Lecture # 07: Laminar and Turbulent Flows

Dr. Hui Hu

Department of Aerospace Engineering
Iowa State University
Ames, Iowa 50011, U.S.A

Reynolds' experiment

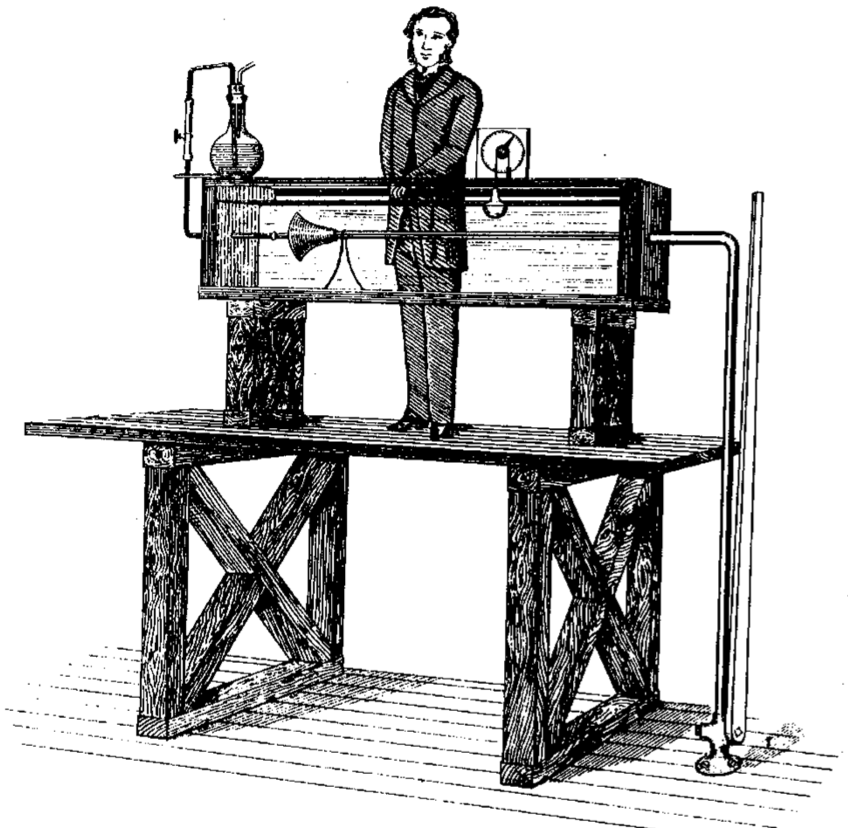


Fig. 9.1. Sketch of Reynolds's dye experiment, taken from his 1883 paper

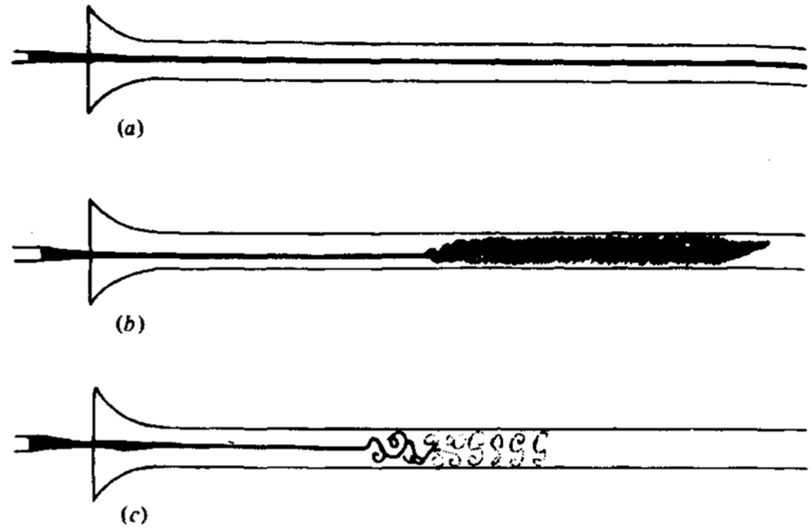
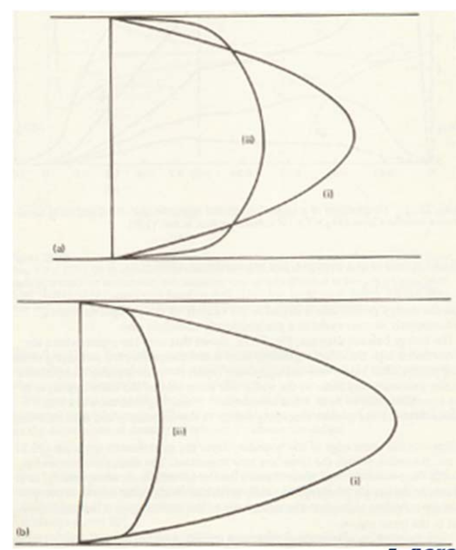


Fig. 9.2. Reynolds's drawings of the flow in his dye experiment.

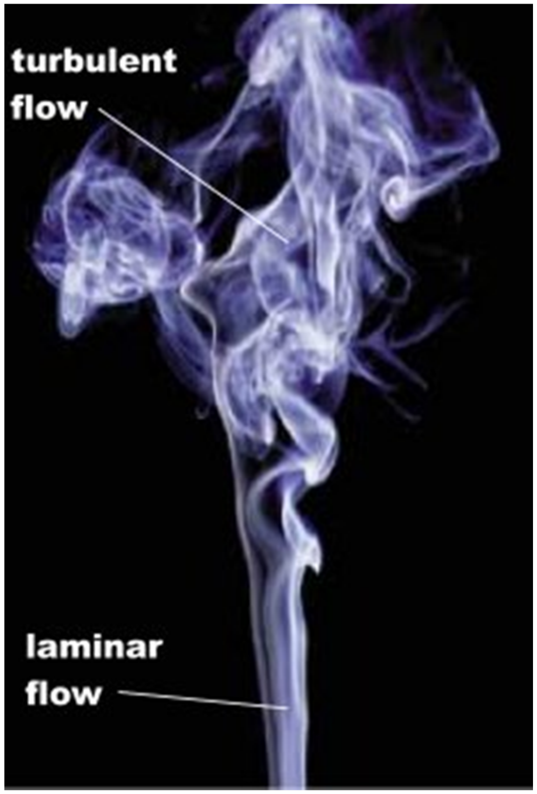
$$\mathrm{Re} = \frac{\rho D U}{\mu}$$



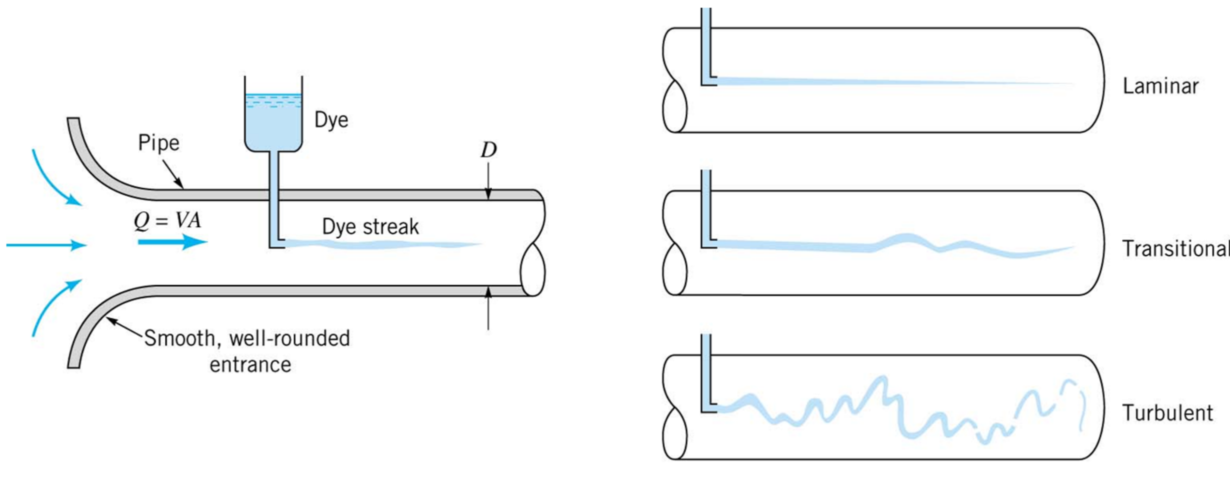
Laminar Flows and Turbulence Flows

- *Laminar flow, sometimes known as streamline flow, occurs when a fluid flows in parallel layers, with no disruption between the layers. Inflow dynamics laminar flow is a flow regime characterized by high momentum diffusion, low momentum convention, pressure and velocity almost independent from time. It is the opposite of turbulent flow.*
  - *In nonscientific terms laminar flow is "smooth," while turbulent flow is "rough."*

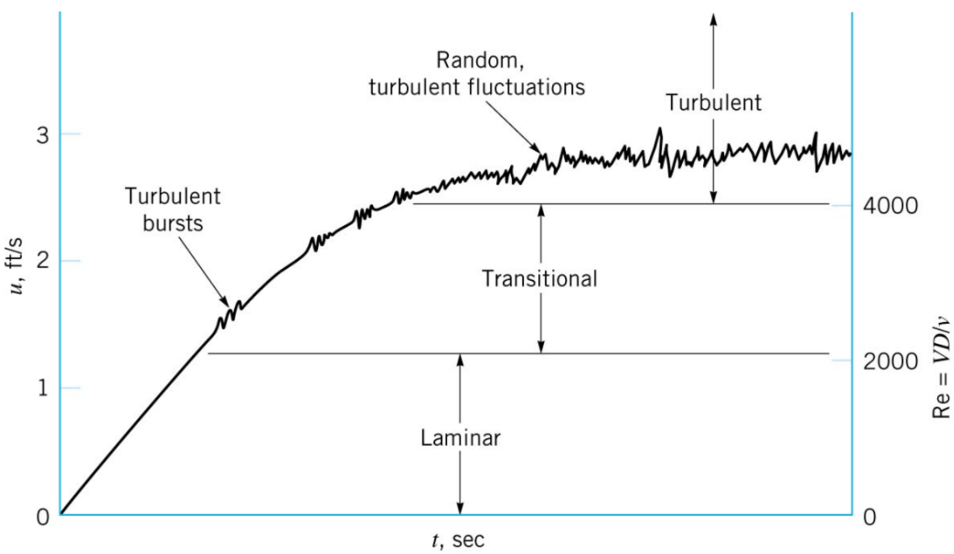
- *In fluid dynamics, turbulence or turbulent flow is a fluid regime characterized by chaotic, stochastic property changes. This includes low momentum diffusion, high momentum conversation, and rapid variation of pressure and velocity in space and time.*
  - *Flow that is not turbulent is called laminar flow*



Turbulent Flows in a Pipe



(a) (b)



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

Characterization of Turbulent Flows

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

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

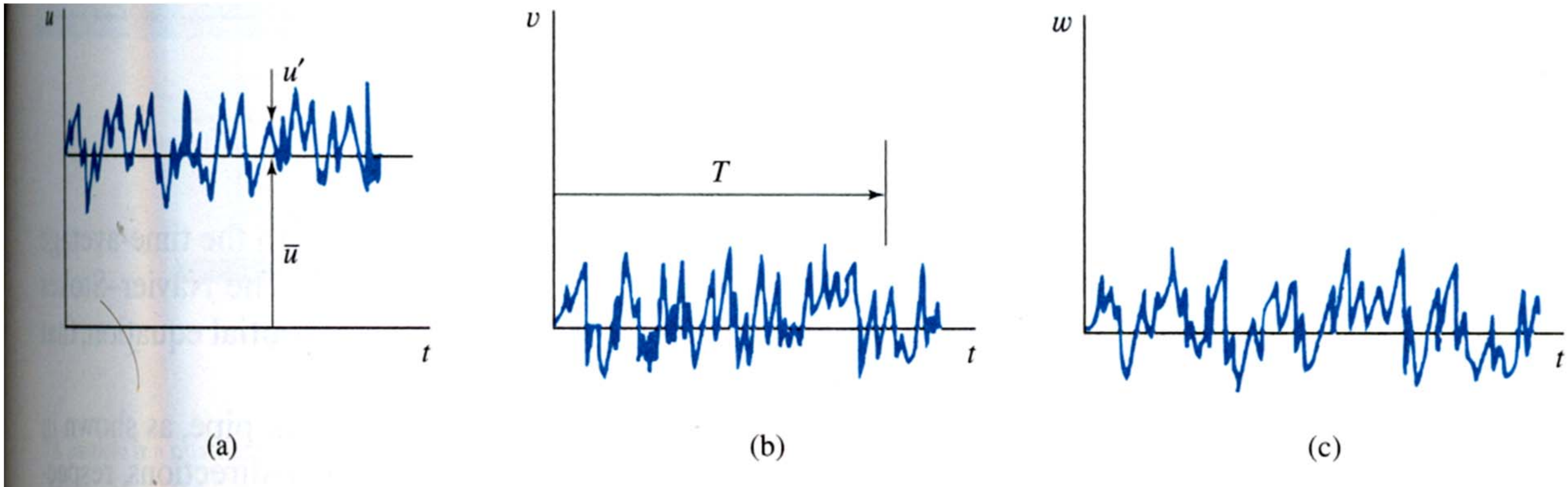
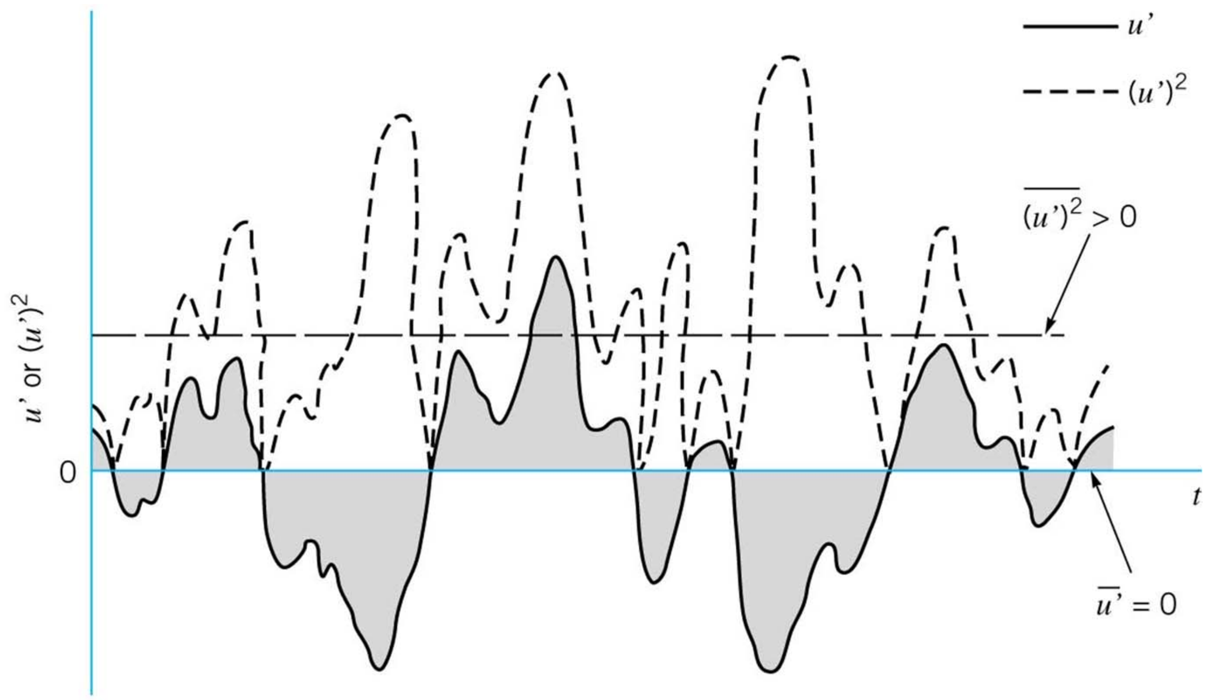


