Airfoil Lab Supporting Information

Research question

- Compare the lift and drag forces on a NACA 0012 airfoil measured by a force balance to the lift and drag forces estimated from the integrated pressure on the airfoil, the estimated induced drag, and the estimated skin friction drag.

Experimental tasks

- Measure lift and drag force on NACA 0012 airfoil as a function of angle of attack using a force balance.
- Measure pressure distribution on a NACA 0012 airfoil as a function of angle of attack for three angles of attack.
- Measure pressure on Pitot-static tube to estimate fluid velocity.
- Measure the air temperature and the barometric pressure.

Data analysis and reduction

- Compute the mean air speed from the Pitot-static tube reading. You must compute the density of air at the current barometric pressure and temperature. Use the ideal gas law.
- Use the measurements of lift and drag forces to calculate the coefficient of lift, C_L, and coefficient of drag, C_D as a function of angle of attack.
- Integrate the resolved pressure forces over the airfoil to determine the “pressure lift” and “pressure or form drag”
- Compare the “pressure lift” to the lift measured using the force balance.
- Estimate the induced drag and the skin friction drag.
- Compare the sum of the form drag and estimates of the induced drag, and the skin friction drag to the measured drag.

Lift and drag coefficients from force balance measurements

$$dF_y = -(pdA)\sin\theta + (\tau_w dA)\cos\theta$$

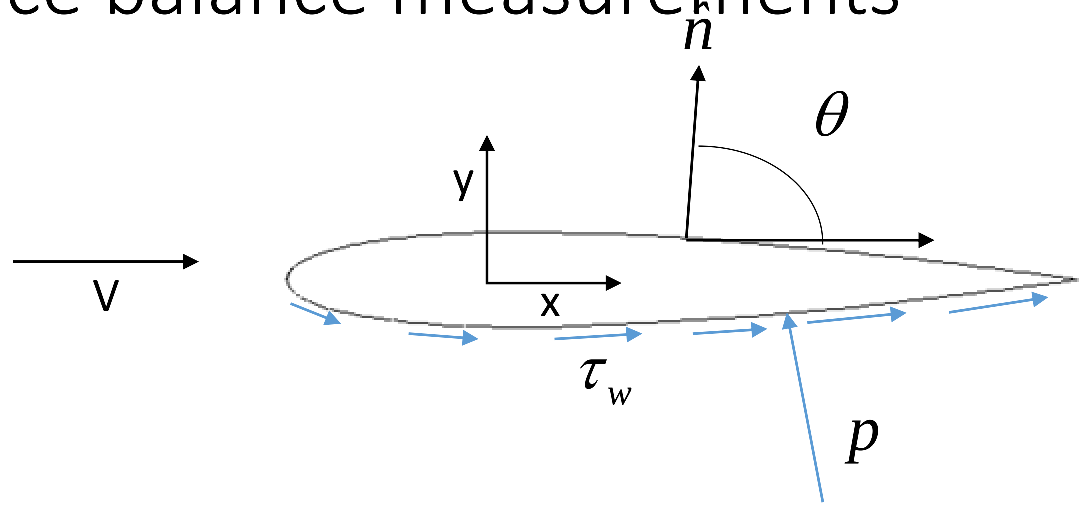
$$L = \int dF_y = -\int p\sin\theta dA + \int \tau_w \cos\theta dA$$

$$C_L = \frac{L}{\frac{1}{2}\rho V^2 A}$$

$$dF_x = (pdA)\cos\theta + (\tau_w dA)\sin\theta$$

$$D = \int dF_x = \int p\cos\theta dA + \int \tau_w \sin\theta dA$$

$$C_D = \frac{D}{\frac{1}{2}\rho V^2 A}$$



$\tau_w = wall\ shear\ stress$

$p = pressure$

$A = planform\ area$

$V = streamwise\ velocity^*$

$*\ many\ books\ use\ U$

C_D for bluff bodies

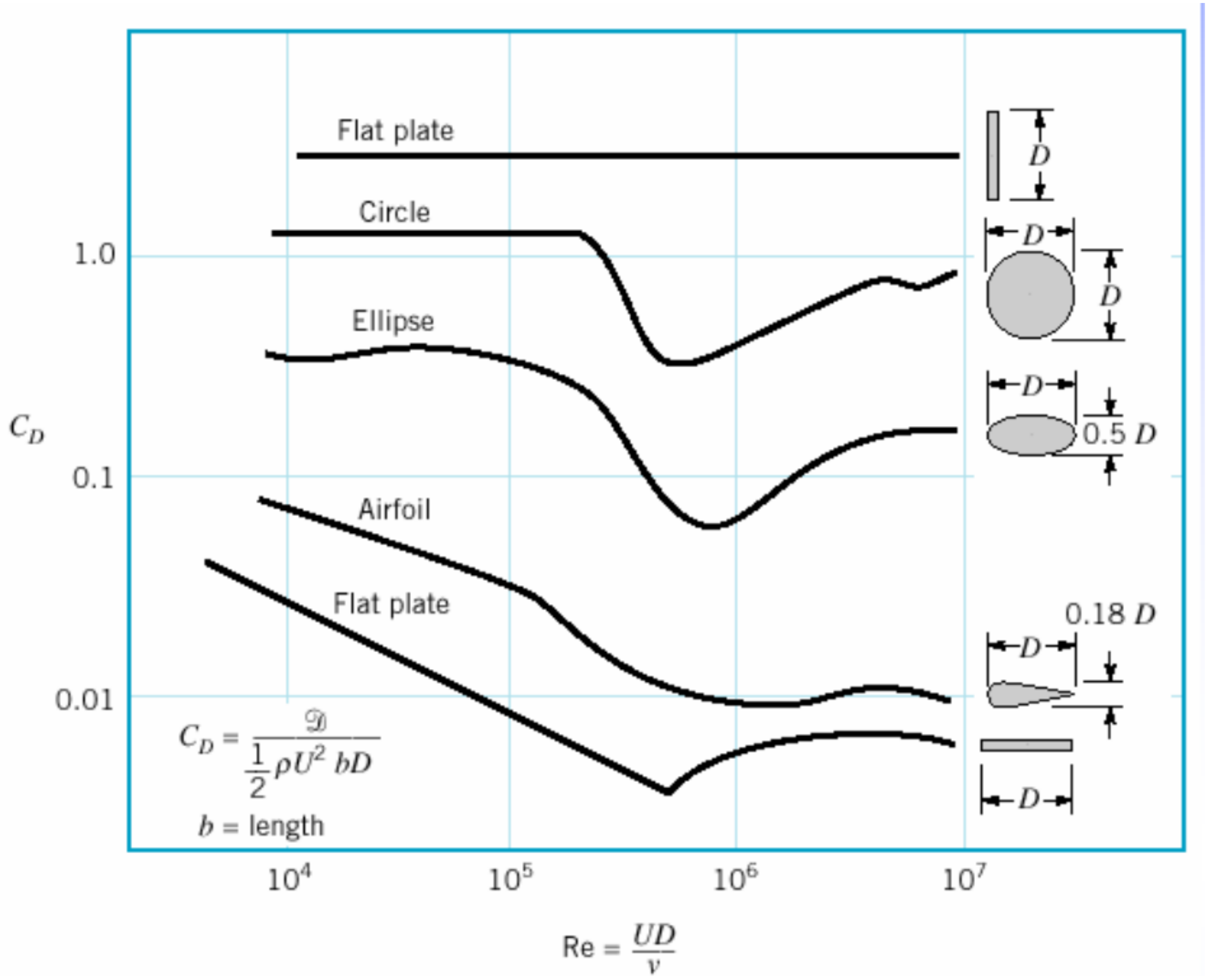
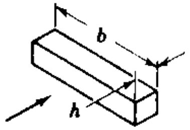


