Lecture # 07: Laminar and Turbulent Flows

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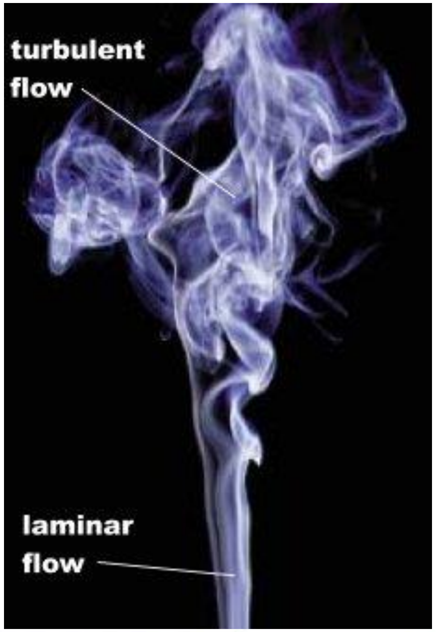
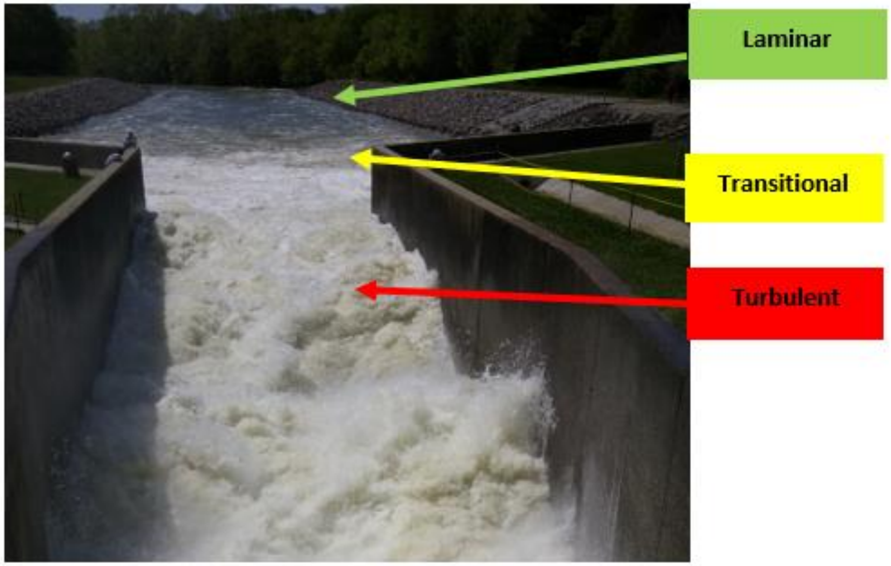
Sources/ Further reading:
Munson, Young, & Okiishi, "Fundamentals of Fluid Mechanics," 4th ed, Ch 8
Tropea, Yarin, & Foss, "Springer Handbook of Experimental Fluid Mechanics," Part C Ch 10
Tritton, "Physical Fluid Dynamics," 2nd ed, Chs 2, 19–21

Sources/ Further reading:
Schlichting, "Boundary Layer Theory," *any* ed
White, "Viscous Fluid Flow," 3rd ed.
Kundu & Cohen, "Fluid Mechanics," 3rd ed.

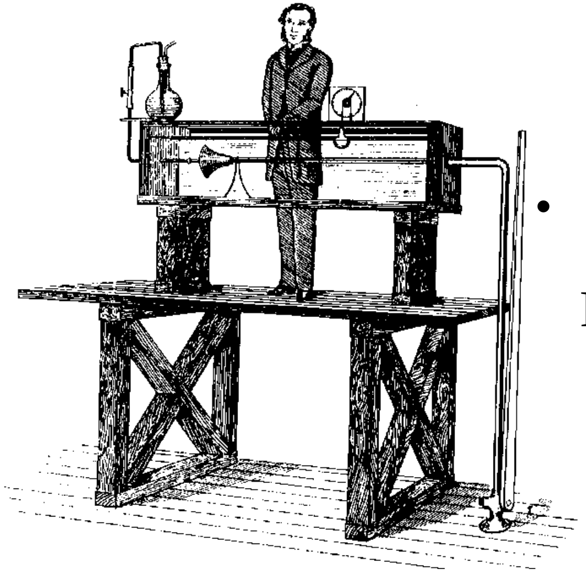
Laminar Flows and Turbulence Flows

- *Laminar flow, sometimes known as streamline flow, occurs when a fluid flows in parallel layers, with no disruption between the layers. Viscosity determines momentum diffusion.*
  - *In nonscientific terms laminar flow is "smooth," while turbulent flow is "rough."*
- *Turbulent flow is a fluid regime characterized by chaotic, stochastic property changes. Turbulent motion dominates diffusion of momentum and other scalars. The flow is characterized by rapid variation of pressure and velocity in space and time.*
  - *Flow that is not turbulent is called laminar flow*



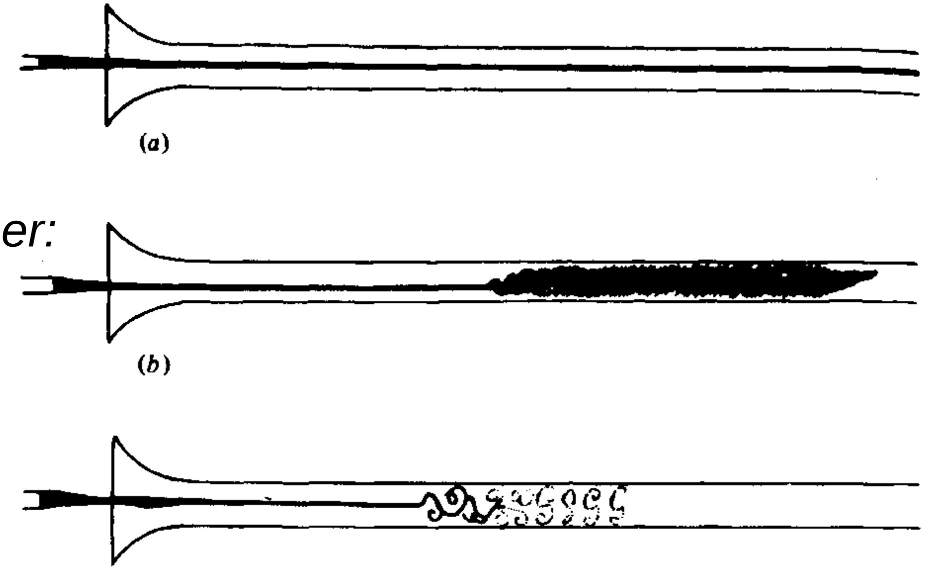


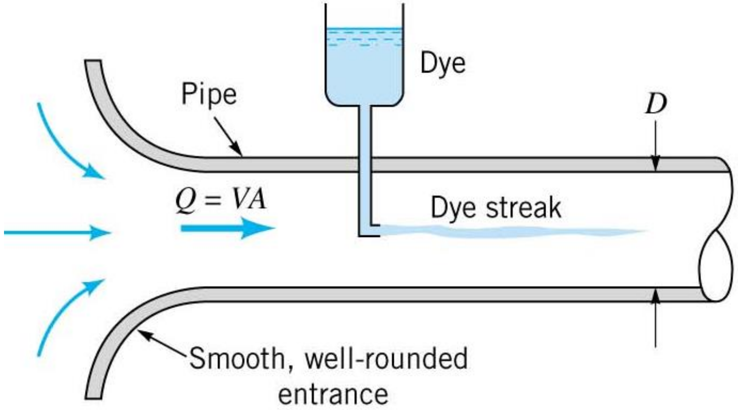
Reynolds' experiment

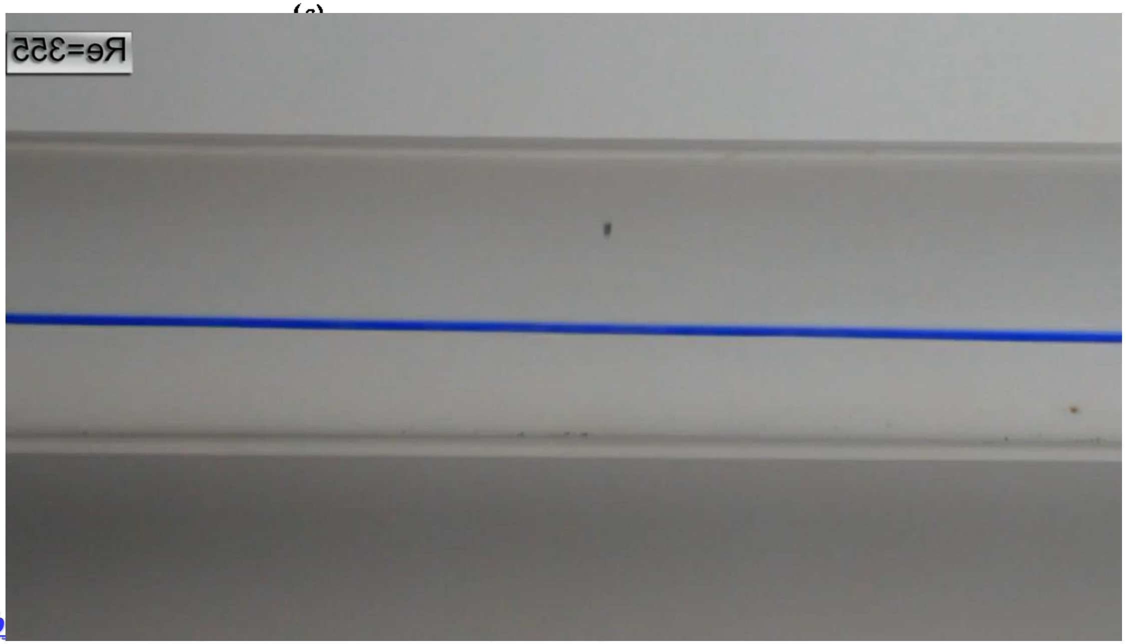


- *Reynolds number:*

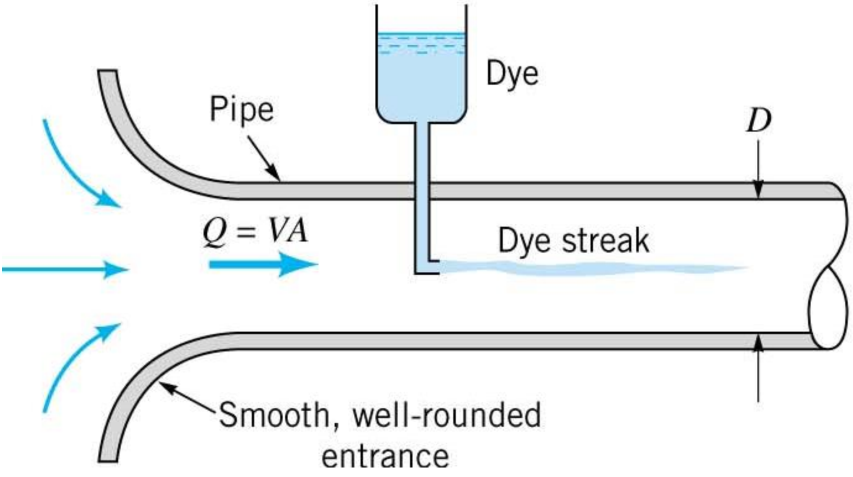
$$\mathrm{Re} = \frac{\rho D U}{\mu}$$

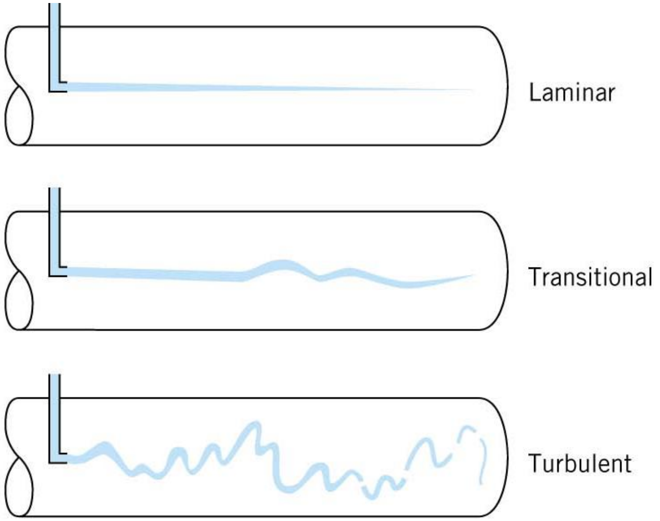


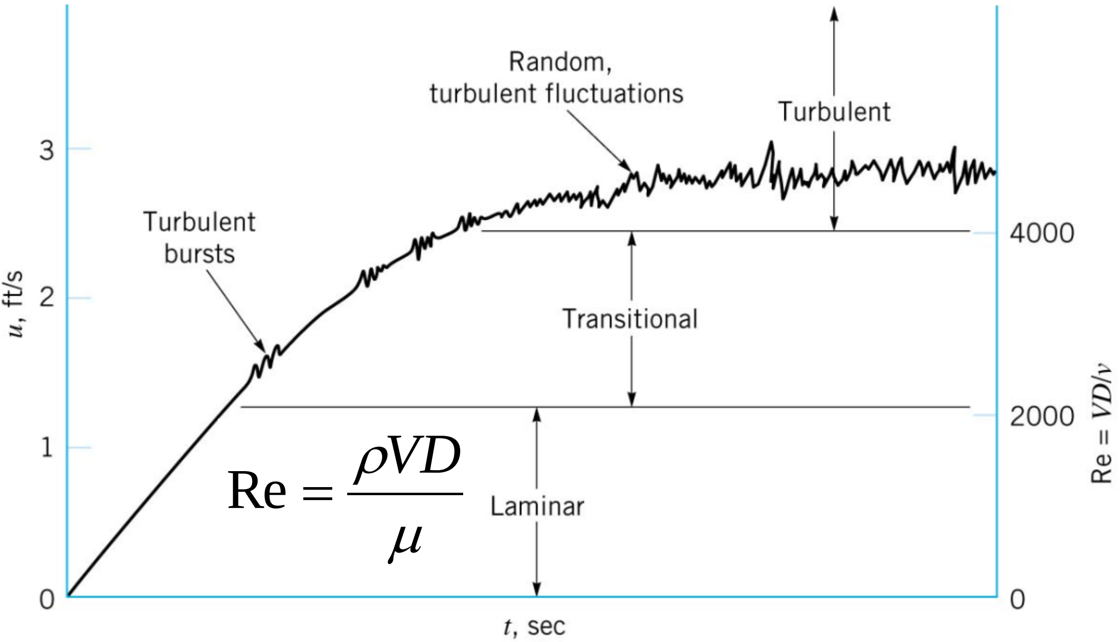




Turbulent flows in a pipe







$$\mathrm{Re} = \frac{\rho V D}{\mu}$$

Empirically,

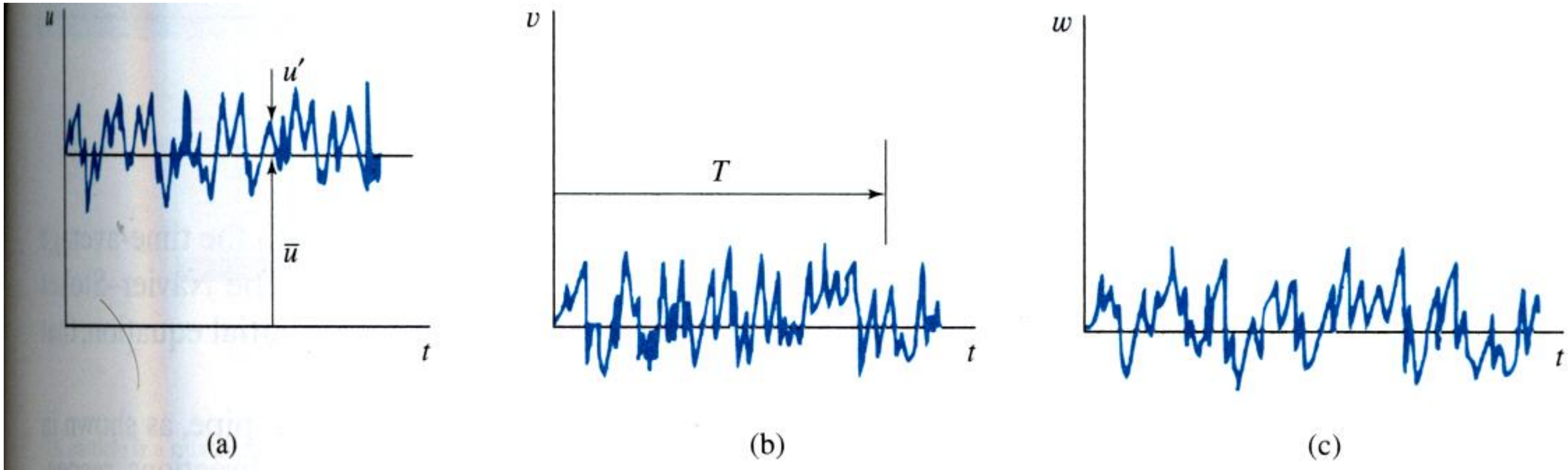
- *Re < 1,000, laminar flow*
- *Re ≈ 1,000 ~ 3,000, transition*
- *Re > 3000, turbulent flow.*

Re_C ~ critical Reynolds number, above which flow exhibits turbulent characteristics

Characterization of Turbulent Flows

$$u = \overline{u} + u'; \quad v = \overline{v} + v' \quad w = \overline{w} + w'$$

$$\overline{u} = \frac{1}{T}\int_{t_0}^{t_0+T} u(x,y,z,t)dt; \quad \overline{v} = \frac{1}{T}\int_{t_0}^{t_0+T} v(x,y,z,t)dt; \quad \overline{w} = \frac{1}{T}\int_{t_0}^{t_0+T} w(x,y,z,t)dt$$



