



Copertina

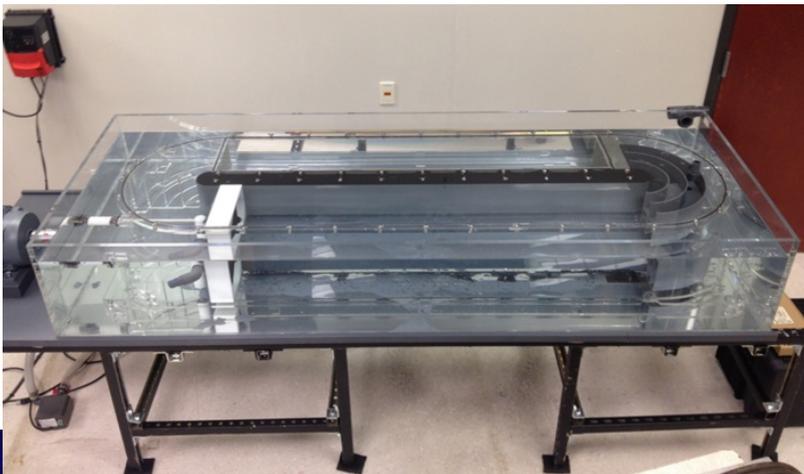
# Corso di Fisica dello Strato Limite Atmosferico

## Considerazioni sui regimi di flusso a partire dalle equazioni di Navier-Stokes e da esperimenti

## La dinamica dei fluidi deve molto agli esperimenti di laboratorio

Quasi tutto quello che conosciamo sul comportamento dei fluidi in movimento deriva da una forte sinergia tra risultati sperimentali e studi teorici a partire dalle equazioni di Navier-Stokes

Oggi, XXI secolo, anche le simulazioni numeriche danno un contributo significativo, specialmente nelle applicazioni



## Considerazioni derivanti dall'osservazione del moto di un fluido attorno ad oggetto

Un esperimento condotto sin dai tempi di Osborne Reynolds (1842 – 1912) e George Gabriel Stokes (1819 – 1903) è quello di osservare gli effetti di un corpo immerso in un fluido che al contorno ha un moto omogeneo e costante

Cilindro o sfera immersa nel fluido

$\vec{V}$

$\rho$

$\vec{F} = (D, L)$

Drag Lift [N]

$C_D = \frac{D}{1/2\rho v^2 S}$

$C_L = \frac{L}{1/2\rho v^2 S}$

Misurare la forza per unità di superficie agente sul corpo immerso

Osservare cosa accade al fluido nei pressi della superficie confinante

Osservazione dello strato limite (boundary layer)

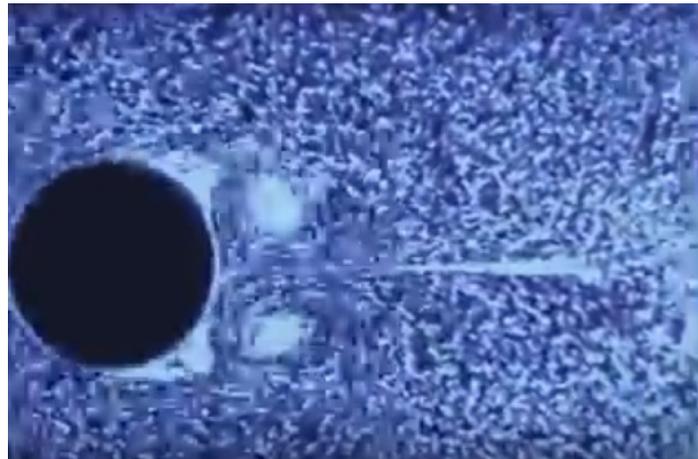
Drag coefficients  
Coefficienti di resistenza (adimensionali)

3

## Gli esperimenti e la scelta del numero di Reynolds

Gli esperimenti vengono svolti con opportune scelte della velocità, viscosità cinematica e dimensioni dei corpi immersi in modo da coprire il più ampio dominio di esistenza del numero di Reynolds

Per esempio si veda: <https://www.youtube.com/watch?v=hrX11VtXXsU>



Per distrarsi un po' imparando si guardino le lezioni filmate negli anni 60  
Ascher Herman Shapiro (1916 — 2004) Prof al MIT.

Part I <https://www.youtube.com/watch?v=Lp3OHZnt7Iw>

Part II [https://www.youtube.com/watch?v=Js3i8xJ\\_S3Y](https://www.youtube.com/watch?v=Js3i8xJ_S3Y)

Part III <https://www.youtube.com/watch?v=r3hZnKoz1F0>

Part IV <https://www.youtube.com/watch?v=acySDnGYzVM>

Anche <https://www.youtube.com/watch?v=wMxK2GtFFq0>

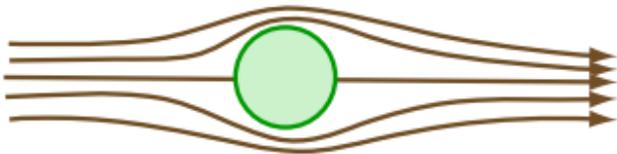
Per ulteriori informazioni si veda <http://web.mit.edu/hml/ncfmf.html>

## Il comportamento del fluido nei pressi del corpo immerso all'aumentare di $Re$ (a)

Le osservazioni del comportamento del fluido nei pressi del corpo immerso mostrano diversi regimi.

