Cross-slot flow for extensional rheometry: from optimization to experimentation

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ABSTRACT

In this work we propose and test an optimized cross-slot device able to generate a strong extensional flow comprising a large region of constant strain-rate along the centerline, a fundamental requirement for meaningful extensional rheometry measurements. In this type of opposed flow geometry there is a stagnation point at the center of symmetry (marked with an “S” in Figure 1), where the fluid velocity is zero but the local extension rate is finite [1]. A successful design would yield significant advantages over classical cross-slot devices, in which the imposed strain rate is well-defined only in the region very close to the stagnation point and decays rapidly along the exit channels.

For the optimal shape design, we use the methodology proposed by Alves [2] which combines computational fluid dynamics (CFD) simulations, using a finite-volume viscoelastic code [3], with a CONDOR optimizer [4] and an automatic mesh generation procedure. The initial configuration (a conventional cross-slot with rounded corners) and the final optimized design are illustrated in Figure 1. The proposed microfluidic device consists of a cross-slot flow geometry with a non-conventional shape, which generates a homogeneous elongational flow with large regions of nearly constant extensional strain-rate. The optimized shape was found to be very insensitive to the imposed flow rate (and the corresponding dimensionless Deborah number), making it possible to obtain a nearly universal cross-slot capable of generating an ideal planar extensional flow for Newtonian and viscoelastic fluids at low Reynolds number.

Figure 1: Conventional cross-slot flow geometry with rounded corners used as initial configurations (left hand-side) and optimized flow geometry obtained through optimal shape design (right hand-side).
A prototype of the 2D optimized cross-slot microchannel was produced from stainless steel by wire-electro-discharge machining (EDM) and is shown in Figure 2a, where a micrograph of the real shape of the geometry is compared with the predicted optimized shape obtained from the numerical simulations. The channel is then assembled between two glass discs to allow for optical access (cf. Figure 2b). The device has a constant depth of 2 mm and a characteristic width of 200 µm for the inlets/outlets, yielding an aspect ratio of 10:1 and a good approximation to 2D flow in the inlet and outlet regions. In terms of birefringence, the large depth of the channel also provides a long optical path for the accumulation of optical retardation in complex fluids as plane-polarized light passes through the birefringent flowing test fluids.

Figure 2: (a) Comparison of the optimized cross-slot produced in stainless steel by wire-EDM (micrograph) and the optimal shape proposed numerically (in green); (b) exploded view of the prototype showing (1) glass front window, (2) stainless-steel cross-slot, (3) glass rear window with holes to allow fluid flow, (4) stainless steel flow-cell mount with four pipe connections to the flow system and a central ‘‘thru’’ hole to allow optical access.

For the experimental characterization of the flow field we use various optical techniques as well as conventional macroscopic pressure drop measurements. Micro-particle image velocimetry (µ-PIV) is used to quantify the velocity field and examine the linearity of the velocity profiles along the centerline, and birefringence microscopy is used to evaluate the local state of stress in the fluid. In the experiments we have used several different fluids. First, a Newtonian fluid is used for validation purposes and the experimental results are compared to corresponding numerical calculations. The experimental results closely correspond to the idealized extensional flow profile exhibiting an extended homogeneous region in which the outflow velocity increases linearly with distance from the stagnation point “S”. We have also used the device to examine the extensional flow of a number of non-Newtonian fluids, including viscoelastic polymer solutions and wormlike micellar solutions. For the viscoelastic fluids, together with the linear velocity profiles, a narrow localized birefringent strand was observed along the exit channel centerline resulting from the strong extensional flow. By quantifying the magnitude of this flow-induced extensional stress and the corresponding rate of deformation it is possible to compute the true extensional viscosity of complex fluids in steady homogeneous extensional flow.

References