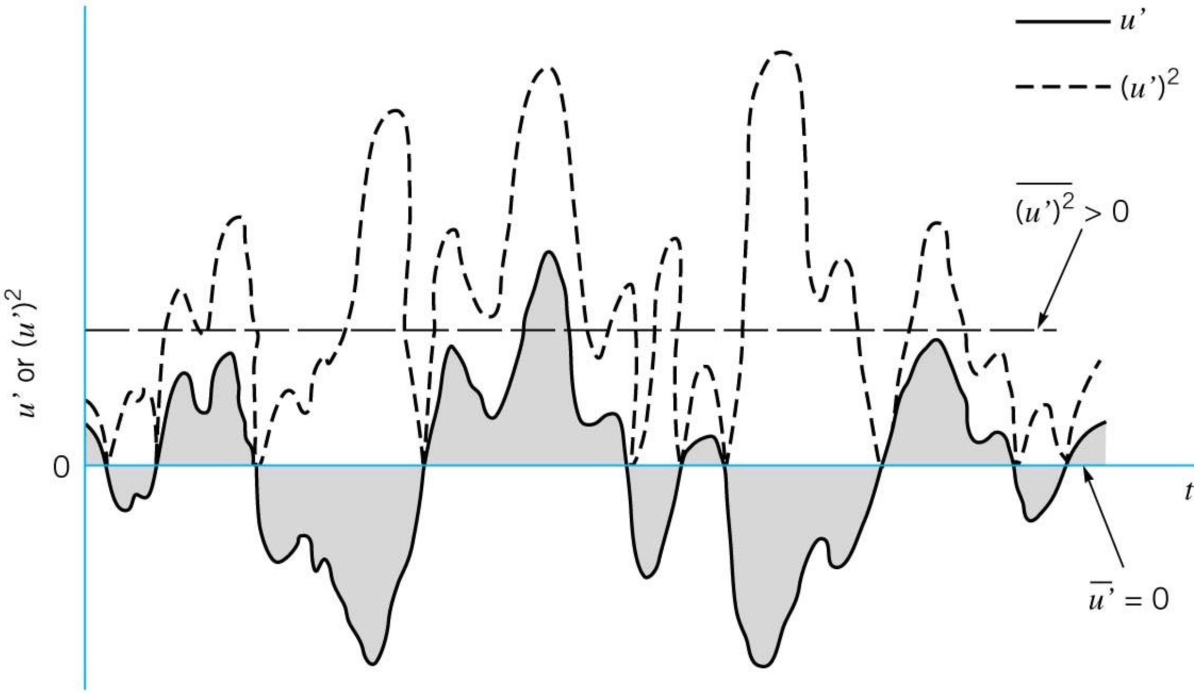
(a) (b) (c)

FIGURE 7.7 Velocity components in a turbulent pipe flow: (a) *x*-component velocity; (b) *r*-component velocity; (c) *θ*-component velocity.

Turbulence intensities

$$\overline{u'} = 0; \quad \overline{v'} = 0 \quad \overline{w'} = 0$$

$$\overline{(u')^2} = \frac{1}{T}\int_{t_0}^{t_o+T}(u')^2\,dt > 0; \quad \overline{(v')^2} > 0 \quad \overline{(w')^2} > 0$$

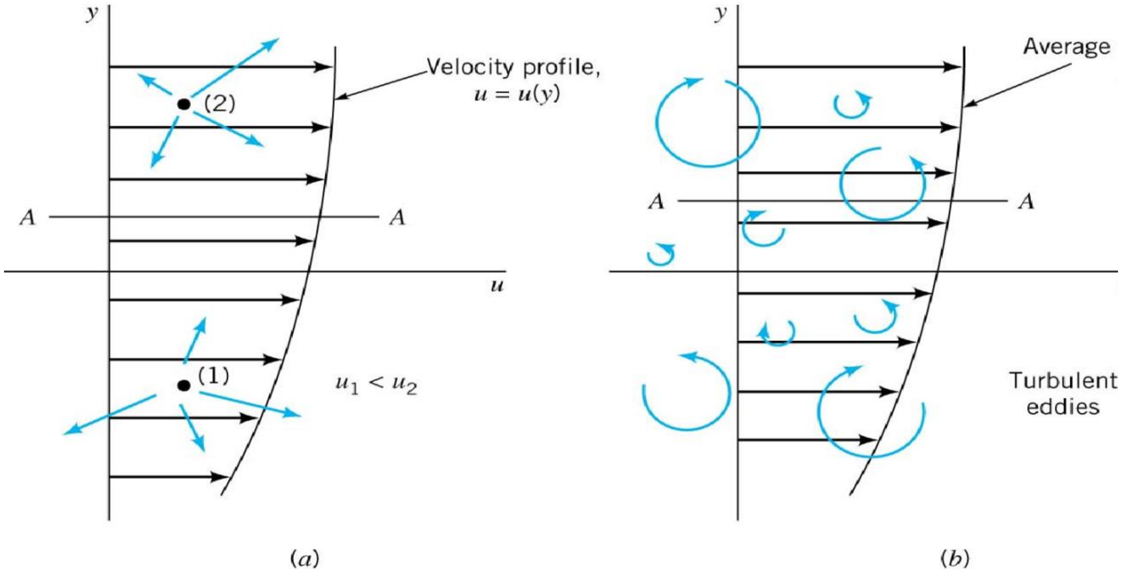


Turbulent Shear Stress

Laminar flows: $$\tau_{lam} = \mu \frac{\partial u}{\partial y}$$

Turbulent flows: $$\overline{\tau_{turb}} = -\rho \overline{u'v'}$$

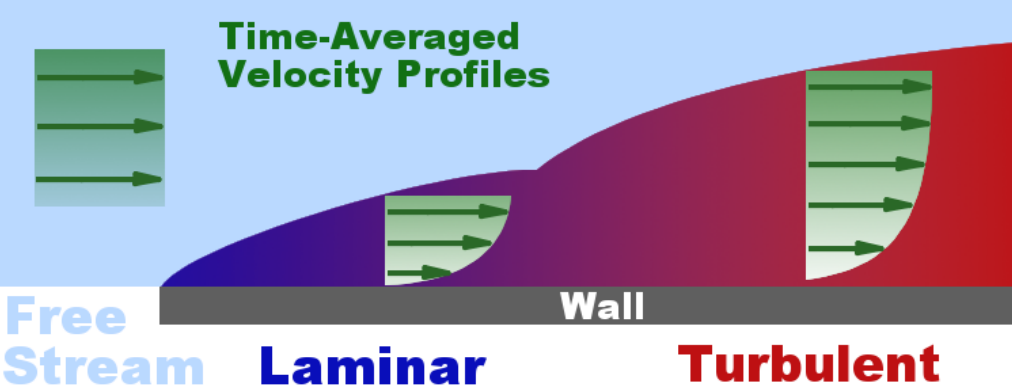
$$\overline{\tau} = \overline{\tau_{lam}} + \overline{\tau_{turb}} = \mu \frac{\partial \overline{u}}{\partial y} - \rho \overline{u'v'}$$

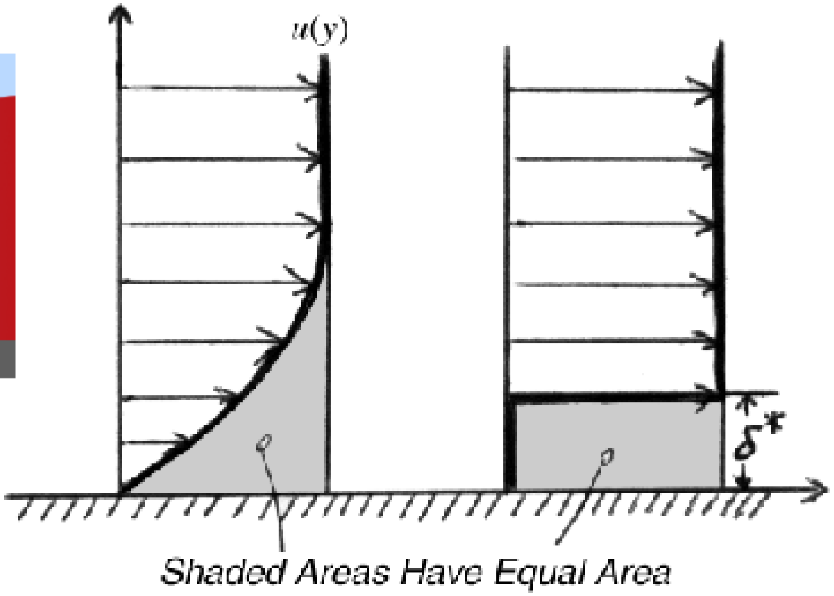


(a) laminar flow

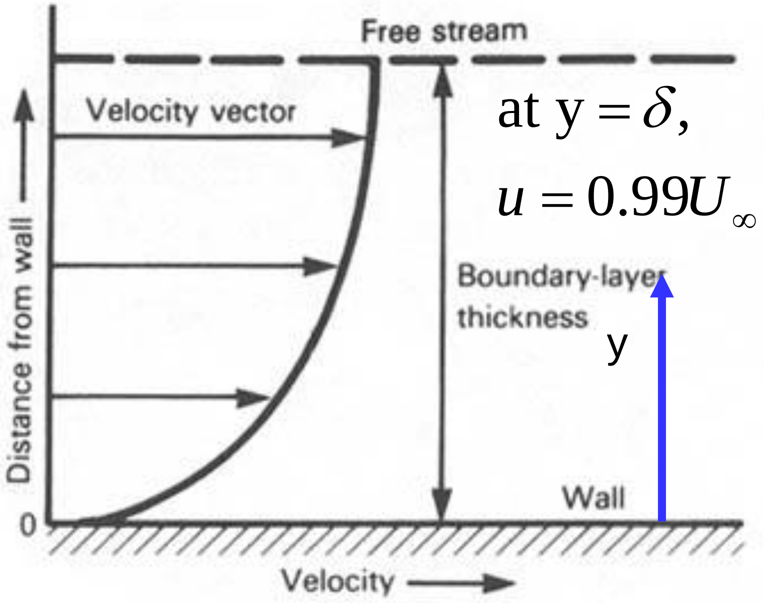
(b) turbulent flow

Quantification of Boundary Layer Flow





Shaded Areas Have Equal Area

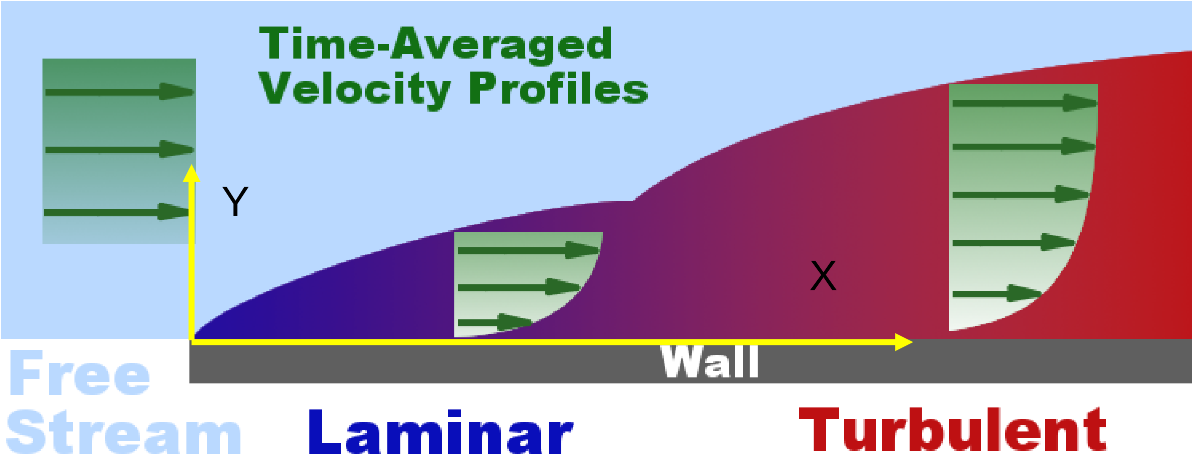


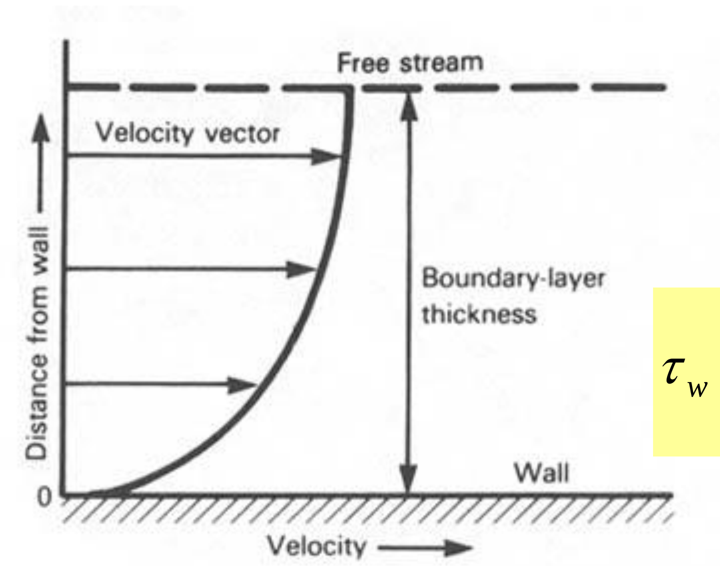
$$\text{at } y = \delta,$$
$$u = 0.99U_\infty$$

Displacement thickness: $$\delta^* \equiv \int_0^\infty \left(1 - \frac{u}{U}\right) dy$$

Momentum thickness: $$\theta \equiv \int_0^\infty \frac{u}{U}\left(1 - \frac{u}{U}\right) dy$$

Boundary Layer Theory





$$\tau_w = \mu \left. \frac{\partial U}{\partial y} \right|_{wall}$$

$$\frac{\partial p}{\partial y} \approx 0$$

Blasius solution for laminar boundary layer:

$$\mathrm{Re}_X = \frac{\rho U_\infty X}{\mu}$$

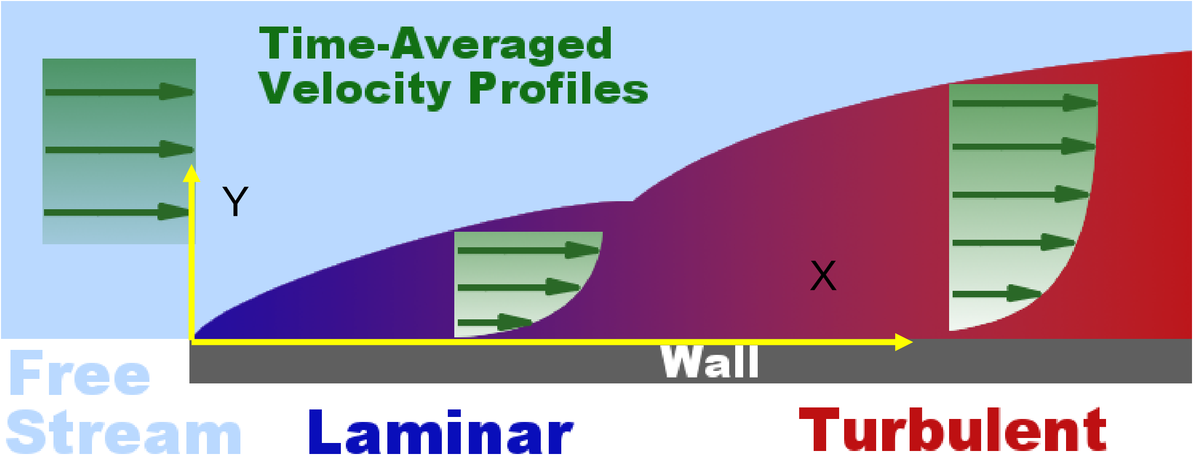
$$C_f = \frac{1.328}{\sqrt{\mathrm{Re}_X}}$$

$$\delta = \frac{5.0X}{\sqrt{\mathrm{Re}_X}}$$

$$\delta^* = \frac{1.72X}{\sqrt{\mathrm{Re}_X}}$$

$$\theta = \frac{0.664X}{\sqrt{\mathrm{Re}_X}}$$

Boundary Layer Theory



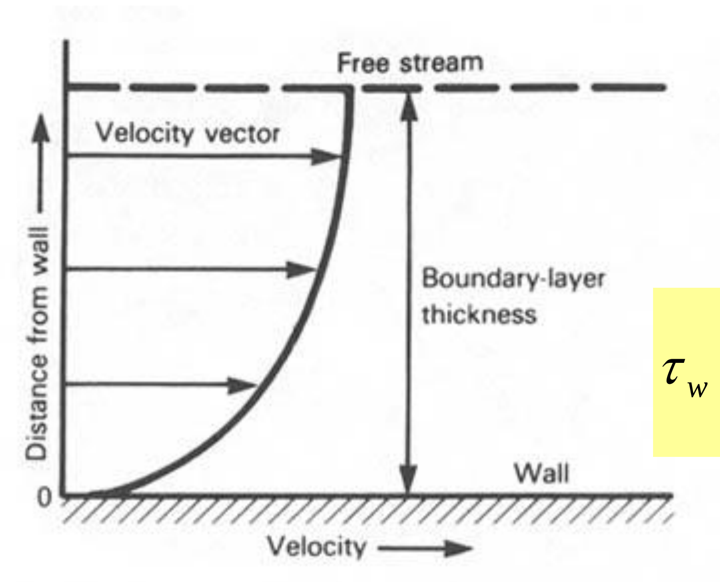
$$\frac{\partial p}{\partial y} \approx 0$$

