Aerodynamics of Sports Balls

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Unless Otherwise Specified, All Data From
Mehta, R.D., "Aerodynamics of Sports Balls"
Annual Review of Fluid Mechanics, 1985.17:15

Spherical Sports Balls

- Complex Aerodynamics : Rotation & Non-Uniform Surface
- Begin with Non-Rotating Uniform Sphere→Spherical Symmetry Implies Aerodynamic Force Must be Opposite to Direction of Flight (*Drag*)
- Then Consider Seams & Spin→Asymmetry→*Lift*

Drag on Non-Rotating Uniform Sphere

Dimensional Analysis

- Drag (F_D) Depends on:
  - Speed, V
  - Diameter, D
  - Density, ρ
  - Viscosity, μ
  - Roughness Length, k
- 6 Parameters Minus 3 Dimensions (Mass, Length, Time) = 3 Dimensionless Parameters
  - Significantly Reduce Experimental Testing Required
  - Match Re and ε to Find C_D and Then Compute Drag

$$F_D = f\left(V, D, \rho, \mu, k\right)$$

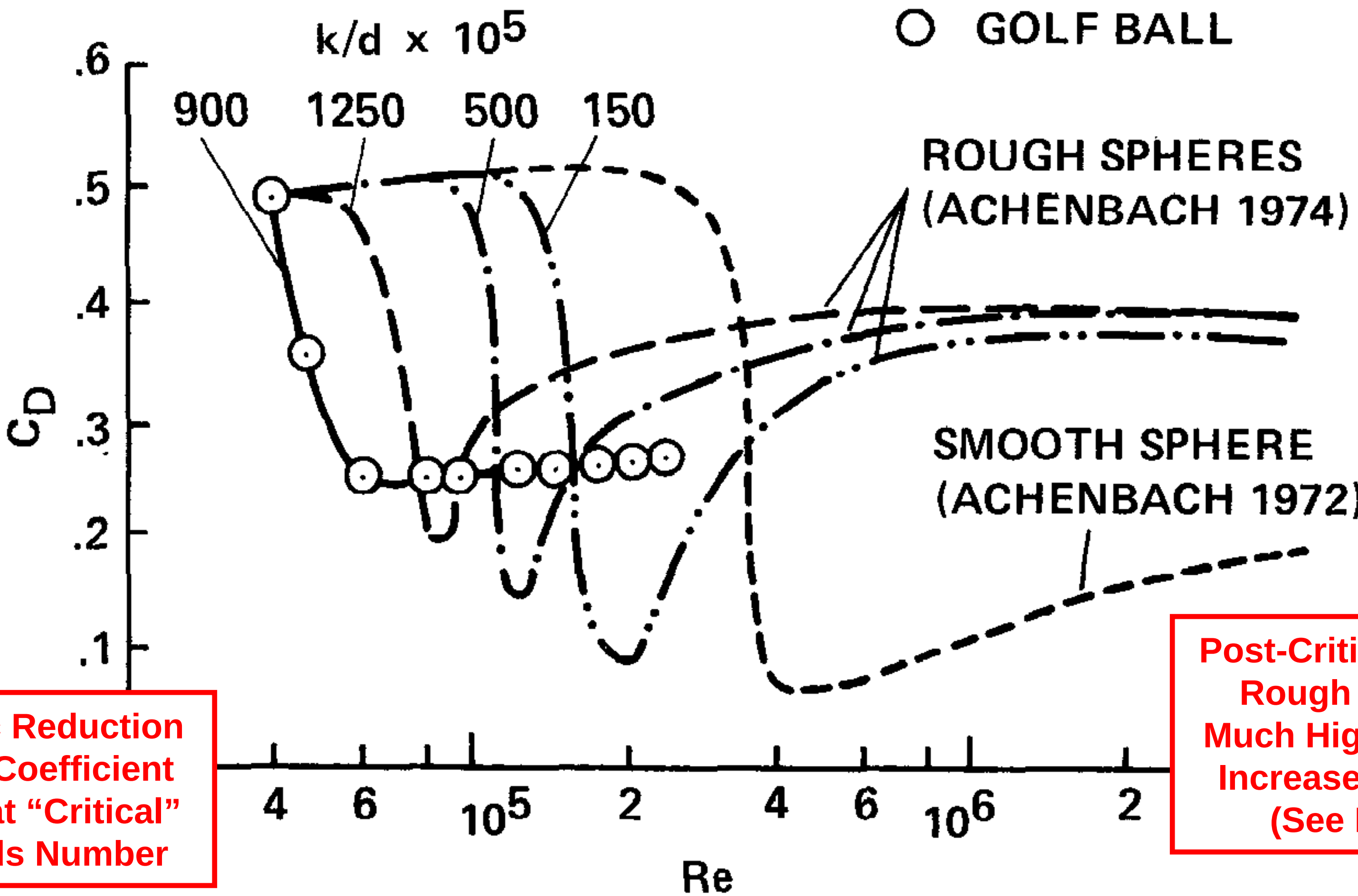
$$C_D \equiv \frac{F_D}{0.5\rho V^2 A}$$