Fig. 2 Drag Coefficient Data for Selected Objects ($Re \gtrsim 1000$)

Object	Diagram		$C_D (Re \gtrsim 10^3)$
Square cylinder		$b/h = \infty$ $b/h = 1$	2.05 1.05
Disk			1.17
Ring			1.20
Hemisphere (open end facing flow)			1.42
Hemisphere (open end facing downstream)			0.38
C-section (open side facing flow)			2.30
C-section (open side facing downstream)			1.20

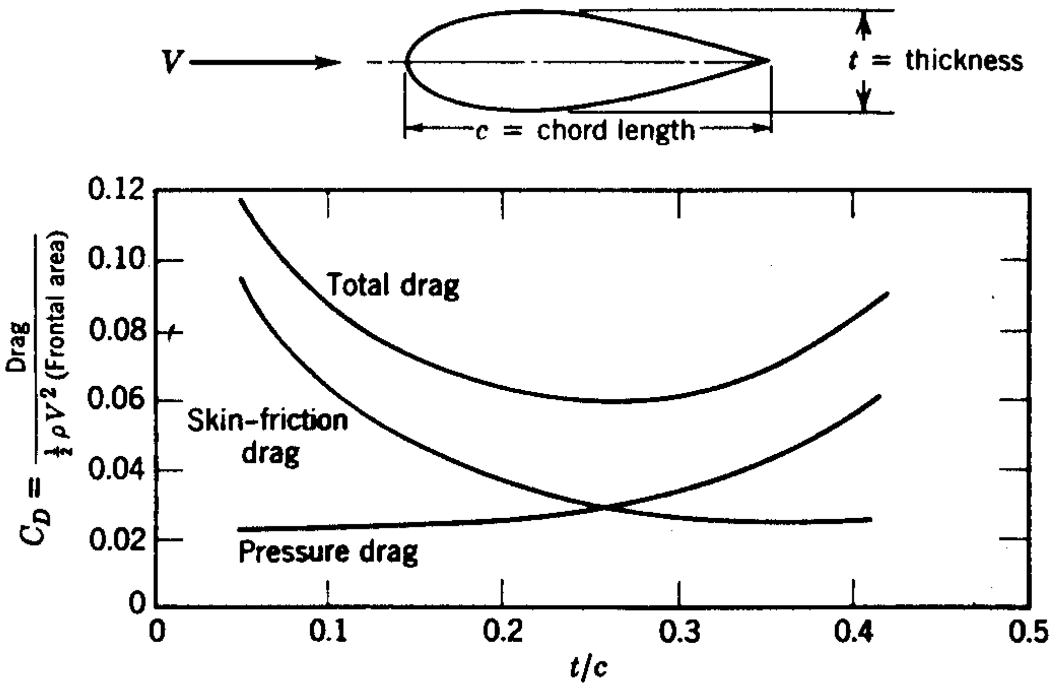


Fig. 3 Drag coefficient on a streamlined strut as a function of thickness ratio, showing contribution of skin friction and pressure to total drag

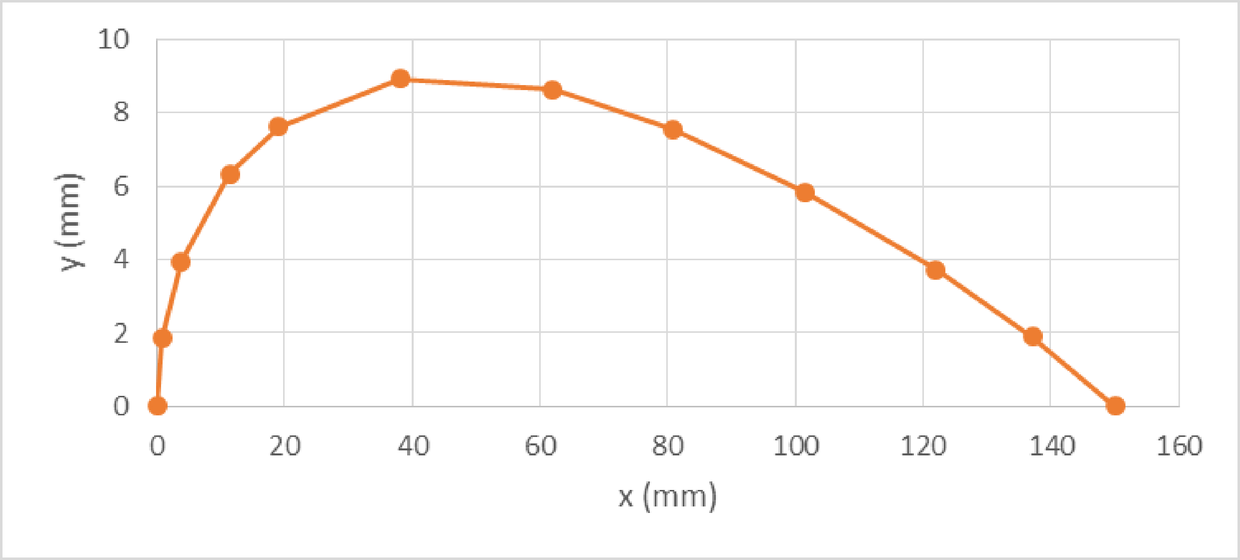
http://www.me.metu.edu.tr/courses/me410/exp6/exp6.html

Estimating force on airfoil from integrated pressure

- The airfoil has pressure taps running in the streamwise direction along the center of the span.
- Integrating these pressures will be used to estimate the lift force and the form drag.
- The drag force also consists of skin friction drag and induced drag. Both of those quantities will be estimated.
  - The skin friction drag will be estimated by assuming the airfoil is similar to a flat plate described on p. 446-448 in your Fluid Dynamics text.
  - The induced drag will be estimated from a model described on p. 463-466 in your Fluid Dynamics text.