Turbulent boundary layer:

$$\mathrm{Re}_X = \frac{\rho U_\infty X}{\mu}$$

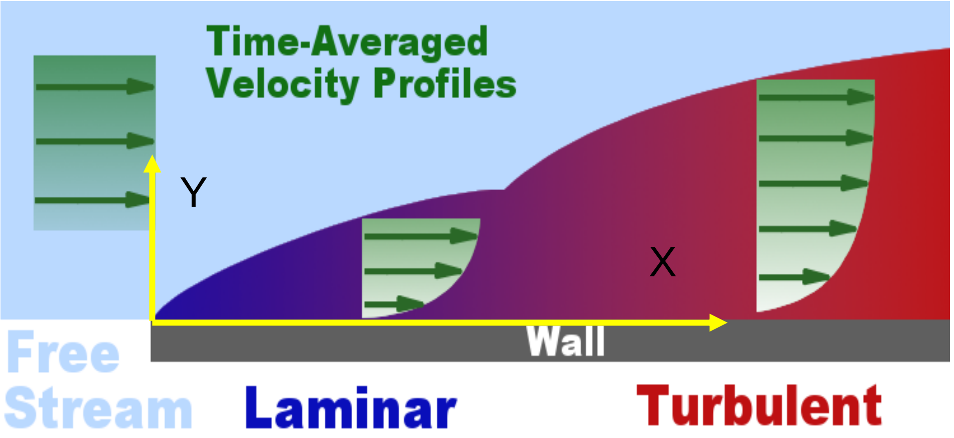
$$C_f = \frac{0.074}{(\mathrm{Re}_X)^{1/5}}$$

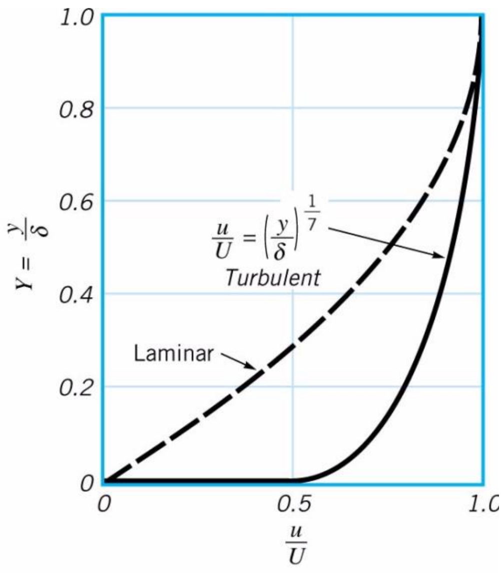
$$\delta = \frac{0.37X}{(\mathrm{Re}_X)^{1/5}}$$



$$\tau_w = \mu \left.\frac{\partial U}{\partial y}\right|_{wall}$$

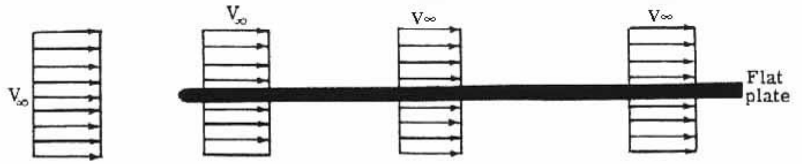
Boundary Layer Flows



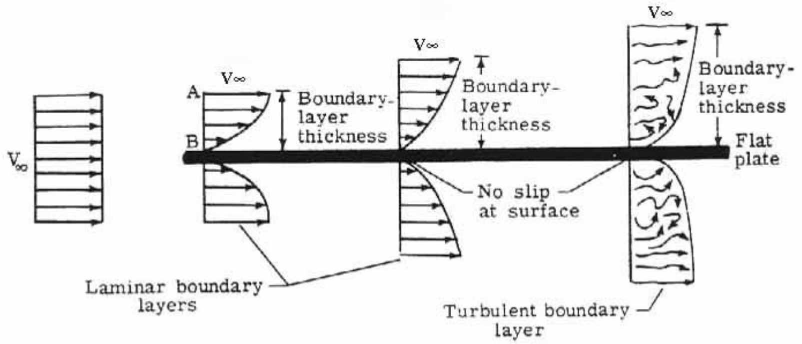


$$\tau_w = \mu \frac{\partial U}{\partial y}\bigg|_{wall}$$

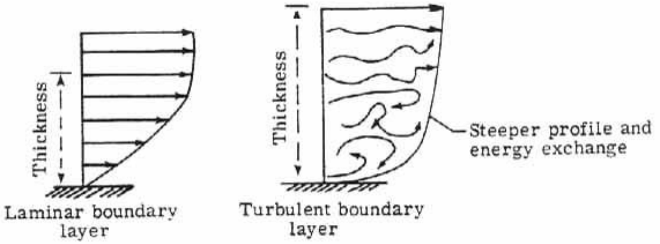
Which one will induce more drag?
Laminar boundary layer?
Turbulent boundary layer?



(a) Inviscid flow along a flat plate.

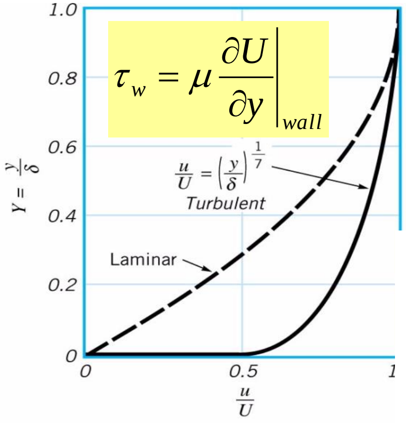


(b) Viscous flow along a flat plate.

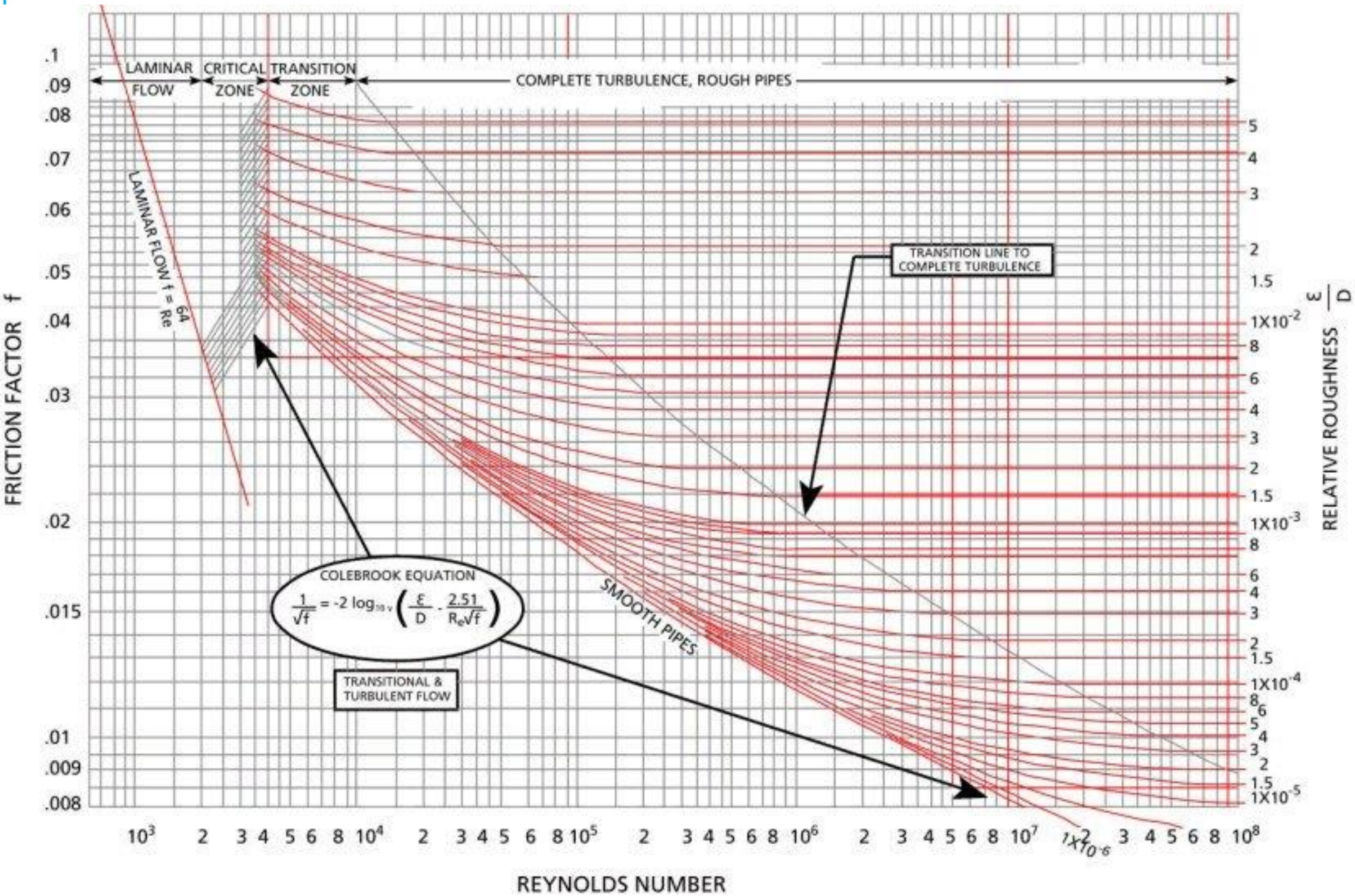


(c) Comparison of laminar and turbulent flow.

Boundary Layer Flows



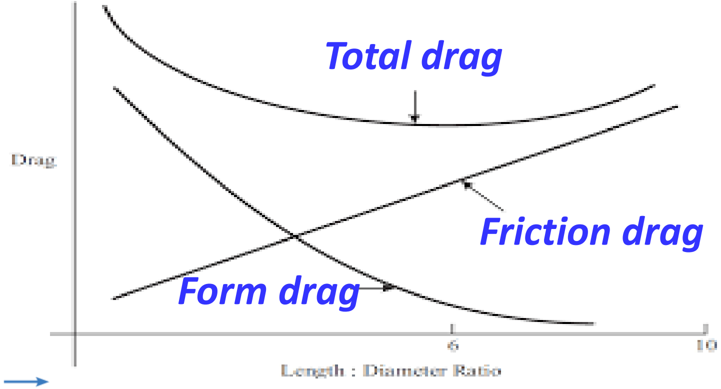
- *Which one will induce more drag?*
- *Laminar boundary layer? Turbulent boundary layer?*

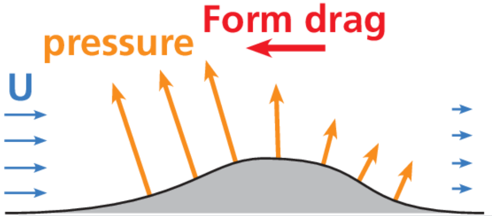


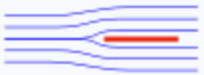
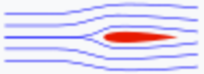
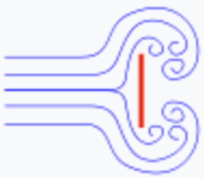
Laminar Flows and Turbulent Flows

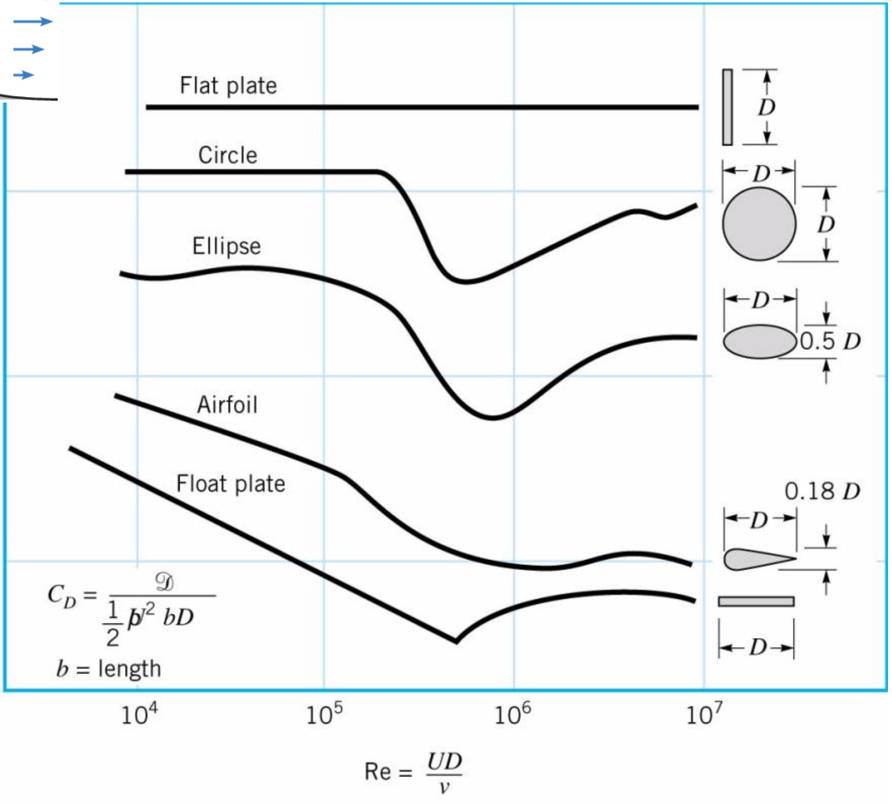
Total Drag = Friction Drag + Form Drag

- ***Friction Drag:*** *due to friction force at the surface*
- ***Form Drag:*** *also known as Pressure Drag or Profile Drag, due to unbalanced pressure distribution*





Shape and flow	Form Drag	Skin friction
	0%	100%
	~10%	~90%
	~90%	~10%
	100%	0%

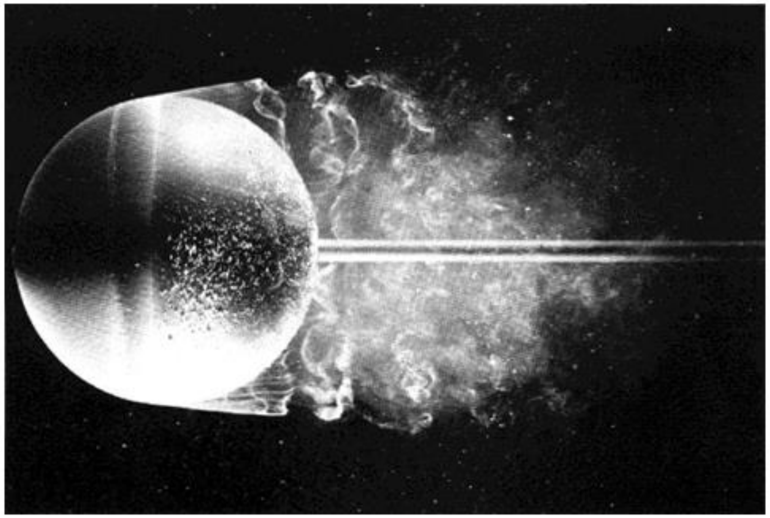


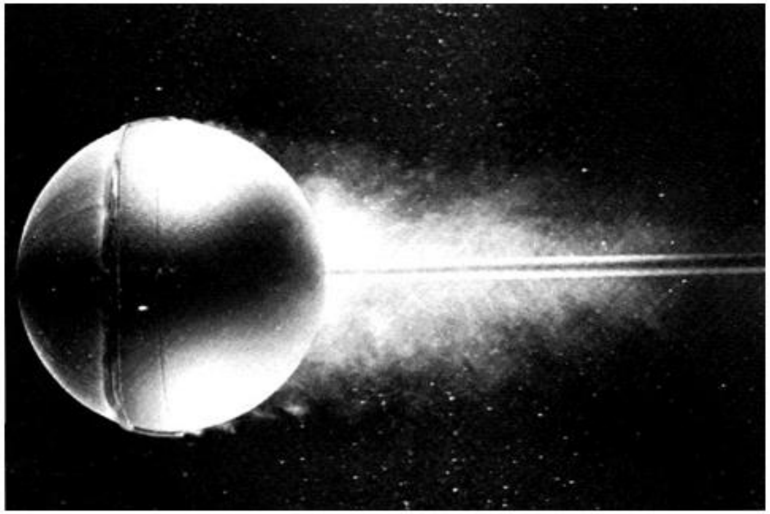
$$C_D = \frac{\mathscr{D}}{\frac{1}{2}\rho U^2 bD}$$

b = length

$$\text{Re} = \frac{UD}{\nu}$$

Flow Around A Sphere with laminar and Turbulence Boundary Layer



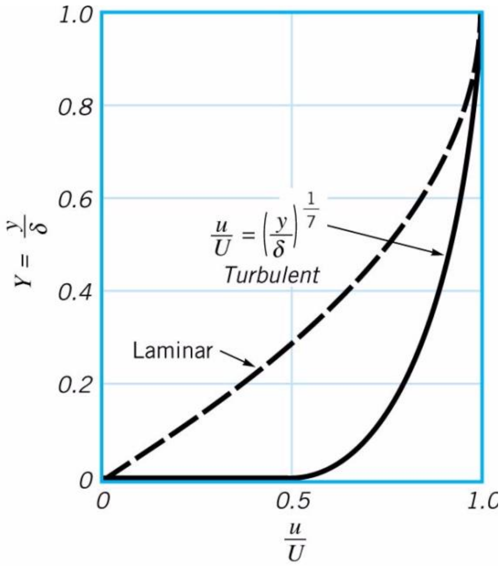


Top:

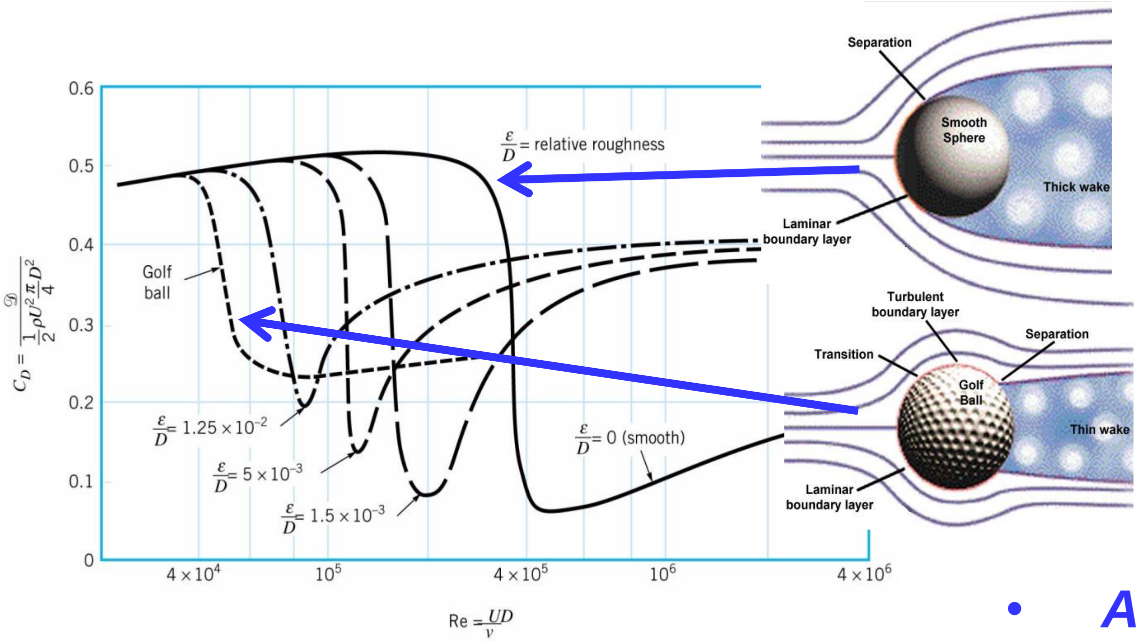
Instantaneous flow past a sphere at Re_D = 15,000. Dye in water shows a laminar boundary layer separating ahead of the equator and remaining laminar for almost one radius. It then becomes unstable and quickly turns turbulent.

