Boundary Layers – Pressure Gradient Effects

https://www.youtube.com/watch?v=VUiGhyHC-1A

no dimples: 26+ mpg
with dimples: 29+ mpg

A bit more on the topic:
https://www.theborneopost.com/2014/04/08/vehicle-aerodynamics-drag-reduction-through-surface-dimples/

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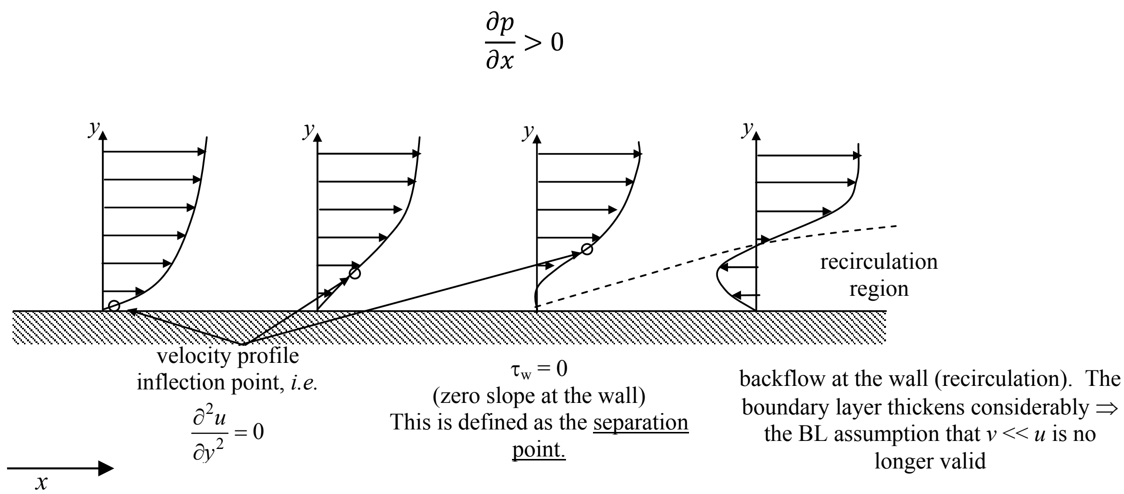

