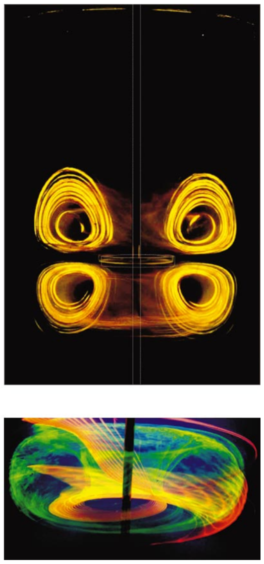

FIG. 1.

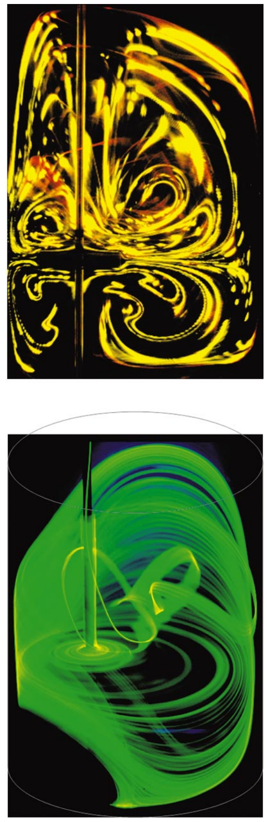

FIG. 2.

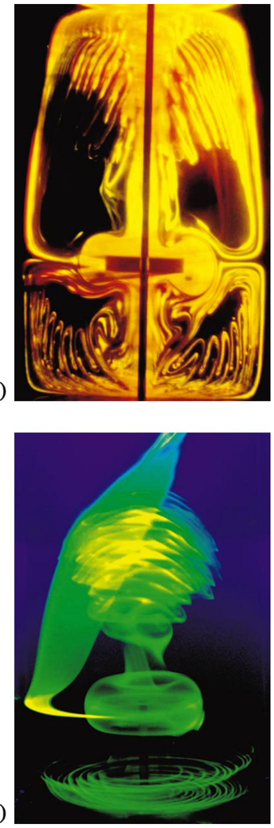

FIG. 3.

Three-Dimensional Chaotic Mixing

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Laminar mixing in stirred tanks can be very inefficient since linear viscous forces dominate the flow. One way to achieve efficient mixing at low Reynolds numbers (Re) is to operate under conditions that lead to chaotic behavior.[1,2] The difficulty of mixing in the laminar regime is illustrated in Fig. 1 for a tank stirred by a single axisymmetric disc filled with a Newtonian fluid at Re=10. The snapshot, obtained using planar laser induced fluorescence (pLIF), reveals closely spaced, concentric sets of rings around elliptic points [Fig. 1(a)]; no signs of chaotic mixing are observed. In Fig. 1(b), green and red dyes are injected at different times to show the three-dimensional (3D) regular structure of nested tori and dye segregation using ultraviolet fluorescence.

Breaking spatial symmetry, by placing the disc off-center, can be used as a means of inducing chaos in stirred tanks.[3,4] The pLIF snapshot in Fig. 2(a) demonstrates that the unstable manifolds of the flow are drastically modified by eccentricity. Chaos is achieved and a significant reduction in mixing time is observed with respect to the concentric case.[3] Figure 2(b) shows that the underlying two-dimensional (2D) flow becomes fully 3D, giving rise to an extremely heterogeneous and complex structure.

Next, we demonstrate that chaotic mixing is achieved, even in the concentric configuration, by simply replacing the Newtonian fluid by a shear-thinning and viscoelastic one [Fig. 3(a)]. Here, we experiment with a 1% aqueous solution of carboxymethyl cellulose (CMC) to show that shear-dependent viscosity and normal stresses are responsible for a lobe formation process strongly reminiscent of periodically forced 2D flows, indicating that the ingredients of chaotic mixing, folding and stretching, are present. The flow again becomes 3D as shown in Fig. 3(b), which also reveals the progression of a thin sheet of dye being stretched and compressed into filaments and rolls, indicating that material surfaces in three dimensions have the potential to be one-dimensional or 2D (lines and planes).

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