Enhanced microfluidic mixing via a tricritical spiral vortex instability

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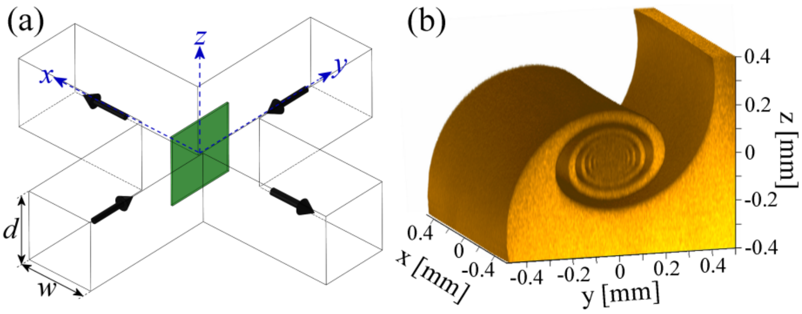
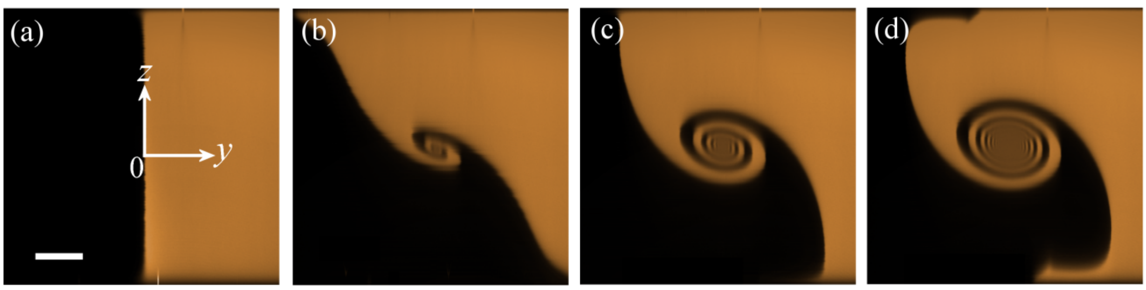
Experimental measurements and numerical simulations are made on fluid flow through cross-slot devices with a range of aspect (depth:width) ratios, $0.4 < \alpha < 3.87$. For low Reynolds numbers Re, the flow is symmetric and a sharp boundary exists between fluid streams entering the cross-slot from opposite directions. Above an α-dependent critical value $20 < Re_c(\alpha) < 100$, the flow undergoes a symmetry-breaking bifurcation (though remains steady and laminar) and a spiral vortex structure develops about the central axis of the outflow channel. An order parameter characterizing the instability grows according to a sixth-order Landau potential, and shows a progression from second order to first order transitions as α increases. A tricritical point occurs for α ~0.55. The spiral vortex acts as a mixing region in the flow field and this phenomenon can be used to drive enhanced mixing in microfluidic devices.



(a) Schematic diagram of a cross-slot device. Fluorescently-dyed fluid enters from positive *y* and undyed fluid enters from negative *y*. Flow exits along the *x*-direction. Confocal microscopy is performed in *z*-planes, which are scanned through the full depth of the device and used to reconstruct images in the $x = 0$ plane (green shaded region).
(b) Three-dimensional (3D) rendering of a vortex structure observed for the flow of water at Re = 75.8 in a cross-slot with $\alpha = 1$. The image is generated from *z*-plane images spaced at $\delta z = 5$ μm and has been cropped around the central vortex. The volume shown corresponds to the fluorescently-dyed fluid stream.



Development of the spiral vortex structure in the $x = 0$ plane as the Reynolds number (Re) is varied: (a) Re = 15.2, (b) Re = 42.8, (c) Re = 60.6, (d) Re = 91.0. Scale bar in (a) represents 200 μm.