VIT

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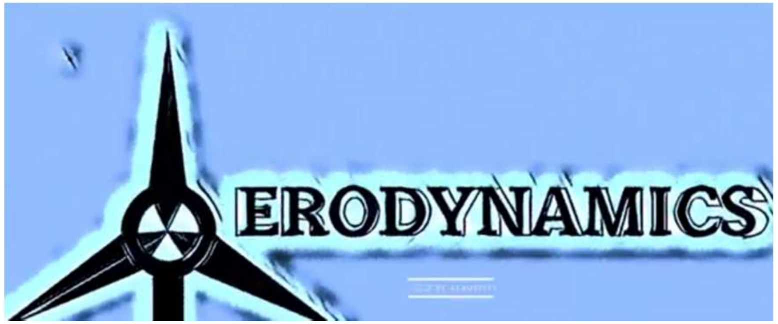


MEE1004-FLUID MECHANICS

Boundary Layer Flow
Lecture 3

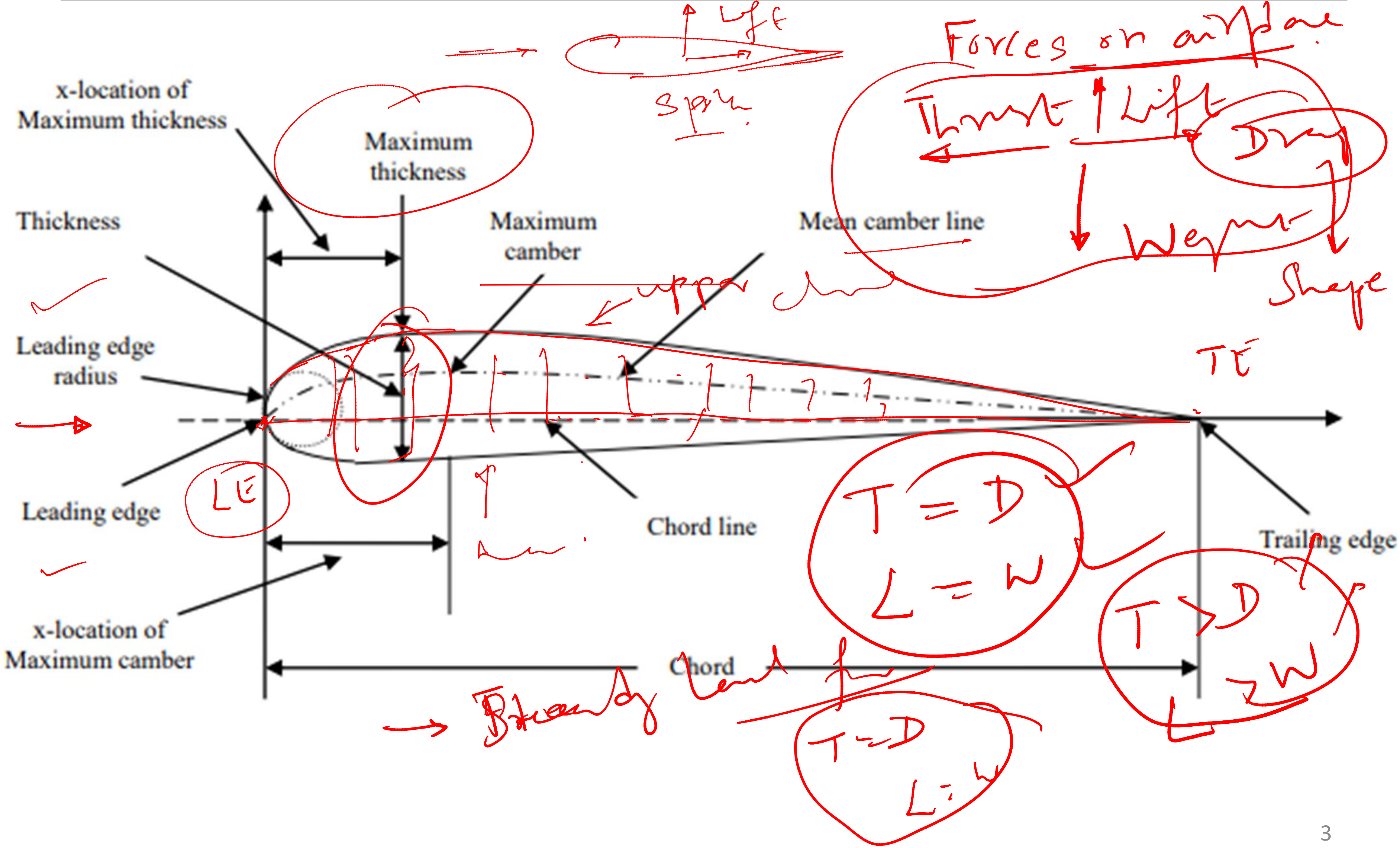
Vinayagamurthy G, Dr. Eng.,
Associate Professor
School of Mechanical and Building Sciences
VIT Chennai

Flow field around Airfoil and Wings

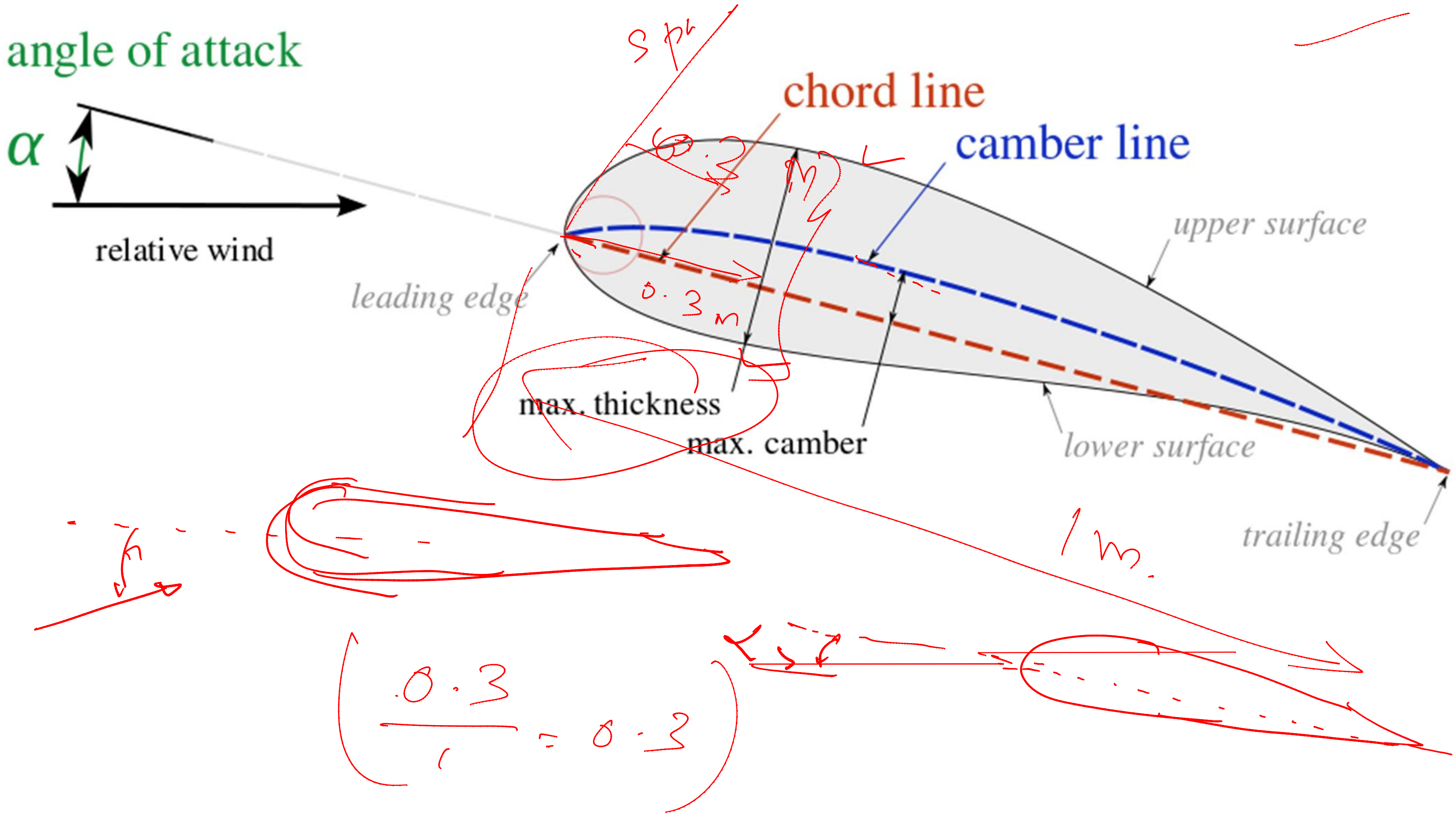
Dr. G. Vinayagamurthy

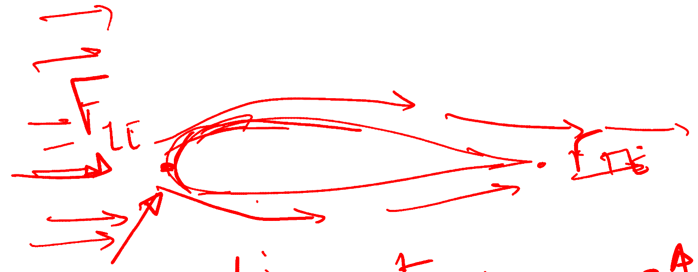
VIT Chennai

Aerofoil Nomenclature



Aerofoil Nomenclature





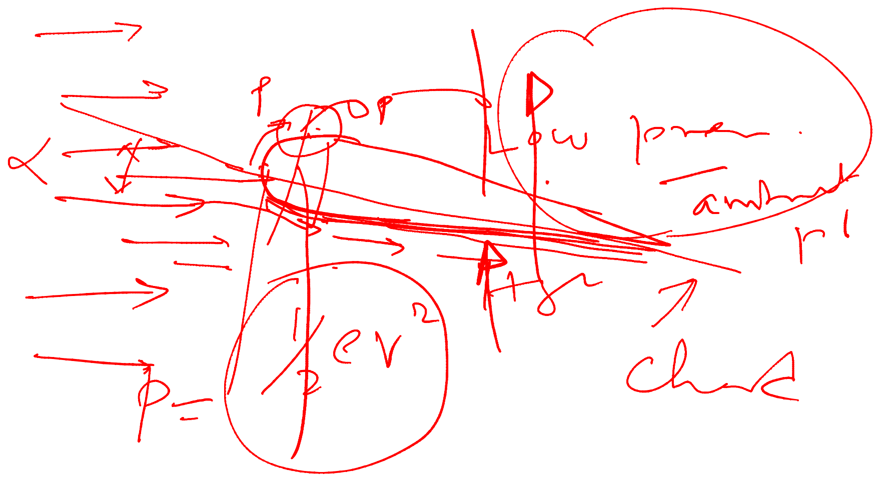
Stagnation pt, $V = 0$, $P\uparrow$

Net force $P_u = P_l$

a small drag

x% of chord

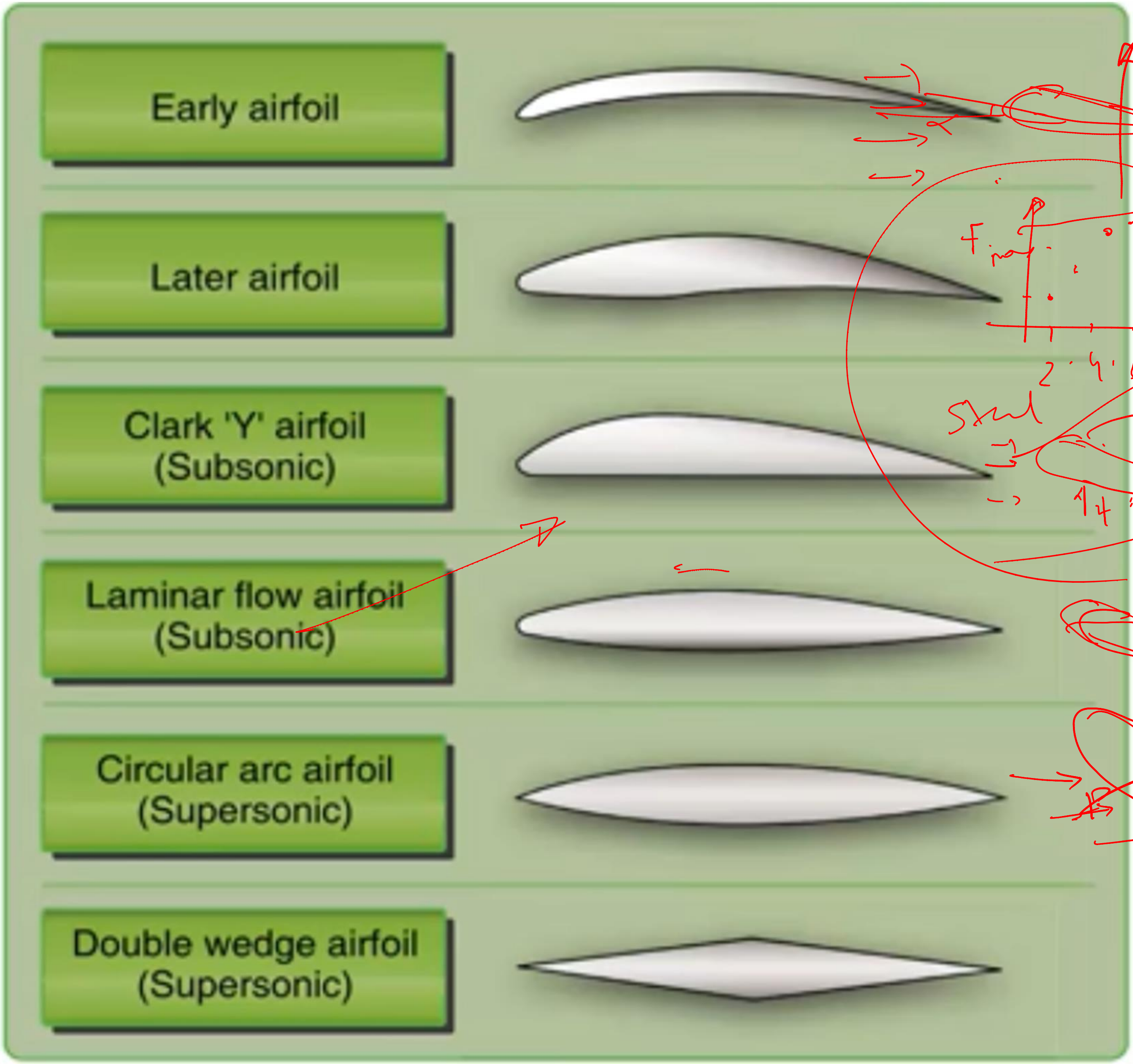
Define whole



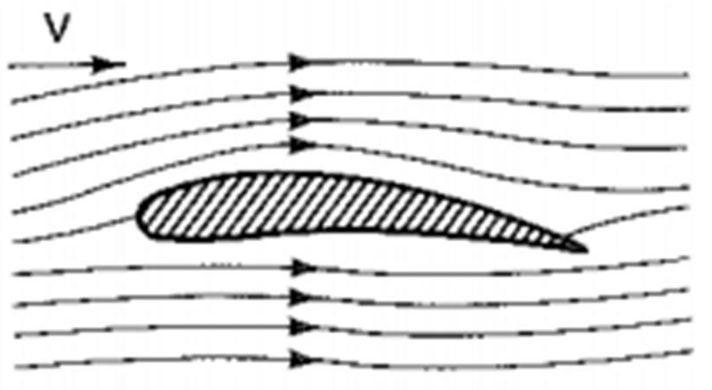
Aerofoil Nomenclature

- ***Mean camber line*** is the locus of points halfway between the upper and lower surfaces as measured perpendicular to the mean camber line.
- Forward & rearward points of mean camber line are ***leading*** and ***trailing edges***.
- Straight line connecting leading and trailing edges is ***chord line c*** of airfoil.
- ***Camber*** is the maximum distance between the mean camber line and the chord line, measured perpendicular to the chord line.
- ***Thickness*** is the distance between the upper and lower surfaces, also measured perpendicular to the chord line.
- The shape of the airfoil at the leading edge is usually circular, with a **leading-edge radius** of approximately 0.02*c*.
- **Angle of attack, lift** and **drag** directions are defined w.r.t. the chord.

