WIND TUNNEL PHOTOGRAPHS

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The following photographs of fluid motion are taken from two books. One is "See the wind blow" by Professor F. Brown from University of Notre Dame, published in 1971. He spent a large part of his professional career developing techniques for visualising flow in wind tunnels. The other book is "An album of fluid motion", first published in 1982 by Professor Milton Van Dyke, from Stanford University. Both books are copyright but I have reproduced a small selection of photos here for educational purposes and to encourage you to read or buy the books (at amazon.com and elsewhere).

BOUNDARY LAYER SEPARATION

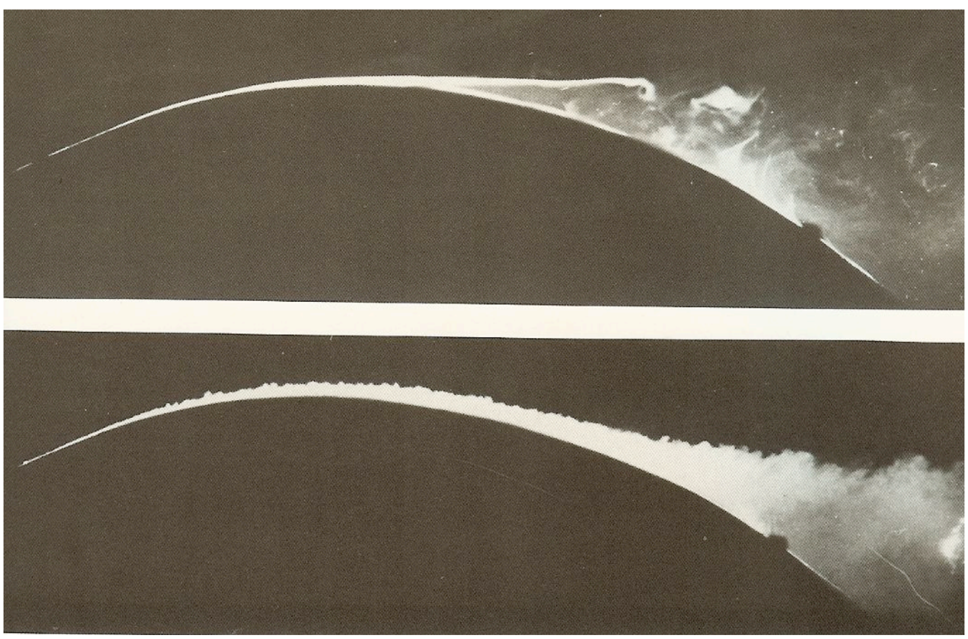

Figure 1: Photos showing the difference between laminar and turbulent boundary layers for air flowing over a curved surface. Laminar flow results in early separation, while at higher air speeds or over rough surfaces, the boundary layer becomes turbulent and remains attached to the surface for a longer distance. The flow was made visible using titanium tetrachloride painted on the front surface. It forms a thick white cloud on contact with humid air. Photo 56, p 91, Album of Fluid Motion.

