Microfluidic analog of an opposed-jets device

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S. J. Haward, C. C. Hopkins, K. Toda-Peters, and A. Q. Shen

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S. J. Haward,a) C. C. Hopkins, K. Toda-Peters, and A. Q. Shen

AFFILIATIONS
Okinawa Institute of Science and Technology, Onna-son, Okinawa 904-0495, Japan

a)Electronic mail: simon.haward@oist.jp

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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...stagnation point elongational flow is generated. The device has had success as a planar extensional rheometer since shear stresses can be directly measured from the pressure drop around one corner of the geometry, allowing elongational stresses to be isolated from the total. 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. 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 \( Q_{in} \) through two pairs of opposed inlets, and is withdrawn at a rate \( Q_{out} = 2Q_{in} \) 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.
scopic study of elastic instabilities in uniaxial and biaxial stagnation point flows,
construction such a device for experimental measurements, we use a Newtonian fluid (50 wt.
% aqueous glycerol, viscosity \( \eta = 5 \text{ mPa s} \), and density \( \rho = 1123.6 \text{ kg m}^{-3} \) at 25 \(^\circ\)C) seeded with
5 \( \mu \text{m} \) diameter fluorescent microspheres (PS-Fluored, MicroParticles GmbH). A 5 \( \times \) objective lens focuses on the plane of interest within the
device, which is placed in its desired orientation on the imaging stage of an inverted microscope (Nikon Eclipse Ti). The microscope is equipped with a volume illumination \( \mu \text{-PIV} \) system (TSI Inc.) 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 \( \Delta z \approx 170 \mu \text{m} \) or \( \approx 0.3 L \).

Figure 2 summarizes the results of \( \mu \text{-PIV} \) experiments conducted under uniaxial extension. Figure 2(a) shows the velocity magnitude \( |v| \), normalized by the average outflow velocity \( U_{\text{out}} = Q_{\text{out}}/A \), for uniaxial elongation as viewed in the \( z = 0 \) 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(e) shows normalized velocity profiles measured along the outlet (x) and one inlet (y) axis. Over this range of $Q_{in}$, $0.3 \leq \text{Re} \leq 6$, 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., $-0.5L \leq x \leq 0.5L$), 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 $\approx 25\%$ 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 µ-PIV set up, $\delta m \approx 0.3L$. 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 µ-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 "sinklike" 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 flow rates, Fig. 3(c) shows normalized velocity profiles measured along the outlet (x) and one inlet (y) axis. Over this range of $Q_{in}$, $0.3 \leq \text{Re} \leq 6$, 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., $-0.5L \leq x \leq 0.5L$), 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 $\approx 25\%$ 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 µ-PIV set up, $\delta m \approx 0.3L$. 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.

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**Appl. Phys. Lett.**

Progressive increase in the signal as outlet axes are velocimetry with high spatial resolution.

Velocimetry instrument able to perform volumetric three-component of the.

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 $c^* \approx 2000$ ppm. The fluid is weakly shear-thinning with a zero-shear viscosity $\eta_0 \approx 130$ mPa s and has a relaxation time $\lambda \approx 40$ ms. For the measurement, we employ an Exicor MicroImager (Hinds Instruments Inc.), which is composed of a 532 nm light source, photelastic modulators on either side of the sample, a $10 \times$ magnification Mitutoyo objective lens focused on the measurement plane, and a 2048 x 2048 pixel camera. The system provides spatially resolved ($\approx 0.55 \mu m/pixel$) values for the retardation $R$ and the orientation of the fast optical axis. The birefringence is directly related to the retardation taken across the birefringent sheet along the $x$-axis most likely to be oriented in the polymer backbone. Interestingly though, for similar elongation rates we assume it to be an elasticity-induced flow asymmetry.3–5

In summary, we have presented the first microfluidic analog of an aPS in TCP solution. Top row shows the retardation $R$ with color scale in nanometers, bottom row shows the corresponding orientation of the fast optical axis for: (a) $Q_{in} = 0.1$ ml/min, $\dot{\varepsilon}_{xx} \approx 70$ s$^{-1}$, (b) $Q_{in} = 0.4$ ml/min, $\dot{\varepsilon}_{xx} \approx 280$ s$^{-1}$, (c) $Q_{in} = 0.6$ ml/min, and $\dot{\varepsilon}_{xx} \approx 420$ s$^{-1}$. Profiles of the retardation measured along the $y$-axis for a range of imposed inlet flow rates.

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 $x$ ($\ell_x \approx 10 \mu m$ from Fig. 5) compared with that along either $y$ or $z$ ($\ell_y \approx \ell_z \sim L = 590 \mu m$), 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 $\approx 0.5$ nm, and the range of retardation shown in Fig. 5 is $0 < R < 4$ 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 $\dot{\varepsilon}_{yy} = 266$ and $\dot{\varepsilon}_{yy} = 305$ 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 (Re $\approx 4$), so we assume it to be an elasticity-induced flow asymmetry.6,7

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...
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 of fluid required for an experiment. Flow-induced birefringence measurements on a dilute polymer solution demonstrate that macro-molecular 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.11,36,37 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.).

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