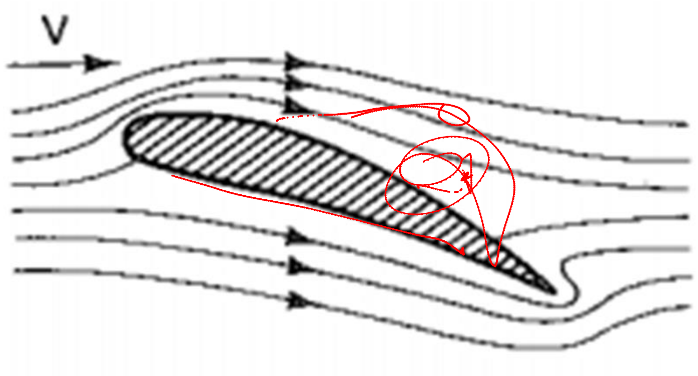
Aerofoil Nomenclature



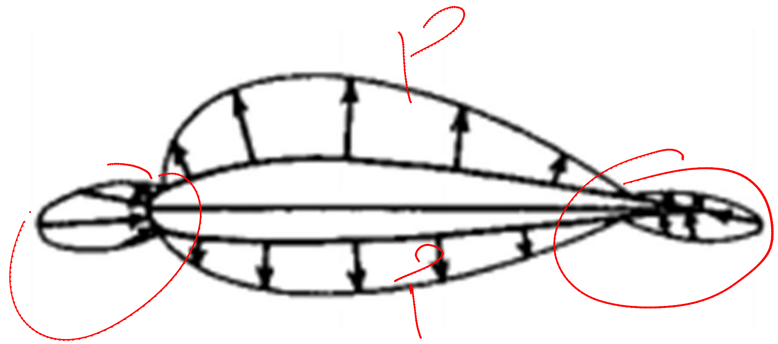
Flow-field around a Airfoil



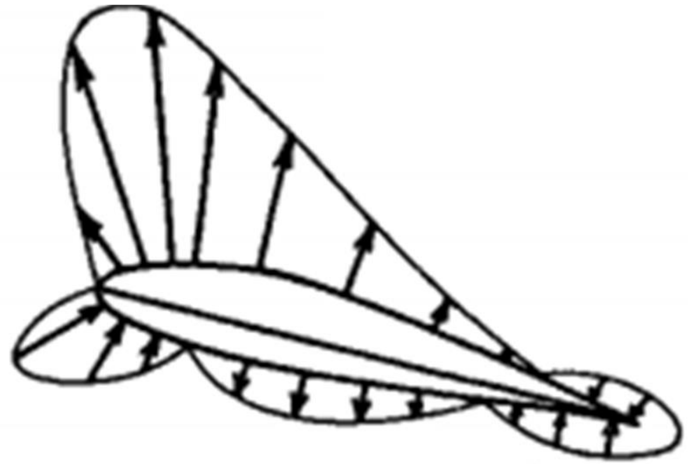
a. Small angle of attack



b. Large angle of attack

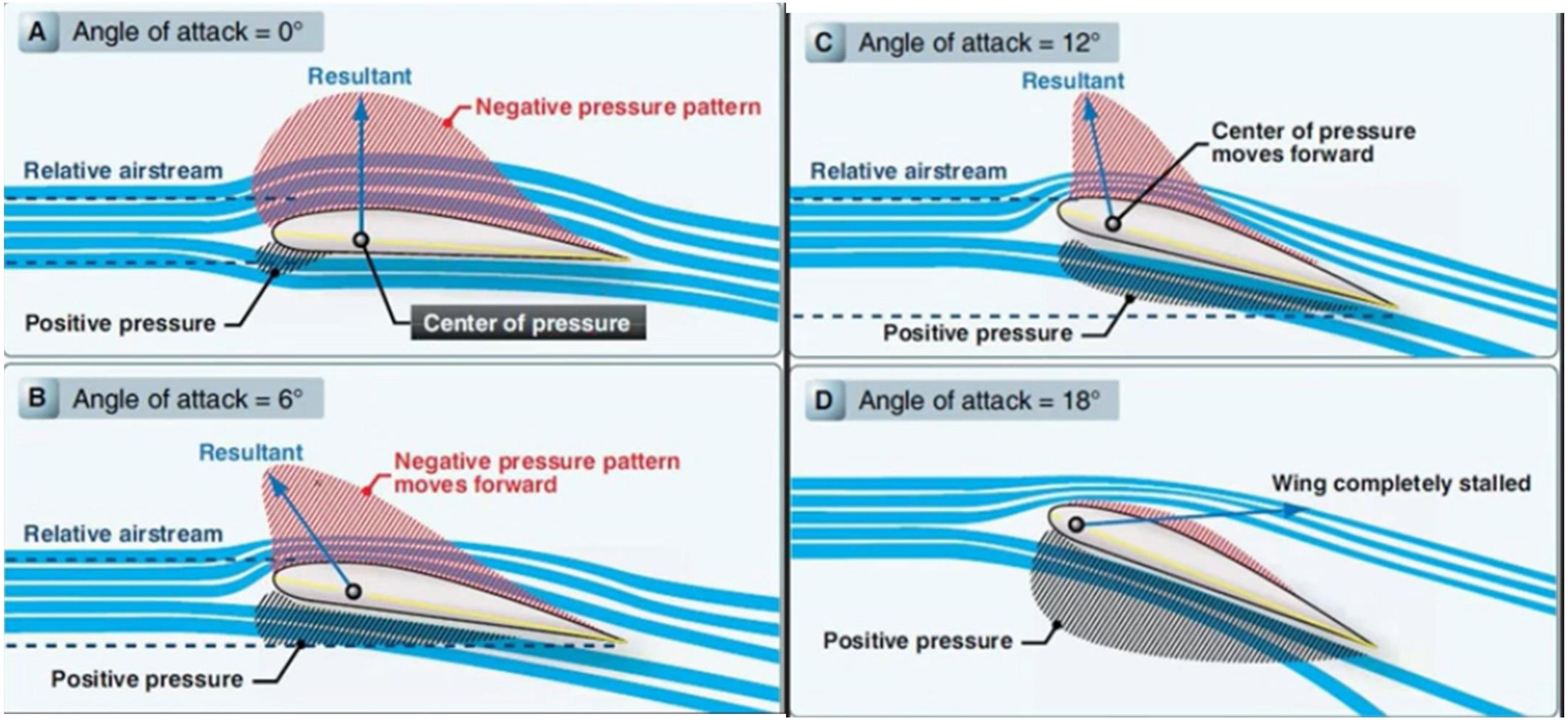


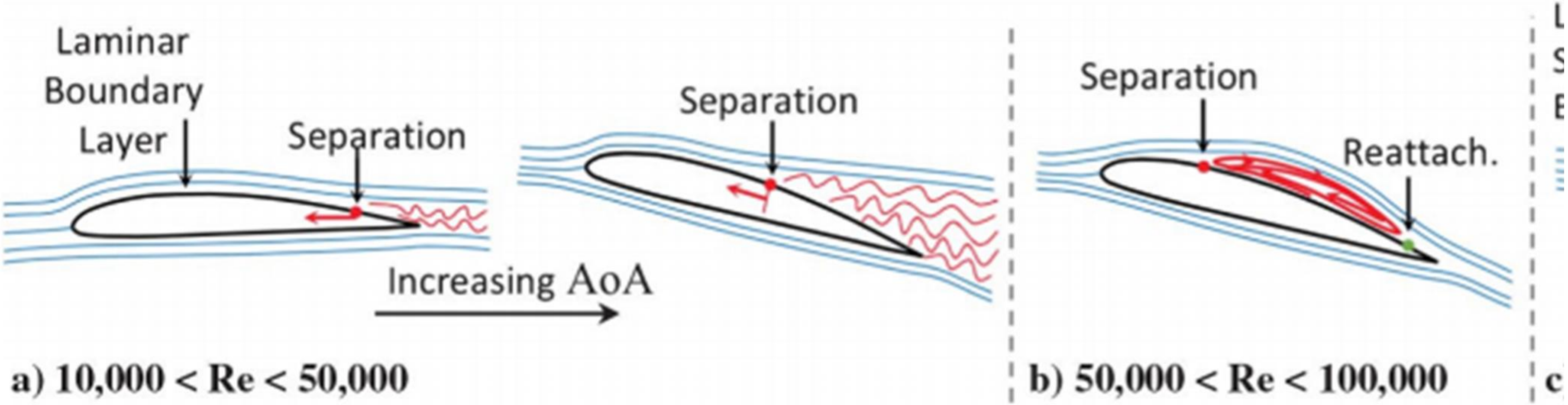
a. Small angle of attack



b. Large angle of attack

Flow-field around a Airfoil





ig. 2 Illustration highlighting conventional airfoil separation characteristics at different Reyn

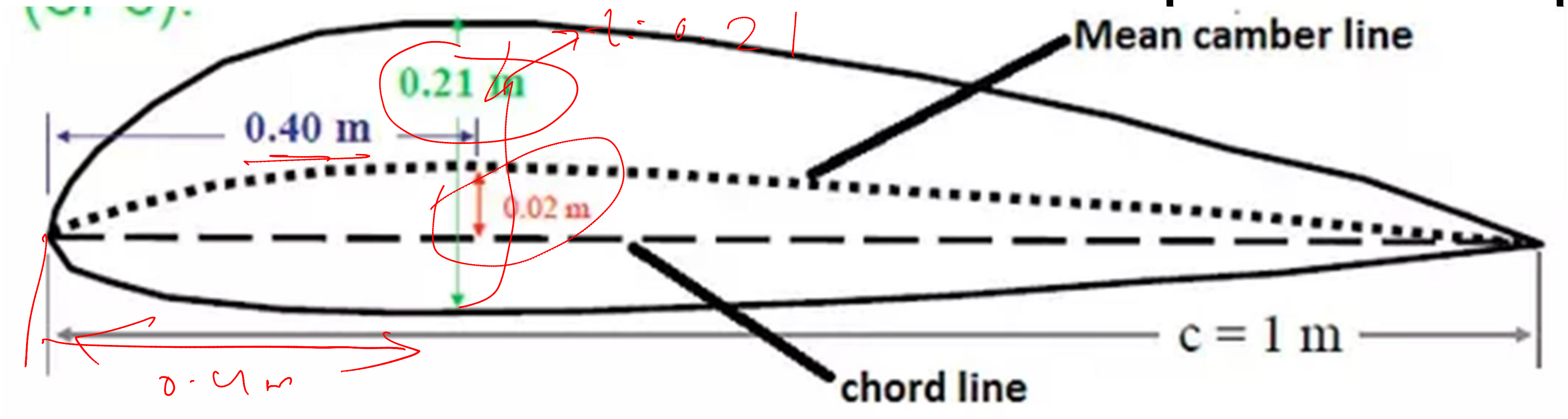
NACA – 4 digit series

NACA X(2) X(4) XX(21)

Camber in percentage (%) of chord

Location of maximum camber from LE x 10 %

Maximum thickness in percentage of chord



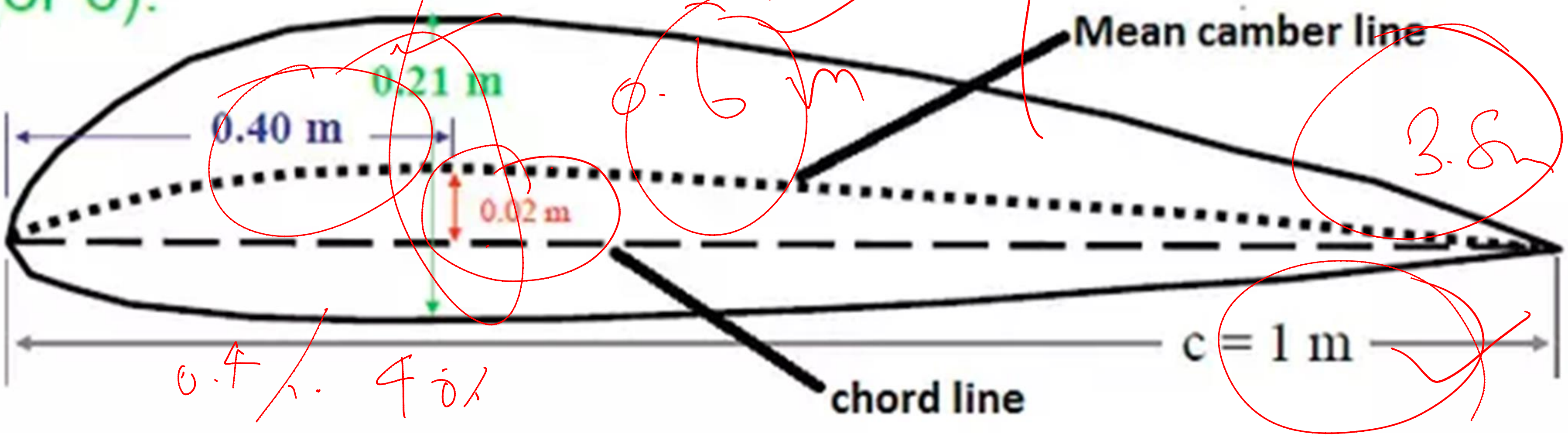
http://airfoiltools.com/airfoil/naca4digit

NACA 2 4 21

1st Digit: Maximum camber is 2% of 2D airfoil chord length, c (or 3D wing mean chord length, $\bar{c}$).

2nd Digit: Location of maximum camber is at 4/10ths (or 40%) of the chord line, from the LE.

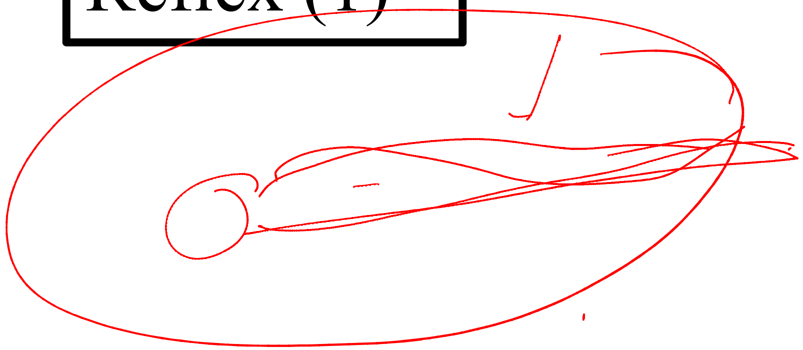
3rd & 4th Digits: Maximum thickness is 21% of c (or $\bar{c}$).



NACA – 5 digit series

NACA X X X XX

- **Lift Coefficient**: **X** x 0.15
- **Location of maximum camber from LE**: x 10 %
- **Whether the camber is Simple (0) or Reflex (1)**
- **Maximum thickness in percentage of chord**



NACA – 1 series, NACA X X -X X XX

NACA 1 X -X XX

Indicate series

Maximum pressure area distance in 10% of chord

Lift coefficient x 0.1

Maximum thickness in percentage of chord

NACA – 6 digit series

NACA X X x -X XX

Indicate series

Maximum pressure area distance in 10% of chord

Drag coefficient x 0.1

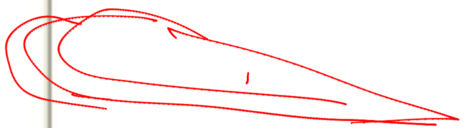
Lift coefficient x 0.1

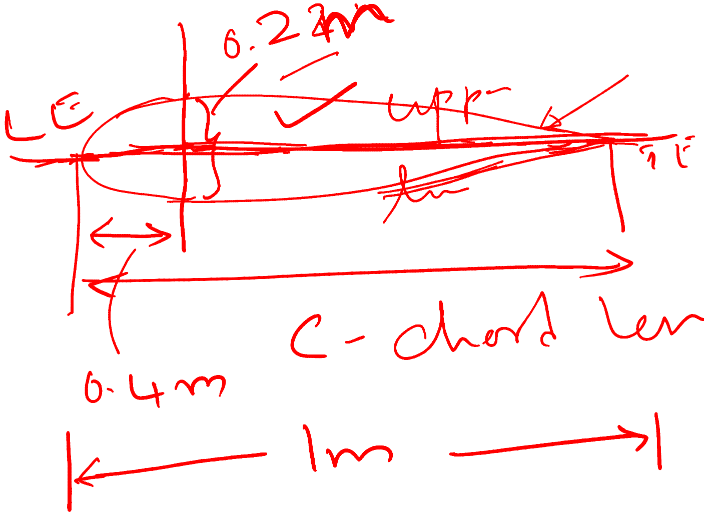
Maximum thickness in percentage of chord

NACA – Characteristics of Airfoils

Family	Advantages	Disadvantages	Applications
4-Digit	1. Good stall characteristics 2. Small center of pressure movement across large speed range 3. Roughness has little effect	1. Low maximum lift coefficient 2. Relatively high drag 3. High pitching moment	1. General aviation 2. Horizontal tails ***Symmetrical:*** 3. Supersonic jets 4. Helicopter blades 5. Shrouds 6. Missile/rocket fins
5-Digit	1. Higher maximum lift coefficient 2. Low pitching moment 3. Roughness has little effect	1. Poor stall behavior 2. Relatively high drag	1. General aviation 2. Piston-powered bombers, transports 3. Commuters 4. Business jets
16-Series	1. Avoids low pressure peaks 2. Low drag at high speed	1. Relatively low lift	1. Aircraft propellers 2. Ship propellers

NACA – Characteristics of Airfoils

6-Series	1. High maximum lift coefficient 2. Very low drag over a small range of operating conditions 3. Optimized for high speed	1. High drag outside of the optimum range of operating conditions 2. High pitching moment 3. Poor stall behavior 4. Very susceptible to roughness	1. Piston-powered fighters 2. Business jets 3. Jet trainers 4. Supersonic jets
7-Series	1. Very low drag over a small range of operating conditions 2. Low pitching moment	1. Reduced maximum lift coefficient 2. High drag outside of the optimum range of operating conditions 3. Poor stall behavior 4. Very susceptible to roughness	Seldom used 



Sym

Symmetric

Cambered

amount of camber

1 → ~~Slne~~ Symm

2 → Position of the camber

3 → Max. thic...

4 →

NACA 0421

NACA 2421

Pressure field around a simple car

→ B. L

→ Airfoil [illegible] | [illegible]

External Flow - Basic equations for inviscid incompressible flow

- The development of the inviscid flow at the outer edge of the boundary layer determines the pressure distribution on the body surface.
- To begin with, the law of mass conservation has to be formulated. The most simple form of this law is for incompressible flow (p = constant):

$$ws = \text{constant}$$

indicates narrow distances between the streamlines in regions of high velocity and vice versa.

where *s* denotes the local cross-section of a small stream-tube and *w* is the local velocity, which is assumed to be constant across *s*.

- Furthermore the flow obeys Newton's law of momentum conservation: mass times acceleration is equal to the sum of the acting forces.
- If this law is applied to an inviscid flow, it turns out that inertia forces and pressure forces are balanced. The integration of the momentum equation along a streamline for incompressible flow leads to

2 +

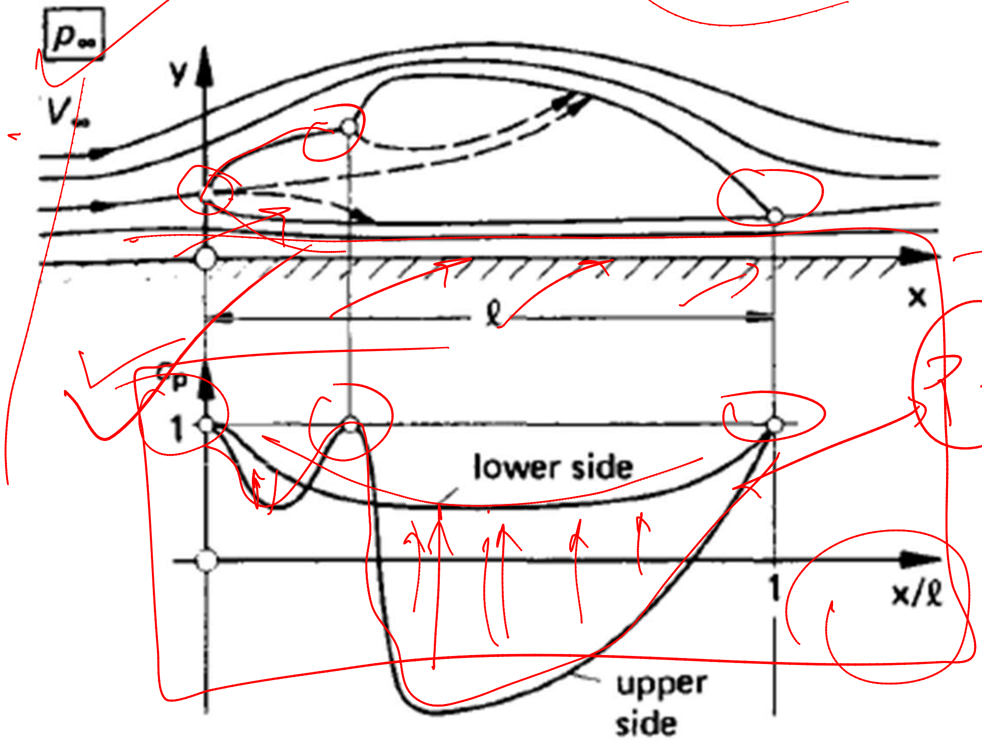
$$g = \boxed{p + \frac{\rho}{2} w^2} = \text{constant}$$

PRESSURE DISTRIBUTION

$$g = p + \frac{\rho}{2} w^2 = \text{constant}$$

Such a flow field is called 'isoenergetic', and g is Bernoulli's constant of it

In inviscid flow, the sum of static pressure and dynamic pressure is constant along a streamline.



Flow field and pressure distribution for vehicle-shaped body in two-dimensional inviscid flow (schematic)

If the flow comes to rest, $w = 0$, a so-called 'stagnation point', as on the nose of a vehicle the static pressure there will be equal to the total pressure, and this is the highest possible pressure in the flow field.

