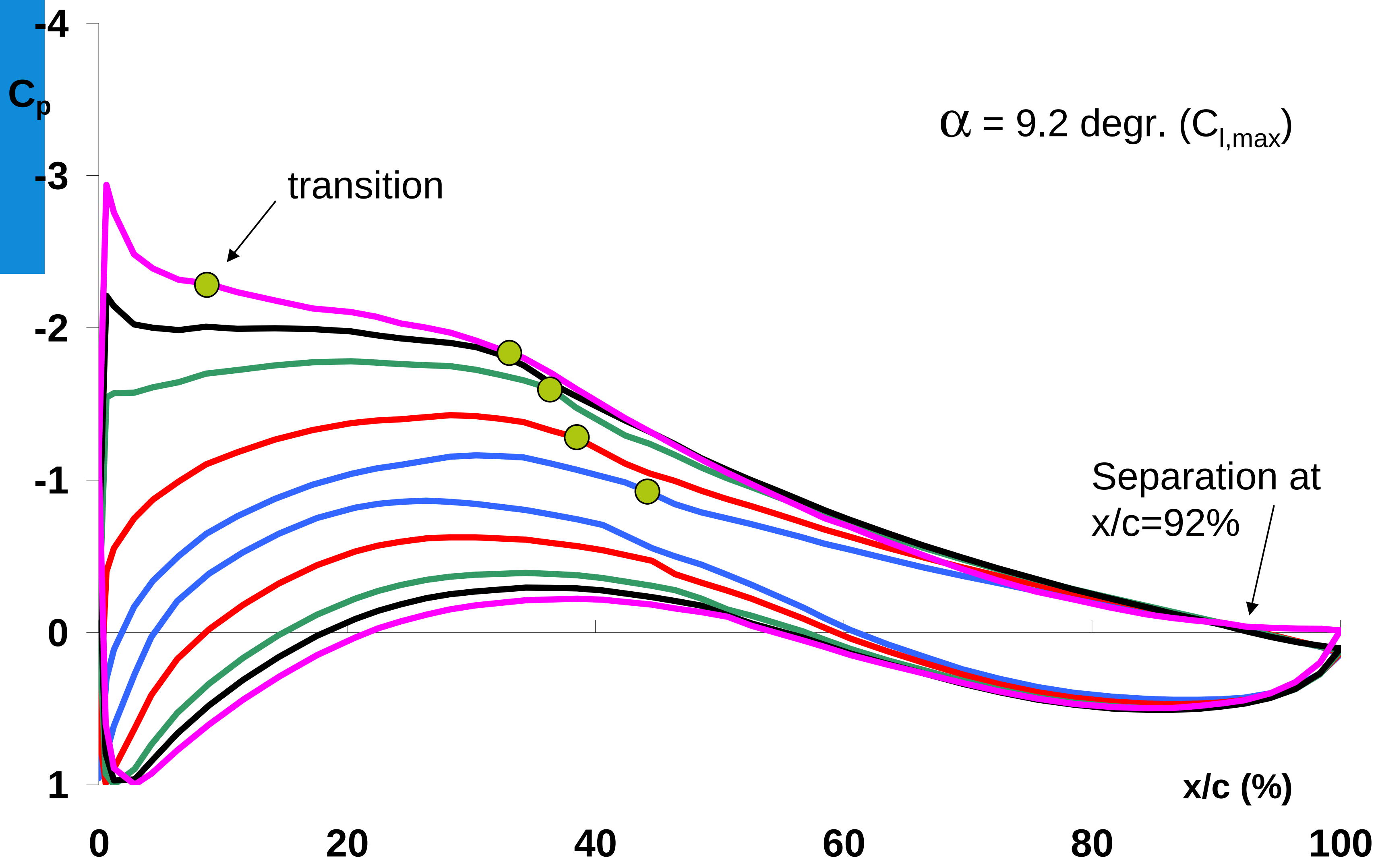


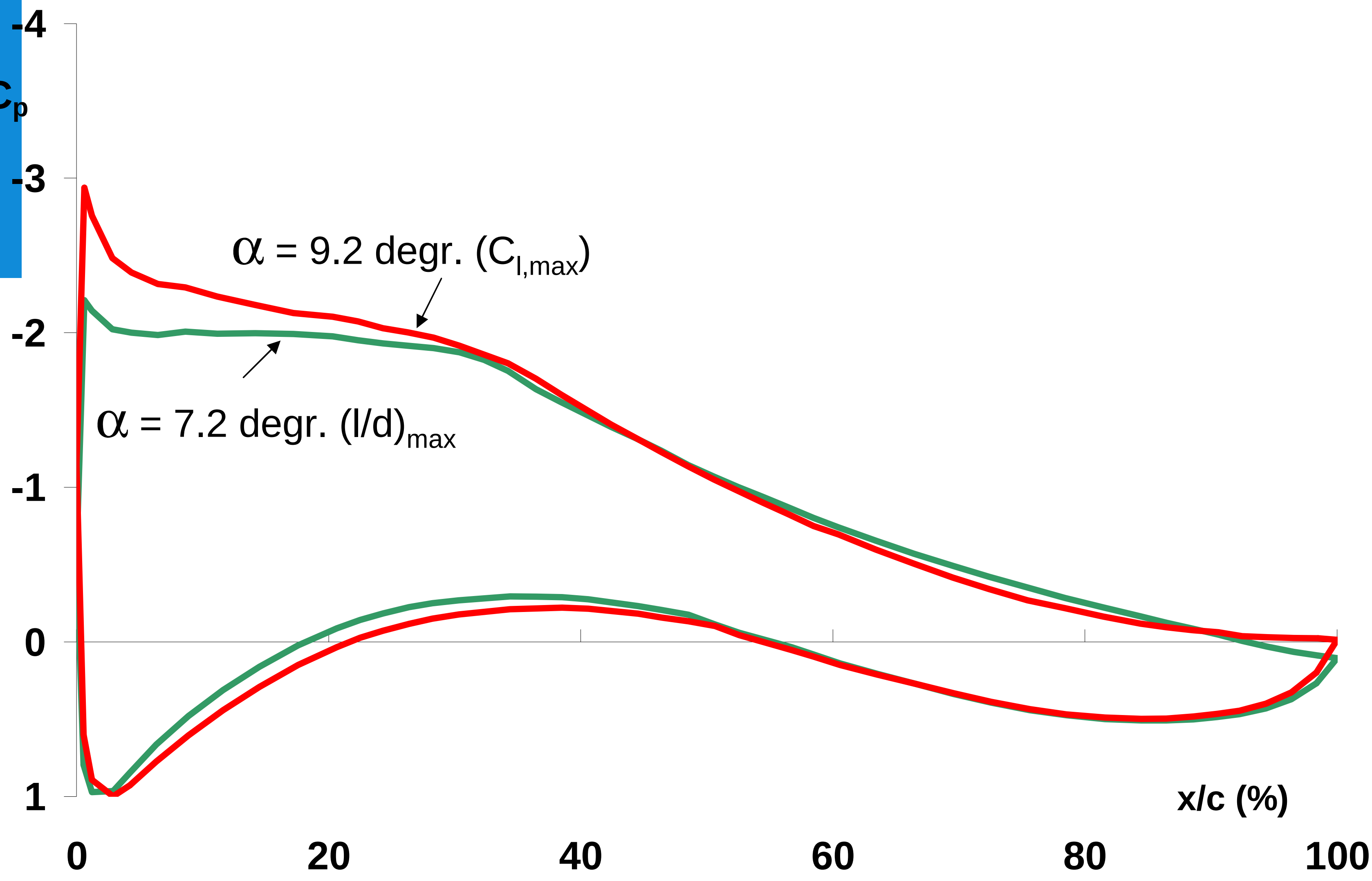
-4
$C_p$
-3
-2
-1
0
1
α = 5.6 degr.
x/c (%)
0
20
40
60
80
100