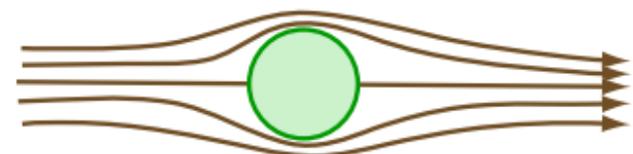
Tali regimi sono funzione del numero di Reynolds ( $Re$ ), quindi le soluzioni delle equazioni di Navier-Stokes hanno soluzioni ben diverse a seconda del numero  $Re$

$Re \ll 1$



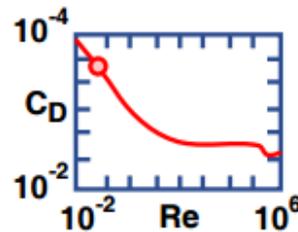
(A)

$Re \simeq 1$

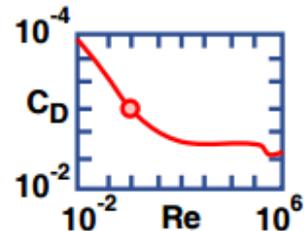


(B)

- streamlines symmetrical fore and aft, qualitatively like inviscid flow
- creeping flow; Stokes' Law holds
- disturbance in velocity extends many sphere diameters away



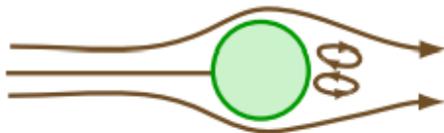
- streamlines converge more slowly than diverge
- still creeping flow, Stokes' Law holds to about this point
- disturbance in velocity still extends far away



$Re$  1  
D 0.11 mm  
W 0.9 cm/s

## Il comportamento del fluido nei pressi del corpo immerso all'aumentare di $Re$ (b)

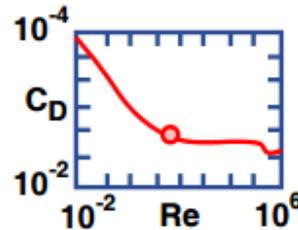
$Re \simeq 10 - 100$



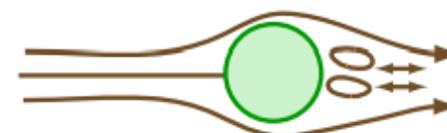
(C)

- there's a ring or "doughnut" with closed circulation behind sphere. it's stable
- outside the ring, streamlines depart from sphere surface; precursor to fully separated flow

Re	10	100
D	0.27 mm	0.81 mm
W	3.7 cm/s	12.4 cm/s



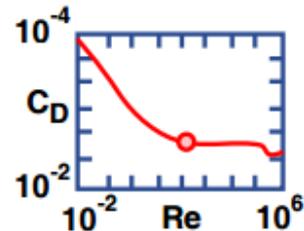
$Re \simeq 10 - 150$



(D)

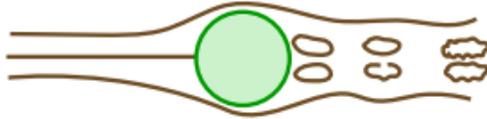
- the ring vortex oscillates back and forth in position with time

Re	100	150
D	0.81 mm	0.99 mm
W	12.4 cm/s	15.3 cm/s



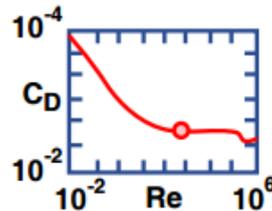
## Il comportamento del fluido nei pressi del corpo immerso all'aumentare di $Re$ (c)

**Re = 150 - thousands**



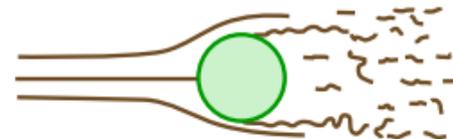
**(E)**

- cyclic shedding of ring vortices: ring breaks away, drifts downstream in wake flow, degenerates; a new ring forms behind sphere



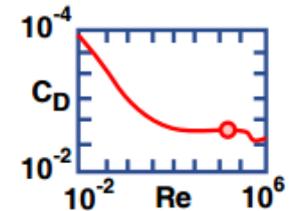
Re	1000	10,000
D	2.8 mm	15.5 mm (a marble)
W	3.5 cm/s	80 cm/s

**Re = thousands -  $2 \times 10^5$**



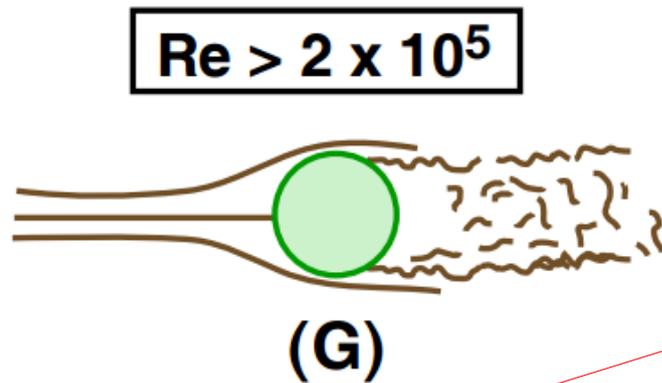
**(F)**

- gradual development of sharply separated flow
- gradual decrease in regularity of vortex structure in wake of sphere until fully turbulent
- boundary layer is progressively thinner on front surface
- boundary layer still laminar