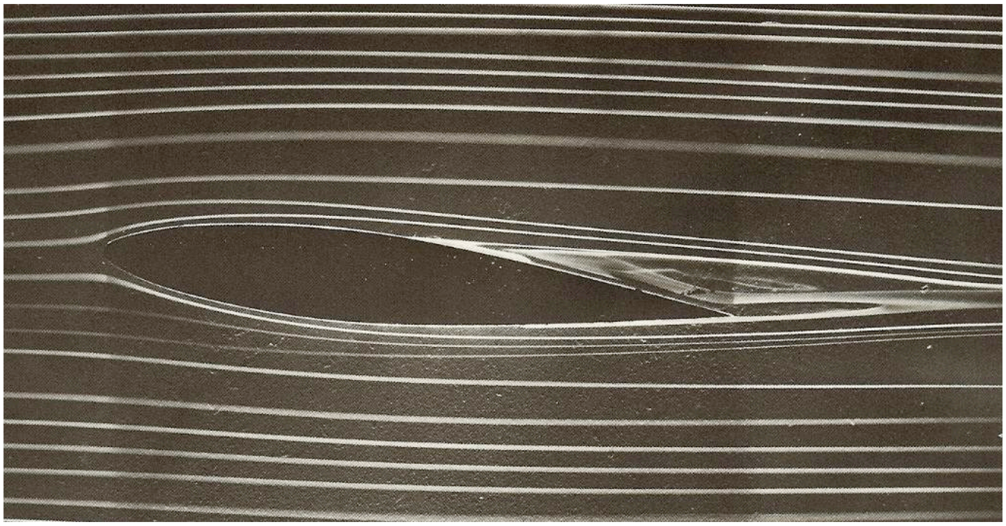

Figure 2: The boundary layer on the upper surface of an inclined airfoil separates from the surface but the boundary layer on the lower surface remains attached. Air is deflected downwards, so the air exerts an equal and opposite upward force on the airfoil. Photo 34, page 25, Album of Fluid Motion.

Figure 3: Low speed flow of water past a sphere at Reynolds number R = 118. Water circulates back to the low pressure region at the rear of the sphere after it separates. Photo 53, page 33, Album of Fluid Motion.

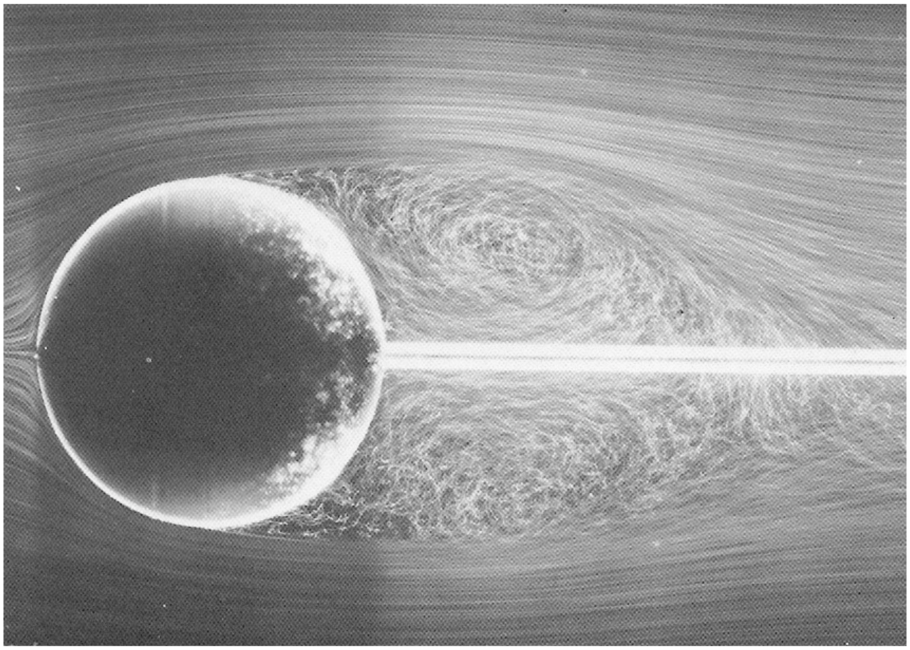

Figure 4: Flow of water past a sphere at Reynolds number R = 15,000 showing separation of the flow at the top and bottom of the sphere and a turbulent wake at the rear of the sphere. Photo 56, page 34, Album of Fluid Motion.

