## PHYSICS IN ACTION

# Suction power provides a new route to make microdrops

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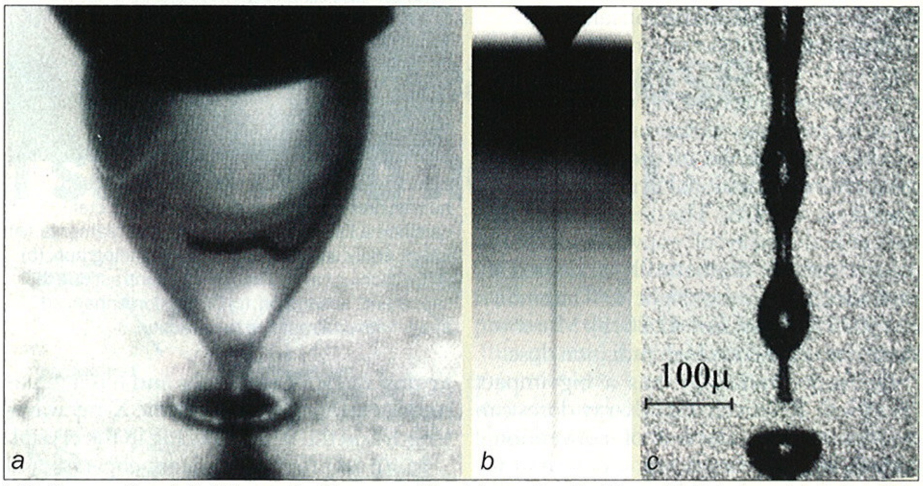

(*a*) In the experiment, fluid is supplied from a capillary tube and sucked through a hole in a plate below. This leads to a much thinner microjet (*b*), which decays into droplets due to surface-tension forces (*c*).

When performing tasks as diverse as irrigating a cornfield or spraying perfume, the key objective is to spread a fluid uniformly by generating a fine spray of droplets. There is an almost endless list of applications for sprays, including internal combustion, spray painting, drug delivery and inkjet printing. And the more advanced the application, the greater the need for micron-sized droplets of specific size.

These seemingly simple demands have kept engineers busy for generations, leading to the development of a puzzling variety of nozzles. Now, however, Alfonso Gañán-Calvo of the University of Seville in Spain has suggested that very fine and uniformly sized droplets could be produced by simply sucking the liquid out of a capillary tube through a small hole (*Phys. Rev. Lett.* 1998 **80** 285). The method has the hallmark of simplicity, yet it illustrates the general scaling concepts of nonlinear science.

The first studies of drop formation were performed in 1833 by Felix Savart, most famous for discovering the Biot–Savart law of electromagnetism. Savart investigated fluid jets emerging from a hole in a container and found that the jets decay into a steady stream of drops. It took another 40 years and the work of two of the most eminent scientists of the 19th century, the Belgian mathematician Jean Plateau and the English physicist Lord Rayleigh, to understand the laws governing this decay.

They concluded that surface tension acts to reduce the surface area of the jets, squeezing the column of liquid and reducing its radius. Uniform squeezing causes the greatest reduction in the surface area but is unfavourable insofar as the fluid has to be pushed out at the ends of the cylinder. The most efficient way of reducing the jet radius is thus to squeeze the jet periodically, with drops forming between two successive minima of the radius. Surface tension thus provides us with a natural mechanism for drop formation, but it dictates that the drop size must be similar to the nozzle radius.

The usual way to produce micron-sized drops is to design more complicated nozzles. Some blow the fluid into thin sheets, while others send a rapid airstream across the fluid surface. In all of these designs, however, the decay becomes unsteady and the resulting chaotic fluid motion produces many different drop sizes, rather than a single controllable size.

Gañán-Calvo, in contrast, has exploited pressure forces to mould a fluid jet into the desired size. In the experiment, a steady stream of fluid is supplied through a capillary (figure *a*). A plate with a hole drilled through it is placed just below the end of the capillary, and the air pressure below this plate is kept lower than the pressure at the nozzle. The stream of fluid is therefore sucked into the hole, forming a jet with a much smaller radius than that of either the capillary tube or the hole (figure *b*).

The subsequent decay of this "microjet" is again driven by surface tension (figure *c*) and follows the laws established by Rayleigh. In this way it is possible to beat the geometrical constraints imposed by conventional methods, while also keeping the fluid motion perfectly steady.

So what experimental parameters control the radius of the microjet that comes through the hole? The shape of the jet is moulded by the pressure difference between the exit of the nozzle and the region below the hole. These pressure forces have to work against the jet's inertia, determined by the total mass within a section of the jet. The jet diameter below the hole is therefore determined by the density of the fluid, $\rho$, the flow rate, $Q$, and the pressure difference, $\Delta p$.

To find the expression that relates these parameters to the jet diameter, they are combined in such a way that they yield a quantity of unit length. Since $\Delta p/\rho$ is measured in cm$^2$ s$^{-2}$ and $Q$ in cm$^3$ s$^{-1}$, we find that $d \sim (Q^2\rho/\Delta p)^{0.25}$. By increasing the pressure difference, the jet diameter can be made as small as required, independent of experimental parameters, such as the nozzle and hole diameters, and the fluid viscosity.

This procedure is known as dimensional analysis and is the most powerful tool of nonlinear physics. Its trademarks are the power-law form and the universality of the resulting expression. However, one should not be fooled by the simplicity of the argument. Success lies in the correct identification of the driving forces; competing effects – such as surface tension or viscous shear forces – must be carefully excluded. Among a large set of experimental measurements, only the combination of parameters derived above were found to determine the jet diameter, confirming the theoretical arguments.

Returning to the decay of the microjet into droplets (figure *c*), we see that the separation of drops is accompanied by the formation of long filaments between successive drops. Each filament eventually decays into a much smaller "satellite" drop, indicating that Rayleigh's theory does not tell us everything about drop formation and that more complex time-dependent phenomena come into play. A new balance of surface tension, inertial, and viscous forces is at work here, and dimensional analysis provides the universal scaling laws that govern the shape of filaments close to the pinch point.

The problem of drop formation has been studied for over 150 years, and yet it involves so many interesting physical concepts that it still remains a fascinating research topic today. It has led to a fruitful exchange between engineering and theoretical physics, and also has important implications for real applications.