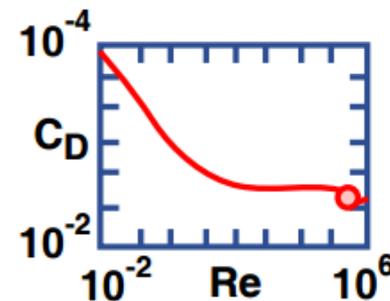
Re	10,000	200,000
D	12.5 mm	96 mm (a grapefruit)
W	80 cm/s	210 cm/s

## Il comportamento del fluido nei pressi del corpo immerso all'aumentare di $Re$ (d)



La turbolenza è un fenomeno tipico per valori elevati del numero di Reynolds

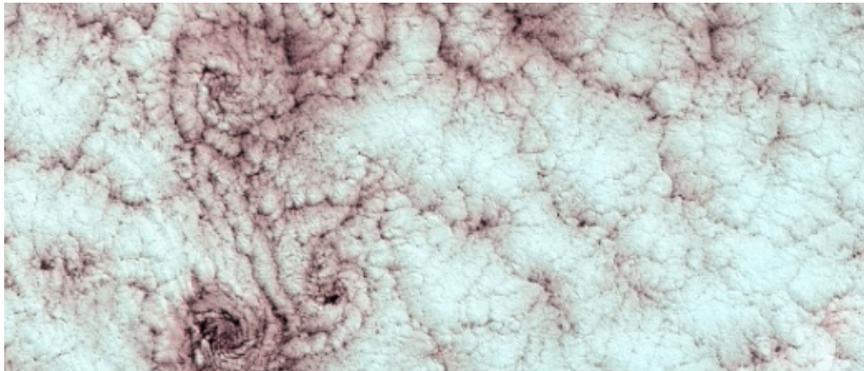
- boundary layer is turbulent
- separation point is farther back along sphere surface
- drag decreases abruptly in change from lam. to Turb. BL ("drag crisis")



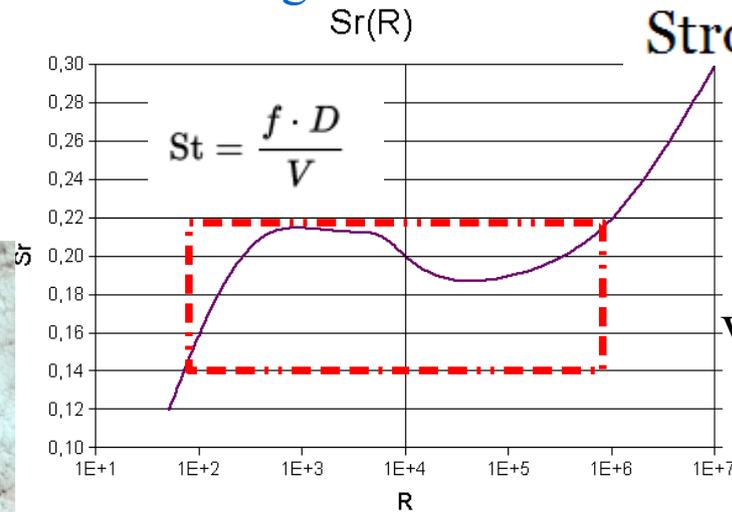
**Re 1,000,000**  
**D 219 mm (almost a basketball)**  
**W 460 cm/s (15 fps)**

## Esperimenti di laboratorio e comportamenti analoghi in atmosfera

Vortici di Von-Karman  
Isola-Juan-Fernandez  
Cile



Isola, corpo immerso nel  
fluido atmosferico



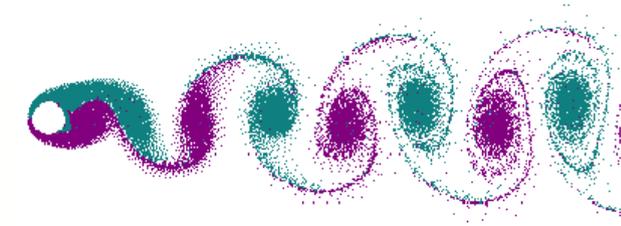
### Strouhal number

$f$  is the vortex shedding frequency,  
 $D$  is the diameter of the cylinder,  
 $V$  is the flow velocity.

