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Variable density vortex ring dynamics in sharply stratified ambient fluids

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Vertical density stratification is a key element in the dynamics of geophysical fluids such as lakes, oceans, and the atmosphere. Often, the vertical transport of matter through such density profiles results in self-propagating coherent vortex structures and their breakdown or persistence can greatly affect mixing of the surrounding fluid. Such processes can contribute to the formation of trapped plumes in the ocean and atmosphere, as occurred for instance in the 2010 Deepwater Horizon oil spill in the Gulf of Mexico [1]. To gain some understanding of the vortex stability it is advantageous to consider the simplest possible setup involving a single vortex. The case of a density matched vortex traveling in a homogeneous fluid is the scenario most commonly examined in the literature. Here we consider the more complex variable density setup involving a vortex settling in a stratified ambient fluid, with an initial vortex density greater than the bottom fluid. In our experiments, this stratification is characterized by three regions in a 10 cm × 10 cm × 19 cm acrylic tank: a constant density fresh water top layer (0.9998 g/cc), approximately 2 cm thick, a linear stratification of 5 cm thickness, and a constant deep layer of salty water (1.025 g/cc). The diameter of the vortex is initially approximately 1 cm and generally grows during the course of the experiment (as noticed in the computational and experimental study [2]). In Fig. 1, we show a sequence of snapshots (side view: left and center columns; bottom view: right column) documenting the vortex ring evolution and its breakup as it passes into and through the stratified region. A Nikon D4 camera equipped with a 105 mm micro-Nikkor lens, focused below the stratified region, was used to capture images. The color shadowgraphs are visualized using a parallel light source illuminating the vortex ring from the top and the side. The heavy vortex ring is created by a rhodamine dyed salt water drop (1.05 g/cc), generated by a Harvard syringe infusion pump model 975 connected to a stainless steel needle of 2 mm external diameter located 25 mm above the surface, following generation methods documented in the literature [2,3]. The presented pictures are finally obtained by inverting the color map, resulting in a blue background and a green vortex ring. As the vortex ring travels into the stratified region, it entrains light, top-layer fluid into dense bottom fluid. This enhances the vortex ring deceleration, leading to the observed vortex breakup which can be attributed mostly to a Rayleigh-Taylor type instability. The dense core

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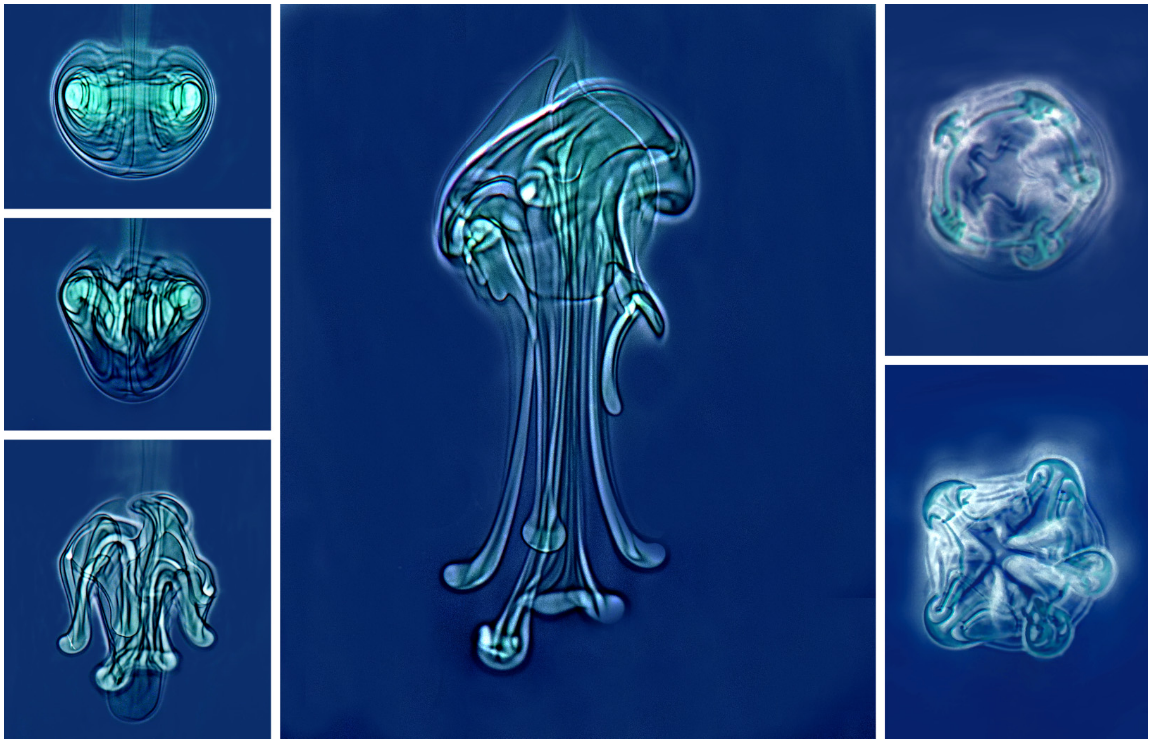

