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Microfluidic analog of an opposed-jets device

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ABSTRACT
A fully three-dimensional (3D) stagnation point microfluidic device is fabricated that, similar to the classical opposed-jet apparatus, can be operated in either a uniaxial or a biaxial extensional flow mode with an easily controllable strain rate. The microchannel is etched inside fused silica and has optical access through all three planes. A detailed characterization of the Newtonian flow field by microparticle image velocimetry confirms the expected nature of the flow and compares well with the prediction of 3D numerical simulations. Flow-induced birefringence of a model polymer solution demonstrates the extension of macromolecules in both modes of operation and the potential use of the device for quantitative rheo-optical studies. This microfluidic opposed jet device could also be used for examining the deformation and dynamics of drops, cells, fibers, and single molecules in well-defined and relevant flow fields.

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Extensional flows with a stagnation point are extremely effective at stretching fluid elements and have wide utility for the study of the deformation and breakup of bubbles, drops, fibers, and cells, for observing macromolecular dynamics and elastic instabilities, and for performing extensional rheometry of complex fluids. The microchannel is etched inside fused silica and has optical access through all three planes. A detailed characterization of the Newtonian flow field by microparticle image velocimetry confirms the expected nature of the flow and compares well with the prediction of 3D numerical simulations. Flow-induced birefringence of a model polymer solution demonstrates the extension of macromolecules in both modes of operation and the potential use of the device for quantitative rheo-optical studies. This microfluidic opposed jet device could also be used for examining the deformation and dynamics of drops, cells, fibers, and single molecules in well-defined and relevant flow fields.

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Extensional flows with a stagnation point are extremely effective at stretching fluid elements and have wide utility for the study of the deformation and breakup of bubbles, drops, fibers, and cells,1–4 for observing macromolecular dynamics5–7 and elastic instabilities,8,9 and for performing extensional rheometry of complex fluids.10,11 The device is also readily reduced to the microscale, minimizing required fluid volumes and obviating complications arising from inertia. The cross-slots continue to be widely used among the microfluidics community for both fundamental and applied studies (see the review in Ref. 19).

Microfluidic analogs have since been developed for the four-roll mill.16–22 These devices have multiple inlets and outlets and enable the generation of various flow types ranging between solid body rotation and planar elongation by varying the inlet/outlet flow rate ratio (analogous to regulating the rotation rates of the individual rollers in the classical setup).

In this work, we present the first experimental realization of a microfluidic opposed jet analog: the operating principle of which is illustrated in Fig. 1. The system consists of three mutually bisecting channels of square cross section. If the fluid is injected at a rate Qin through two pairs of opposed inlets, and is withdrawn at a rate Qout from the remaining pair of opposed inlets, a uniaxial extensional flow is generated along the outlet axis [see Fig. 1(a)]. This is analogous to the opposed jets operating in sucking mode. If the flow is simply reversed, as illustrated in Fig. 1(b), equibiaxial extensional flow is generated over the outlet plane. This is analogous to the opposed jets operating in blowing mode.
imposing different flow rates in the two pairs of outlet channels a gen-

important. Note also that in the microfluidic opposed-jet analog, by

similar method to that employed in the planar cross-slot geometry18),

used to quantify shearing contributions to the total pressure loss (by a

pressure measurements made across an inlet and an outlet could be

entages over the classical opposed jets. Most obviously, by enclosing the

ick function are expected in each case.24 Thus, the development of

esional flows are either uniaxial or biaxial, and different extensional vis-

king stage of an inverted microscope (Nikon Eclipse Ti). The micro-

scope is equipped with a volume illumination

consisting of a dual-pulsed laser (Continuum Terra-PIV) and a high

speed camera (Phantom Miro). Pairs of laser pulses with user-
specified time separation \( \delta t \) excite fluorescence of the microparticles

and their positions are captured in a corresponding pair of images. Particle

positions are cross-correlated in interrogation areas to obtain the local particle displacement over the time \( \delta t \) and hence local velocity

vector, denoted as \( \mathbf{v} = (u, v, w) \). Note that only in-plane velocity

components are acquired. The measurement depth over which out of

plane particles contribute to the determination of velocity vectors is

\( \delta m \approx 170 \mu m \) or \( \approx 0.3L \)29.