Vortici di Von-Karman  
Isola-Jan Mayen  
Norvegia



## Una quadro complessivo del comportamento del moto di un fluido incomprimibile



**Table 1.1.** Flow regimes at a circular cylinder (incompressible flow)

Reynolds number  $Re = V d / \nu$   
Strouhal number  $Sr = f d / V$

Reynolds number regime	Flow regime	Flow form	Flow characteristic	Strouhal number $Sr$	Drag coefficient $c_D$	Separation angle $\Theta_S$
$Re \rightarrow 0$	Creeping flow		Steady, no wake	–	see Fig. 1.12	–
$3 - 4 < Re < 30 - 40$	Vortex pairs in wake		Steady, symmetric separation	–	$1.59 < c_D < 4.52$ ( $Re = 30$ ) ( $Re = 40$ )	$130^\circ < \Theta_S < 180^\circ$ ( $Re = 35$ ) ( $Re = 5$ )
$\frac{30}{40} < Re < \frac{80}{90}$	Onset of Karman vortex street		Laminar, unstable wake	–	$1.17 < c_D < 1.59$ ( $Re = 100$ ) ( $Re = 30$ )	$115^\circ < \Theta_S < 130^\circ$ ( $Re = 90$ ) ( $Re = 35$ )
$\frac{80}{90} < Re < \frac{150}{300}$	Pure Karman vortex street		Karman vortex street	$0.14 < Sr < 0.21$		
$\frac{150}{300} < Re < \frac{10^5}{1.3 \cdot 10^5}$	Subcritical regime		Laminar, with vortex street instabilities	$Sr = 0.21$	$c_D \approx 1.2$	$\Theta_S \approx 80^\circ$
$\frac{10^5}{1.3 \cdot 10^5} < Re < 3.5 \cdot 10^6$	Critical regime		Laminar separation Turbulent reattachment Turbulent separation Turbulent wake	No preferred frequency	$0.2 < c_D < 1.2$	$80^\circ < \Theta_S < 140^\circ$
$3.5 \cdot 10^6 < Re$	Supercritical regime (transcritical)		Turbulent separation	$0.25 < Sr < 0.30$	$c_D \approx 0.6$	$\Theta_S \approx 115^\circ$



## La viscosità e la viscosità cinematica per l'acqua e l'aria

La viscosità dell'acqua dipende pochissimo dalla pressione e diminuisce con l'aumento della Temperatura

La viscosità dell'aria dipende poco dalla pressione (a bassi valori) e aumenta con la Temperatura

Table 1.2. Density, viscosity, and kinematic viscosity of water and air in terms of temperature

Temperature °C	W a t e r			A i r at a pressure of 0.099 MPa (14.696 lbf/in <sup>2</sup> )		
	Density $\rho$ kg/m <sup>3</sup>	Viscosity $\mu$ Pa sec	Kinematic viscosity $\nu \times 10^6$ [ft <sup>2</sup> /sec]	Density $\rho$ kg/m <sup>3</sup>	Viscosity $\mu$ $\mu$ Pa sec	Kinematic viscosity $\nu \times 10^6$ m <sup>2</sup> /sec
-20	—	—	—	1.39	15.6	11.2
-10	—	—	—	1.34	16.2	12.1
0	999.3	1795	1.80	1.29	16.8	13.0
10	999.3	1304	1.30	1.25	17.4	13.9
20	997.3	1010	1.01	1.21	17.9	14.8
40	991.5	655	0.661	1.12	19.1	17.1
60	982.6	474	0.482	1.06	20.3	19.2
80	971.8	357	0.367	0.99	21.5	21.7
100	959.1	283	0.295	0.94	22.9	24.4

## Variazioni significative del comportamento del moto di un fluido incomprimibile (a)

Al variare del numero di Reynolds il moto di un fluido nei pressi di un corpo immerso manifesta bruschi cambiamenti di regime. I coefficienti di resistenza diminuiscono sino al crollo per  $R = 2 \times 10^5$

