A simple formula that could be useful for air purification, space propulsion, and molecular analyses

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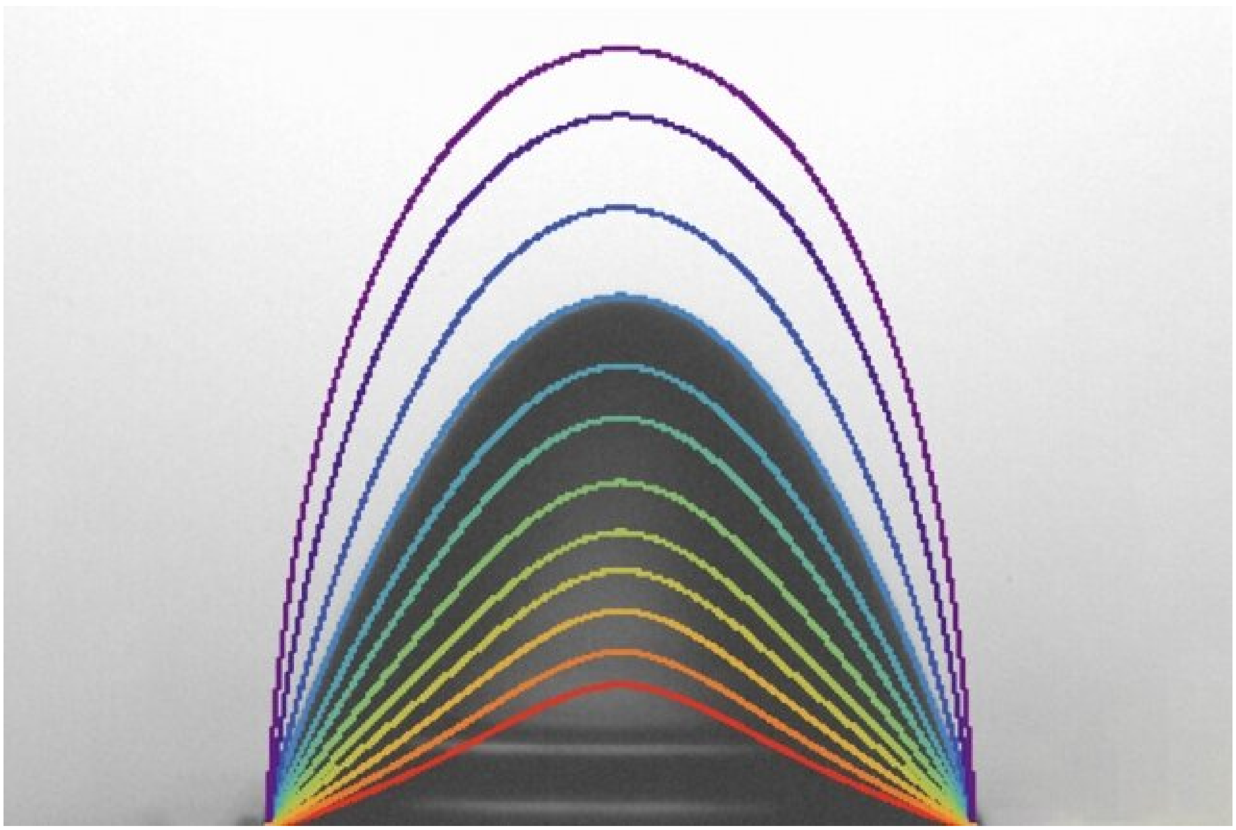


Electrified water droplets take on a variety of distorted shapes just before bursting, based on the strength of the electric field. The profiles of different distorted droplet shapes are shown, overlaid on an image of one particular distorted droplet for comparison. Credit: Massachusetts Institute of Technology

When a raindrop falls through a thundercloud, it is subject to strong electric fields that pull and tug on the droplet, like a soap bubble in the wind. If the electric field is strong enough, it can cause the droplet to burst apart, creating a fine, electrified mist.

Scientists began taking notice of how droplets behave in electric fields in the early 1900s, amid concerns over lightning strikes that were damaging newly erected power lines. They soon realized that the power lines' own electric fields were causing raindrops to burst around them, providing a conductive path for lightning to strike. This revelation led engineers to design thicker coverings around power lines to limit lightning strikes.

Today, scientists understand that the stronger the electric field, the more likely it is that a droplet within it will burst. But, calculating the exact field strength that will burst a particular droplet has always been an involved mathematical task.

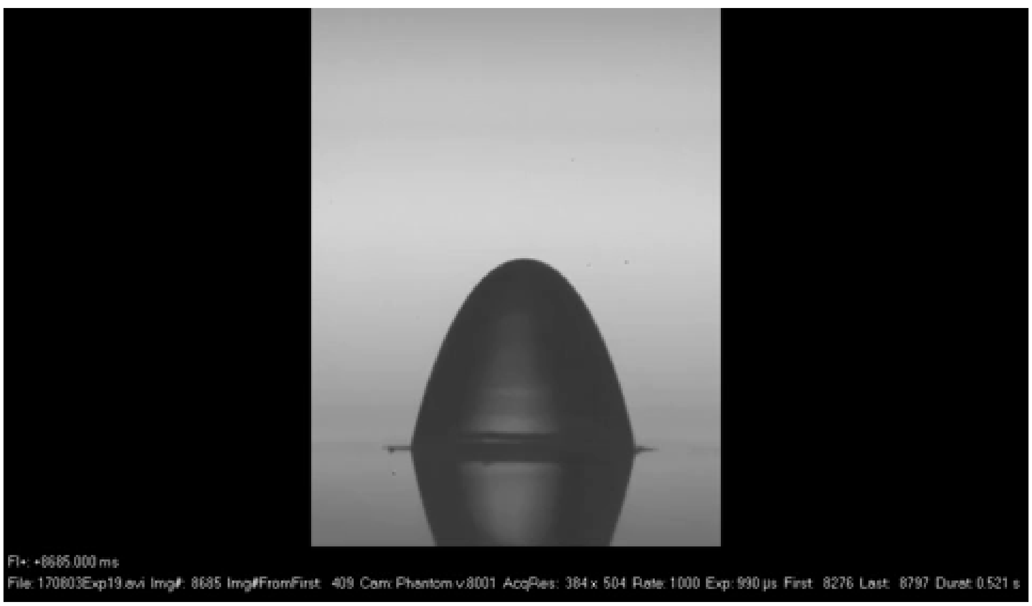
Now, MIT researchers have found that the conditions for which a droplet bursts in an electric field all boil down to one simple formula, which the team has derived for the first time.