-4
Cp
-3
-2
-1
0
1
α = 7.2 degr. (l/d)max
x/c (%)
0
20
40
60
80
100

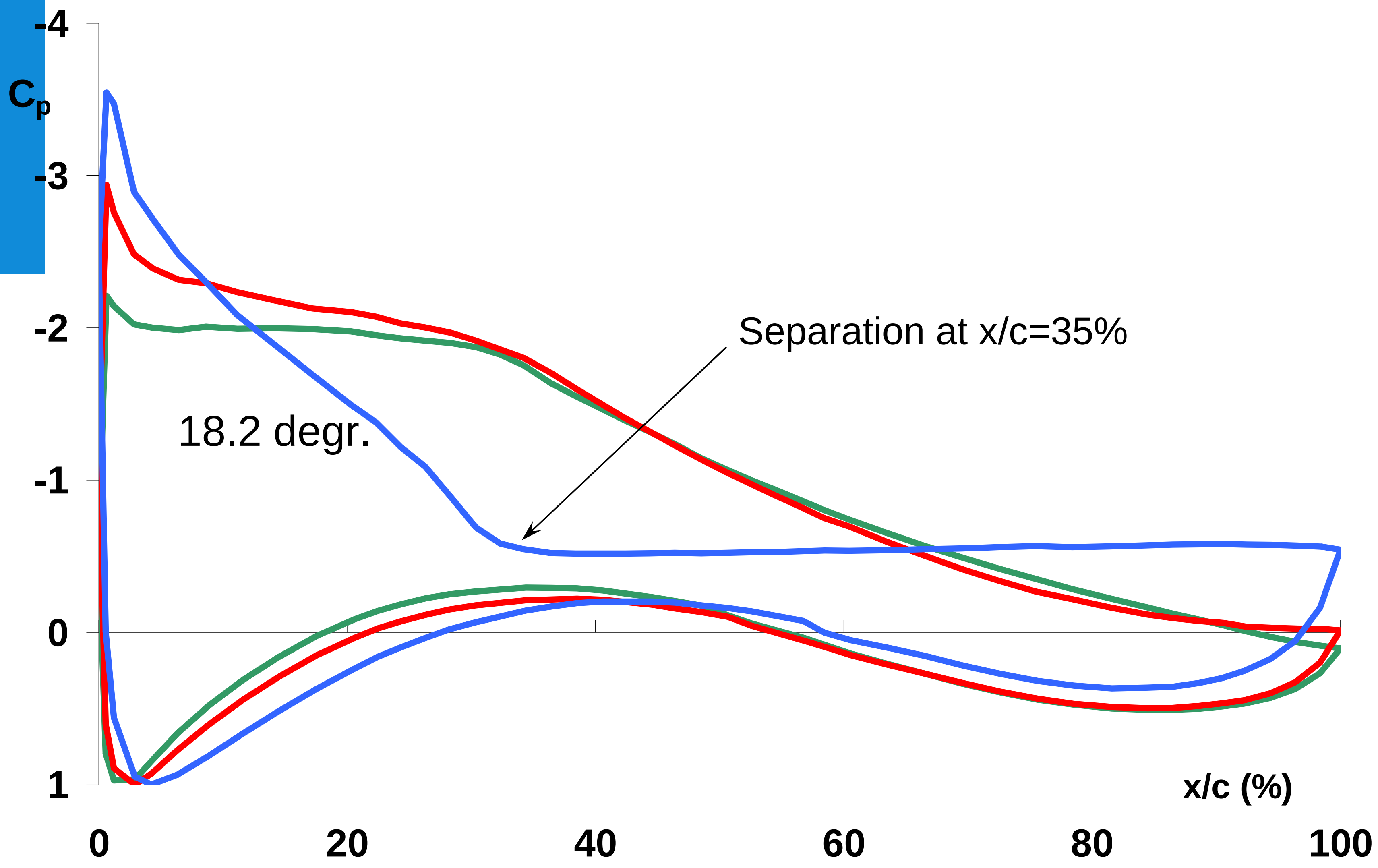



TU Delft


-4
Cp
-3
-2
-1
0
1
α = 9.2 degr. ($C_{l,max}$)
transition
Separation at
x/c=92%
x/c (%)
0
20
40
60
80
100



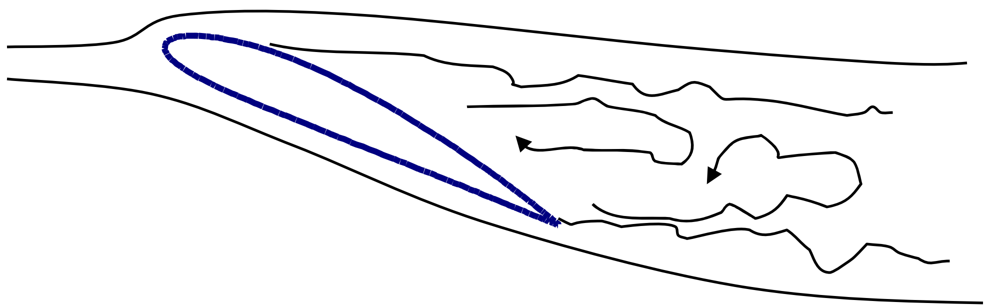
-4
Cp
-3
α = 9.2 degr. (Cl,max)
-2
α = 7.2 degr. (l/d)max
-1
0
1
x/c (%)
0
20
40
60
80
100

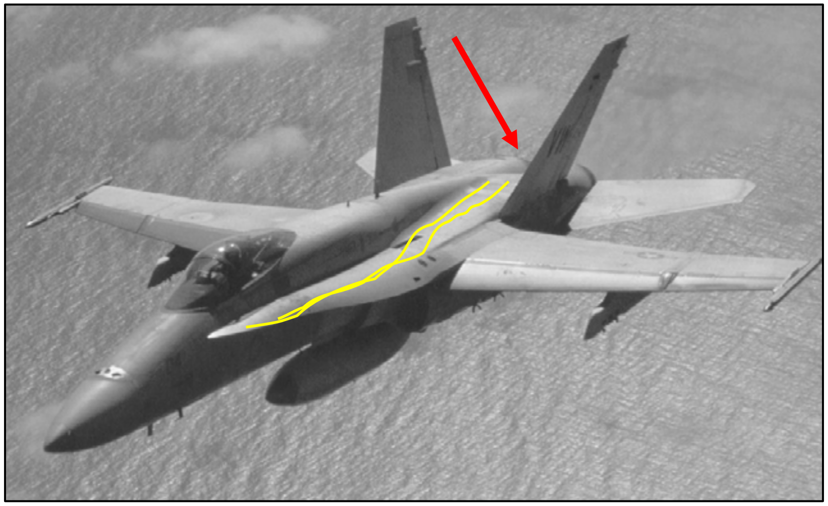

-4
Cp
-3
-2
-1
0
1
0
20
40
60
80
100
x/c (%)
18.2 degr.
Separation at x/c=35%

# Flow Separation

Why is it important ?

