Single-Mode Incompressible Richtmyer-Meshkov Instability Experiments

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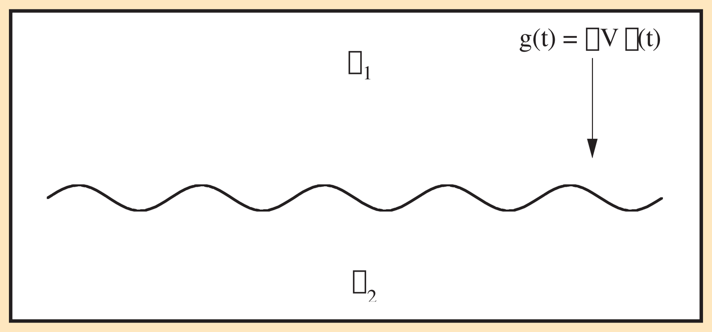
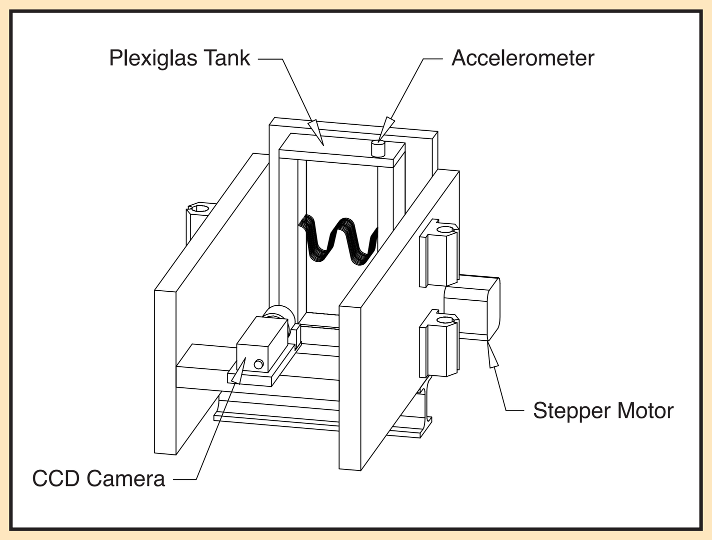


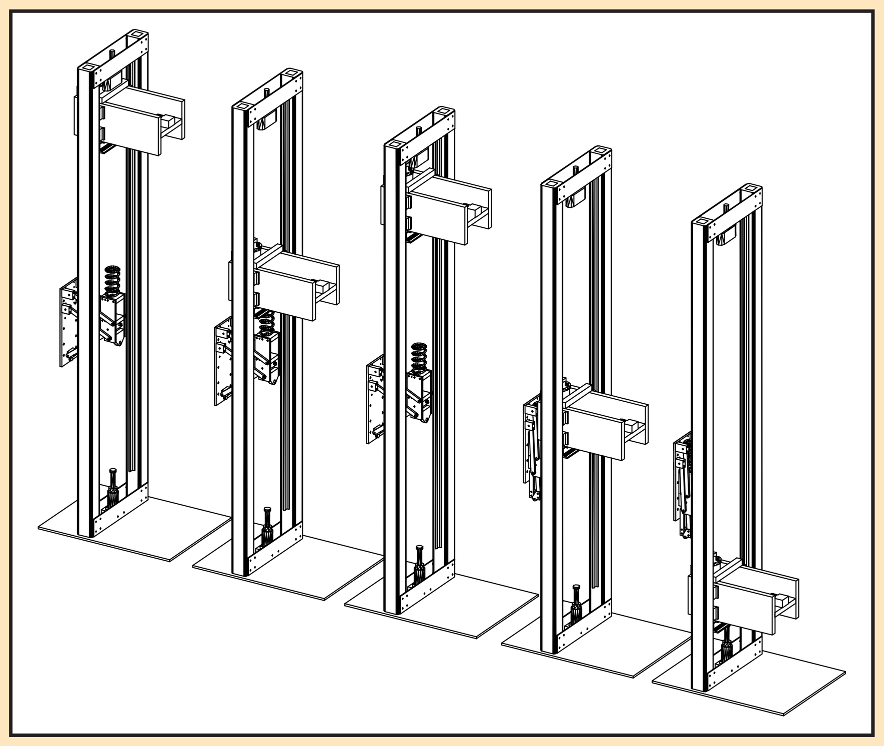
Richtmyer-Meshkov (R–M) instability occurs when two different density fluids are impulsively accelerated in the direction normal to their nearly planar interface. The instability causes small perturbations on the interface to grow and possibly become turbulent given the proper initial conditions. R–M instability is similar to the Rayleigh-Taylor (R–T) instability, which is generated when the two fluids undergo a constant acceleration. R–M instability is a fundamental fluid instability that is important to fields ranging from astrophysics to high-speed combustion. For example, R–M instability is currently the limiting factor in achieving a net positive yield with inertial confinement fusion.