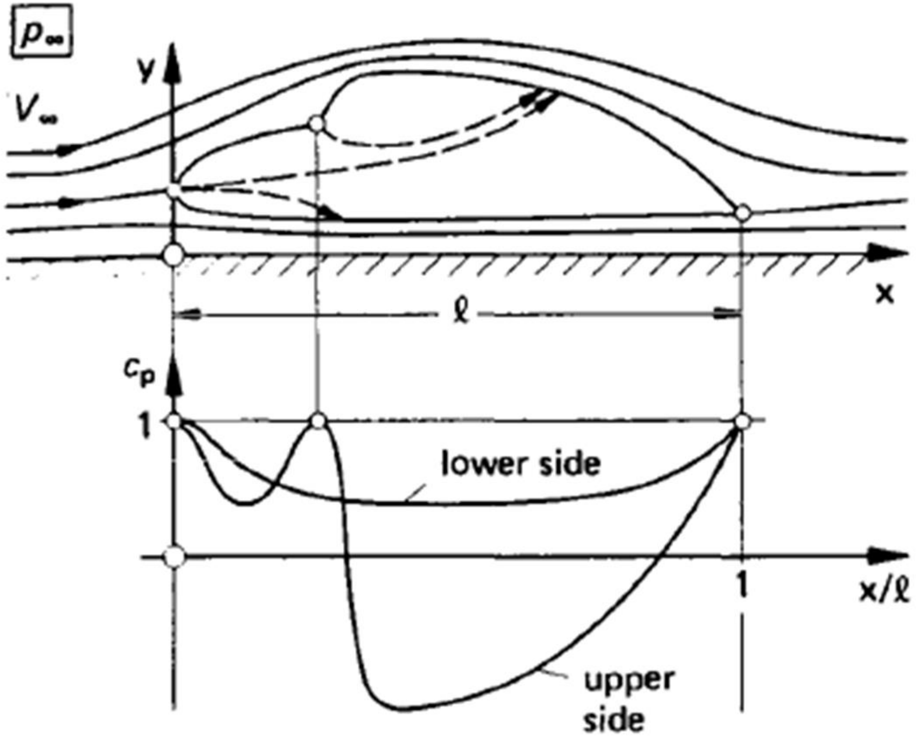
For the external flow around a vehicle, all streamlines start from the same free stream with static pressure P_∞ and free stream velocity V_∞. Therefore the total pressure g is constant for all streamlines

CO-EFFICIENT OF PRESSURE

$$p + \frac{\rho}{2} w^2 = p_\infty + \frac{\rho}{2} V_\infty^2$$

leads to

$$c_p = \frac{p - p_\infty}{\frac{\rho}{2} V_\infty^2} = 1 - \left(\frac{w}{V_\infty} \right)^2$$



Three stagnation points occur - in the nose region, in the corner between bonnet and windscreen, and at the trailing edge.

$$c_p = \frac{p - p_\infty}{\frac{\rho}{2} V_\infty^2}$$

CO-EFFICIENT OF PRESSURE

$$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho_\infty V_\infty^2}$$

where:

p is the pressure at the point at which pressure coefficient is being evaluated

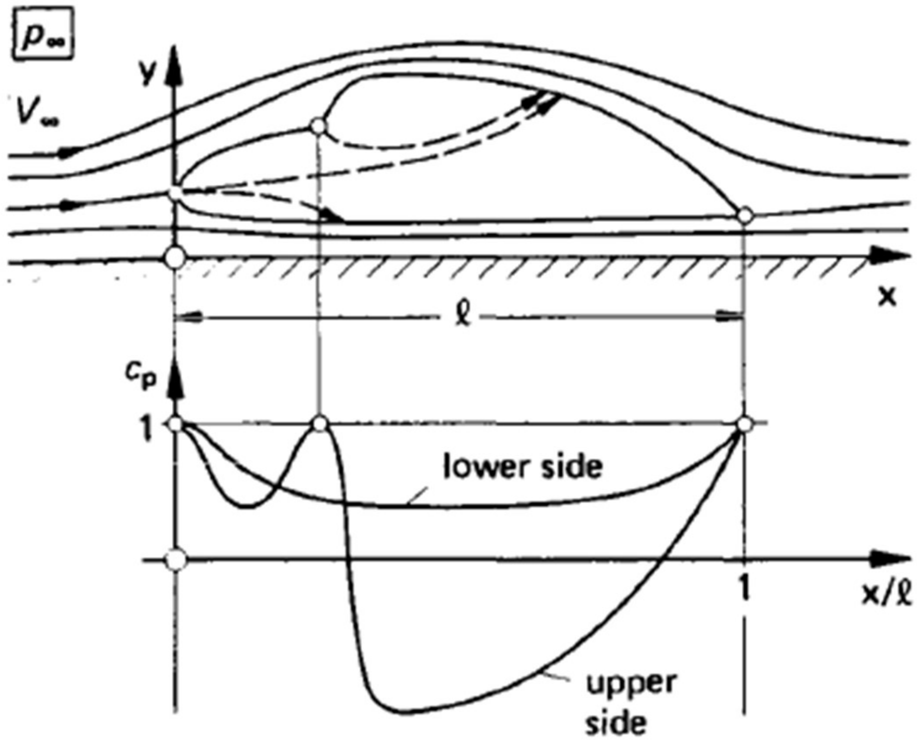
p_∞ is the pressure in the freestream (i.e. remote from any disturbance)

ρ_∞ is the freestream fluid density (Air at sea level and 15 °C is 1.225 kg/m^3)

V_∞ is the freestream velocity of the fluid, or the velocity of the body through the fluid

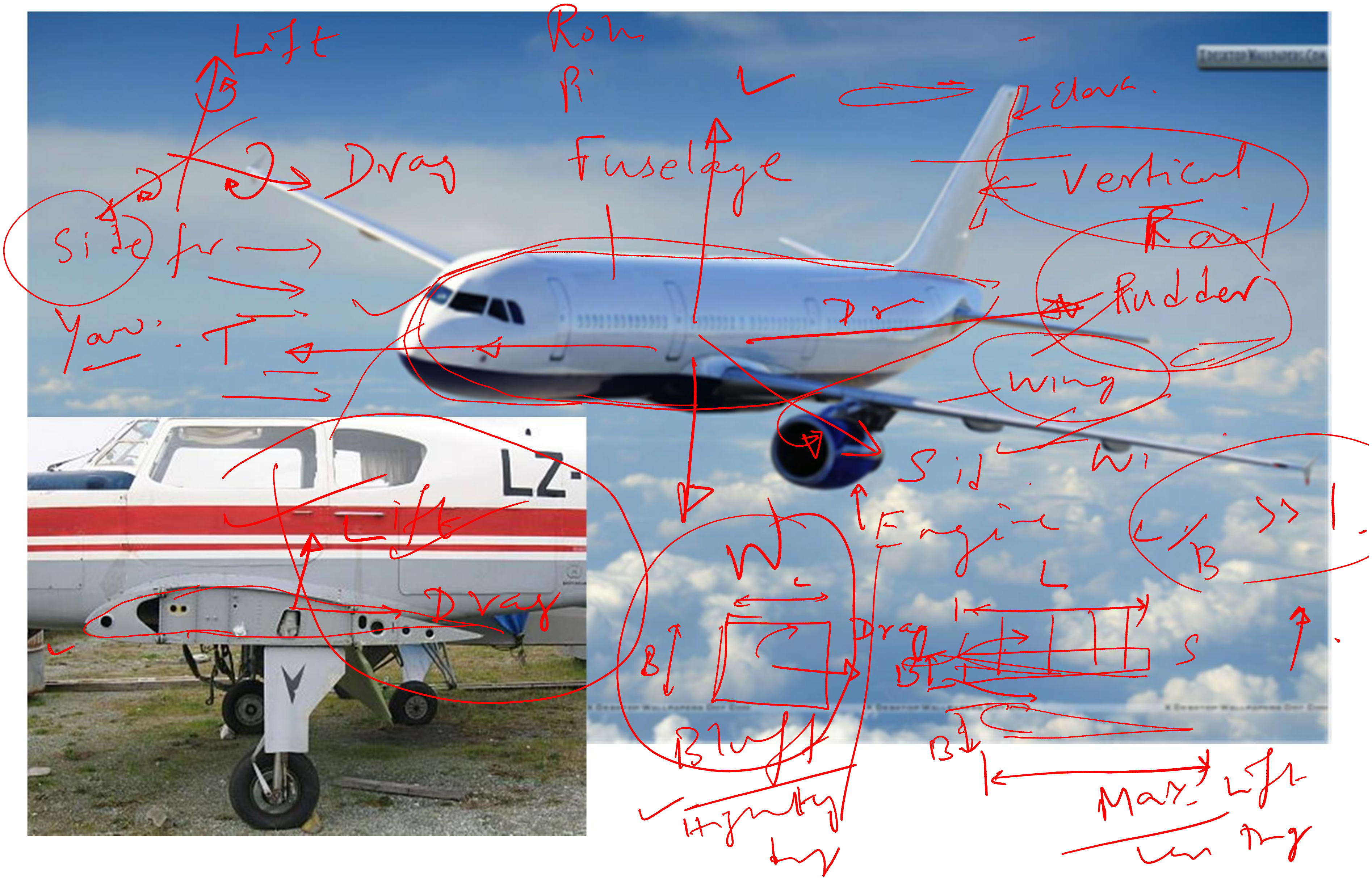
$$C_p = 1 - \left(\frac{V}{V_\infty}\right)^2$$

where V is the velocity of the fluid at the point at which pressure coefficient is being evaluated.

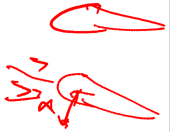


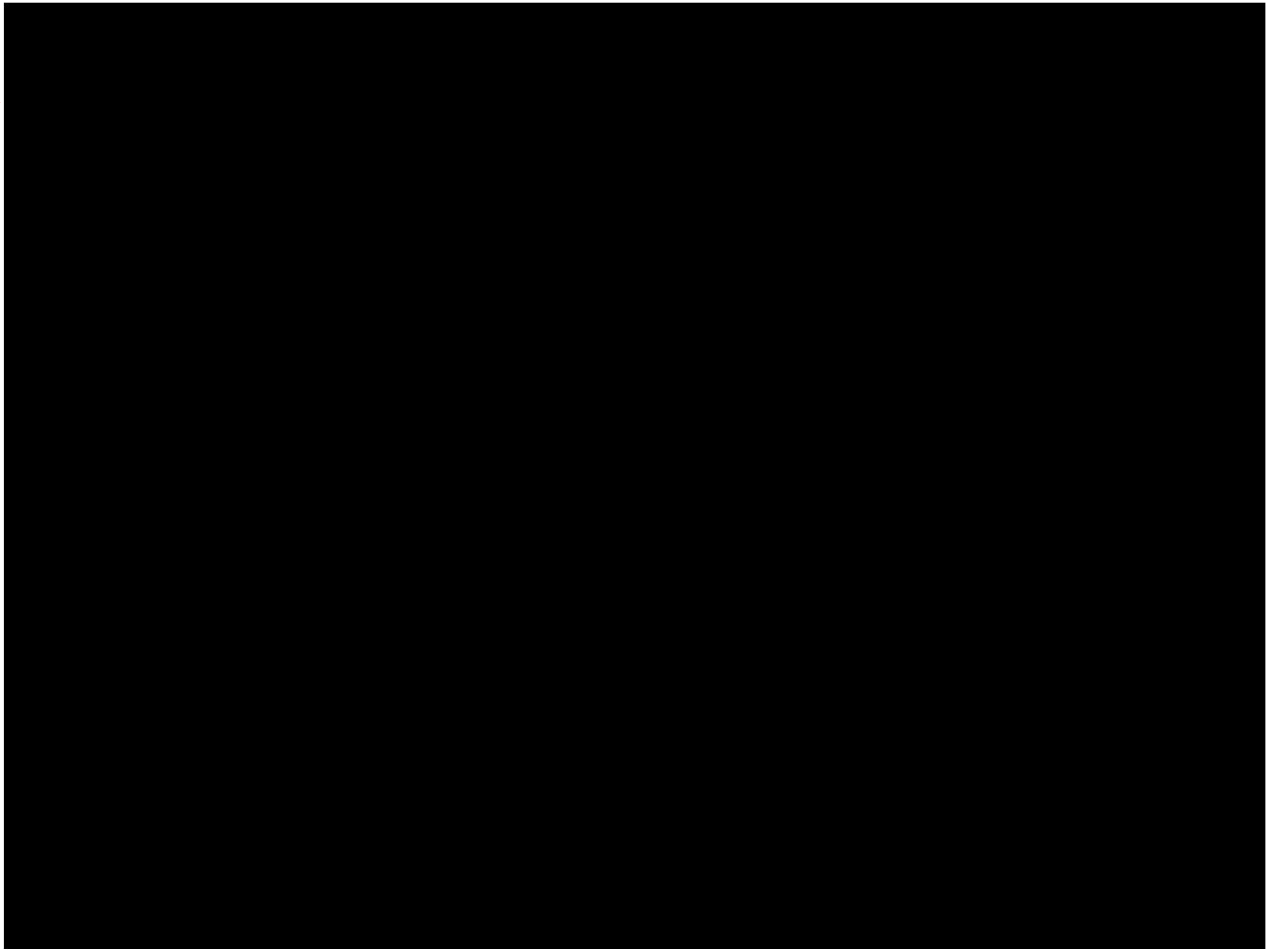
If all x-components of the pressure distribution on the vehicle surface are integrated, the result for the drag will be $D = 0$. This is the well-known d'Alembert's paradox, which means that in **incompressible, inviscid, two-dimensional** flow no drag is present. In the real, viscous flow there exists a drag force, but it cannot be explained by considering an ideal, inviscid fluid.