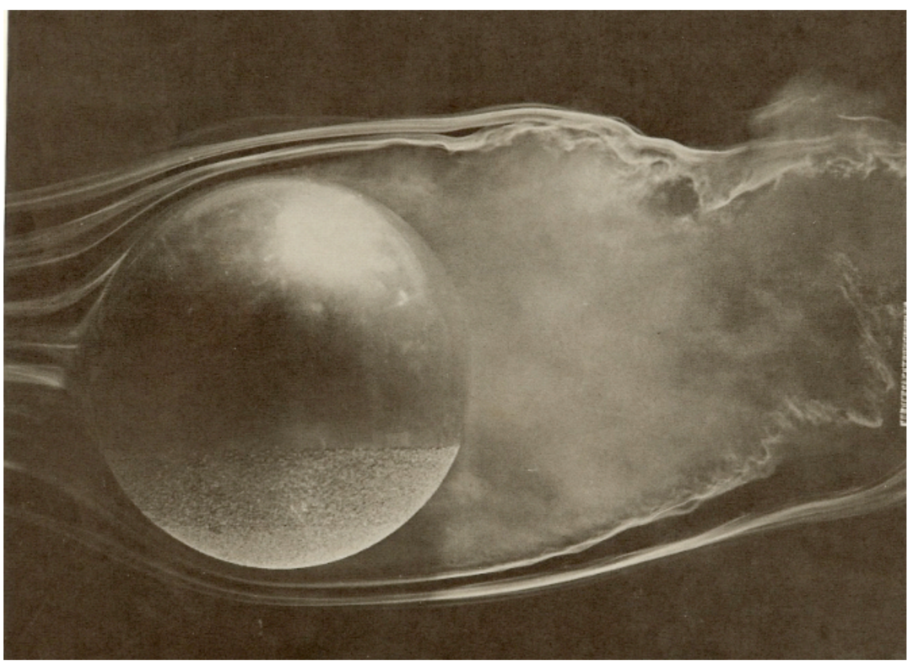

Figure 5: Flow past smooth sphere with grit covering part of the lower half, resulting in late separation at the bottom. Air is deflected upward, resulting in a downward force on the sphere. This photo captures the effect of the rough and smooth sides of a cricket ball, and even the roughening effect of raised seams. Page 38, See the wind blow.

MAGNUS FORCE ON A SMOOTH CYLINDER

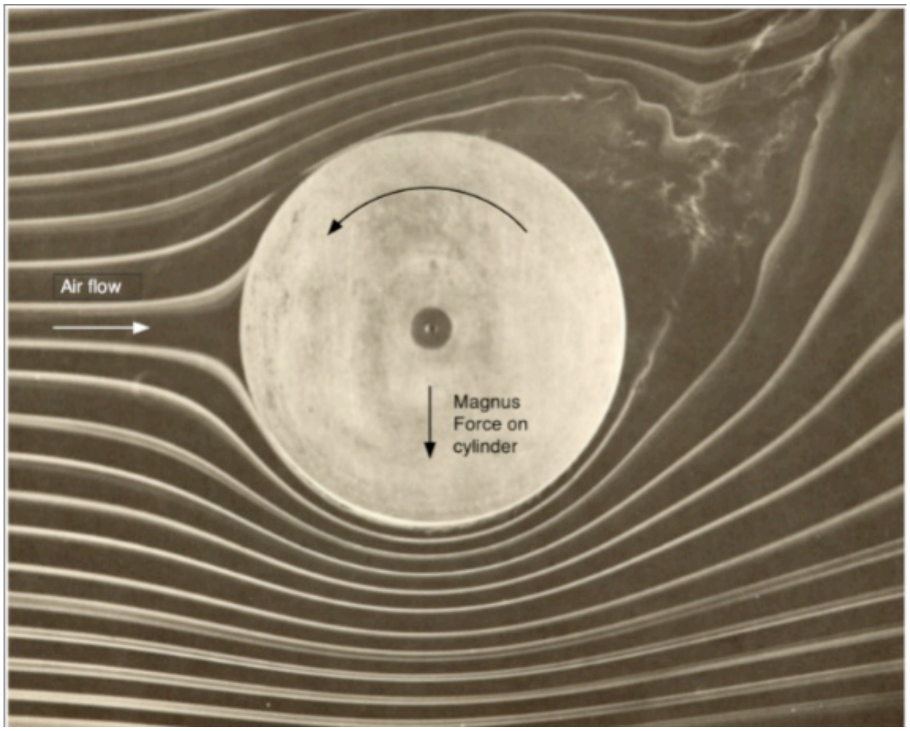

Figure 6: Flow past smooth cylinder rotating counter–clockwise. Air is deflected upward, resulting in a downward (positive) Magnus force on the cylinder. The peripheral speed of the cylinder, due its rotation, is slightly larger than the flow speed of the air. Page 82, See the wind blow.

In Fig. 6, the air speed and cylinder spin are both relatively small and the flow is laminar on both sides. Near the bottom surface, the cylinder rotates faster than the the air and drags the boundary air almost all the way to the rear. The top surface rotates in the opposite direction to the air stream and brings the boundary layer air to rest sooner, due to viscous forces. Separation occurs sooner on the top surface. The result is a net upward deflection of the air and a downward or positive Magnus force on the cylinder.