$$\mathrm{Re} \equiv \frac{\rho V D}{\mu} \qquad \varepsilon \equiv \frac{k}{D}$$

$$C_D = \hat{f}\left(\mathrm{Re}, \varepsilon\right)$$

Experimental Data for Drag on Non-Rotating Uniform Spheres

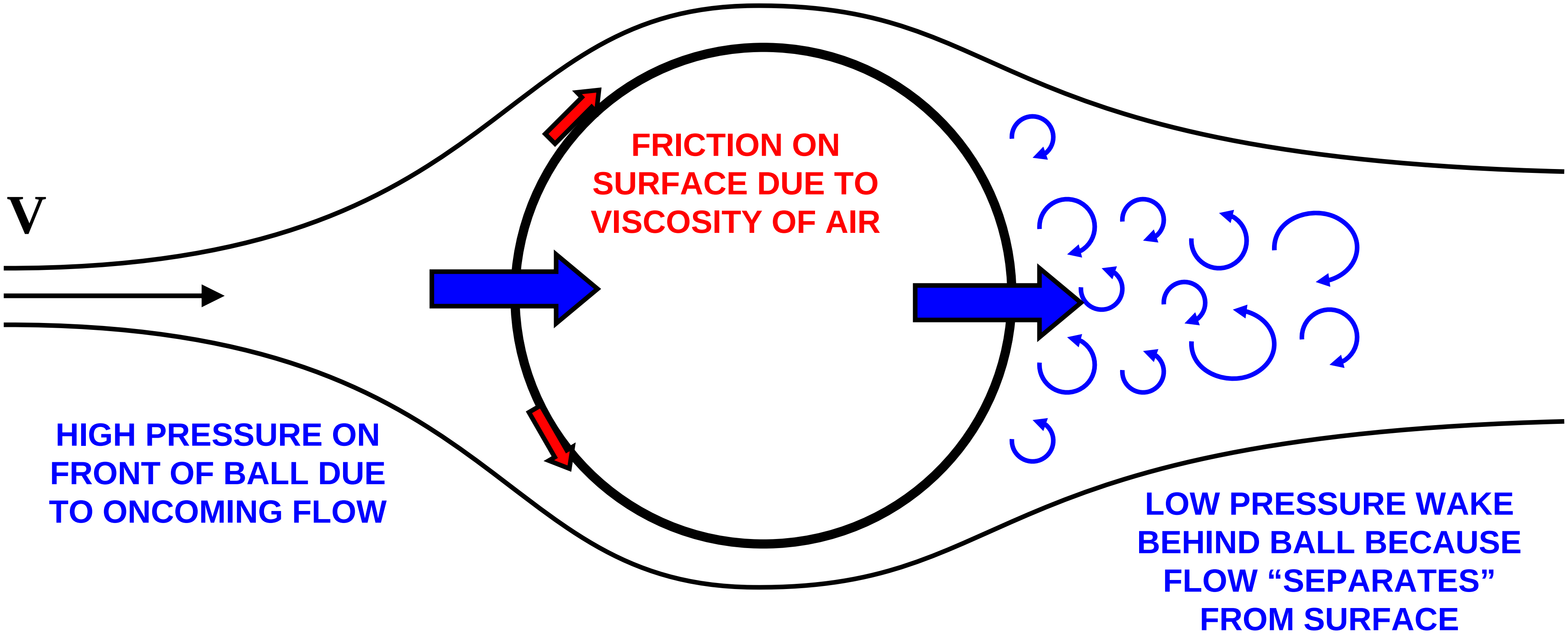
Dramatic Reduction in Drag Coefficient Occurs at "Critical" Reynolds Number



