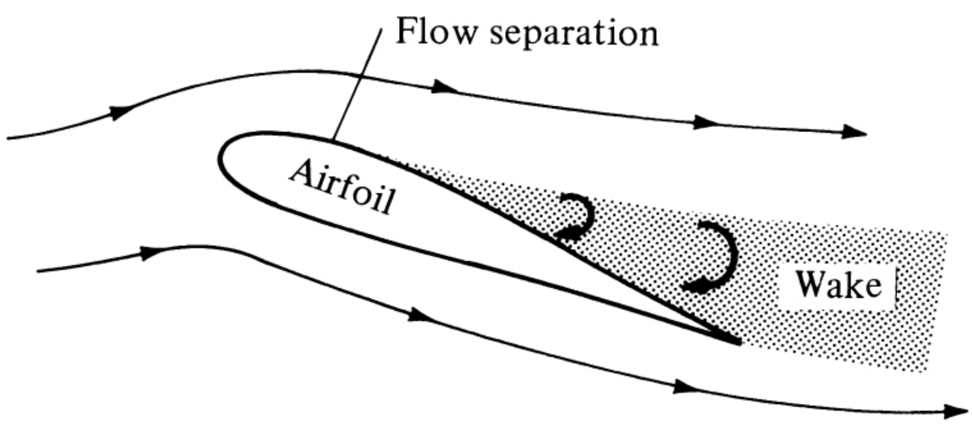
Section 5

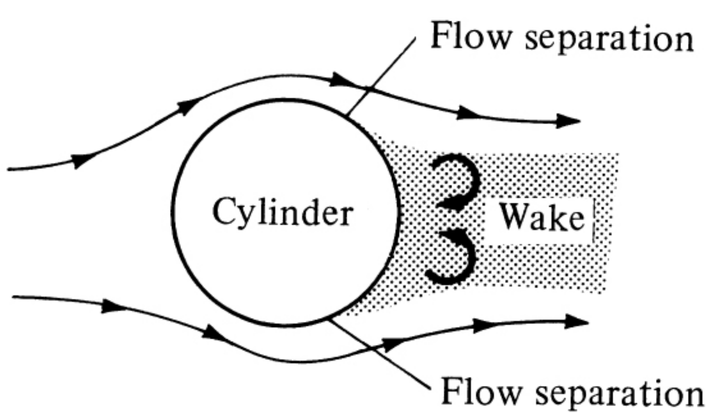
Viscous Flows

<u>Inviscid vs Viscous Flow (A1.10, F4.15)</u>

Figure 4.37 Comparison between ideal frictionless flow and real flow with the effects of friction.

Viscous-Dominated Flows:





Airfoils:

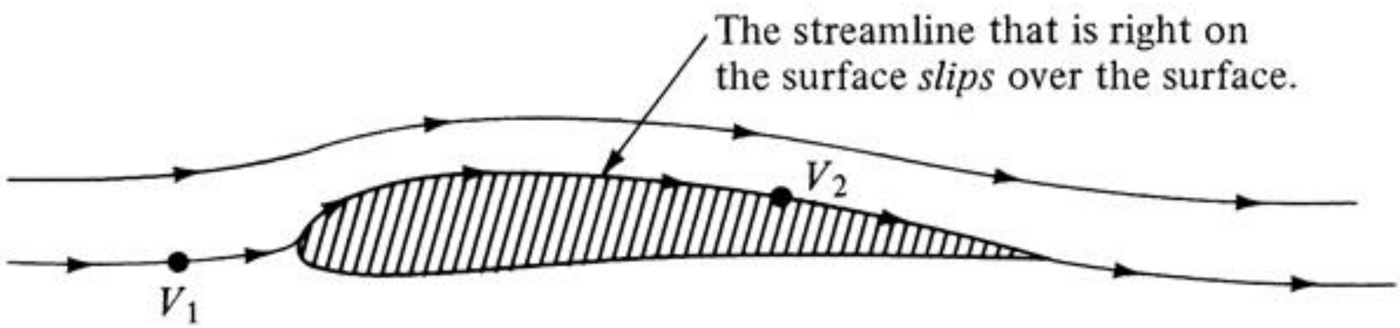
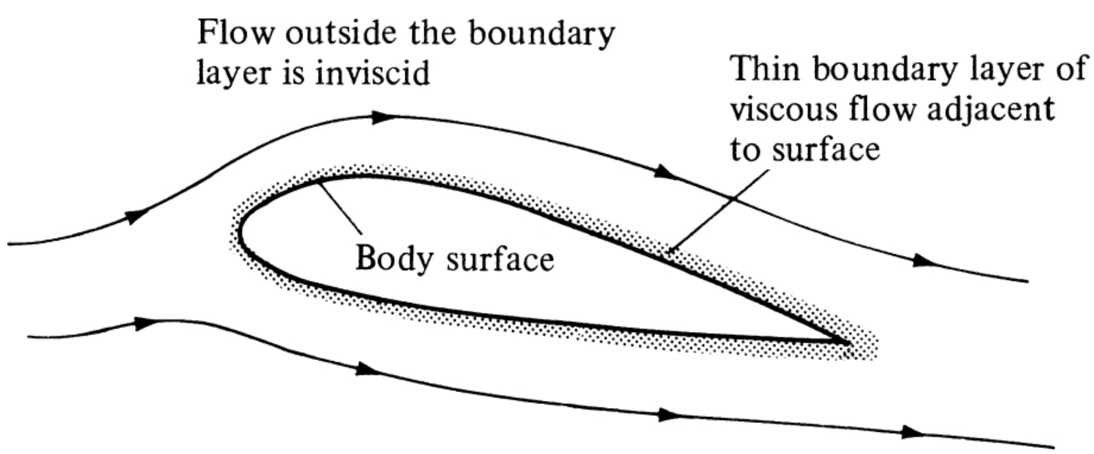


Figure 4.38 Frictionless flow.



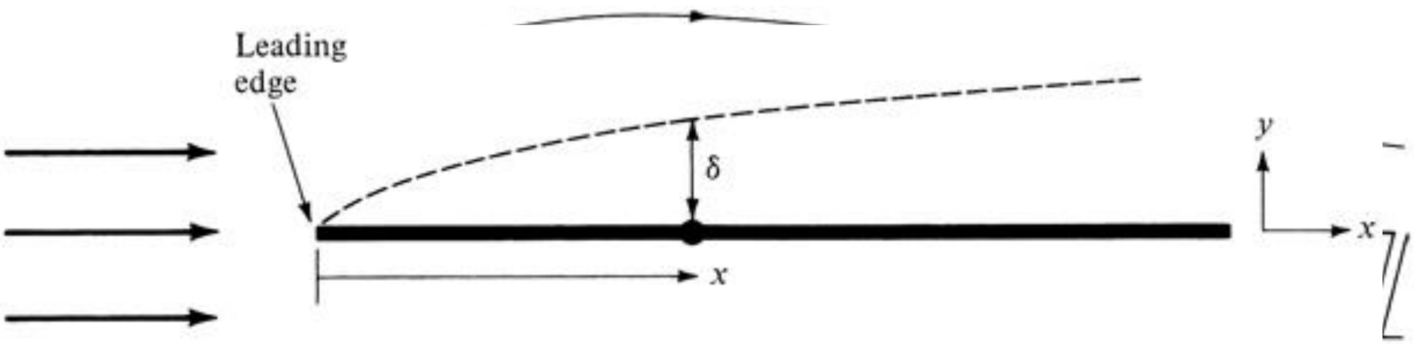


Figure 4.42 Growth of the boundary layer thickness.