- Loss in lift (airfoil)
- Increase in pressure drag
- Generation of unsteady loads

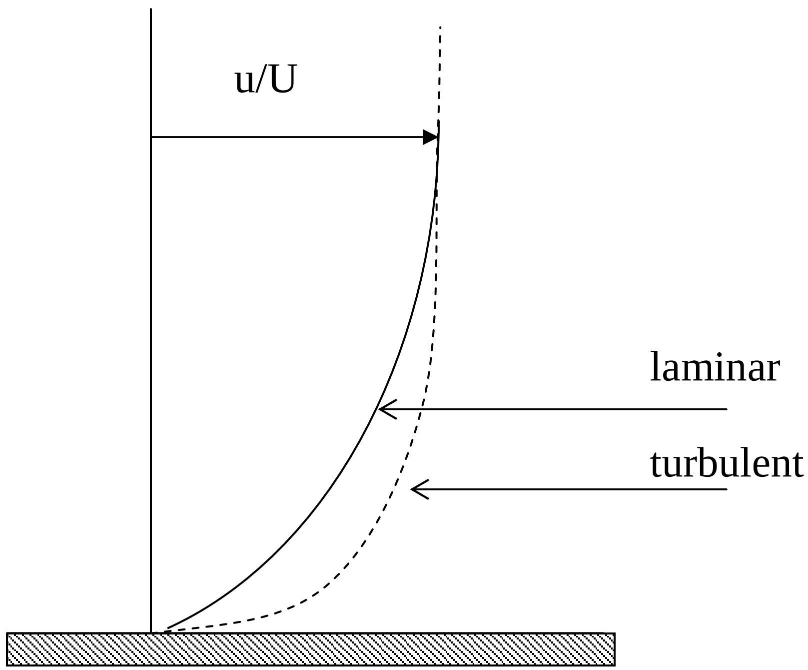




Example : Interaction of separated vortex flow with vertical stabilizer (F18)

# Flow Separation

- Effect of turbulence




Boundary layer

Turbulent boundary layer has more flow **kinetic energy** near the surface. Thus flow separation may be postponed.

# Viscous drag

Drag due to viscous effects = friction drag + pressure drag

= profile drag

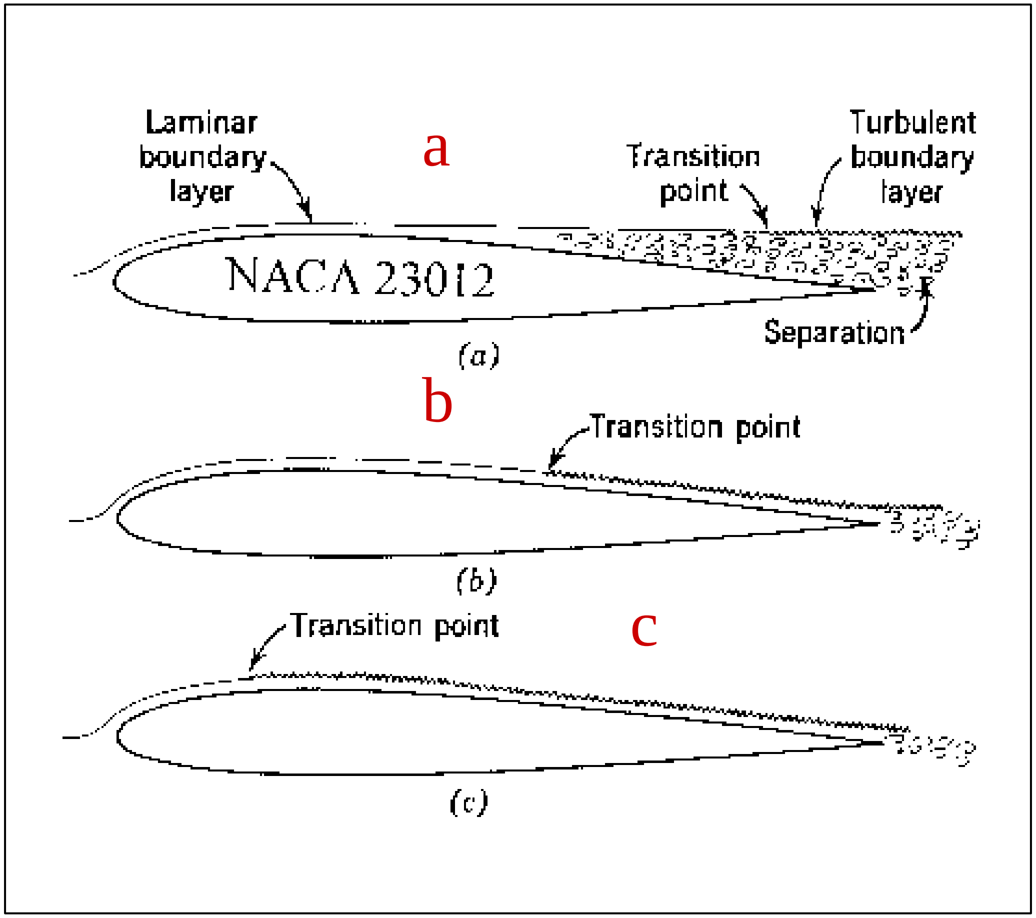
$$C_{D_p} = C_{D_{pressure}} + C_{D_{friction}}$$

# Influence of the Reynolds number

Re=300000

Re=650000

Re=1200000

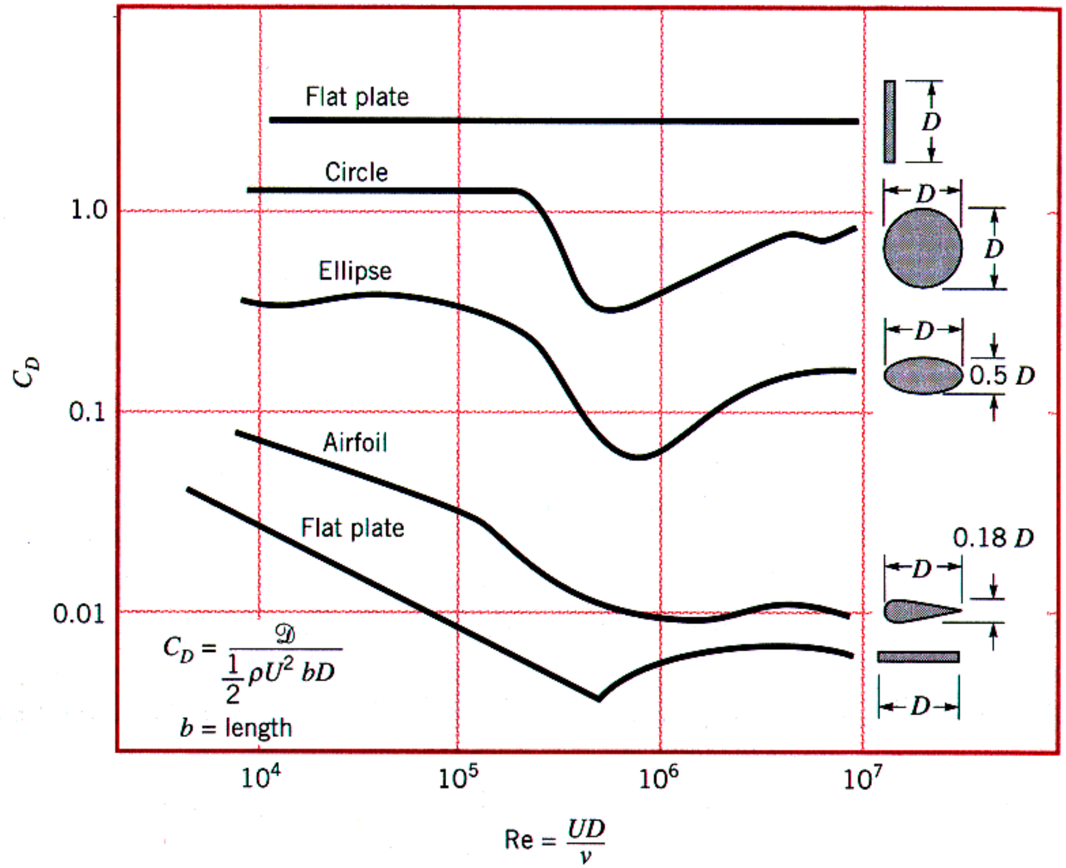



$C_d$ high

$C_d$ lower

$C_d \approx C_d$(b)