Post-Critical Drag of Rough Spheres Much Higher Due to Increased Friction (See Below)

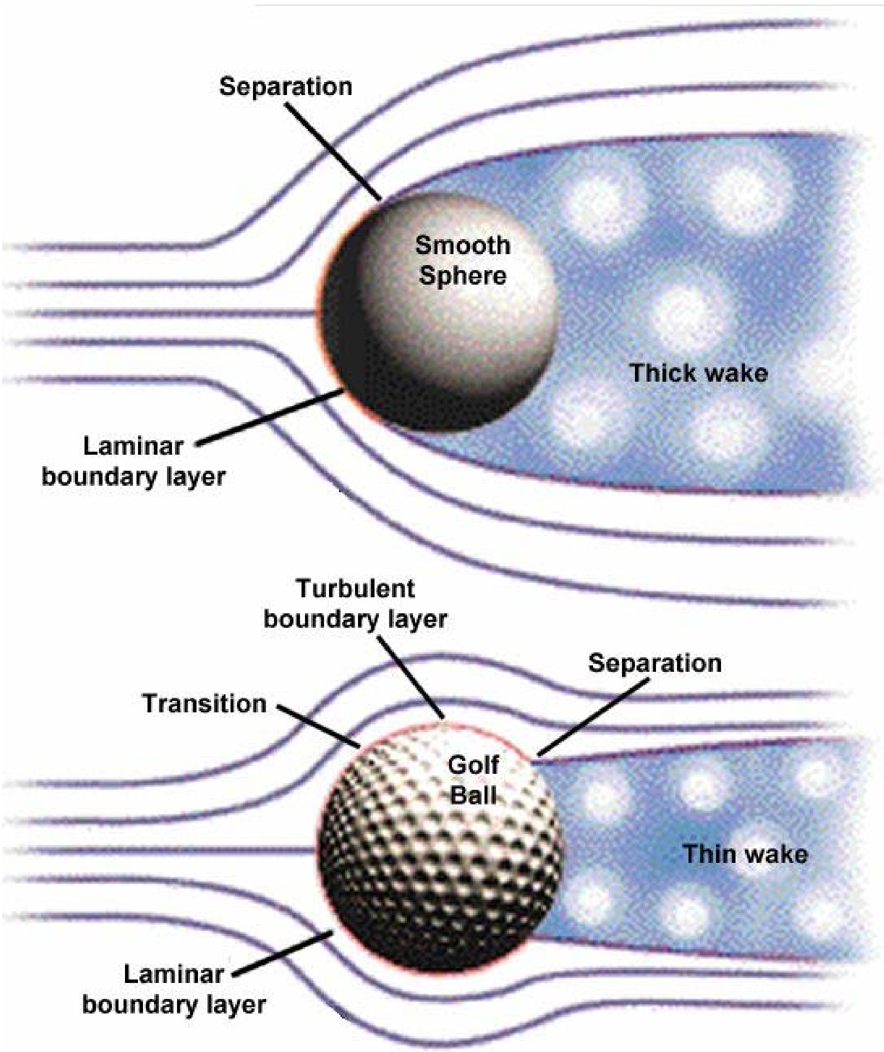
Figure 21 Variation of golf ball and sphere drag, where *k* is the sand-grain roughness height and *d* is the ball diameter (Bearman & Harvey 1976).