Formula for NACA 00xx airfoil surface profile. "x" is the distance along the chord, c, and y is the distance normal to the chord. "t" is the thickness:chord length ratio which is 0.12 in the NACA 0012 airfoil.
See http://en.wikipedia.org/wiki/NACA_airfoil
Table is provided giving x locations of pressure taps for your airfoil

$$y_t = 5tc\left[0.2969\sqrt{\frac{x}{c}} + (-0.1260)\left(\frac{x}{c}\right) + (-0.3516)\left(\frac{x}{c}\right)^2 + 0.2843\left(\frac{x}{c}\right)^3 + (-0.1015)\left(\frac{x}{c}\right)^4\right],$$



$$F_{12} = \int P_{12} d\vec{A}_{12} = \int P_{12} L d\vec{S}_{12} =$$

$$\theta_{12} = tan^{-1}\left(\frac{y_2 - y_1}{x_2 - x_1}\right)$$

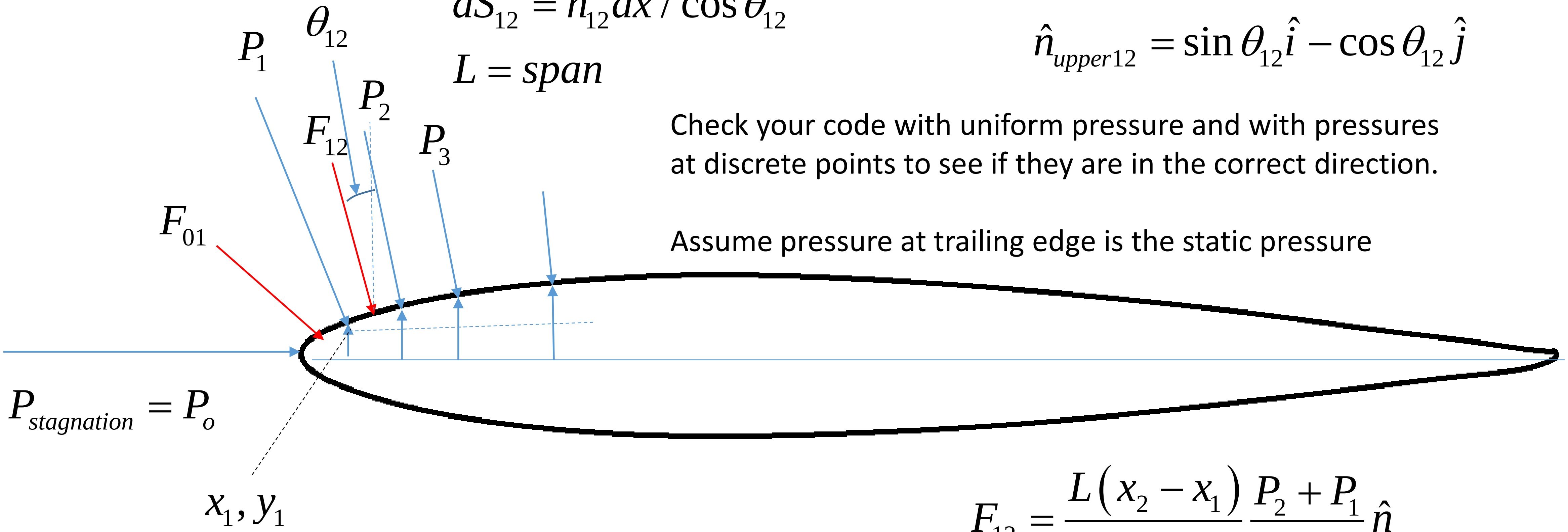
$$d\vec{S}_{12} = \hat{n}_{12} dx / \cos\theta_{12}$$

$$\hat{n}_{upper12} = \sin\theta_{12}\hat{i} - \cos\theta_{12}\hat{j}$$

$$L = span$$

Check your code with uniform pressure and with pressures at discrete points to see if they are in the correct direction.

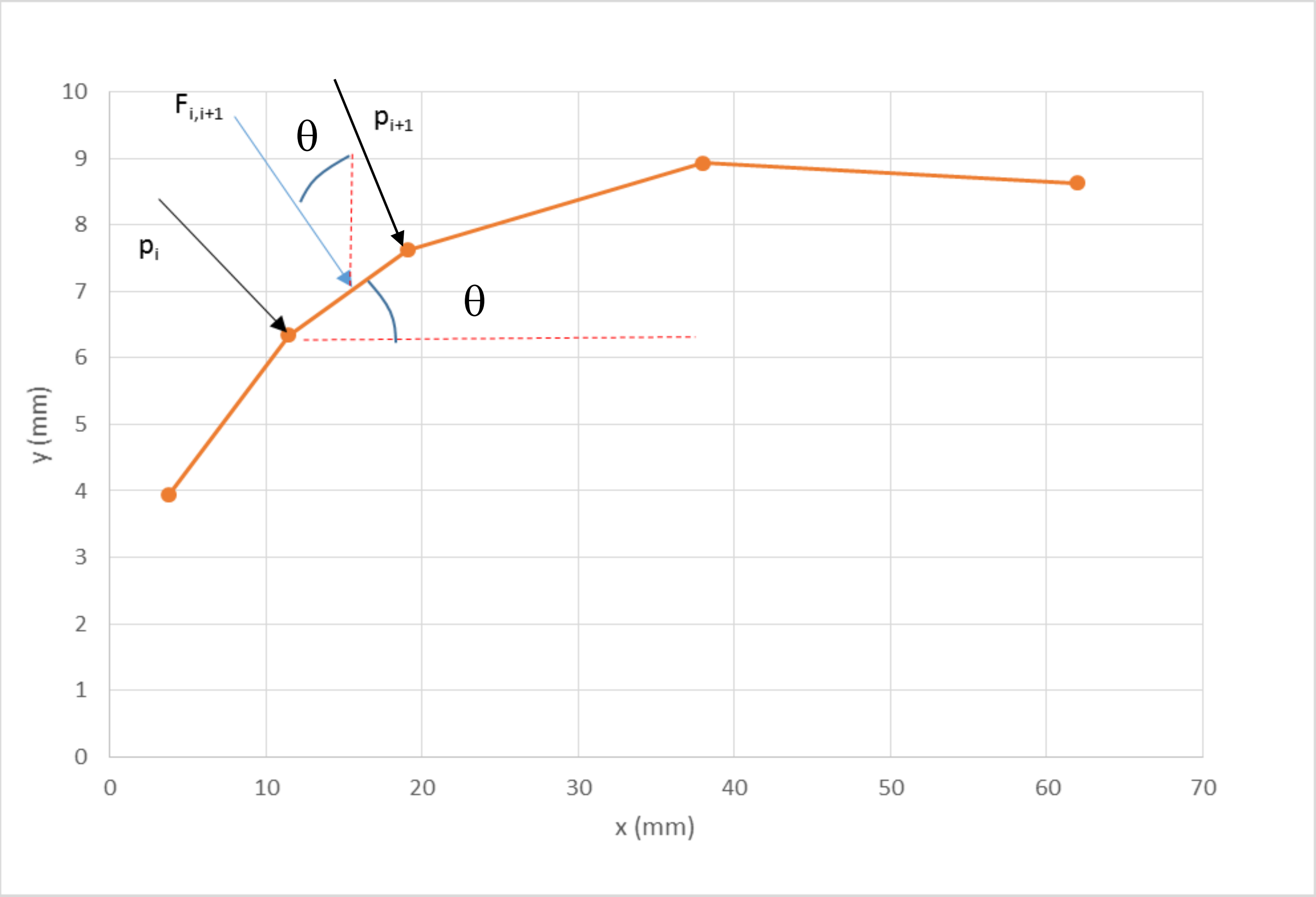
Assume pressure at trailing edge is the static pressure



$$F_{12} = \frac{L\left(x_2 - x_1\right)}{\cos\theta} \frac{P_2 + P_1}{2} \hat{n}$$