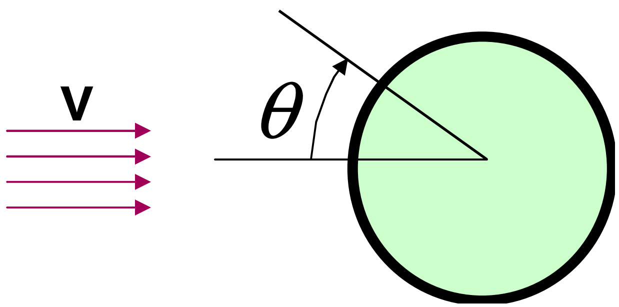
# Effect on $C_D$ of shape and Re-no.

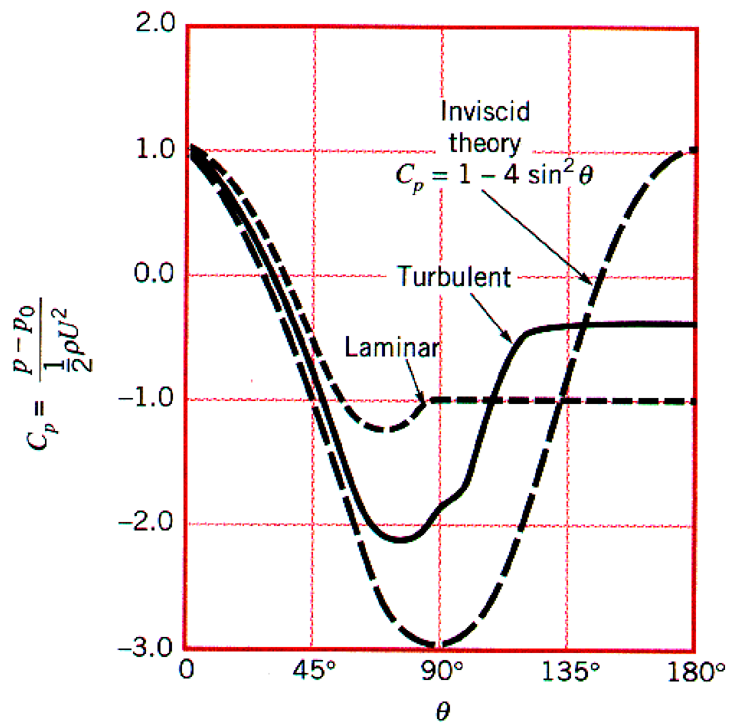


# Pressure drag

Drag distribution

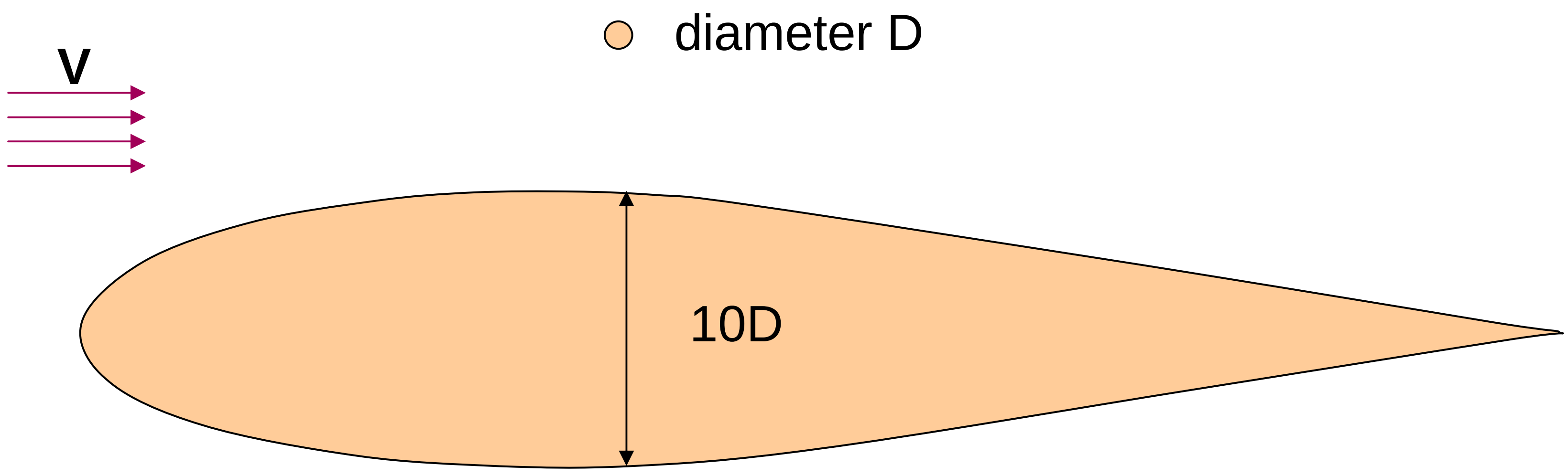
on Cylinder

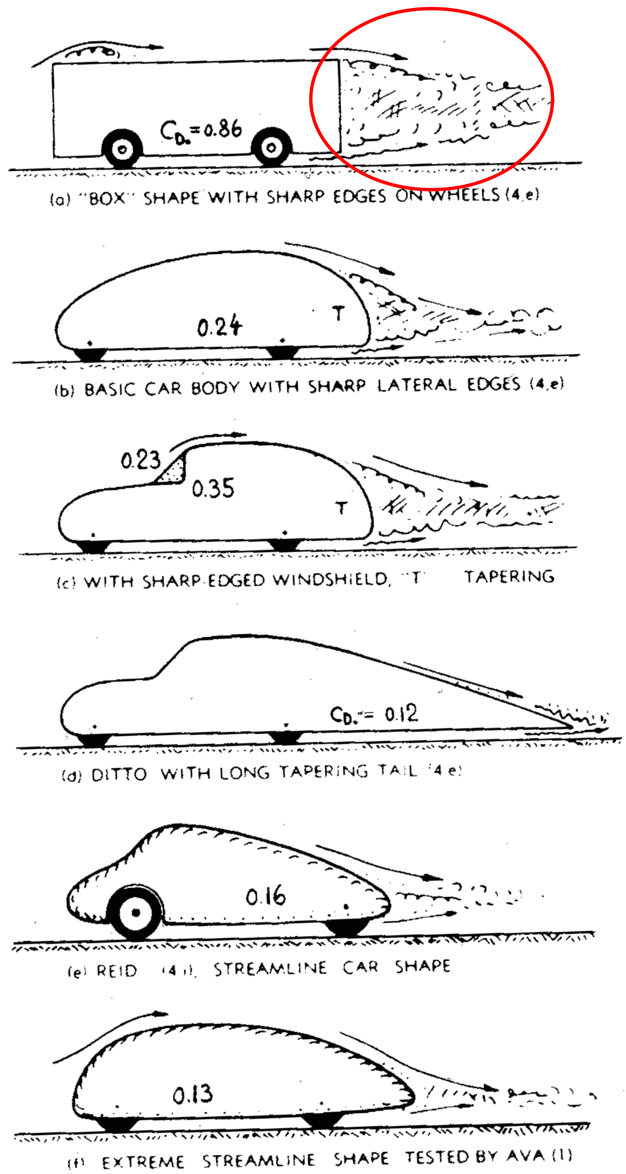



# Two objects with the same drag force

($Re_D=10^5$)