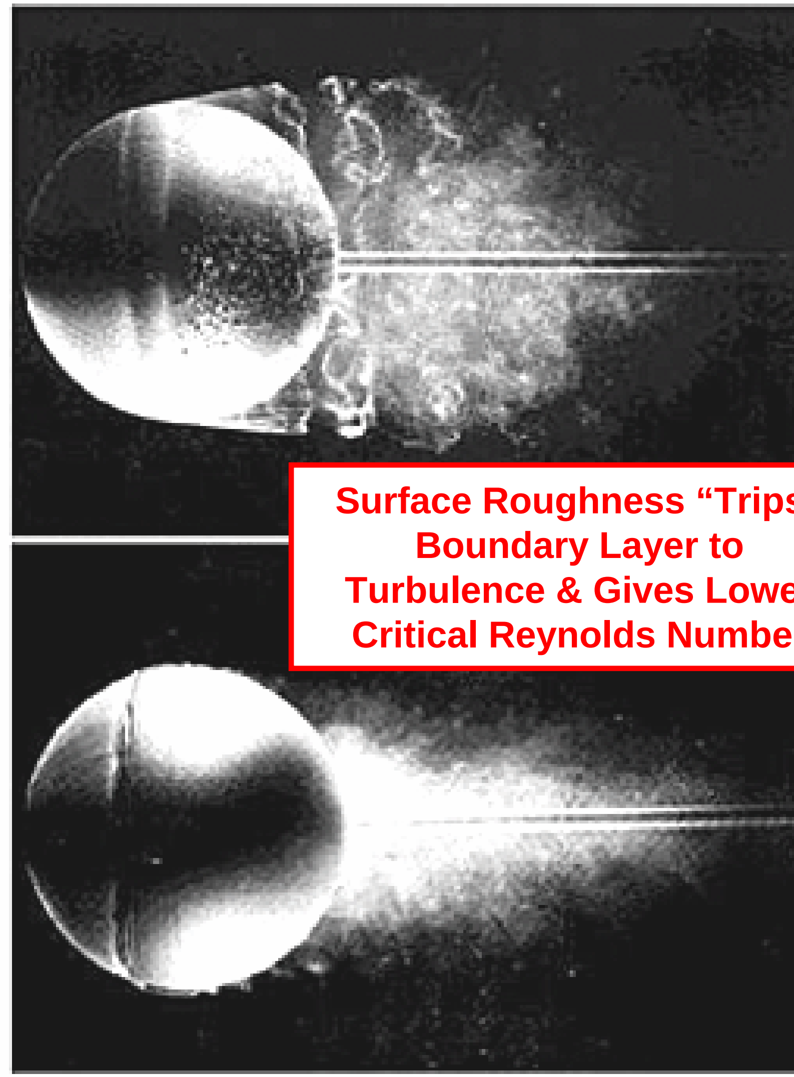
Two Sources of Aerodynamic Drag
Friction & Pressure



Pressure Drag Much Larger Than Friction Drag for Spheres @ Pre-Critical Reynolds Numbers

High Re or Surface Roughness→Turbulent Boundary Layer→Separation Delayed→Much Lower Pressure Drag



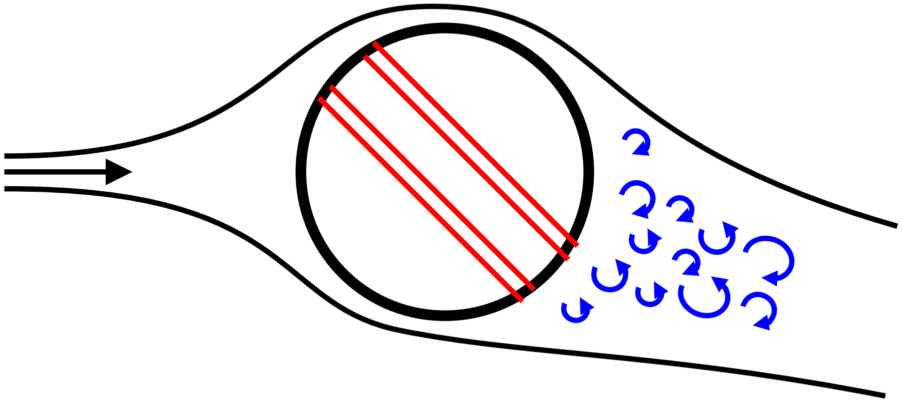


Surface Roughness “Trips” Boundary Layer to Turbulence & Gives Lower Critical Reynolds Number