$$F_{12x} = L\left(x_2 - x_1\right) \frac{P_2 + P_1}{2} tan\theta\hat{i}$$

$$F_{12y} = -L\left(x_2 - x_1\right) \frac{P_2 + P_1}{2} \hat{j}$$

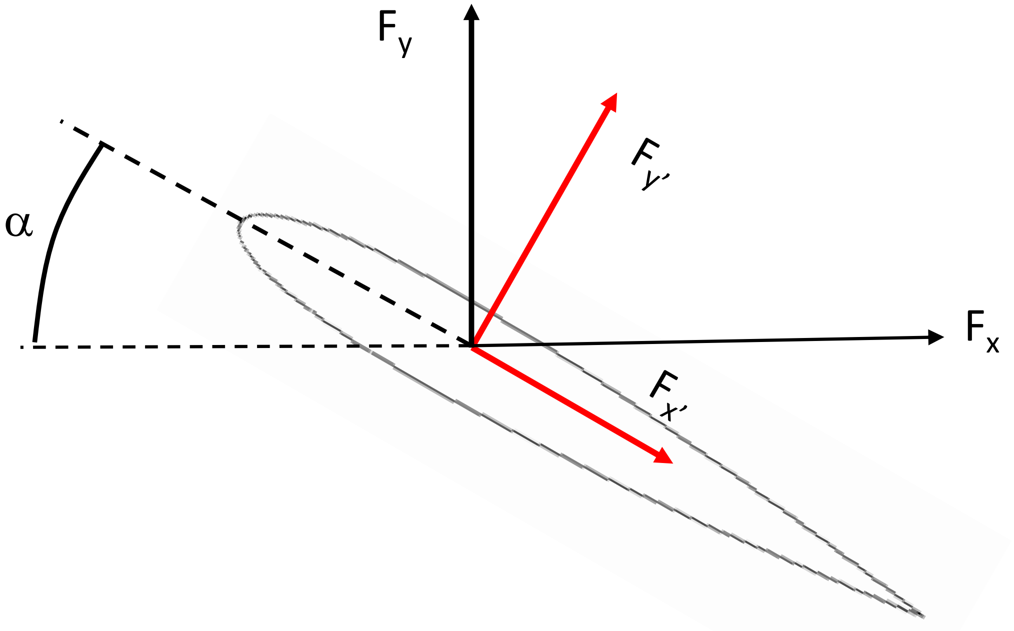


F i,i+1
p i+1
p i
θ
θ
y (mm)
x (mm)
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60
70

Calculating lift and drag forces for non-zero attack angles

Perform integration in airfoil reference frame and transform to inertial reference frame once you have the two force components.

Alternate strategy is to explicitly include α with the θ term in the integration.



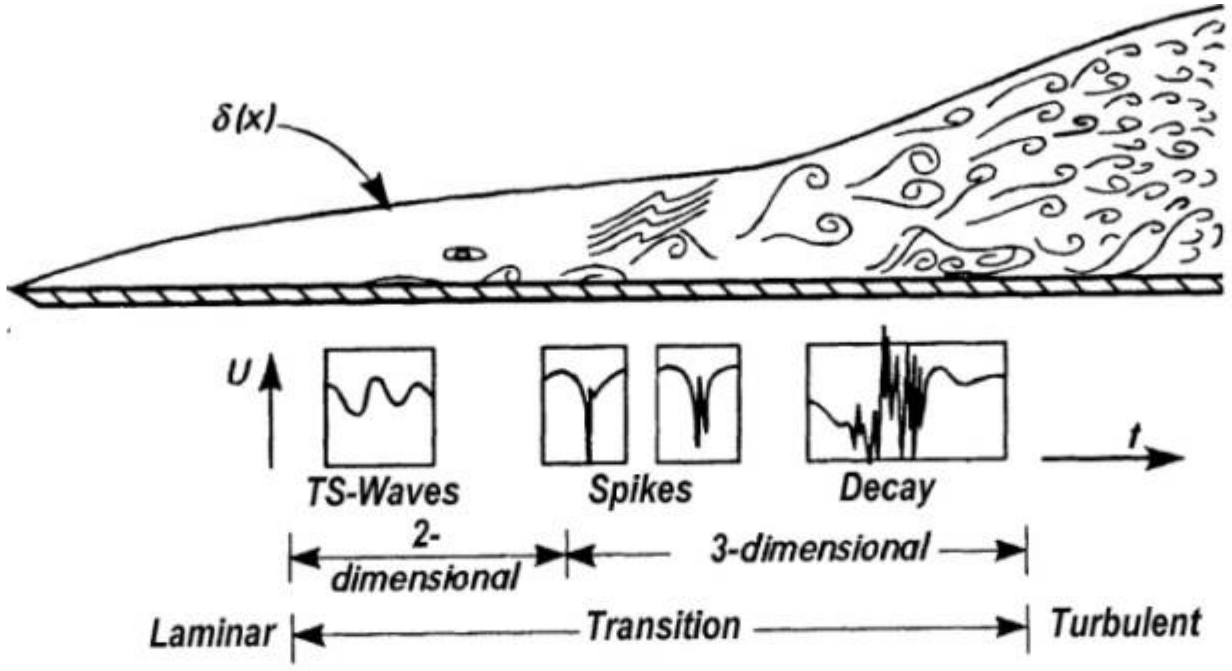
$$F_x = F_x' \cos\alpha + F_y' \sin\alpha$$

$$F_y = -F_x' \sin\alpha + F_y' \cos\alpha$$

Estimating drag from pressure measurements and estimates of skin friction and induced drag

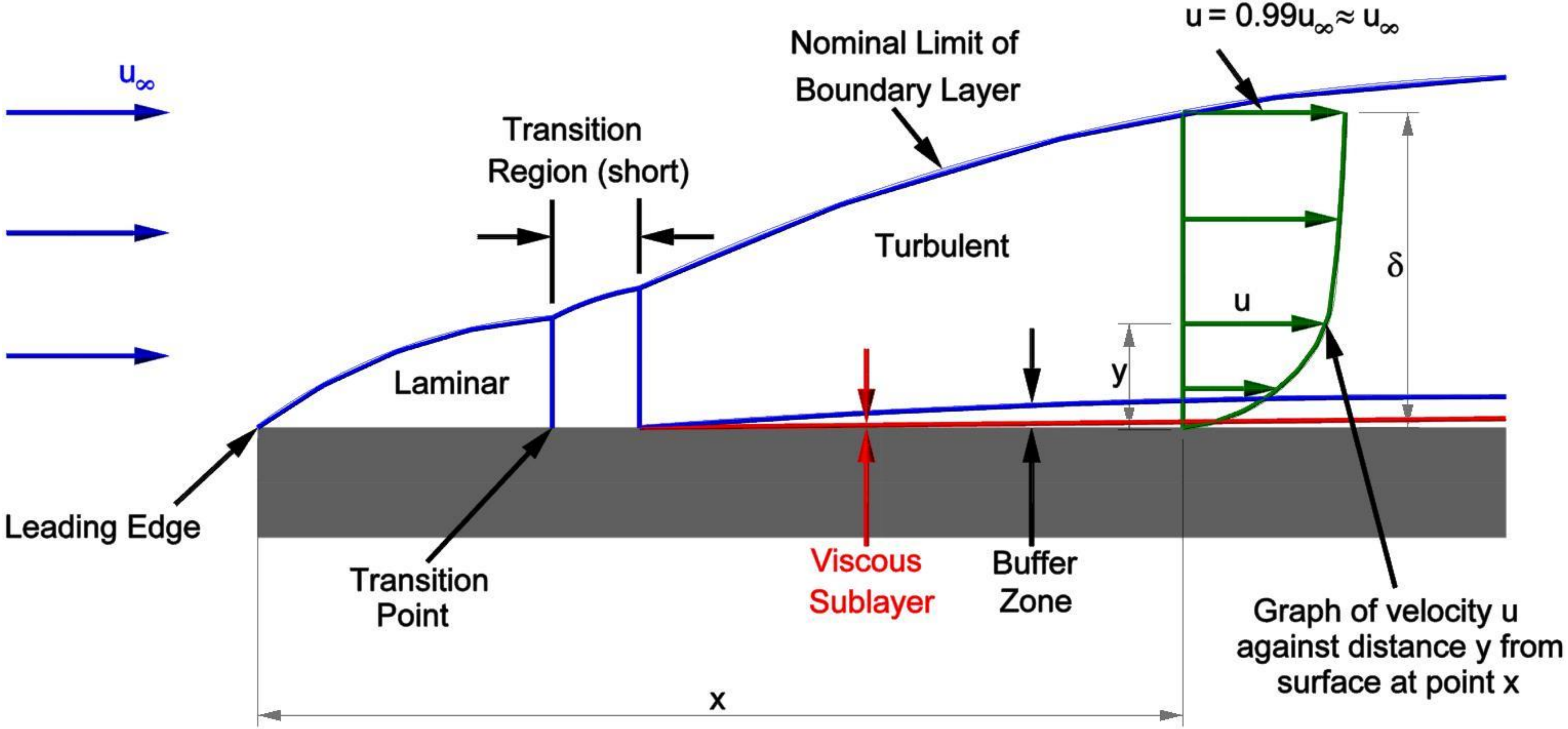
Estimating friction drag on a flat plate

