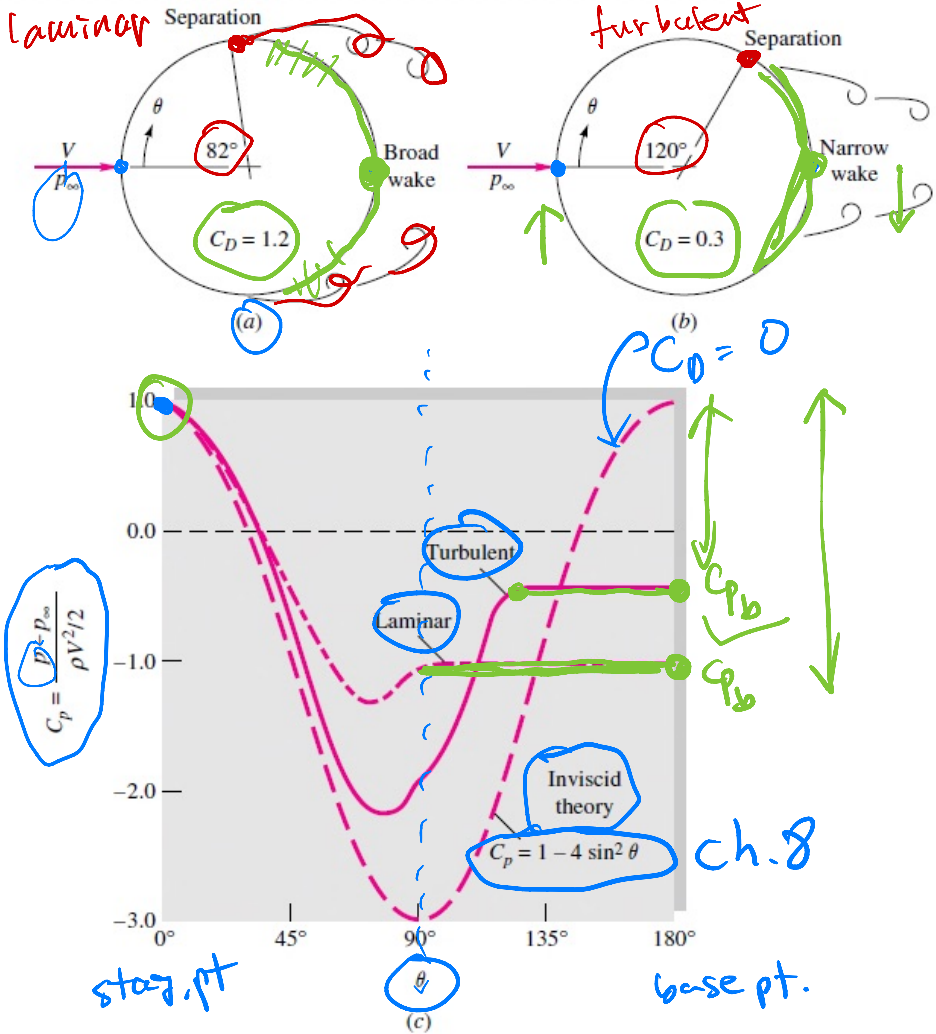


Fig. 7.13 Flow past a circular cylinder: (*a*) laminar separation; (*b*) turbulent separation; (*c*) theoretical and actual surface pressure distributions.

