EXTENSIONAL FLOW OF WORM-LIKE MICELLAR SOLUTIONS IN A MICROFLUIDIC CROSS-SLOT DEVICE

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Worm-like micellar surfactant solutions are encountered in a wide variety of applications, including enhanced oil recovery and ink-jet printing, in which the fluids are subjected to high extensional strain rates. We investigate the stagnation point extensional flow of worm-like micellar solutions consisting of cetyl pyridinium chloride (CPyCl) and sodium salicylate (NaSal) in a microscale cross-slot geometry using micro-particle image velocimetry (μ-PIV), full-field birefringence microscopy coupled with macroscopic measurements of the bulk pressure drop. Prior to testing in the cross-slot device, the fluids are characterized using a combination of cone-and-plate steady and oscillatory shear, microfluidic rheometry and capillary break-up extensional rheometry (CaBER). The micromachined cross-slot geometry has a width of 200 μm and a depth of 1 mm, thus providing a quasi-2D flow upstream and a wide viewing window for resolving the local kinematics and state of stress near the stagnation point. In the case of Newtonian fluids, μ-PIV shows the flow field in the cross-slot remains symmetric and stable up to moderate Reynolds number, Re ~ 20. In the worm-like micellar solutions the flow field remains symmetric only for low values of the strain rate, $\dot{\varepsilon}$, such that $\dot{\varepsilon} \leq \tau^{-1}$, where τ is the fluid relaxation time determined using CaBER. In this stable flow regime the fluid displays a sharp birefringent strand extending along the outflow streamline from the stagnation point. Estimates of the apparent extensional viscosity, η_E, can be obtained using either the stress-optical rule or from the total pressure drop measured across the cross-slot channel. For moderate deformation rates ($\dot{\varepsilon} \geq \tau^{-1}$) the flow remains steady, but becomes increasingly asymmetric with increasing flow rate. This symmetry breaking bifurcation is entirely elastic in origin since the Reynolds number at its onset is ~ $O(10^{-5})$. The combination of fluid elasticity and shear-thinning in the micellar solution rheology results in a very sharply-defined and strongly-curved birefringent strand along the dividing streamline between the two arms of the cross-slot device. Eventually, with further increases in the imposed deformation rate , this asymmetric divided flow becomes unsteady and time dependent.