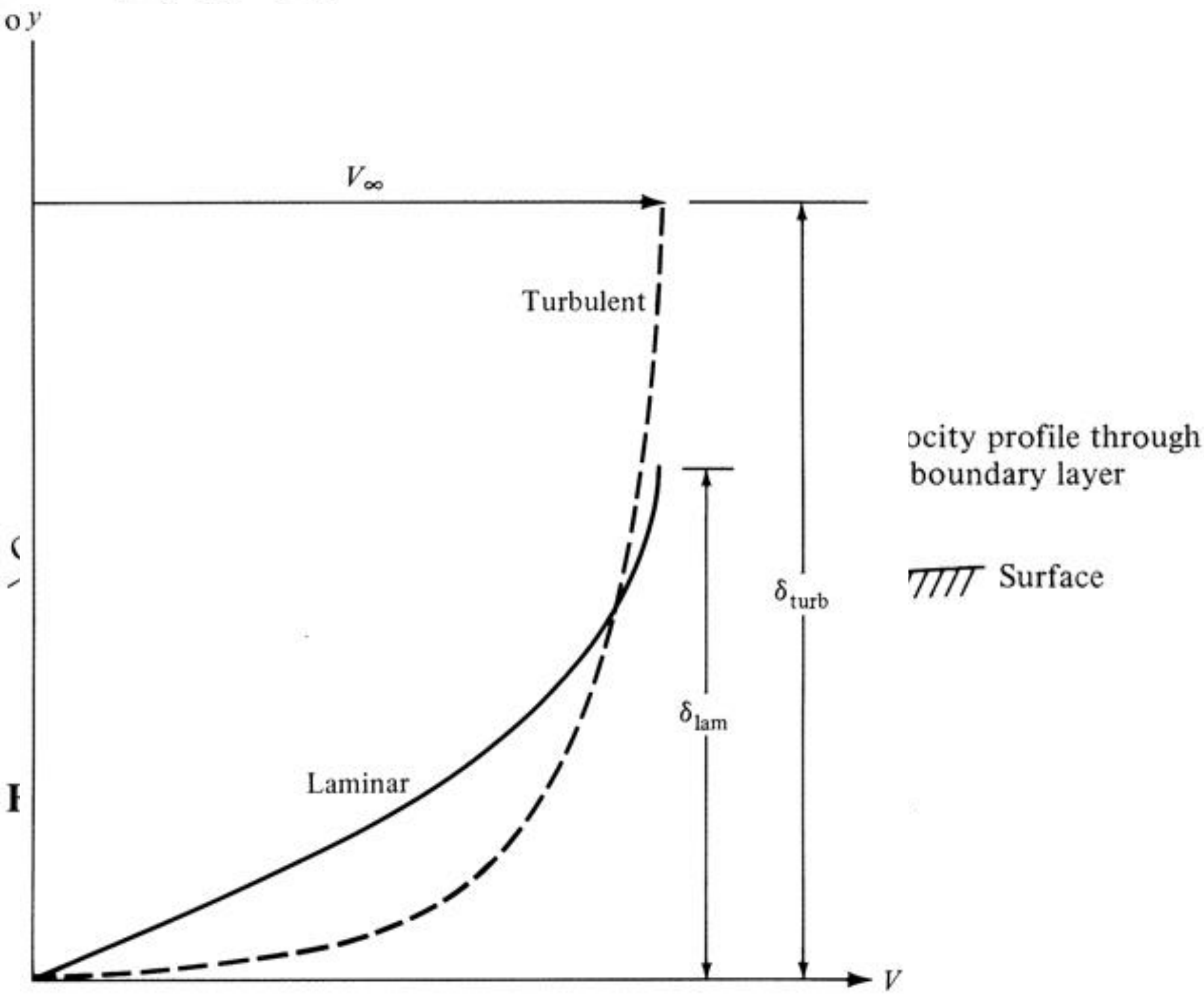
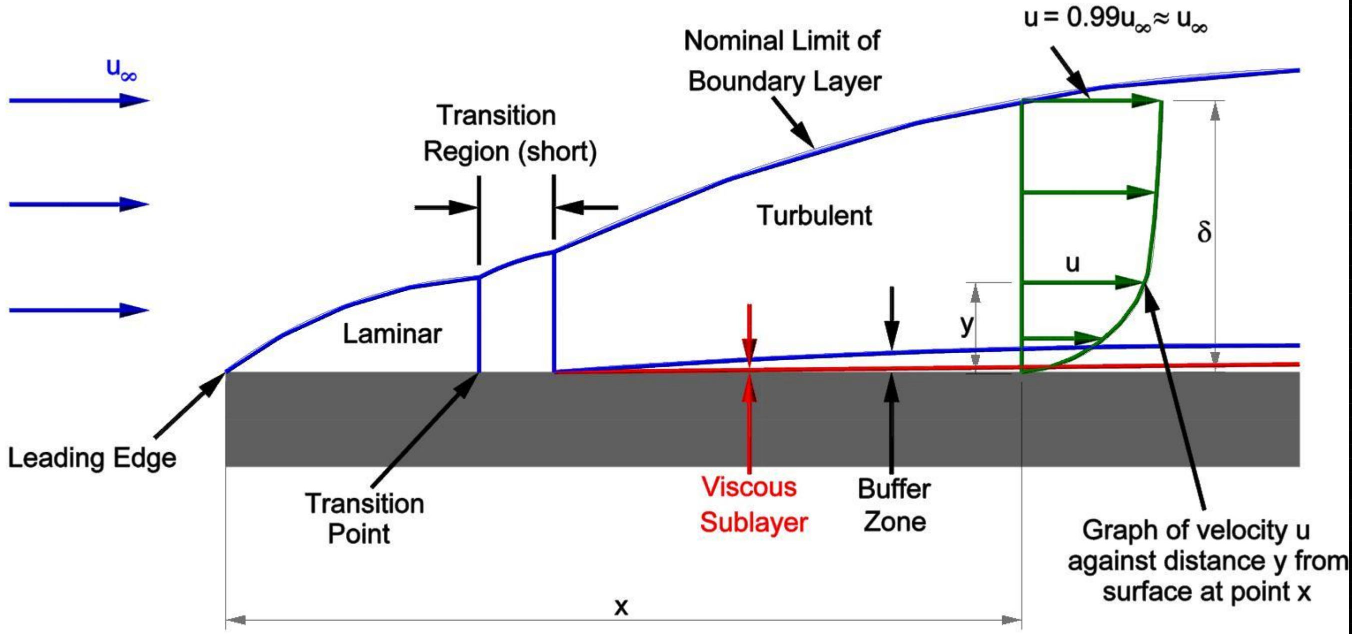


Figure 4.44 Velocity profiles for laminar and turbulent boundary layers. Note that the turbulent boundary layer thickness is larger than the laminar boundary layer thickness.

Laminar-to-Turbulent Transition:



Turbulent Boundary Layer:

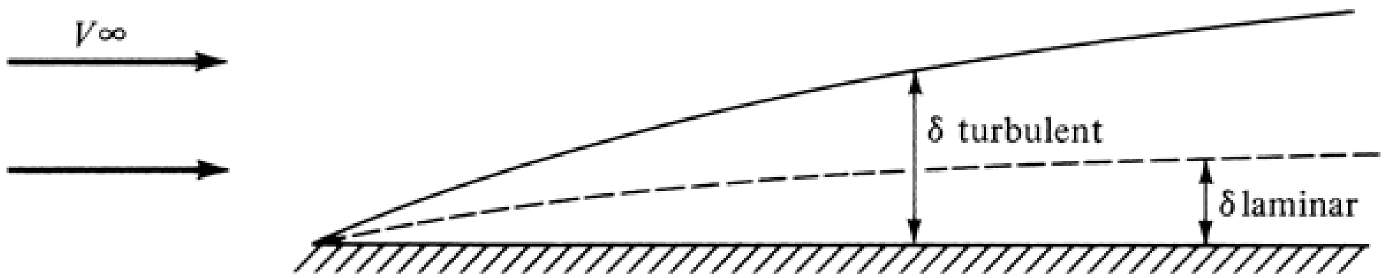


Figure 4.49 Turbulent boundary layers are thicker than laminar boundary layers.

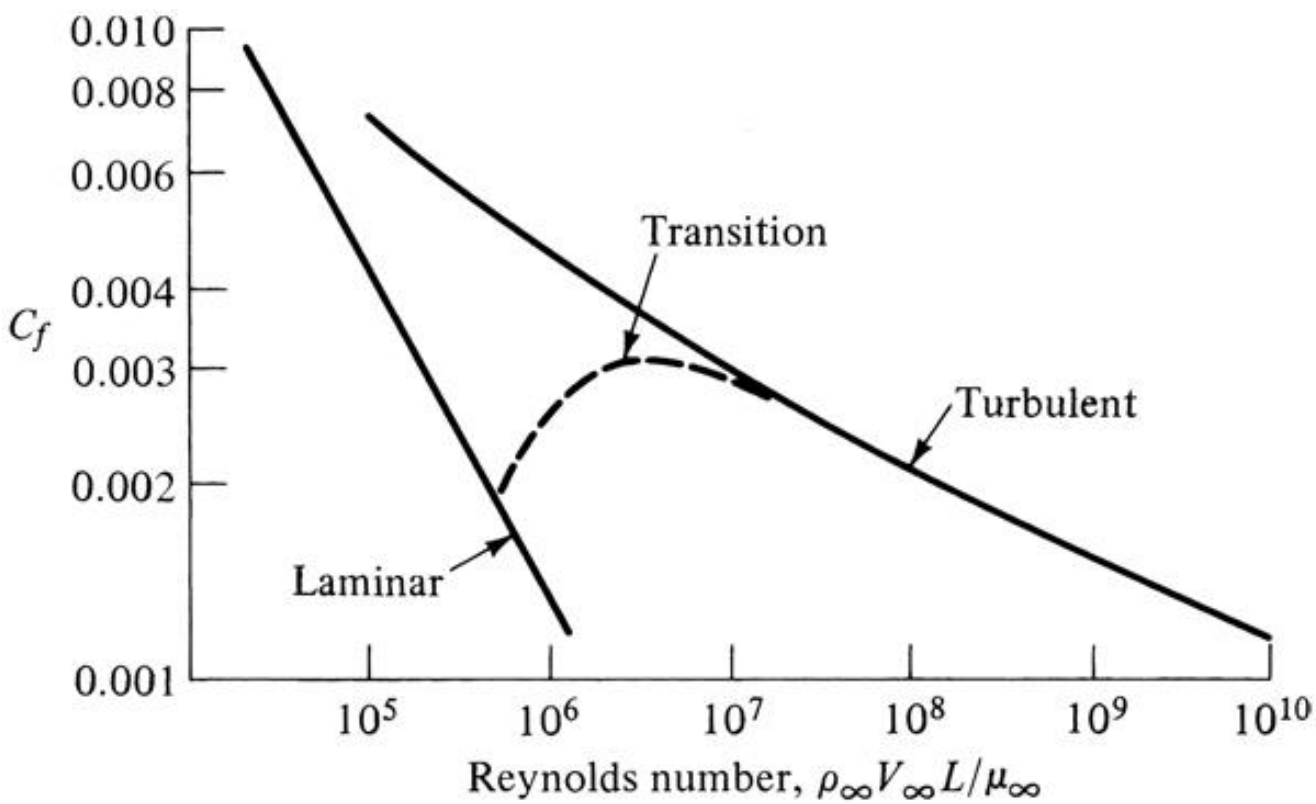
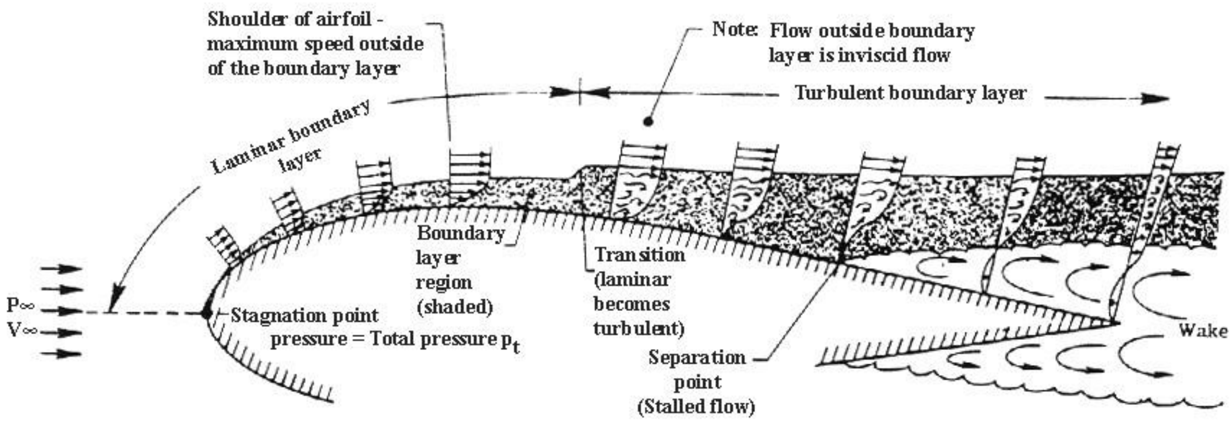
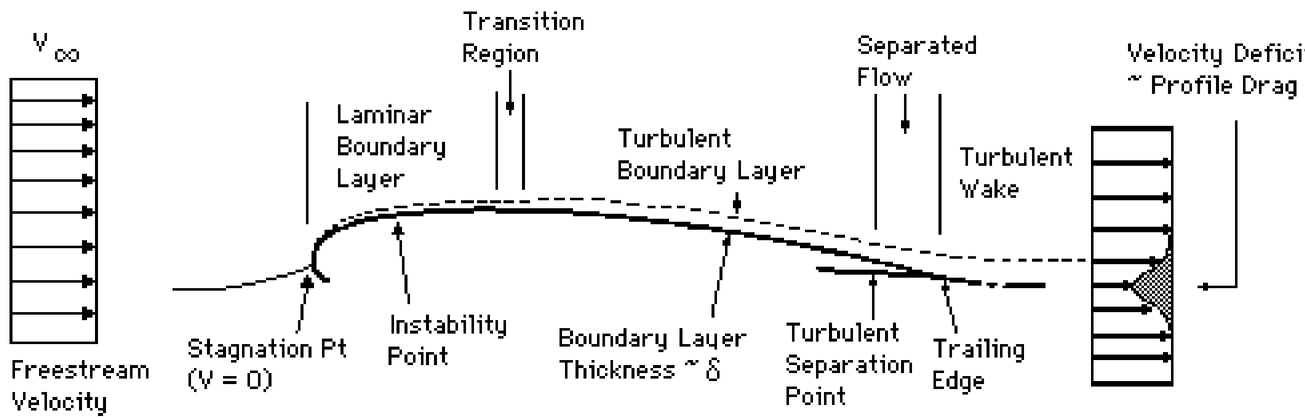
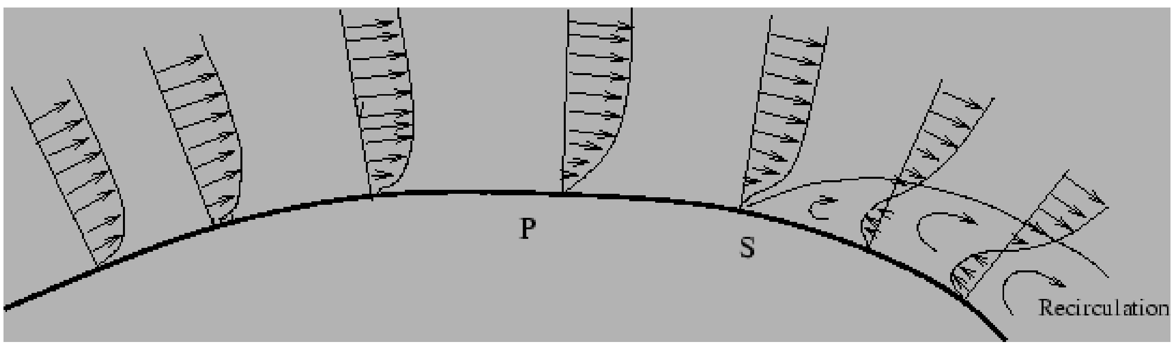