The experiments described here utilize a novel technique that circumvents many of the experimental difficulties previously limiting the study of the R–M instability. A Plexiglas tank contains two unequal density liquids and is gently oscillated horizontally to produce a controlled initial fluid interface shape. The tank is mounted to a sled on a high-speed, low-friction linear rail system, constraining the main motion to the vertical direction. The sled is released from an initial height and falls vertically until bouncing off of a movable spring, imparting an impulsive acceleration in the upward direction. As the sled travels up and down the rails, the spring retracts out of the way, allowing the instability to evolve in freefall until the sled impacts a shock absorber at the end of the rails. The impulsive acceleration provided to the system is measured by a piezoelectric accelerometer mounted on the tank, and a capacitive accelerometer measures the low-level drag of the bearings. Planar Laser-Induced Fluorescence is used for flow visualization, with an Argon ion laser illuminating the flow and a CCD camera mounted to the sled capturing images of the interface.

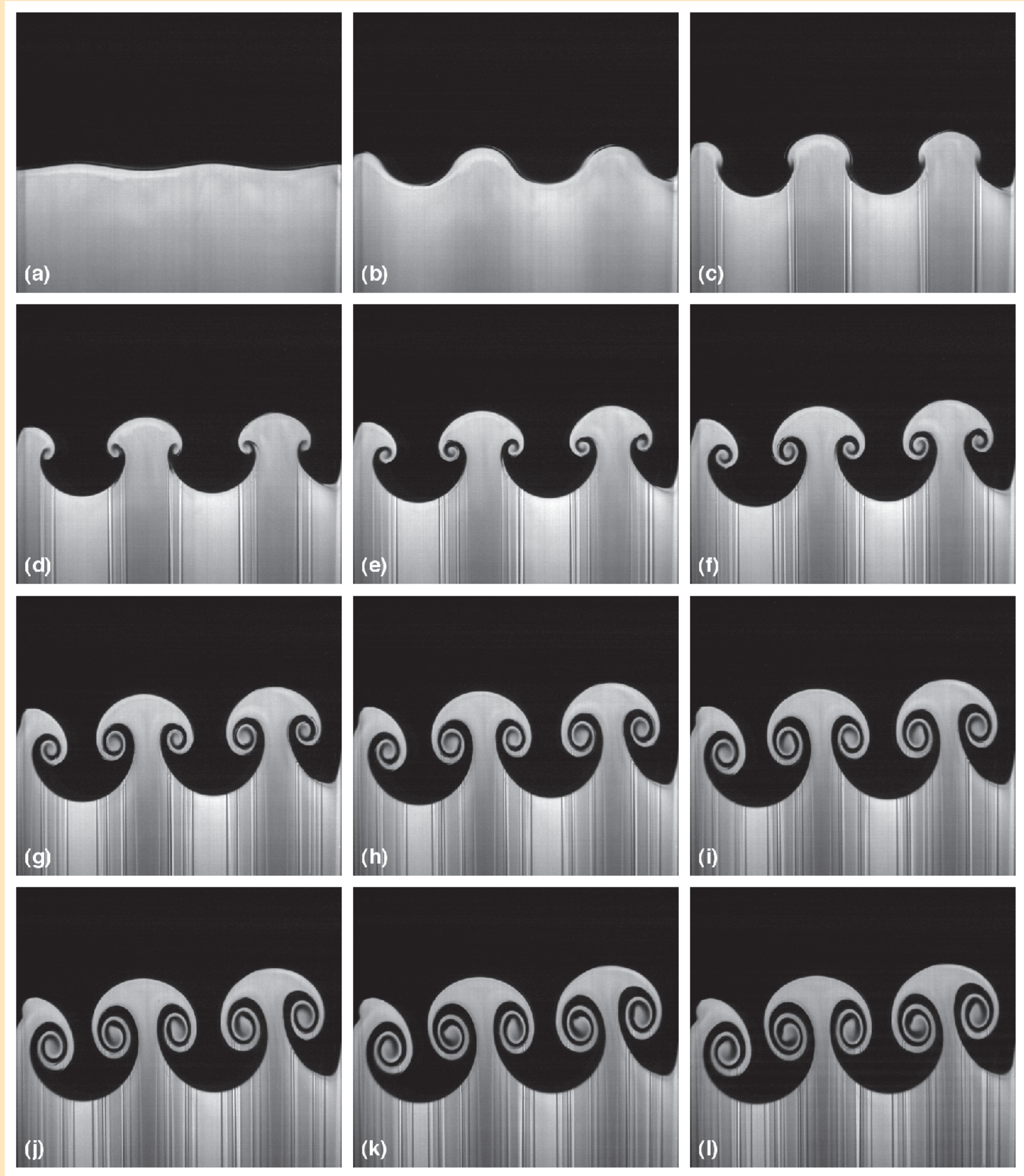