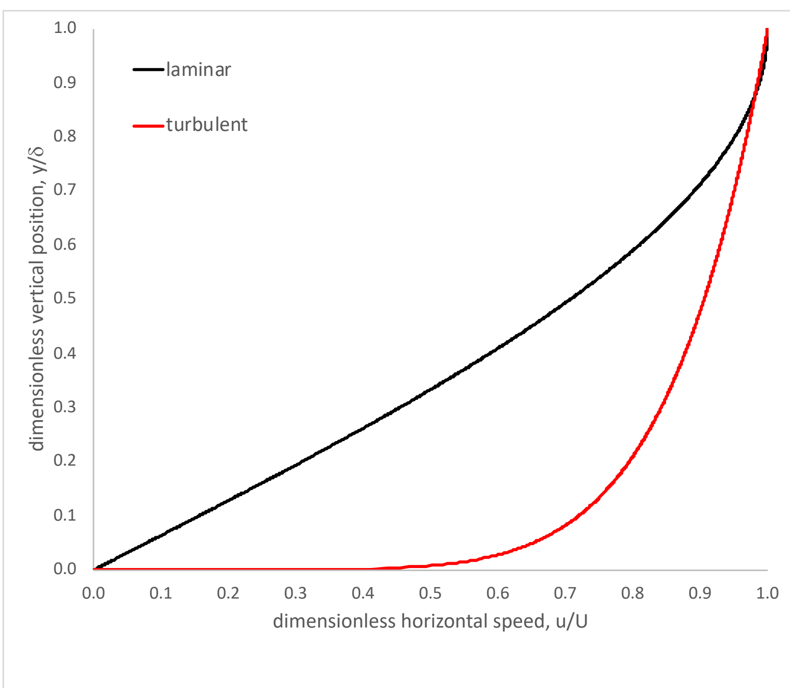

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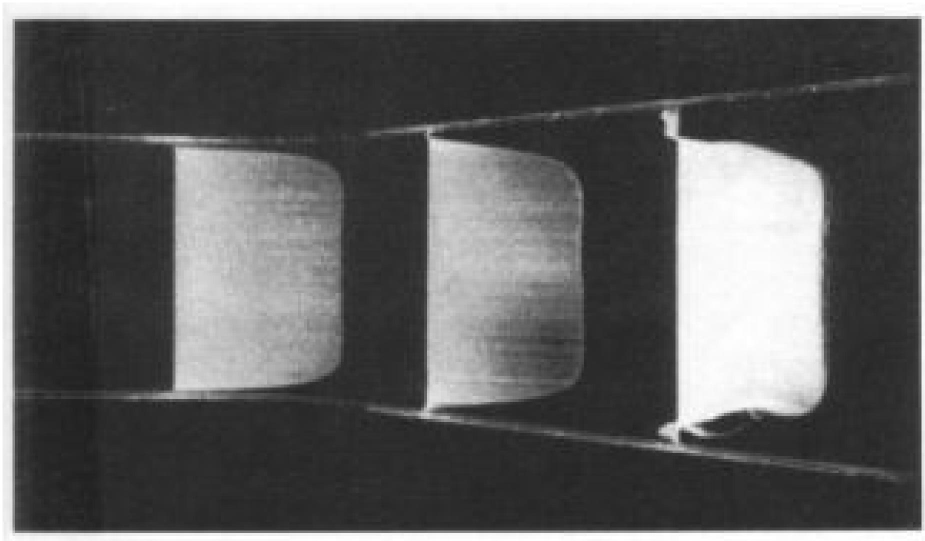

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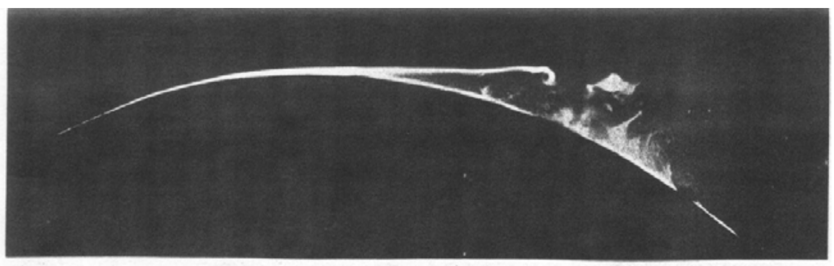
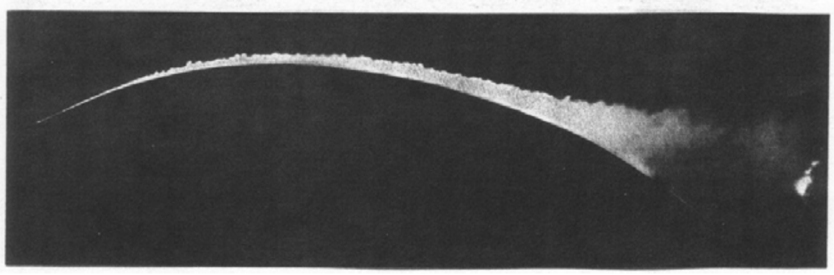
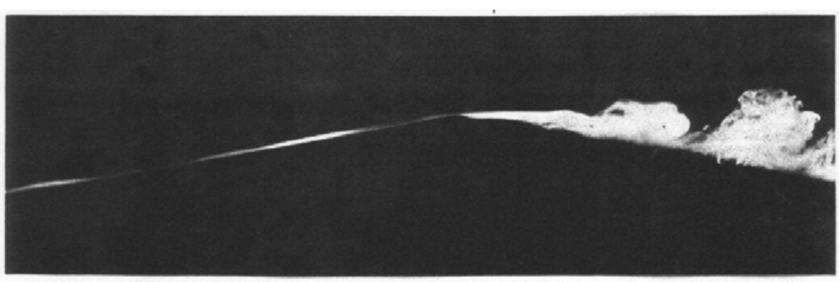
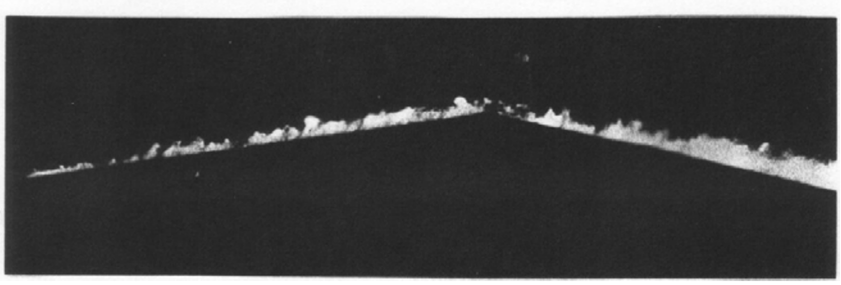
Bernoulli’s Eqn:









(From Van Dyke, M., *An Album of Fluid Motion*, Parabolic Press.)