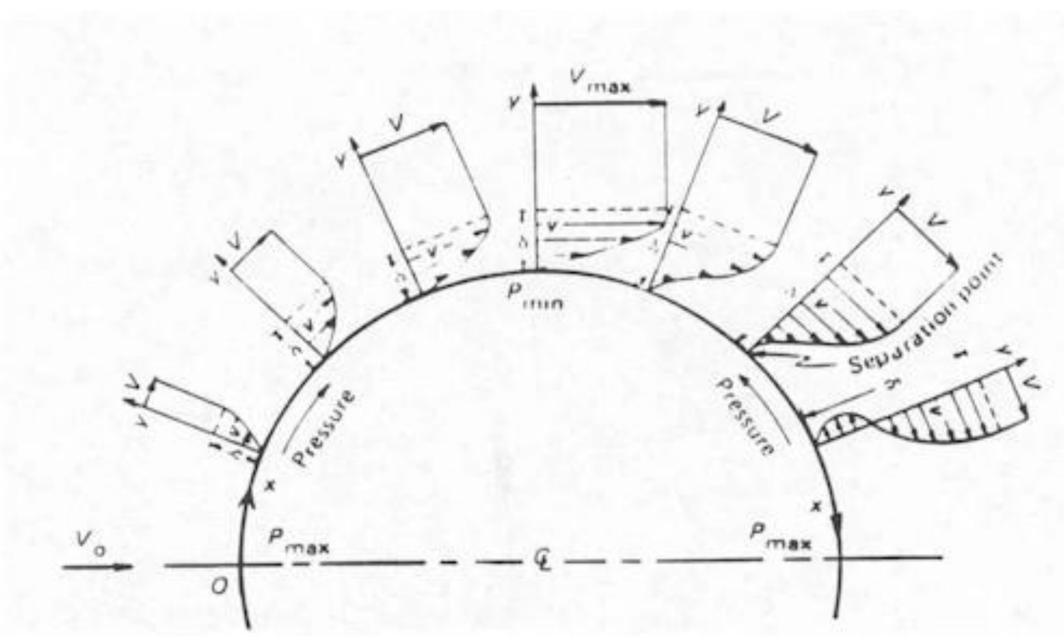
Figure 4.50 Variation of skin friction coefficient with Reynolds number for low-speed flow. Comparison of laminar and turbulent flow.

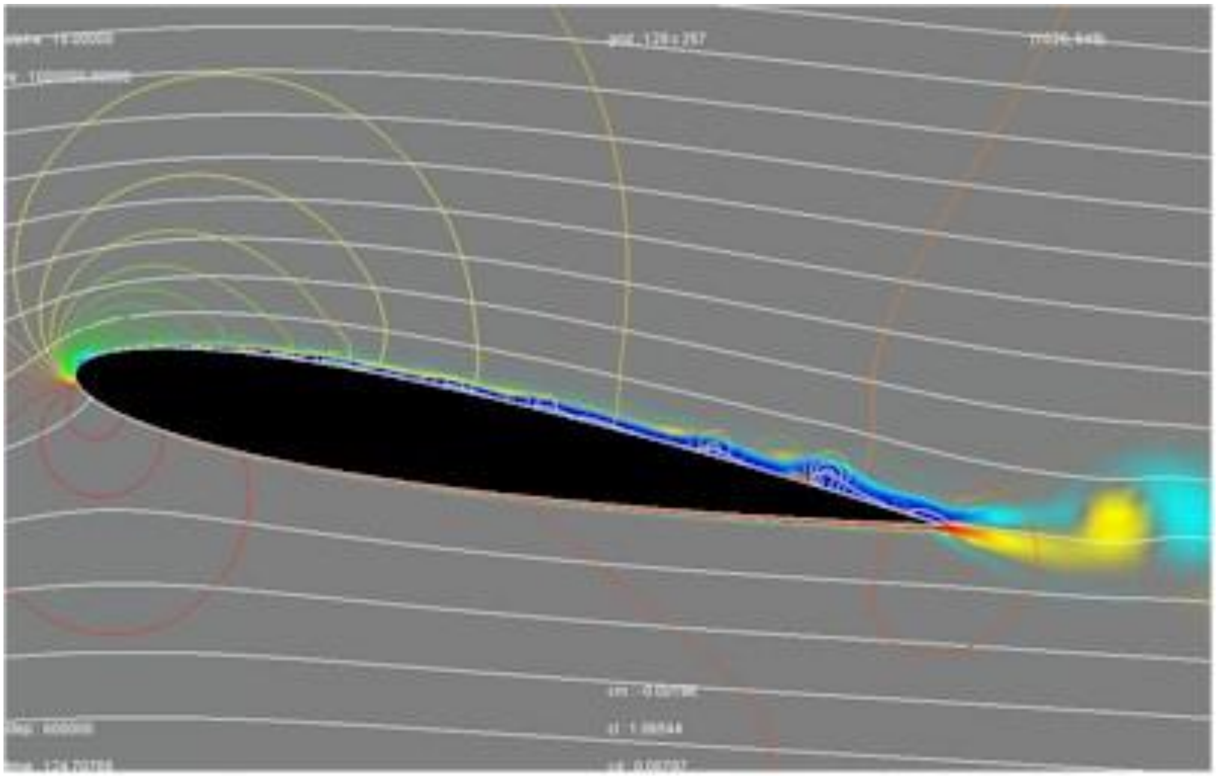

Shoulder of airfoil - maximum speed outside of the boundary layer
Note: Flow outside boundary layer is inviscid flow
Turbulent boundary layer
Laminar boundary layer
Boundary layer region (shaded)
Transition (laminar becomes turbulent)
P∞
V∞
Stagnation point pressure = Total pressure p_t
Separation point (Stalled flow)
Wake

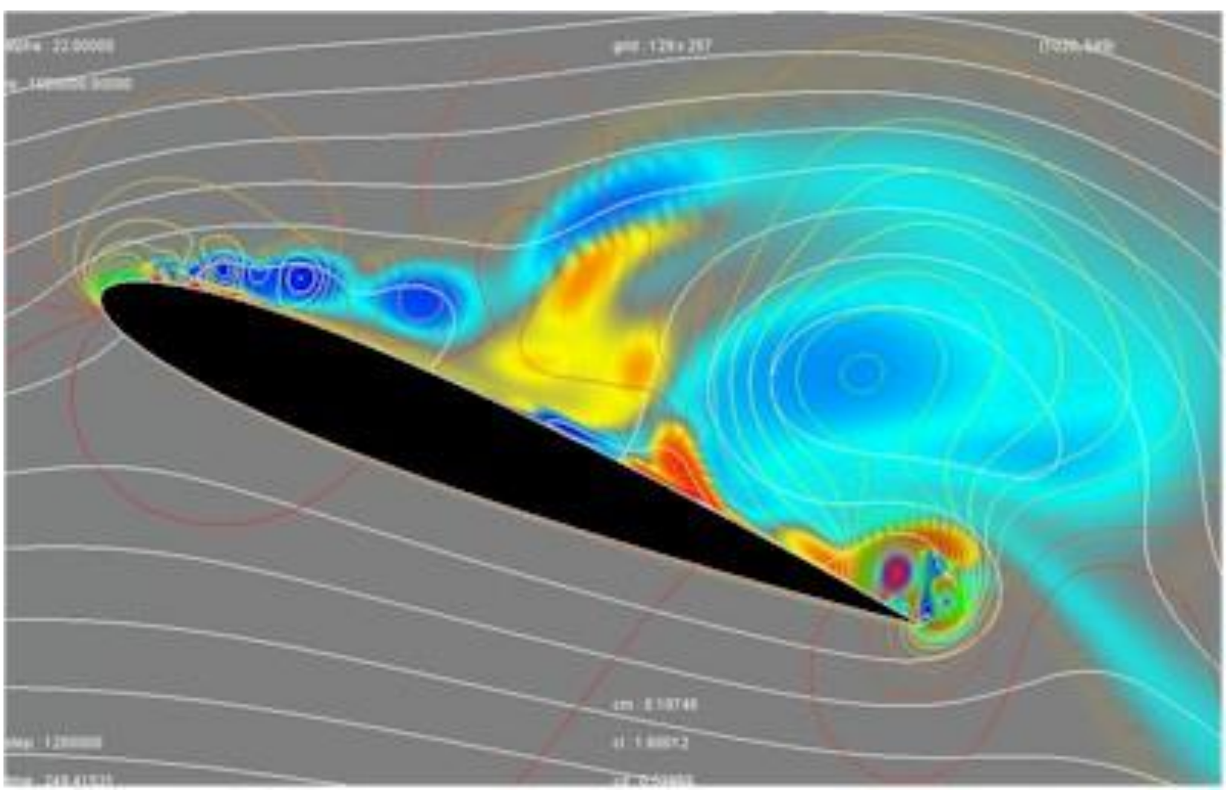

V∞
Transition Region
Separated Flow
Velocity Deficit ~ Profile Drag
Laminar Boundary Layer
Turbulent Boundary Layer
Turbulent Wake
Freestream Velocity
Stagnation Pt (V = 0)
Instability Point
Boundary Layer Thickness ~ δ
Turbulent Separation Point
Trailing Edge