MAGNUS FORCE ON A SMOOTH SPHERE

It has been observed in many experiments that a ball (or a cylinder) can deflect in the "wrong" direction when it is spinning. In that case, the Magnus force is negative. The effect is observed when the ball speed or the spin is high enough so that the boundary layer can become turbulent. In that case, the boundary layer can become turbulent on one side of the ball and remain laminar on the other side.

At high ball speeds or spins, the upper boundary layer can become turbulent due to the high relative speed of the air and the surface, resulting in delayed separation. If the lower boundary layer remains laminar, due to the low relative speed of the air and the surface, then it separates earlier than the turbulent layer at the top, resulting in a negative Magnus force. Brown (See the Wind Blow) showed that a negative Magnus force arises at high speeds for smooth spheres and cylinders if $V/U < 0.5$ where $V = R\omega$ is the peripheral speed of the ball or cylinder and U is the ball speed (or the wind speed in a wind tunnel). A smooth table tennis ball with strong backspin can curve down rather than up if the higher relative velocity at the bottom of the ball results in a turbulent boundary layer while the top layer remains laminar.

Alternatively, the boundary layer can be turbulent both at the top and bottom of the ball at sufficiently high ball speeds. In that case, the separation point moves closer to the front of the ball as the ball speed increases. A consequence is that the drag coefficient increases as the ball speed increases above that at which the drag crisis occurs. The drag coefficient drops suddenly at the drag crisis but increases again at higher ball speeds. If the ball is spinning then the separation point will be closer to the front of the ball on the side where the relative speed of the air and the ball is largest. That will result in a positive Magnus force, as indicated below:

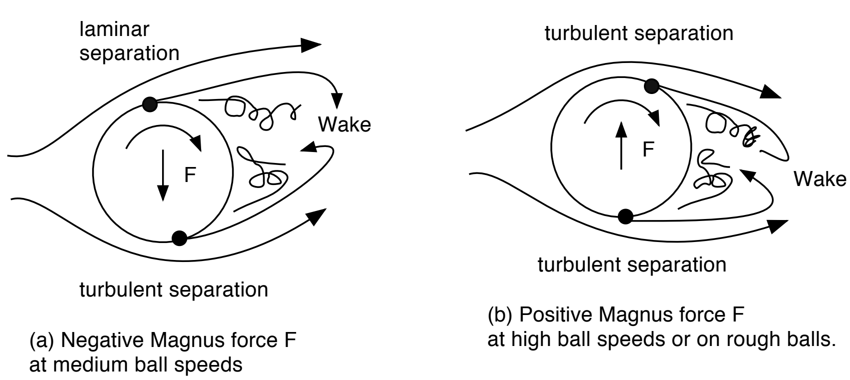

Figure 7: The Magnus force on a smooth sphere can be negative at medium ball speeds but is usually positive at high ball speeds or when balls have rough surfaces. Ball here rotates clockwise.