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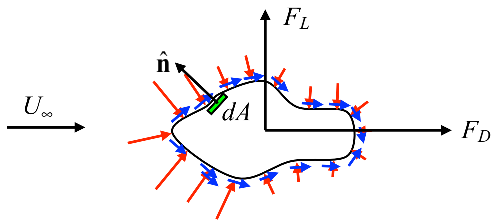
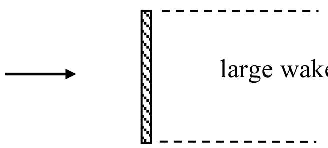
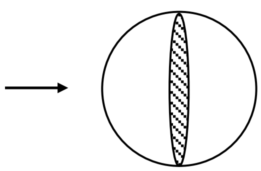
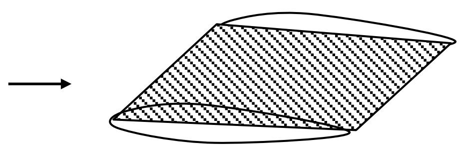


Two contributions to the total drag force:





bluff body
(use the frontal projected area)



streamlined body
(use the planform area)

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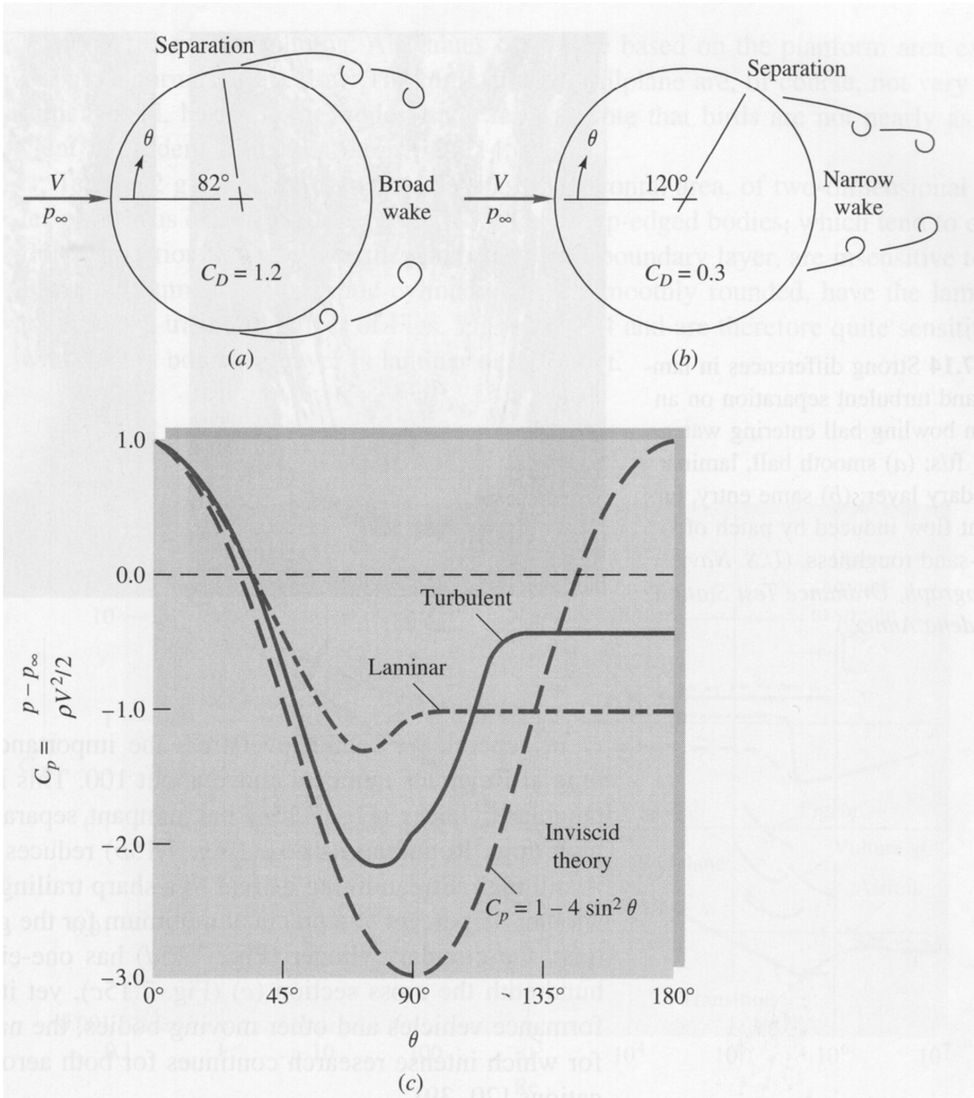


(From White, F.M., *Fluid Mechanics*, 3rd ed., McGraw-Hill.)