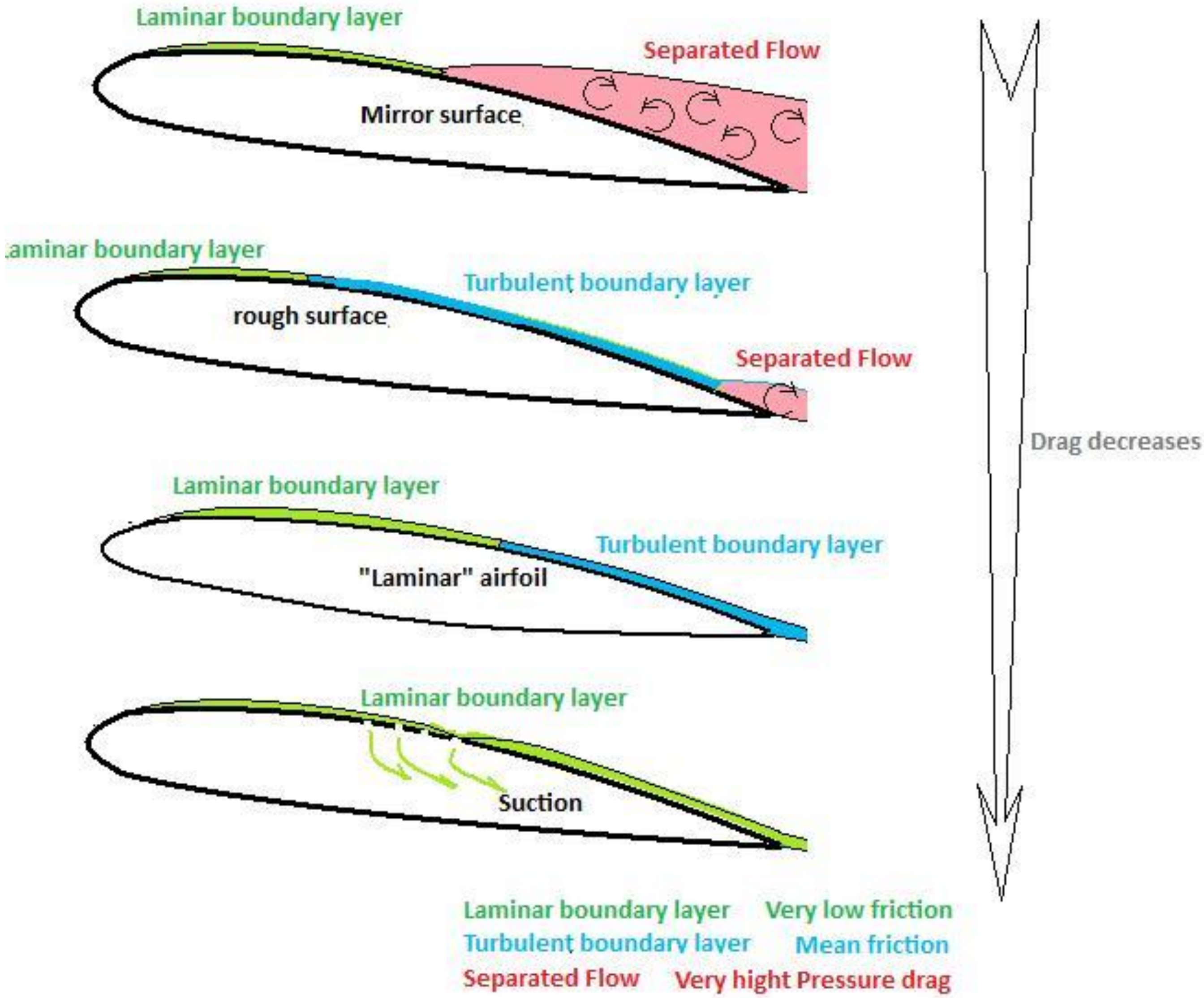
Flow Separation (F4.20)