FIG. 1. Left column: Side view of the vortex entering the bottom denser layer and the progression of vortex breakup. Center panel shows the later time structure, with the entrained top-layer fluid returning upward, though the center of the ring, creating a "jellyfish" pattern. Right column: Bottom view showing the pentagonal symmetry of the growth of the underlying instability. See the original poster at http://dx.doi.org/10.1103/APS.DFD.2015.GFM.P0050

fluid settles, while a mixture of mostly top-layer fluid generates a rising plume forming the "jellyfish"-like cap. The "tentacles" of heavy core fluid following the vortex breakup bear resemblance to those recently reported [4] for the case of vortex rings with a core density larger than homogeneous ambient fluid, while the rising plume in the form of a cap is due to the ambient fluid stratification.

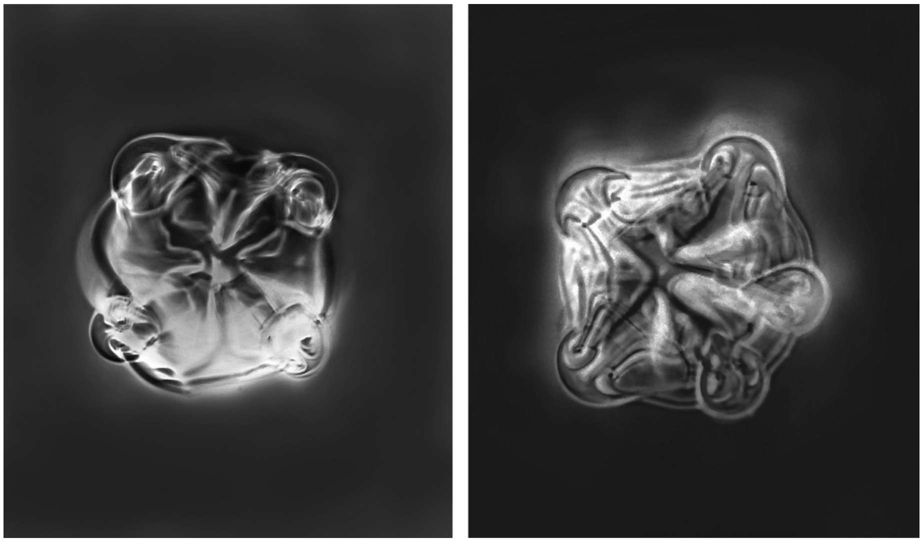

FIG. 2. Comparison of four- and fivefold symmetry of the vortex breakup visualized from below.

The Rayleigh-Taylor instability mechanism provides a simple estimate for predicting the N-fold symmetry leading to vortex breakup by selecting a most unstable viscous wavelength. This suggests the possibility of obtaining different than pentagonal shapes. An example contrasting the pentagonal symmetry with a diamond configuration is presented in Fig. 2 (black and white) where the height of the injector was increased by 5 mm. This results in a faster and smaller initial vortex ring where only four folds are observed in our stratified system.

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