This experimental study investigates the instability of an interface between incompressible, miscible liquids with an initial sinusoidal perturbation. The lighter fluid is an isopropyl alcohol and water solution, and the heavier fluid is a calcium nitrate salt solution. The resulting Atwood number A (density difference over density sum) is 0.155. The amplitude of the disturbance during the experiment is measured and compared to theories. The results are nondimensionalized using the wave number k and initial growth rate $\dot{a}_0$. The initial growth rate and time for zero amplitude are obtained from an integration routine utilizing linear theory along with measured initial conditions and accelerations. The amplitude measurements are compared to several theories in the linear, weakly nonlinear, and late-time nonlinear regimes. The effect of Reynolds number on the vortices' evolution is also investigated. At higher Reynolds Number (based on circulation), an instability of the vortex cores has been observed. While time limitations of the apparatus prevent determination of a critical Reynolds Number, the lowest Reynolds Number this vortex instability has been observed at is 2000.



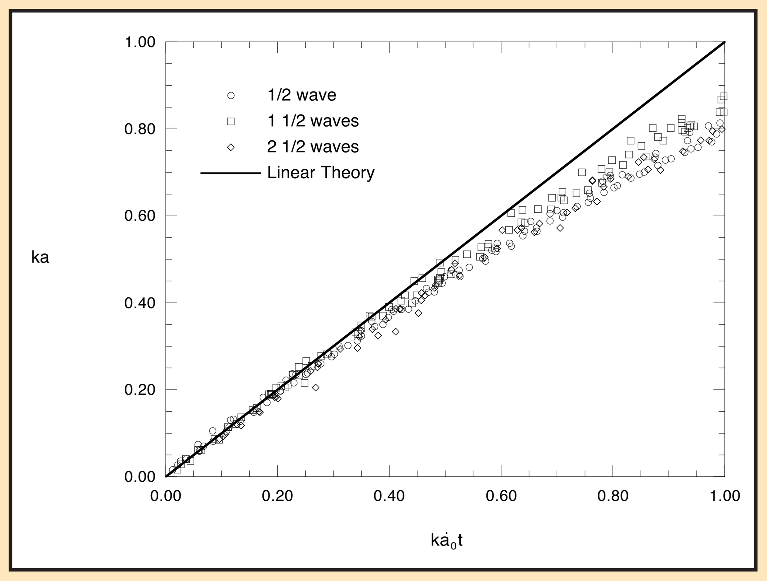
Experimental fluid container mounted on the sled.