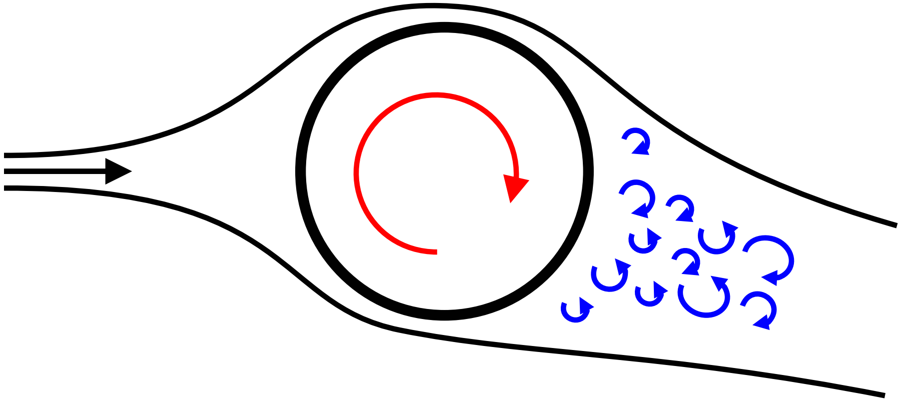
http://www.aerospaceweb.org/question/aerodynamics/q0215.shtml
http://www.scielo.br/scielo.php?pid=S0102-47442004000400003&script=sci_arttext&tlng=en