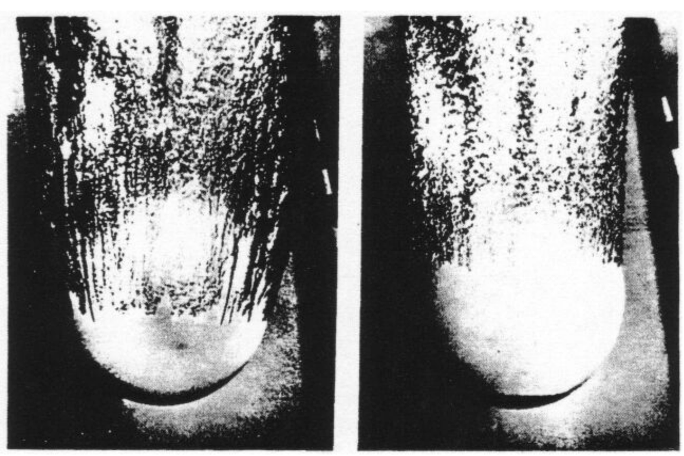


Fig. 7.14 Strong differences in laminar and turbulent separation on an 8.5-in bowling ball entering water at 25 ft/s: (*a*) smooth ball, laminar boundary layer; (*b*) same entry, turbulent flow induced by patch of nose-sand roughness. (*U.S. Navy photograph, Ordnance Test Station, Pasadena Annex.*)

Boundary Layers – Pressure Gradient Effects

Dimpled disc cycle wheels (from Zipp) for bicycle racing.
"…the Re_{cr} is reduced by the presence of the dimples….dimples make the flow turbulent at an earlier point so the more energetic turbulent flow may stay attached to the surface for longer."

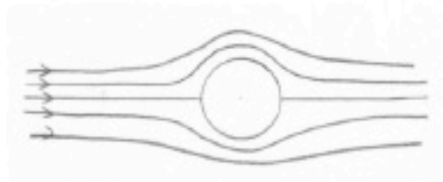
https://www.racecar-engineering.com/articles/technology/can-dimpled-aerodynamic-surfaces-reduce-drag/

Boundary Layers – Pressure Gradient Effects

Flow Around a Cylinder (or Sphere) As a Function of Reynolds Number

Note: $\mathrm{Re} = \dfrac{VD}{\nu}$

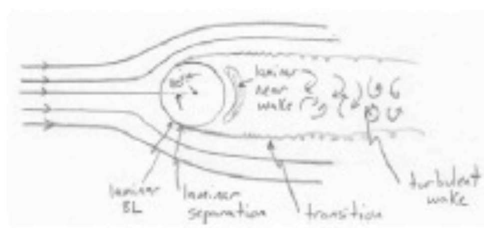
$\mathrm{Re} \ll 1$
(creeping or Stoke's flow)



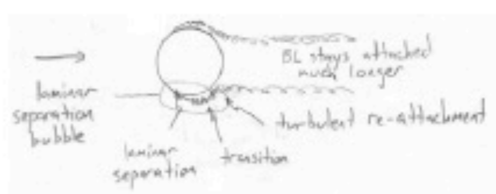
$5 < \mathrm{Re} < 50$
(fixed eddies)

$60 < \mathrm{Re} < 5000$
(Karman Vortex Street,
periodic shedding of vortices)

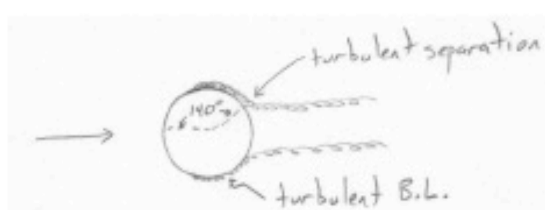
$5000 < \mathrm{Re} < 200{,}000$



$\mathrm{Re} \approx 200{,}000$
(drag crisis)