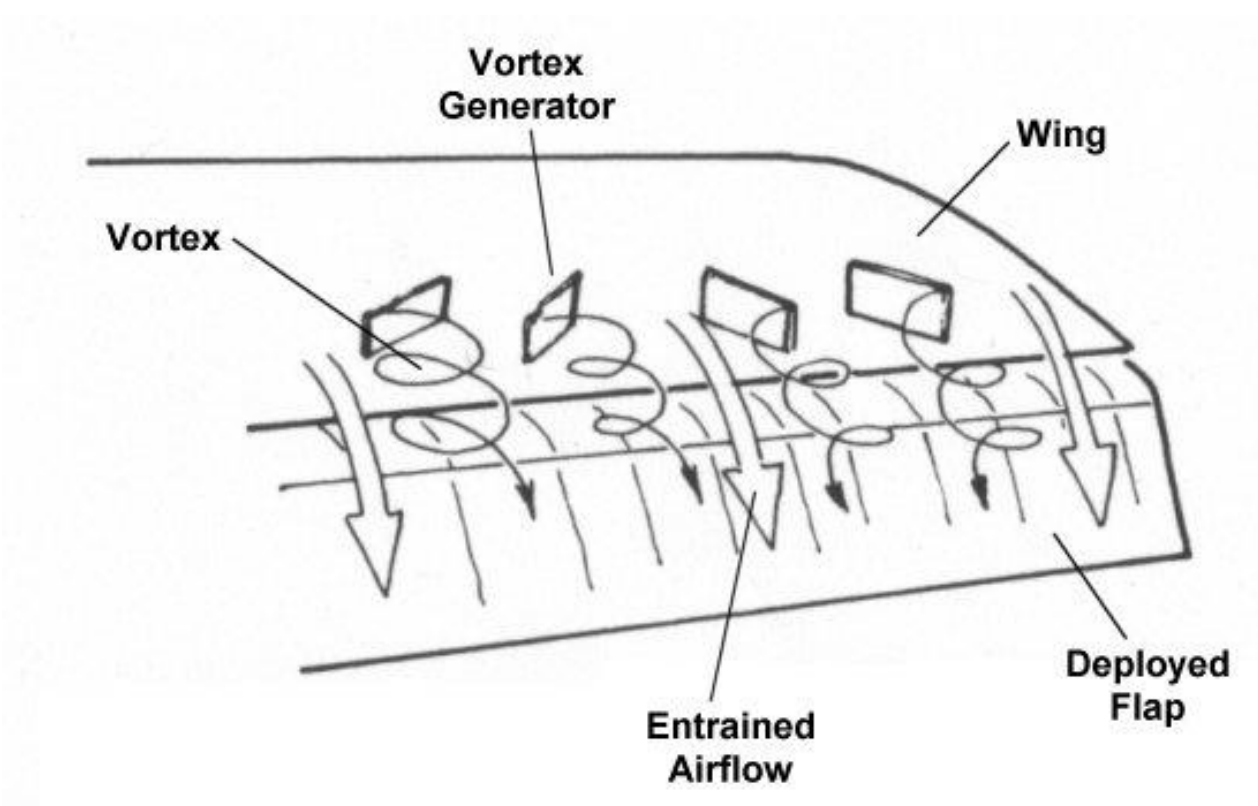


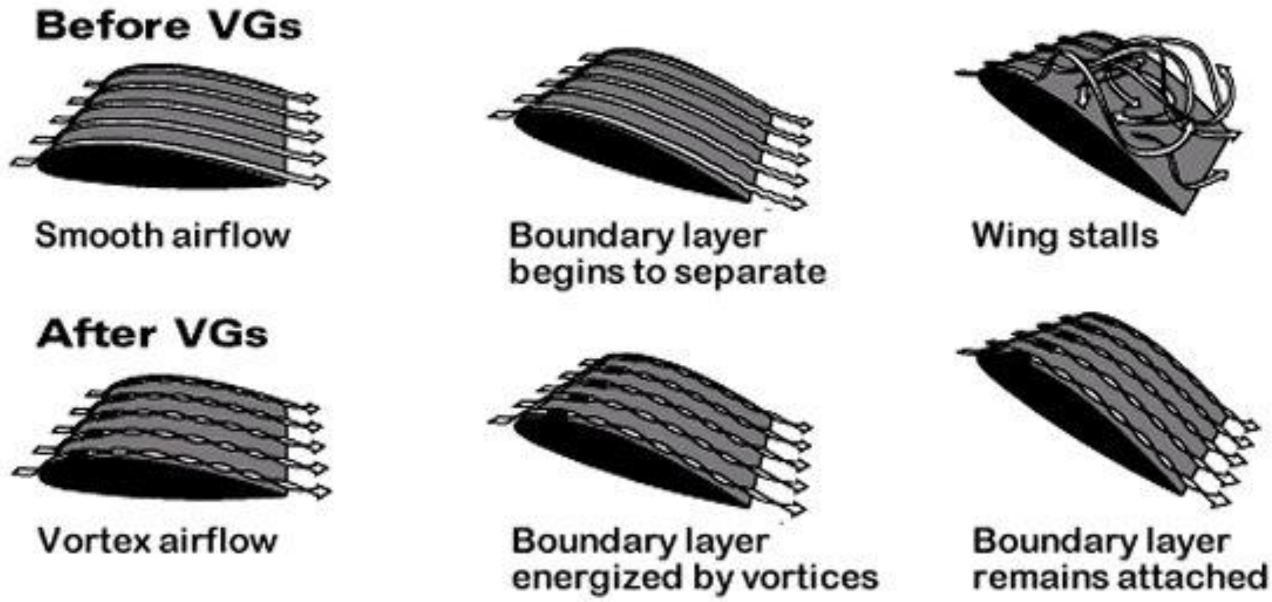




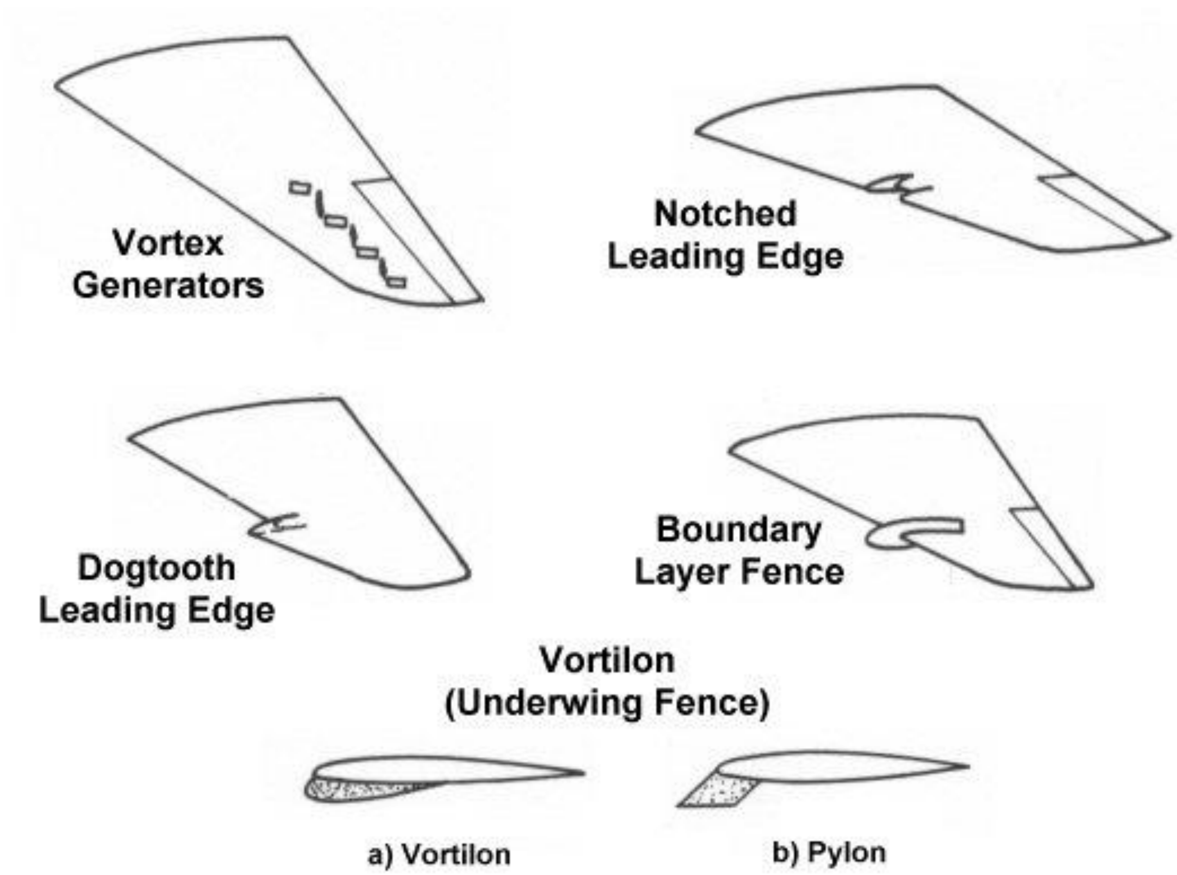
Laminar boundary layer
Separated Flow
Mirror surface
aminar boundary layer
Turbulent boundary layer
rough surface
Separated Flow
Laminar boundary layer
Turbulent boundary layer
"Laminar" airfoil
Laminar boundary layer
Suction
Drag decreases
Laminar boundary layer Very low friction
Turbulent boundary layer Mean friction
Separated Flow Very hight Pressure drag

Vortex Generators to Delay Separation

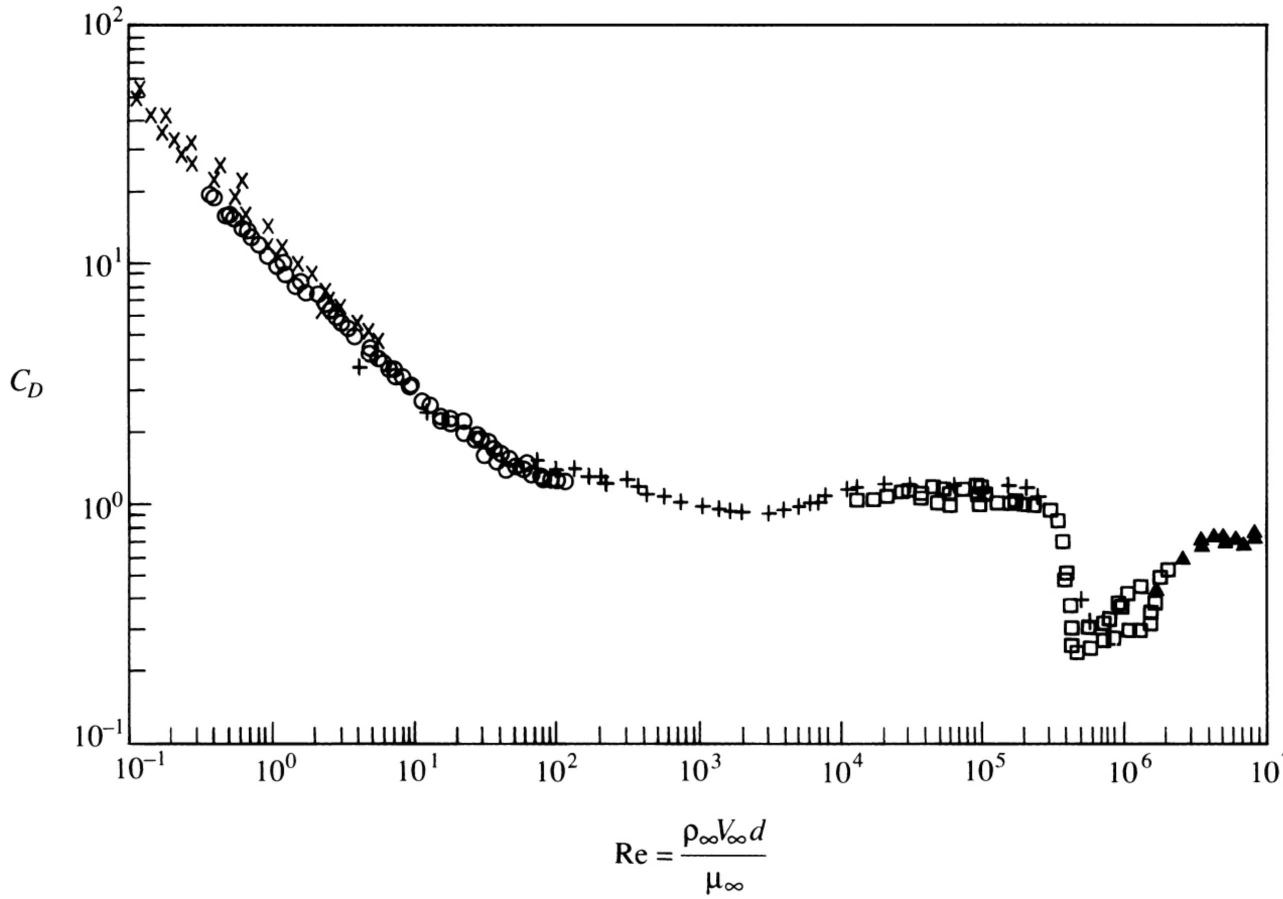



Before VGs
Smooth airflow
Boundary layer begins to separate
Wing stalls
After VGs
Vortex airflow
Boundary layer energized by vortices
Boundary layer remains attached

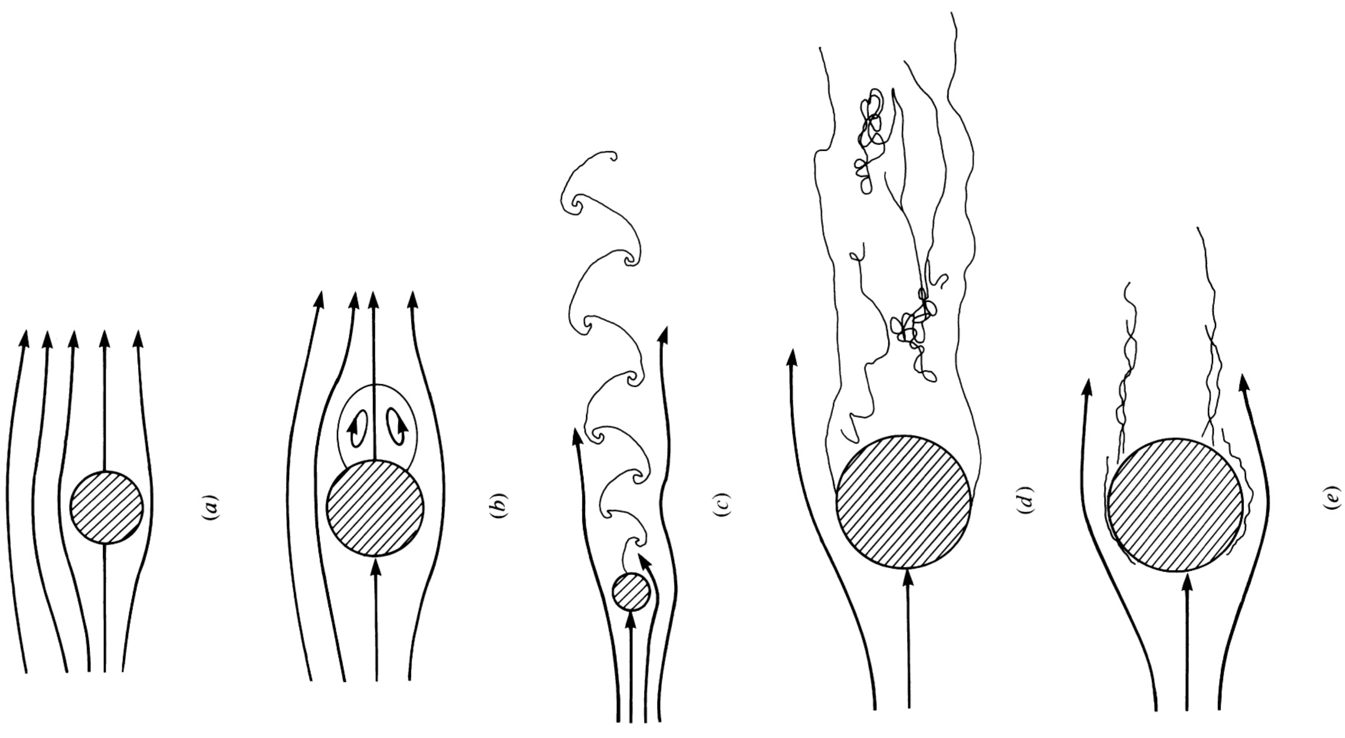
Examples:


Vortex Generators
Notched Leading Edge
Dogtooth Leading Edge
Boundary Layer Fence
Vortilon (Underwing Fence)
a) Vortilon
b) Pylon