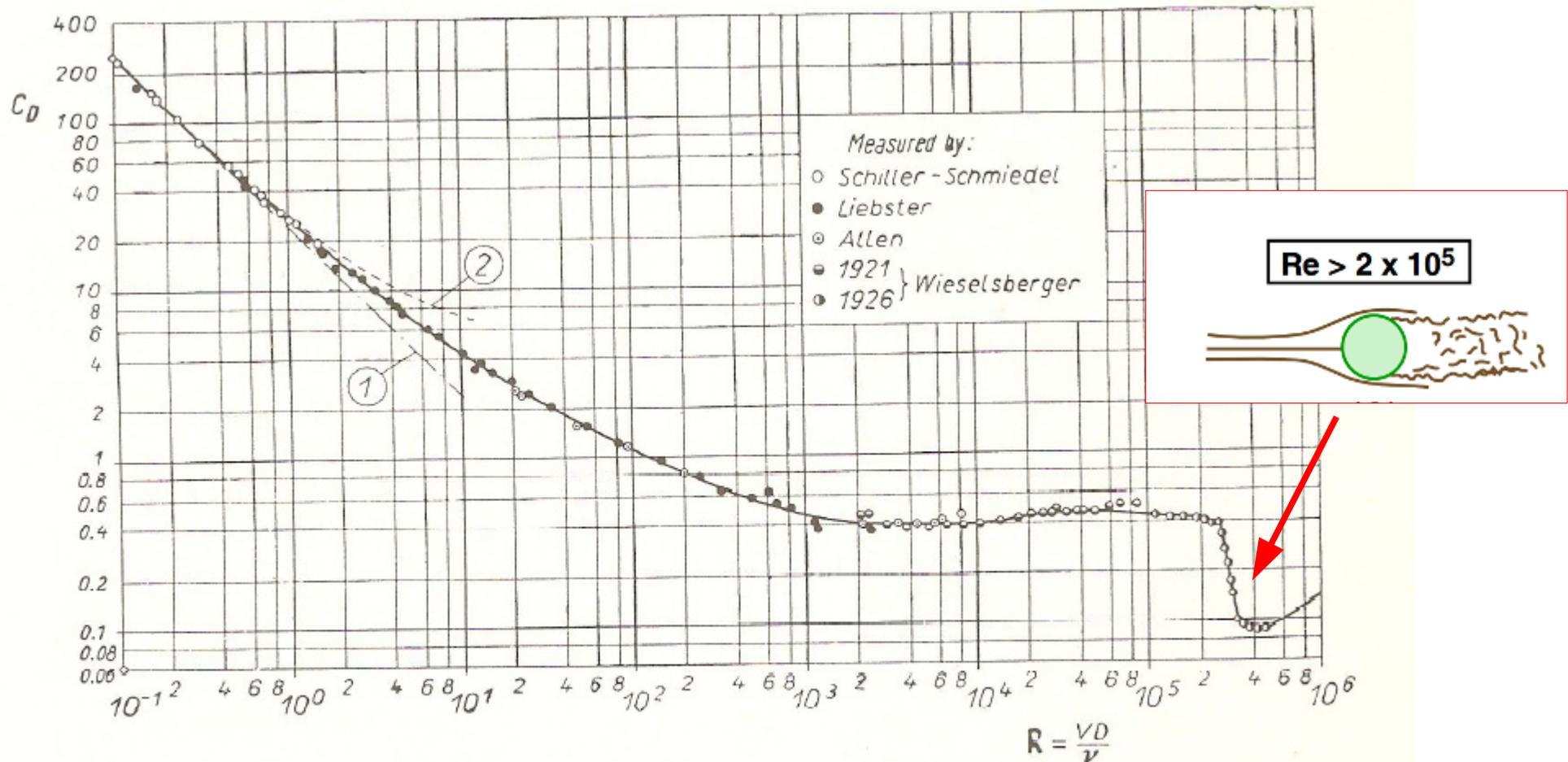


Fig. 1.5. Drag coefficient for spheres as a function of the Reynolds number  
Curve (1): Stokes's theory, eqn. (0.10); curve (2): Oseen's theory, eqn. (6.13)

## Variazioni significative del comportamento del moto di un fluido incompressibile (b)

Dopo la zona critica, ( $R_e = 2 \times 10^5$ ), all'aumentare del numero di Reynolds i coefficienti di resistenza aumentano nuovamente. Nel caso in cui il fluido sia supersonico la zona critica non viene rilevata.

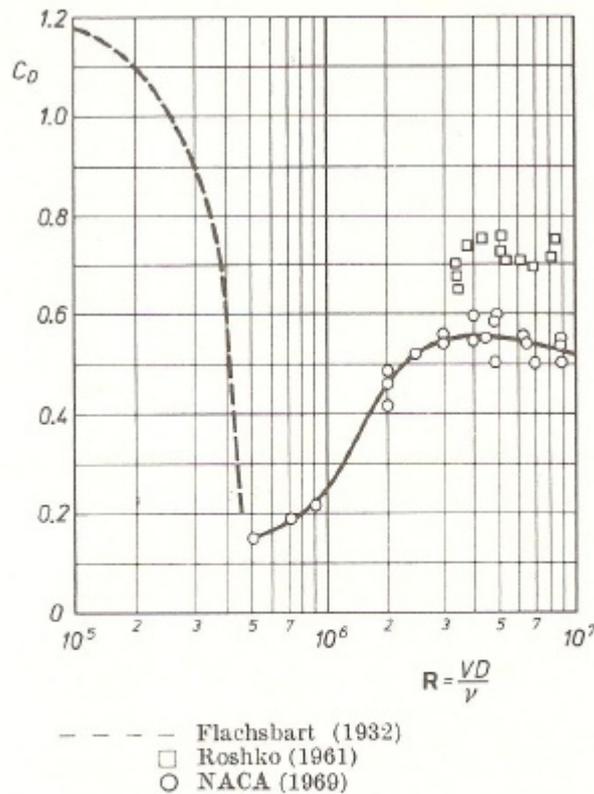


Fig. 1.7. Drag coefficient of a circular cylinder at very large Reynolds numbers and for Mach numbers  $M < 0.2$  after the measurements of A. Roshko [13] and G. W. Jones, J. J. Cinotta and R. W. Walker [8]