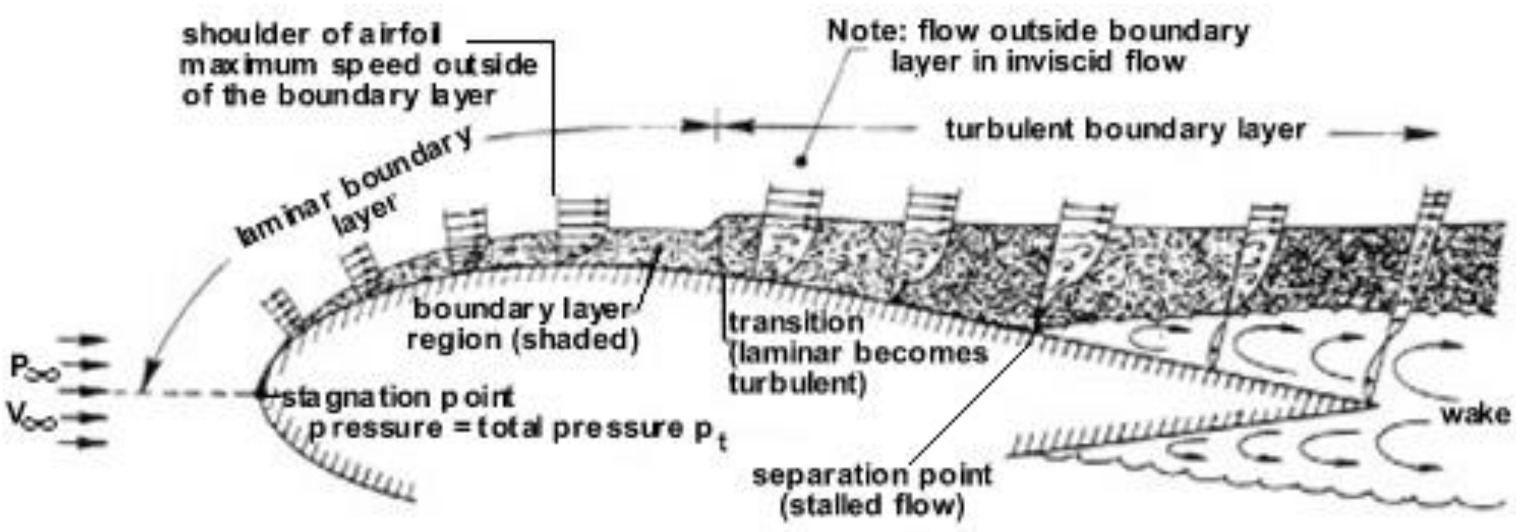
$$F_D = \int_{plate\,surface} \tau_w dA$$



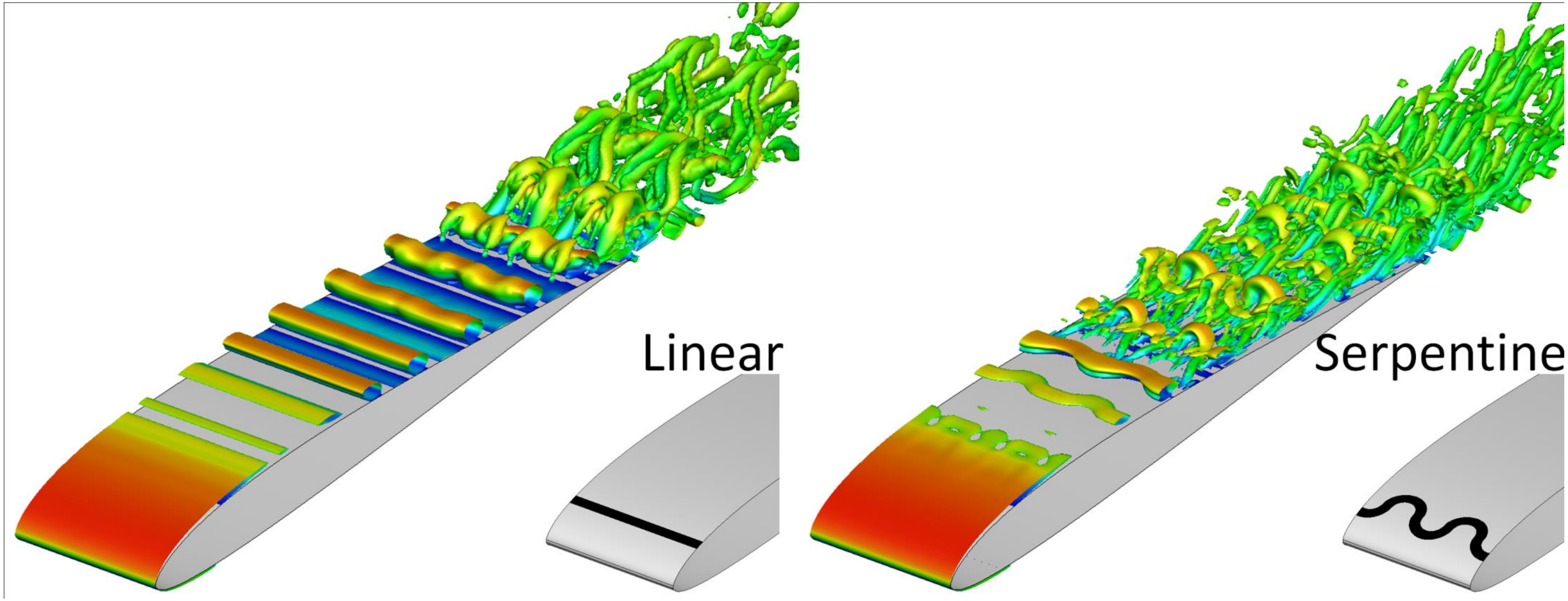
http://www.intechopen.com/books/advances-in-modeling-of-fluid-dynamics/surface-friction-and-boundary-layer-thickening-in-transitional-flow