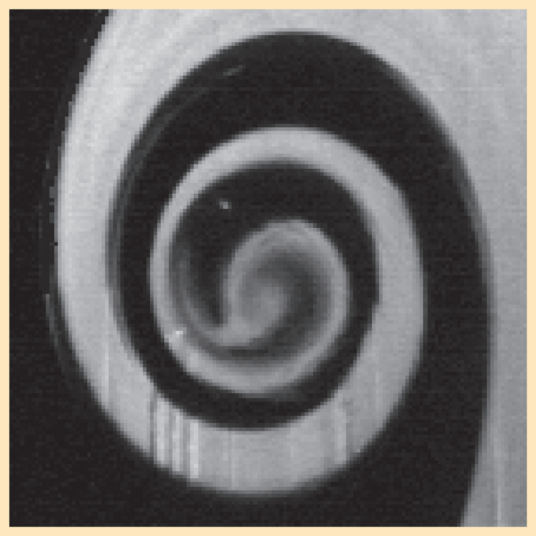
Animation of sled traveling along drop tower rails.



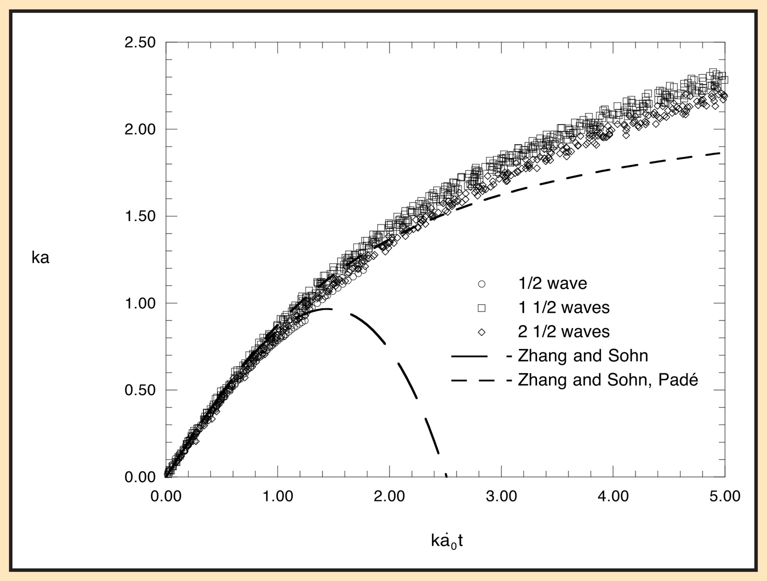
The above sequence of PLIF images shows the evolution of the Richtmyer-Meshkov instability generated from a sinusoidal initial perturbation with $ka_i = 0.16$ and 2 1/2 waves inside the experiment tank. Image (a) was taken just before the sled impacted the spring and thus shows the initial interface shape. The impulsive acceleration in these experiments is directed from the heavier fluid into the lighter fluid, causing the initial perturbation to invert before growing. Immediately after inversion, the interface retains a sinusoidal shape, but with time the vorticity begins to concentrate at points midway between the crests and troughs. These vortices roll the interface around their centers, forming a spiral pattern. Note that, characteristic of the instability with small density differences, the interface retains its top-to-bottom symmetry well into the nonlinear regime.