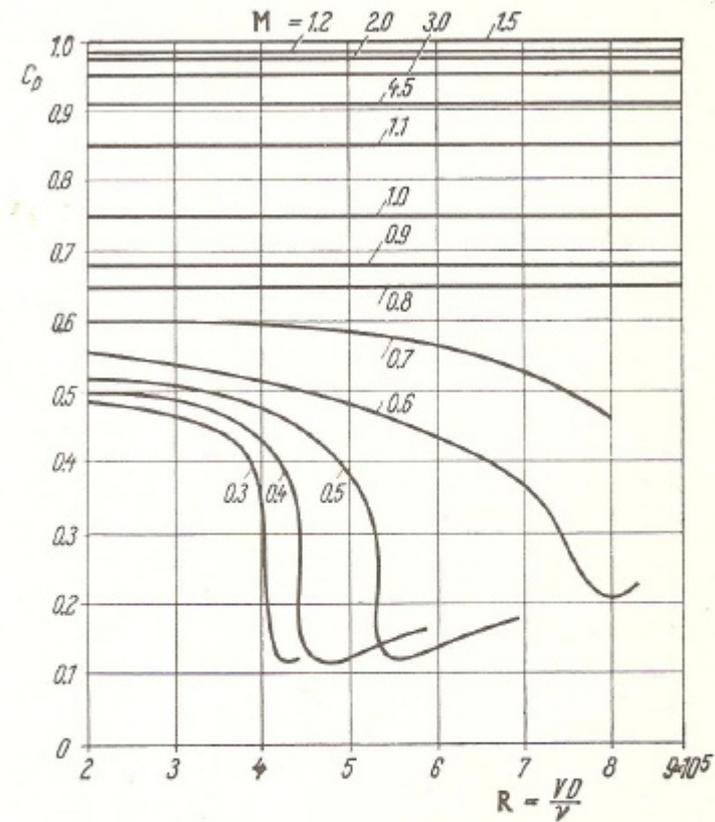
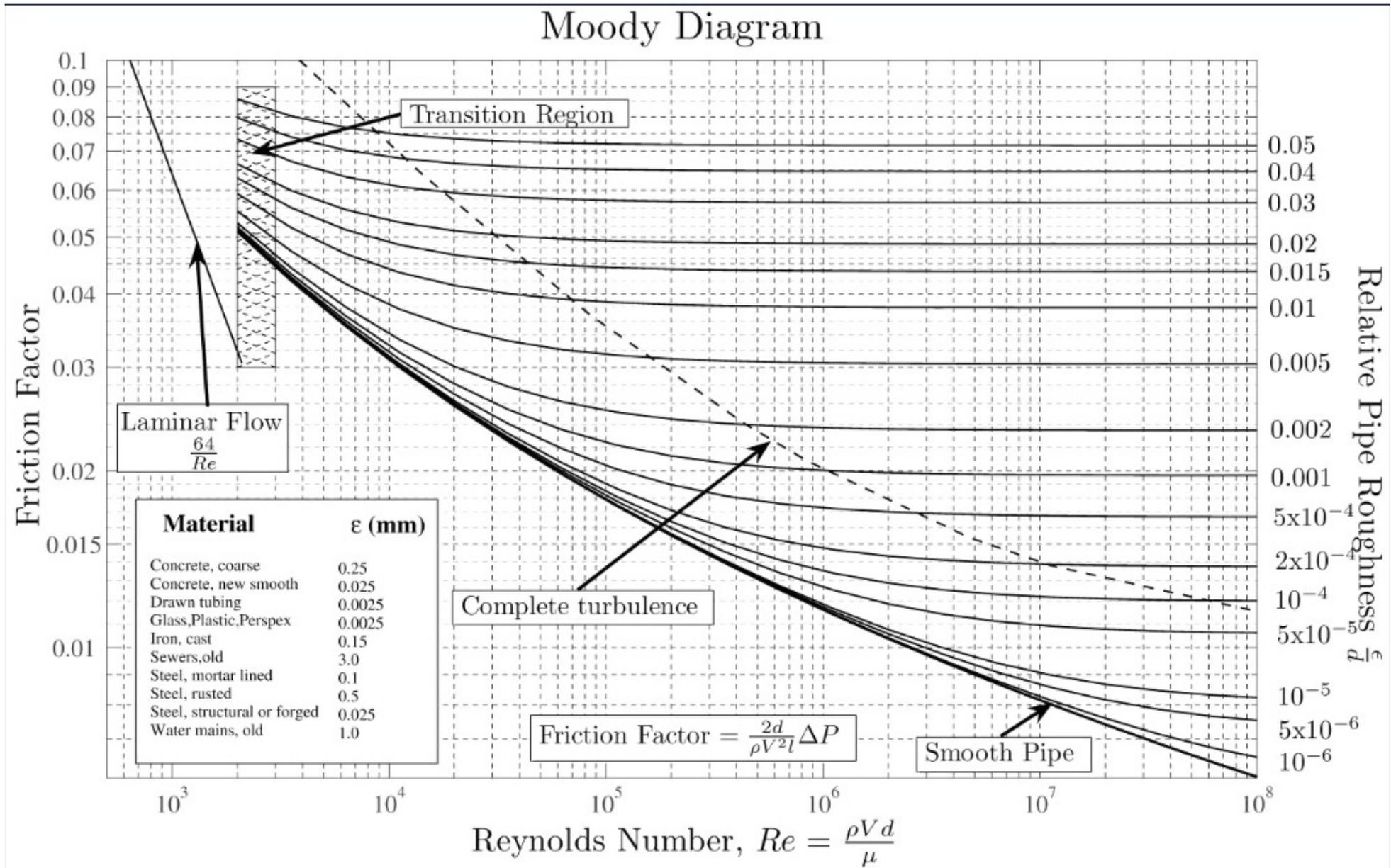