Development of boundary layer on flat plate





http://www.pilotfriend.com/training/flight_training/aero/images/42.jpg



http://cdn.phys.org/newman/gfx/news/hires/2013/wranglingflo.png

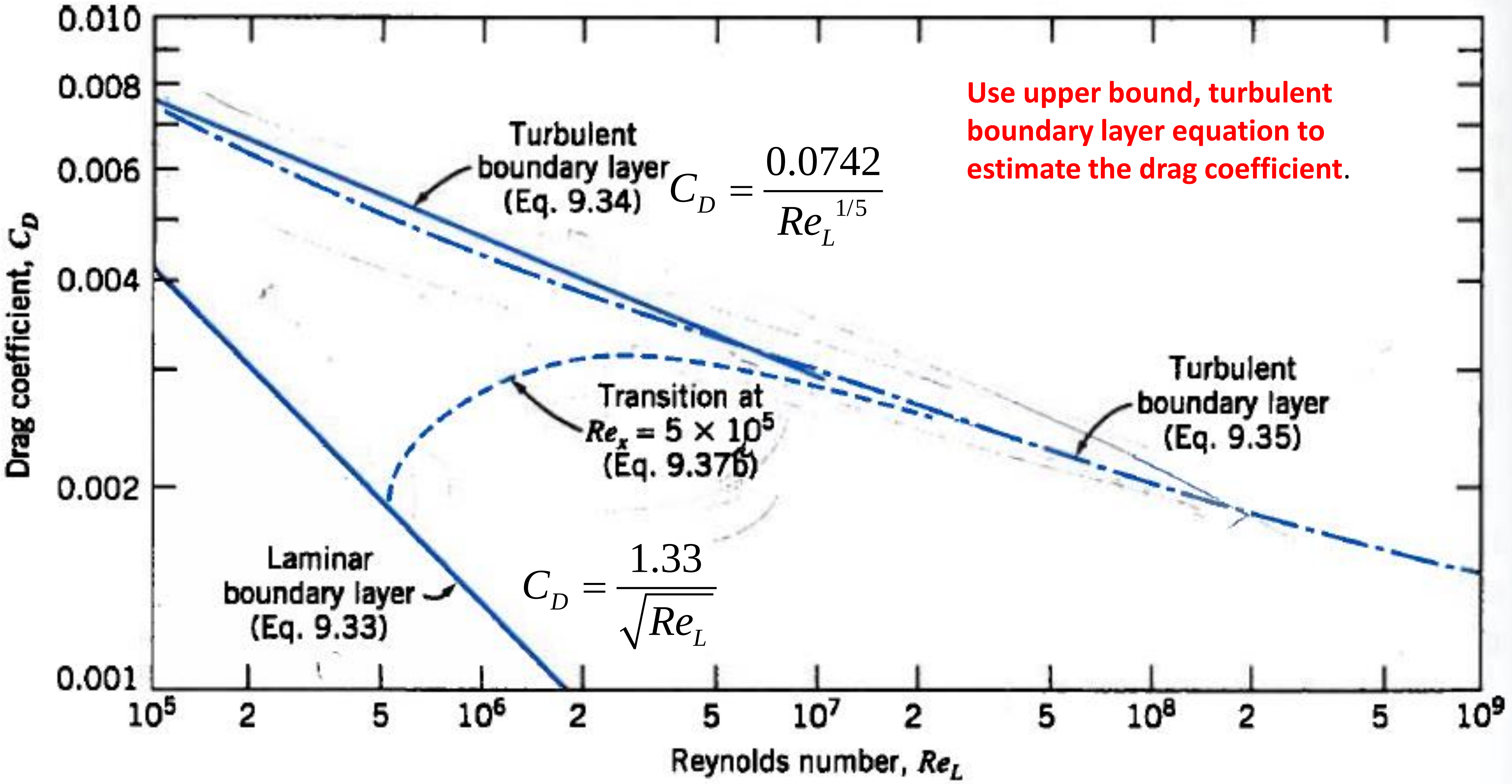
Drag coefficient flow over a flat plate

$$C_D = \frac{F_D}{\frac{1}{2}\rho V^2 A} = \frac{\int_{PS} \tau_w dA}{\frac{1}{2}\rho V^2 A} \qquad (9.32,\ p.447)$$

$$C_D = \frac{1.33}{\sqrt{Re_L}} \quad \mathrm{Re}_L = \frac{VL}{\nu} \quad (Laminar\ \ flow) \qquad (9.33,\ p.\ 447)$$

$$\mathrm{C}_D = \frac{0.0742}{\mathrm{Re}_L^{1/5}} \quad (Turbulent\ \ flow\ \ 5x10^5 < \mathrm{Re}_L < 10^7) \quad (9.34,\ p.\ 447)$$

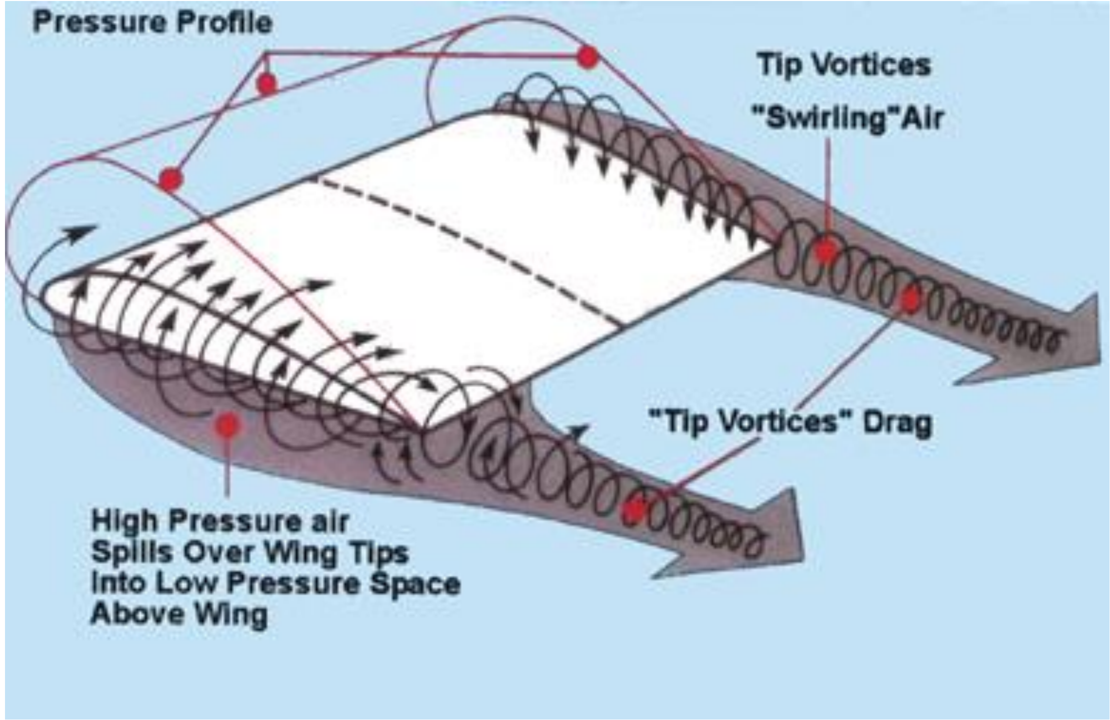
$$\mathrm{C}_D = \frac{0.455}{\mathrm{Re}_L^{2.58}} \quad (Turbulent\ \ flow\ \ \mathrm{Re}_L < 10^9) \qquad (9.35,\ p.\ 447)$$



Use upper bound, turbulent boundary layer equation to estimate the drag coefficient.

