Air cavity formation in the wake of a spinning sphere impacting a free surface

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A spherical object impacting the free surface generates both a splash curtain and a subsurface air cavity. These high-speed video sequences capture a spinning sphere (diameter, \( d = 5.7 \text{ cm} \)) as it collides with the free surface at \( 7.6 \text{ m/s} \) with an initial spin rate of \( 172 \text{ rad/sec} \), in the clockwise direction. The subsurface air cavity forms when the sphere imparts momentum into the surrounding fluid and deforms the free surface. The cavity grows as the inertia from the sphere drives the cavity open. The clockwise angular momentum of the sphere, combined with its forward momentum, causes the sphere to move along a curved path to the left. The cavity collapses when the hydrostatic pressure force, acting on the wall of the cavity, is greater than the momentum forcing the cavity open. After cavity collapse a small pocket of air remains attached to the sphere and an upward moving jet of fluid ejects from the point of collapse, traveling vertically up through the cavity and splash dome. The first frame (far left) is taken at the time of impact \( (t = 0 \text{ ms}) \); subsequent frames are \( 8 \text{ ms} \) apart. Close-up image sequences of the splash formation and air cavity are shown below.

Splash curtain formation above the free surface evolves as the sphere imparts momentum into the fluid. Initially, at impact, the momentum transfer forms a radial jet just above the free surface (frame 1); then vertical splash growth occurs radial expansion (frames 2 & 3). Since the gravitational force limits the vertical splash height and the pressure inside the curtain is reduced by the air flowing into the growing subsurface cavity (Bernoulli effect), the splash curtain is forced inward and down (frame 4). Eventually the curtain closes, forming a dome (frame 5). As the sphere spins, it draws fluid from the left side of the cavity causing the dome to form asymmetrically (frame 5 - 7), in contrast to an axisymmetric dome in the non-spinning case. Effects of spin are discussed below. Shortly after the subsurface cavity collapses, a rapidly upward traveling water jet ruptures the dome, which occurs after the last frame in this sequence. Cavity collapse is shown in the bottom sequence. Images in this series are \( 16 \text{ ms} \) apart.

Asymmetric formation of the splash curtain is caused by the spinning motion of the sphere drawing water away from the left side of the cavity. Looking down on the surface, with a slightly off-axis view, this image sequence shows a wedge of fluid being pulled away from the left wall (frames 3 - 5). The sphere, spinning to the right, draws water into the cavity along its equator, only when the maximum tangential velocity is higher than the impact velocity. The loss of fluid at the cavity wall hinders symmetrical growth of the splash curtain. As the ball moves through the fluid, the wedge stretches into a thin wall traveling towards the right side of the cavity (frames 6 & 7). Eventually the wall impacts the opposite side of the cavity. This impact forces air to be ejected from the cavity. The ejected air forms a line of bubbles that can be seen on the right side of the cavity in the large, single image at left or in the cavity collapse sequence below. Frame 1 corresponds to the moment of impact \( (t = 0 \text{ ms}) \) and subsequent frames are \( 6.4 \text{ ms} \) apart.

Cavity collapse occurs when the radial expansion of the cavity is slowed by the opposing hydrostatic pressure of the surrounding fluid. As the ball travels along its trajectory the cavity continues to elongate but no longer grows radially, eventually causing a neck region to form (frame 1). Necking reduces the ability of the cavity to resist collapse. Pinch-off occurs at the point of the cavity neck (frames 2 - 4), forming two distinct, separate cone-shaped air cavities (frames 5 - 7). The apex of the upper cone moves rapidly upward, into the air cavity forming a jet of water which ejects out of the cavity. A small volume of air remains attached to the sphere. Images presented in this sequence start \( 94.3 \text{ ms} \) after impact and are \( 0.74 \text{ ms} \) apart.

This image shows a snapshot of the splash and air cavity formed by a spinning sphere. The photograph is \( 80 \text{ ms} \) after impact and corresponds to the 11th frame in the long sequence shown at top. The spin direction is clockwise, indicated by the arrow.

Photographed by Brent Avondet and Tadd Truscott.

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