$\mathrm{Re} > 200{,}000$



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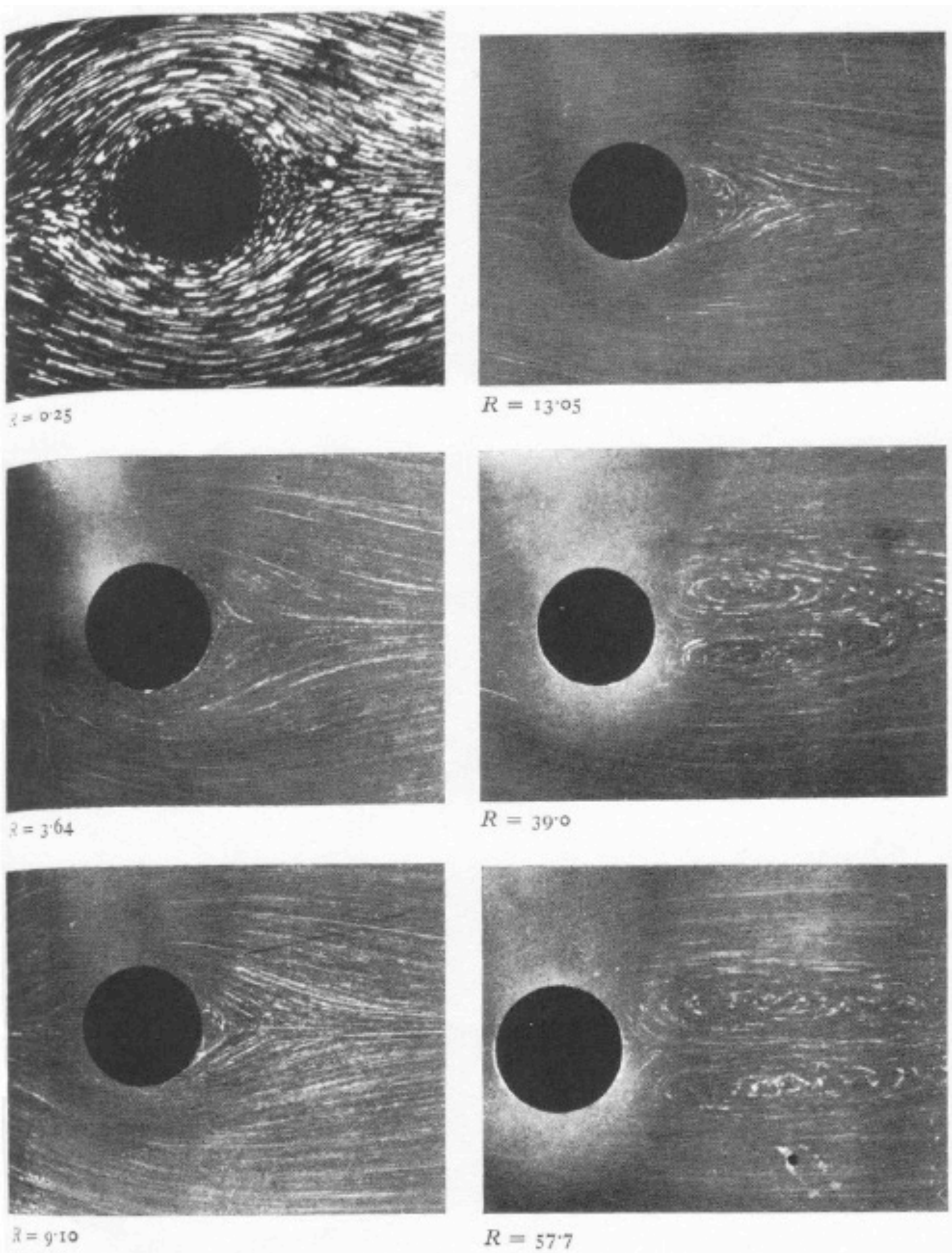
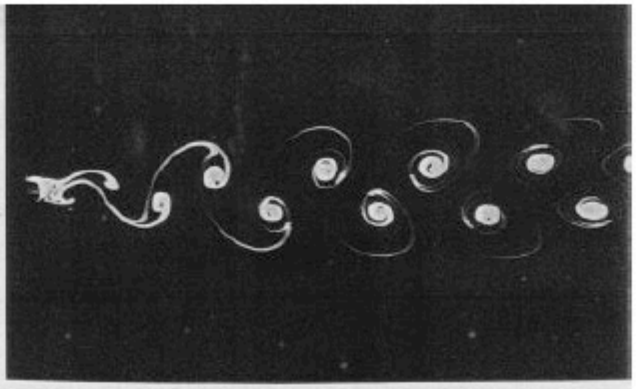