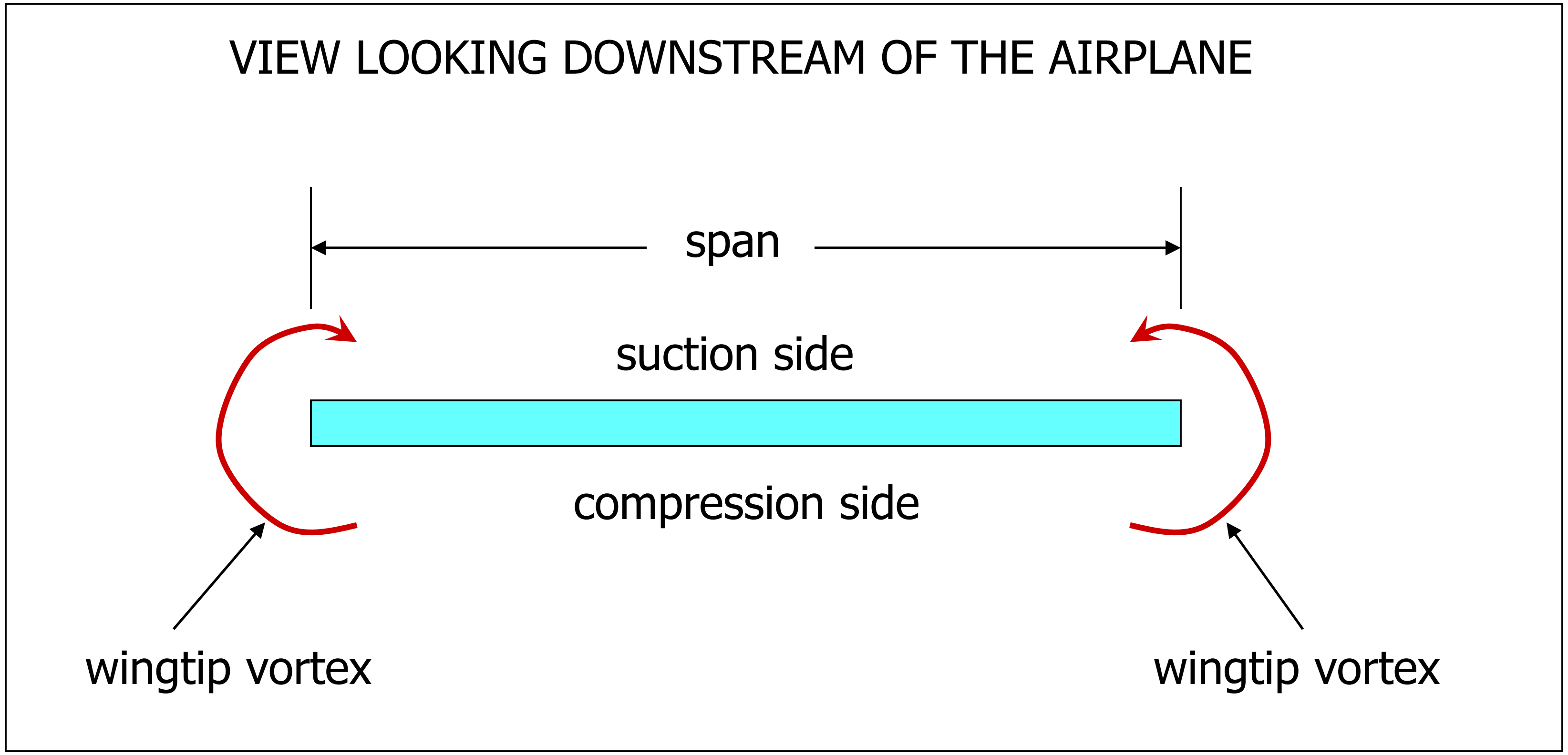
Fig. 9.8 Variation of drag coefficient with Reynolds number for a smooth flat plate parallel to the flow.

End effects of wing tips: Induced drag



Tip vortex created by leakage of flow from high-pressure side (bottom) to low-pressure side (top) of wing.

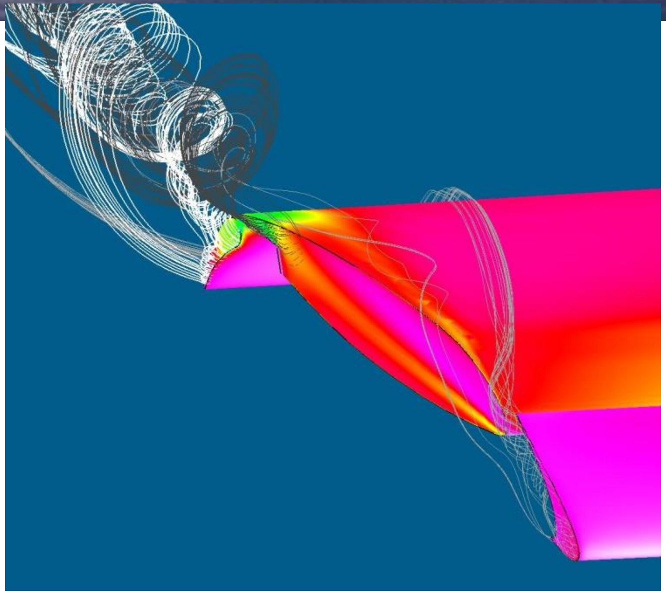
Induced Drag: A Closer Look



Energy required to create wingtip vortices COMES AT the expense of a loss in momentum (i.e. drag). Comparable to wave drag on a ship.

We call this drag the induced drag.