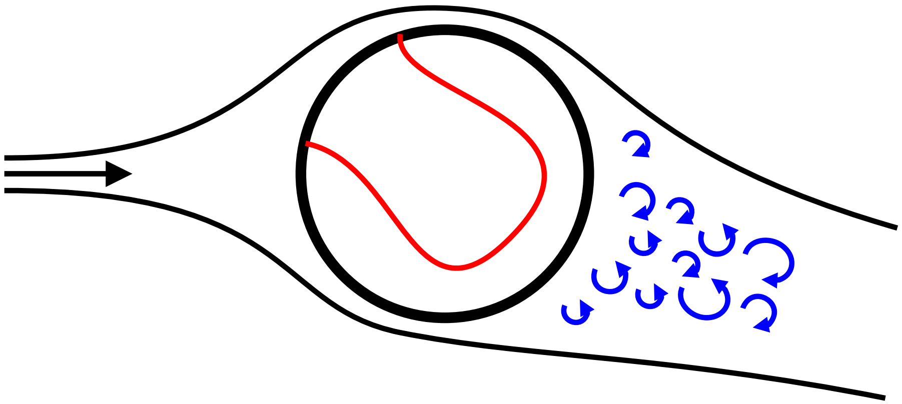
Two Sources of Flow Asymmetry

SEAMS



SPIN



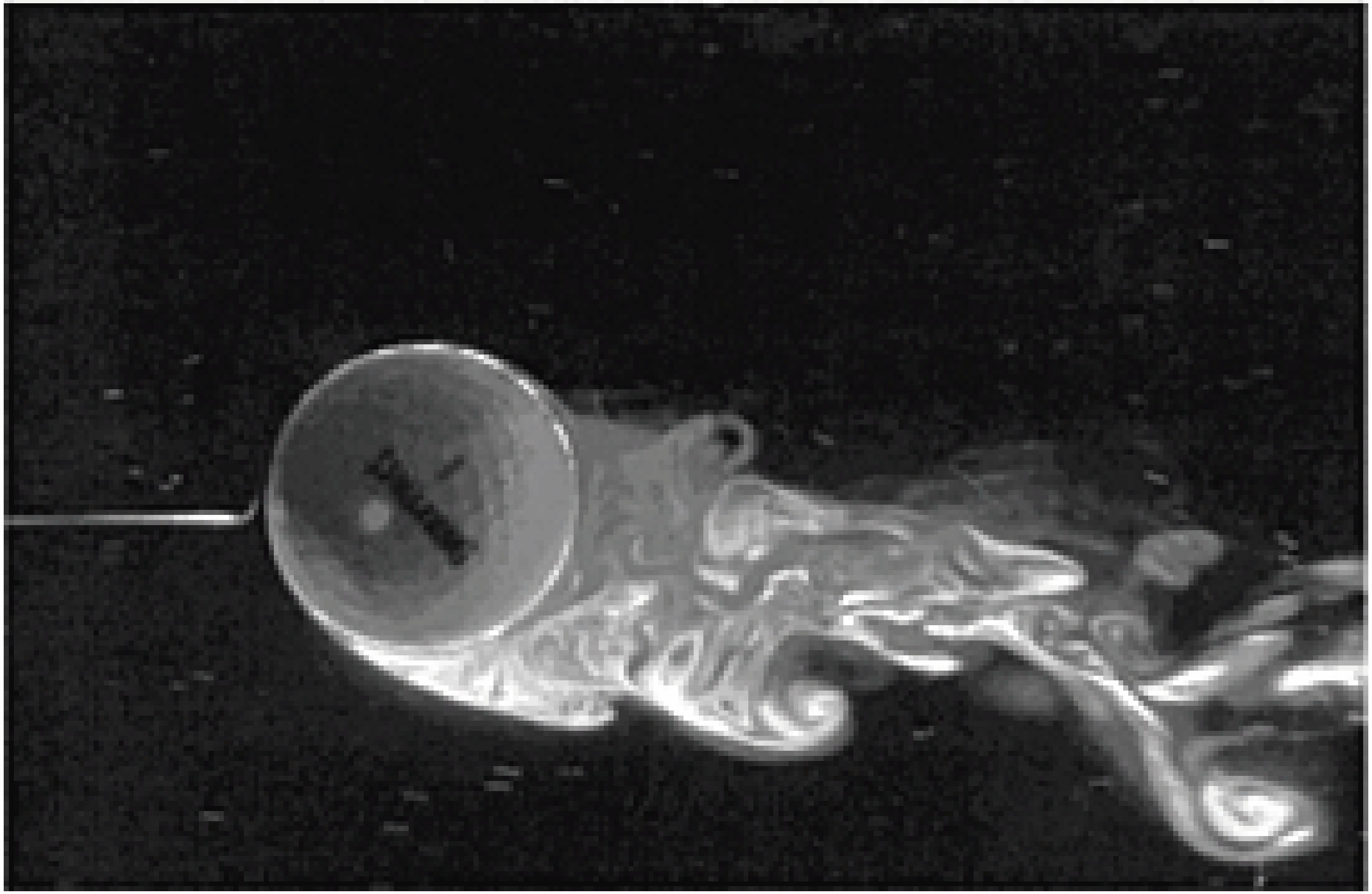


Effect of Seams Depends on Both Re and Orientation of Seams (Difficult to Represent With Simple Models)

SEAMS OR SPIN