Introduction to Aerodynamics- Airofil Aerodynamics

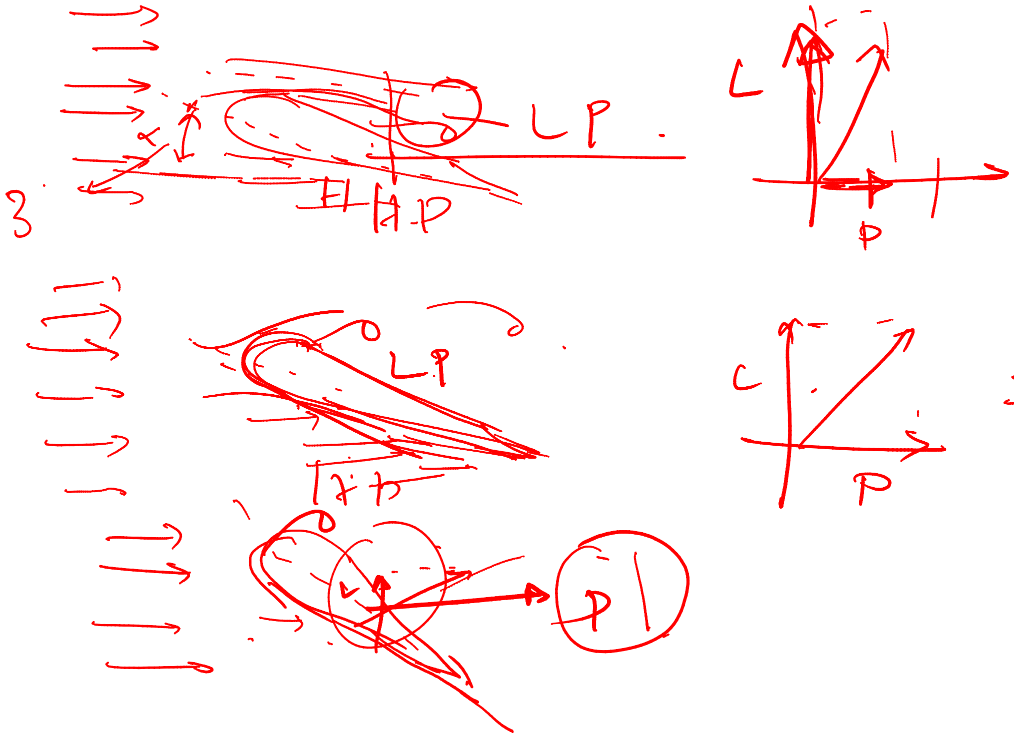


Flow past a streamline body

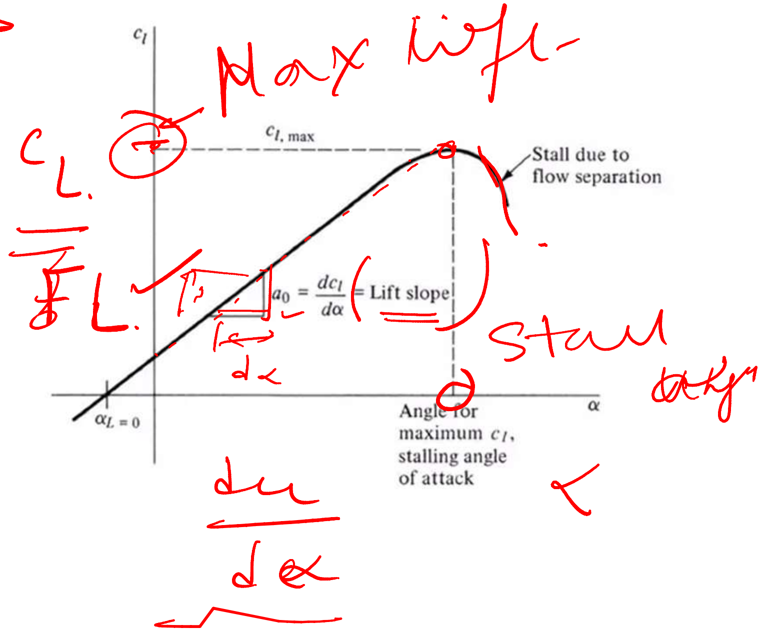




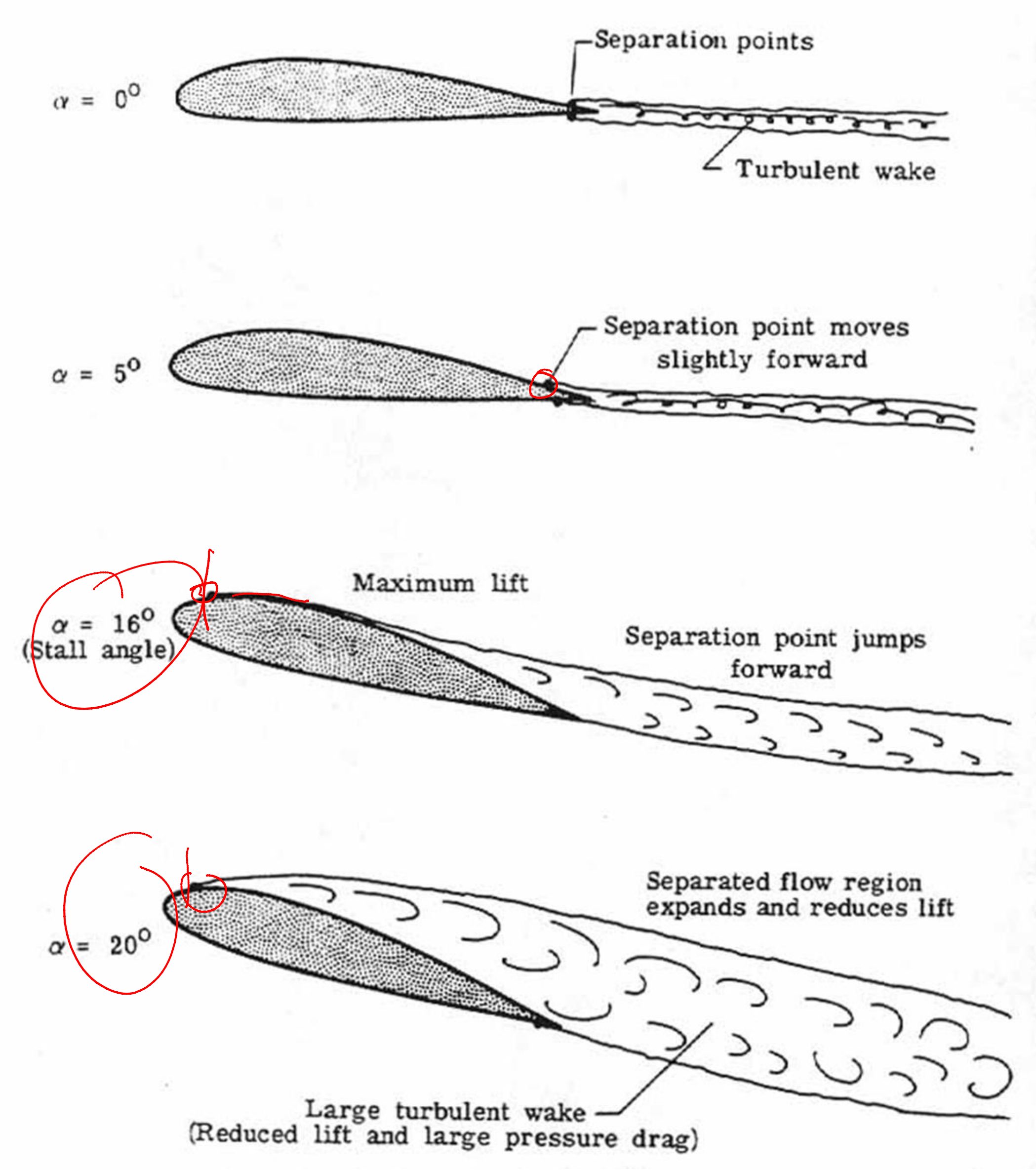
Basic Aerodynamic forces- Lift and Drag



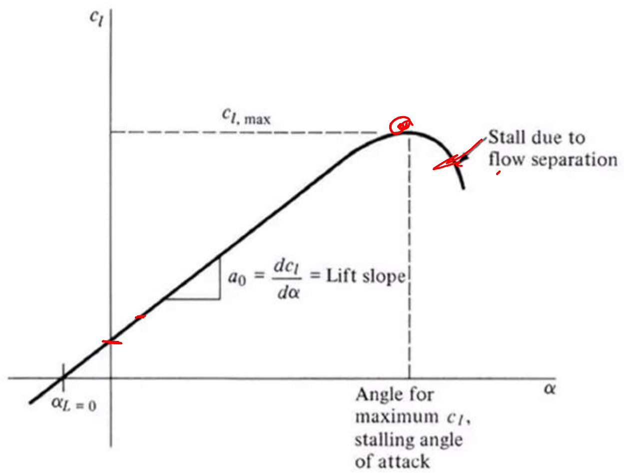
Aerodynamic Forces on Airfoils



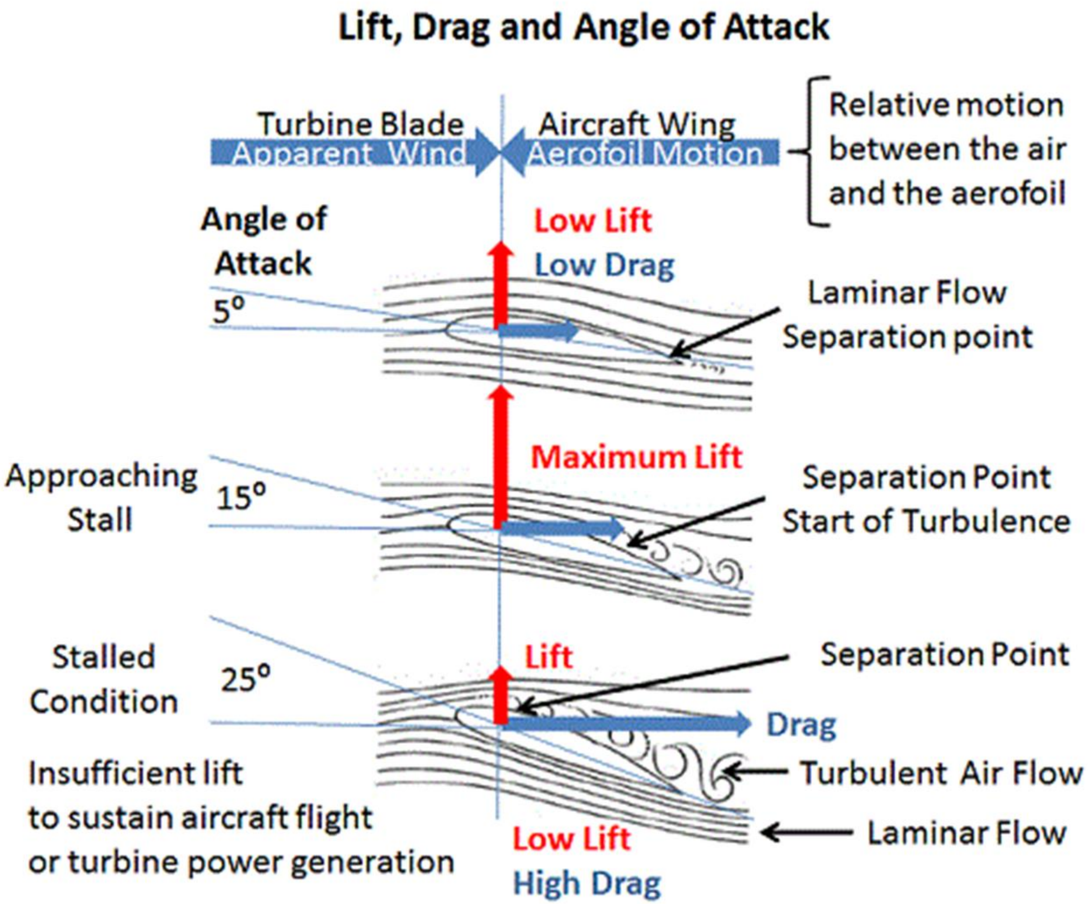
Basic Aerodynamic forces- Lift and Drag

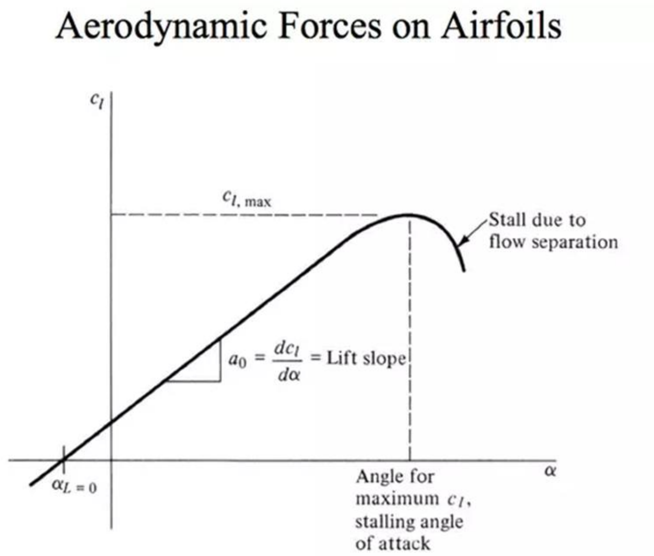


Aerodynamic Forces on Airfoils

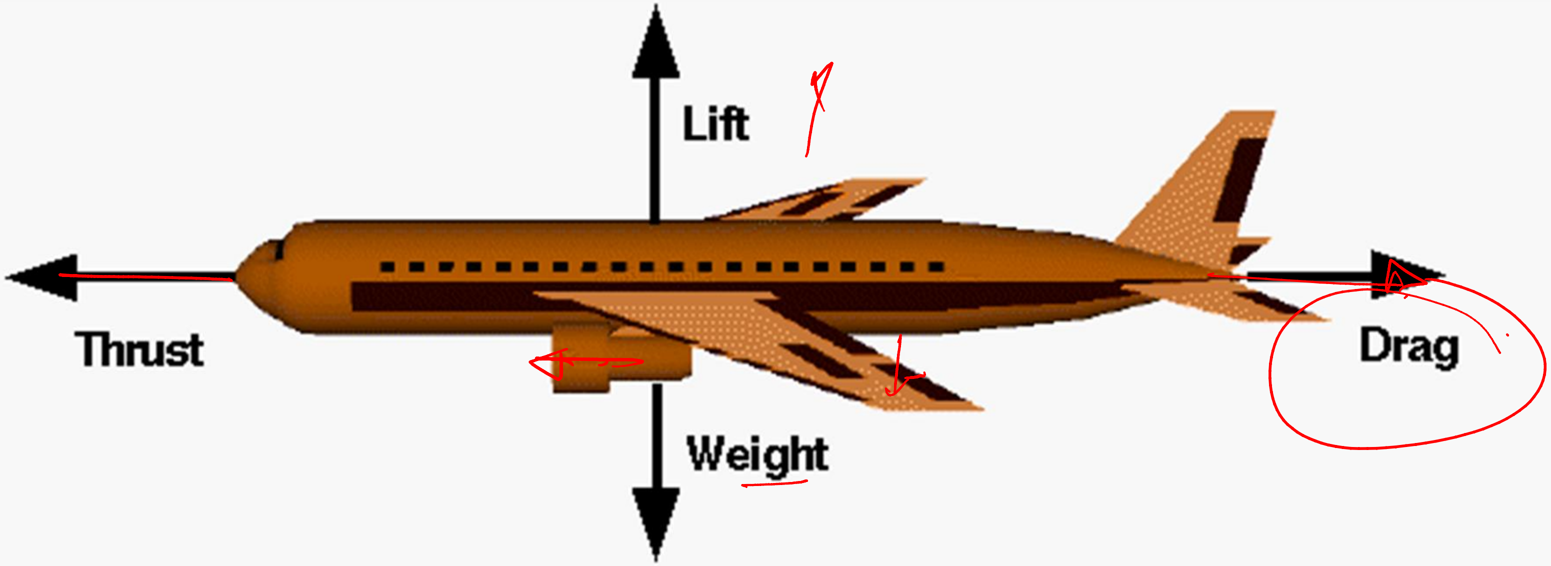


Basic Aerodynamic forces- Lift and Drag





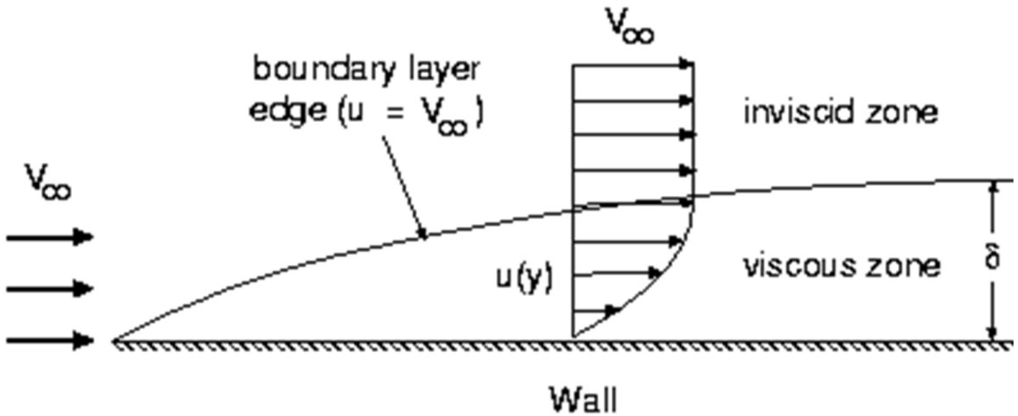
Introduction to Aerodynamics- Airofil Aerodynamics



Flight Condition	Effect
Lift > Weight	Plane Rises
Weight > Lift	Plane Falls
Drag > Thrust	Plane Slows
Thrust > Drag	Plane Accelerates

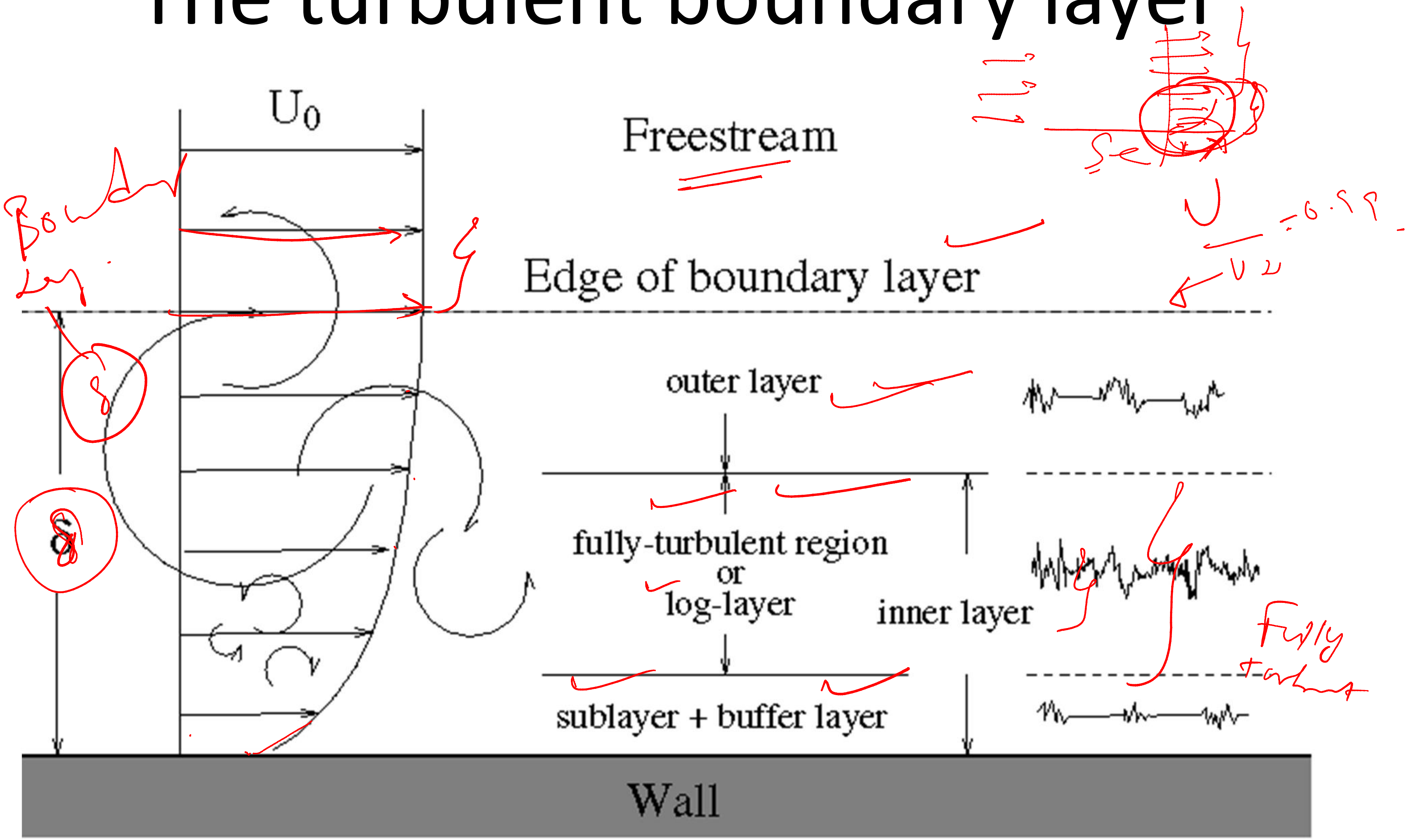
The turbulent boundary layer

- In turbulent flow, the boundary layer is defined as the thin region on the surface of a body in which viscous effects are important.
- The boundary layer allows the fluid to transition from the free stream velocity U_τ to a velocity of zero at the wall.
- The velocity component normal to the surface is much smaller than the velocity parallel to the surface: v << u.
- The gradients of the flow across the layer are much greater than the gradients in the flow direction.
- The boundary layer thickness δ is defined as the distance away from the surface where the velocity reaches 99% of the free-stream velocity.



$$\delta = y, \; where \; {}^{u}\!/_{U} = 0.99$$

The turbulent boundary layer

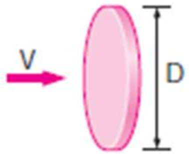


Representative drag coefficients C_D for various three-dimensional bodies for $Re > 10^4$ based on the frontal area (for use in the drag force relation $F_D = C_D A \rho V^2/2$ where V is the upstream velocity)

Cube, $A = D^2$

$C_D = 1.05$

Thin circular disk, $A = \pi D^2/4$



$C_D = 1.1$

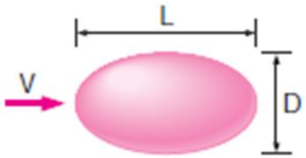
Cone (for $\theta = 30°$), $A = \pi D^2/4$

$C_D = 0.5$

Sphere, $A = \pi D^2/4$

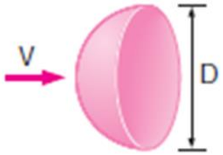
Laminar:
$C_D = 0.5$
Turbulent:
$C_D = 0.2$

Ellipsoid, $A = \pi D^2/4$

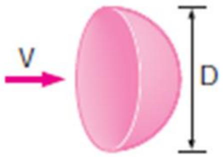


	C_D	
L/D	Laminar	Turbulent
0.75	0.5	0.2
1	0.5	0.2
2	0.3	0.1
4	0.3	0.1
8	0.2	0.1

Hemisphere, $A = \pi D^2/4$

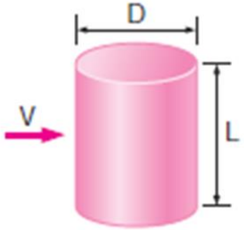


$C_D = 0.4$



$C_D = 1.2$

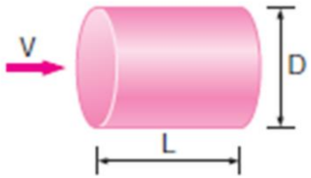
Short cylinder, vertical, $A = LD$



L/D	C_D
1	0.6
2	0.7
5	0.8
10	0.9
40	1.0
∞	1.2

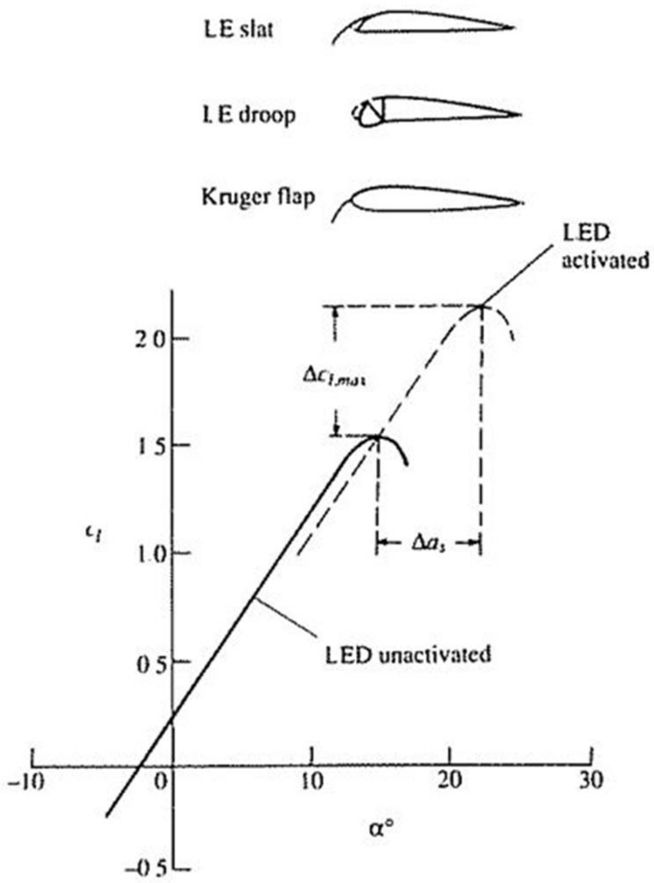
Values are for laminar flow

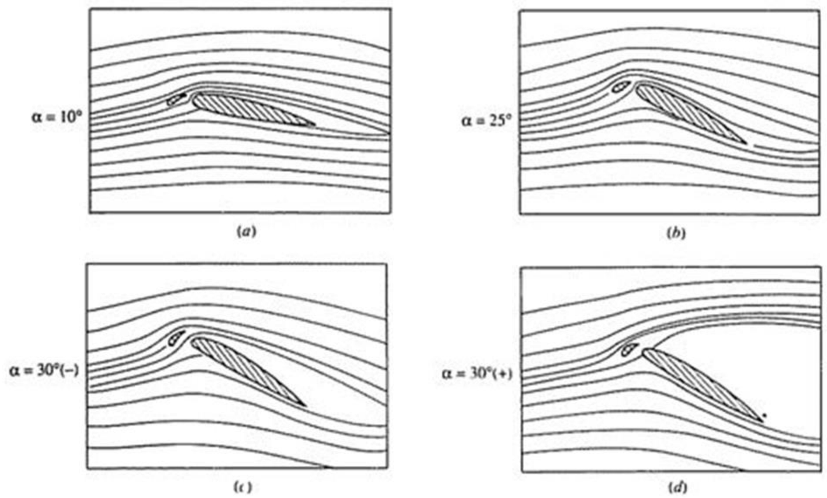
Short cylinder, horizontal, $A = \pi D^2/4$



L/D	C_D
0.5	1.1
1	0.9
2	0.9
4	0.9
8	1.0

HIGH LIFT DEVICES: SLATS





- Allows for a secondary flow between gap between slat and airfoil leading edge
- Secondary flow modifies pressure distribution on top surface delaying separation