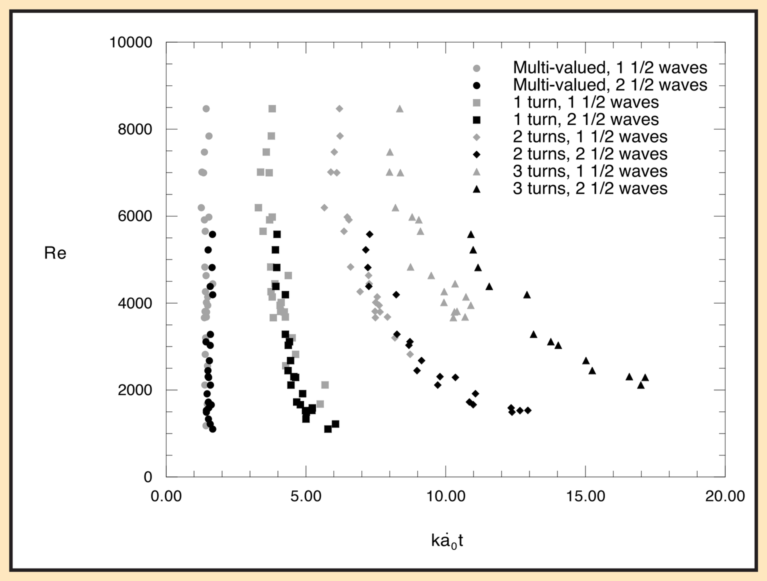
The nondimensional amplitude versus time is shown for the early stages of the instability. Linear theory (Richtmyer, *Commun. Pure Appl. Math* **13**, 1960) is shown by the solid line. The experiments show excellent agreement with linear theory up to $k\dot{a}_0t = 0.3$ and are within 10% of linear theory at $k\dot{a}_0t = 0.7$, where nonlinear effects start to become important. It should be noted that linear theory is derived assuming $|ka| << 1$ and is surprisingly accurate at moderate values of ka. Also, the ka_i (dimensionless amplitude before impact) for these experiments ranged from 0.07 to 0.66 and does not seem to effect the agreement with linear theory.



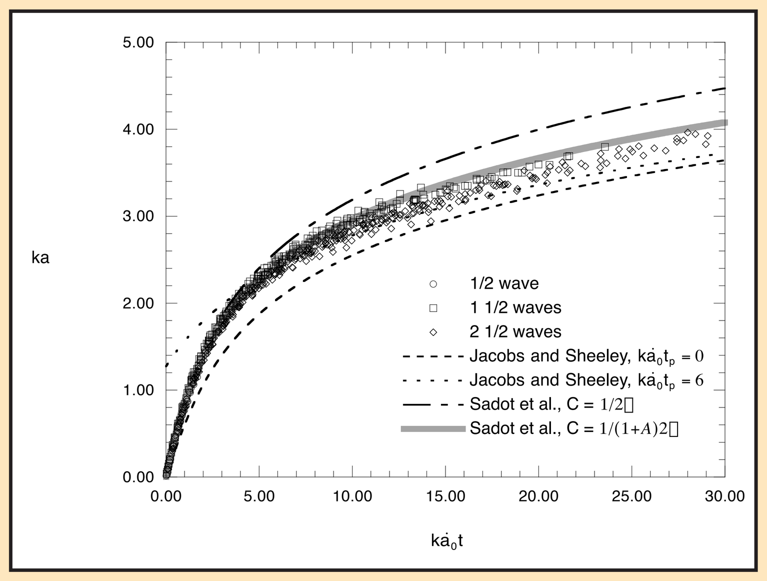
One parameter that has not received previous study is the influence of Reynolds number on the flow. The Reynolds number for this vortex dominated flow is defined using the circulation of the vortices and the average kinematic viscosity of the fluids, i.e. □/□. While the overall amplitude was not found to be a function of the Reynolds number, the dynamics of the vortex core was influenced by the flow Reynolds number. Measurements were made of when the interface first became multi-valued, and when the vortex had completed a given number of turns. The image to the left shows a vortex that has just made 2 complete turns.