Wingtip Vortices in Practice



Winglets are used to reduce induced drag

Boeing 737-300

Induced Drag Formula

See p. 461-466 in your Fluid dynamics text

$$C_{D,i} = \frac{\mathrm{C_L}^{2}}{\pi(AR)\varepsilon}$$

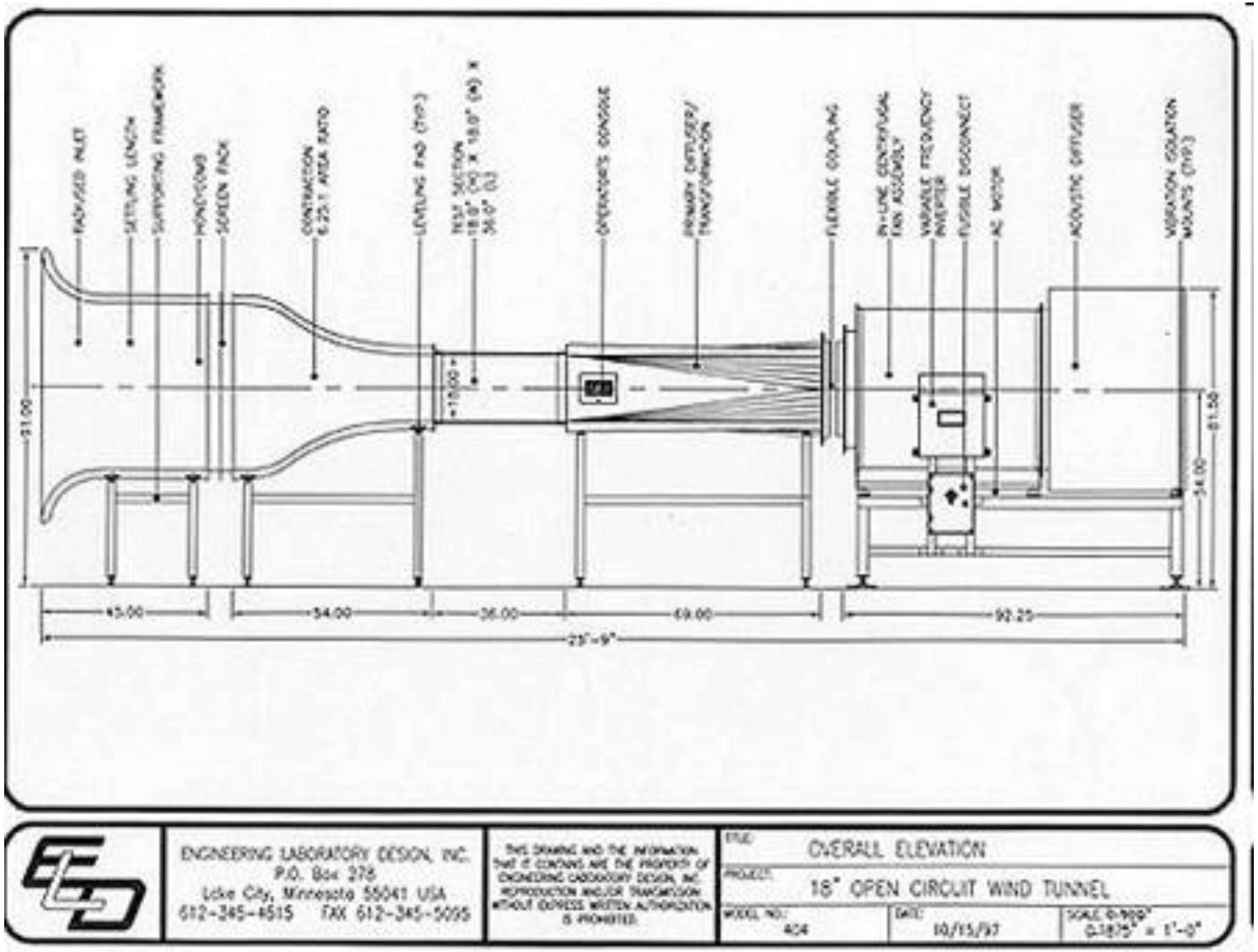
where ε is a efficiency factor ≈ 0.7
AR is the aspect ratio (span:chord) of the wing

Total estimated drag

$$F_D = F_{pressure} + F_{skin\ friction} + F_{induced}$$

UNH Student Wind Tunnel

UNH Student Wind Tunnel



Engineering Laboratory Design Model 404

- test section
  - 18 x 18 in^2 cross-section
  - 36 in length
- Max speed of 150 mph

Turbulence Management Section (before contraction)

Turbulence can be reduced by installing honeycombs and screens upstream of the contraction cone.

– Screens reduce axial turbulence more than lateral turbulence

– Honeycombs reduce lateral velocities

screens

honeycomb

Contraction

Purpose

• The object of the contraction cone is to accelerate the flow from the low power loss speed to the test section speed.

Design Problems

• There are two problems with their design:

– Adverse pressure gradients in the entrance and exit of the contraction cone can cause boundary layer separation

– Secondary flow in the corners of rectangular cross-section cones

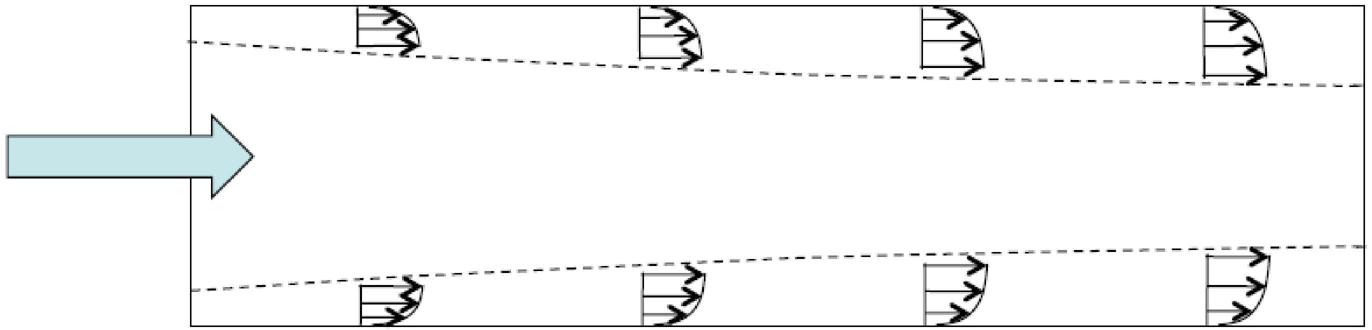
Design Solutions

• The secondary flow problem is solved by making the contraction cone octagonal

• The adverse pressure gradient problem is solved by carefully designing the geometry

Test Section

- The test section is not completely straight
- The boundary layer grows in the test section, reducing its effective area, increasing the velocity and decreasing the static pressure



- The length of a test section is usually chosen as one or two times the size of the major dimension of the cross section. E.g. for a 3mx2m cross section, the length would be 3m-6m.
- There are significant losses in the test section so it should be kept as short as possible
- There must be adequate windows in the test section
- There must be good lighting in the test section
- There must be holes for passing cables, tubes, shafts, etc.

Diffuser

- The purpose of the diffuser is to reduce airspeed in the sections of the tunnel that are not used for experiments
  - power losses depend on the cube of the airspeed

- As the diffuser decreases airspeed, it increases static pressure, causing an adverse pressure gradient.

- An adverse pressure gradient can cause separation at the wall that can possibly lead to vibrations, increased losses, oscillating airspeed in the test section (surging), oscillating fan loading etc.

- To avoid separation diffusers usually increase the area by a total maximum factor of 5 or 6 times the test section area.

Fan

- The fan operates in a constant area duct; due to continuity, the airspeed is constant across the fan.
- Therefore, the fan does not accelerate the flow. It creates a difference in static pressure across its two sides.
- This static pressure difference can be high in order to set the flow in motion.
- It can also be equal to the losses in static pressure in the tunnel in order to keep the flow speed constant
- Fans develop their highest efficiency when in a relatively high speed flow.
- Therefore, they are not positioned in the section of the tunnel with the largest area.