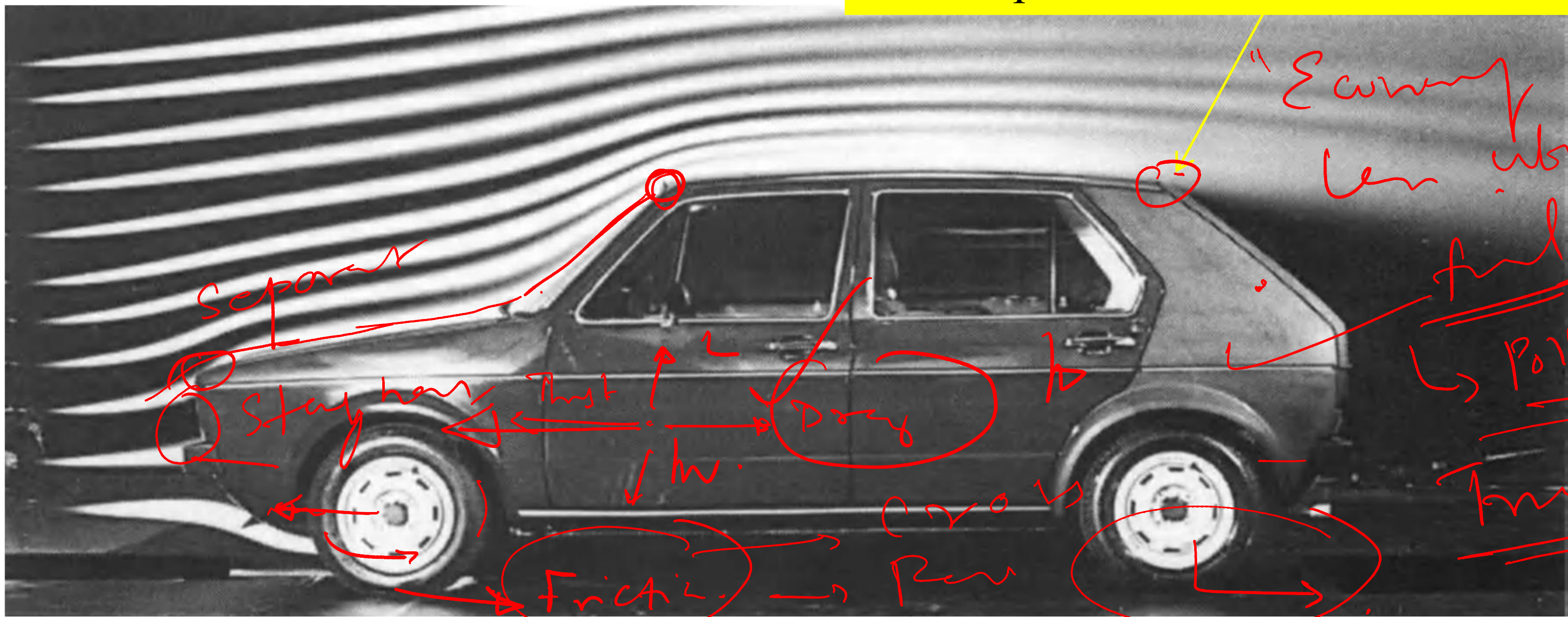
- Slats increase stalling angle of attack, but do not shift the lift curve (same $\alpha_{L=0}$)

External and Internal Flow - Aerodynamics

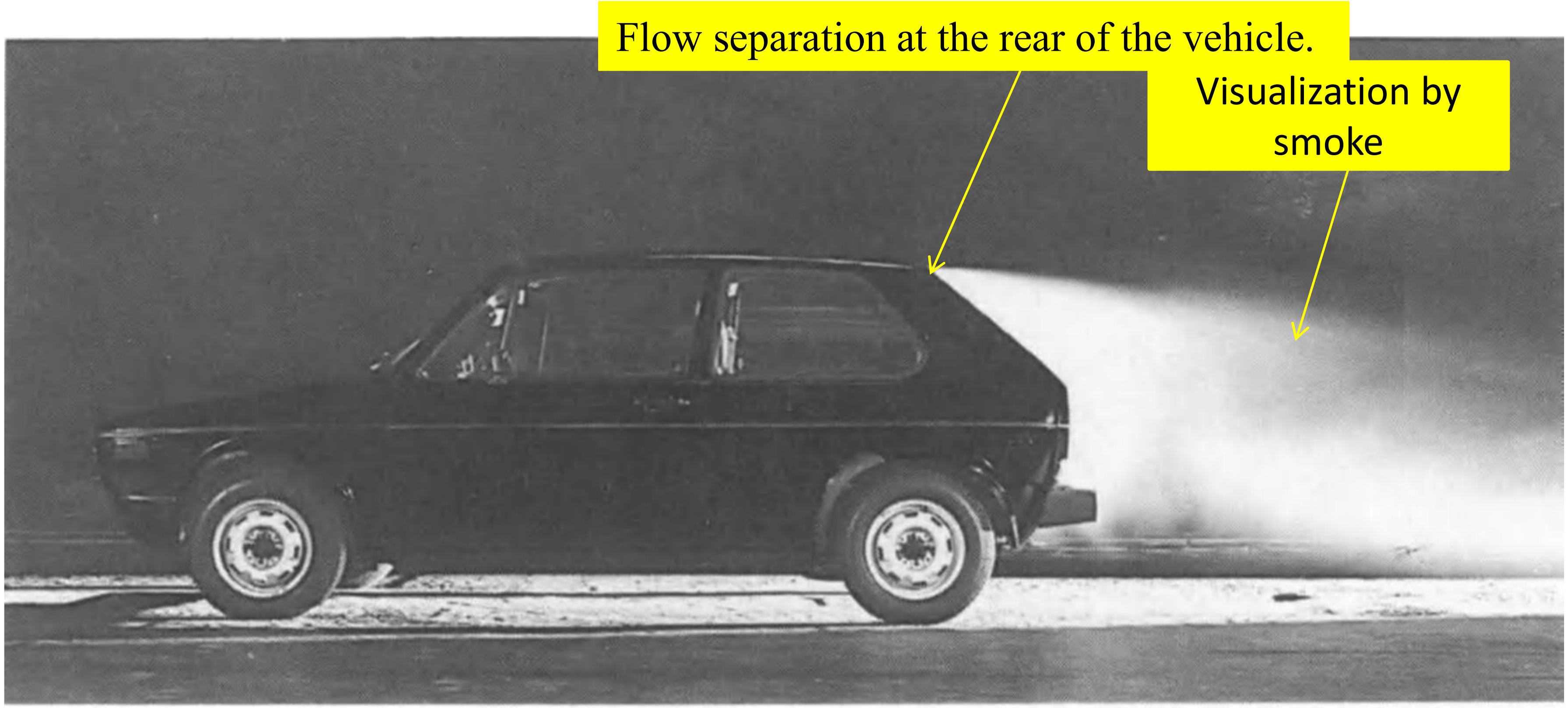
The flow processes to which a moving vehicle is subjected fall into three categories:

- flow of air around the vehicle;
- flow of air through the body;
- flow processes within the machinery.

Flow separation at the rear of the vehicle.



Streamlines in the longitudinal midsection of a VW Golf I (Rabbit), photographed for a full-sized vehicle in the large climatic wind tunnel of the Volkswagen AG.
The lines of smoke were introduced in the plane of the longitudinal centreline to show the flow pattern with symmetrical oncoming flow. This flow state exists only when there is no side wind



Although the streamlines follow the contour of the vehicle over long stretches, even in the area of sharp curves, the air flow separates at the rear edge of the roof, forming a large wake which can be observed by introducing smoke.

AERODYNAMIC DRAG

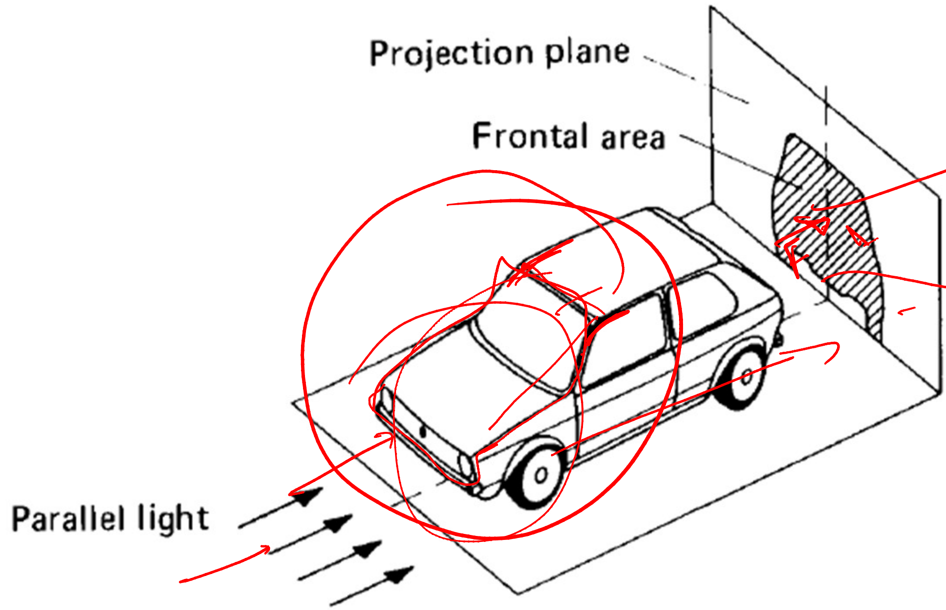


Figure 1.3 Definition of the frontal area A of a vehicle

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

C_D is the non-dimensional drag coefficient
A is the projected frontal area of the vehicle
ρ is the density of the surrounding air.

Related fields/ Application of Aerodynamics – Low speed

- flow around bluff bodies
- flow fields governed by separation
- ground influence and ground boundary layer
- interference between buildings
- wind tunnel testing techniques.

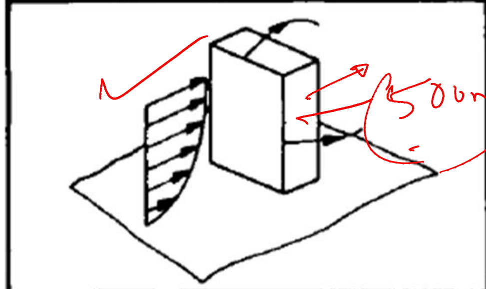
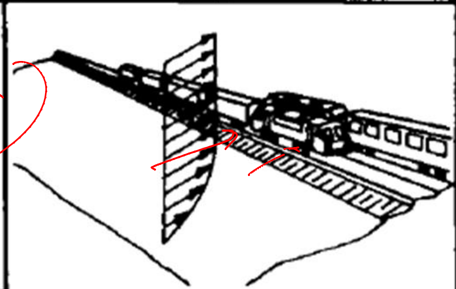
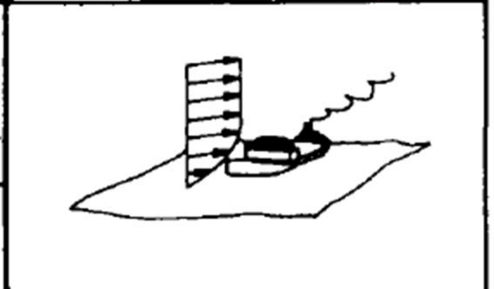
Buildings	Railways	Ships (Superstructure)
		
Total aerodynamic forces Aerodynamic forces on parts Flow field Ventilation	Drag Pressure peaks Cross-wind Flow field Ventilation	Air drag (for gliders and hydro-foil boats) Sideforce Ventilation Stack plume Sail

Figure 1.7 Fields related to automobile aerodynamics

Building Aerodynamics

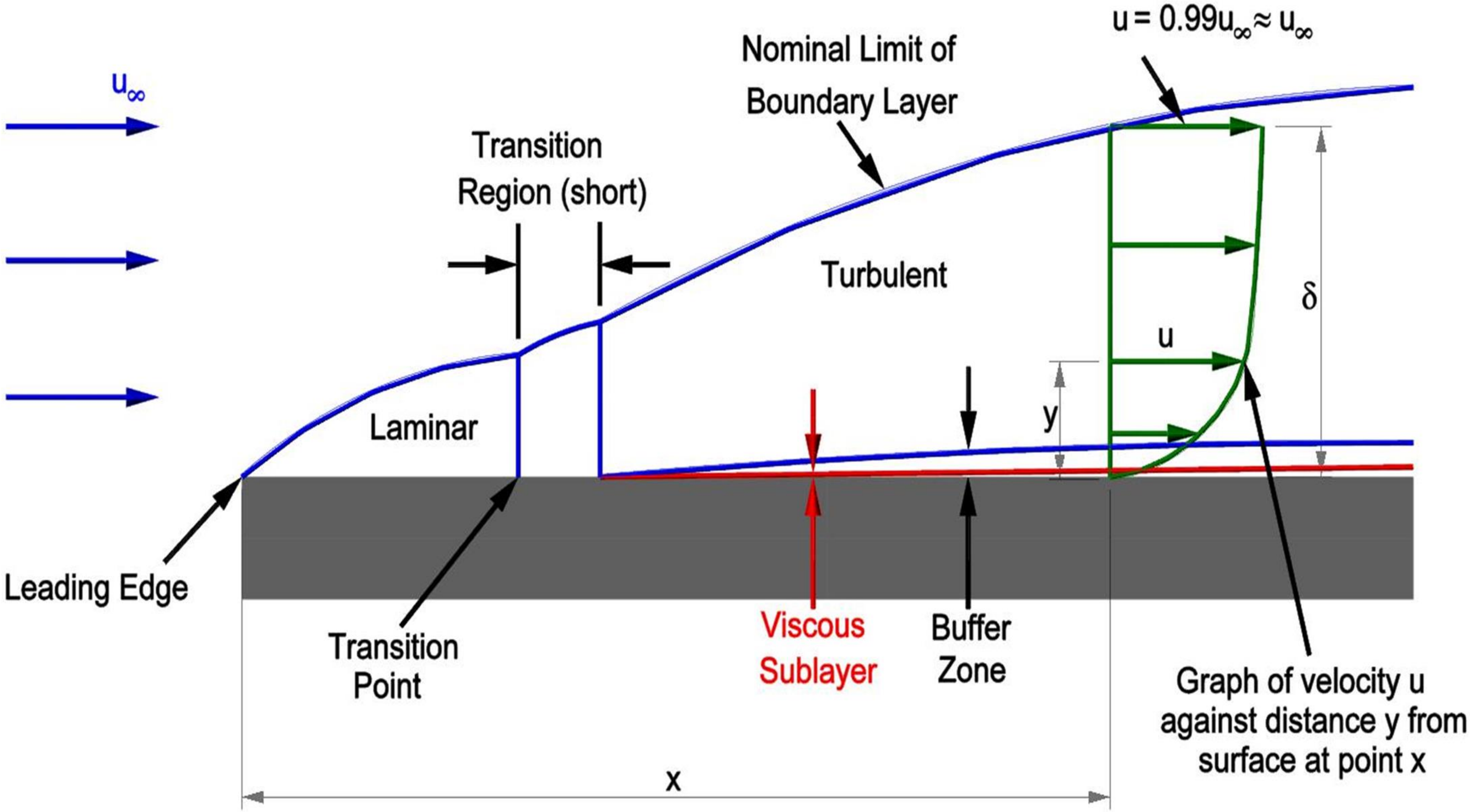
Building aerodynamics addresses a number of similar objectives:

- determination of the effective air forces on the building as a whole
- calculation of the air forces upon parts such as roofs, facades and windows
- influencing the surrounding flow field for protection of pedestrians
- matching of the surrounding flow and the internal flow (climate, chimney draught).

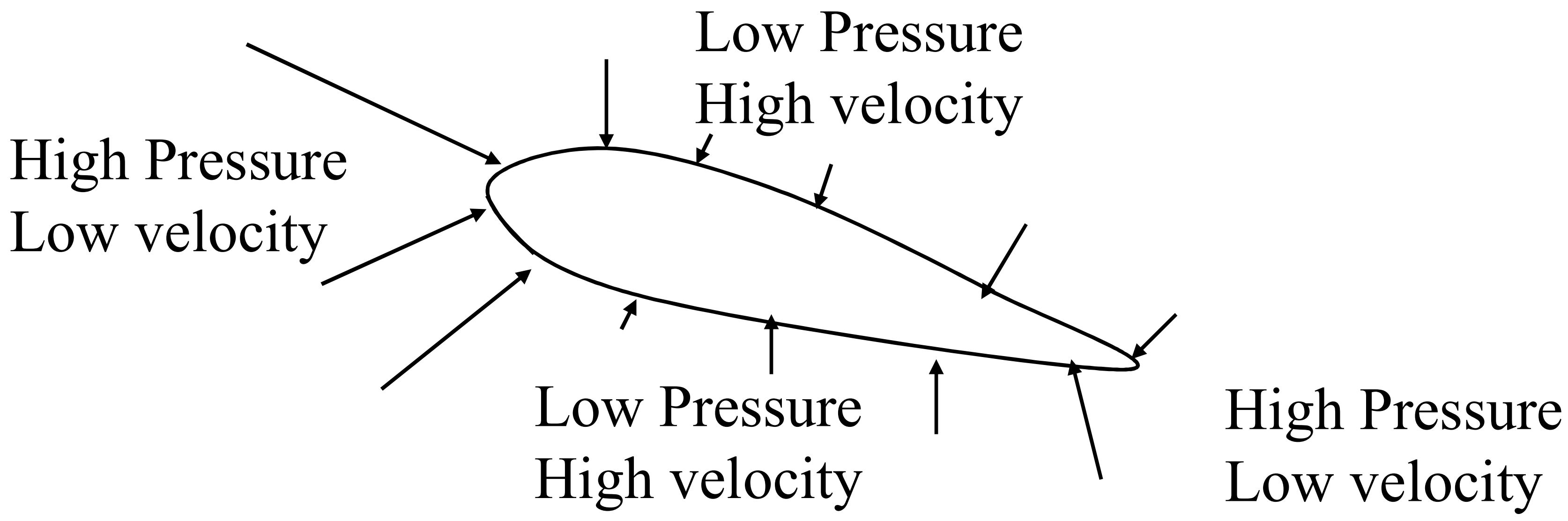
Railway Aerodynamics

- low aerodynamic drag
- reduction of the pressure peaks when trains meet one another, and when driving into a tunnel
- reduction of the influence of side winds
- matching internal and external flow for purposes of cooling and ventilation.

Reynolds No, Boundary Layer Transition and surface roughness

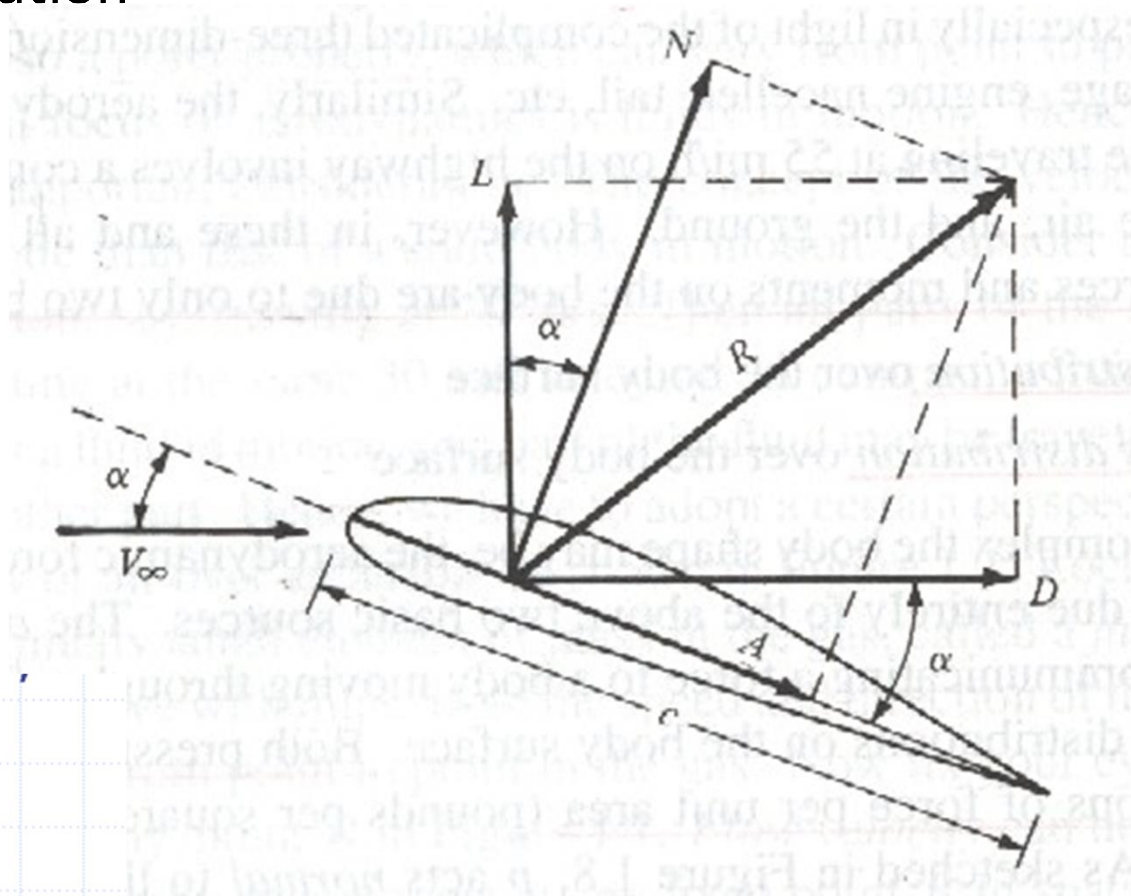


Pressure Forces acting on the Airfoil



Bernoulli's equation says where pressure is high, velocity will be low and vice versa.