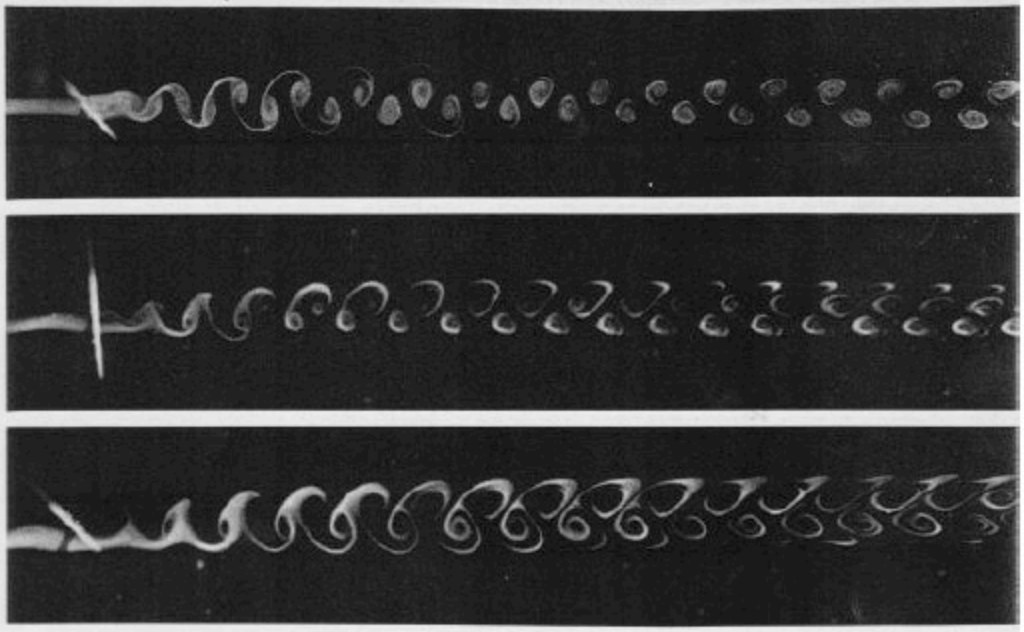
Figure 4.12.1. Streamlines of steady flow (from left to right) past a circular cylinder of radius a; $R = 2aU/\nu$. The photograph at $R = 0{\cdot}25$ (from Prandtl and Tietjens 1934) shows the movement of solid particles at a free surface, and all the others (from Taneda 1956*a*) show particles illuminated over an interior plane normal to the cylinder axis.

(From Batchelor, G.K., *An Introduction to Fluid Dynamics*, Cambridge University Press.)

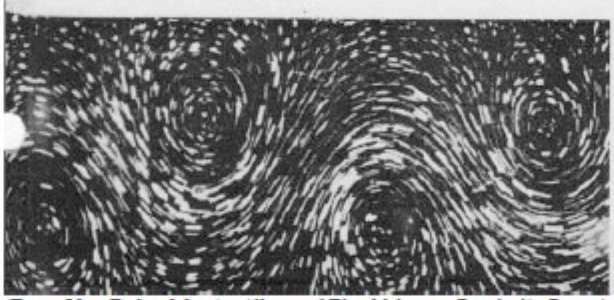
Boundary Layers – Pressure Gradient Effects

96. Kármán vortex street behind a circular cylinder at R=105. The initially spreading wake shown opposite develops into the two parallel rows of staggered vortices that von Kármán's inviscid theory shows to be stable when the ratio of width to streamwise spacing is 0.28. Streaklines are shown by electrolytic precipitation in water. *Photograph by Sadatoshi Taneda*





97. Smoke at various levels in a vortex street. A smoke filament in air shows, at a Reynolds number of 100, both shear layers (top photographs), only one shear layer (middle), and the irrotational flow below the wake (bottom). *Zdravkovich 1969*



98. Kármán vortices in absolute motion. Here the camera moves with the vortices rather than the cylinder. The streamline pattern closely resembles the inviscid one calculated by von Kármán. The flow is visualized by particles floating on water. *Photograph by R. Wille, from Wehle 1973. Reproduced, with permission, from the* Annual Review of Fluid Mechanics, *Volume 5, © 1973 by Annual Reviews Inc.*

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(From Van Dyke, M., *An Album of Fluid Motion*, Parabolic Press.)