Figure 2 summarizes the results of \( \mu \)-PIV experiments conducted under uniaxial extension. Figure 2(a) shows the velocity magnitude

\(|v|\), normalized by the average outflow velocity \( U_{out} = Q_{out}/L^2 \), for uniaxial elongation as viewed in the \( x = 0 \) plane, showing inflow along \( y \) and the outflow accelerating along \( x \) from a central stagnation point
For a range of inlet flow rates, Fig. 2(c) shows normalized velocity profiles measured along the outlet (x) and one inlet (y) axis. Over this range of \(Q_{in} \leq 3/11351 \leq 6\), indicating that inertial effects are moderate. Consequently, the experimental data collapse well. The normalized experimental velocity profiles averaged over the various imposed flow rates compare well with the numerical predictions. The extensional rate along the outlet axis, averaged between the outlet channel mouths (i.e., \(-0.5L \leq z \leq 0.5L\)), is \(\dot{e}_{xx} = \partial u/\partial x = 2.6U_{out}/L\) (experimental) and \(\dot{e}_{xx} = 3.5U_{out}/L\) (numerical). We attribute the discrepancy of \(\dot{e}_{xx} \approx 25\%\) to the significant (relative to within the inlet and outlet channels) out of plane motion of particles in the central cross over region. This is likely to cause an error in the determination of planar velocity vectors due to the appreciable measurement depth of the \(\mu\)-PIV set up, \(\delta \approx 0.3L\). The extensional rate along the inlet axis is \(\dot{e}_{yy} = \partial v/\partial y \approx -0.5\dot{e}_{xx}\) in both the experimental and the numerical results, as expected for a uniaxial extensional flow.

The results of \(\mu\)-PIV experiments conducted under equibiaxial extension are summarized in Fig. 3. Here, we only report data from one plane (x = 0) showing how the flow in the four outlet channels appears to emerge from a “sourcelike” central stagnation point located on the x-axis, Figs. 3(a) and 3(b). The normalized experimental velocity magnitude field [Fig. 3(a)] is again in reasonable qualitative agreement with a numerical simulation [Fig. 3(b)]. Normalized velocity profiles measured along the two outlet axes for a range of experimental...
Q_{in} values show good collapse in Fig. 3(c). The average experimental elongation rates between the outlet channel mouths are \( \dot{e}_{yy} \approx \dot{e}_{zz} \approx 2.8 U_{out} / L \). The numerically predicted extensional rates along the outlet axes are \( \dot{e}_{yy} = \dot{e}_{zz} \approx 3.8 U_{out} / L \). As in uniaxial extension, the discrepancy is of \( \approx 25\% \), which is attributed to the measurement depth of the \( \mu\)-PIV set up. It will be instructive in future to confirm this assertion by using a state-of-the-art stereoscopic particle tracking velocimetry instrument able to perform volumetric three-component velocimetry with high spatial resolution.  

As a demonstration of both the good optical quality of our microfluidic device and of the possibility of using it to study macromolecular dynamics under uniaxial and biaxial extension, we have also performed quantitative birefringence imaging on a model dilute polymer solution. The fluid is a 1400 ppm (weight) solution of 7 MDa atactic polystyrene (aPS) in the thermodynamically good organic solvent tricresyl phosphate (TCP). The overlap concentration is \( c^* \approx 2000 \text{ppm} \). The fluid is weakly shear-thinning with a zero-shear viscosity \( \eta_0 \approx 130 \text{ Pa s} \) and has a relaxation time \( \lambda \approx 40 \text{ ms} \). For the measurement, we employ an Exicor Micromager (Hinds Instruments Inc.), which is composed of a 532 nm light source, photoelastic modulators on either side of the sample, a 10× magnification Mitutoyo objective lens focused on the measurement plane, and a 2048 × 2048 pixel camera. The system provides spatially resolved \((\approx 0.55 \mu\text{m/pixel})\) values for the retardation \( R \) and the orientation of the fast optical axis. The birefringence is directly related to the retardation by \( \Delta n = R / \ell \), where \( \ell \) is the optical path length through the birefringent material. As shown in Fig. 4(a), at low flow rates no birefringence can be measured and the orientation angle map is composed of uniform random noise. At progressively higher flow rates [Figs. 4(b) and 4(c)], a birefringent signal is registered in a rather broad region around the outlet \((x)\) axis. The orientation angle map indicates that the fast axis is aligned along the outflow direction, as expected since for aPS the fast optical axis is aligned with the polymer backbone. The plot in Fig. 4(d) shows profiles of the retardation \( R \) taken along the \( y \)-axis through the regions of high birefringence. Clearly there is a progressive increase in the signal as \( \dot{e}_{yy} \) is incremented, indicating that the polymer molecules become progressively more oriented. Interestingly, there is a consistent dip in the signal close to \( y = 0 \), i.e., along the outlet axis. This has also been observed in the classical opposed-jet experiments and referred to as a birefringent “pipe”. The phenomenon is explained by strong flow modification due to the extensional viscosity of the polymer.  