- Aerodynamic forces and moments are due to
  - Pressure distribution
  - Shear stress distribution
- Nomenclature
  - R ≡ resultant force
  - L ≡ lift
  - D ≡ drag
  - N ≡ normal force
  - A ≡ Axial force

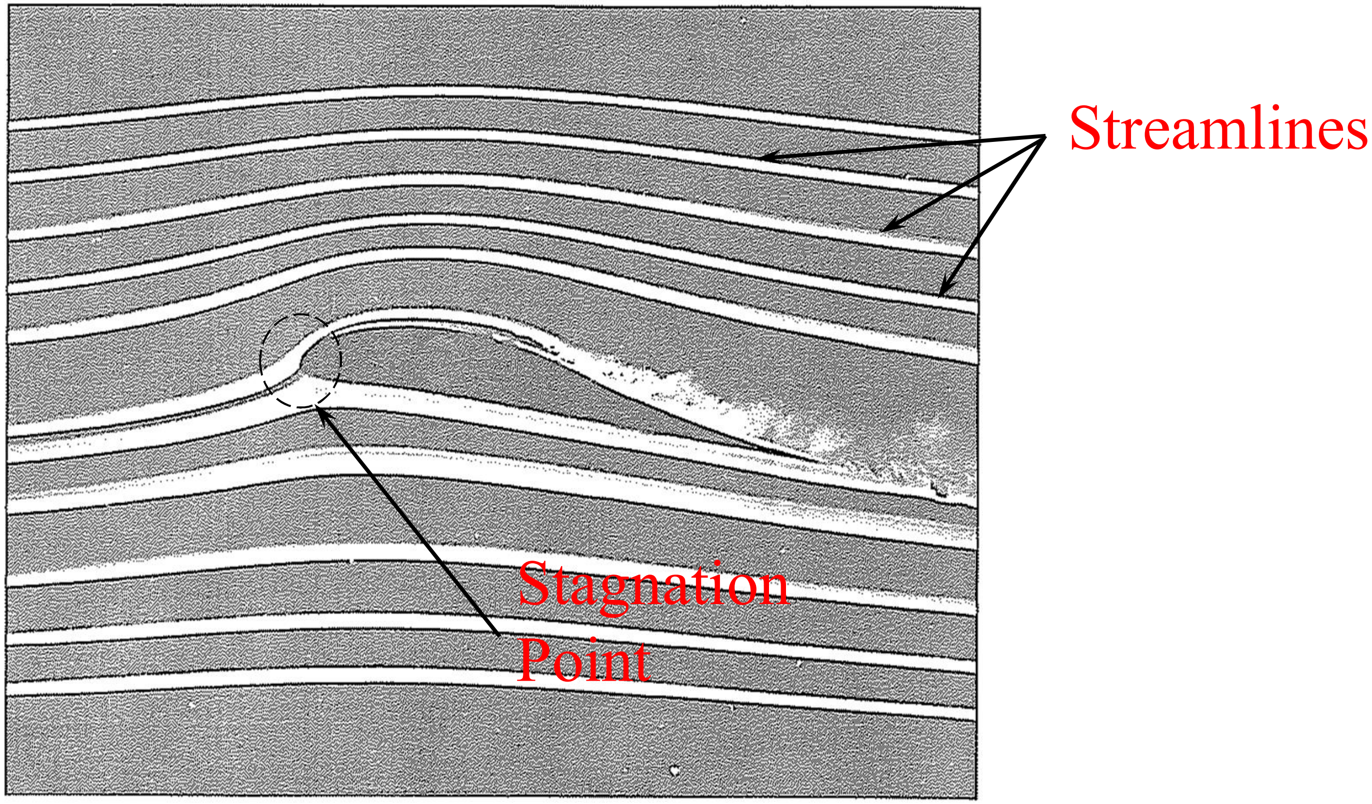


$$L = N\cos\alpha - A\sin\alpha$$

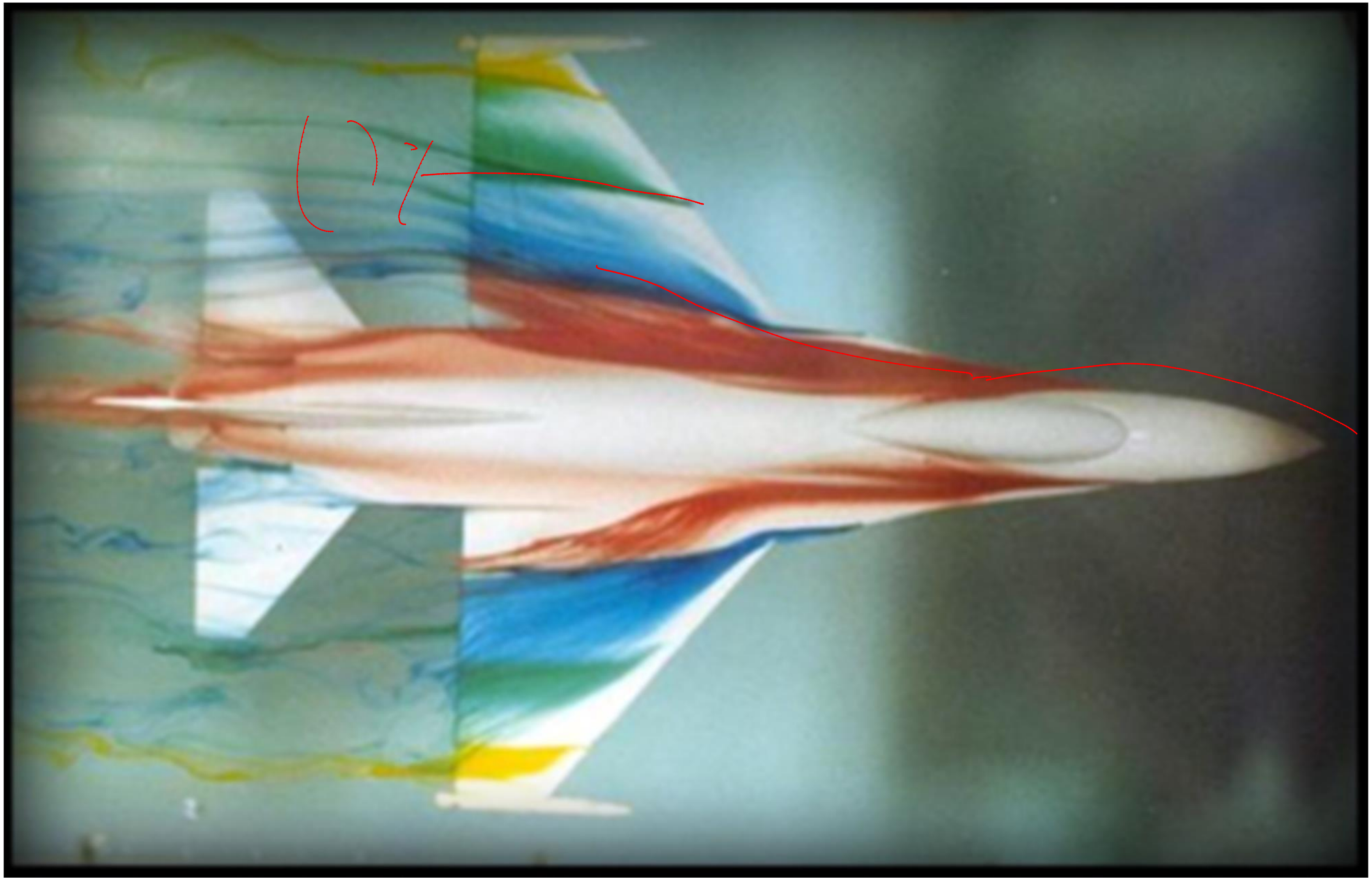
$$D = N\sin\alpha + A\cos\alpha$$

Figure 2.6 Smoke photograph of the low-speed flow over a Lissaman 7769 airfoil at 10° angle of attack. The Reynolds number based on chord is 150,000. This is the airfoil used on the Gossamer Condor human-powered aircraft

(The photograph was taken in one of the Notre Dame University smoke tunnels by Dr. T. J Mueller, Professor of Aerospace Engineering at Notre Dame, and is shown here through his courtesy.)



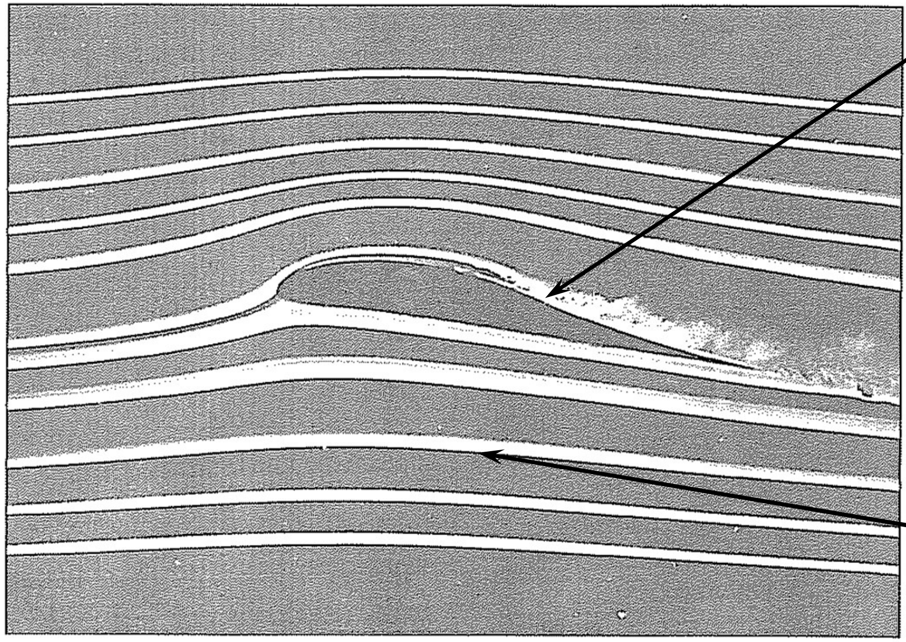
WATER STREAMLINES ON F-16 MODEL



http://www.aerolab.com/water.html

TYPES OF FLOWS: FRICTION VS. NO-FRICTION

- **Viscous**: Flows with friction
  - All real flows are viscous
  - Inviscid flow is a useful idealization
  - By neglecting friction analysis of flow is usually much easier!
- **Inviscid**: Flows with no friction



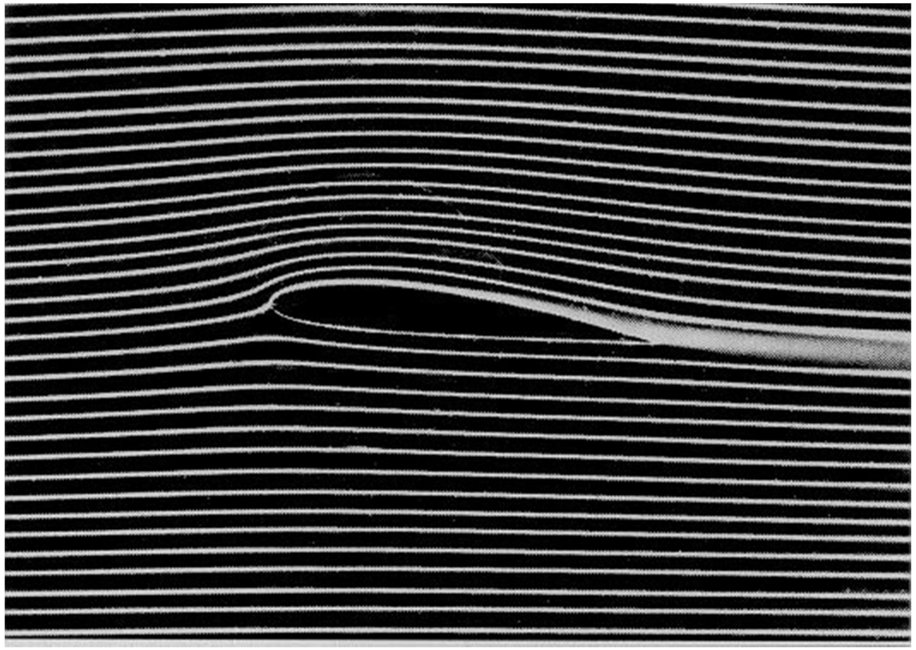
Flow very close to surface of airfoil is Influenced by friction and is viscous (boundary layer flow)

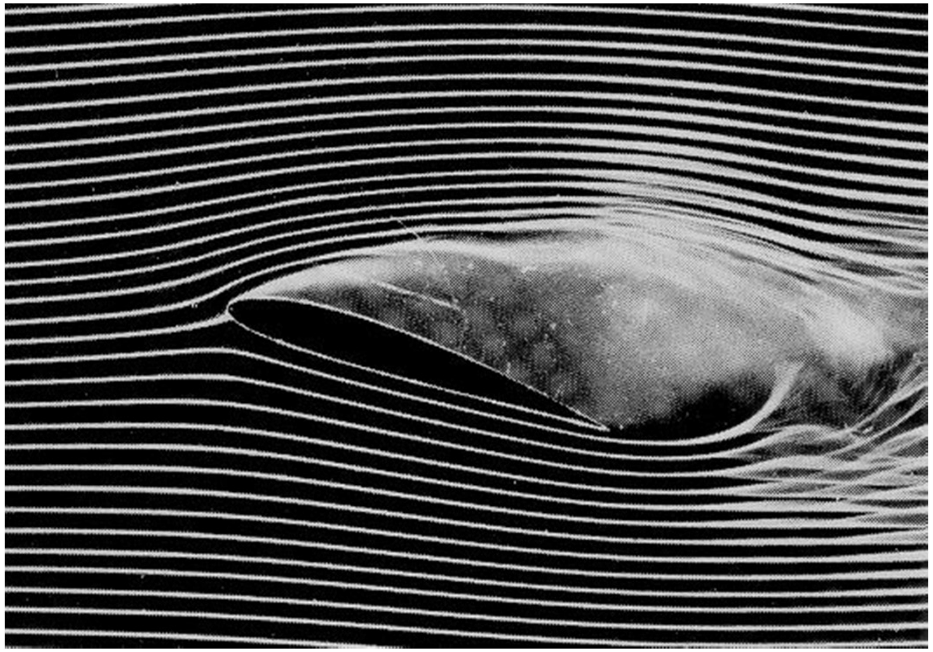
Stall (separation) is a viscous phenomena

Flow away from airfoil is not influenced by friction and is wholly inviscid

FRCTION EXAMPLE: AIRFOIL STALL

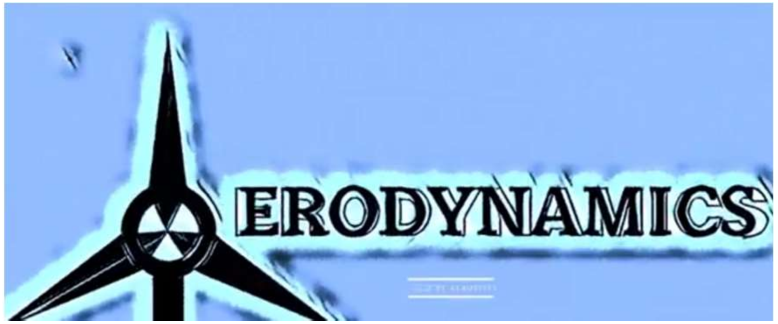
- Key to understanding: Friction causes flow separation within boundary layer
    1. Boundary layers are either **laminar** or **turbulent**
    2. All laminar B.L. → turbulent B.L.
    3. Turbulent B.L. 'fuller or fatter' than laminar B.L., more resistant to separation
- Separation creates another form of drag called pressure drag due to separation
    - Dramatic **loss of lift** and **increase in drag**





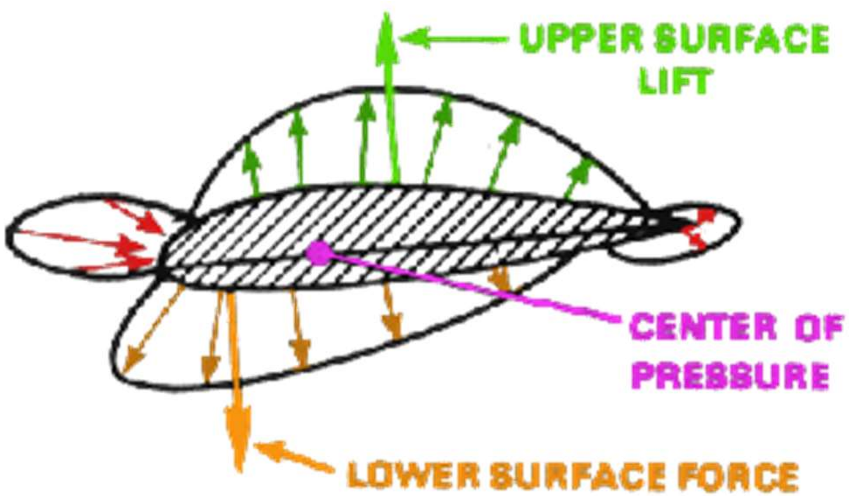
VIT

Vellore Institute of Technology

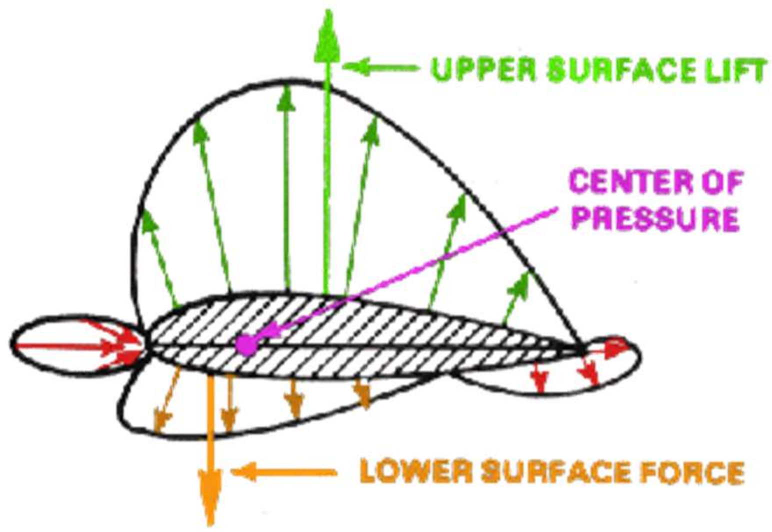


MEE1004-FLUID MECHANICS

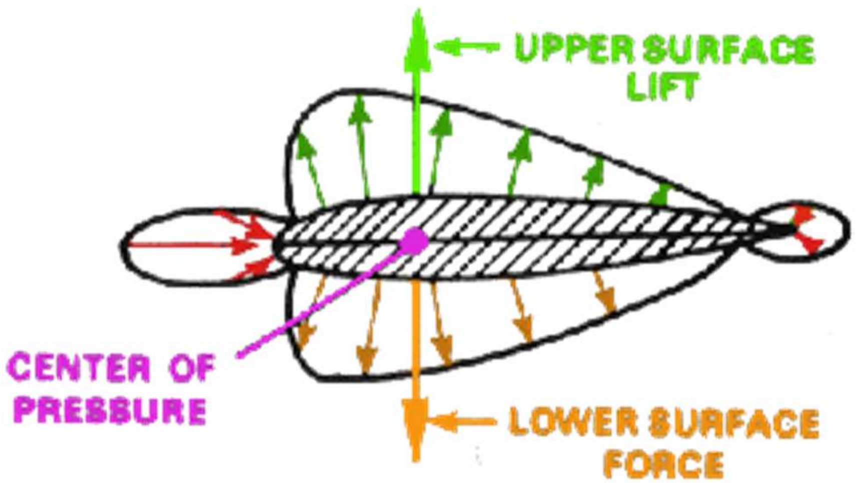
- **Components of Drag**
- **Streamline and Bluff bodies**
- **Drag Coefficient for slender and bluff bodies**
- **Problems**



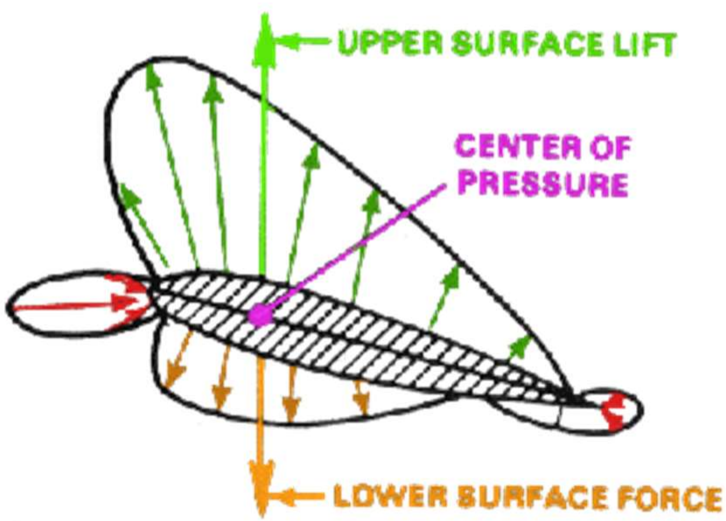
CAMBERED AIRFOIL AT ZERO LIFT



CAMBERED AIRFOIL AT POSITIVE LIFT



SYMMETRICAL AIRFOIL AT ZERO LIFT



SYMMETRICAL AIRFOIL AT POSITIVE LIFT

Potential Flow Theory $\rightarrow$ Drag $= 0$.