FIGURE 7.7 Velocity components in a turbulent pipe flow: (a) x-component velocity; (b) r-component velocity; (c) θ-component velocity.

Turbulence intensities

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

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

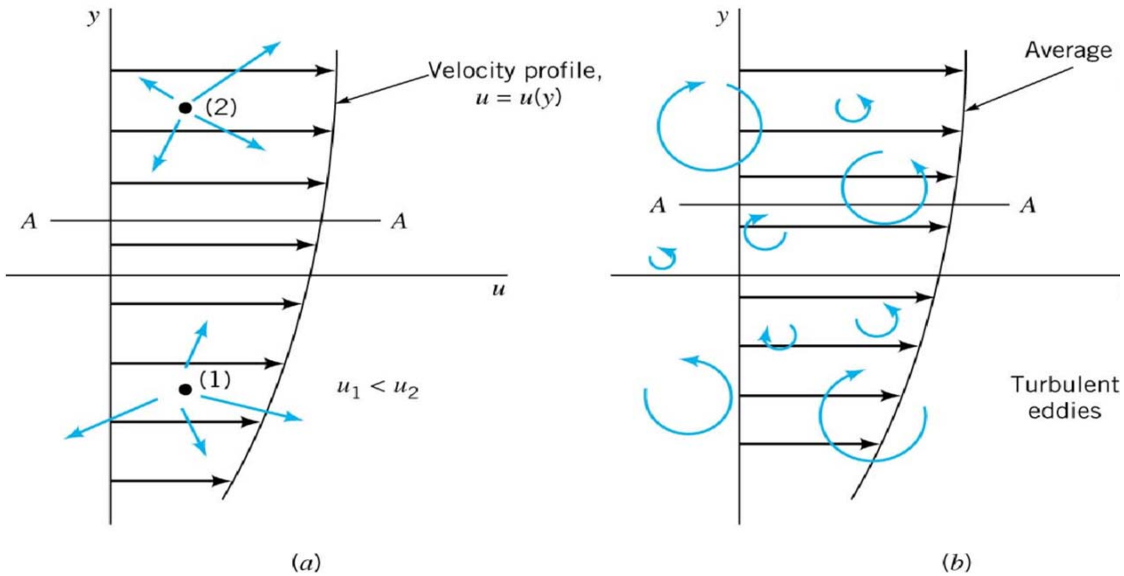


Turbulent Shear Stress

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

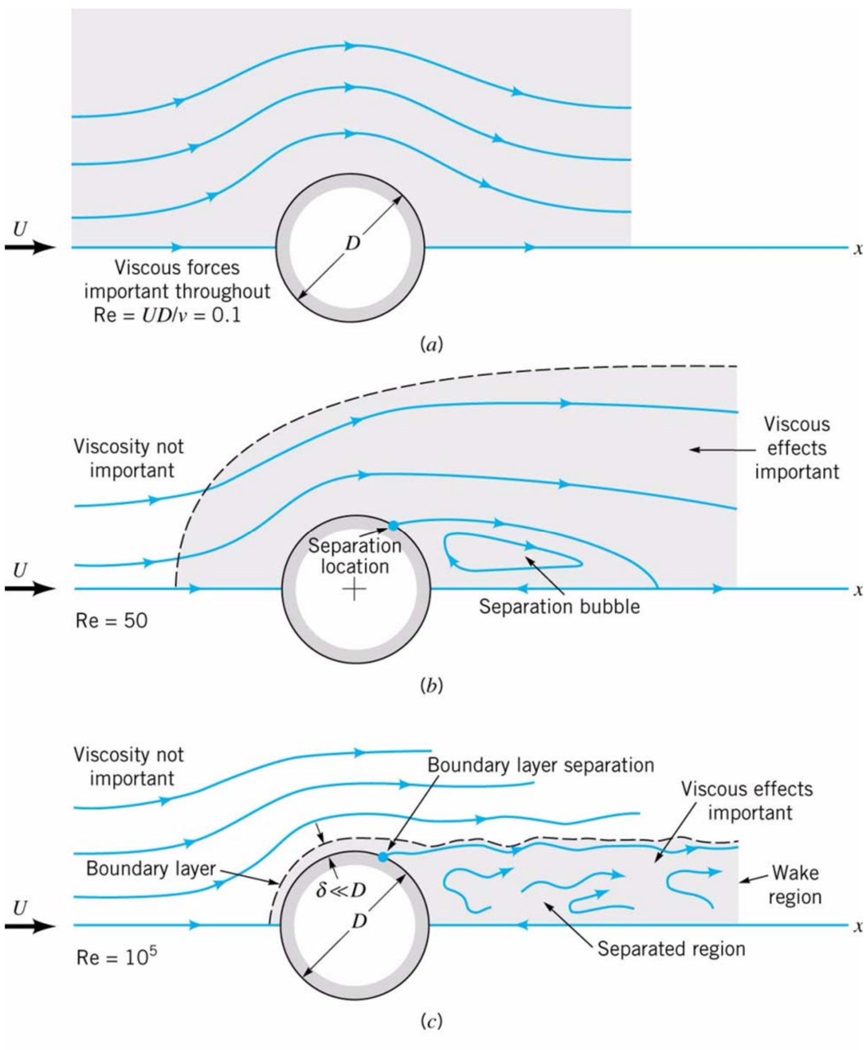
Turbulent flows: $$\overline{\tau_{turb}} = -\rho \overline{u'v'}$$

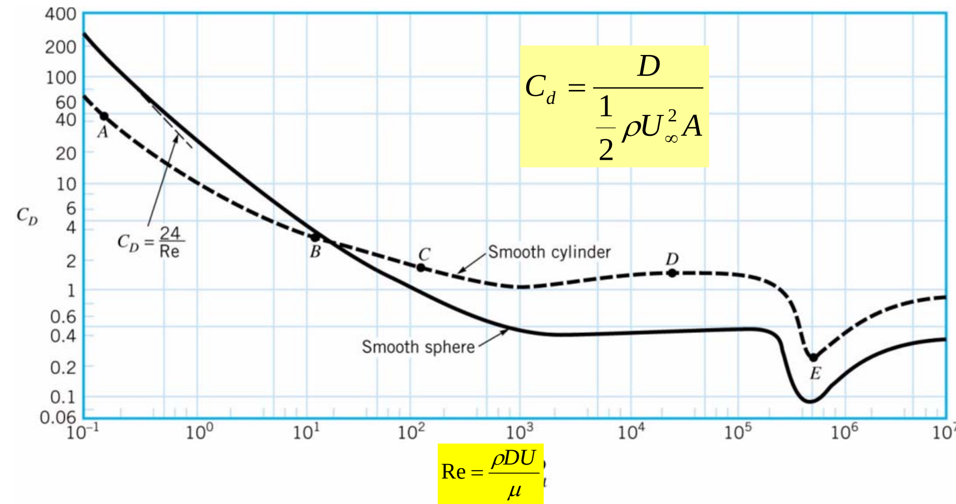
$$\bar{\tau} = \overline{\tau_{lam}} + \overline{\tau_{turb}} = \mu \frac{\partial \bar{u}}{\partial y} - \rho \overline{u'v'}$$

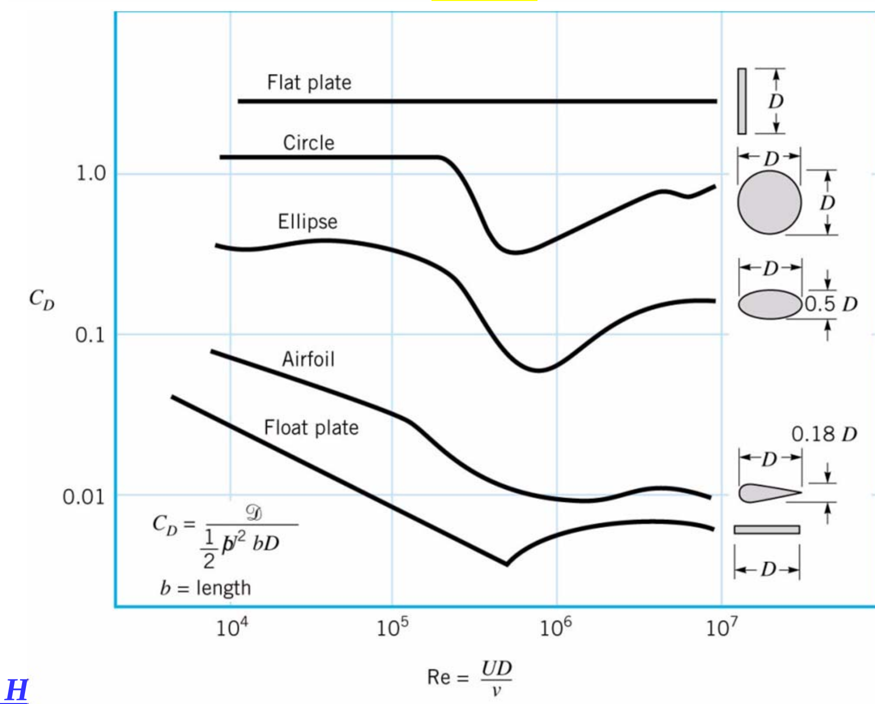


A.laminar flow *b.turbulent flow*

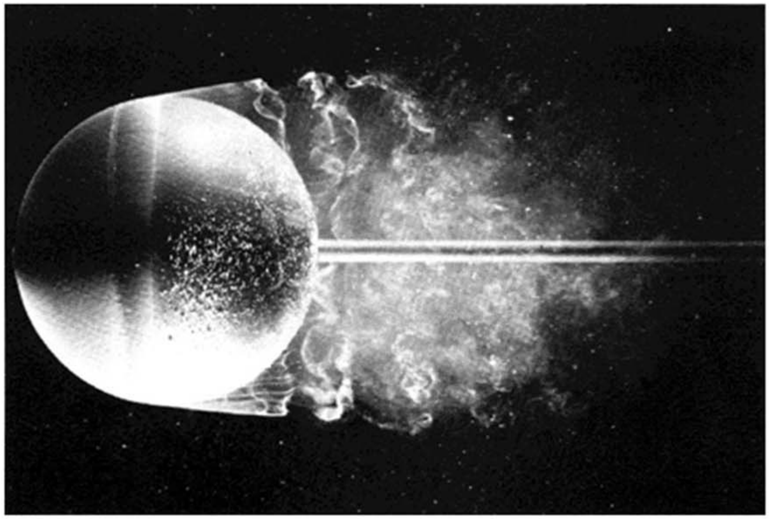
Laminar Flows and Turbulence Flows

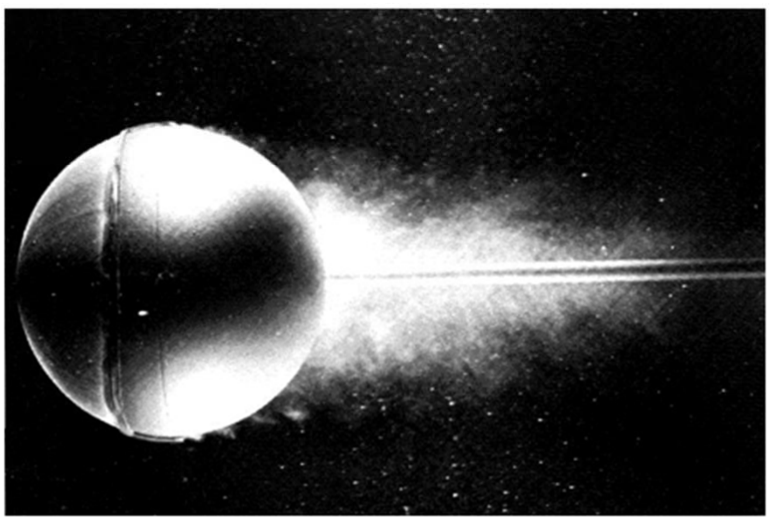






Flow Around A Sphere with laminar and Turbulence Boundary Layer





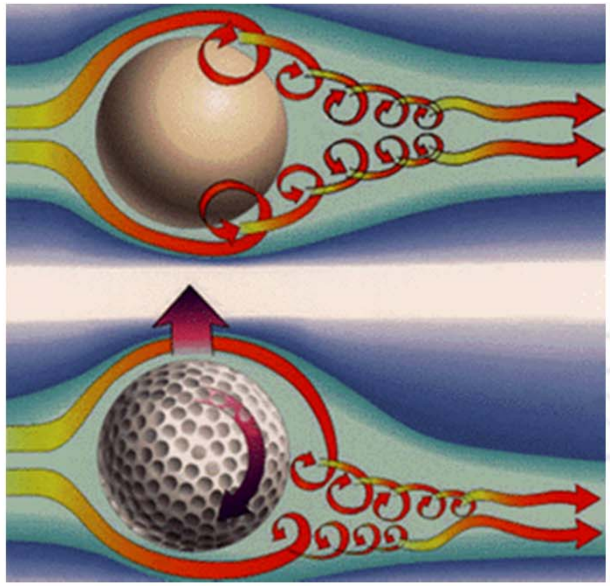
Top:

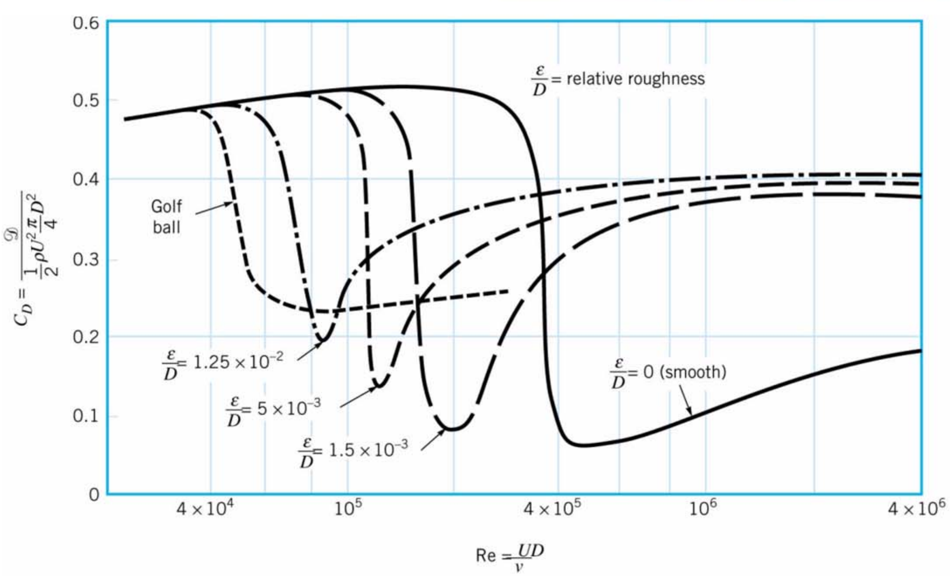
Instantaneous flow past a sphere at Re_D = 15,000. Dye in water shows a laminar boundary layer separating ahead of the equator and remaining laminar for almost one radius. It then becomes unstable and quickly turns turbulent.

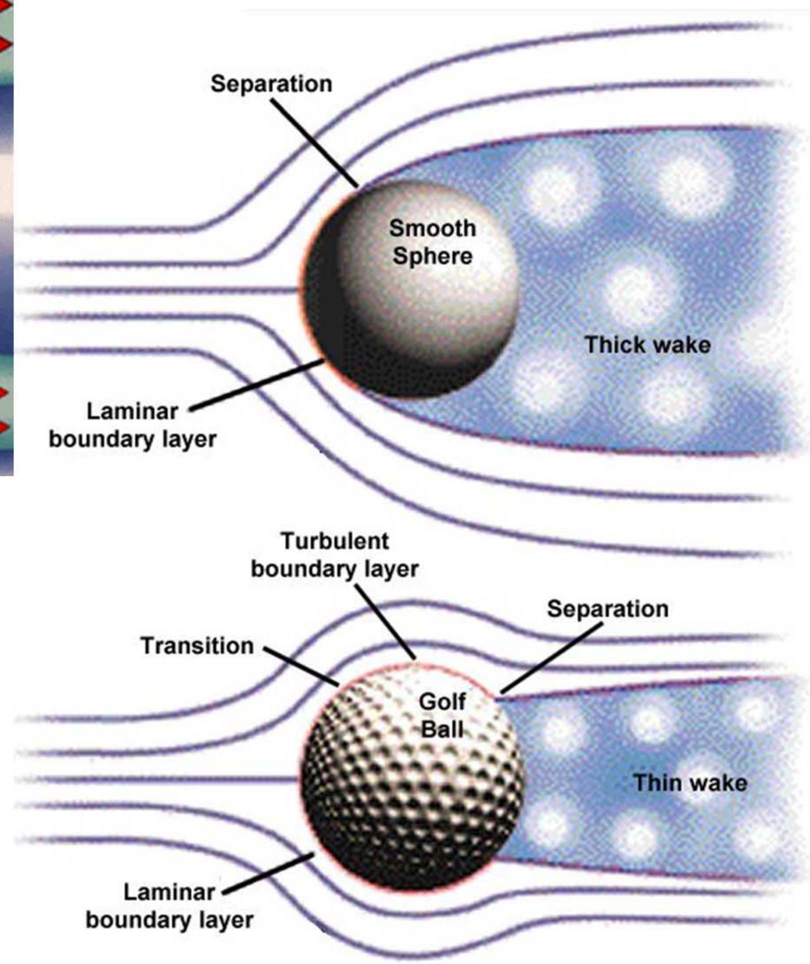
Bottom:

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.