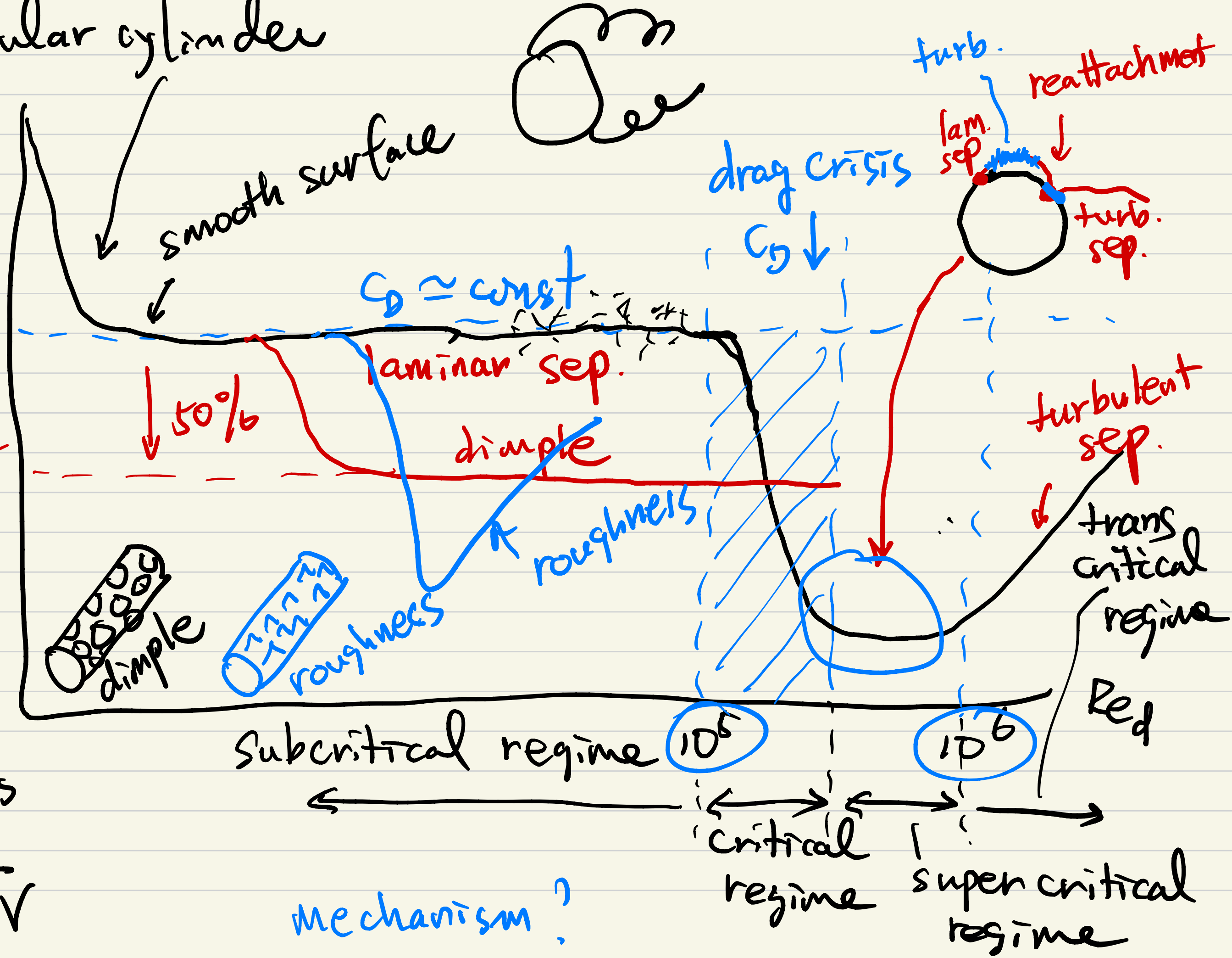
Circular cylinder

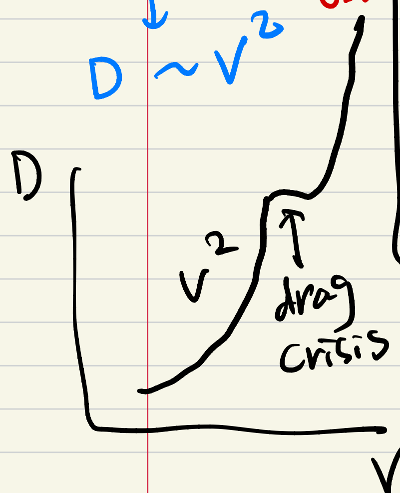
$$\frac{D}{\frac{1}{2}\rho V^2 A} = C_D \qquad A = \frac{\pi}{4}d^2$$