In equibiaxial extension, we could also measure a birefringent signal in the \( z = 0 \) plane, as shown in Figs. 5(a)–5(c) for progressively increasing values of \( Q_{in} \). In this case, the polymer is oriented in a very thin birefringent sheet over the \( x = 0 \) plane. Note that we could not measure any retardation when we viewed the flow in the \( x = 0 \) plane, which is most likely explained by the extremely short optical path length through the oriented material along the \( x \) direction. By considering the ratio of the optical path length along \( x \) (\( \ell_x \), clearly \( \approx 10 \mu\text{m} \) from Fig. 5) compared with that along either \( y \) or \( z \) (\( \ell_y = \ell_z \approx L = 550 \mu\text{m} \)), it is evident that the expected retardation when viewing along \( x \) will be more than an order of magnitude smaller than when viewing along \( y \) or \( z \). Since the detection limit of the birefringence imaging system employed is \( \approx 0.5 \text{ nm} \), and the range of retardation shown in Fig. 5 is \( R < 4 \text{ nm} \), this explains the absence of a clear retardation signal when viewing in the \( yz \) plane. Profiles of the retardation taken across the birefringent sheet along the \( x \)-axis [Fig. 5(d)] show a progressive increase in the birefringence as the flow rate is incremented. Interestingly though, for similar elongation rates along the outlets, the retardation is generally much lower in biaxial than in uniaxial extension. This may be explained by the likelihood of a radial distribution of molecular orientations over the \( x = 0 \) plane, with molecules on the \( z \)-axis most likely to be oriented in the \( z \) direction (i.e., along the direction of light propagation) which would therefore not be expected to contribute to the measured signal. Between \( \dot{e}_{yy} = 266 \) and \( \dot{e}_{yy} = 305 \text{ s}^{-1} \) there is a dramatic increase in the retardation to a value comparable with that seen in uniaxial extension. However, we note that the sheet of birefringence is no longer localized on the \( x = 0 \) plane, which is a likely indication that the flow field has lost stability. Although this instability remains to be properly investigated, we are confident in the accuracy of our flow control and we note that the Reynolds number of the flow is quite moderate at its onset (\( \text{Re} \approx 4 \)), so we assume it to be an elasticity-induced flow asymmetry.  

In summary, we have presented the first microfluidic analog of an opposed-jet apparatus that can generate both uniaxial and biaxial stagnation point extensional flow fields with easily controlled extensional...
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FIG. 5. Birefringence visualized in the z = 0 plane for biaxial extensional flow of an aPS in TCP solution. The top row shows the retardation R with a color scale in nanometers; the bottom row shows the corresponding orientation of the fast optical axis. The bottom row shows the retardation measured in nanometers; the bottom row shows the corresponding orientation of the fast optical axis for: (a) Qin = 0.8 ml/min, ζyy ≈ 152 s⁻¹, (b) Qin = 1.2 ml/min, ζyy ≈ 228 s⁻¹, (c) Qin = 1.6 ml/min, and ζyy ≈ 305 s⁻¹. (d) Profiles of the retardation measured along the x-axis for a range of imposed inlet flow rates.

The device has interesting features that are not offered by the classical opposed jets, such as the ability to observe the region of extensional flow from multiple perspectives and also of generating a general biaxial, as opposed to simply equibiaxial, flow. In addition, the small size scale reduces inertial effects in the flow and also reduces the volume required for an experiment. Flow-induced birefringence measurements on a dilute polymer solution demonstrate that macromolecular orientation can occur under both modes of flow and also the high optical quality of the fused silica-fabricated device. We believe that the device should be amenable to numerical optimization in order to homogenize the flow fields, as has been done already for various planar extensional flow geometries. This could provide for an interesting and novel microfluidic uniaxial and biaxial extensional rheometer based on either rheo-optical measurements or by using pressure drop measurements to isolate extensional stresses from the total, similar to the planar cross-slot device. Furthermore, the device could be used for understanding deformation and dynamics of bubble drops, fibers, cells, and single molecules in well-defined flow fields relevant to widespread applications (e.g., fiber spinning, particle sedimentation, inkjet printing, spin coating, blow molding, etc.).