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Folding and swirling instabilities of viscous fluid threads in microchannels

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We study the behavior of viscous fluid threads formed by hydrodynamic focusing as they are swept along by the flow of a different outer fluid in hard microfluidic channels. By examining pairs of miscible liquids for which interfacial tension is essentially absent, such as silicone oils having different molecular weights, we reveal a rich variety of fluid instabilities that occur at low Reynolds numbers. When a single thread that propagates stably in the center of a straight channel encounters a divergence in the channel's width, the thread simply dilates if its viscosity is similar to that of the outer fluid. However, due to the extensional flow and deceleration in the diverging channel, a thread that is sufficiently viscous becomes unstable and reduces energy dissipation by performing sinuous bending oscillations, or 'folding', rather than dilating. By tuning the flow rates, we reveal a novel period-doubling route to chaotic folding. The folding and stretching of a thread in a diverging channel provides a simple means of mixing viscous liquids and creating controlled viscosity gradients. Moreover, using a sequence of two cross-channels, we make a pair of viscous threads that become unstable when swept along near the walls of a straight channel as a result of the viscous torque induced by the velocity gradient. The amplification of lateral undulations ultimately causes the threads to break up and form an array of viscous swirls, the miscible counterparts of droplets. This swirling instability provides a means for producing discrete and uniform ephemeral swirls, the miscible counterpart of droplets. By injecting three different miscible liquids into a dual cross-channel geometry, we examine the complex patterns that form when several fluid instabilities interact and compete. Overall, we anticipate that these measurements will provide important insight into the behavior of flowing threads in which interfacial tension plays a more substantial role.

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