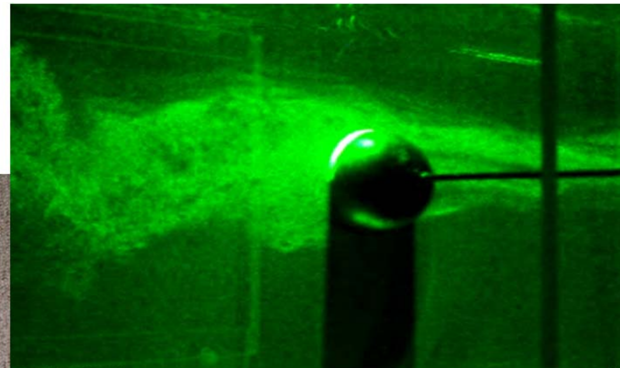
Aerodynamics of Golf Ball

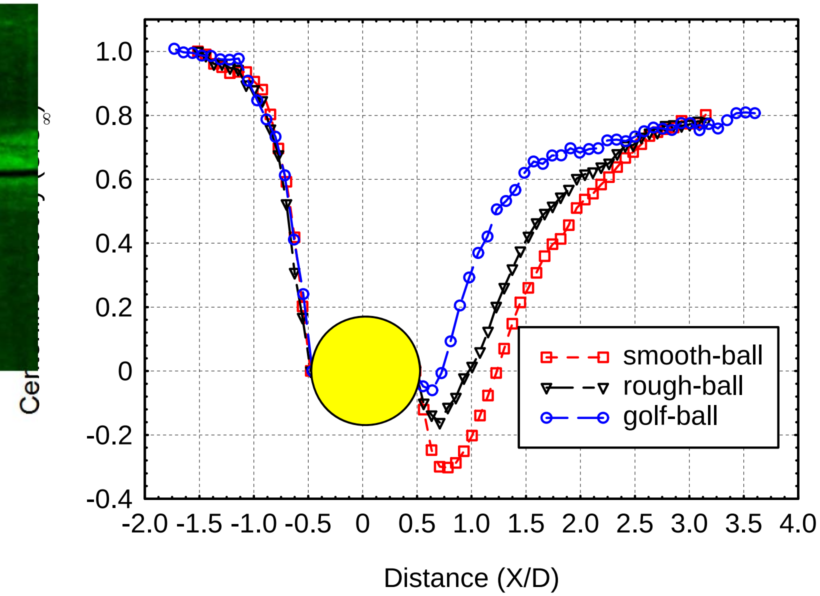






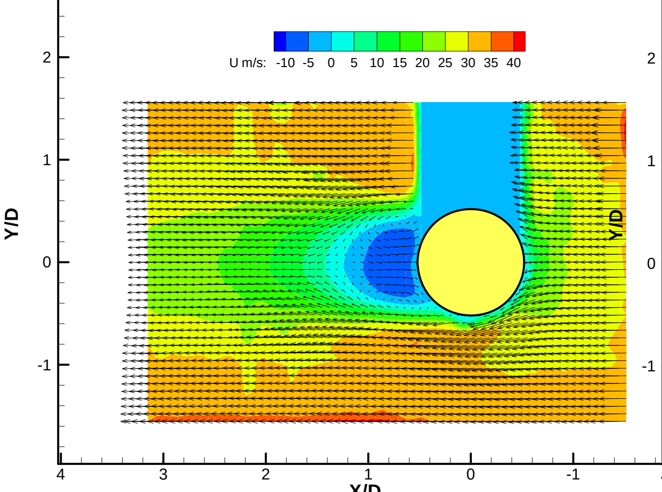
Laminar Flows and Turbulence Flows



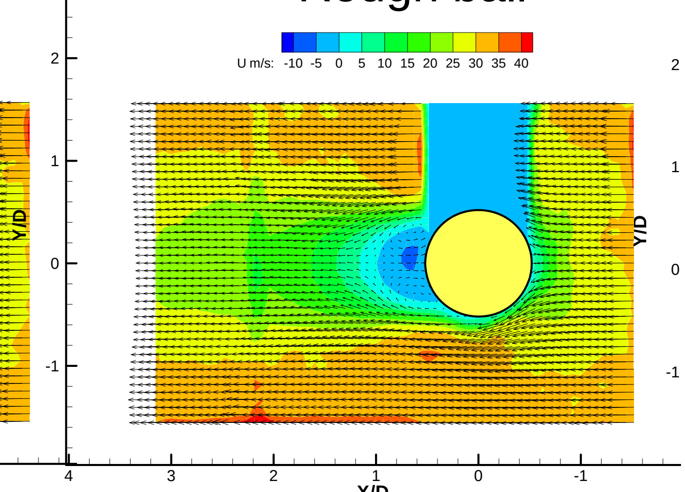


Re=100,000

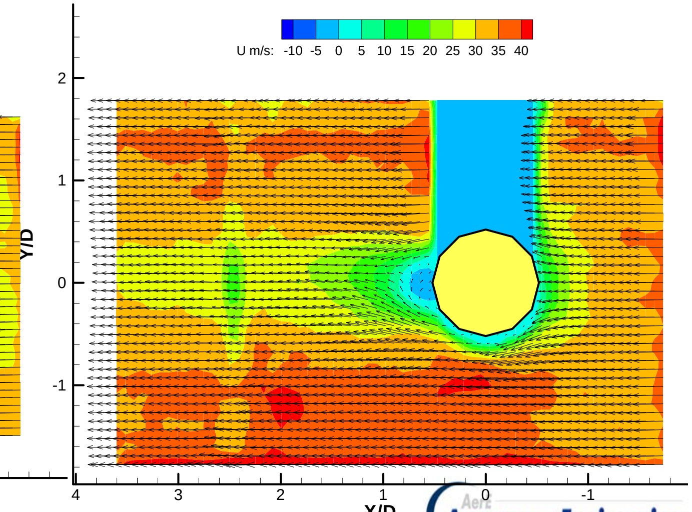
Smooth ball



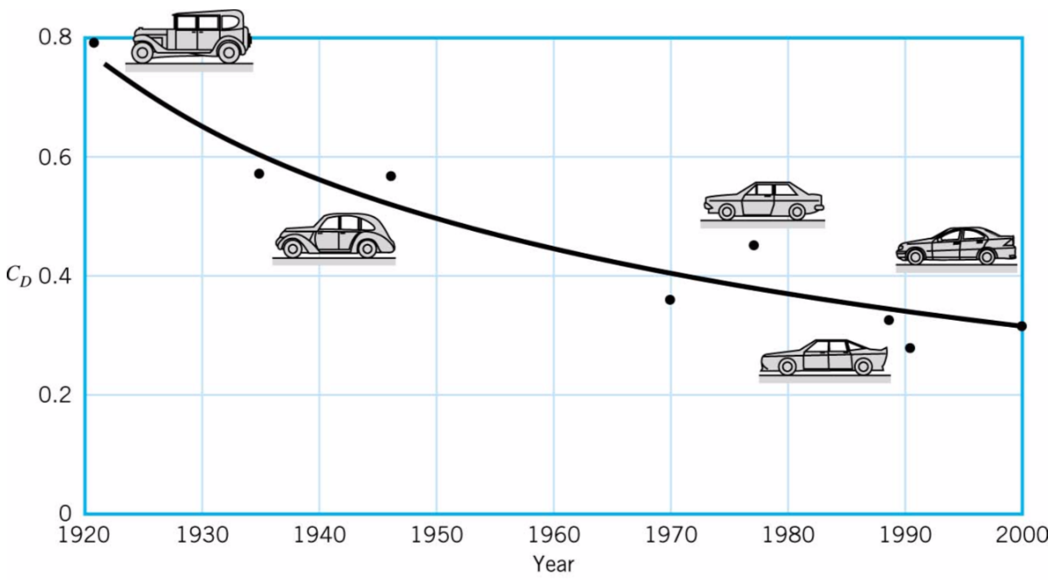
Rough ball

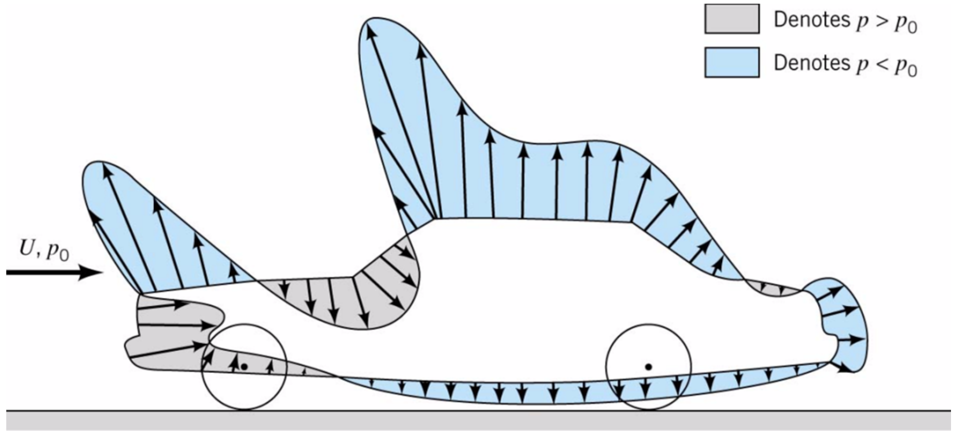


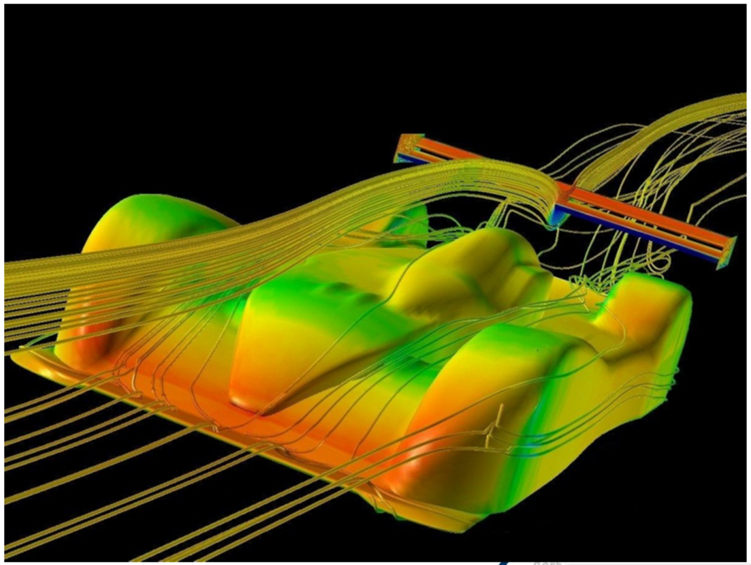
Golf ball



Automobile aerodynamics

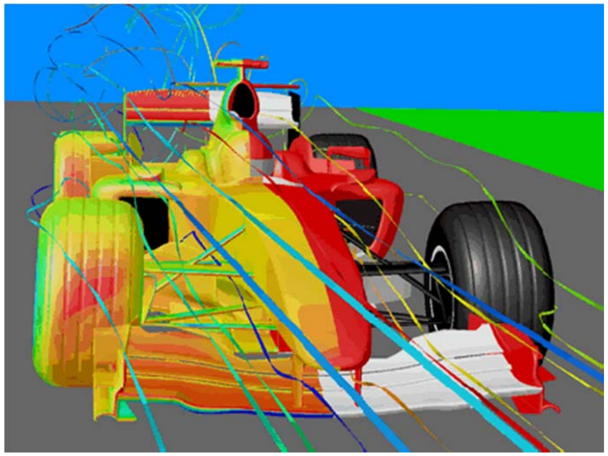


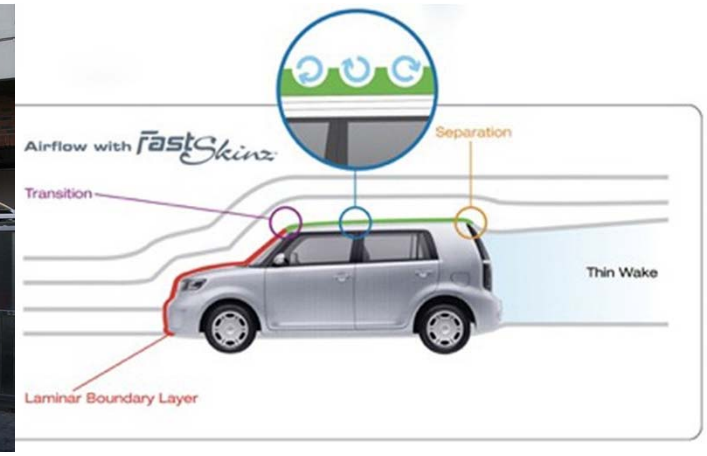




IOWA STATE UNIVERSITY Aerospace Engineering

Automobile Aerodynamics



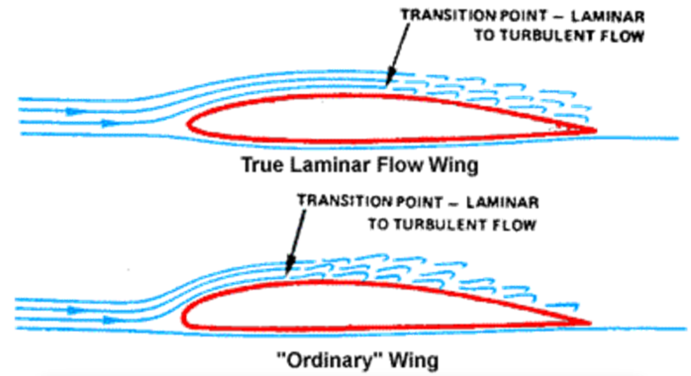


Mercedes Boxfish

Vortex generator above a Mitsubishi rear window

CONVENTIONAL AIRFOILS and LAMINAR FLOW 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*



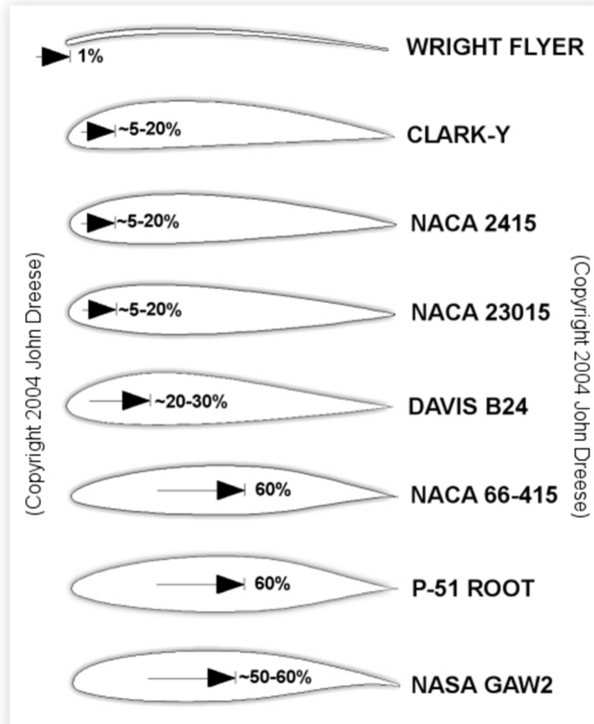
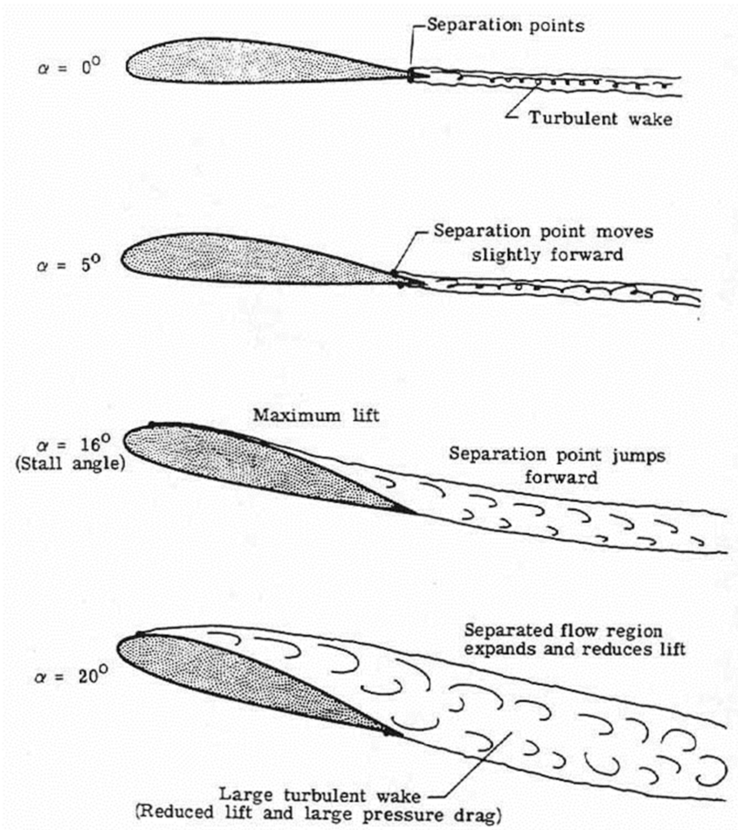
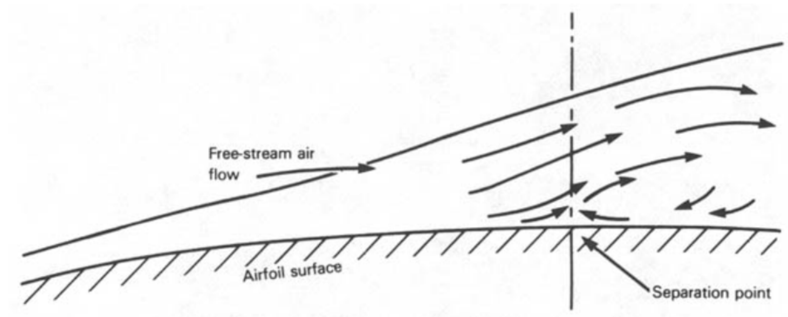
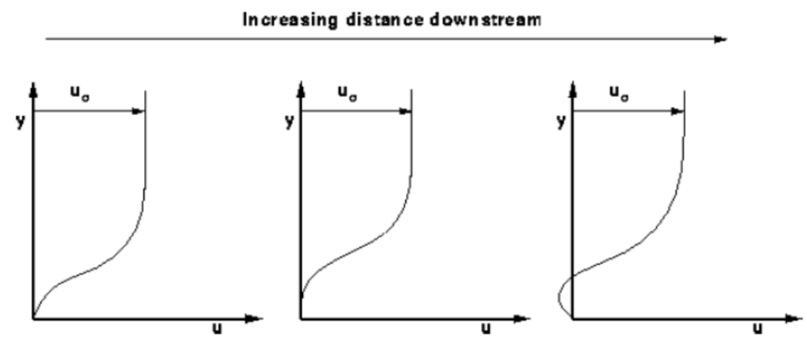


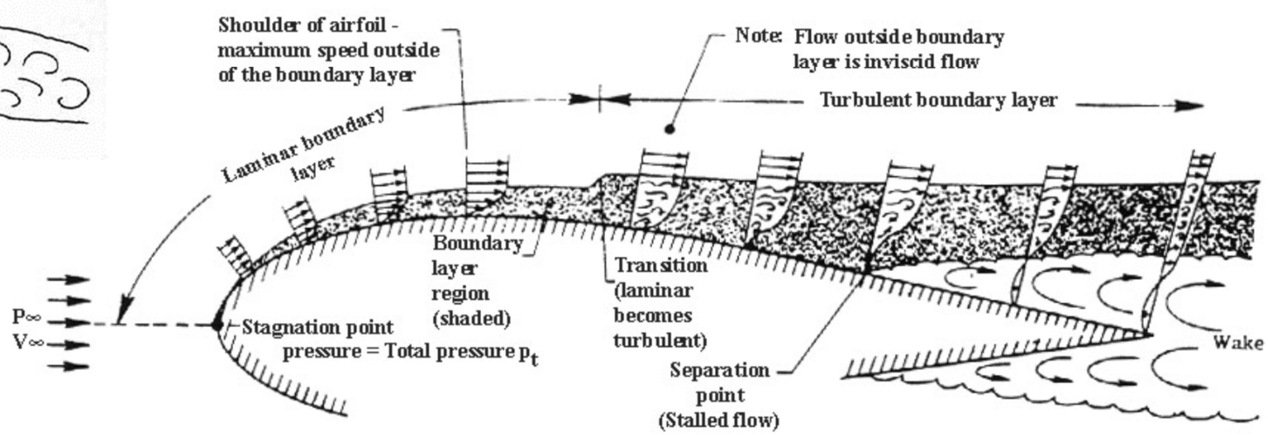
FIGURE 2: Extent of laminar flow on some famous airfoils.