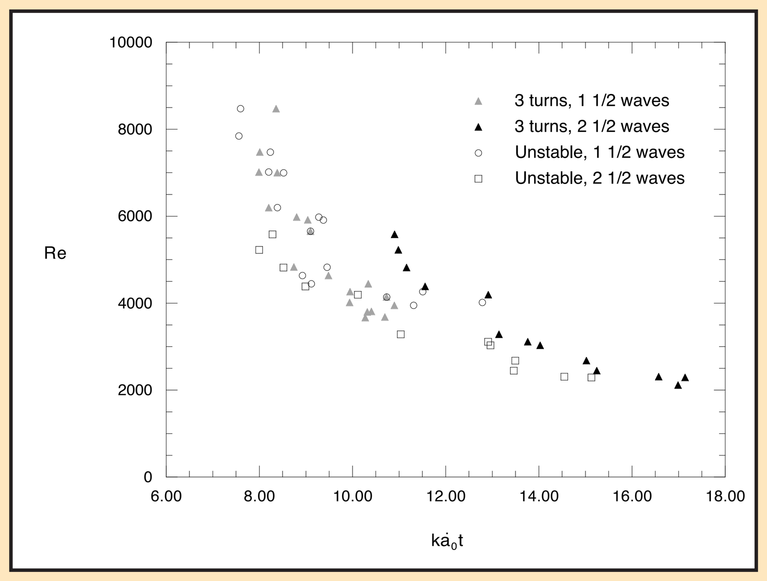
Intermediate-time amplitude measurements are shown along with two theories developed by Zhang and Sohn (*Phys. Fluids* **9**, 247, 1997) that are a function of Atwood number. The first is a weakly nonlinear fourth order perturbation theory, shown for a representative A of 0.155. This solution agrees with experimental data to within 10% up to $k\dot{a}_0t = 1.3$, but then rapidly becomes invalid due to its cubic form. Recognizing the limited range of validity, Zhang and Sohn used this solution to develop a Padé approximate for velocity which was then integrated to determine amplitude. This extended the range of agreement (to within 10%) up to $k\dot{a}_0t = 3$.