With this simple new equation, the researchers can predict the exact strength an electric field should be to burst a droplet or keep it stable. The formula applies to three cases previously analyzed separately: a droplet pinned on a surface, sliding on a surface, or free-floating in the air.

Their results, published today in the journal *Physical Review Letters*, may help engineers tune the electric field or the size of droplets for a range of applications that depend on electrifying droplets. These include technologies for air or water purification, space propulsion, and molecular analysis.

"Before our result, engineers and scientists had to perform computationally intensive simulations to assess the stability of an electrified droplet," says lead author Justin Beroz, a graduate student in MIT's departments of Mechanical Engineering and Physics. "With our equation, one can predict this behavior immediately, with a simple paper-and-pencil calculation. This is of great practical benefit to engineers working with, or trying to design, any system that involves liquids and electricity."

Beroz' co-authors are A. John Hart, associate professor of mechanical engineering, and John Bush, professor of mathematics.



A water droplet, subject to an electric field of slowly increasing strength, suddenly bursts by emitting a fine, electrified mist from its apex. Credit: Massachusetts Institute of Technology

"Something unexpectedly simple"

Droplets tend to form as perfect little spheres due to surface tension, the cohesive force that binds water molecules at a droplet's surface and pulls the molecules inward. The droplet may distort from its spherical shape in the presence of other forces, such as the force from an electric field. While surface tension acts to hold a droplet together, the electric field acts as an opposing force, pulling outward on the droplet as charge builds on its surface.

"At some point, if the electric field is strong enough, the droplet can't find a shape that balances the electrical force, and at that point, it becomes unstable and bursts," Beroz explains.

He and his team were interested in the moment just before bursting, when the droplet has been distorted to its critically stable shape. The team set up an experiment in which they slowly dispensed water droplets onto a metal plate that was electrified to produce an electric field, and used a high-speed camera to record the distorted shapes of each droplet.

"The experiment is really boring at first—you're watching the droplet slowly change shape, and then all of a sudden it just bursts," Beroz says.

After experimenting on droplets of different sizes and under various electric field strengths, Beroz isolated the video frame just before each droplet burst, then outlined its critically stable shape and calculated several parameters such as the droplet's volume, height, and radius. He plotted the data from each droplet and found, to his surprise, that they all fell along an unmistakably straight line.

"From a theoretical point of view, it was an unexpectedly simple result given the mathematical complexity of the problem," Beroz says. "It suggested that there might be an overlooked, yet simple, way to calculate the burst criterion for the droplets."

Volume above height

Physicists have long known that a liquid droplet in an electric field can be represented by a set of coupled nonlinear differential equations. These equations, however, are incredibly difficult to solve. To find a solution requires determining the configuration of the electric field, the shape of the droplet, and the pressure inside the droplet, simultaneously.

"This is commonly the case in physics: It's easy to write down the governing equations but very hard to actually solve them," Beroz says. "But for the droplets, it turns out that if you choose a particular combination of physical parameters to define the problem from the start, a solution can be derived in a few lines. Otherwise, it's impossible."

Physicists who attempted to solve these equations in the past did so by factoring in, among other parameters, a droplet's height—an easy and natural choice for characterizing a droplet's shape. But Beroz made a different choice, reframing the equations in terms of a droplet's volume rather than its height. This was the key insight for reformulating the problem into an easy-to-solve formula.

"For the last 100 years, the convention was to choose height," Beroz says. "But as a droplet deforms, its height changes, and therefore the mathematical complexity of the problem is inherent in the height. On the other hand, a droplet's volume remains fixed regardless of how it deforms in the electric field."

By formulating the equations using only parameters that are "fixed" in the same sense as a droplet's volume, "the complicated, unsolvable parts of the equation cancel out, leaving a simple equation that matches the experimental results," Beroz says.

Specifically, the new formula the team derived relates five parameters: a droplet's surface tension, radius, volume, electric field strength, and the electric permittivity of the air surrounding the droplet. Plugging any four of these parameters into the formula will calculate the fifth.

Beroz says engineers can use the formula to develop techniques such as electrospraying, which involves the bursting of a droplet maintained at the orifice of an electrified nozzle to produce a fine spray. Electrospraying is commonly used to aerosolize biomolecules from a solution, so that they can pass through a spectrometer for detailed analysis. The technique is also used to produce thrust and propel satellites in space.

"If you're designing a system that involves liquids and electricity, it's very practical to have an equation like this, that you can use every day," Beroz says.

More information: Stability limit of electrified droplets. *Phys. Rev. Lett*. journals.aps.org/prl/abstract/ … ysRevLett.122.244501

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