Bottom:

Instantaneous flow past a sphere at Re_D = 30,000 with a trip wire. A classical experiment of Prandtl and Wieselsberger is repeated here, using air bubbles in water. A wire hoop ahead of the equator trips the boundary layer. It becomes turbulent, so that it separates farther rearward than if it were laminar (compare with top photograph). The overall drag is thereby dramatically reduced, in a way that occurs naturally on a smooth sphere only at a Reynolds numbers ten times as great.

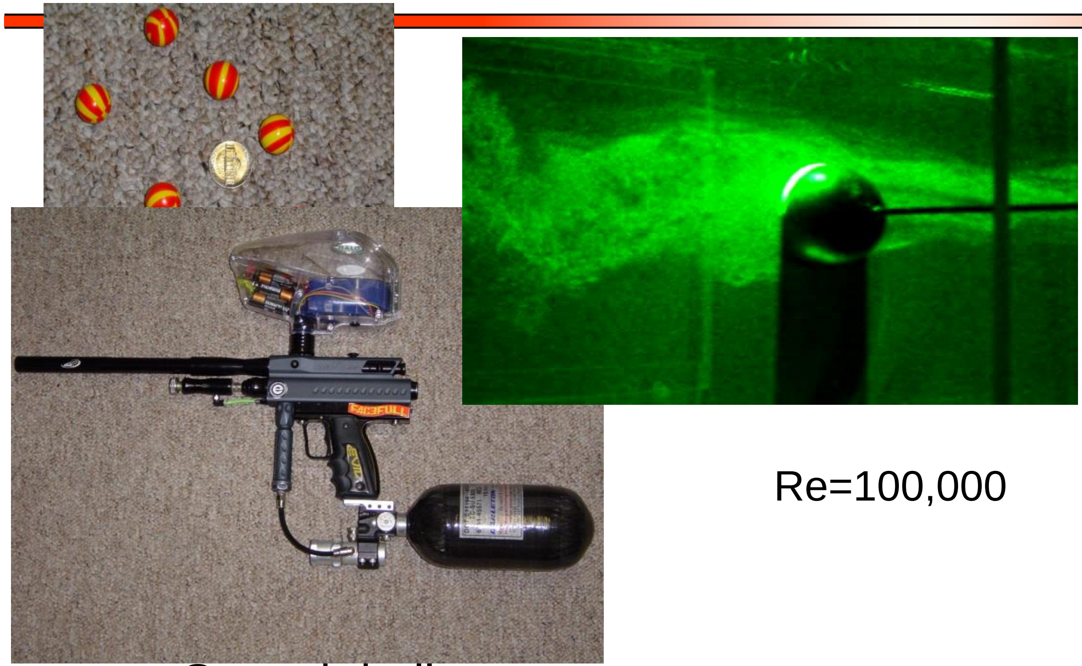


Golf Ball Aerodynamics

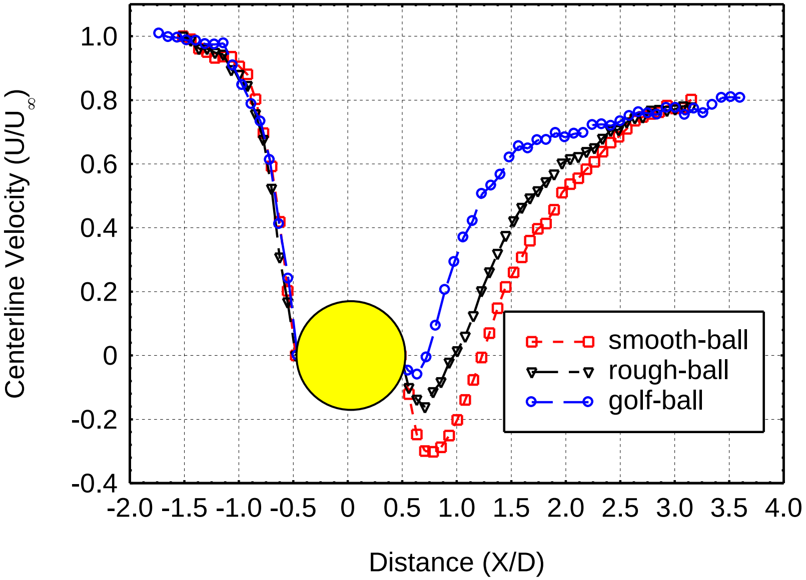


- *Aolf ball aerodynamics*

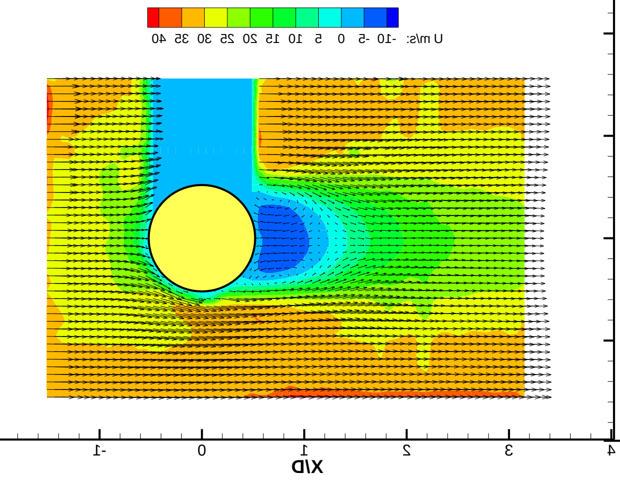
Laminar and turbulent flows



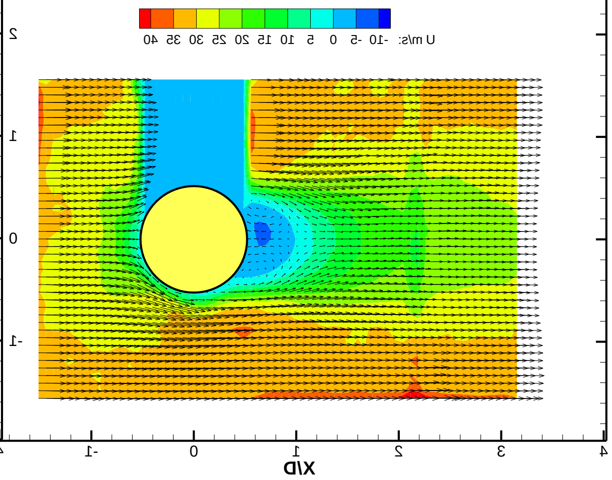
Re=100,000



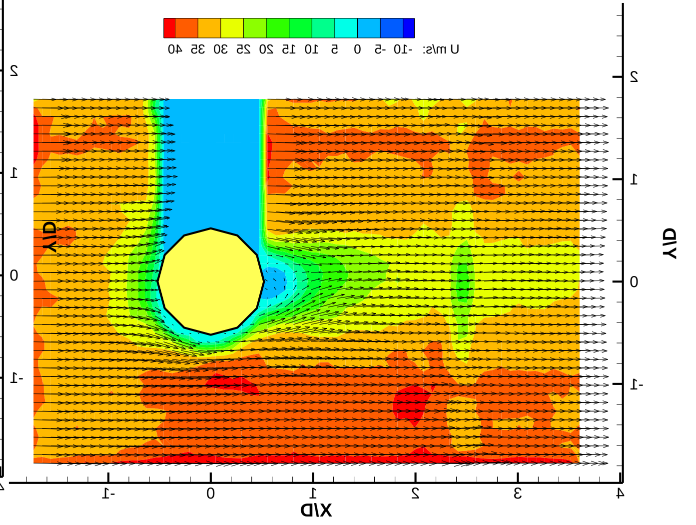
Smooth ball



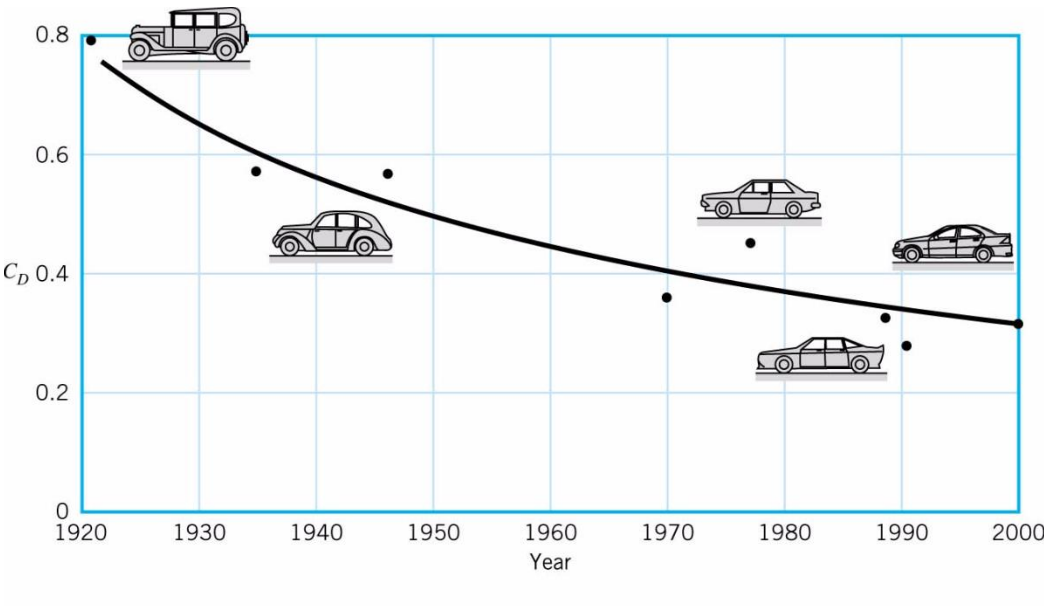
Rough ball

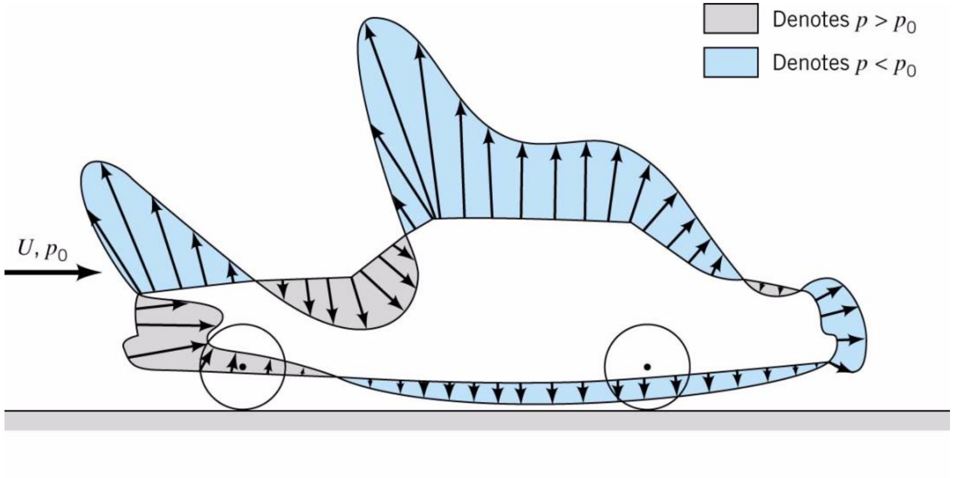


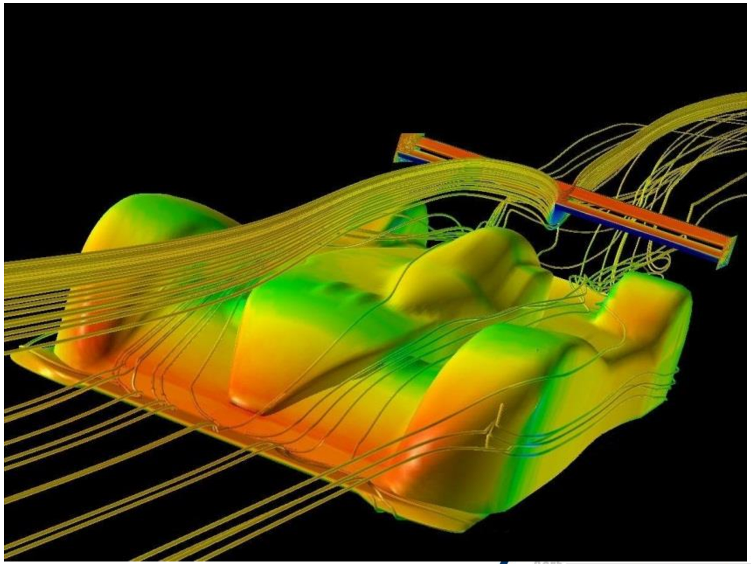
Golf ball



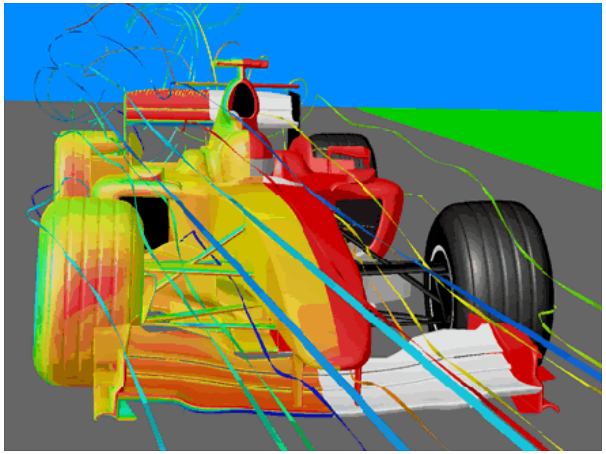
Automobile aerodynamics

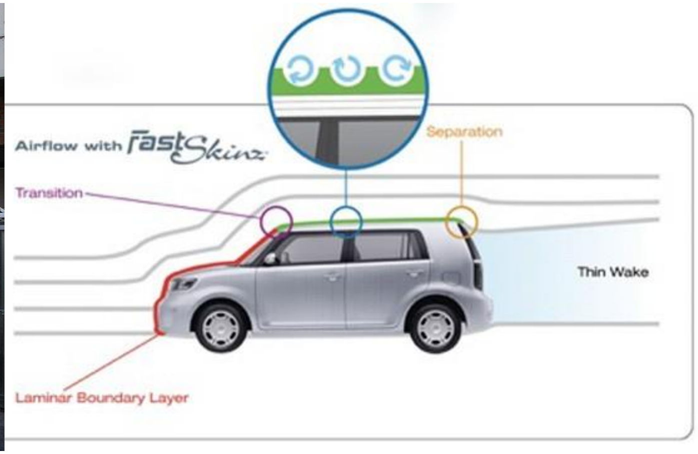






Automobile aerodynamics

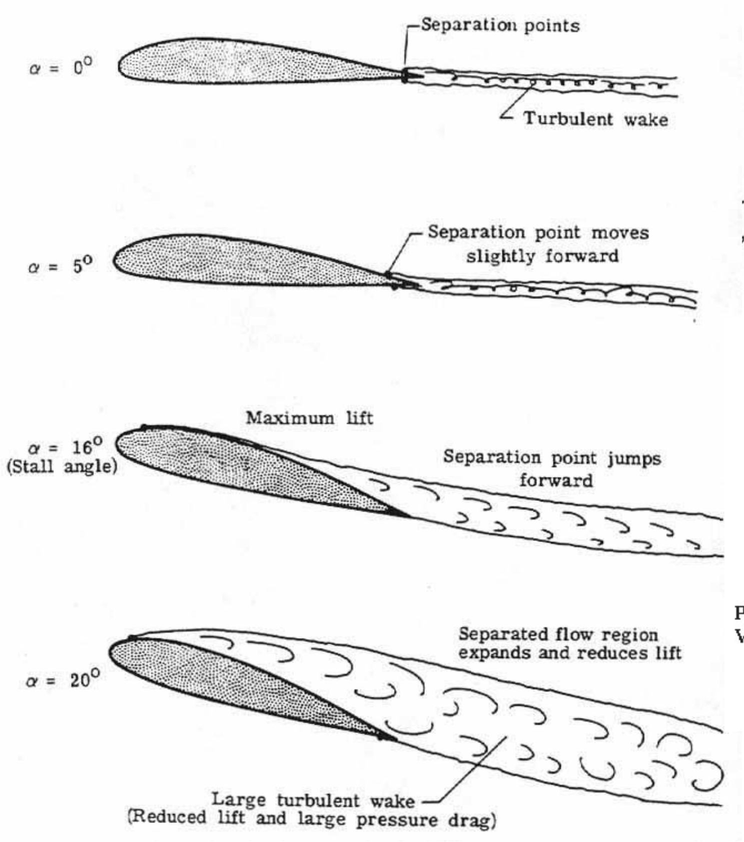


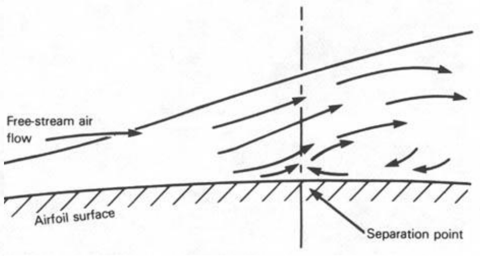


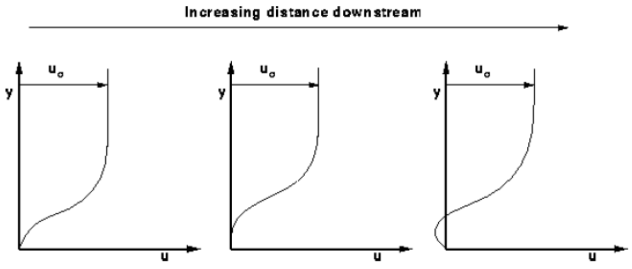
Mercedes Boxfish

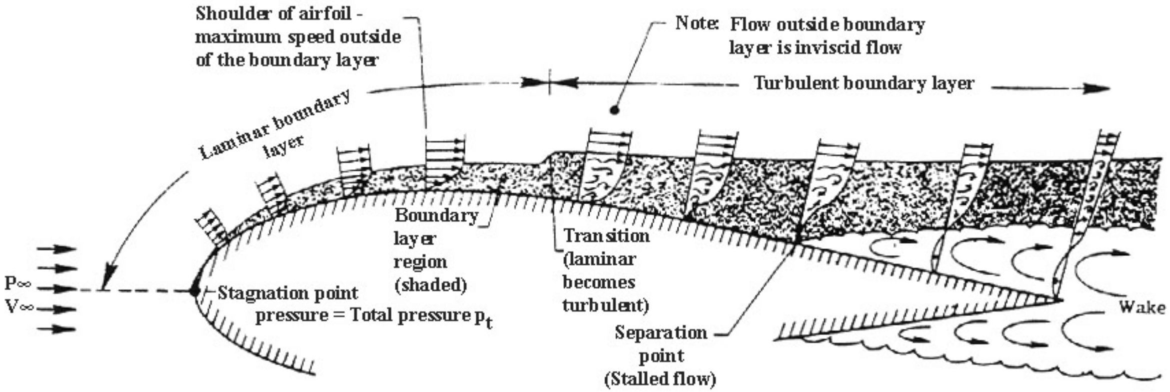
Vortex generator above a Mitsubishi rear window

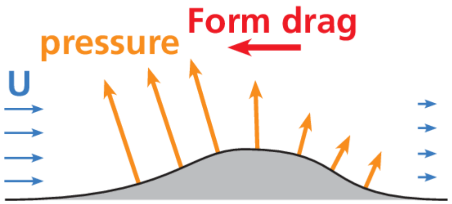
Flow Separation on an Airfoil





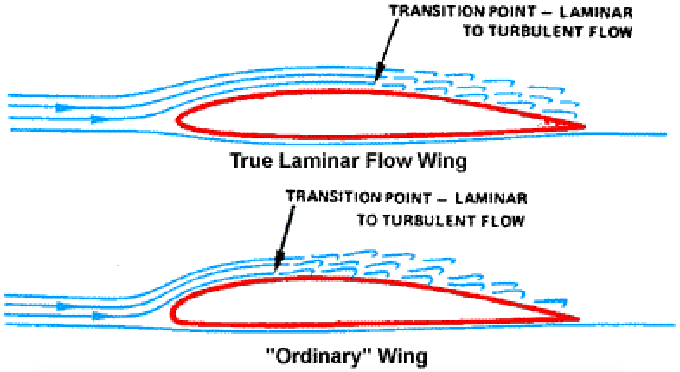






Conventional vs Laminar Airfoils

- Laminar flow airfoils are usually thinner than the conventional airfoil.
- The leading edge is more pointed and its upper and lower surfaces are nearly symmetrical.
- The major and most important difference between the two types of airfoil is this, the thickest part of a laminar wing occurs at 50% chord while in the conventional design the thickest part is at 25% chord.