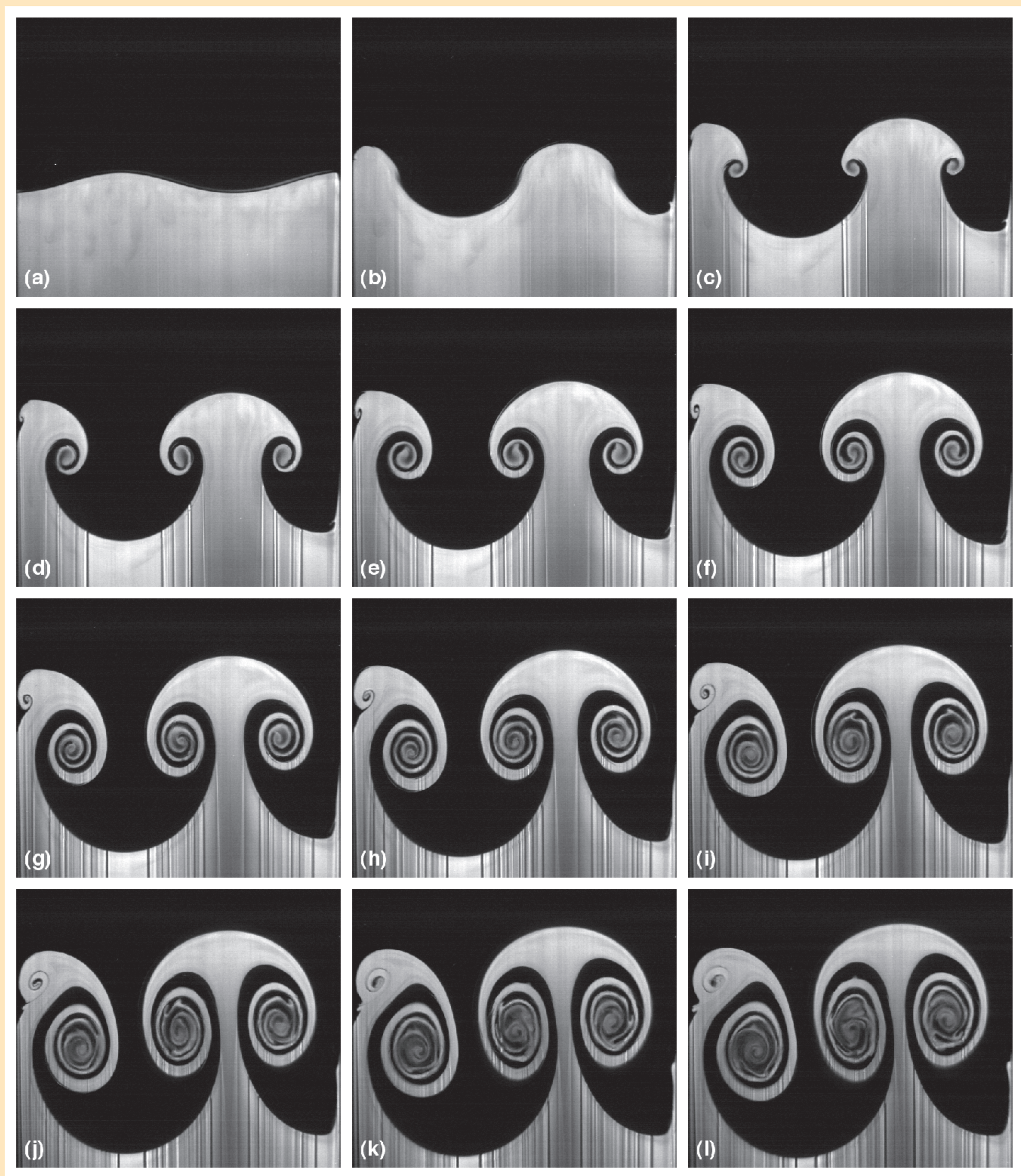
This graph shows the evolution of the vortex core as a function of the experimental Reynolds number. At early-times when the vorticity is still distributed along the interface, the flow is not a function of Reynolds number and the interface first becomes multi-valued at $k\dot{a}_0t$ □1.5 for all Reynolds numbers investigated. After the vorticity has concentrated, the lower Reynolds number experiments have a slower turning rate due to viscous diffusion of vorticity from the cores. However, because perturbation amplitudes were not found to be a function of Reynolds number, the size of the vortex core is still small compared to the perturbation amplitude.



Late-time amplitude measurements are shown along with nonlinear theories. Jacobs and Sheeley (*Phys. Fluids* **8**, 405, 1996) modeled the late-time flow as a row of point vortices in fluids with $A = 0$, where $k\dot{a}_0t_p$ is the time when the vorticity has coalesced into a point. Sadot et al. (*Phys. Rev. Lett.* **80**, 1998) used several models' results to develop a rational equation for growth that captures the early stages to second order (with A dependence) and converges to the correct asymptotic velocity. The parameter C is a function of the asymptotic velocity, with the functional form of A dependence developed in Niederhaus (Ph.D. dissertation, University of Arizona, 2000).



Shown on the graph to the left is the nondimensional time when the disturbance amplitude equals the spiral thickness (see images to right) for those experiments exhibiting the secondary instability. Higher Reynolds number experiments become unstable sooner, with the lower Reynolds number experiment taking more than twice as long to exhibit the instability. The instability appears to be correlated to the number of turns in the vortex core, occurring roughly after three turns over the Reynolds number range investigated. Due to experimental time limitations, a critical Reynolds number for the secondary instability cannot be determined.



Shown above is a sequence of images from an experiment with $ka_i = 0.29$ and 1 1/2 waves inside the tank. The Reynolds number (based on circulation) of the experiment is 4830. Initially the instability develops very similarly to the lower Reynolds number cases. Starting at frame (h), however, one can see the start of a secondary instability in the core of the vortex. The secondary instability takes the form of oscillations superimposed on the vortex spiral. The waves start near the center of the core and grow in size and extent until all layers of the core spiral are effected. By frame (k) the instability has spread throughout the vortex core and it appears that the interface is no longer sharp and the fluids are starting to mix on a smaller scale.