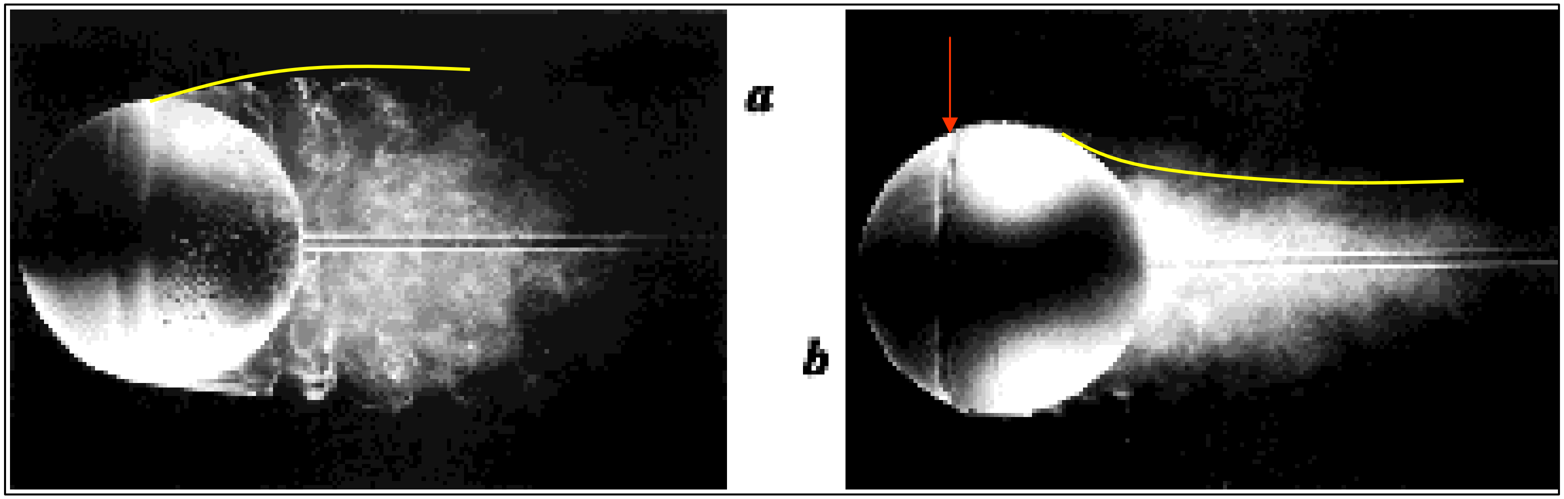


$C_{D_0}$=0.86
(a) "BOX" SHAPE WITH SHARP EDGES ON WHEELS (4,e)
0.24
T
(b) BASIC CAR BODY WITH SHARP LATERAL EDGES (4,e)
0.23
0.35
T
(c) WITH SHARP-EDGED WINDSHIELD, "T" TAPERING
$C_{D_0}$= 0.12
(d) DITTO WITH LONG TAPERING TAIL (4 e)
0.16
(e) REID (4 i), STREAMLINE CAR SHAPE
0.13
(f) EXTREME STREAMLINE SHAPE TESTED BY AVA (1)