- Drag is considerably reduced since the laminar airfoil takes less energy to slide through the air.
- Extensive laminar flow is usually only experienced over a very small range of angles-of-attack, on the order of 4 to 6 degrees.
- Once you break out of that optimal angle range, the drag increases by as much as 40% depending on the airfoil



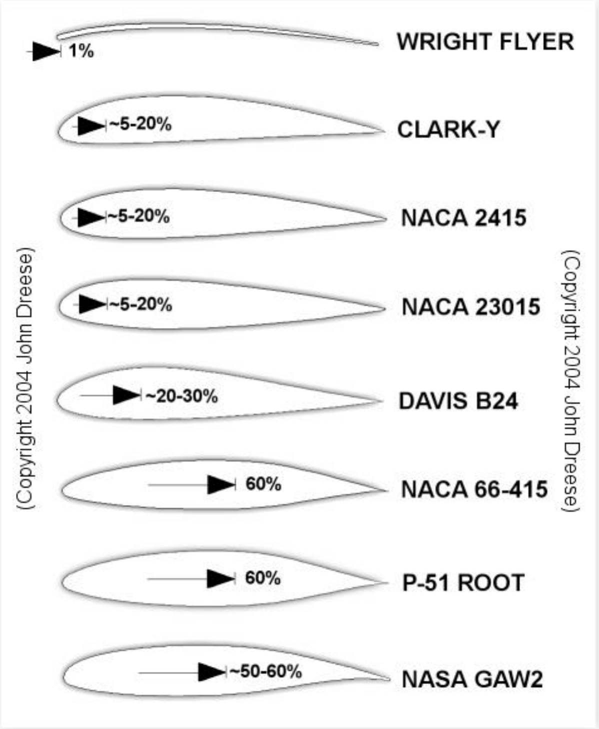
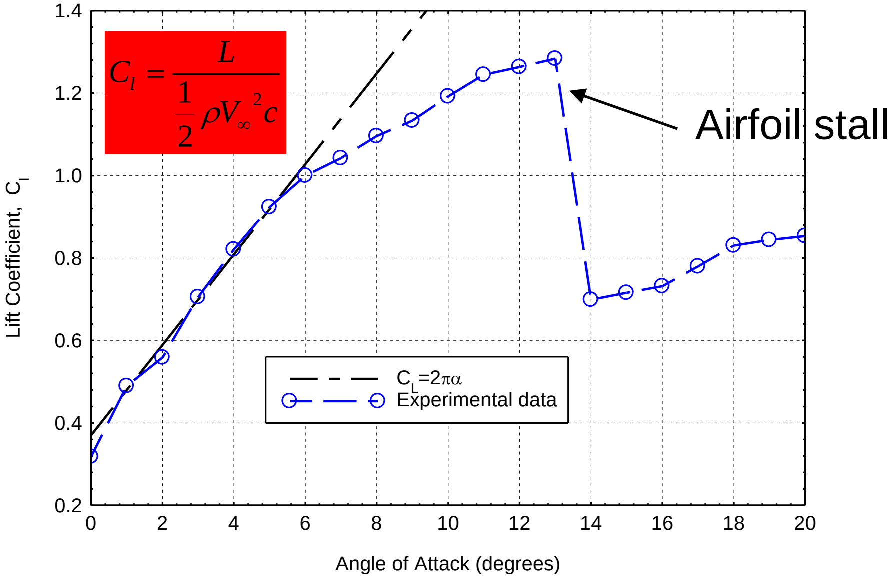
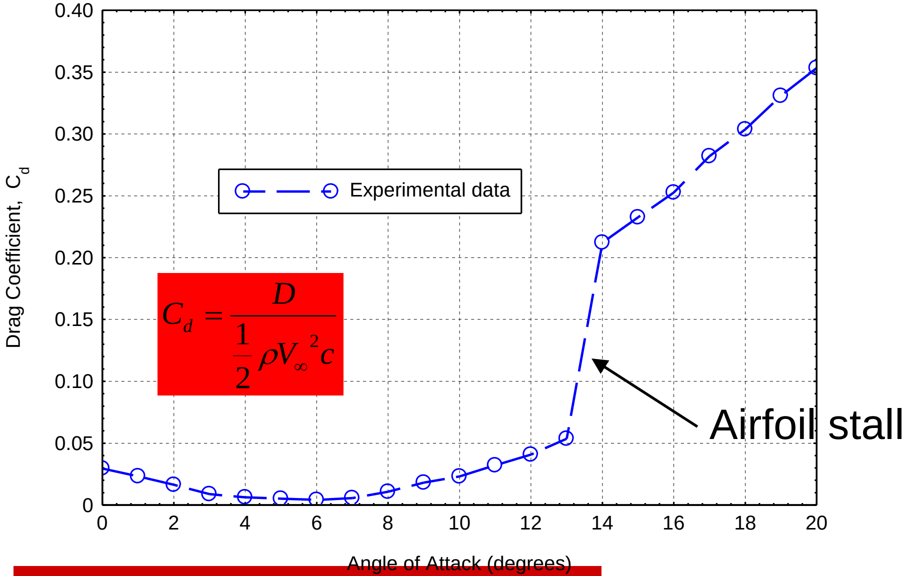
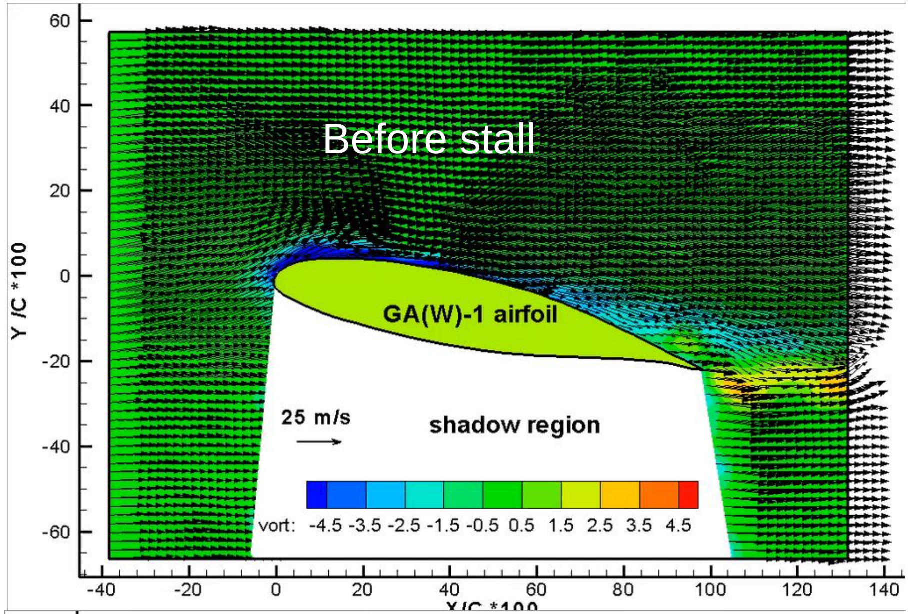


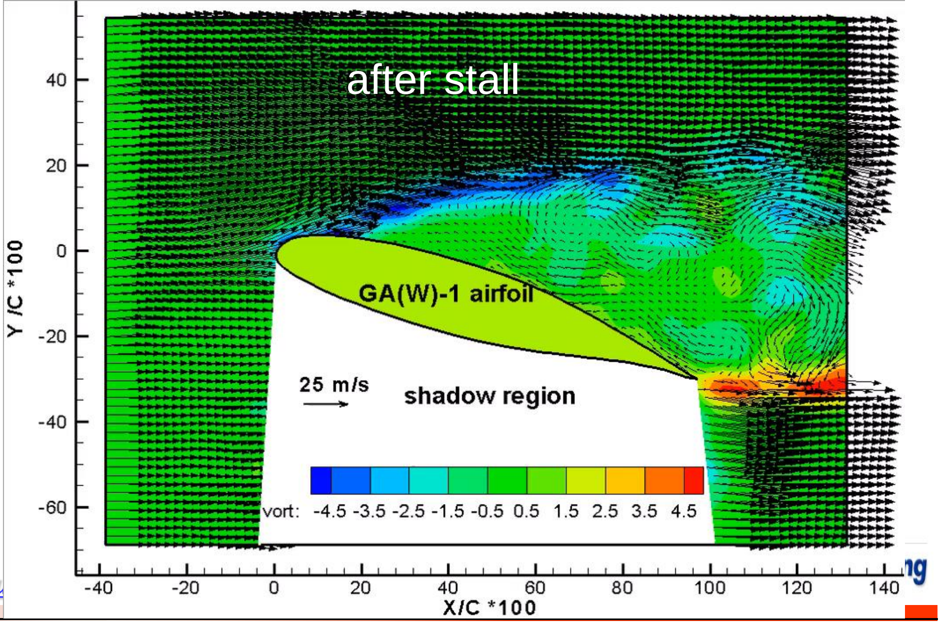
FIGURE 2: Extent of laminar flow on some famous airfoils.

Aerodynamic performance of an airfoil



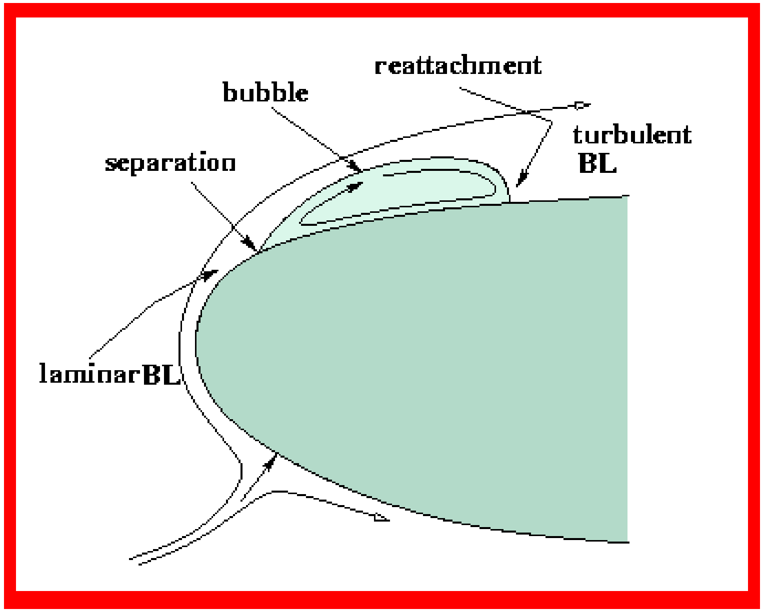


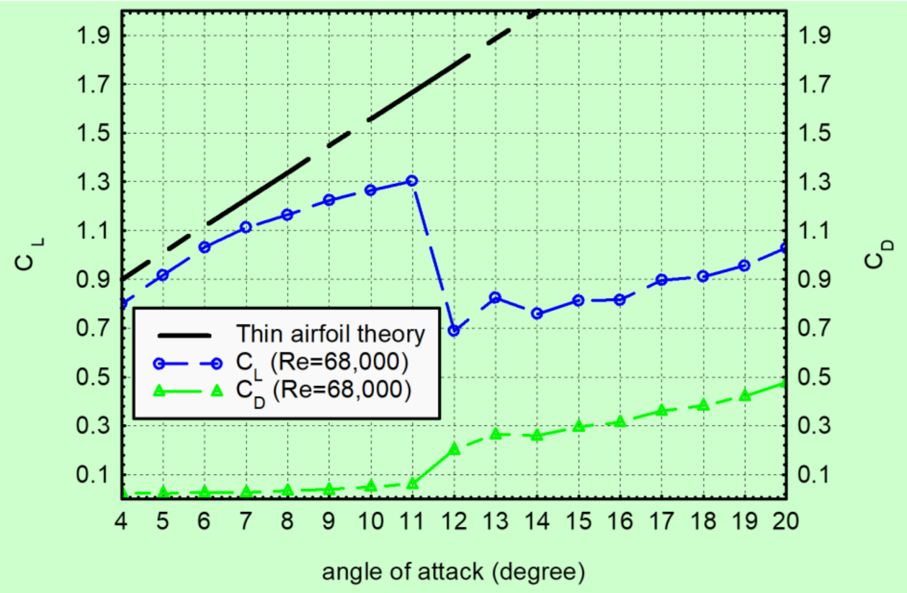




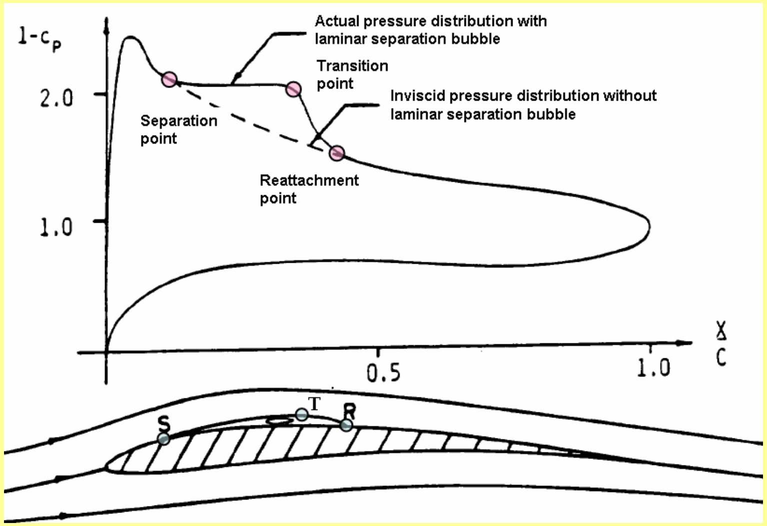
Flow Separation and Transition on Low-Reynolds-number Airfoils

- Low-Reynolds-number airfoil (with Re<500,000) aerodynamics is important for both military and civilian applications, such as propellers, sailplanes, ultra-light man-carrying/man-powered aircraft, high-altitude vehicles, wind turbines, unmanned aerial vehicles (UAVs) and Micro-Air-Vehicles (MAVs).
- Since laminar boundary layers are unable to withstand any significant adverse pressure gradient, laminar flow separation is usually found on low-Reynolds-number airfoils. Post-separation behavior of the laminar boundary layers would affect the aerodynamic performances of the low-Reynolds-number airfoils significantly
- Separation bubbles are usually found on the upper surfaces of low-Reynolds-number airfoils . Separation bubble bursting can cause airfoil stall at high AOA when the adverse pressure gradients become too big.