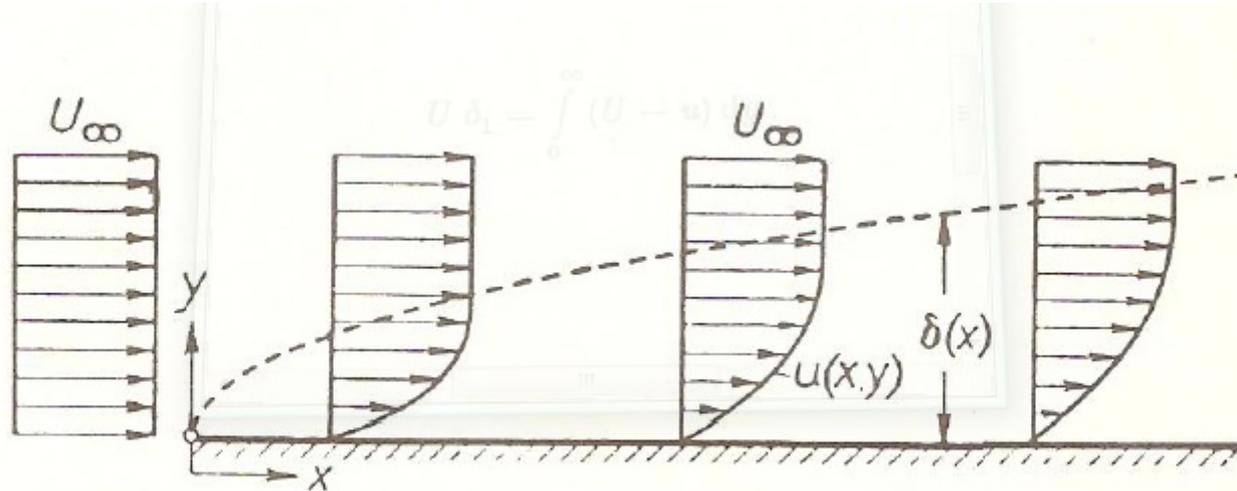
Fig. 1.8. Drag coefficient of spheres in terms of the Reynolds and Mach numbers as measured by A. Naumann [9, 10]



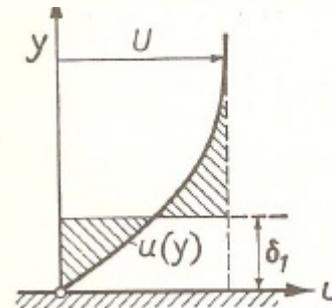
## La rugosità e i suoi effetti sul regime del fluido



## Spessore dello strato limite in moti laminari



$$U \delta_1 = \int_0^{\infty} (U - u) dy .$$



Nel caso di fluidi con numero di Reynolds elevato, si ha il fenomeno della separazione

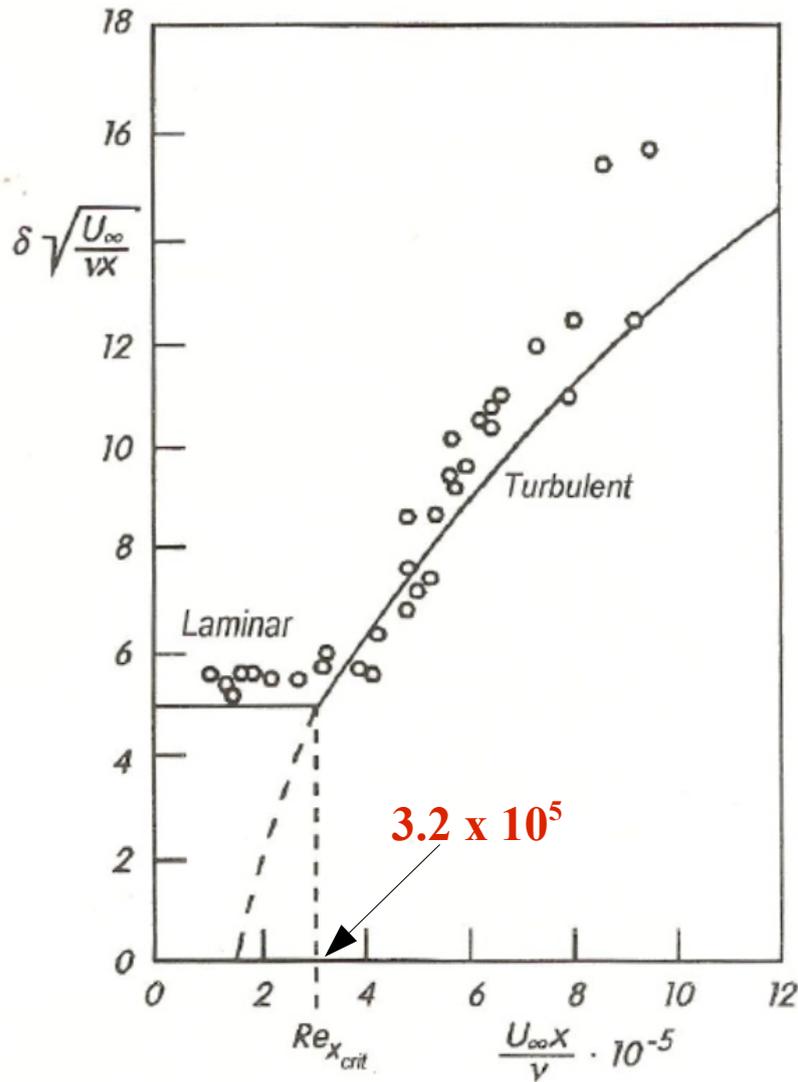
## Lo spessore dello strato limite in caso di moti su superfici piane per regimi turbolenti