TU Delft

# Artificial transition

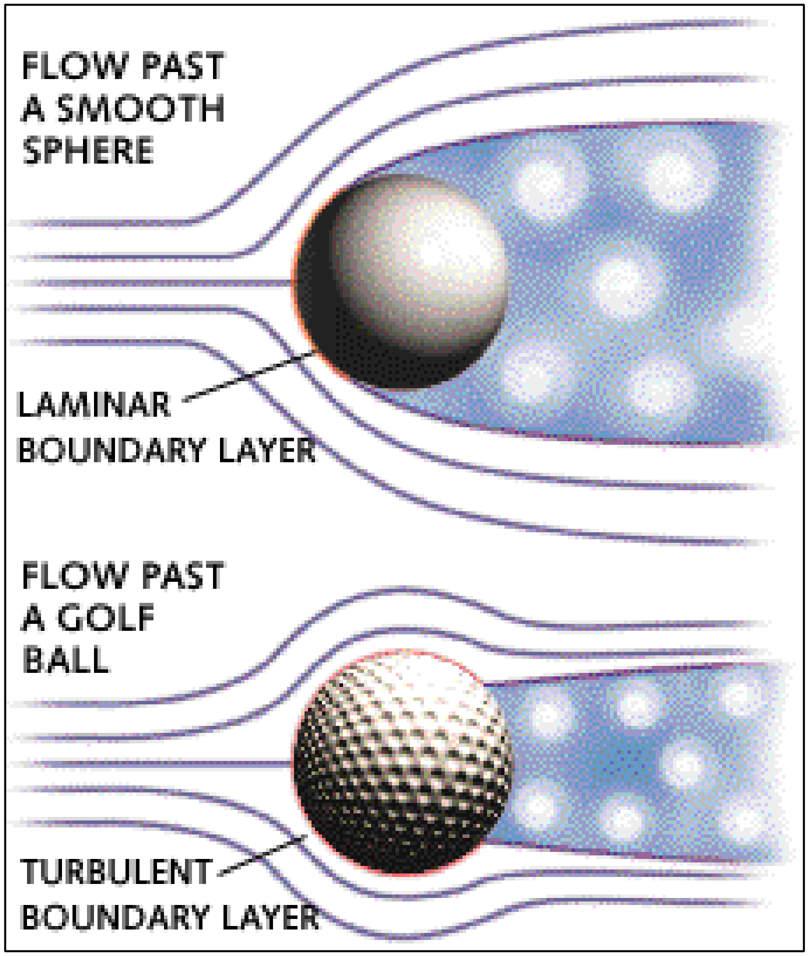
Flow over a sphere



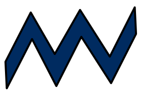

free transition
Re = 15000

artificial transition
Re = 30000

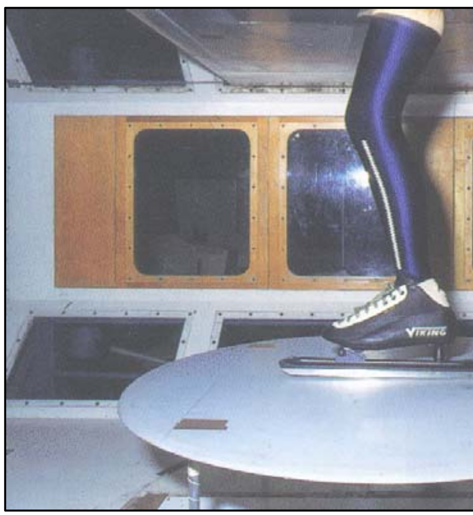
# Artificial transition

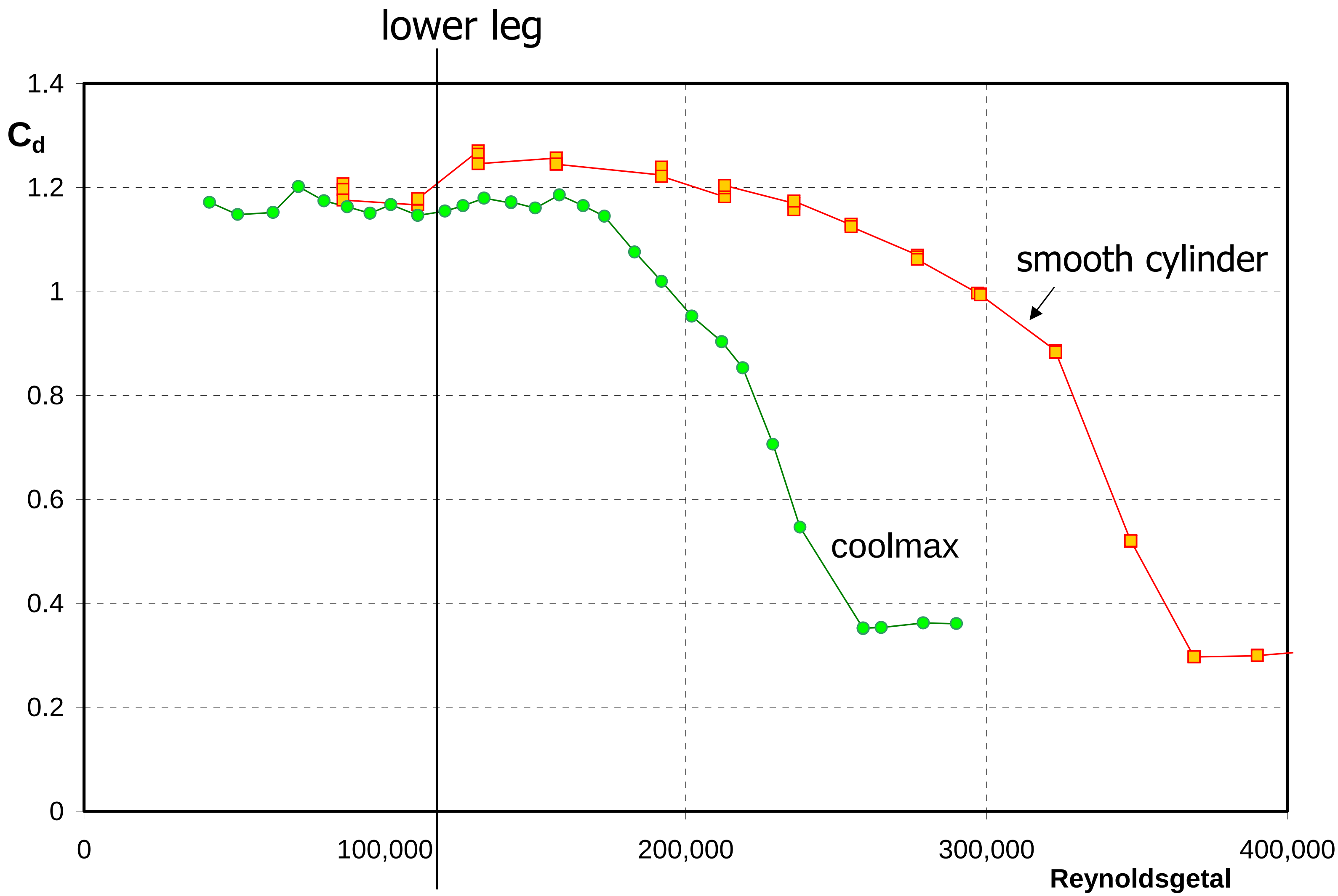


# Use in sports:
# example 1 :speed skating

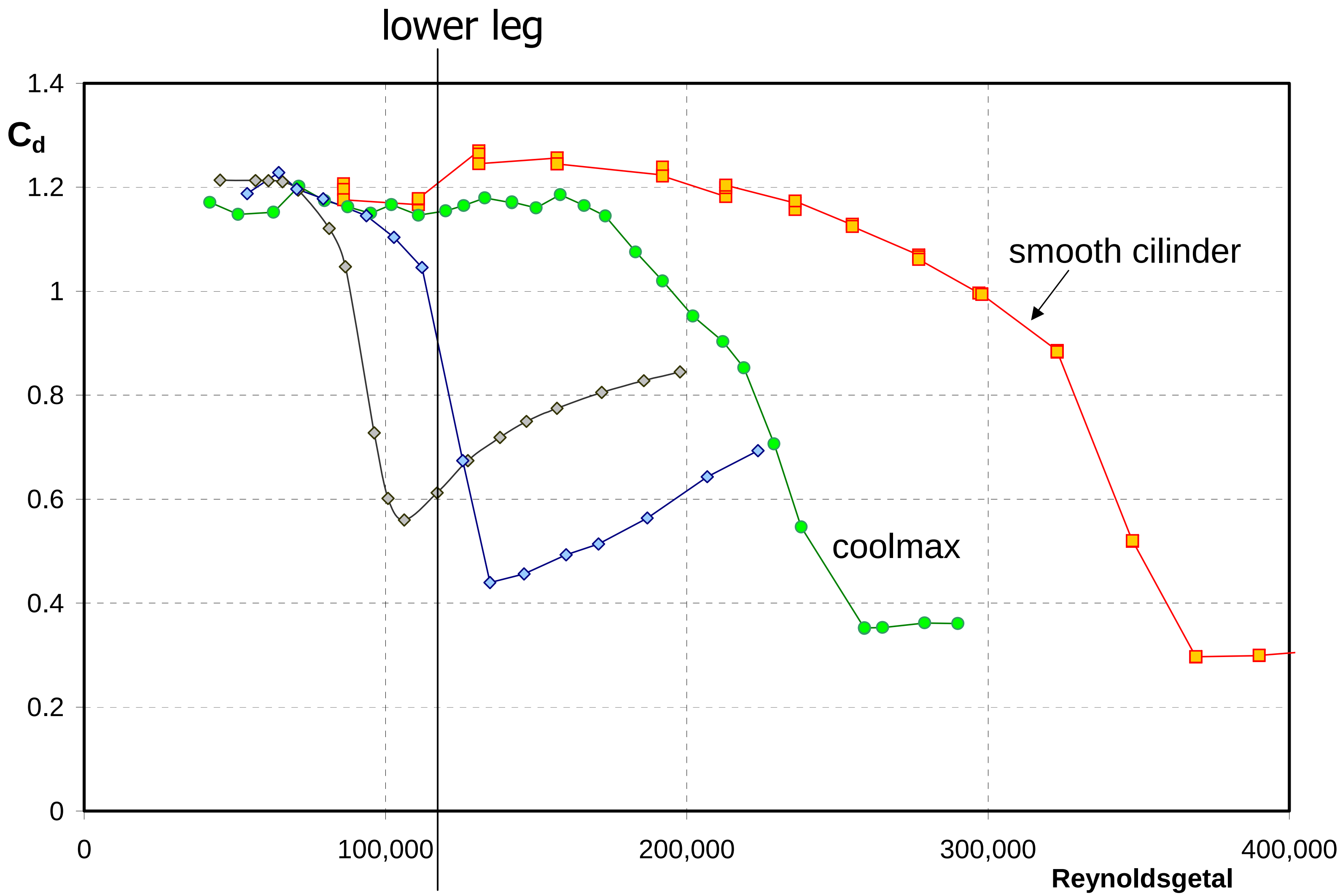


Effect of zigzag strips

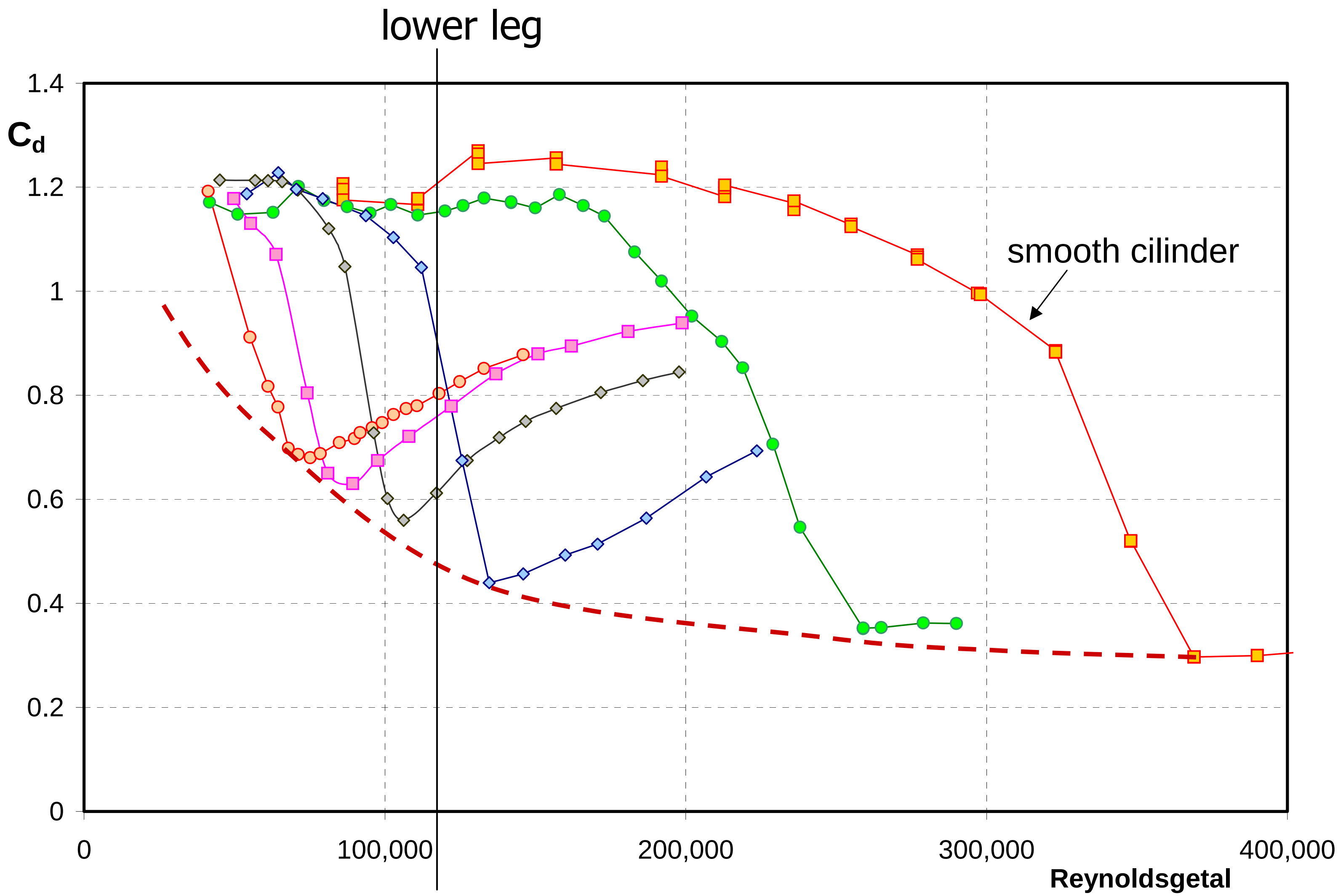


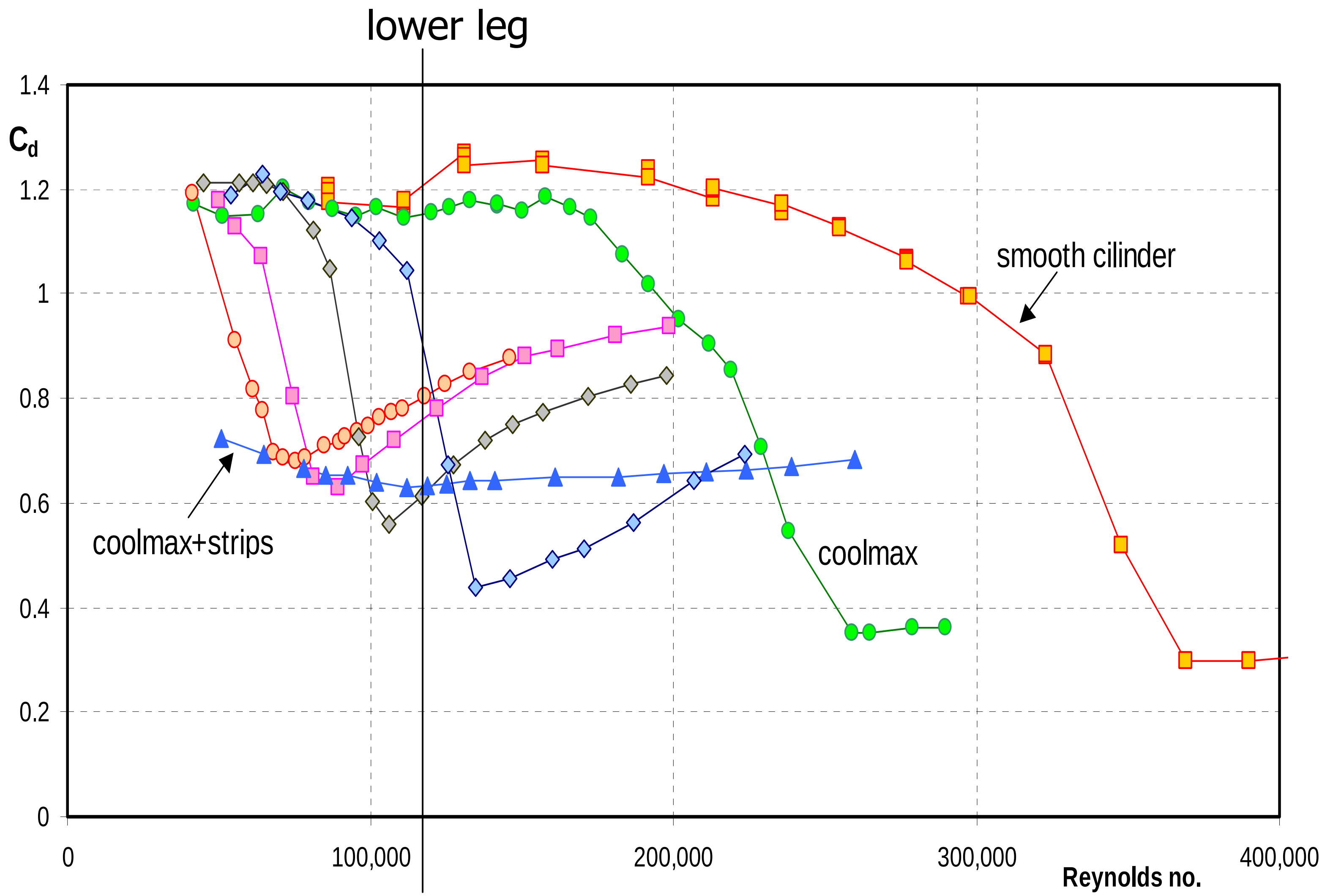


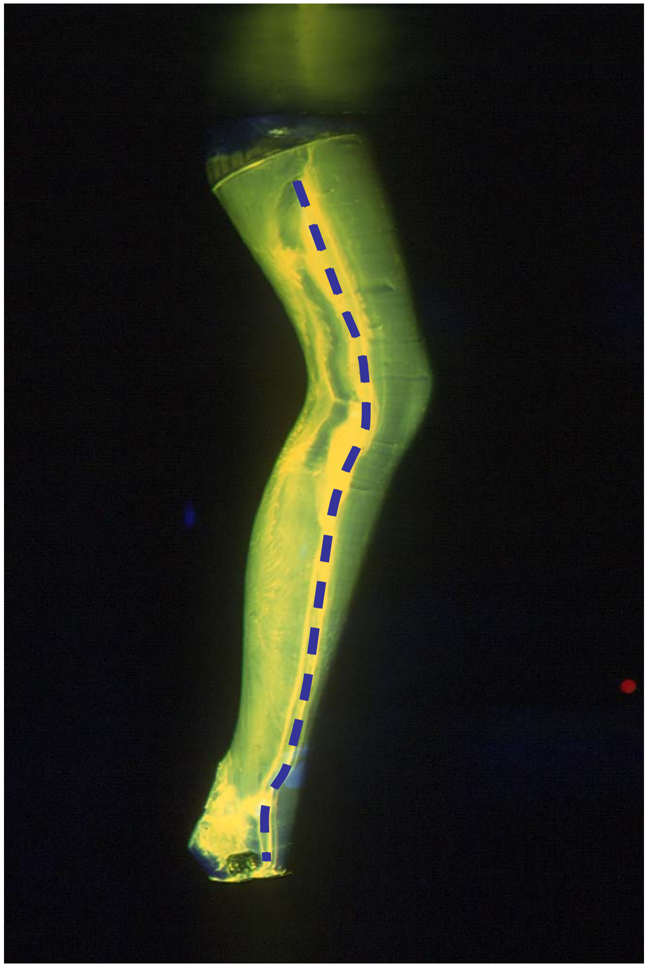

Measured drag characteristics of different fabrics on a cylinder



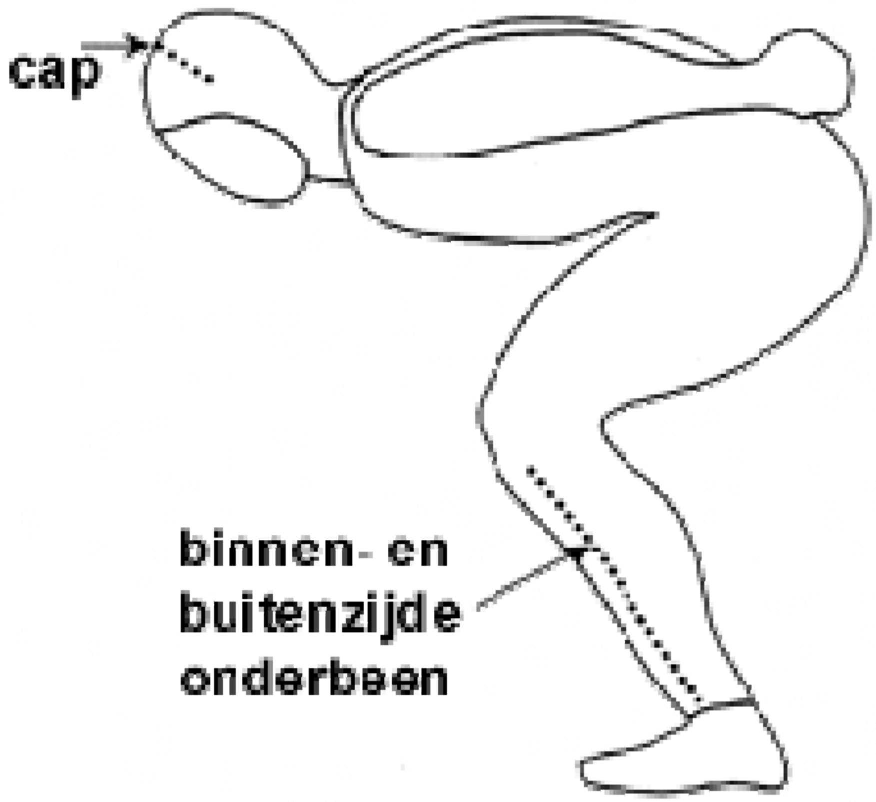
lower leg
1.4
Cd
1.2
1
0.8
0.6
0.4
0.2
0
smooth cilinder
coolmax
0
100,000
200,000
300,000
400,000
Reynoldsgetal


lower leg
1.4
Cd
1.2
1
0.8
0.6
0.4
0.2
0
smooth cilinder