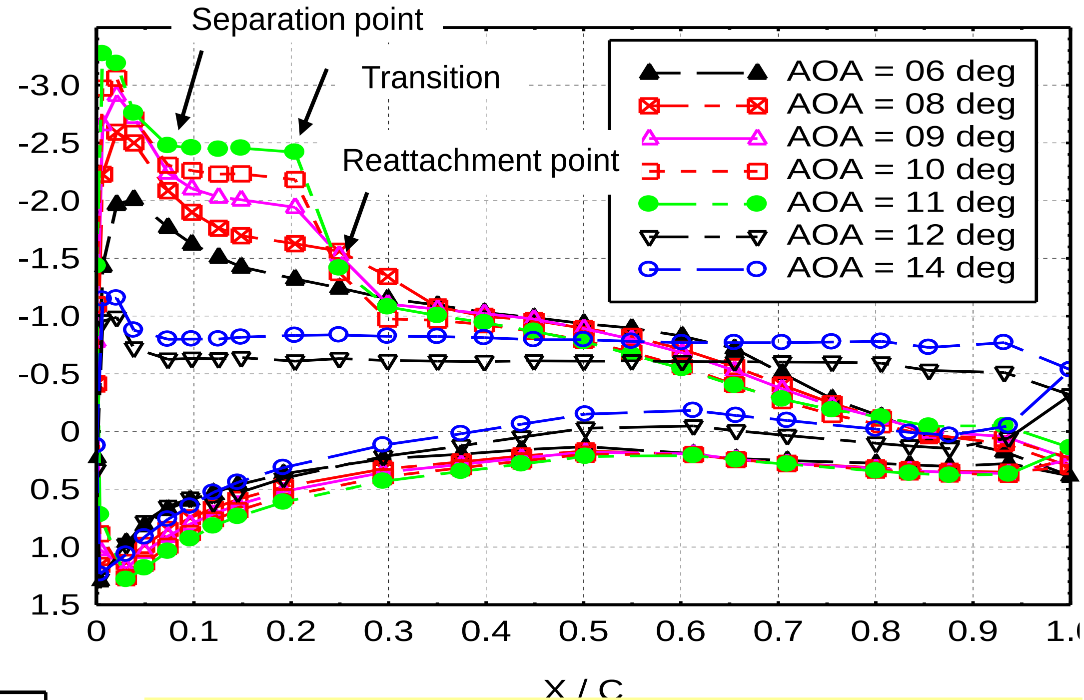


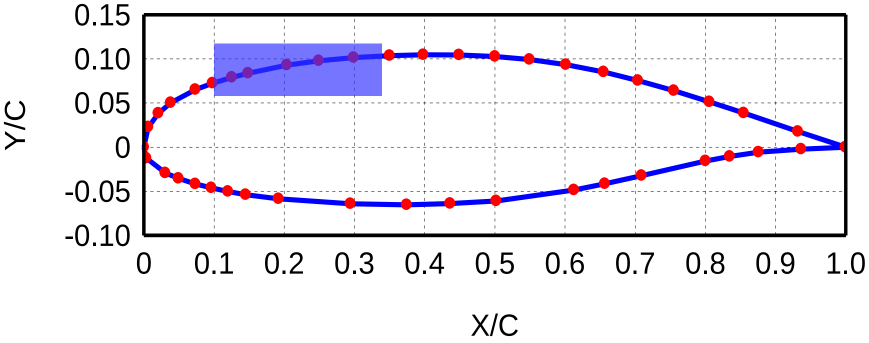


Surface Pressure Coefficient distributions (Re=68,000)



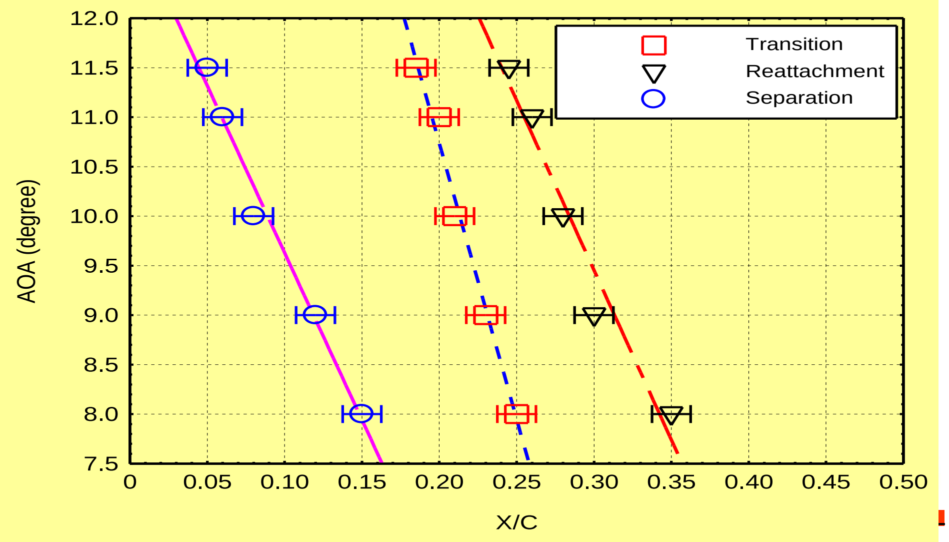
Typical surface pressure distribution when a laminar separation bubble is formed (Russell, 1979)





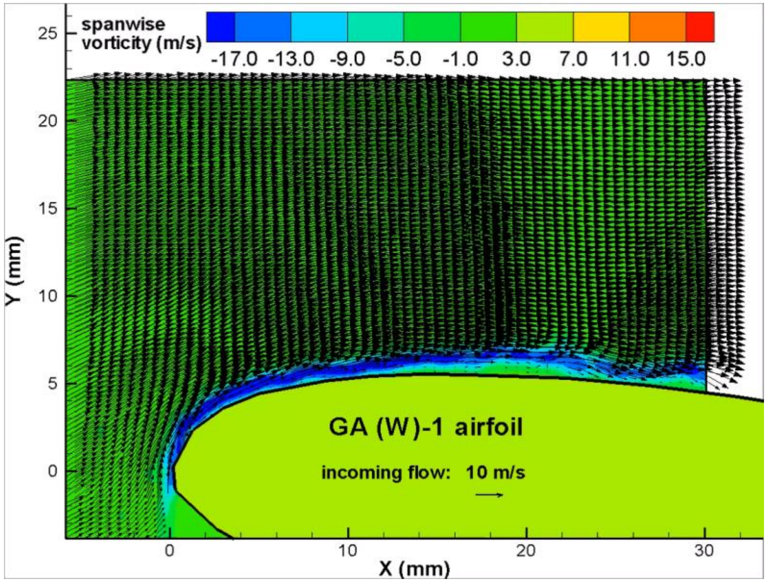
GA (W)-1 airfoil

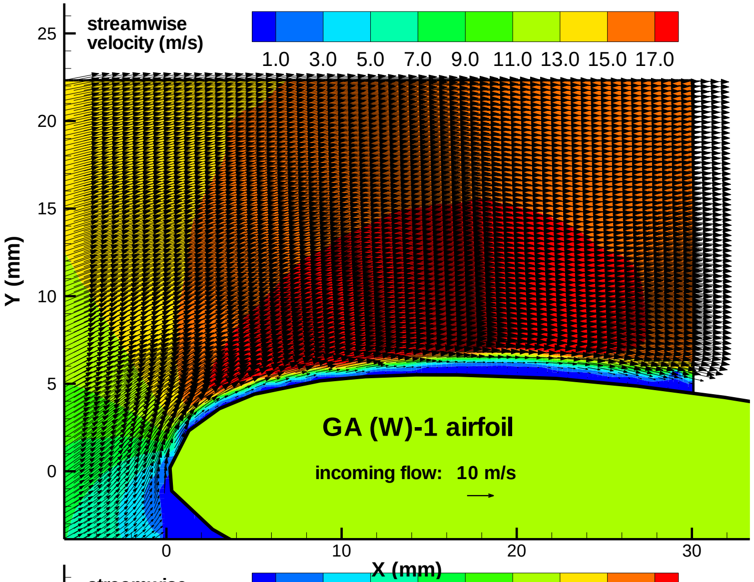
(also labeled as NASA LS(1)-0417)

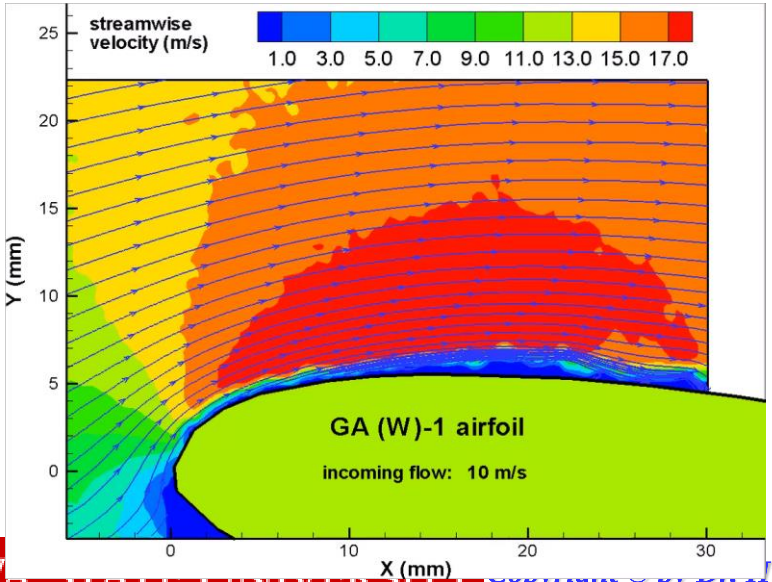


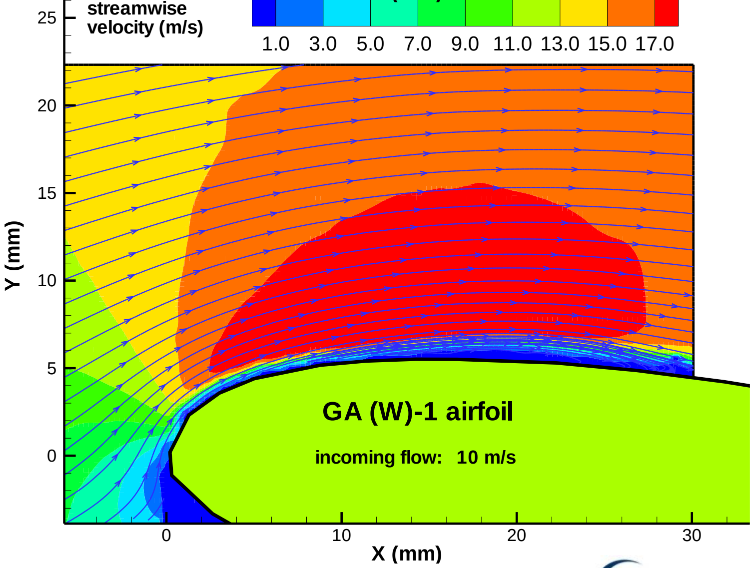
PIV Measurement Results

(AOA=10.0 degrees, Re=68,000, spatial resolution $\Delta/C \approx 0.01$)