**Table 2.1.** Boundary-layer thickness  $\delta$  and thickness of the viscous sublayer  $\delta_v$  at the end of a flat plate at zero incidence in turbulent flow according to Eqs. (2.12) and (2.15).  $l$ : plate length,  $U_\infty$ : free stream velocity,  $\nu$ : kinematic viscosity

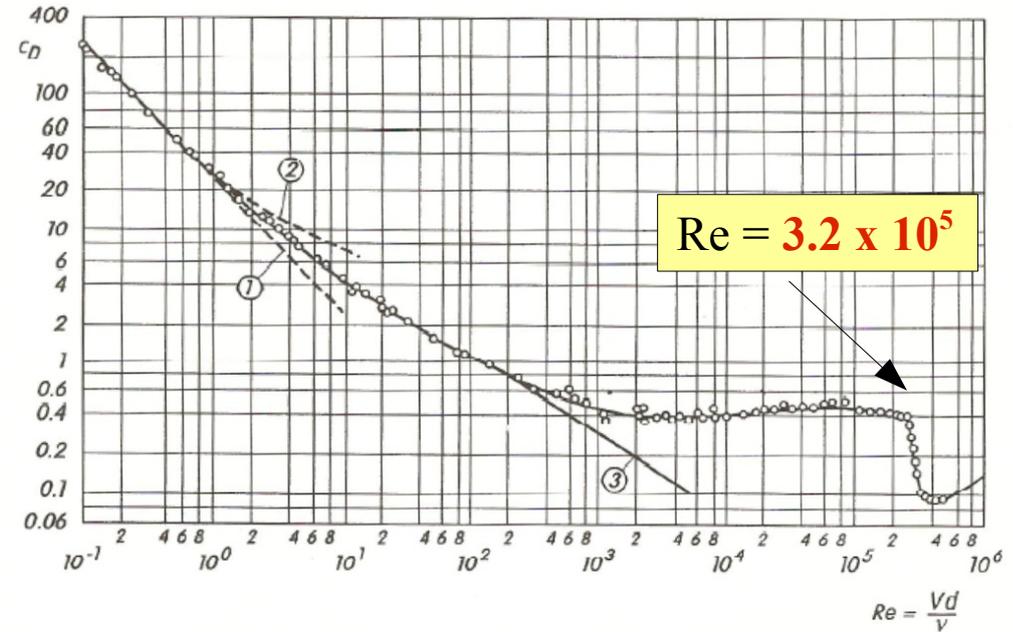
	$\frac{U_\infty}{\text{m/s}}$	$\frac{l}{\text{m}}$	$\text{Re} = \frac{U_\infty l}{\nu}$	$\frac{\delta}{\text{mm}}$	$\frac{\delta_v}{\text{mm}}$
air $\nu = 15 \cdot 10^{-6} \frac{\text{m}^2}{\text{s}}$	50	1	$3.3 \cdot 10^6$	8	0.4
	100	1	$6.6 \cdot 10^6$	8	0.2
	100	5	$3.3 \cdot 10^7$	36	0.2
	200	10	$1.3 \cdot 10^8$	69	0.1
water $\nu = 10^{-6} \frac{\text{m}^2}{\text{s}}$	1	2	$2 \cdot 10^6$	17	1
	2	5	$1 \cdot 10^7$	39	0.6
	5	50	$2.5 \cdot 10^8$	321	0.4
	10	200	$2 \cdot 10^9$	1122	0.1

## Lo spessore dello strato limite e i regimi laminare e turbolento

La transizione avviene per numeri di Reynolds prossimi a  $3 \times 10^5$



**Fig. 2.4.** Dependence of the boundary-layer thickness on the distance along a plate at zero incidence, after M. Hansen (1928)  
laminar: Eq. (2.2)  
turbulent: Eq. (2.12) with fictitious origin at  $Re_x = 1.5 \cdot 10^5$



**Fig. 1.19.** Dependence of the drag coefficient of spheres on the Reynolds number  
Curve 1: theory, after G.G. Stokes (1856),  $c_D = 24/Re$   
Curve 2: theory, after C.W. Oseen (1911),  $c_D = 24/Re[1 + 3Re/16]$   
For the extension of this theory for higher Reynolds numbers, cf. M. Van Dyke (1964b)  
Curve 3: numerical results, after B. Fornberg (1988)  
Onset of unsteady flow at  $Re = 200$ , cf. U. Dallmann et al. (1993)