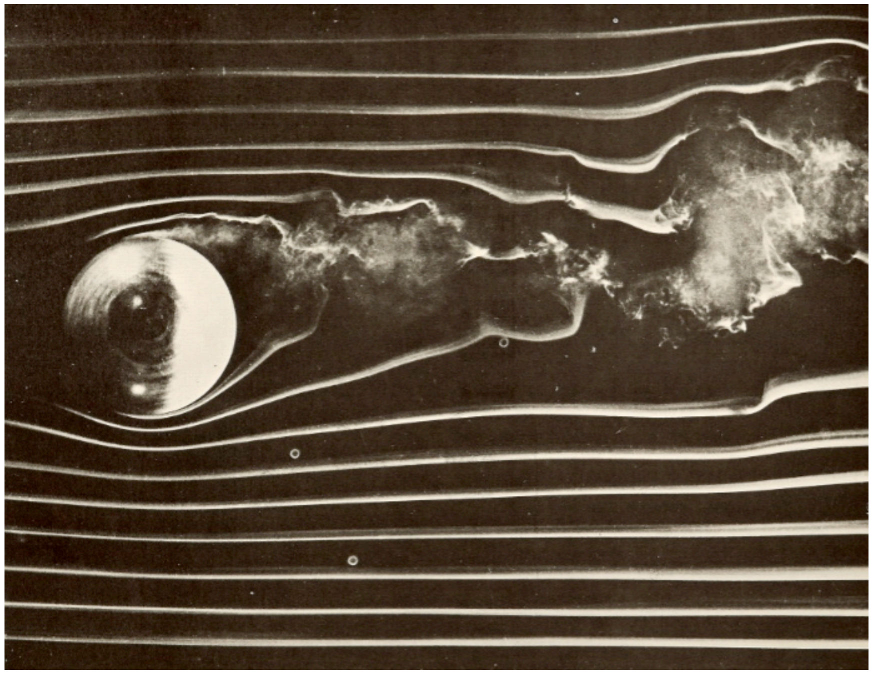

Figure 8: Flow past a sphere rotating clockwise. Air is deflected upward, resulting in a downward force on the sphere. The peripheral speed due to the spin is about 1/3 the air speed, resulting in a negative Magnus force. Page 86, See the wind blow.

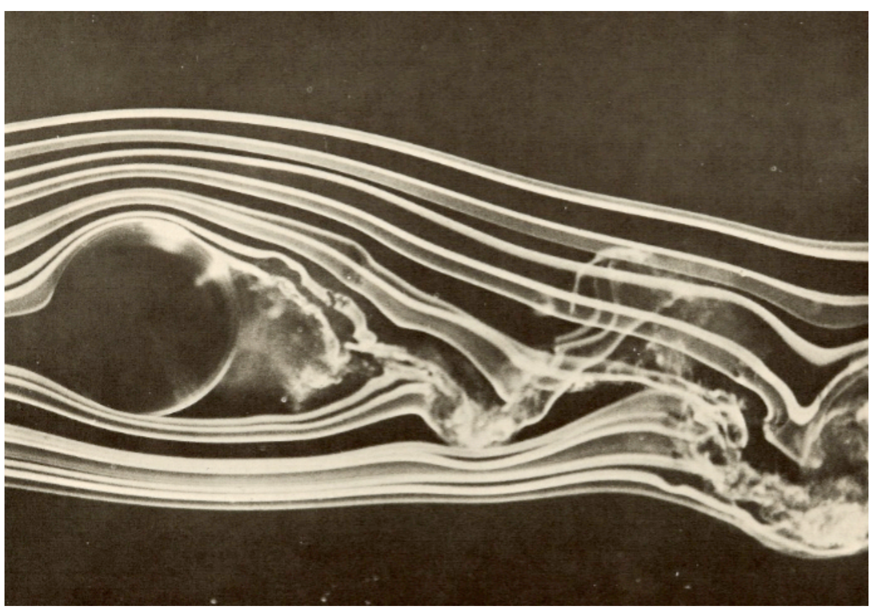

Figure 9: Flow past a sphere rotating clockwise. Air is deflected downward, resulting in an upward force on the sphere.The peripheral speed due to the spin is about twice the air speed, resulting in a positive Magnus force. Page 84, See the wind blow.