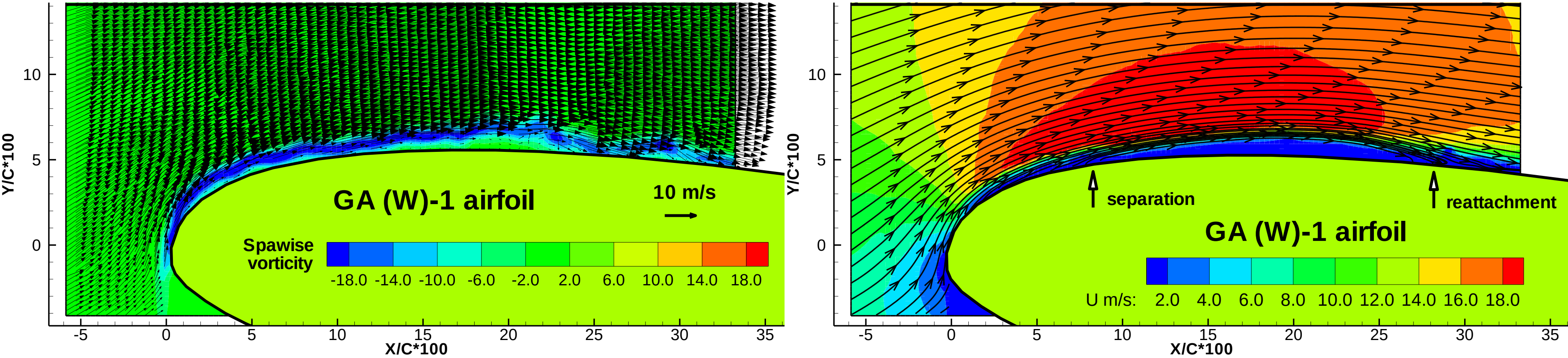






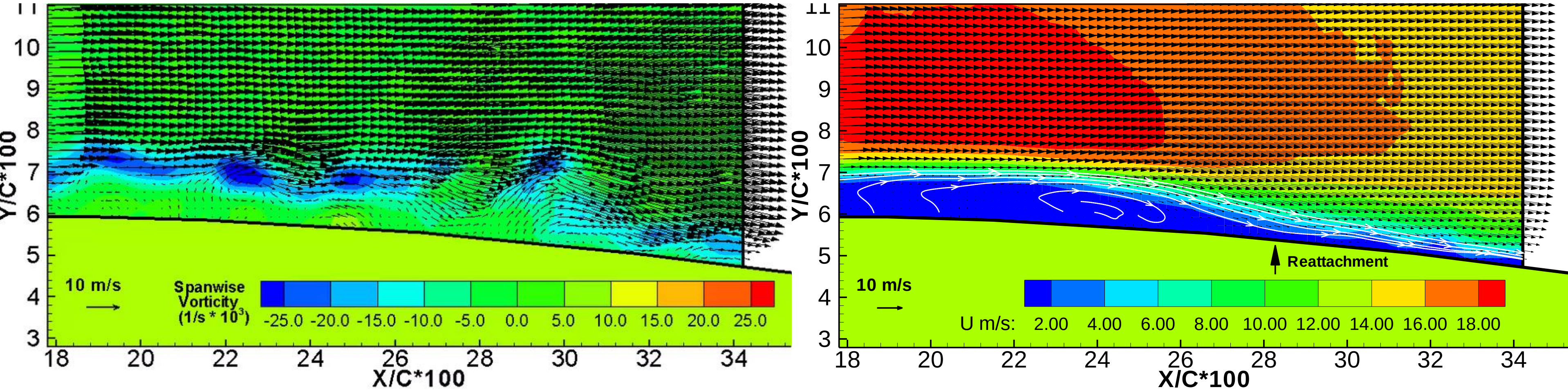
B. ensemble-averaged results

Laminar Separation Bubble on a Low-Reynolds-number Airfoil



Instantaneous flow field

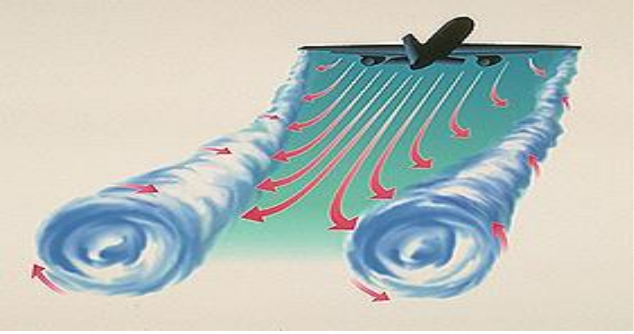
Ensemble-averaged flow field

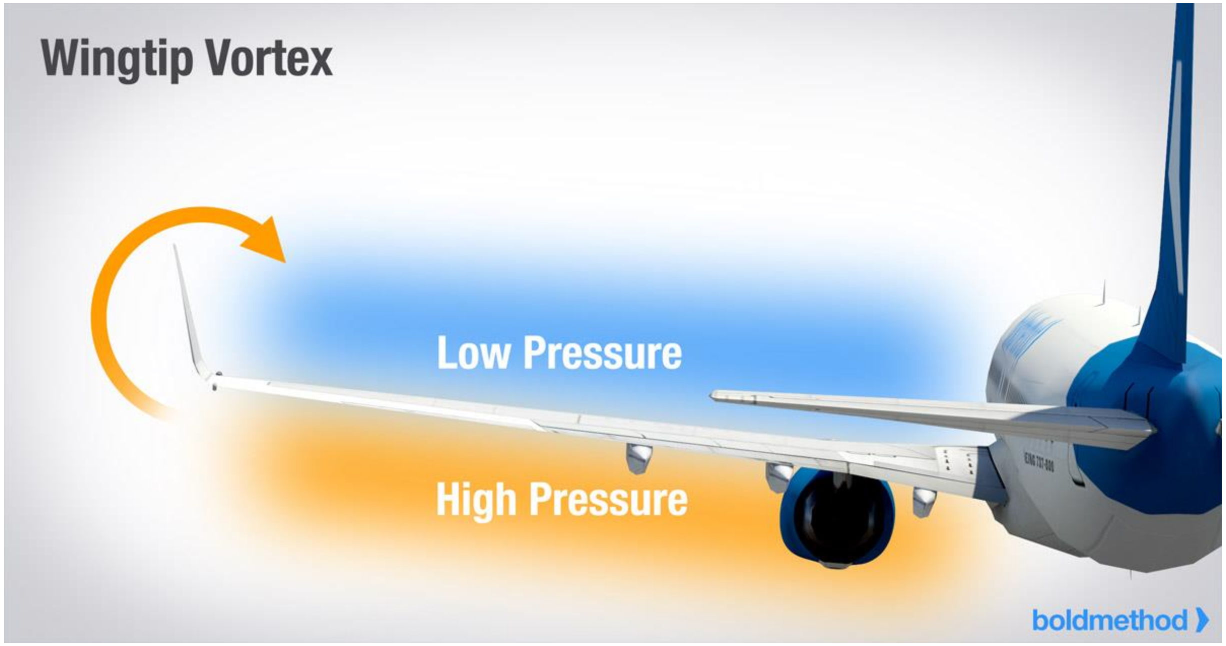


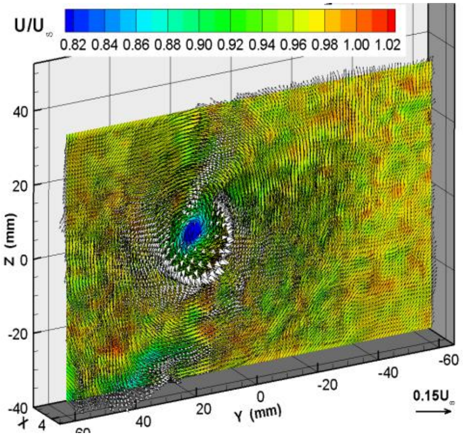
PIV measurement results at AOA = 10 deg, Re=68,000

(Hu et al., ASME Journal of Fluid Engineering, 2008)

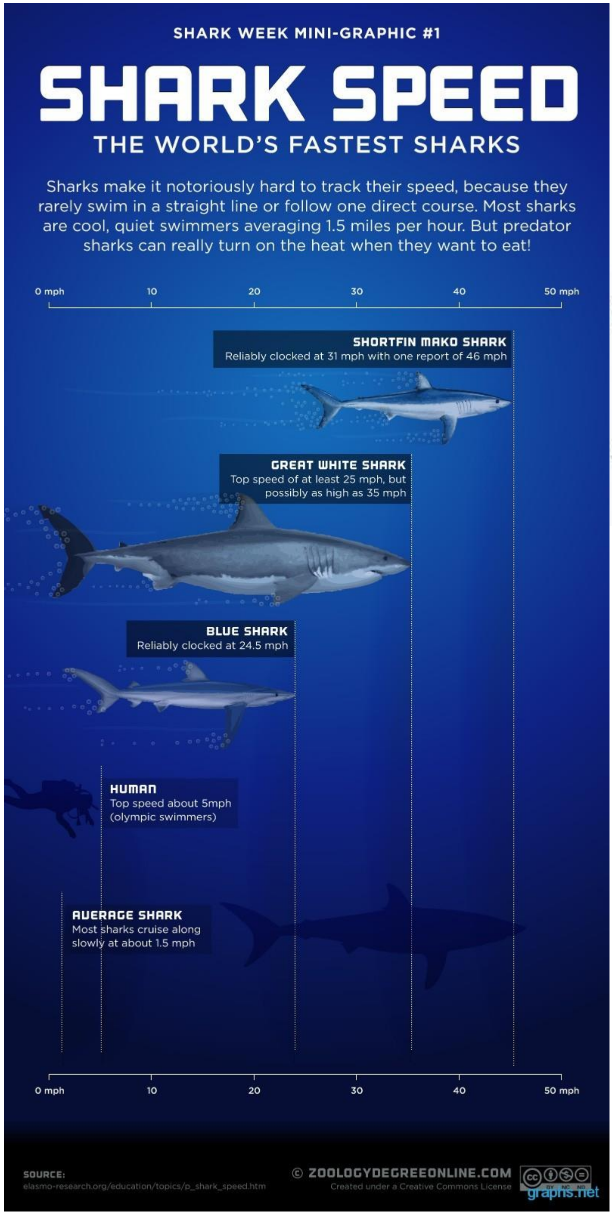
Wingtip Vortex and Winglet







Passive Flow Control: Shark Skin



SHARK WEEK MINI-GRAPHIC #1

SHARK SPEED

THE WORLD'S FASTEST SHARKS

Sharks make it notoriously hard to track their speed, because they rarely swim in a straight line or follow one direct course. Most sharks are cool, quiet swimmers averaging 1.5 miles per hour. But predator sharks can really turn on the heat when they want to eat!

SHORTFIN MAKO SHARK
Reliably clocked at 31 mph with one report of 46 mph

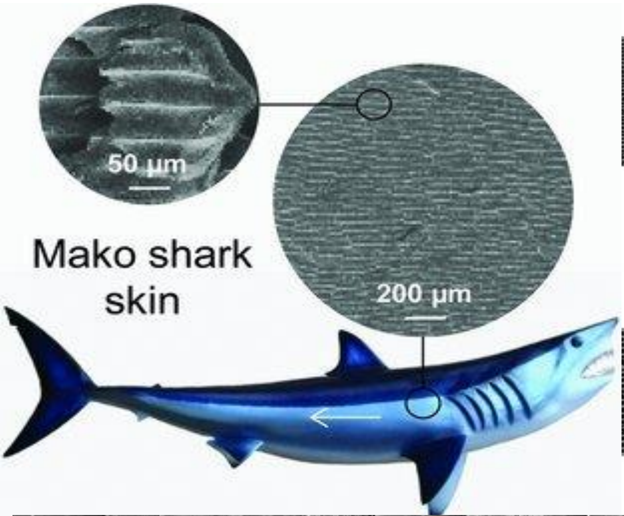
GREAT WHITE SHARK
Top speed of at least 25 mph, but possibly as high as 35 mph

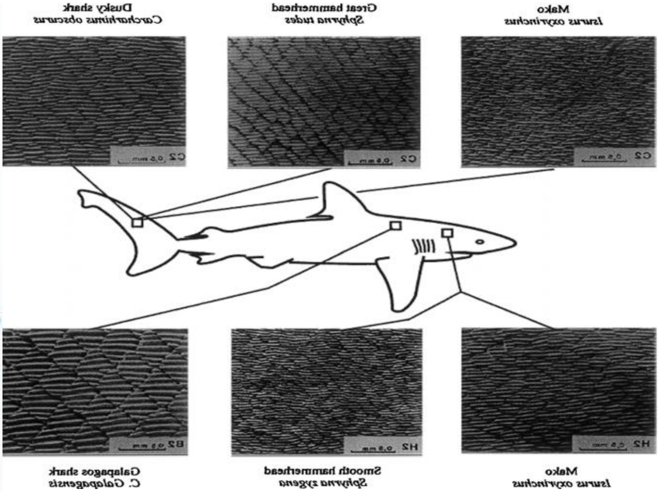
BLUE SHARK
Reliably clocked at 24.5 mph

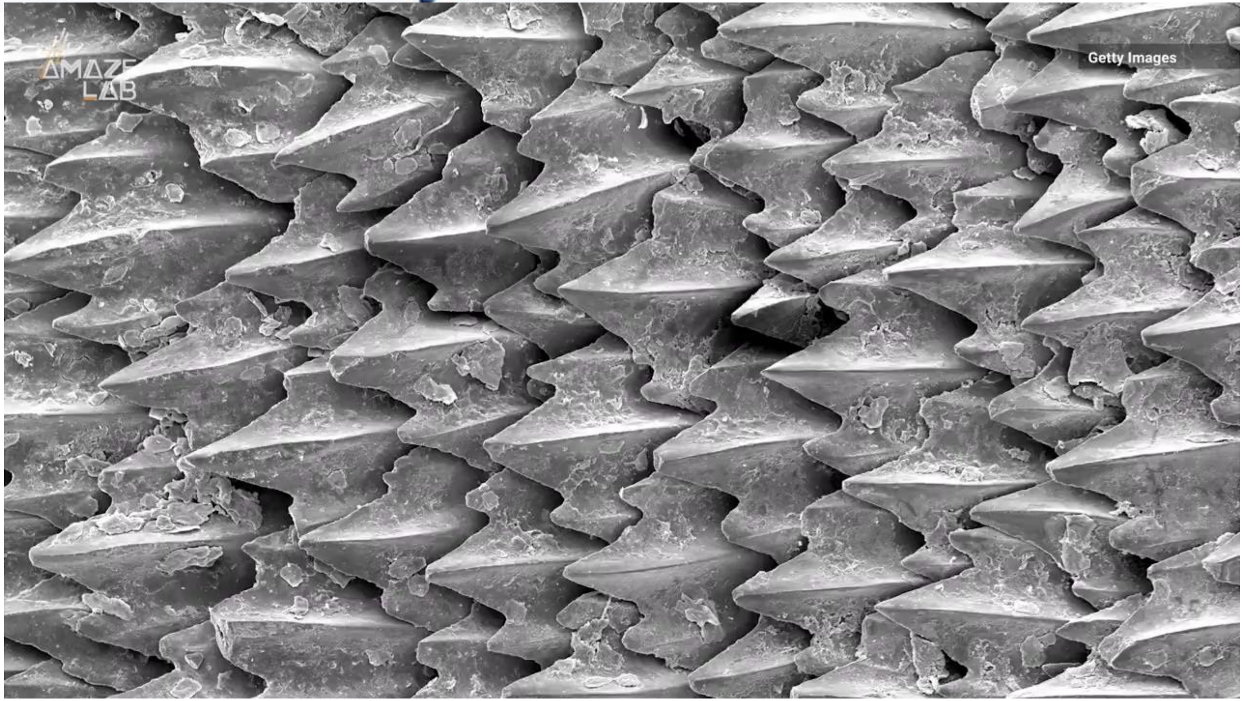
HUMAN
Top speed about 5mph (olympic swimmers)

AVERAGE SHARK
Most sharks cruise along slowly at about 1.5 mph

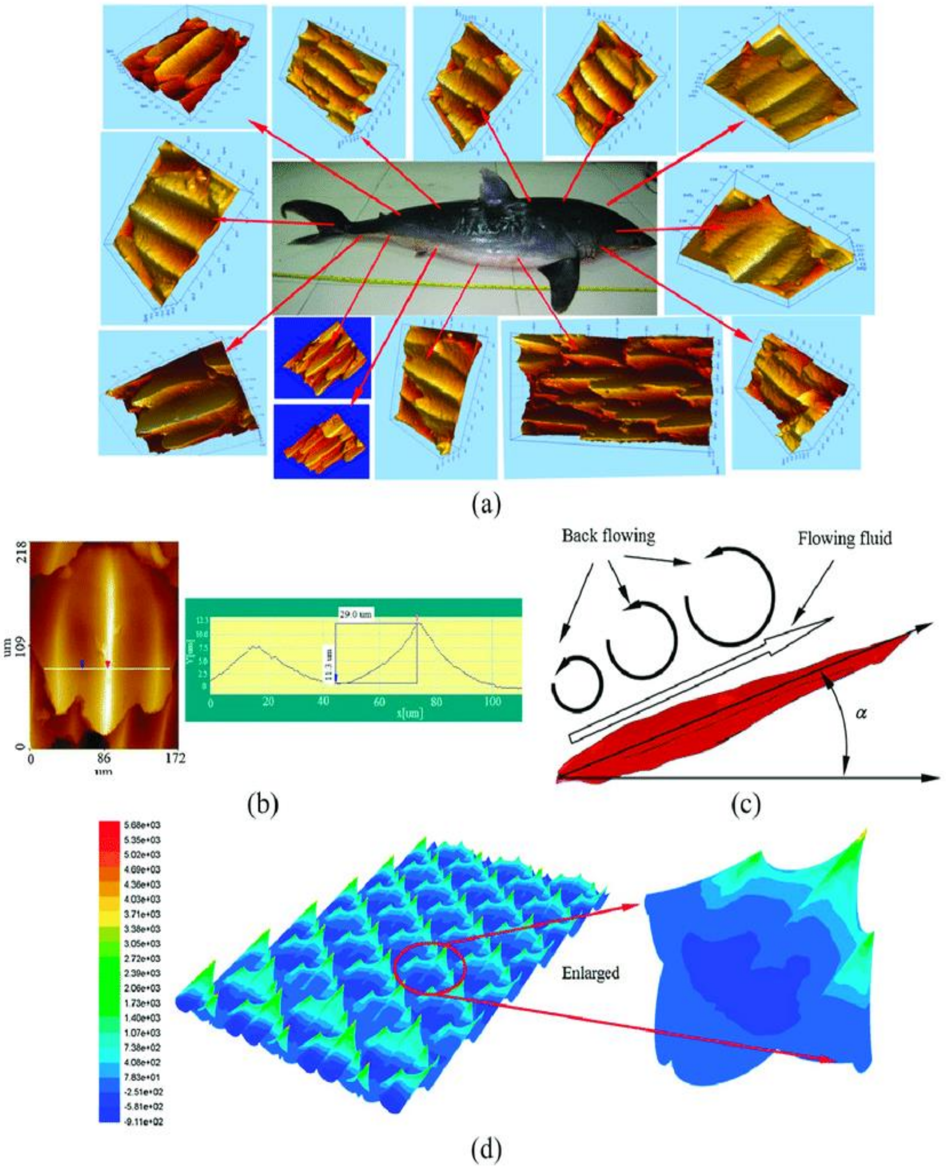
SOURCE:
elasmo-research.org/education/topics/p_shark_speed.htm







Shark Skin Structures for Drag Reduction

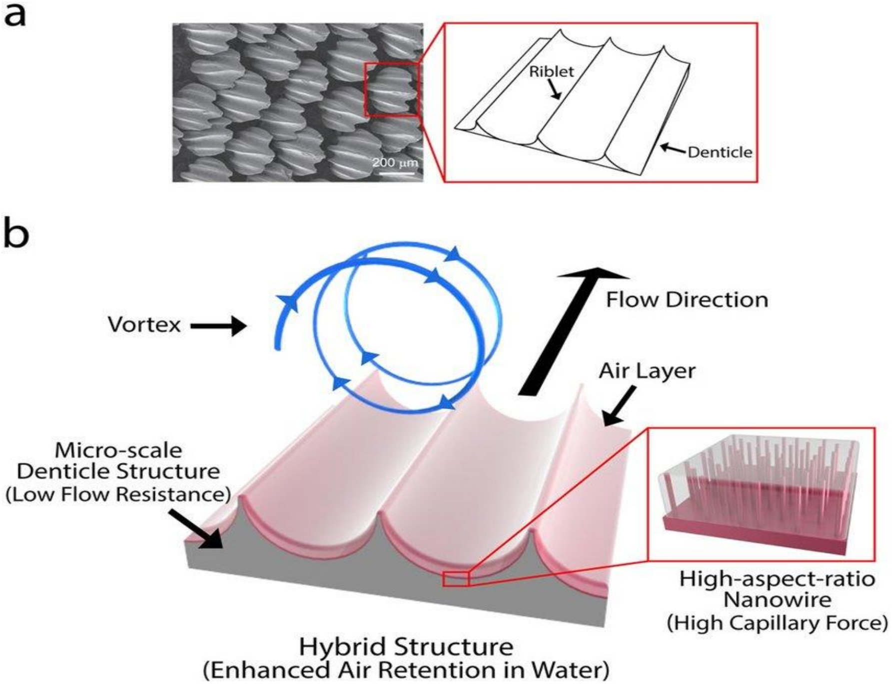


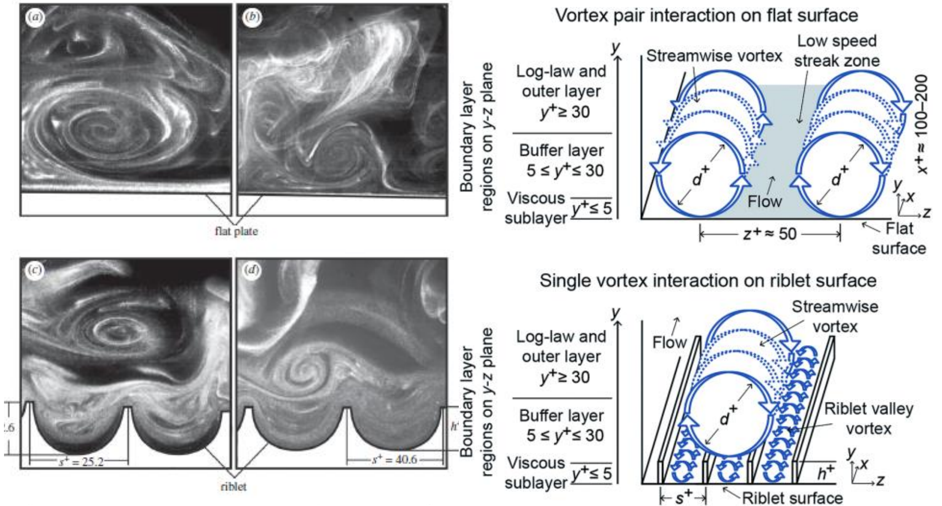
(a)