Flow Separation on an Airfoil





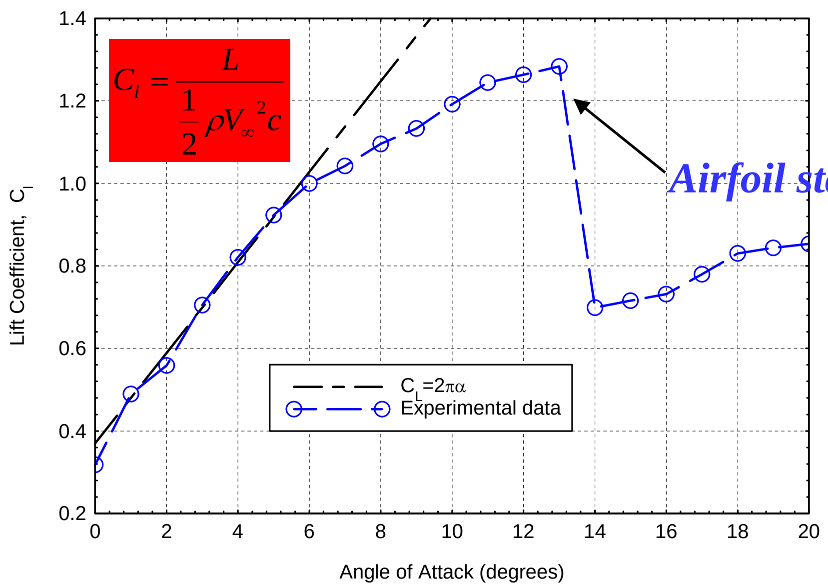


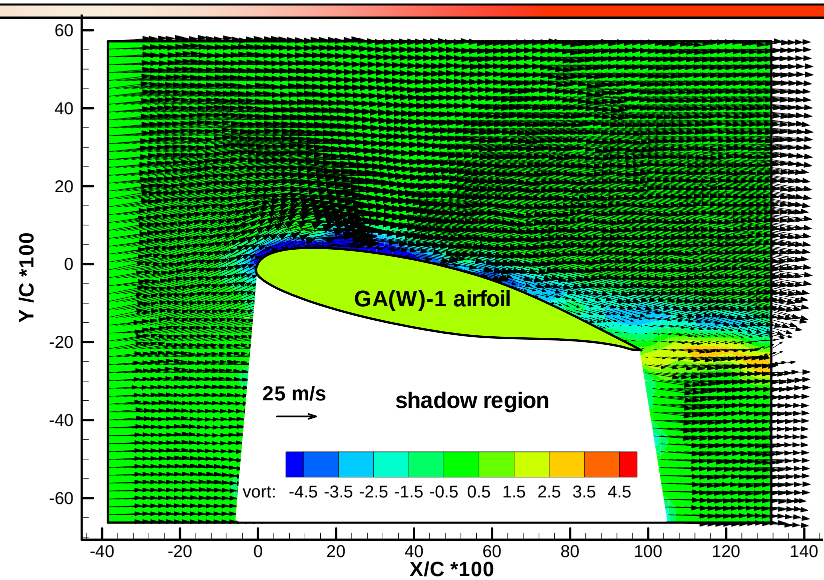


IOWA STATE UNIVERSITY

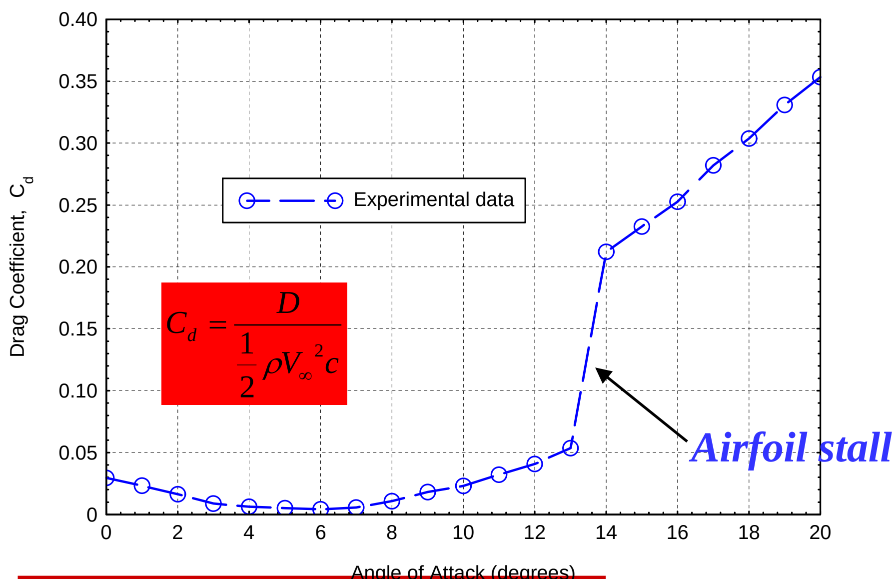
AerE Aerospace Engineering

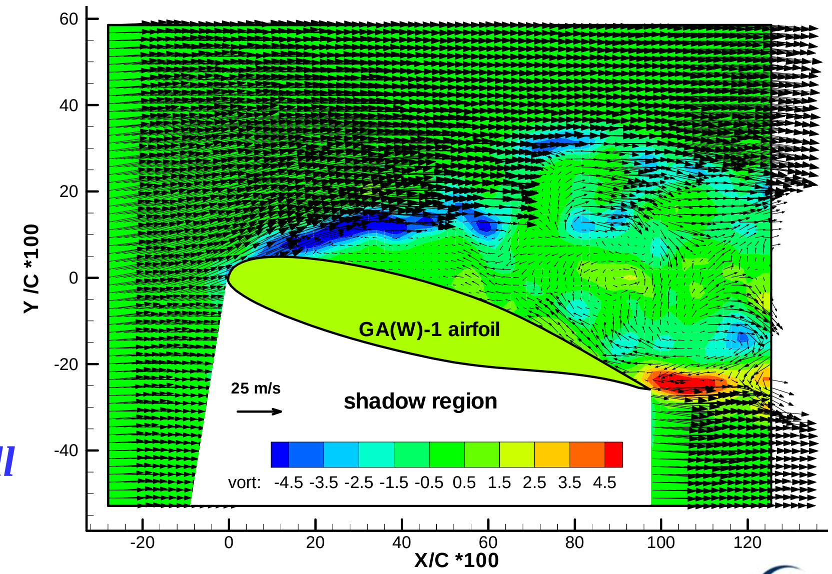
Aerodynamic Performance of An Airfoil





Before stall

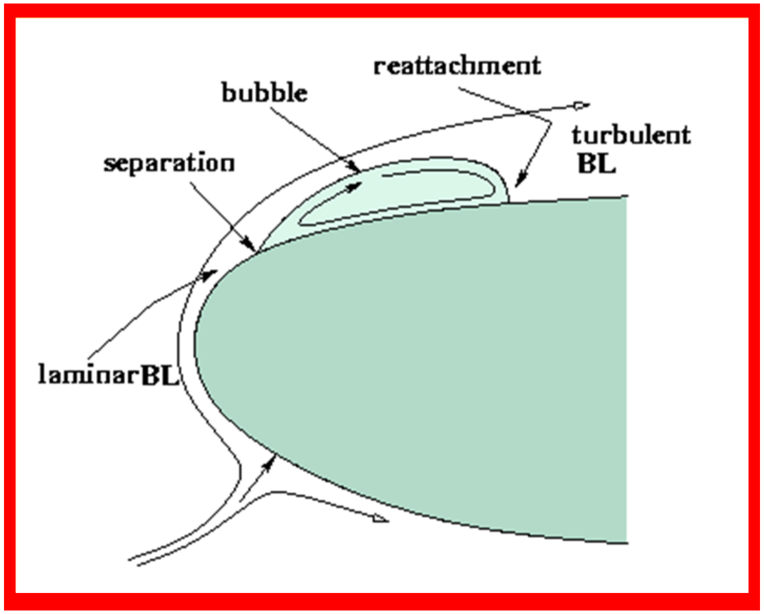


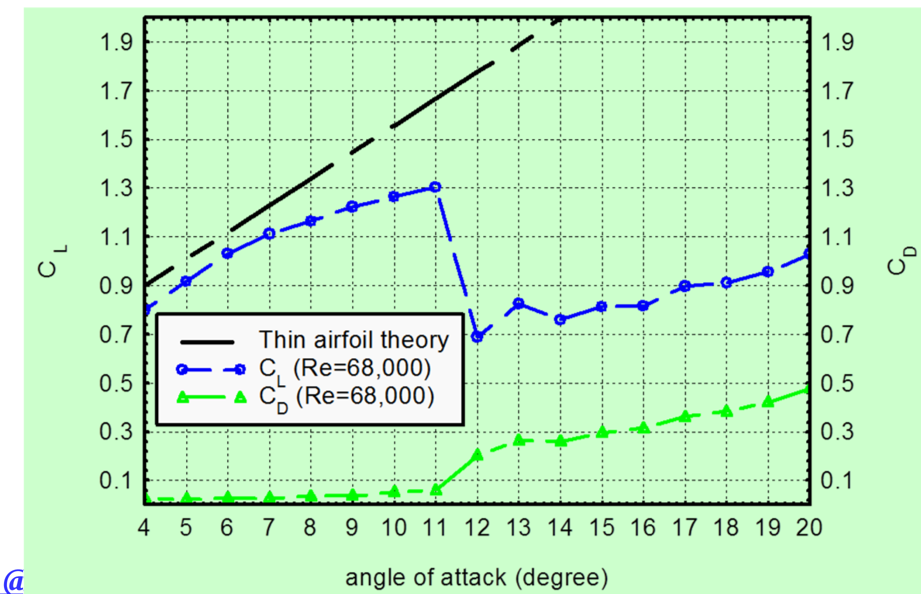


After stall

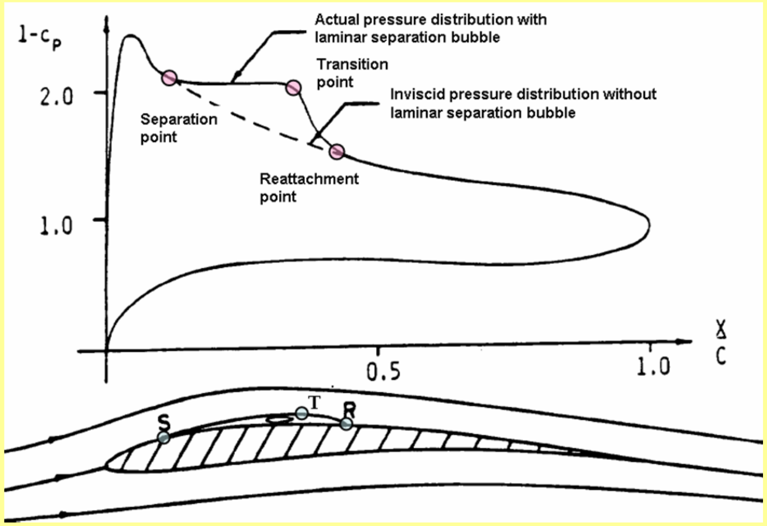
Flow Separation and Transition on Low-Reynolds-number Airfoils

- ***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 to form on the upper surfaces of low-Reynolds-number airfoils . Separation bubble would burst suddenly to cause airfoil stall at high AOA when the adverse pressure gradient becoming too big.***

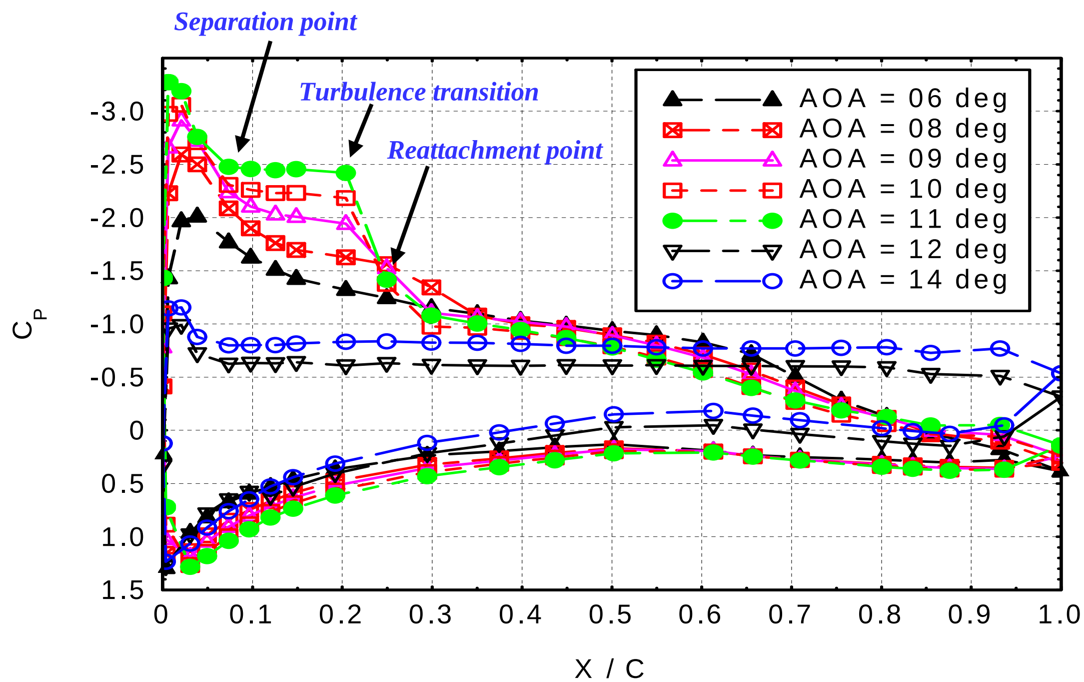


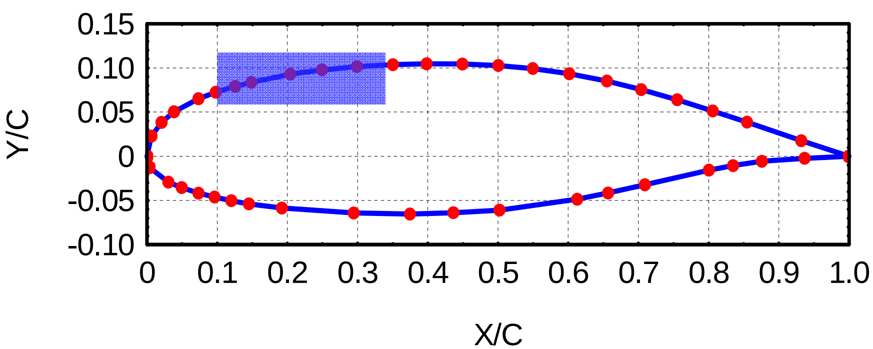


Surface Pressure Coefficient distributions (Re=68,000)