Observed experiment (real fluid $\nu << 1$ but $\neq 0$) $\rightarrow$ Drag $\neq 0$.

In particular the **total** drag measured on a body is regarded as the sum of two components: the **pressure** or **form** drag, and the **skin friction** or **viscous** drag.

Total Drag	=	**Pressure Drag**	+	**Skin Friction Drag**
Profile Drag		or Form Drag		or Viscous Drag
		$\underbrace{\text{Drag Force due to Pressure}}_{\iint_S p\hat{n}ds}$		$\underbrace{\text{Drag Force due to Viscous Stresses}}_{\iint_S \tau\hat{t}ds}$

where $\hat{n}$ and $\hat{t}$ are the normal and tangential unit vectors on the body surface respectively. The pressure and the viscous stresses on the body surface are p and τ respectively.

The form drag is evaluated by integrating the pressure along the surface of the body. For bluff bodies that create large wakes the form drag is $\sim$ total drag.

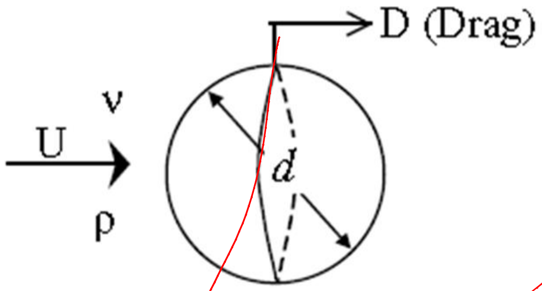
The skin friction drag is evaluated by integrating the viscous stresses on and along the body boundary. For streamlined bodies that do not create appreciable wakes, friction drag is dominant.

4.1.1 Form Drag on a Bluff Body

Consider a sphere of diameter d.

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

$C_D = C_D(R_e)$



If no DBC apply then we have seen from Dimensional Analysis that the **drag coefficient** is a function of the Reynolds number only:

$$C_D = C_D(R_e)$$

The drag coefficient C_D is defined with respect to the body's projected area S:

$$C_D = \frac{D}{\frac{1}{2}\rho U^2 S} = \frac{D}{\frac{1}{2}\rho U^2 \underbrace{\pi d^2/4}_{\text{Projected area}}}$$

The Reynolds number R_e is defined with respect to the body's diameter d:

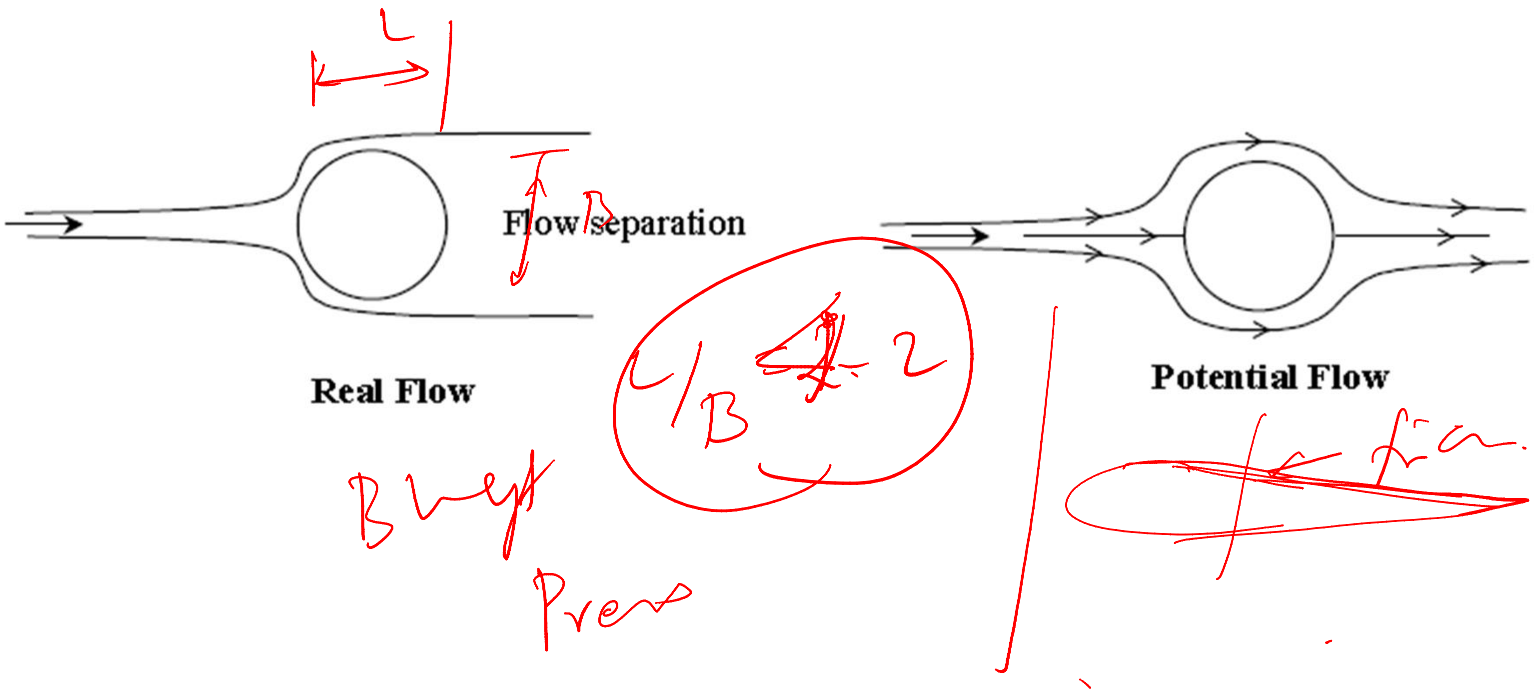
$$R_e = \frac{Ud}{\nu}$$

The following graph shows the dependence of C_D on R_e as measured from numerous experiments on spheres.

i) Bluff Body $\rightarrow$ Form Drag

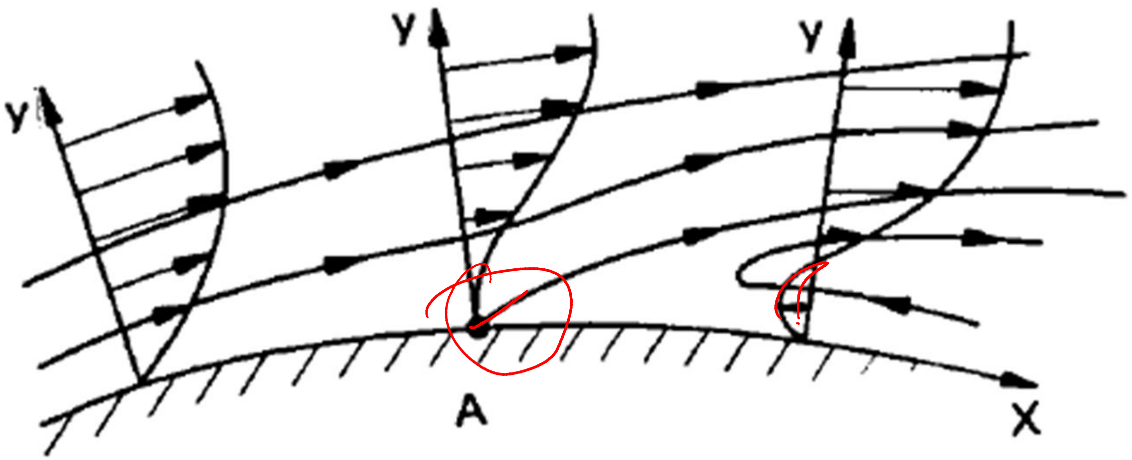
For a bluff body (examples: sphere, cylinder, flat plate, etc.) there is appreciable flow separation and a wake is formed downstream of the body. The pressure within the wake is significantly smaller than that upstream of the body. Therefore the integral of the pressure along the body boundary (= form drag) does not evaluate to zero as predicted by P-Flow.

In general, for bluff bodies $\boxed{\text{form drag} >> \text{friction drag}}$



FLOW SEPERATION

- Turbulent boundary layers can withstand much steeper pressure gradients without separation than can laminar boundary layers. This is because the turbulent mixing process leads to an intensive momentum transport from the outer flow towards the wall.
- For a pressure decrease in the flow direction there exists no tendency to flow separation.



$$\left(\frac{du}{dy}\right)_w = 0$$

Figure 2.7 Separation of the boundary layer flow at a wall (schematic)

Friction drag

If a velocity gradient du/dy is present in a viscous fluid at the wall, due to molecular friction a shear stress τ_w acts everywhere on the surface of a

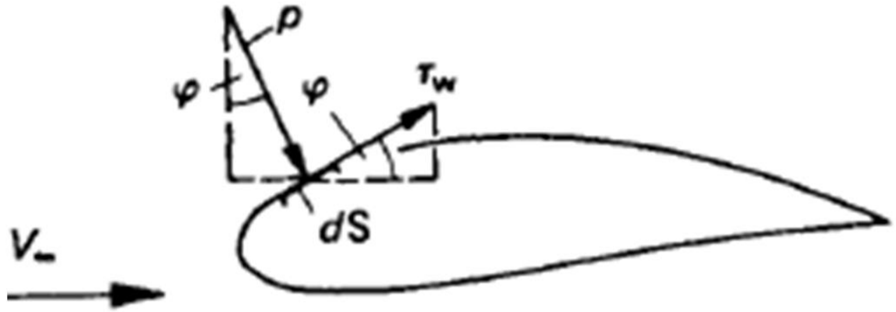


Figure 2.8 Determination of the drag of a body (example of two-dimensional flow)

body as indicated in Fig. 2.8. The integration of the corresponding force components in the free-stream direction according to

$$D_f = \oint \tau_w \cos\varphi \, dS \qquad (2.19)$$

In the absence of flow separation, this is the main contribution to the total drag of a body in two-dimensional viscous flow.

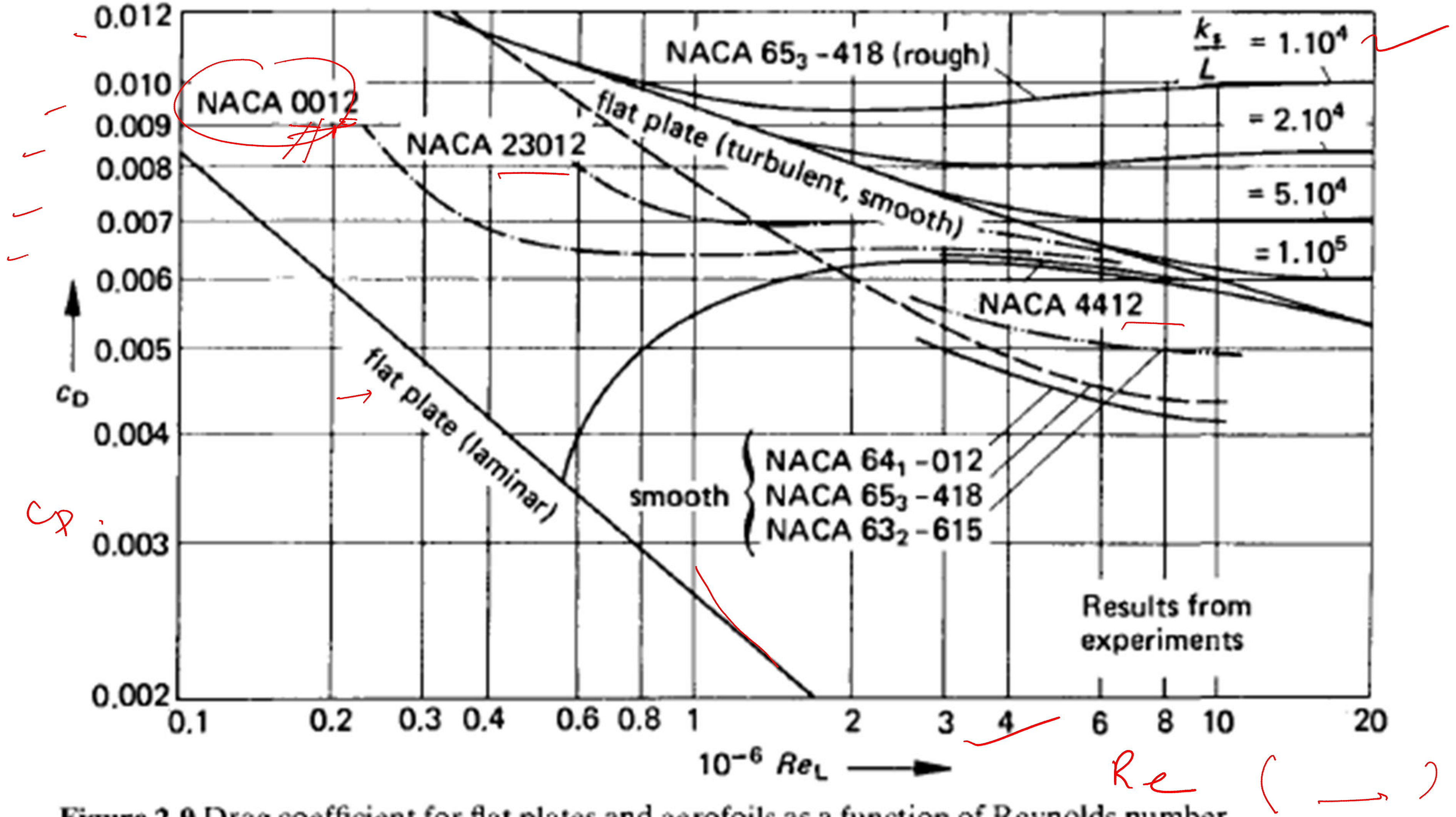


Figure 2.9 Drag coefficient for flat plates and aerofoils as a function of Reynolds number, from Schlichting[2.1]

Results for flat plates are discussed first. For laminar boundary layers, the resistance law is

$$c_{\mathrm{D}} = \frac{2.656}{\sqrt{(Re_l)}} \quad (\text{for } Re_l < 5 \times 10^5) \tag{2.21}$$

and for turbulent boundary layers over the whole length l of the plate and medium Reynolds numbers, the corresponding law is

$$c_{\mathrm{D}} = \frac{0.148}{\sqrt[5]{(Re_l)}} \quad (\text{for } 5 \times 10^5 < Re_l < 10^7) \tag{2.22}$$

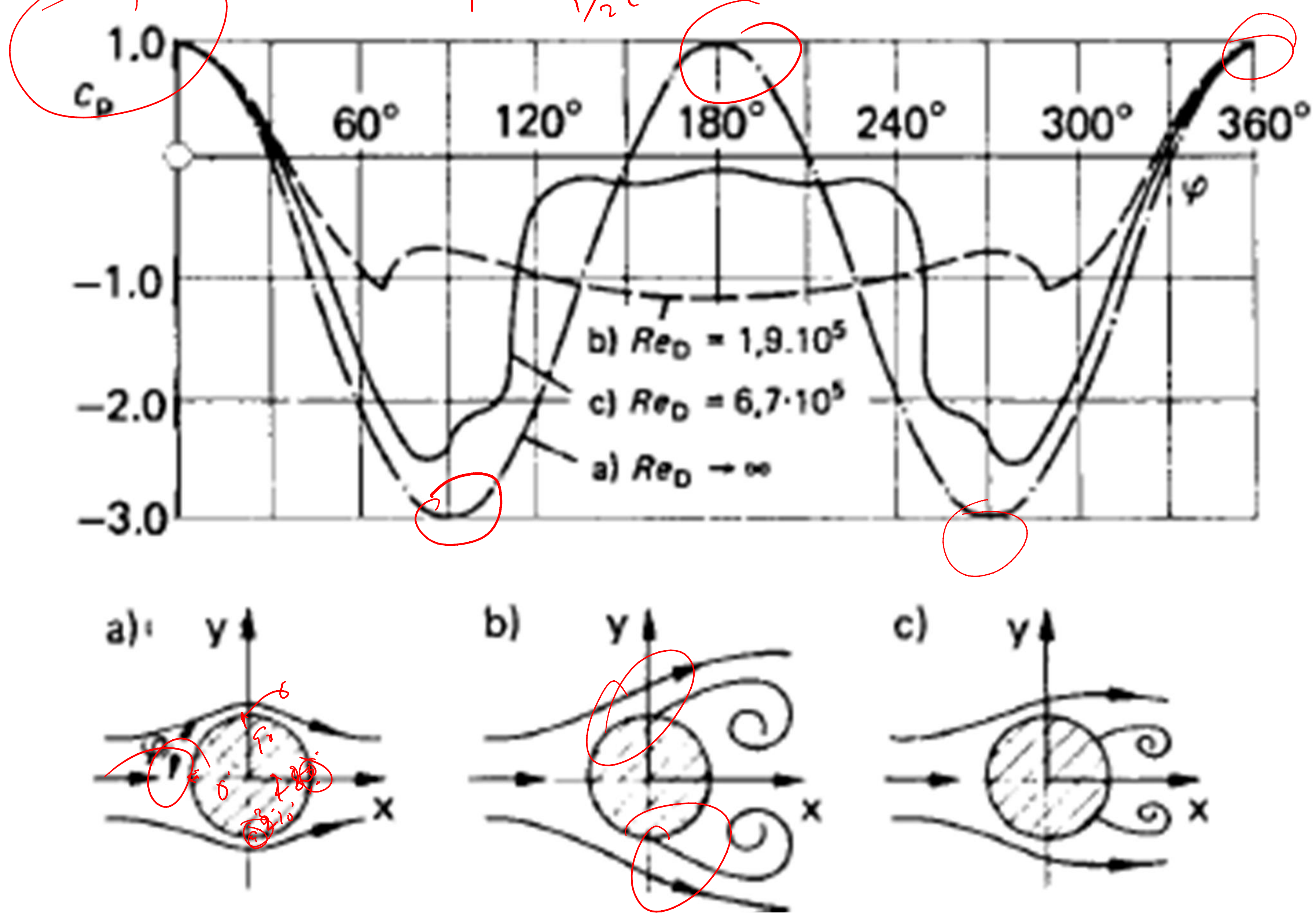
For even larger Reynolds numbers, an asymptotic law holds:

$$c_{\mathrm{D}} = \frac{0.91}{(\log Re_l)^{2.58}} \quad (\text{for } Re_l > 10^7) \tag{2.23}$$

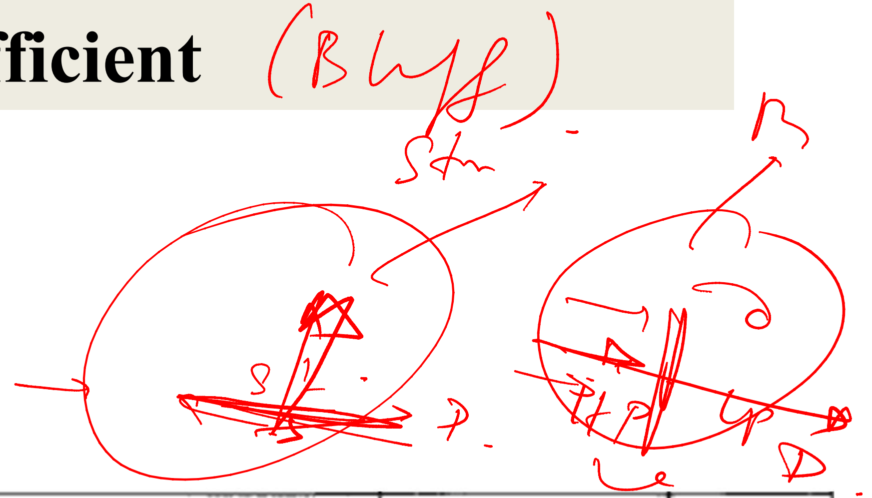
Pressure drag

- Blunt bodies, such as a circular cylinder, a sphere or a flat plate normal to the flow, show quite different drag characteristics.
- On the rear part of such bodies in the inviscid external flow, extremely steep pressure gradients occur which lead to flow separation.
- The pressure distribution is therefore asymmetrical with respect to the y-axis. Integrating the force components in the free stream direction, resulting from the pressure distribution,

$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho v^2}$



Drag Co-efficient



Body	Flow situation	$c_{D,c}$
Circular plate		1.17
Sphere		0.47*
Half-sphere		0.42*
60°-cone		0.50
Cube		1.05*
Cube		0.80*
Circular cylinder $l/D > 2$		0.82
Circular cylinder $l/D > 1$		1.15
Streamlined body $l/D = 2.5$		0.04
Circular half-plate at a ground plane		1.19
Streamlined half-body at a ground plane		0.09

Table 2.1 Drag coefficients for different bodies ($c_{D,C} = D/q_\infty S_c$, see Eqn 2.6, *subcritical flow), after Hoerner[2.9]

The drag coefficient of a car at the design conditions of 1 atm, 25°C, and 90 km/h is to be determined experimentally in a large wind tunnel in a full-scale test. The height and width of the car are 1.40 m and 1.65 m, respectively. If the horizontal force acting on the car is measured to be 300 N, determine the total drag coefficient of this car.