(b)

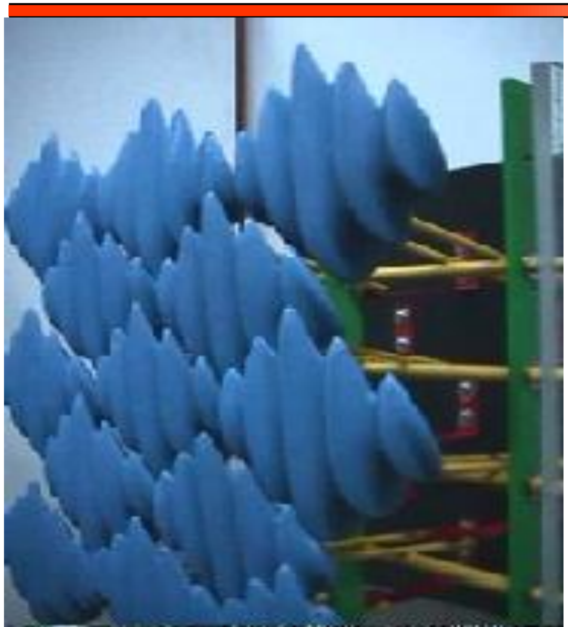
(c)

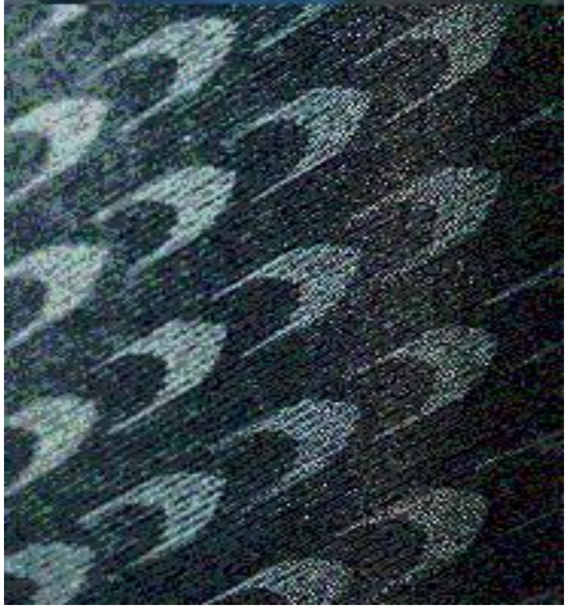
(d)

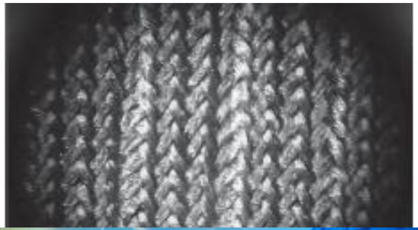




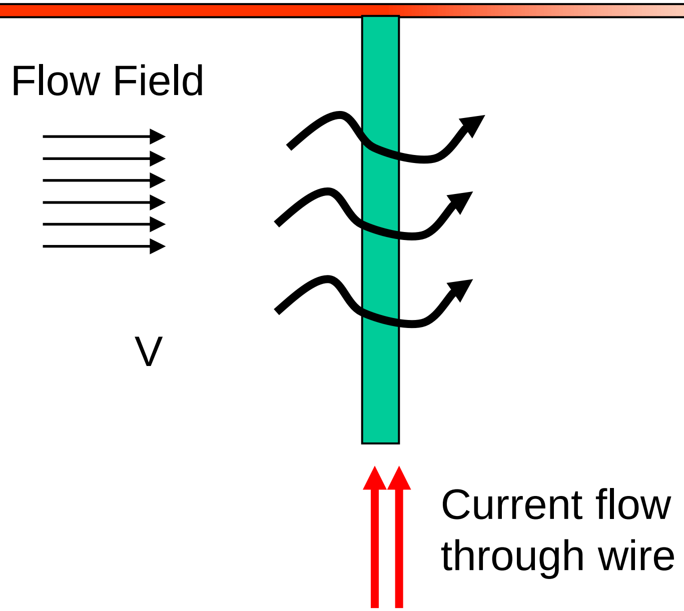
Shark Skin Inspired Engineering

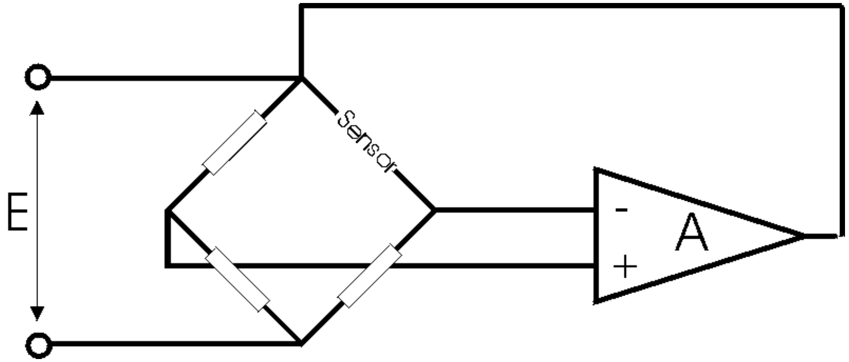






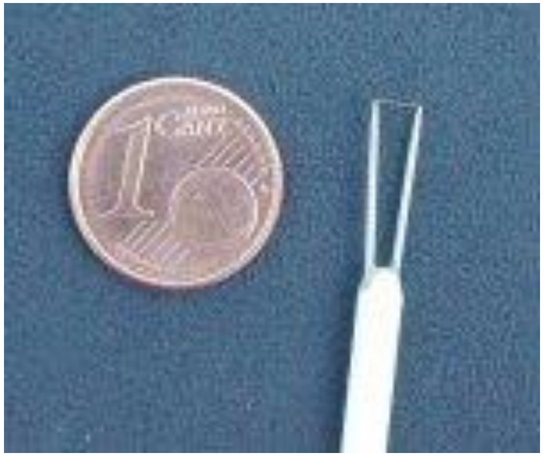
Lab 6: Airfoil Wake Measurements and Hotwire Anemometer Calibration





$$mc\frac{dT_w}{dt} = i^2R_w - \dot{q}(V,T_w)$$

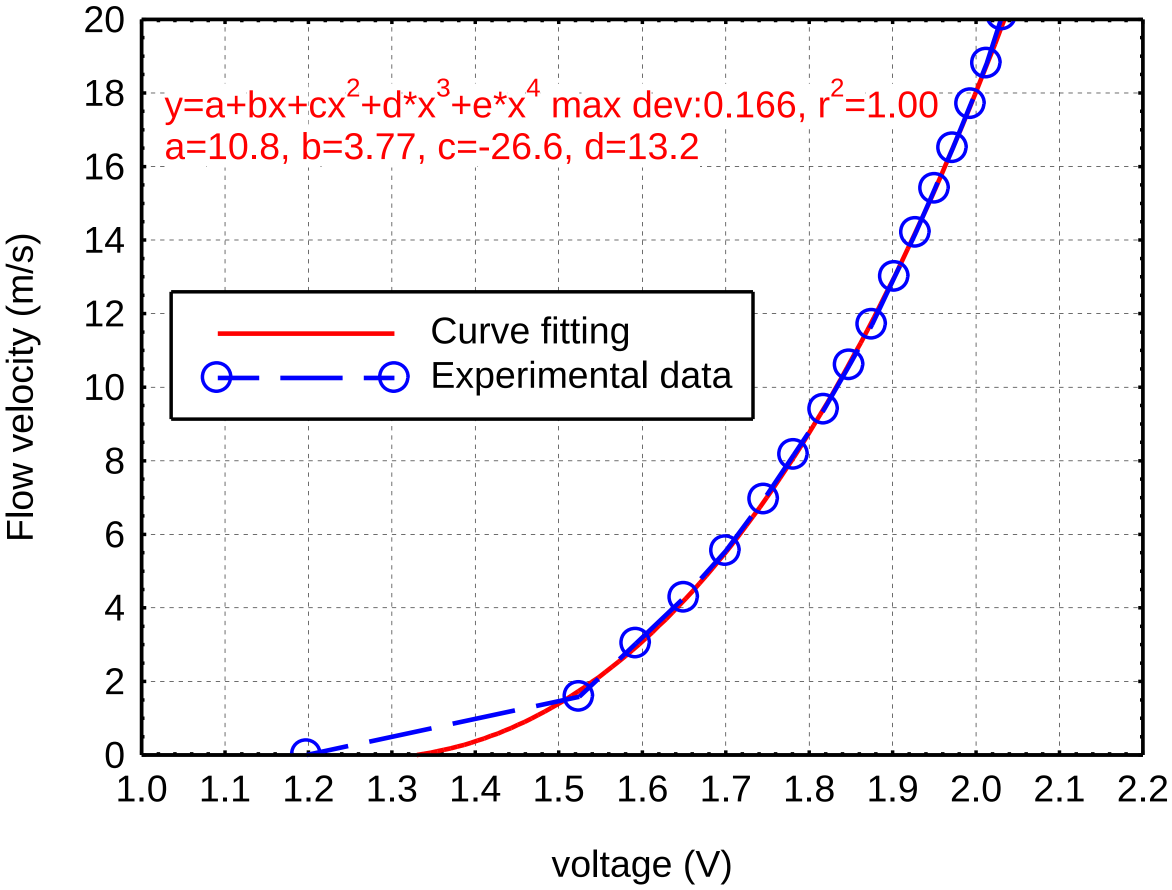
- Constant-temperature anemometry



CTA hotwire probe

Hotwire Anemometer Calibration

- Quantify the relationship between the flow velocity and voltage output from the CTA probe



Lab 6: Airfoil Wake Measurements and Hotwire Anemometer Calibration

Forces on CV = Fluid momentum change

Forces on CV: $\sum F_X = -D + \int_{CS} (p\hat{n}dA)_X = -D + \int_1 p_{up}\, dA - \int_2 p(y)\, dA$

Since $p_{up} = p_\infty, \quad p(y) \approx p_\infty$

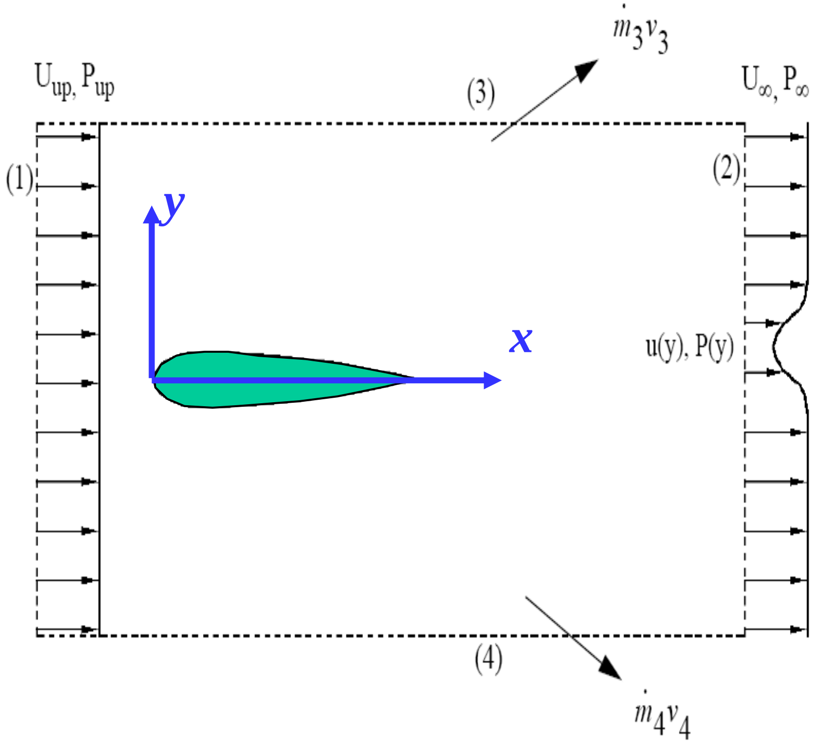
$$\Rightarrow \sum F_X = -D$$

Momentum change: $\int_2 \rho U(y)\big(U(y) - U_\infty\big)\, dA_2 = \sum F_X = -D$

$$\Rightarrow D = \rho U^2_\infty \int_2 \Big[\frac{U(y)}{U_\infty}\Big(1 - \frac{U(y)}{U_\infty}\Big)\Big] dA_2$$

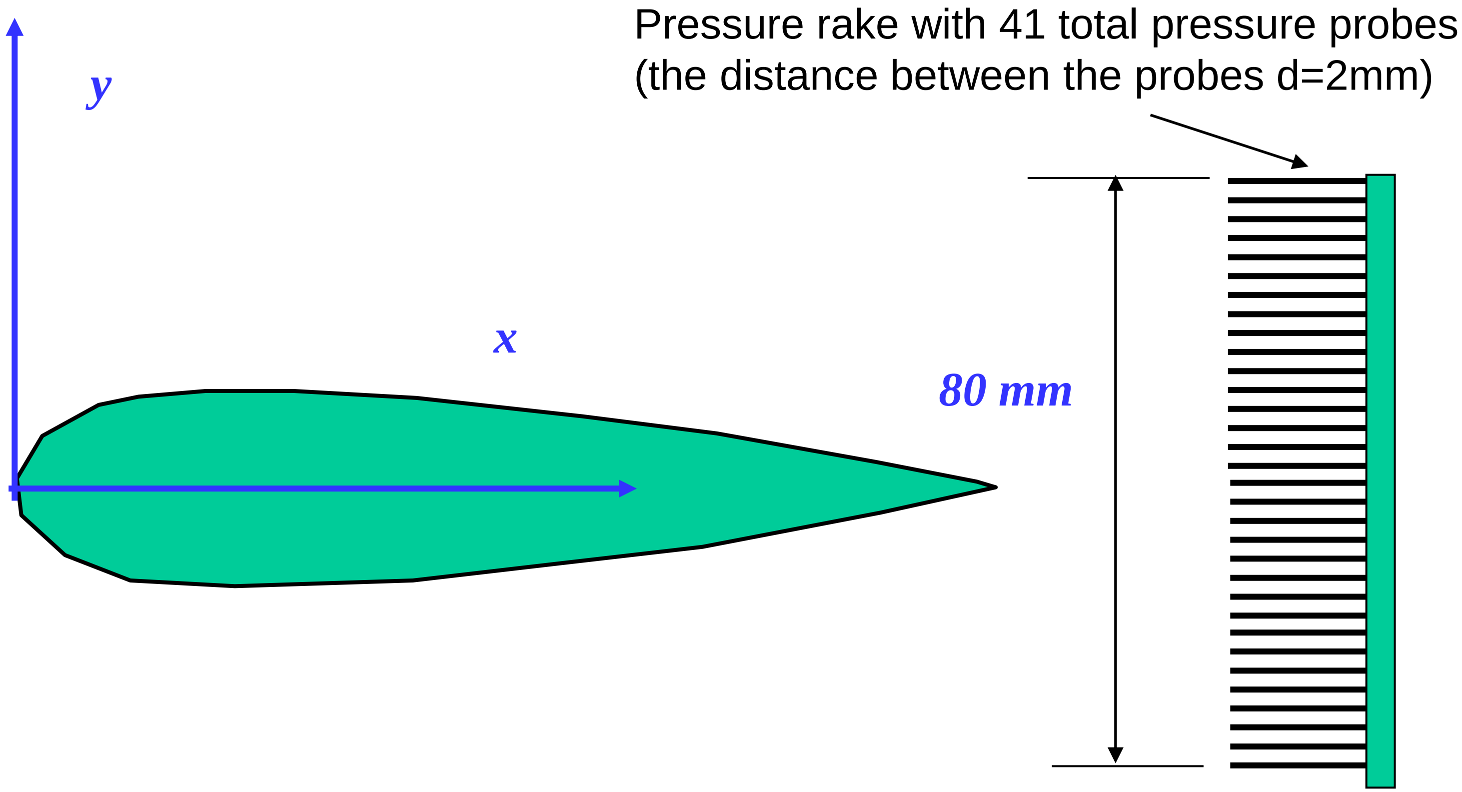
$$C_D = \frac{D}{\frac{1}{2}\rho U_\infty^2 C} = \frac{\rho U^2_\infty \int_2 \Big[\frac{U(y)}{U_\infty}\Big(1 - \frac{U(y)}{U_\infty}\Big)\Big] dA_2}{\frac{1}{2}\rho U_\infty^2 C}$$

$$\Rightarrow C_D = \frac{2}{C}\int_2 \Big[\frac{U(y)}{U_\infty}\Big(1 - \frac{U(y)}{U_\infty}\Big)\Big] dy$$



Compare with the drag coefficients obtained based on airfoil surface pressure measurements at the same angles of attack!

Lab 6: Airfoil Wake Measurements and Hotwire Anemometer Calibration


Pressure rake with 41 total pressure probes
(the distance between the probes d=2mm)

Required Measurement Results

NOTE: We will be using the **GA(W)-1** airfoil from the previous lab for the wake pressure measurements

Required Plots:

- C_p distribution in the wake (for each angle of attack) for the airfoil wake measurements
- C_d vs angle of attack (do your values look reasonable?) based on the airfoil wake measurements
- Your hot wire anemometer calibration curve: Velocity versus voltage output of hotwire anemometer (including a 4th order polynomial fit)

Please briefly describe the following details:

- How you calculated your drag—you should show your drag calculations
- How these drag calculations compared with the drag calculations you made in the previous experiment
- Reynolds number of tests and the incoming flow velocity