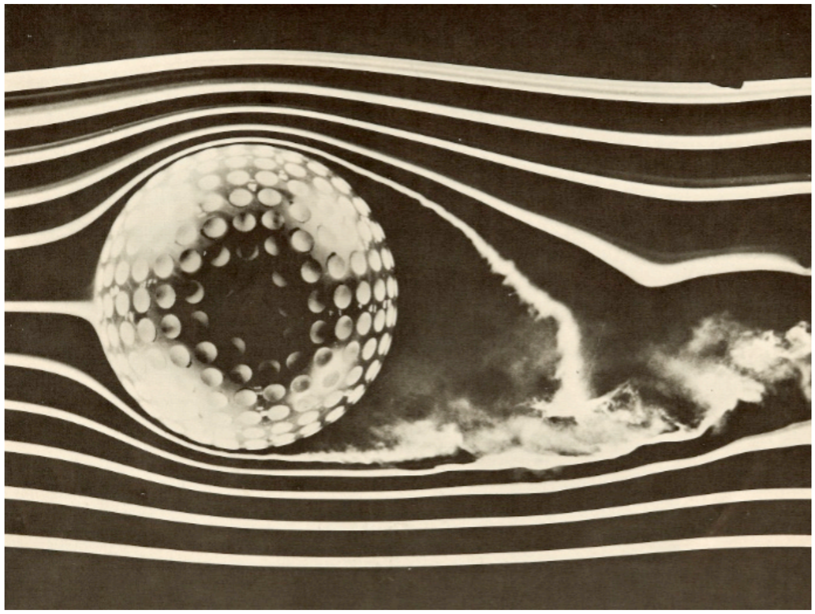

Figure 10: Flow past a golf ball rotating clockwise. Air is deflected downward, resulting in an upward force on the ball. The Magnus force here is positive. Normally, the ball travels to the left with backspin into still air. Here, the ball is spinning clockwise about a fixed axis and air approaches from the left, but the flow pattern is the same. Page 90, See the wind blow.

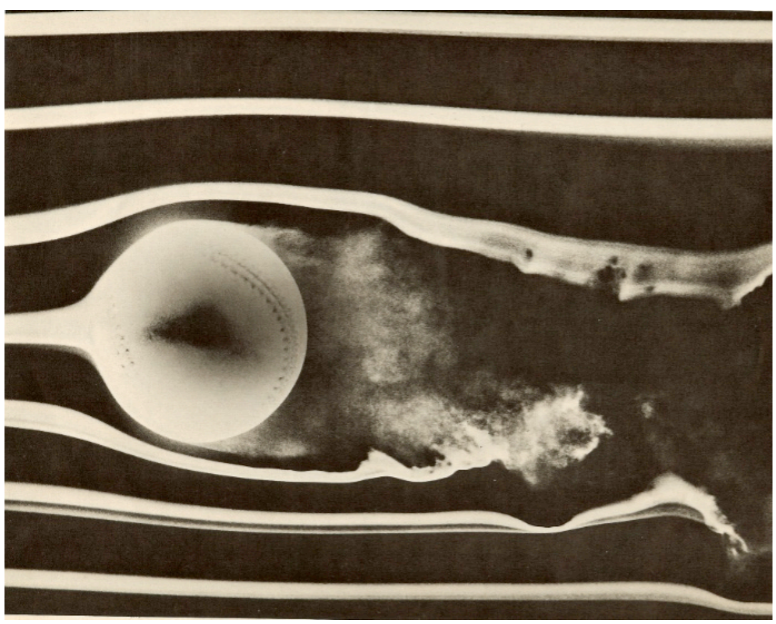

Figure 11: Flow past a stationary baseball, both seams at the front being located in the top half of the ball. Separation is delayed by turbulence at the top and is laminar at the bottom so air is deflected downward, resulting in an upward force on the ball. Page 89, See the wind blow.

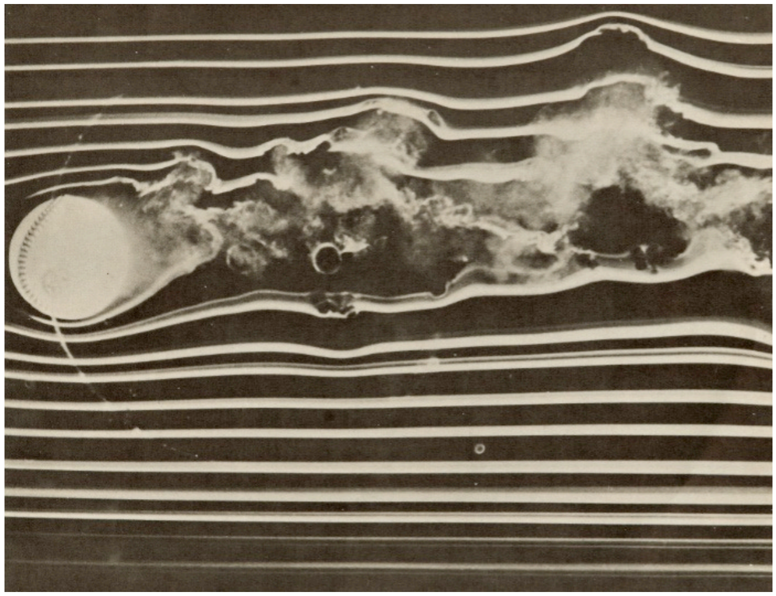

Figure 12: Flow at 21 m/s past a baseball spinning counter–clockwise at 900 rpm. Air is deflected upwards, resulting in a downwards force on the ball. Page 88, See the wind blow.