20
20

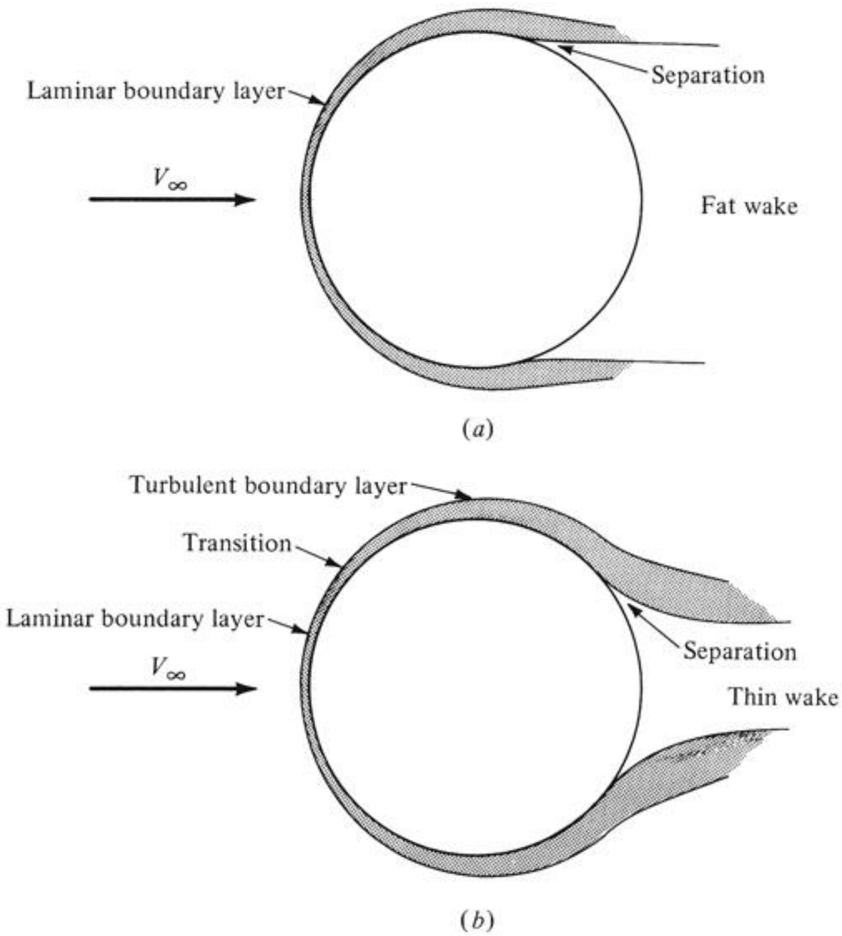


10^2
10^1
10^0
10^{-1}
C_D
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
$\mathrm{Re} = \frac{\rho_\infty V_\infty d}{\mu_\infty}$



(a)
(b)
(c)
(d)
(e)

Turbulent Boundary Layer = Lower Drag?!?!?!



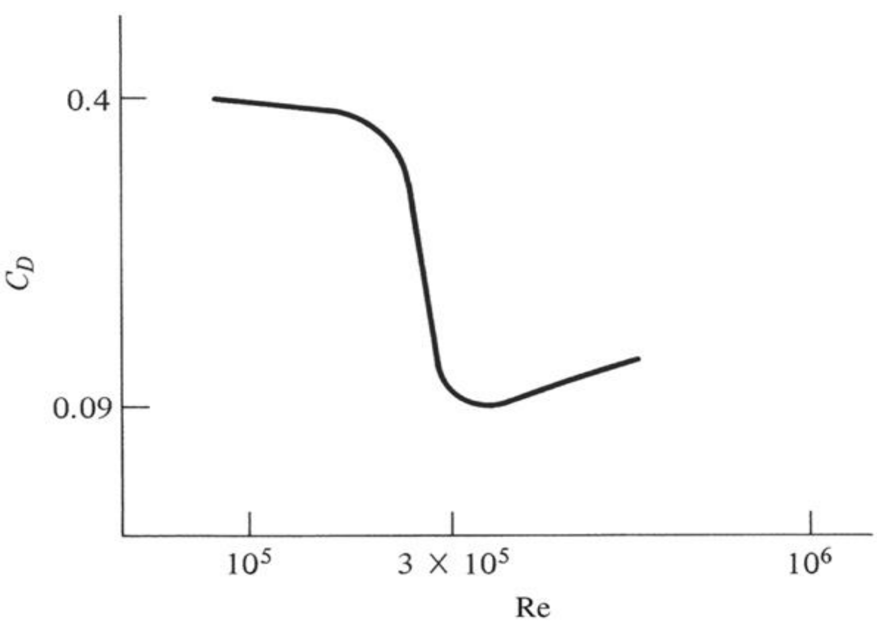
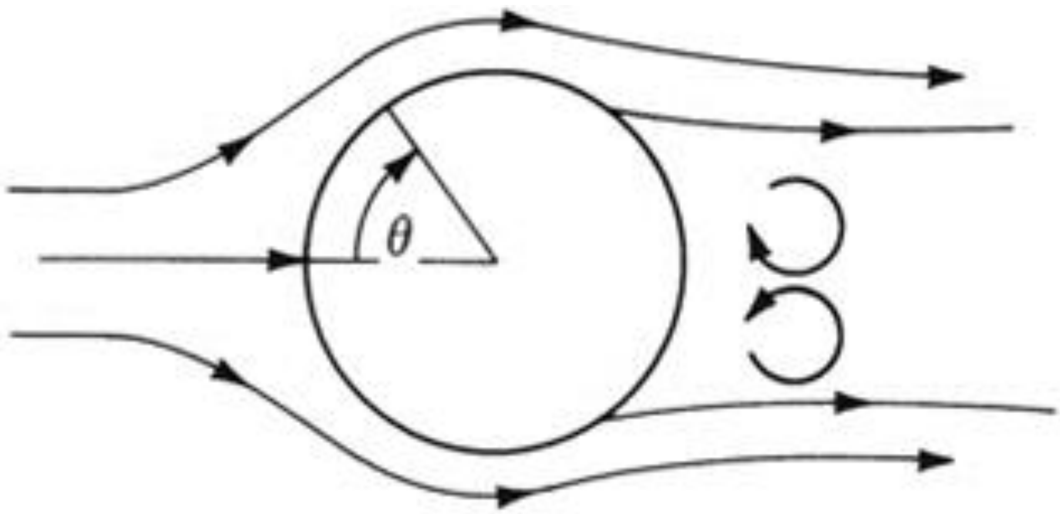
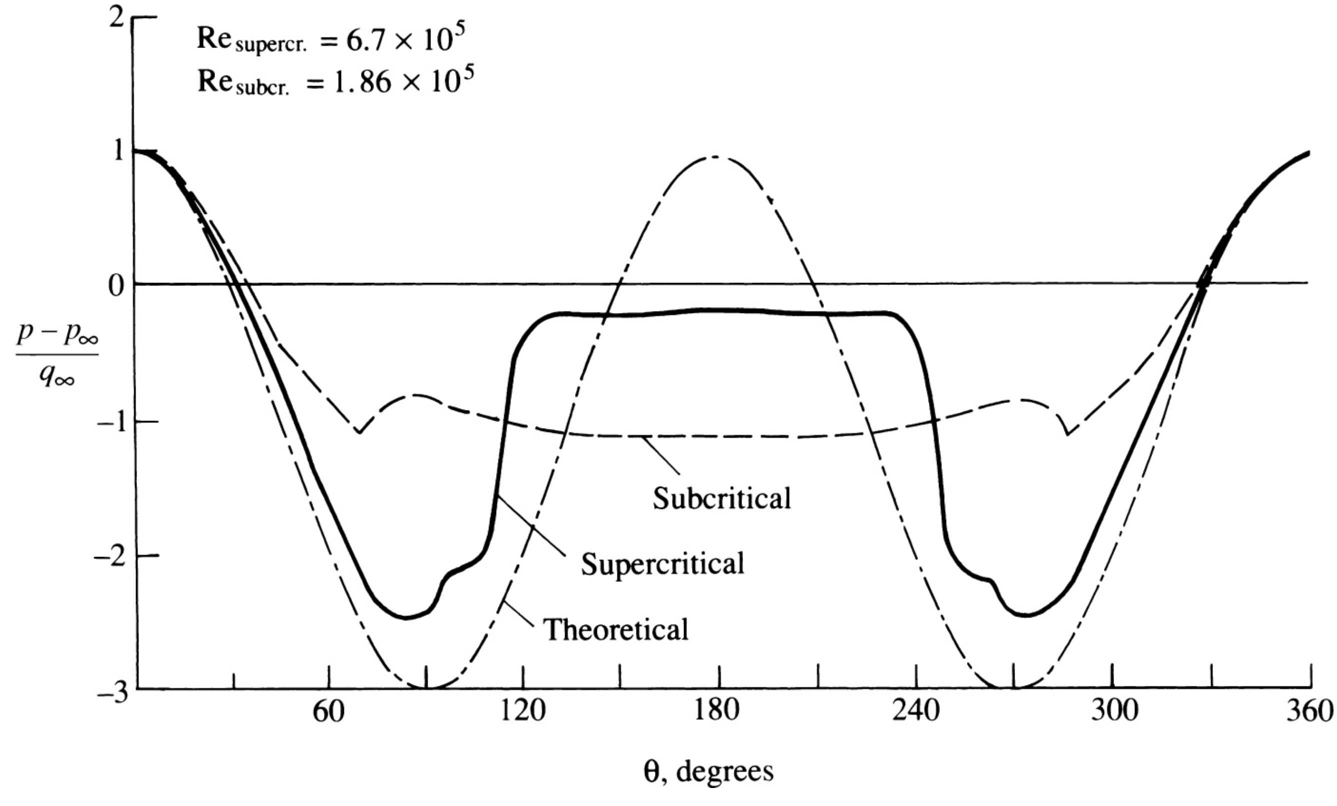
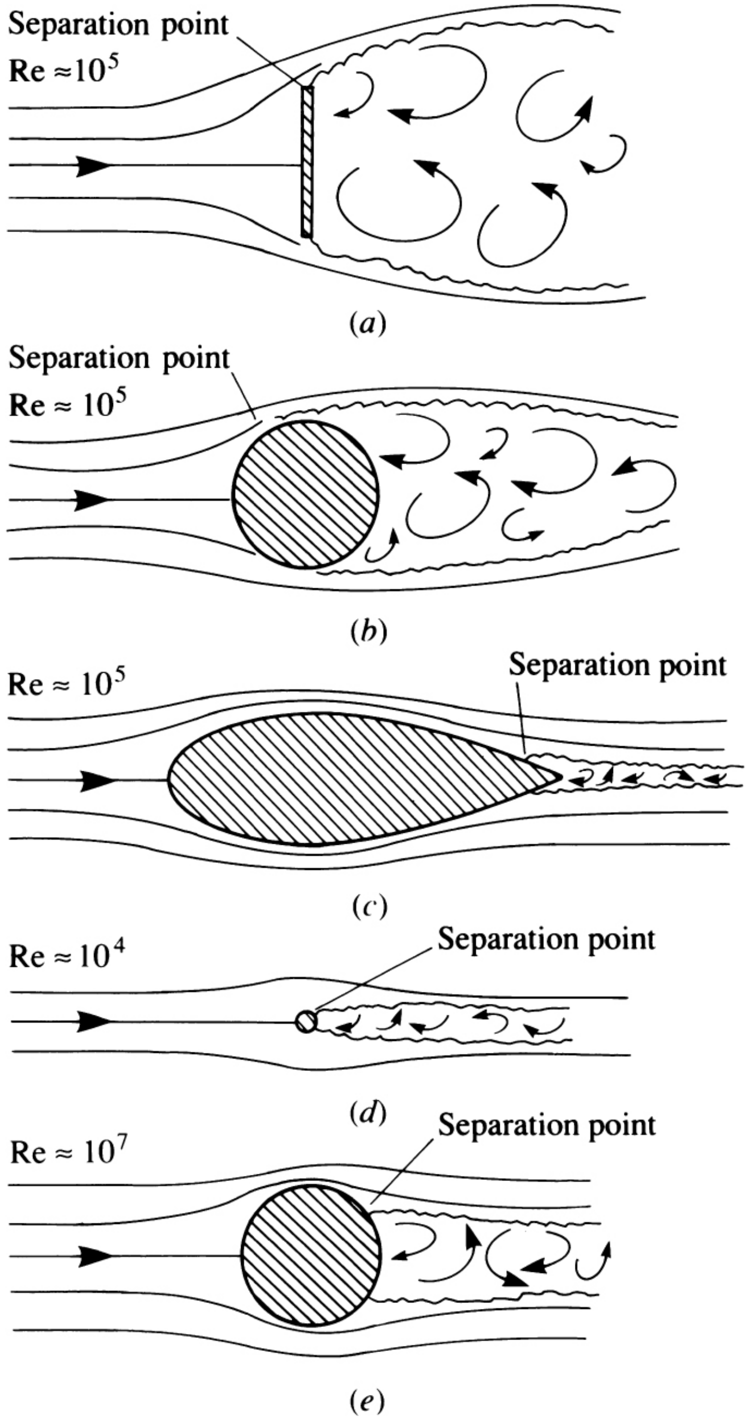