$C_D \simeq$ const

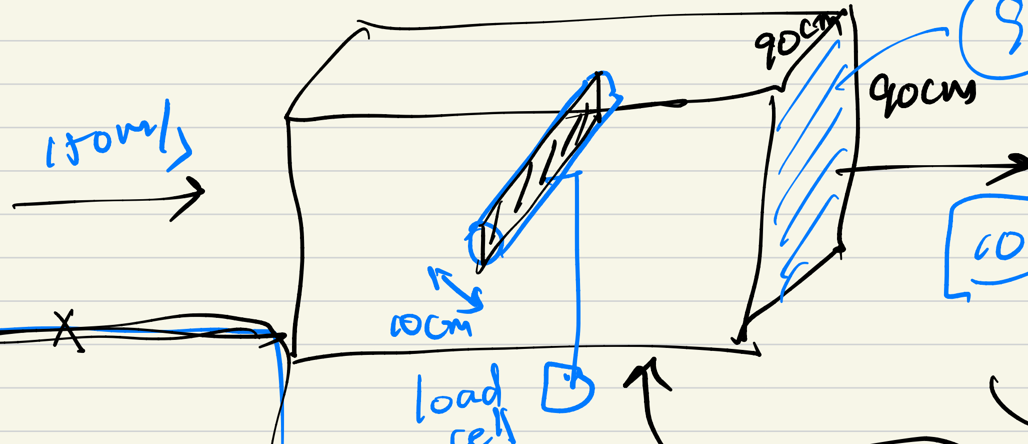
↓

$D \sim V^2$





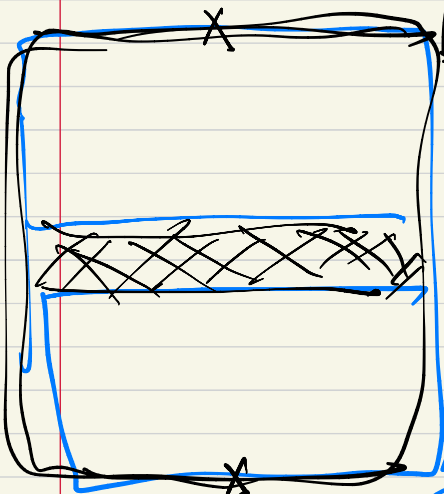
$$Re_d = 10^6 = \frac{Ud}{\nu} = \frac{U \times 0.1}{1.5 \times 10^{-5}} \Rightarrow U = 150\ m/s$$