PROMOTE TRANSITION & DELAY SEPARATION ON UPPER SURFACE
&
DELAY TRANSITION & PROMOTE SEPARATION ON THE LOWER SURFACE

Flow Visualization Of Wake Asymmetry on Spinning Golf Ball



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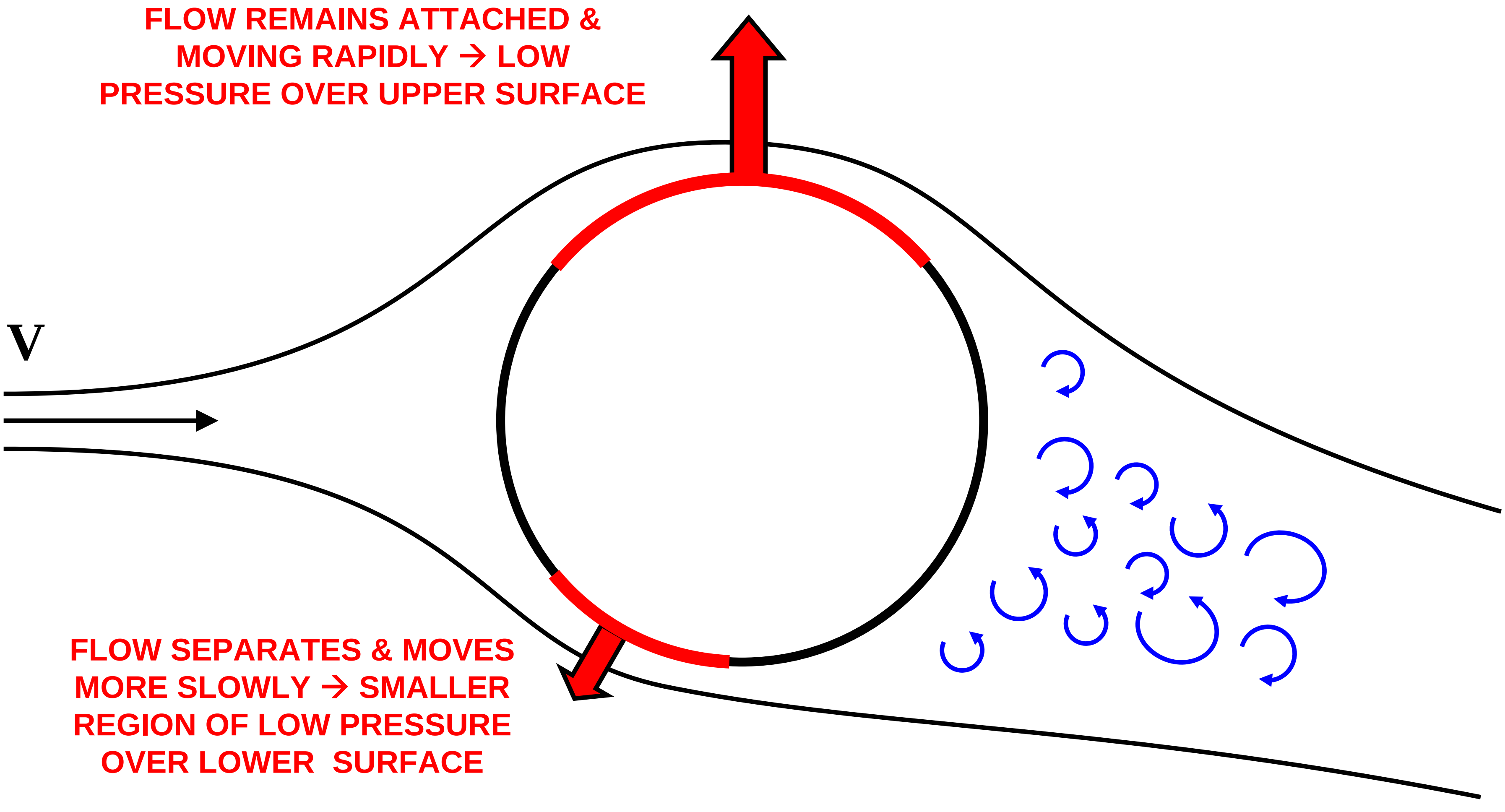
Asymmetry & Generation of Lift