Figure 5.74 Variation of drag coefficient with Reynolds number for a sphere in low-speed flow.


θ


$\text{Re}_{\text{supercr.}} = 6.7 \times 10^5$
$\text{Re}_{\text{subcr.}} = 1.86 \times 10^5$
2
1
0
−1
−2
−3
$\frac{p - p_\infty}{q_\infty}$
60
120
180
240
300
360
θ, degrees
Subcritical
Supercritical
Theoretical

Coefficient of Drag in Real Flows (A1.12)



(a) Flat plate (Broadside) length = d — $C_D = 2.0$

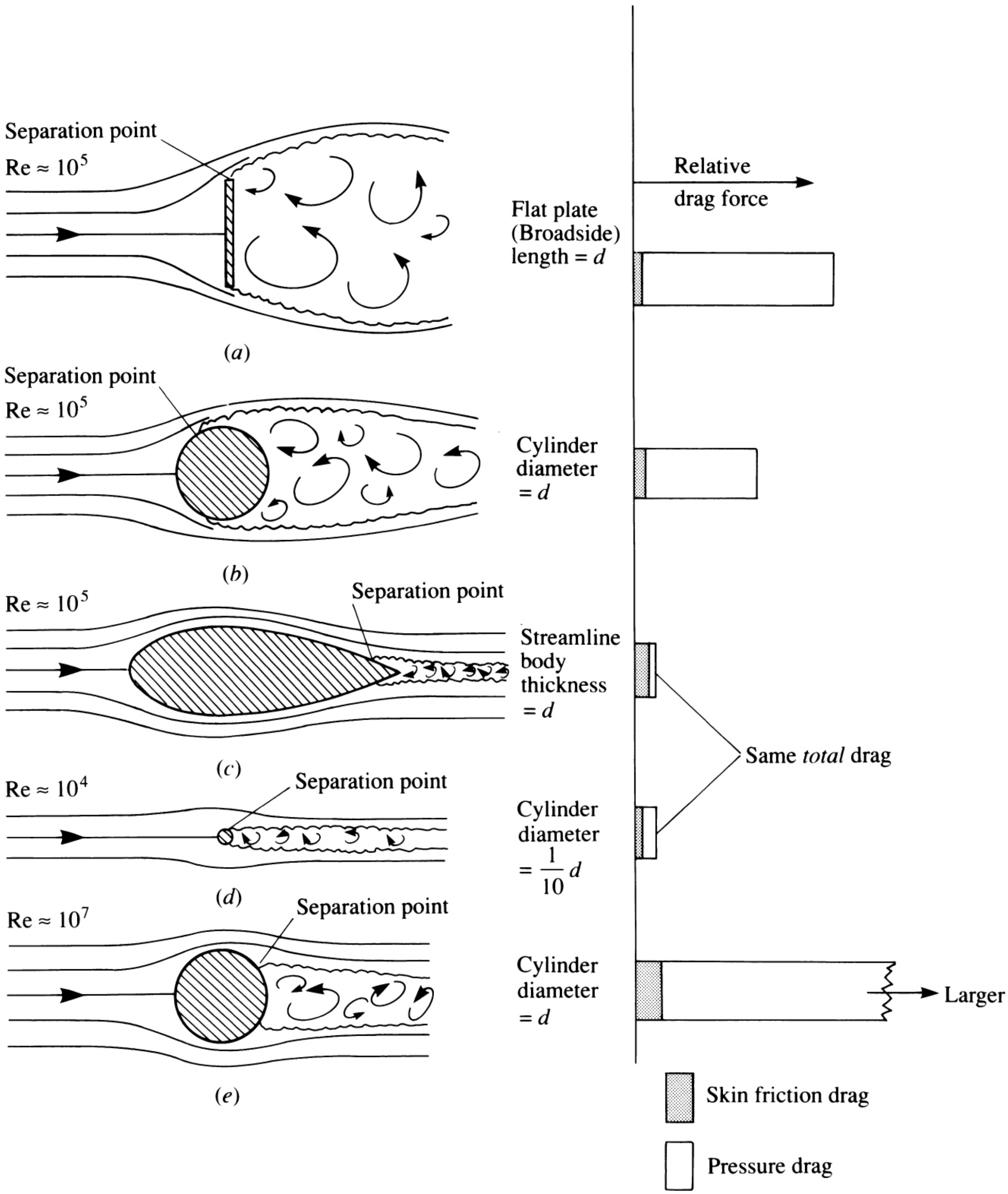
(b) Cylinder diameter = d — $C_D = 1.2$

(c) Streamline body thickness = d — $C_D = 0.12$

(d) Cylinder diameter = $\frac{1}{10} d$ — $C_D = 1.2$

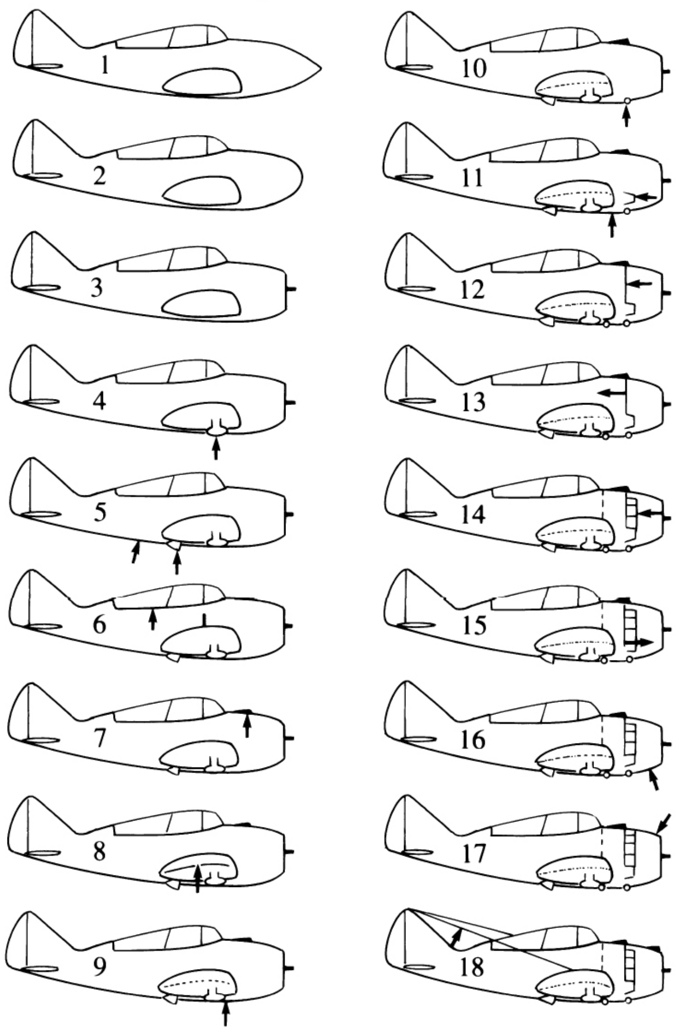
(e) Cylinder diameter = d — $C_D = 0.6$

Friction vs Pressure Drag



Where Does the Drag Come From?