The density of air at 1 atm and 25°C is $\rho = 1.164 \text{ kg/m}^3$.

The drag force acting on a body is given by $F_D = C_D A \frac{\rho V^2}{2}$

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

The drag coefficient is given by $C_D = \frac{2F_D}{A\rho V^2}$

$\rho = 1.164 \text{ kg/m}^3$

Note A is the frontal area $A = 1.40 \times 1.65 m^2$

and $1 m/s = 3.6 km/h$. Then

$A = 1.4 * 1.65 =$

$V = 90 \text{ km/hr} = \frac{90 \times 1000}{3600}$

$$C_D = \frac{2F_D}{A\rho V^2} = \frac{2 \times 350}{(1.40 \times 1.65) \times 1.164 \times (90/3.6)^2} = 0.42$$

5 m

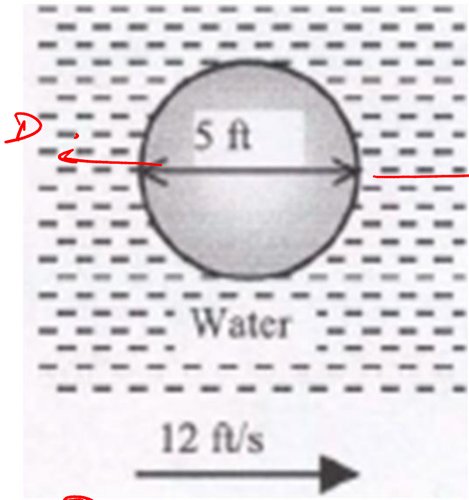
A 5-ft-diameter spherical tank completely submerged in freshwater is being towed by a ship at 12 ft/s. Assuming turbulent flow, determine the required towing power. m/s

The density of water: 62.4 lbm/ft^3.

Drag coefficient for a sphere:

$C_D = 0.2$ for turbulent flow

$C_D = 0.5$ for laminar flow



The frontal area of a sphere is $A = \dfrac{\pi D^2}{4}$

Then the drag force acting on the spherical tank is

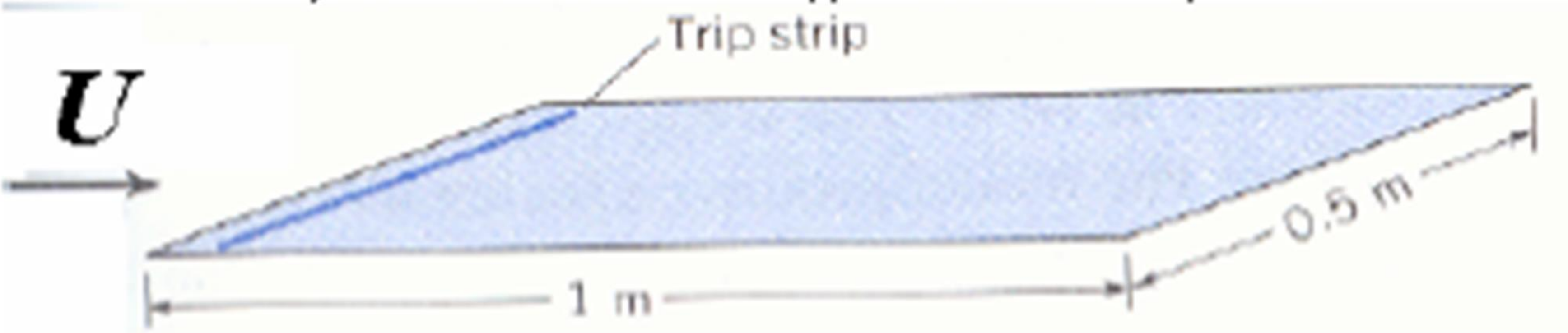
$$F_D = C_D A \frac{\rho V^2}{2} = (0.2)\left(\frac{\pi \times 5^2}{4}\right)\left(\frac{62.4 \times 12^2}{2}\right)\left(\frac{1\,lbf}{32.2\,lbm \cdot ft/s^2}\right) = 548\,lbf$$

$P_W = D \times V$

Note the power is force times velocity, so the power needed to overcome this drag during towing is

$$\dot{W}_{Towing} = \dot{W}_{Drag} = F_D V = (548)(12)\left(\frac{1\,kW}{737.56\,lbf \cdot ft/s}\right) = 8.92\,kW = 12.0\,hp$$

A flat plate is oriented parallel to a $15 m/s$ air flow at $20°C$ and atmospheric pressure. The plate is $1.0 m$ long in the flow direction and $0.5 m$ wide. On one side of the plate, the boundary layer is tripped at leading edge (turbulent flow on that side). Find the total drag force on the plate.



Properties of air at 1 atm and 15 °C:

$$\nu = 1.5\times10^{-5}\ m^2/s \text{ and } \rho = 1.2\ kg/m^3$$

The force due to shear stress is

$$F_D = C_D \frac{1}{2}\rho U^2 BL$$

The Reynolds number based on the plate length is

$$\mathrm{Re}_L = \frac{UL}{\nu} = \frac{15\times 1}{1.5\times 10^{-5}} = 10^6$$

The average shear stress coefficient on the tripped side of the plate is

$$C_D = \frac{0.074}{\left(10^6\right)^{1/5}} = 0.0047$$

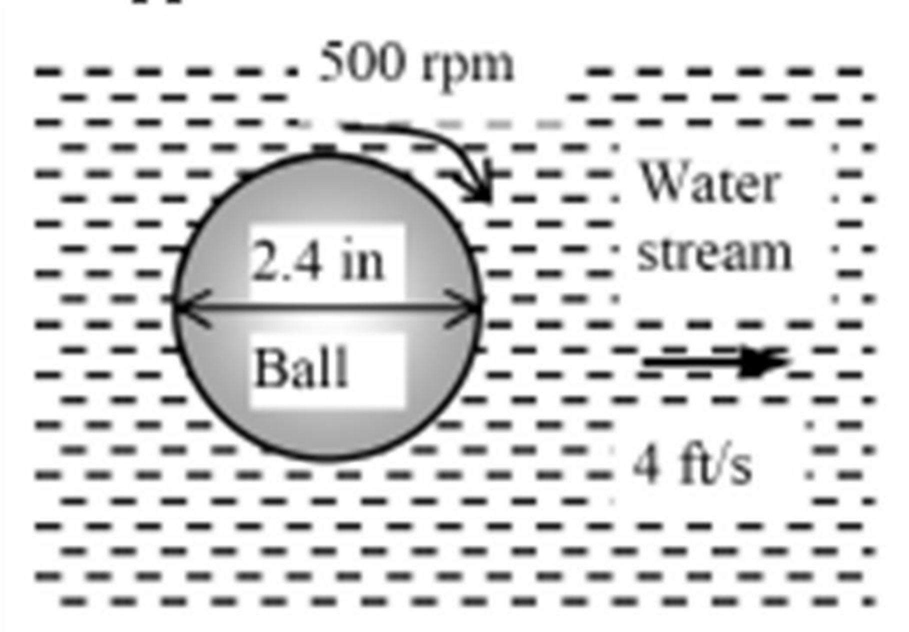
On the untripped side of the plate:

$$C_D = \frac{0.523}{\ln^2\left(0.06\times 10^6\right)} - \frac{1520}{10^6} = 0.0028$$

The totaol force is

$$F_x = (0.0047 + 0.0028)\times\left(\frac{1}{2}\times 1.2\times 15^2\right)\times(1.0\times 0.5) = 0.506N$$

A 2.4-in-diameter smooth ball rotating at 500 rpm is dropped in a water stream at 60°F flowing at 4 ft/s. Determine the lift and the drag force acting on the ball when it is first dropped in the water.



Properties of water at 60°F:

$$\mu = 7.536 \times 10^{-4}\ lbm/ft \cdot s \text{ and } \rho = 62.36\ lbm/ft^3$$

The drag and lift forces can be determined from

$$F_D = C_D A \frac{\rho V^2}{2} \text{ and } F_L = C_L A \frac{\rho V^2}{2}$$

Where $A = \pi D^2/4$ is the frontal area and $D = 2.4/12 = 0.2\,ft$

The Reynolds number and angular velocity of the ball are

$$\mathrm{Re} = \frac{\rho VD}{\mu} = \frac{(62.36)(4)(0.2)}{7.536\times10^{-\cdot}} = 6.62\times10^{\cdot}$$

$$\omega = (500\,rev/min)\left(\frac{2\pi rad}{1rev}\right)\left(\frac{1min}{60s}\right) = 52.4\,rad/s \text{ and}$$

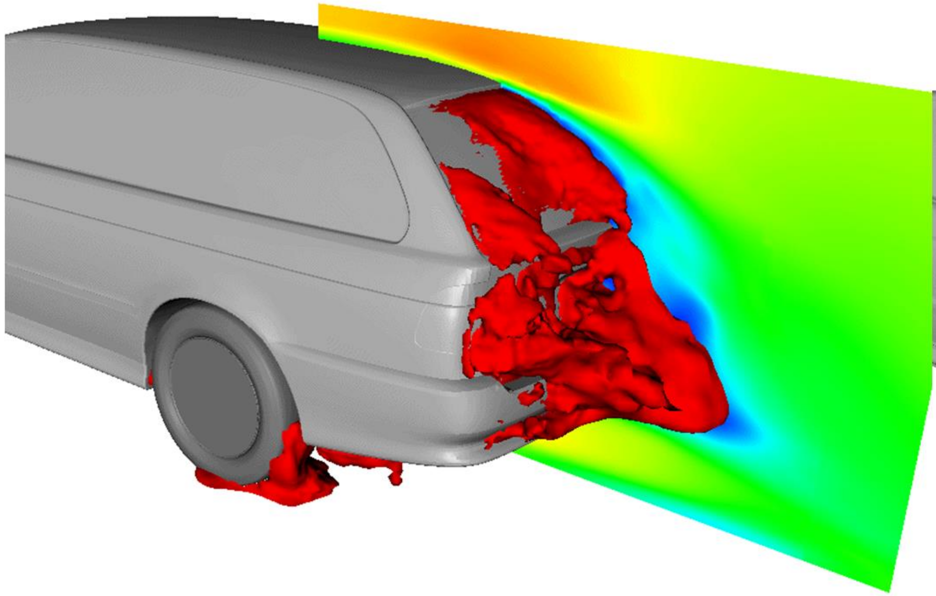
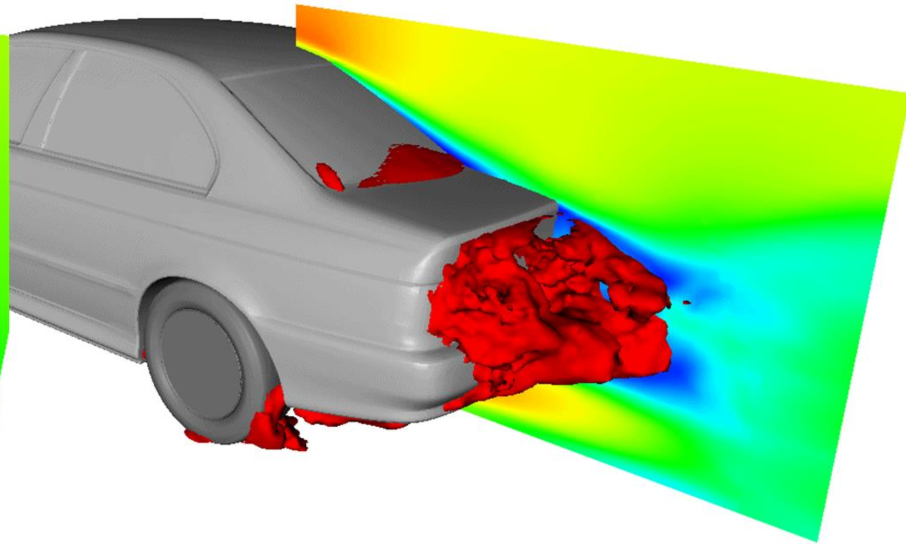
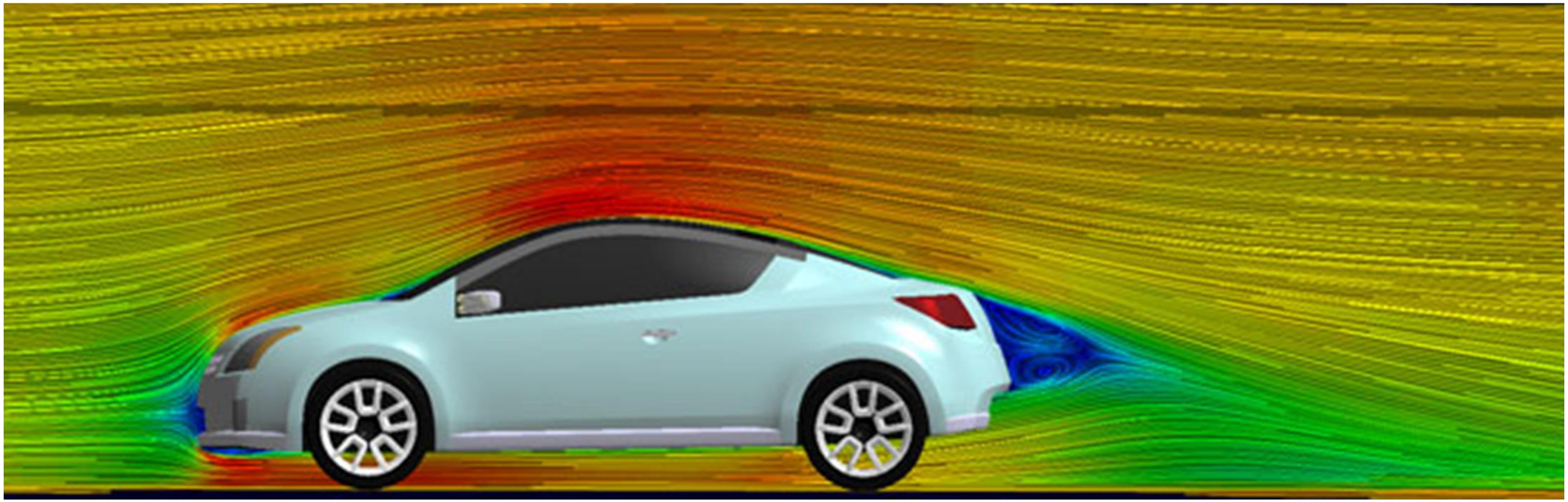
$$\frac{\omega D}{2V} = \frac{(52.4)(0.2)}{2(4)} = 1.31\,rad$$

From Fig. 11-53, $C_D = 0.56$ and $C_L = 0.35$

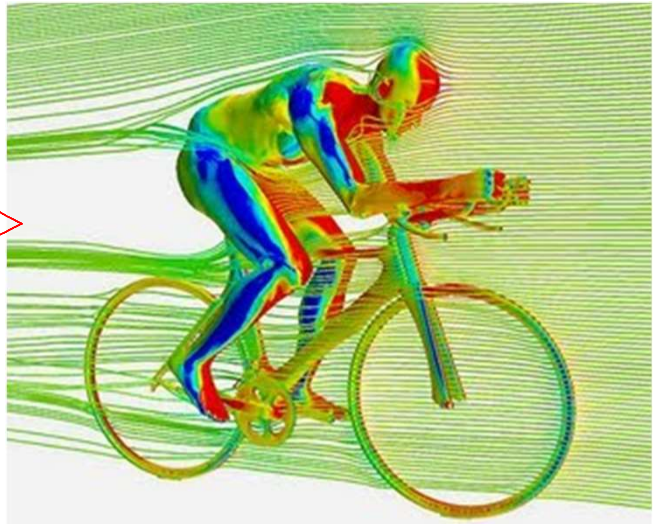
The drag and lift forces are

$$F_D = (0.56)\frac{\pi(0.2\text{ ft})^2}{4}\frac{(62.36\text{ lbm/ft}^3)(4\text{ ft/s})^2}{2}\left(\frac{1\text{ lbf}}{32.2\text{ lbm}\cdot\text{ft/s}^2}\right) = \mathbf{0.27\ lbf}$$

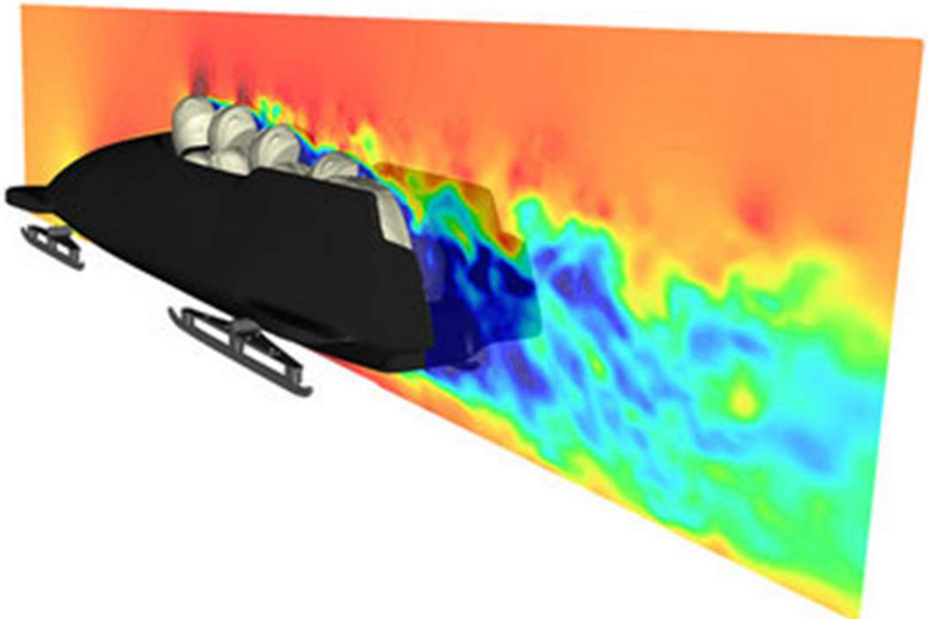
$$F_L = (0.35)\frac{\pi(0.2\text{ ft})^2}{4}\frac{(62.36\text{ lbm/ft}^3)(4\text{ ft/s})^2}{2}\left(\frac{1\text{ lbf}}{32.2\text{ lbm}\cdot\text{ft/s}^2}\right) = \mathbf{0.17\ lbf}$$

CYCLING AERODYNAMICS



BOBSLED AERODYNAMICS



Thank you !