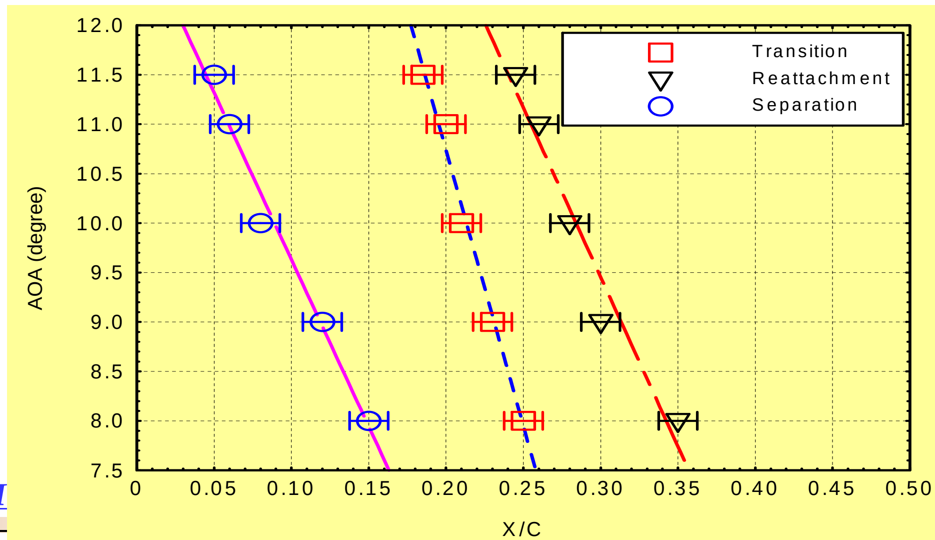
Typical surface pressure distribution when a laminar separation bubble is formed (Russell, 1979)



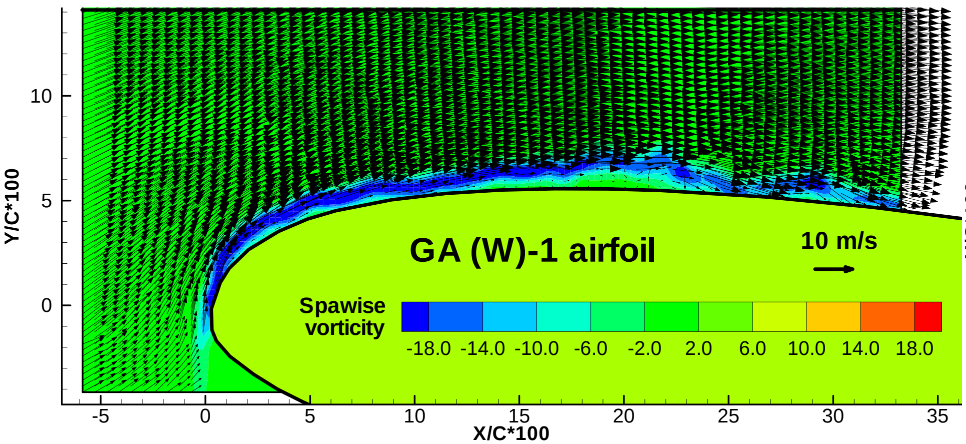


GA (W)-1 airfoil

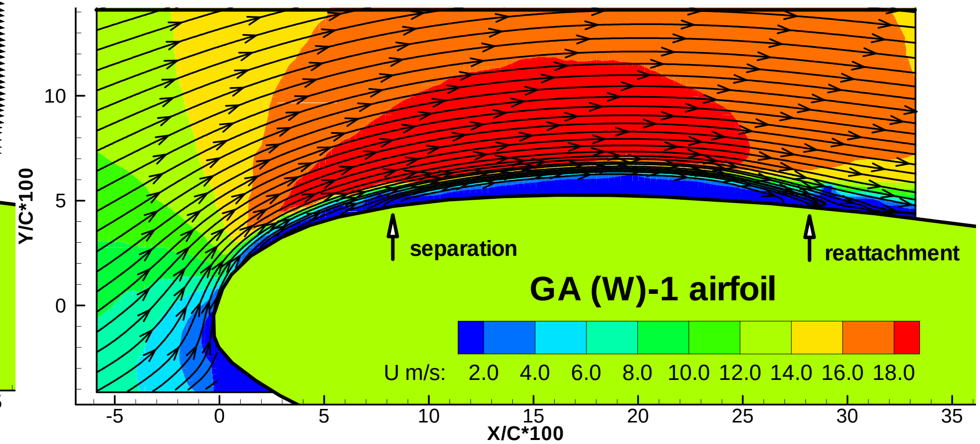
(also labeled as NASA LS(1)-0417)



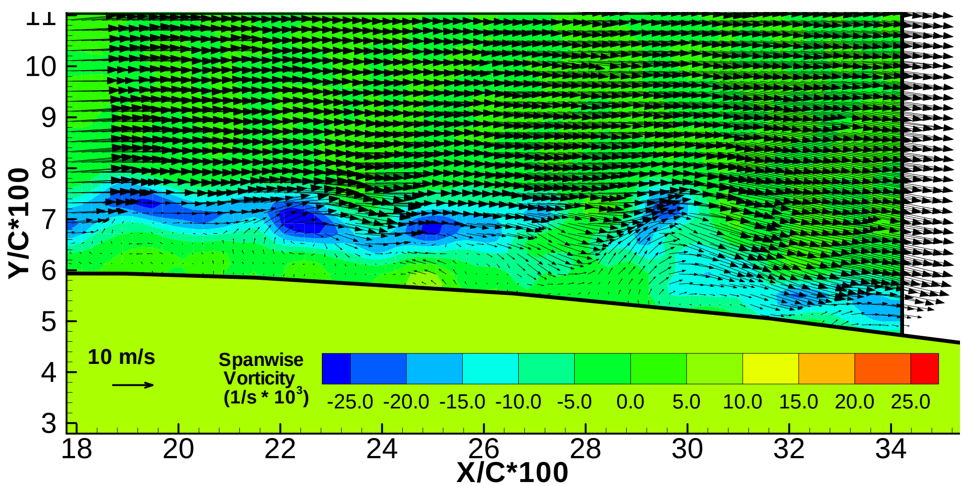
Laminar Separation Bubble on a Low-Reynolds-number Airfoil

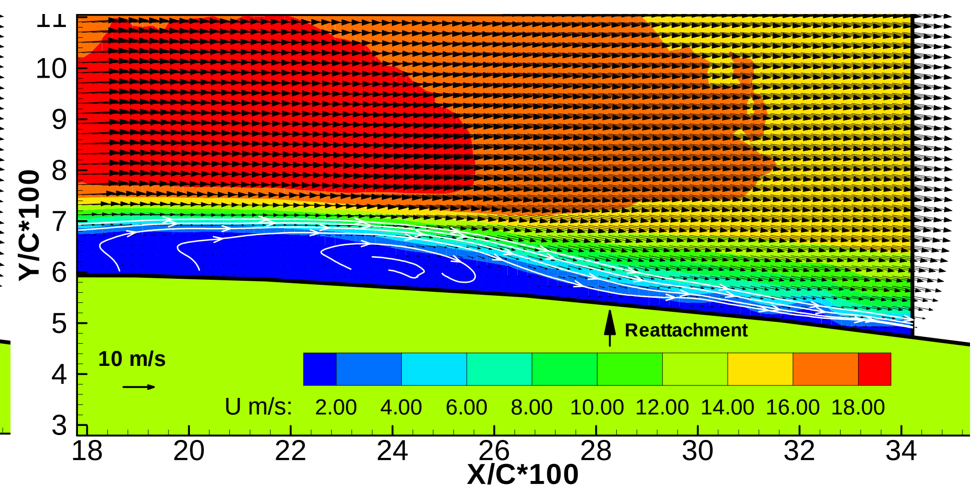


Instantaneous flow field



Ensemble-averaged flow field



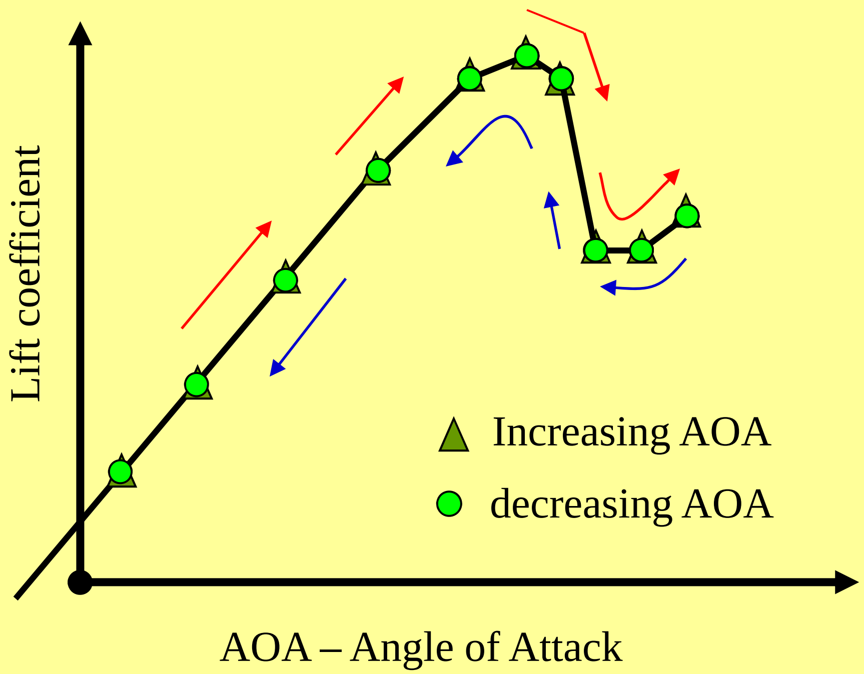


PIV measurement results at AOA = 10 deg, Re=68,000

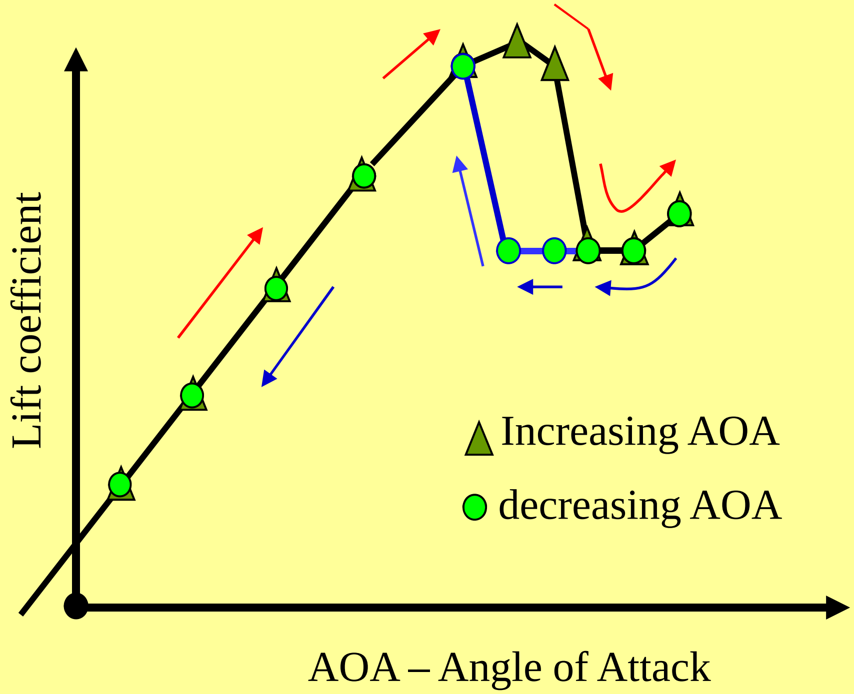
(Hu et al., ASME Journal of Fluid Engineering, 2008)

