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What can citrus teach us about fluid dispersal?

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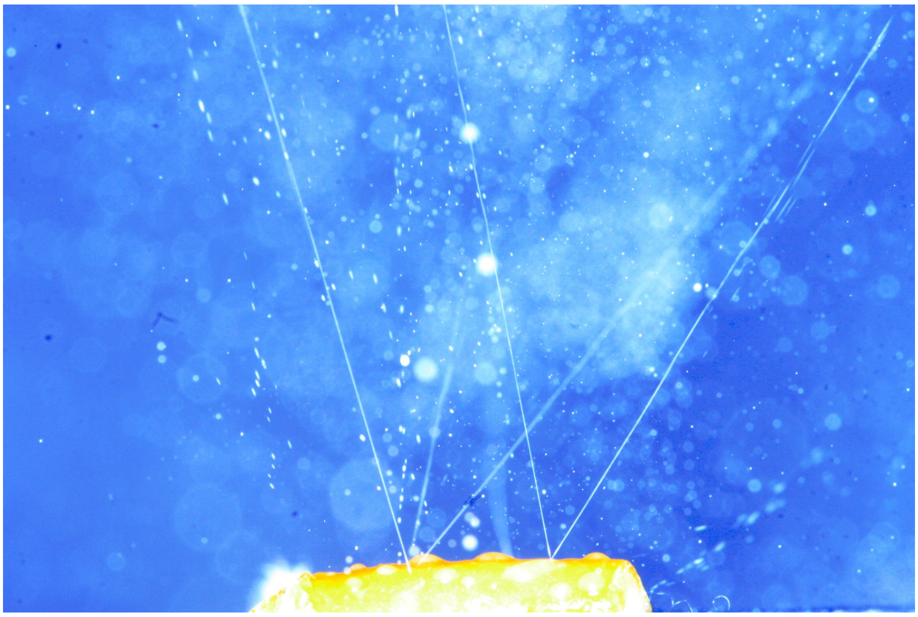
ABSTRACT

Technology has enabled the productions of small-scale fluid jets with precision nozzles and pumps, and pressurized tanks. These can be cumbersome, but nature provides an alternative for fluid dispersal by way of citrus fruit



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The avid citrus consumer knows it is impossible to peel an orange and keep your fingers dry, even if the precious fruit inside remains unmolested. Others will have noticed the ephemeral and fragrant mist that is emitted when peels are broken and tiny fluid jets erupt into the air. Even with the naked eye, one can appreciate the magnificence of fine these 'citrus jets.' With a macro lens and high-speed camera, the beauty of this inconspicuous event can become fully realized.

Citrus peels are composite structures, meaning they are comprised of two main layers, the spongy white pith and the colorful zest. Just beneath the zest (about as thick as our skin) and housed within the white spongy pith, all citrus fruits have oil gland reservoirs which are round in shape and measure about 1 mm across. The oil housed in these glands is volatile and has a density and viscosity comparable to water. By folding the peel such that the zest faces outward and giving it a squeeze, pressure in the oil increases as the surrounding material presses against it. At a certain failure pressure, the zest cracks open atop each individual fluid pouch and the oil bursts free as a jet about the diameter of a human hair. The exit velocity of these jets averages about 10 m/s but has been measured as high as 30 m/s.

Without any knowledge of material properties, we can calculate the approximate range of pressure inside the average oil pocket at the moment of rupture. Simply put, higher pressure generates faster jets. However, we want to know the properties the peel itself, structure and material, allows for the generation of pressure as high as 30-140 kPa (4-20 psi).

The strength of the zest topping each oil pocket limits how much fluid pressure can build. We also find the strength of the zest is related to its stiffness by applying theory from fracture mechanics. The stiffer the zest, the faster the jets that rocket through it. This mechanism also requires the pith underneath the zest to be soft. In fact, it is two orders of magnitude softer. We measured the material stiffness using a tensile tester, which measures how force is needed to stretch a material. Finite-element simulation shows this contrast in material properties is key for jet creation, allowing the pith to compress while the zest is stretched. The greater the stiffness contrast between these two materials, the greater reservoir pressures bending the peel can accomplish. The final secret to a fast jet is the geometry of the oil reservoir, which is deeper than it is wide. This allows more of the fluid volume to reside in the region of the pith being compressed.

So, which fruits were consistently the best and worst performers? The lime had the highest average jets at 13.9 m/s and mandarins the lowest at 8.7 m/s, measured 15 days after purchase. Likewise, these fruits' zest with the highest and lowest stiffness. As fruits age, the zest becomes drier and stiffer. Accordingly, the jet velocity slightly increases, but only up to a point. After too long, the oil itself will evaporate. Perhaps a future scientist will develop a method to determine the quality or age of a citrus fruit by measuring its jet-producing aptitude.

The size of citrus oil reservoirs and the velocity of oil ejection result in large accelerations by jetting fluid. Liquid at rest in the pockets is accelerated to velocities in excess of 10 m/s over the distance of ~1 mm. Therefore, parcels of fluid in the reservoir will experience 5,100 gravities (g) of acceleration before exit, which is comparable to the acceleration of a bullet leaving a rifle. In nature, this acceleration is outdone only be the mantis shrimp at over 10,000 g and Dung Cannon fungus at 180,000 g but is perhaps unmatched in the plant kingdom.

Our findings may be used by future engineers to create new methods of airborne medicine delivery, similar to asthmatic inhalers in use today. Citrus jets break up into droplets very quickly—within two 2 mm of the zest surface. Specialized 'skins' mimicking citrus peels may also find their way onto structure members to detect excessive deformation, such as those used in bridges and cranes. Such a technology, which could be filled with high visibility dye, would allow us to preeminently detect material failure.

Read more about the author on: https://DickersonLab.com