0
100,000
200,000
300,000
400,000
Reynoldsgetal


lower leg
1.4
$C_d$
1.2
1
0.8
0.6
0.4
0.2
0
0
100,000
200,000
300,000
400,000
Reynolds no.
smooth cilinder
coolmax+strips
coolmax



# Position of the strips



# Gianni Romme


World records speed skating men 5000 m:

| | | |
|---|---|---|
| 8.36.6 | Jaap Eden | Hamar 1894 |
| 6.34.96 | J. Olav Koss | Hamar 1994 |
| 6.30.62 | Gianni Romme | H'veen 1997* |
| 6.22.20 | Gianni Romme | Nagano 1998 |
| 6.21.49 | Gianni Romme | Galgary 1998 |
| Current: | | |
| 6.03.32 | Sven Kramer | Galgary 2007 |

* First on clap skates

TU Delft

# Experimenting with aerodynamics

Cathy Freeman, 400 m. gold medalist, Sydney Olympics 2000

# Example 2

Case study :

Usain Bolt
100m men world record holder

# Measured effect of strips on the total aerodynamic drag:

| | |
|---|---|
| • strips on lower legs | -3 to -11 % |
| • strips on the cap | -2 to -6 % |

| Location | Berlin | |
| --- | --- | --- |
| air density | 1.20 | kg/m^3 |
| parameters | Bolt | |
| length | 1.96 | m |
| mass | 86 | kg |
| Cd*S-total | 0.82 | |
| Cd*S-legs | 0.246 | |
| | | |
| distance | 100 | m |
| min | sec | |
| 0 | 9.58 | |
| V-average | 10.44 | m/s |

$$P = C_d.S.½.\rho.V^3$$

⇩

**$P_{propulsion}$ = 560 Watts**


First calculate the required power for the time of 9.58 s (V=10.44 m/s)

**$P_{prop}$ = 560 Watts**

| Location | | |
|---|---|---|
| air density | 1.20 kg/m^3 | |
| | | |
| parameters Bolt | | |
| length | 1.96 m | |
| mass | 86 kg | |
| Cd*S-total | 0.806 | |
| Cd*S-legs | 0.231 | -6% |

$$V^3 = P / C_d . S . ½ . \rho .$$

⇩

**$V_{av}$=10.479 m/s**


Then calculate new V with reduced drag of legs