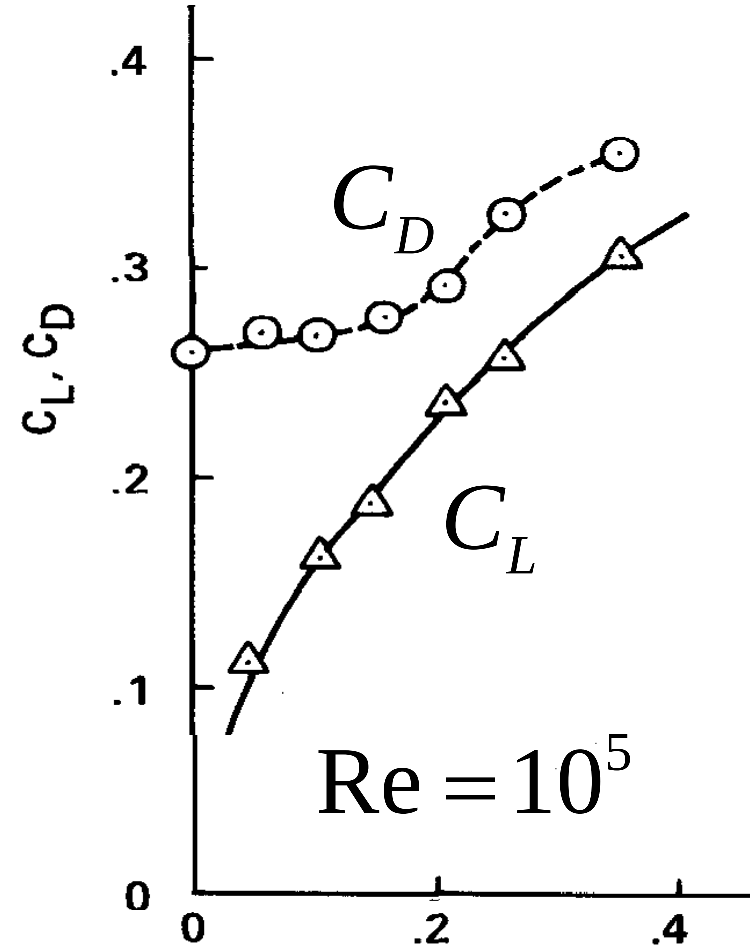


Pressure Asymmetry Causes

"Lift" = Force Normal to Velocity Vector

Lift & Drag Coefficient Data for Spinning Dimpled Golf Ball

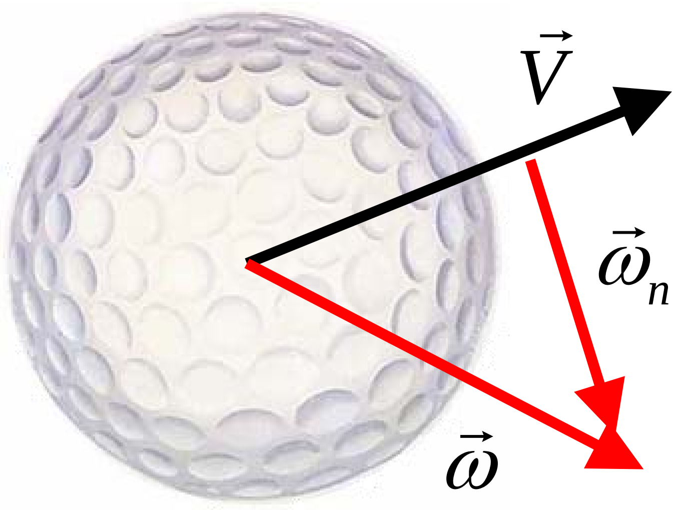
- Lift Strongly Dependent on Spin
  - Insufficient Data to Clearly Establish Effect of Reynolds Number
  - Similar Trends Observed For Soccer Ball
  - Reasonable Approximation: Lift Coefficient Depends Only on Spin #
- Drag Weakly Dependent on Spin
  - General Trend is for Modest Increase in Drag with Spin
  - Reasonable Approximation: Drag Independent of Spin #



SPIN NUMBER $s \equiv \frac{\omega D}{2V}$

Important Detail: Consideration of Relative Orientation of Spin Axis

- Most Test Data Gathered with Angular Velocity Normal to Linear Velocity
  - Simulates Backspin on Golf Ball or Topspin on Tennis Ball
  - For Uniform Ball, Symmetry Guarantees Lift Force Normal to Both Vectors
- Actual Trajectories Involve Arbitrary Orientation of ω and V
  - Ignore Aerodynamic Moments (Assume Direction of ω Fixed in Inertial Space)
  - Assume Only ω_n Affects Lift
  - Compute Effective Spin Number Based on ω_n



EFFECTIVE SPIN NUMBER

$$s_n = \frac{\omega_n D}{2V}$$

Final Recommended Simple Model

Reasonable for Soccer, Golf, Tennis, Baseball (Curveball)

$$C_D \approx \hat{f}\left(\mathrm{Re}, \varepsilon\right)$$

SOCCER		GOLF	
RE	CD	RE	CD
38,000	0.49	38,000	0.48
100,000	0.50	45,000	0.35
160,000	0.51	50,000	0.30
200,000	0.51	60,000	0.24
250,000	0.49	240,000	0.26
300,000	0.46	4,000,000	0.30
330,000	0.39	BASEBALL	
350,000	0.20	RE	CD
375,000	0.09	40,000	0.49
400,000	0.07	90,000	0.50
500,000	0.07	110,000	0.32
800,000	0.10	1,000,000	0.35
2,000,000	0.15	TENNIS	
4,000,000	0.18	CD ~ 0.6	

$$C_L \approx \hat{g}\left(s_n\right)$$

ALL	
S	CL
0.00	0.00
0.04	0.10
0.10	0.16
0.20	0.23
0.40	0.33

- Soccer C_D Estimated from Smooth Sphere
- Tennis Ball "Fuzz" Yields High Drag Nearly Independent of Re
- Baseball C_D Estimated from Moderate Roughness Sphere

Some Typical Numbers

TYPE	D	V	Re	ω	s
	cm	m/s	E+5	rev/s	-
SOCCER	22.2	30	4.44	10	0.23
VOLLEYBALL	21.0	30	4.20		
TENNIS	6.5	45	1.95	72	0.33
BASEBALL	7.3	40	1.95	30	0.17
GOLF	4.3	60	1.72	60	0.14
BASKETBALL	24.3	10	1.62		
CRICKET	7.2	20	0.96		
PING PONG	3.8	5	0.13		

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