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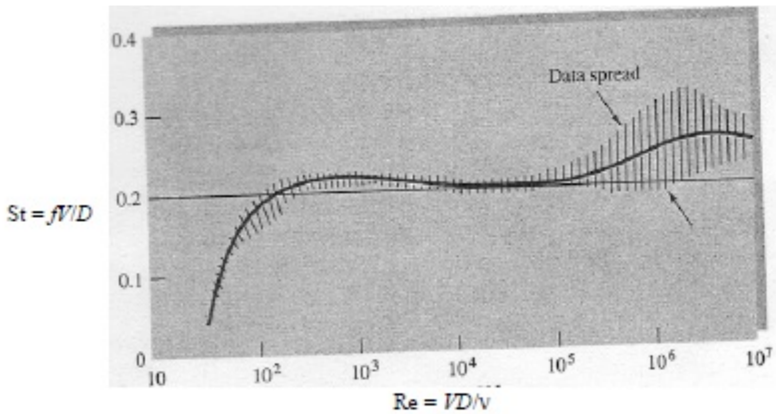

(Figure from White, F.M., *Fluid Mechanics*, McGraw-Hill.)

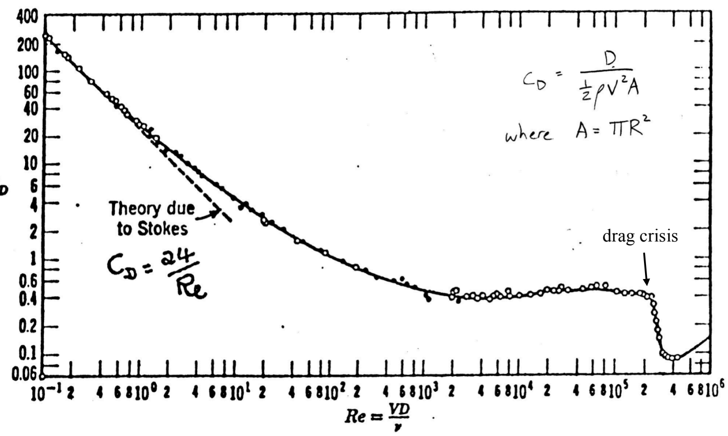

Fig. 8.32 Drag coefficient of a sphere as a function of Reynolds number (Ref. 13).

Commonly used curve fits to the curve shown above are:

- $Re_D < 1$: C_D = $24/Re_D$ (Stokes' drag law)
- $Re_D < 5$: C_D = $24/Re_D\,(1+3/16 Re_D)$ (Oseen's approximation)
- $0 \le Re_D \le 2*10^5$: C_D = $24/Re_D + 6/(1+Re_D^{0.5}) + 0.4$
- $Re_D < 2*10^5$: C_D = 0.44 (Newton's Law)

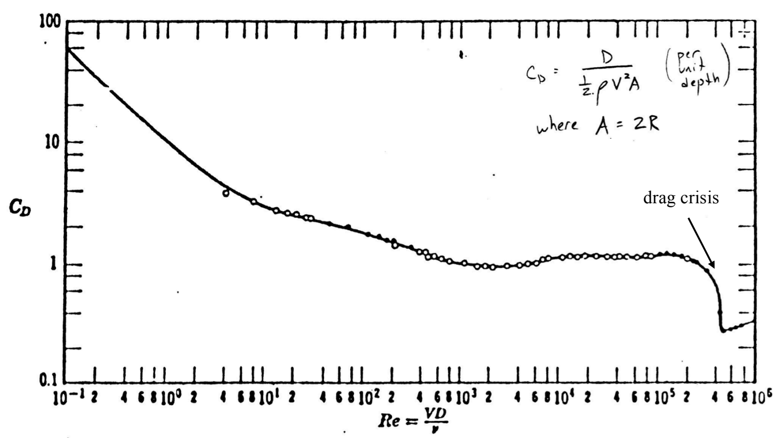

Fig. 8.34 Drag coefficient for circular cylinders as a function of Reynolds number (Ref. 13).