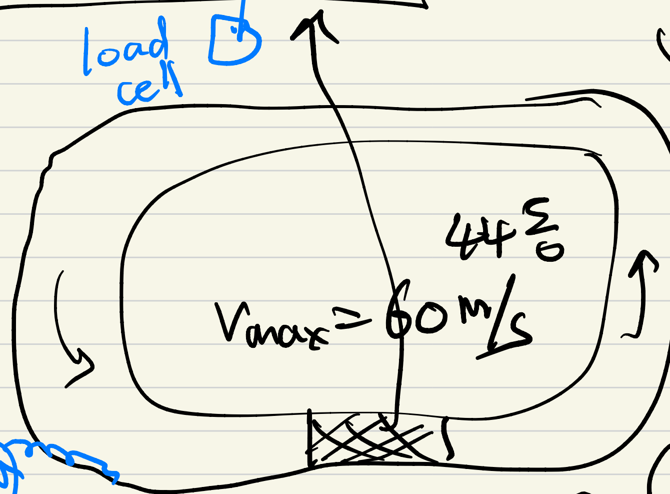


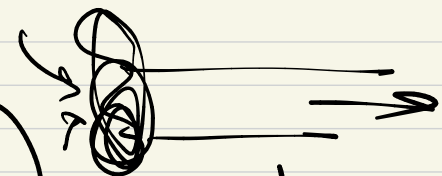
$90 \times 90 = 8100\ cm^2$

1/9 block

$10 \times 90 = 900\ cm^2$







야구공 $d = 72\ mm$

$V = 140\ km/h$

$$Re_d = \frac{Vd}{\nu} = 1.87 \times 10^5$$

subcritical regime

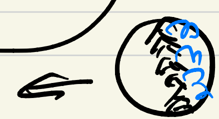
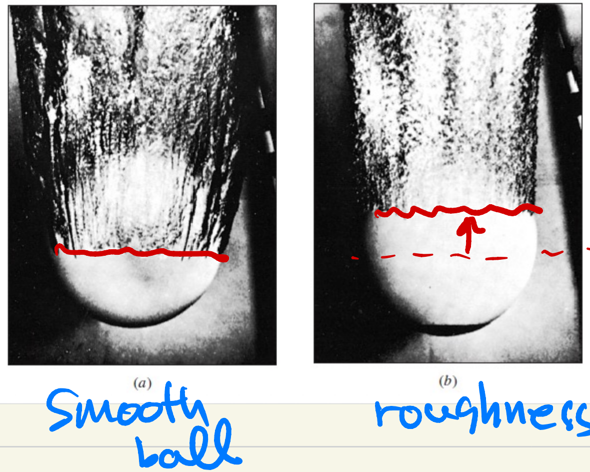


Fig. 7.14 Strong differences in laminar and turbulent separation on an 8.5-in bowling ball entering water at 25 ft/s: (a) smooth ball, laminar boundary layer; (b) same entry, turbulent flow induced by patch of nose-sand roughness. *(NAVAIR Weapons Division Historical Archives.)*

