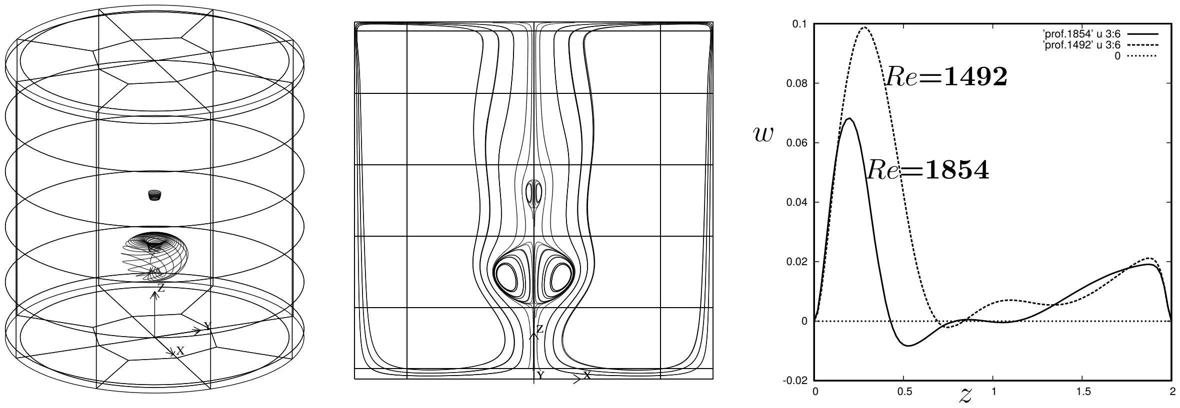

Figure 9: Vortex breakdown results: (left) streamlines for Re=1854, (center) in-plane streamlines for Re=1854, (right) vertical velocity distributions along the centerline.

9 Vortex Breakdown

Escudier[12] studied vortex breakdown in a container with a rotating lid. The domain consists of a cylindrical container of radius R and height $H = 2R$. The top lid rotates at a constant angular velocity Ω, and the Reynolds number is $Re = \Omega^2 R/\nu$. Following the standard approach, we take $\Omega = R = \rho = 1$ and set $\nu = Re^{-1}$.

The mesh in Fig. 9 is constructed from a 2D base swept through z with element boundaries at z=0, 0.06, 0.4, 0.8, 1.2, 1.6, 1.95, and 2. The mesh is concentrated near the cannister walls and near the upper and lower lids. The singularity at r=R, z=2 is handled by shearing the side walls in the top layer of elements using a 5th-order monomial. The initial and boundary condition for $z > 1.95$ are thus $(u, v) = (-y, x) * \alpha(z)$, with $\alpha = (z-2)^5/\Delta_z^5$ and $\Delta_z = .05$. The simulations are time-marched to steady state at varying spatial resolutions (N=7, 9, and 11). Simulation times of $t_f \approx 1000$ are required to form a single bubble in the $Re = 1492$ case.

Depending on the aspect ratio and Reynolds number, one can find various steady and unsteady vortex breakdown regimes with one or more "bubbles" (reversal regions) on the axis. For H/R=2, Escudier documented steady-state flows with with a single bubble at Re=1492 and two bubbles at Re=1854. The streamline plots in Fig. 9 show the bubble structures for Re=1854. Bubble locations can be inferred from zero-crossings of axial velocity w versus z at $(x, y) = (0, 0)$, shown in the right panel. These locations are tabulated below, along with experimental results of Escudier and numerical results of Sotiropoulos and Ventikos.[13]

Locations of Vertical Velocity Reversals						
	Re=1492		Re=1854			
	z_1	z_2	z_1	z_2	z_3	z_4
N=7	.689	.836	.427	.793	.960	1.131
N=9	.671	.831	.420	.776	.954	1.118
N=11	.671	.831	.420	.775	.955	1.117
Escudier	.68	.80	.42	.74	1.04(?)	1.18(?)
Sot. & Ven	.646	.774	.42	.772	.928	1.09

[12] M.P. Escudier, "Observations of the flow produced in a cylindrical container by a rotating endwall," *Exp. Fluids* **2** 189–196 (1984).

[13] F. Sotiropoulos & Y. Ventikos, "Transition from bubble-type vortex breakdown to columnar vortex in a confined swirling flow," *Int. J. Heat and Fluid Flow* **19** 446–458 (1998).