Stall Hysteresis Phenomena

- *Stall hysteresis*, ***a phenomenon where stall inception and stall recovery do not occur at the same angle of attack, has been found to be relatively common in low-Reynolds-number airfoils.***
- ***When stall hysteresis occurs,*** *the coefficients of lift, drag, and moment of the airfoil are found to be multiple-valued rather than single-valued functions of the angle of attack*.
- *Stall hysteresis* ***is of practical importance because it produces widely different values of lift coefficient and lift-to-drag ratio for a given airfoil at a given angle of attack. It could also affect the recovery from stall and/or spin flight conditions.***

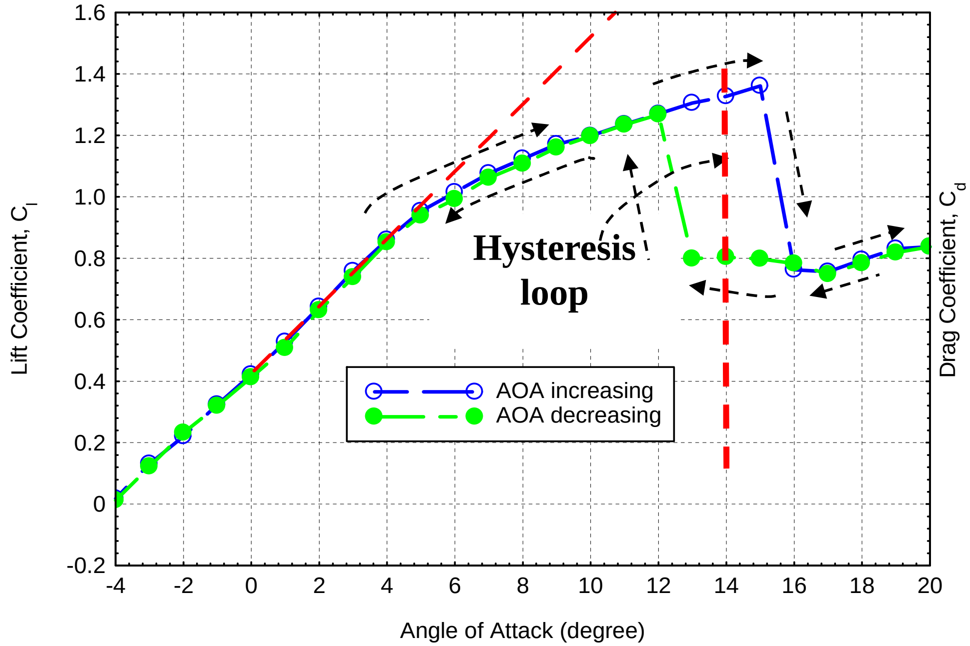


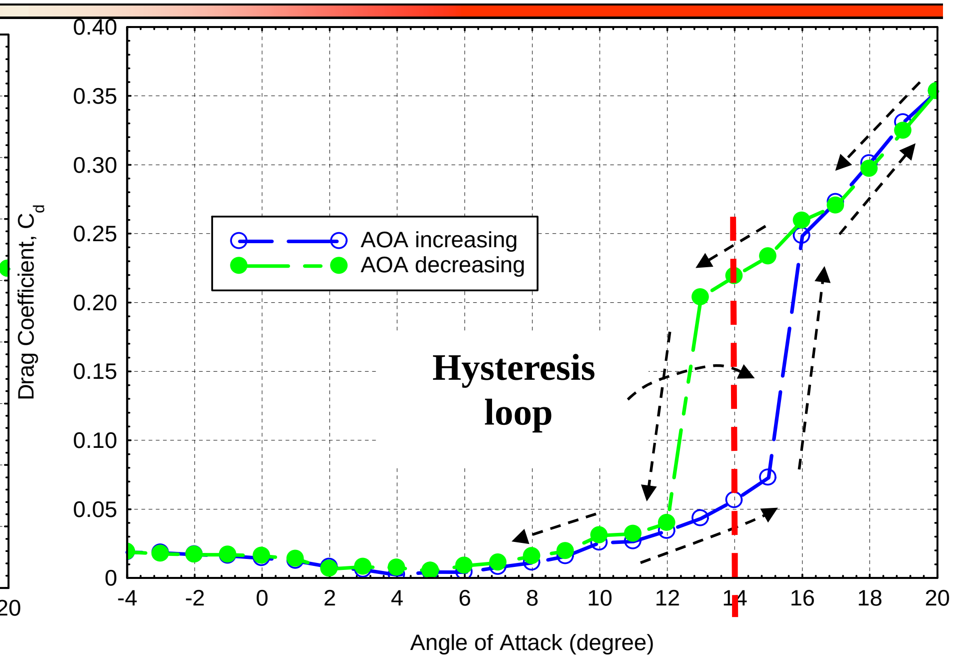
Lift coefficient curve of a "typical" airfoil



Lift coefficient curve with stall hysteresis

Measured airfoil lift and drag coefficient profiles

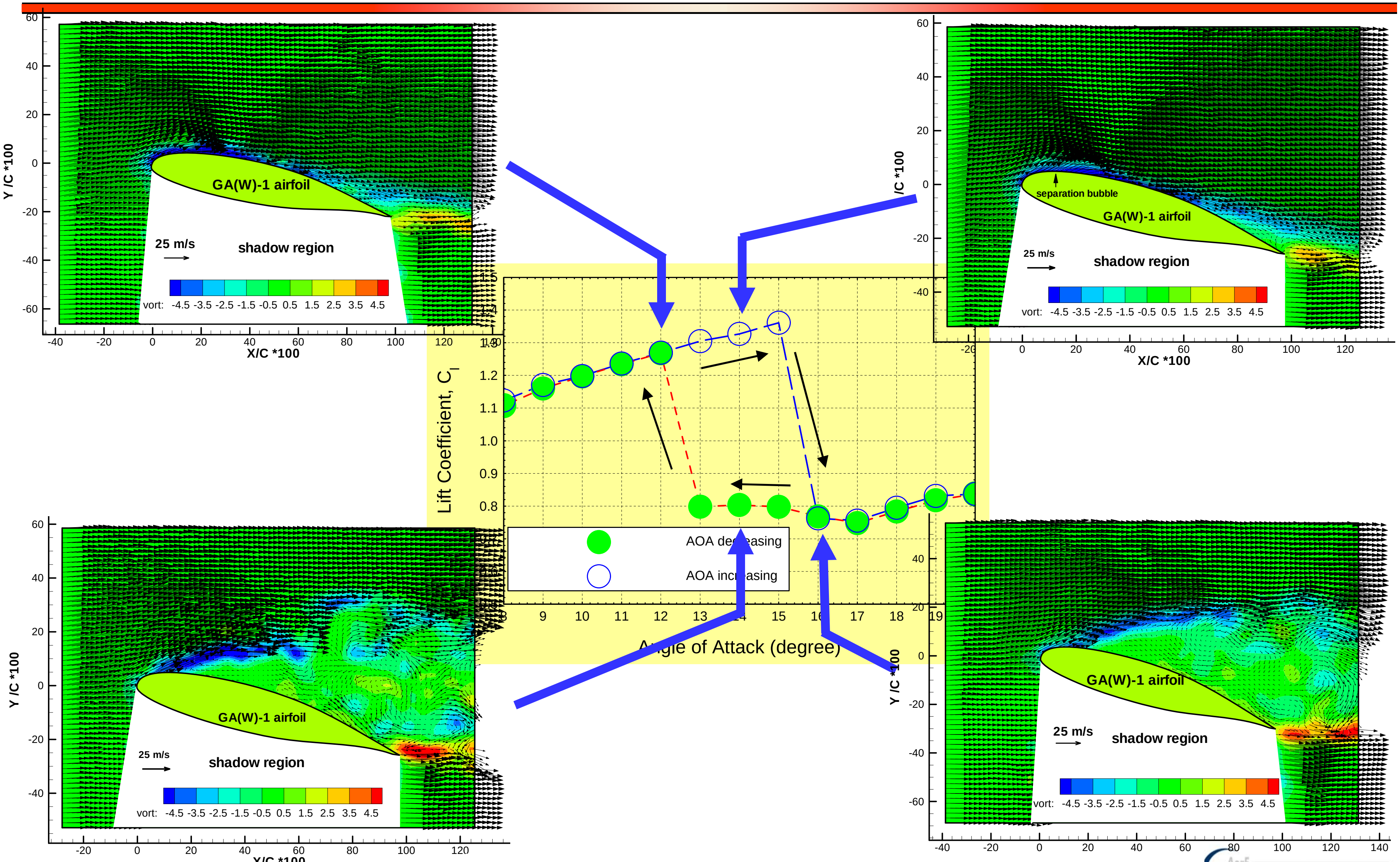




GA(W)-1 airfoil, Re_C = 160,000

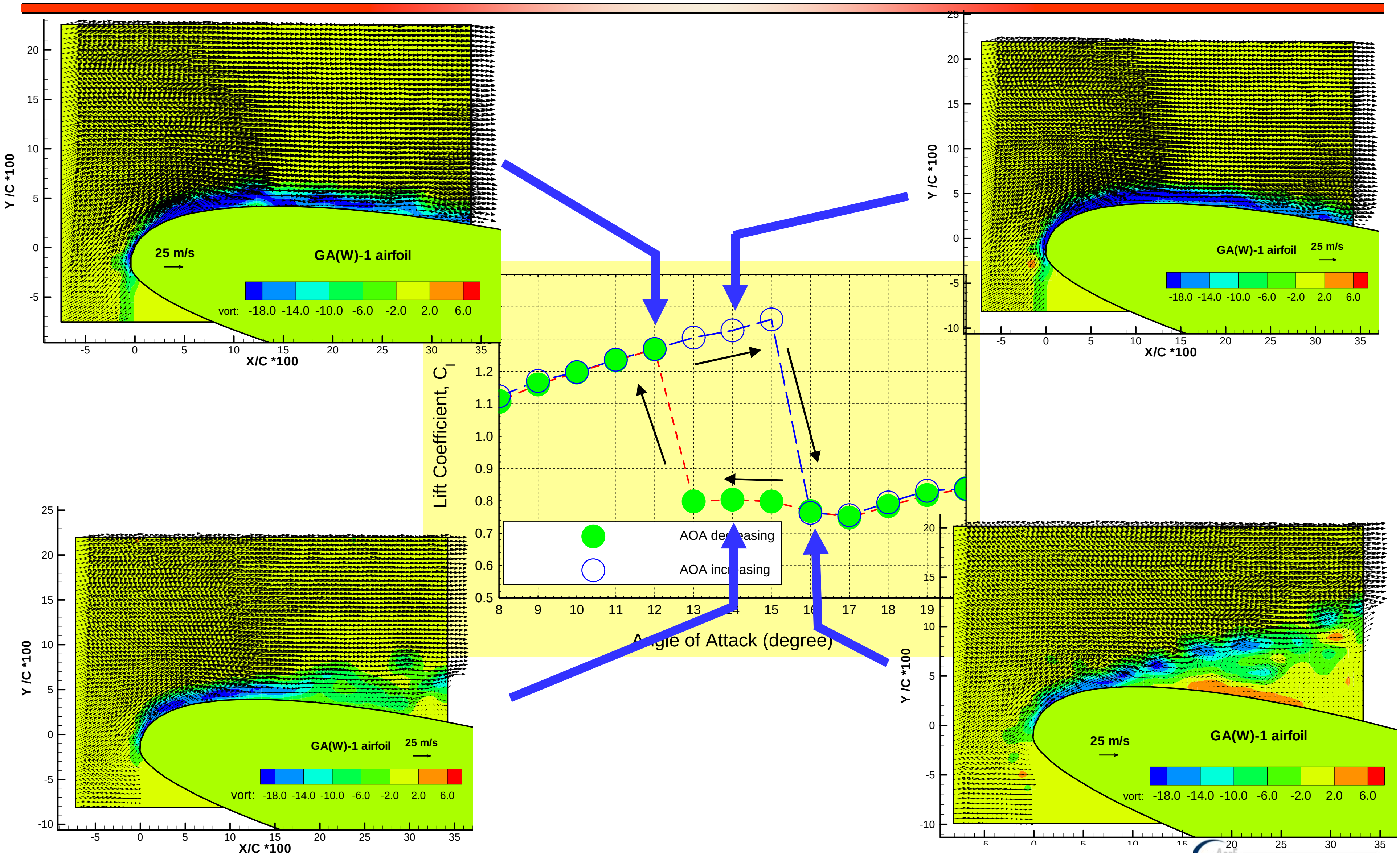
- ***The hysteresis loop was found to be clockwise in the lift coefficient profiles, and counter-clockwise in the drag coefficient profiles.***
- ***The aerodynamic hysteresis resulted in significant variations of lift coefficient, C_l, and lift-to-drag ratio, l/d, for the airfoil at a given angle of attack.***
- ***The lift coefficient and lift-to-drag ratio at AOA = 14.0 degrees were found to be C_l = 1.33 and l/d = 23.5 when the angle is at the increasing angle branch of the hysteresis loop.***
- ***The values were found to become C_l = 0.8 and l/d = 3.66 for the same AOA=14.0 degrees when the angle is at the deceasing angle branch of the hysteresis loop***