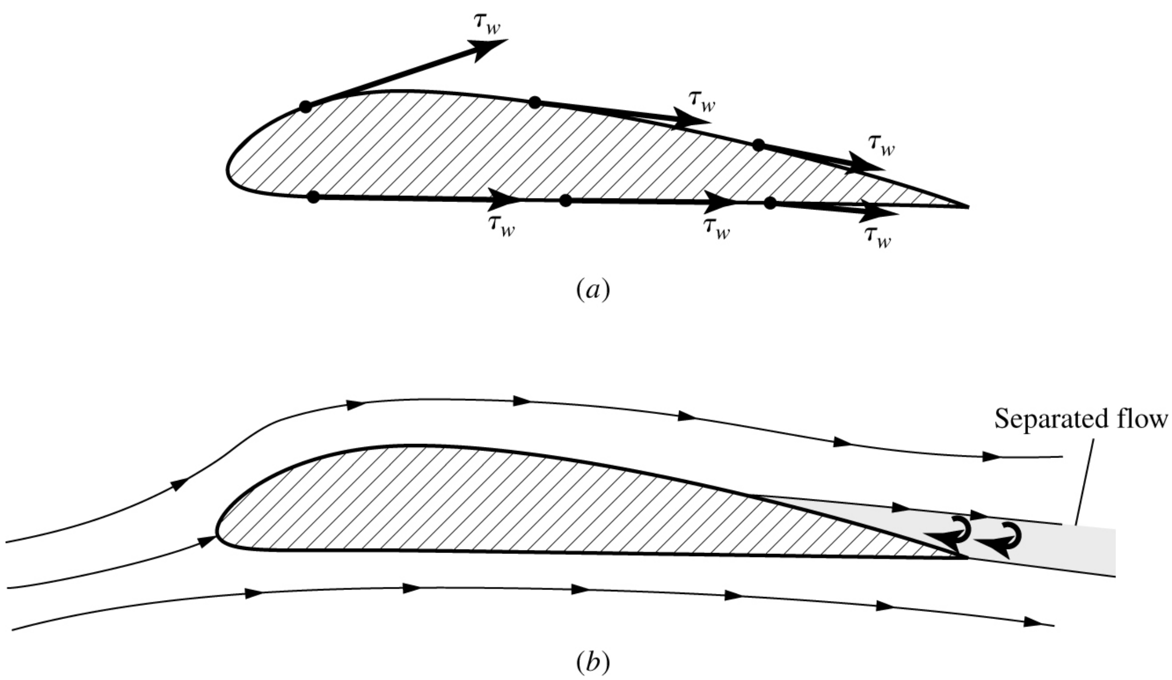
Airplane condition



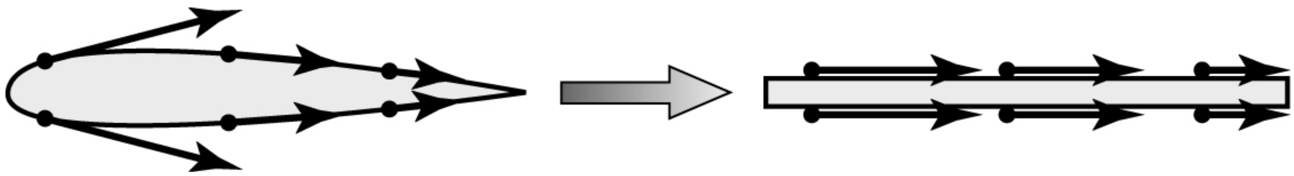
Condition number	Description	C_D ($C_L = 0.15$)	ΔC_D	ΔC_D, %[a]
1	Completely faired condition, long nose fairing	0.0166		
2	Completely faired condition, blunt nose fairing	0.0169		
3	Original cowling added, no airflow through cowling	0.0186	0.0020	12.0
4	Landing-gear seals and fairing removed	0.0188	0.0002	1.2
5	Oil cooler installed	0.0205	0.0017	10.2
6	Canopy fairing removed	0.0203	−0.0002	−1.2
7	Carburetor air scoop added	0.0209	0.0006	3.6
8	Sanded walkway added	0.0216	0.0007	4.2
9	Ejector chute added	0.0219	0.0003	1.8
10	Exhaust stacks added	0.0225	0.0006	3.6
11	Intercooler added	0.0236	0.0011	6.6
12	Cowling exit opened	0.0247	0.0011	6.6
13	Accessory exit opened	0.0252	0.0005	3.0
14	Cowling fairing and seals removed	0.0261	0.0009	5.4
15	Cockpit ventilator opened	0.0262	0.0001	0.6
16	Cowling venturi installed	0.0264	0.0002	1.2
17	Blast tubes added	0.0267	0.0003	1.8
18	Antenna installed	0.0275	0.0008	4.8
	Total		0.0109	

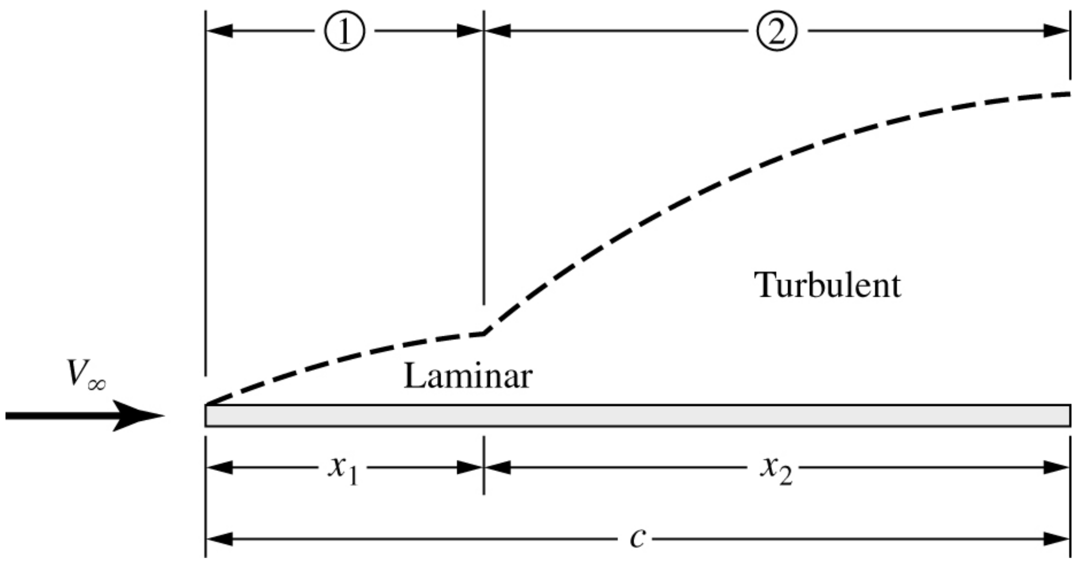
[a]Percentages based on completely faired condition with long nose fairing.

Viscous Airfoil Drag (A4.12)

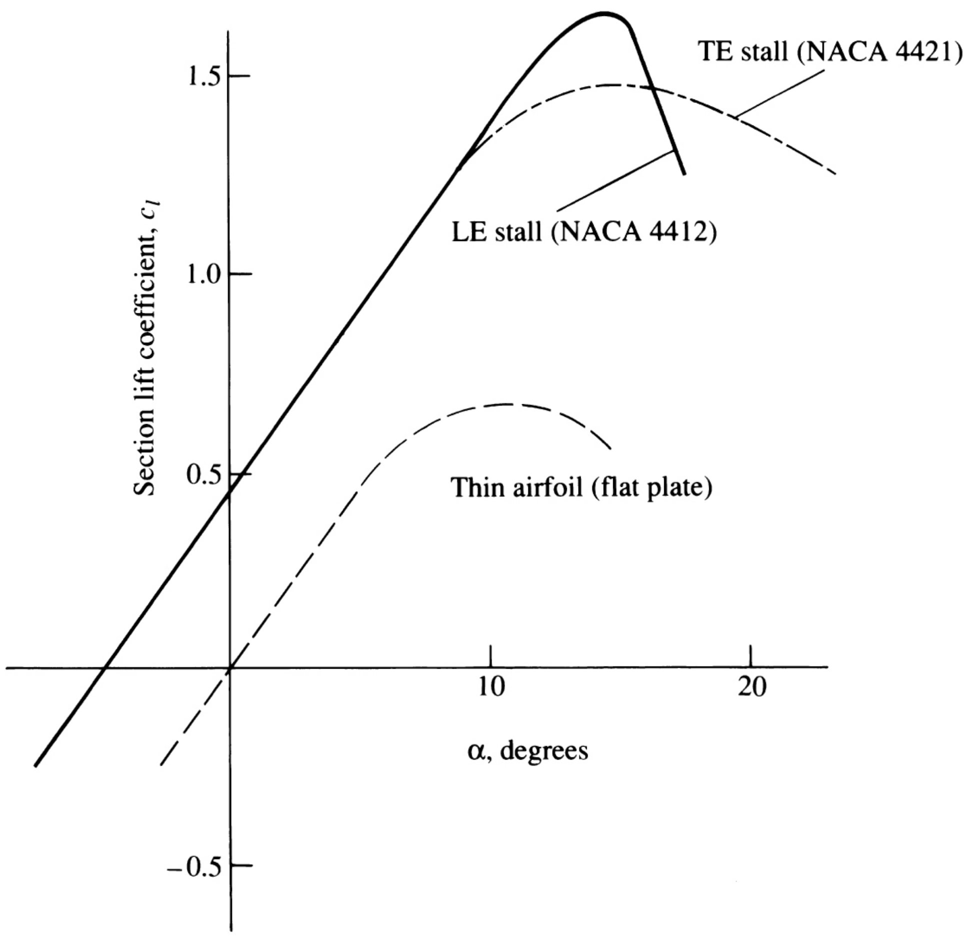


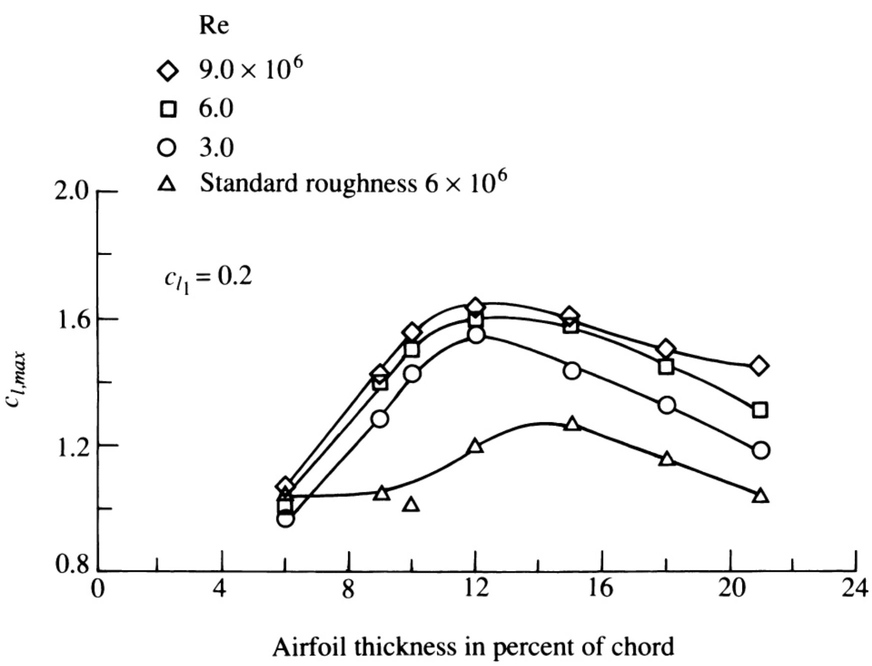
Estimate Skin-Friction Drag of an Airfoil





Flow Over Real Airfoils (4.13)





Review of Airfoil & Wing Drag (F4.21)