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Nitrogen swirl: Creating rotating polygons in a boiling liquid

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When we learn about rotating flows, we usually start with the most famous example: Newton's rotating bucket. Newton attached a bucket of water to the ceiling by a rope and twisted the rope. As he let go, the bucket started rotating, and after a while the water came to rest again. This time, however, the water surface was no longer flat but curved upward towards the rim like a paraboloid, showing that the rest frame of the rotating bucket is not an inertial frame. In the video presented here, we perform an experiment which is a variation on that theme. Here we stir a volume of liquid with very low viscosity in a stationary pot and watch it while the swirling motion gradually decays. Surprisingly, this happens through a sequence of quasistationary states with polygonal surface deformations, as described in Ref. [1].

In the experiment, between 0.5 and 2 l of liquid nitrogen is poured into a stationary pot maintained at a temperature of $T_p = 353$ K (80 °C) in a water bath. This liquid has a viscosity five times smaller than water and a boiling temperature $T_N = 77$ K (−196 °C), which means that it undergoes “film boiling.” Thus, the liquid is separated from the solid surfaces by a thin vapor layer and is held in a “Leidenfrost” state with extremely low friction. The ensuing film boiling also insulates the liquid, so that it takes several minutes before the whole volume of liquid has evaporated.

Then the liquid is set into rotation by stirring manually with a wooden spoon. We stir the liquid so vigorously that it is flung away from the central part of the pot, which then becomes dry while the surface rises at the sides of the pot. The surface rapidly acquires a characteristic convex shape, running from the central dry circle on the bottom of the pot to the liquid interface at the sidewall, as

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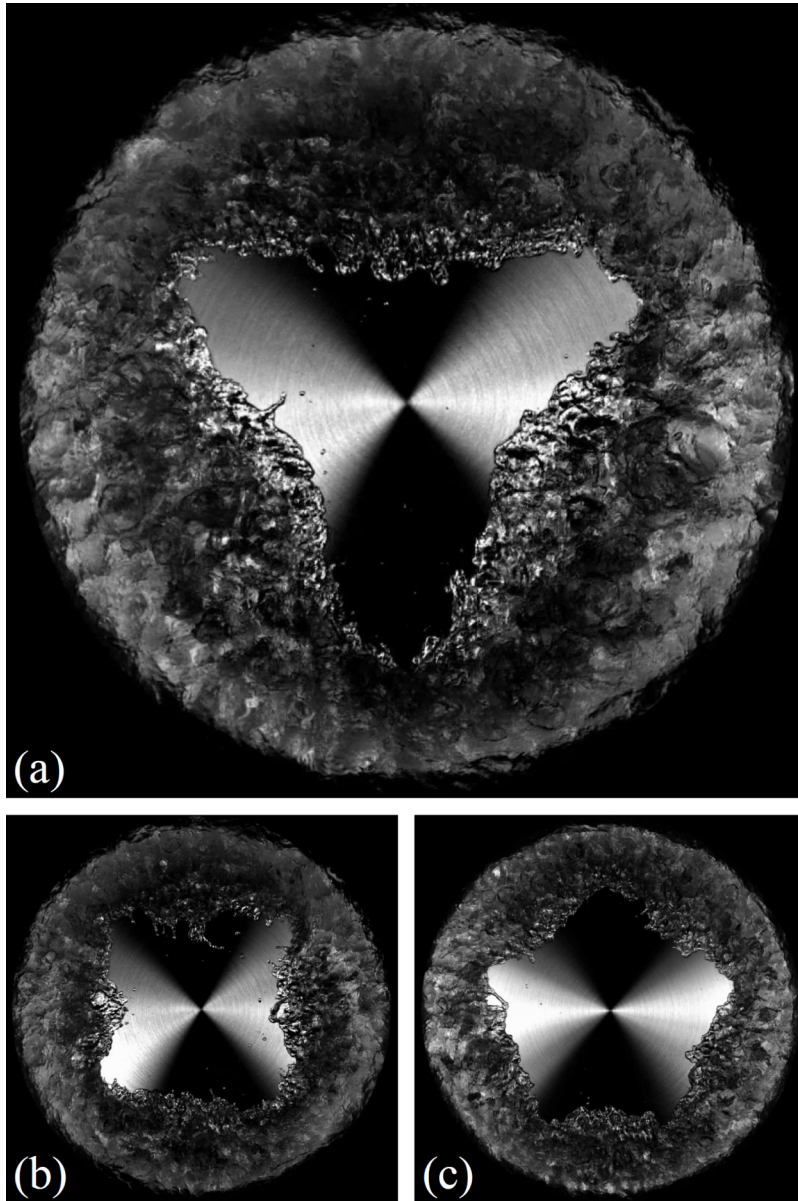


FIG. 1. Rotating polygons in liquid nitrogen rotating flow. Liquid nitrogen (boiling temperature $T_N = 77$ K, viscosity $\nu = 2 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$ and density $\rho = 810 \text{ kg m}^{-3}$) is poured into a stationary pot, placed in a water bath kept at 80°C . The boiling liquid is set into rotation using a wooden spoon, and then the pot is covered with a transparent glass, leaving a small opening allowing the nitrogen vapor to push out the aqueous mist that obstructs the view. From above, one can observe “polygons” with two to six corners, e.g., triangles (a), squares (b), and pentagons (c). As the fluid evaporates and slows down, the number of corners gradually decreases. DOI: [10.1103/APS.DFD.2018.GFM.V0032](https://doi.org/10.1103/APS.DFD.2018.GFM.V0032).

opposed to the concave surface shape of Newton’s bucket. The azimuthal flow speed varies like $1/r$ (like a line vortex) and thus becomes more rapid closer to the axis. The reason is the “frustrated” character of the nitrogen flow: since the pot is standing still, the flow is gradually slowing down,

and this invariably induces a secondary radial flow on top of the dominant azimuthal one, turning it into something like a line vortex flow. Then, on a somewhat longer timescale, symmetry-breaking instabilities set in, they deform the surface into polygonal structures with somewhere between two and six corners, starting at some value depending on the liquid volume and speed and then slowly removing the corners one by one. For a given volume of liquid, the larger the rotation speed, the larger the number of initial corners, and, conversely, for a given rotation speed, the smaller the liquid volume, the larger the number of corners. However, we have never observed polygons with more than six corners.

We believe that this instability leading to the polygons is caused by the resonance between “gravity waves” (living near the almost horizontal surface at the rim) and “centrifugal waves” (living near the strongly inclined surface at the center) as developed in Refs. [1,2]. Interestingly, it is the resonance between a forward-moving gravitational wave and a backward-moving centrifugal wave which creates the instability. For this to be possible, the “backward” centrifugal wave must actually move forward in the laboratory frame, and thus the flow speed near the center has to be greater than that of the wave (corner), making this part of the flow “supercritical”—something one can easily verify by looking at the video. As can be seen from Fig. 1, the flow is strongly turbulent, something which is not included in the model. It is surprising that such orderly coherent states can survive and remain in synchrony despite the chaotic bursts and eruptive drop detachments seen in the video. Actually, we believe that these chaotic bursts enhance the exchange of angular momentum between different parts, thereby facilitating the approach to the constant-angular-momentum line vortex flow, from which the instability can proceed. This phenomenon therefore illustrates the ability of turbulent rotating flows to generate order and is reminiscent of such large-scale planetary phenomena as Jupiter’s Red Spot and Saturn’s North Pole hexagon.

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[2] J. Mougel, D. Fabre, L. Lacaze, and T. Bohr, On the instabilities of a potential vortex with a free surface, *J. Fluid Mech.* **824**, 230 (2017).