PIV Measurement results



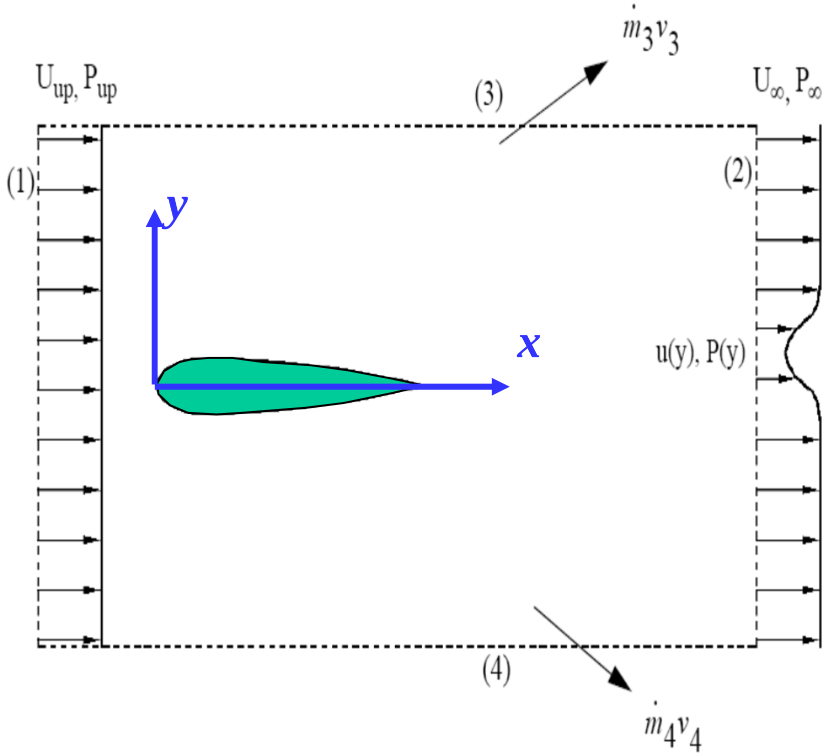
(Hu, Yang, Igarashi, Journal of Aircraft, Vol. 44. No. 6 , 2007)

Refined PIV Measurement Results



(Hu, Yang, Igarashi, Journal of Aircraft, Vol. 44. No. 6 , 2007)

Lab 6: Airfoil Wake Measurements and Hotwire Anemometer Calibration



$$\sum F_X = -D + \int_{CS} (p\hat{n}dA)_X$$

$$= -D + \int_1 p_{up} dA - \int_2 p(y) dA$$

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

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

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

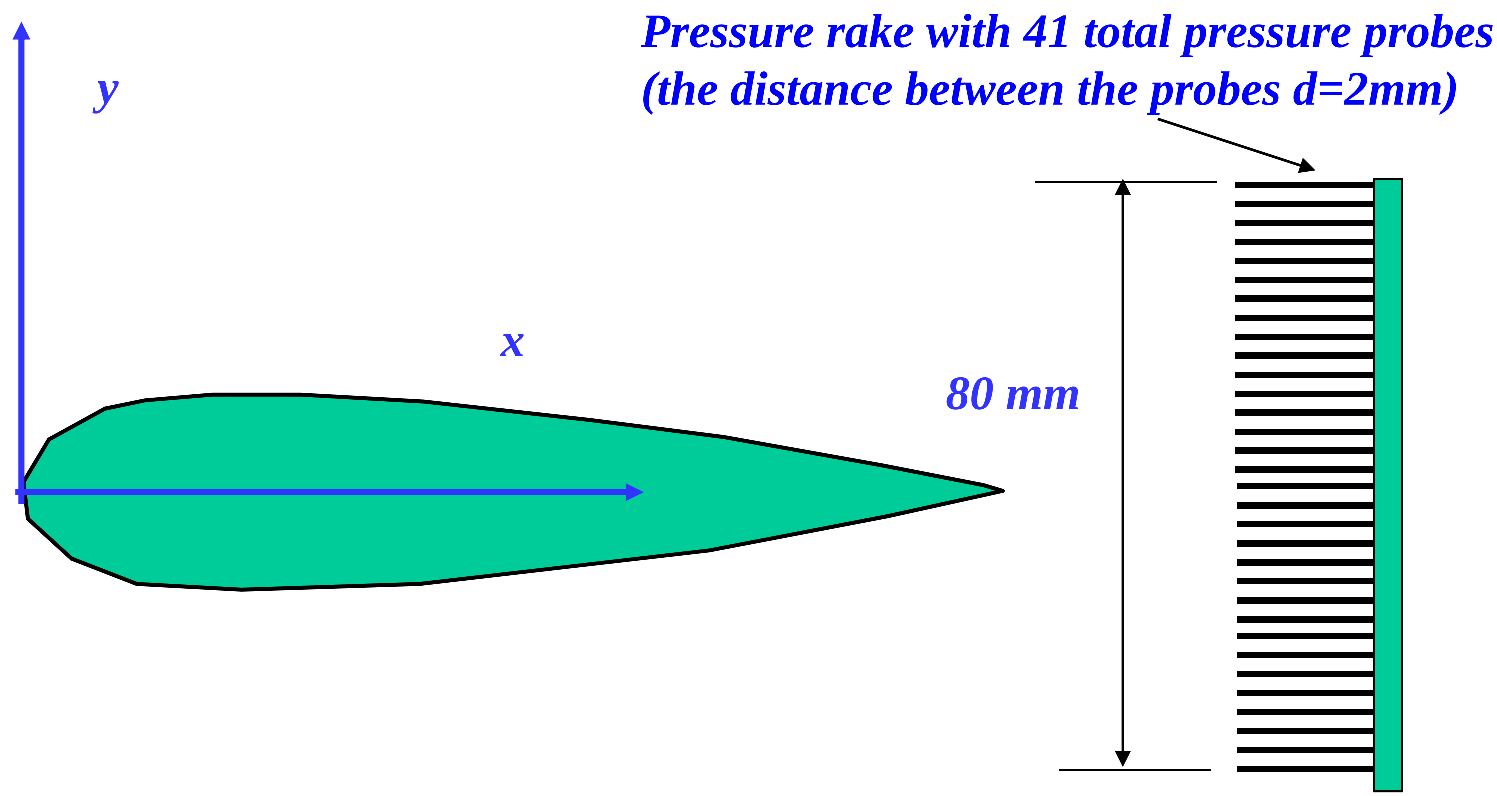
$$\Rightarrow D = \rho U^2{}_\infty \int_2 [\frac{U(y)}{U_\infty}(1 - \frac{U(y)}{U_\infty})] dA_2$$

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

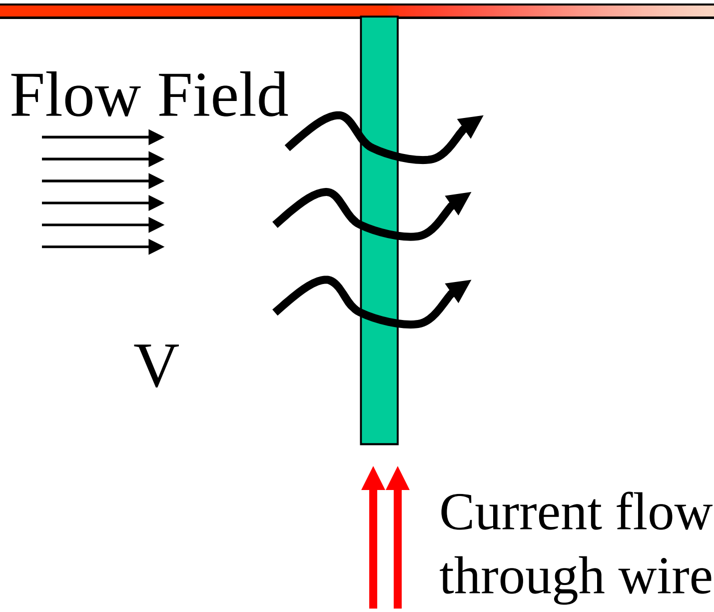
$$\Rightarrow C_D = \frac{2}{C} \int_2 [\frac{U(y)}{U_\infty}(1 - \frac{U(y)}{U_\infty})] dy$$

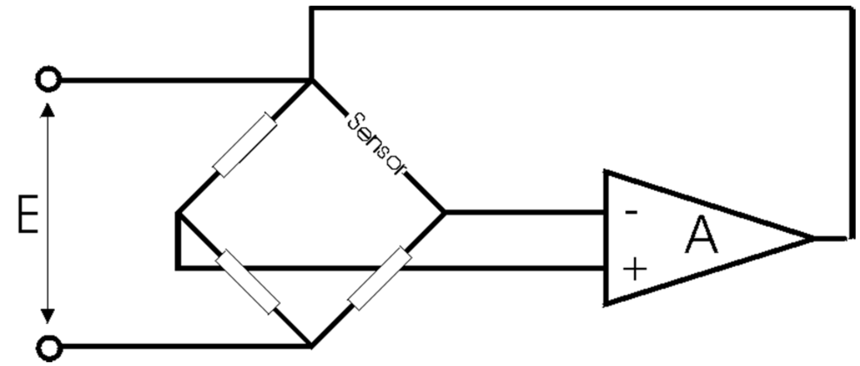
- ***Compared with the drag coefficients obtained based on airfoil surface pressure measurements at the same angles of attack!***

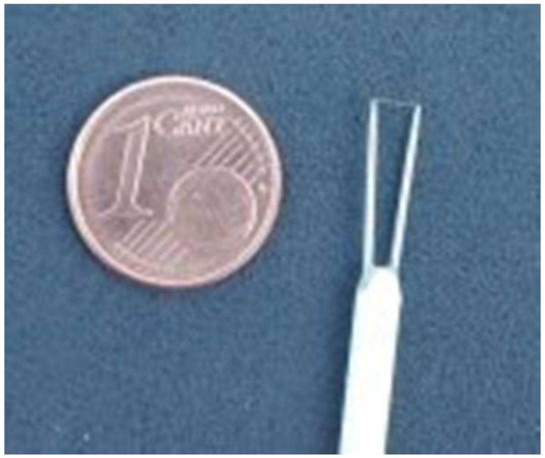
Lab 3: Airfoil Wake Measurements and Hotwire Anemometer Calibration



Lab 3: Airfoil Wake Measurements and Hotwire Anemometer Calibration







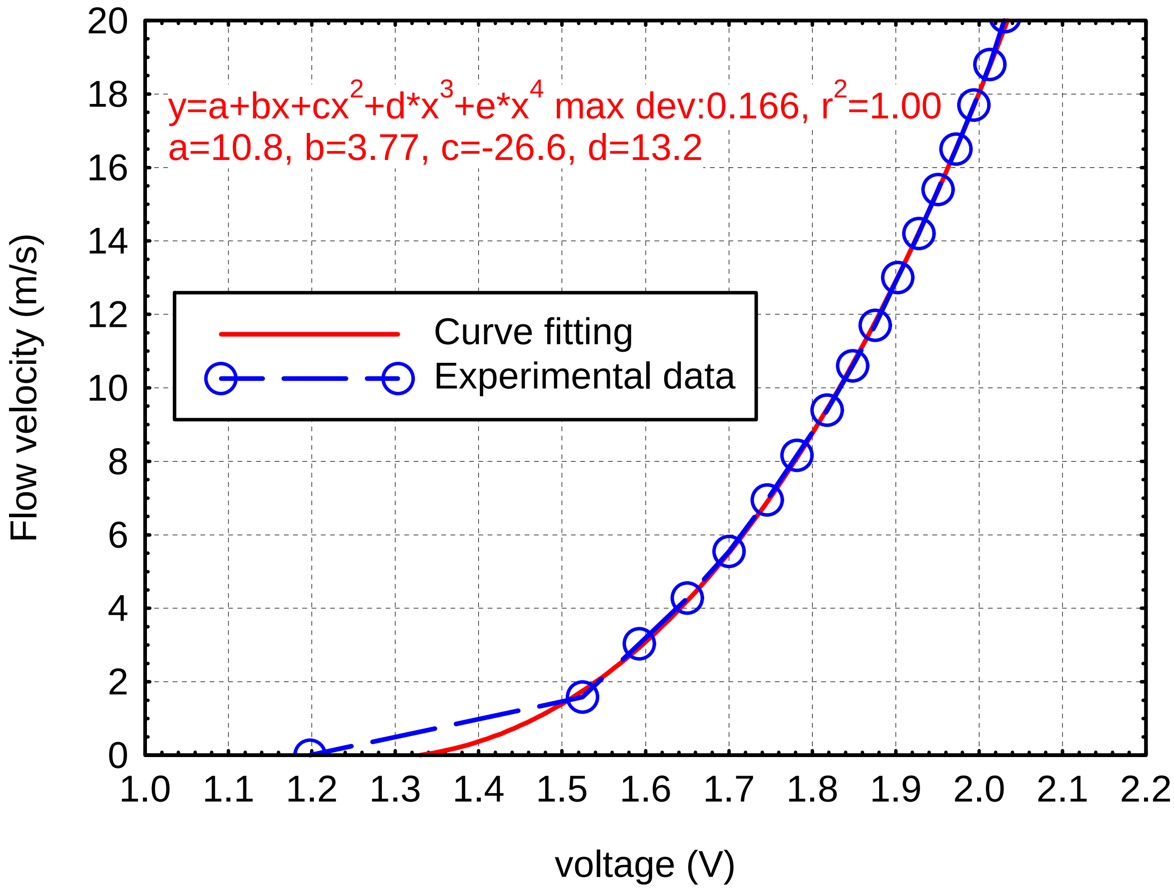
$$mc\frac{dT_w}{dt} = i^2 R_w - \dot{q}(V, T_w)$$

- *Constant-temperature anemometry*

CTA hotwire probe

Hotwire Anemometer Calibration

- *To quantify the relationship between the flow velocity and voltage output from the CTA probe*



Required Measurement Results

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 4^{th} 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***