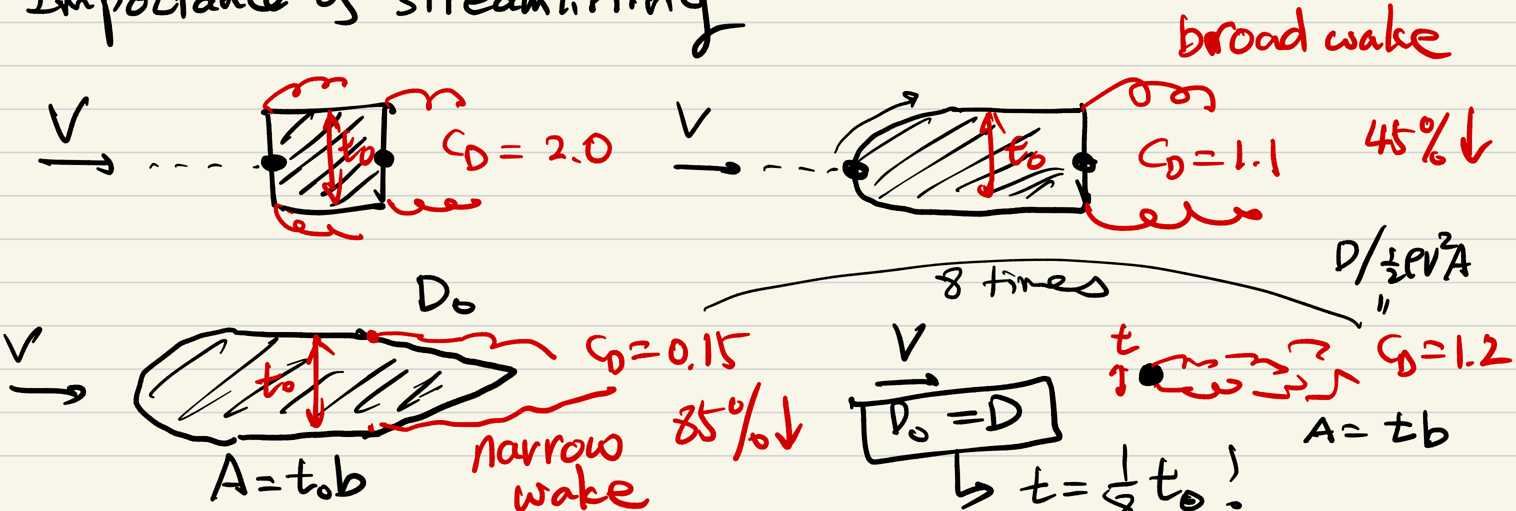


flow visualization

① discovery

② mechanism

• Importance of streamlining

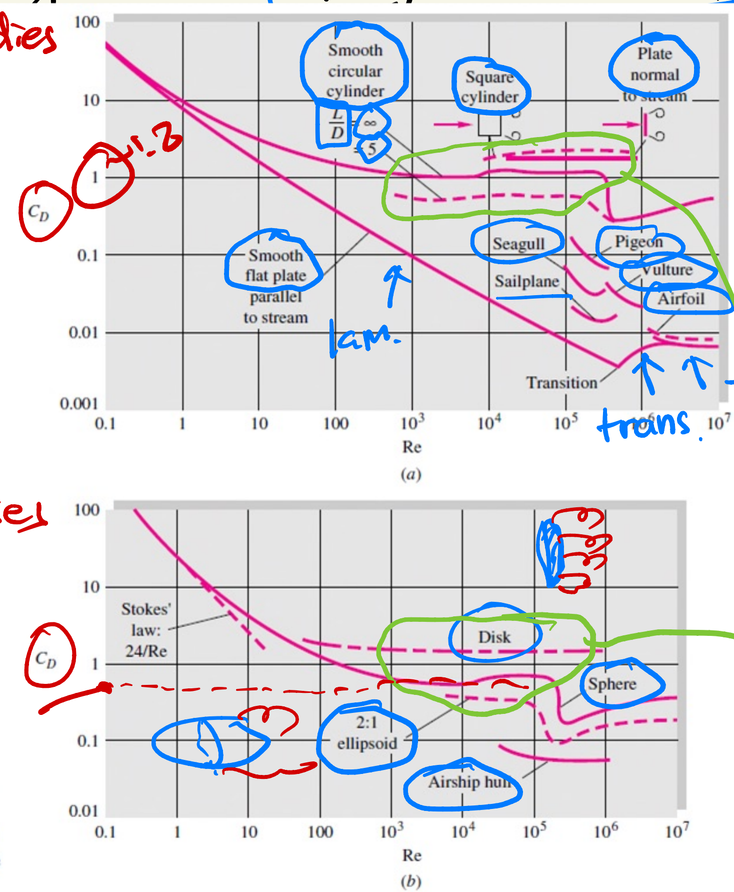


For high-performance vehicles and other moving vehicles, the name of game is **drag reduction**.

2D bodies

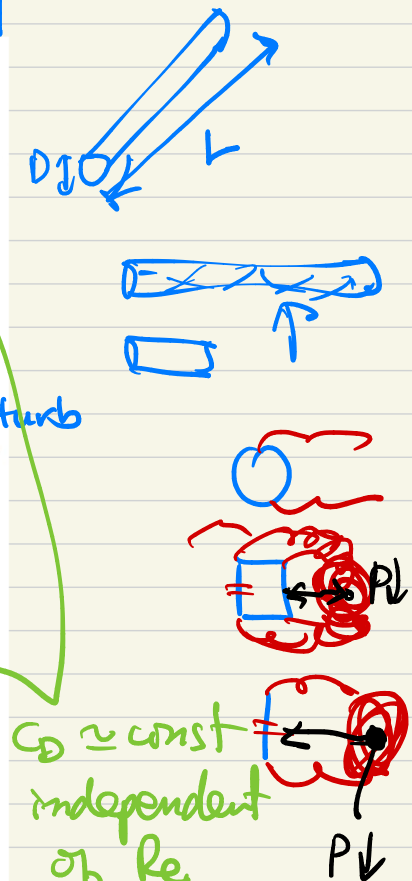
$$C_D = \frac{D}{\frac{1}{2}\rho V^2 A}$$

A → planform area except for normal plate



3D bodies

Fig. 7.16 Drag coefficients of smooth bodies at low Mach numbers: (a) two-dimensional bodies; (b) three-dimensional bodies. Note the Reynolds number independence of blunt bodies at high Re.



$C_D \simeq$ const independent of Re

Table 7.2 Drag of Two-Dimensional Bodies at Re ≥ 10^4

2D bodies at $Re \geq 10^4$ ($C_D \simeq$ const)

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

↑ frontal area

Shape	C_D based on frontal area	Shape	C_D based on frontal area	Shape	C_D based on frontal area
Square cylinder:	2.1	Half cylinder:	1.2	Plate:	2.0
	1.6		1.7	Thin plate normal to a wall:	1.4
Half tube:	1.2	Equilateral triangle:	1.6	Hexagon:	1.0
	2.3		2.0		0.7

Shape	C_D based on frontal area
Rounded nose section:	

L/H:	0.5	1.0	2.0	4.0	6.0
C_D:	1.16	0.90	0.70	0.68	0.64

Flat nose section:

L/H:	0.1	0.4	0.7	1.2	2.0	2.5	3.0	6.0
C_D:	1.9	2.3	2.7	2.1	1.8	1.4	1.3	0.9

Elliptical cylinder:

	Laminar	Turbulent
1:1	1.2	0.3
2:1	0.6	0.2
4:1	0.35	0.15
8:1	0.25	0.1

$C_D \downarrow$

skin friction ↑

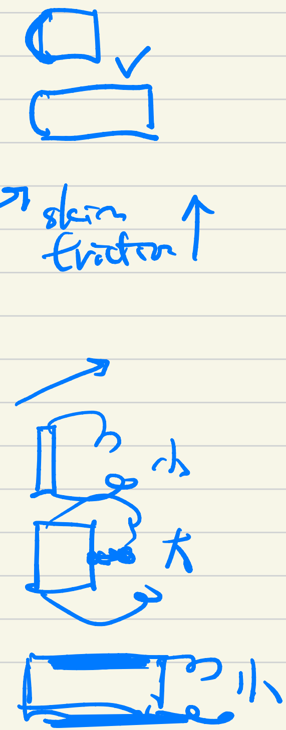
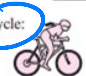


Table 7.3 Drag of Three-Dimensional Bodies at $Re \geq 10^4$ 3D $C_D \simeq$ const

Body	C_D based on frontal area
Cube:	1.07
(Cube, diagonal)	0.81
Cup:	1.4
(Cup, reversed)	0.4
Disk:	1.17
Parachute (Low porosity):	1.2
Streamlined train (approximately 5 cars):	C_DA 8.5 m^2
Bicycle: Upright: $C_DA \approx 0.51\ m^2$; Racing: $C_DA \approx 0.30\ m^2$	



40% ↓

Body	C_D based on frontal area							
Cone:	θ:	10°	20°	30°	40°	60°	75°	90°
	C_D:	0.30	0.40	0.55	0.65	0.80	1.05	1.15
Short cylinder, laminar flow:	L/D:	1	2	3	5	10	20	40	∞
	C_D:	0.64	0.68	0.72	0.74	0.82	0.91	0.98	1.20
Porous parabolic dish [23]:	Porosity:	0	0.1	0.2	0.3	0.4	0.5	
	← C_D:	1.42	1.33	1.20	1.05	0.95	0.82	
	→ C_D:	0.95	0.92	0.90	0.86	0.83	0.80	
Average person:	→ $C_DA \approx 9\ ft^2$	↑ $C_DA \approx 1.2\ ft^2$						
Pine and spruce trees [24]:	U, m/s:	10	20	30	40			
	C_D:	1.2 ± 0.2	1.0 ± 0.2	0.7 ± 0.2	0.5 ± 0.2			
Tractor-trailer truck:	Without deflector: 0.96; with deflector: 0.76							

Body	Ratio	C_D based on frontal area	
Rectangular plate:	b/h 1	1.18	
	5	1.2	
	10	1.3	
	20	1.5	
	∞	2.0	
		Laminar	Turbulent
Ellipsoid:	L/d 0.75	0.5	0.2
	1	0.47	0.2
	2	0.27	0.13
	4	0.25	0.1
	8	0.2	0.08

Body	Ratio	C_D based on frontal area
Flat-faced cylinder:	L/d 0.5	1.15
	1	0.90
	2	0.85
	4	0.87
	8	0.99
Buoyant rising sphere [50], $135 < Re_d < 1E5$		$C_D \approx 0.95$

$C_D \simeq 0.5$

$$C_D = \frac{D}{\frac{1}{2}\rho U^2 A} \Rightarrow C_DA = \frac{D}{\frac{1}{2}\rho U^2}$$

$C_DA = 9\ ft^2$
$= 9 \times 0.3048^2\ m^2$
$= 0.81\ m^2$
100 m 10 s
$v = \frac{100}{10} = 10\ m/s$
$D = C_DA \cdot \frac{1}{2}\rho v^2$
$= 0.81 \times \frac{1}{2} \times 1.2 \times 10^2$
$\simeq 50$ N

plate
$C_D \doteq 1$, $C_D \simeq 0.5 \sim 0.8$