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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, a) b) c) d) for observing macromolecular dynamics e) f) g) and elastic instabilities, h) i) and for performing extensional rheometry of complex fluids. j) k) l)

Classically, three instruments have been used to generate stagnation point flows in the laboratory. The first is the four-roll mill presented by Taylor, a) which can be used to generate a planar elongational flow and was employed to examine the deformation and breakup of droplets trapped at the stagnation point. The second is the opposed-jet apparatus of Frank et al., a) in which two nozzles face each other immersed in a bath of fluid. Two modes of operation are possible. If the fluid is sucked into the nozzles (“sucking mode”), a uniaxial extensional flow is generated along the axis of the nozzles. If the fluid is ejected from the nozzles (“blowing mode”), an equibiaxial extensional flow is generated in the center-plane perpendicular to the nozzle axis. The opposed jets were used in pioneering studies of macromolecular dynamics (summarized in Ref. 14), and were even developed into a commercial extensional rheometer (the Rheometrics RFX). a) b) However, interest in the device declined as it was realized that measurements were inherently affected by inertia and because no satisfactory method could be devised to separate shear and elongational stresses. a) b) The third classical stagnation point flow device is the cross-slot geometry, first presented by Scriven et al., a) which is formed from two bisecting rectangular channels. If fluid is injected into two opposing inlets and withdrawn from two opposing outlets, a planar 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. a) b) j) 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. a) b) c) d) e) 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 set up).

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.
eral, or “ellipsoidal,” biaxial extension could be generated, which is
imposing different flow rates in the two pairs of outlet channels a gen-
terations over the classical opposed jets. Most obviously, by enclosing
The system presented in Fig. 1 has a number of important advan-
tages over the classical opposed jets. Most obviously, by enclosing the
ent point flows, constructing such a device for experimental mea-
surements with complex fluids, or for the observation of single
molecules, for instance.

By using the high resolution (≈1 μm) subtractive three-
dimensional (3D) printing technique of selective laser-induced etching
(SLE), we have achieved the fabrication of a microfluidic opposed-jet
analog device in fused silica glass, which allows good optical access
through four of the six sides (and even full optical transmission
through two of the three planes), see Figs. 1(c) and 1(d). The device is
fabricated using three pieces of 5 mm thick fused silica (the thickest
that can be used in the SLE instrument in our lab). As shown in Fig.
1(c), the active region of the device where the three channels bisect
(with sharp unrounded corners) and the extensional flows are gener-
ated is fabricated in a single central piece of glass. Four of the channels
leading to/from the central cross-over region have uninterrupted
straight sections of length >10 × L, where L is the side-length of the
square cross-section channels. This ensures that the flow can become
fully developed prior to the intersection when the device is operated in
either uni- or biaxial flow mode. The remaining two channels are nec-
essarily shorter as their length is restricted by the 5 mm thickness of
the glass; these two channels are always used as outlets so that their
short length has a minimal impact on the flow and its stability at the
upstream intersection. The central piece of glass is sandwiched
between two additional 5 mm thick glass layers that contain extensions
of the short outlet channels and also allow some of the channels to be
directed through 90°, thus keeping four of the six sides free of inlet
and outlet connections. The three pieces are accurately assembled
using locating pins passed through holes etched in the four corners of
each part and are bonded together using ultraviolet-curing epoxy
resin. A fully assembled device, with channels of side length L = 550 μm, is shown in the photograph in Fig. 1(d). Stainless steel
tubing connectors are bonded to the inlet and outlet holes using two-
part epoxy resin and are joined by silicone tubing to Hamilton
Gasight syringes. The flow is driven using six individually controllable
eMESYS syringe pumps (Cetoni, Gmbh).

Our first experiments involve the use of microparticle image
velocimetry (μ-PIV) in order to confirm the expected flow field in
the device under the two basic modes of operation. For these experi-
ments, we use a Newtonian fluid (50 wt. % aqueous glycerol, viscosity
η = 5 mPa s, and density ρ = 1123.6 kg m⁻³ at 25 °C) seeded with
5 μm diameter fluorescent microspheres (PS-Flouro, MicroParticles
GmbH). A 5× objective lens focuses on the plane of interest within
the microdevice, which is placed in its desired orientation on the imaging
stage of an inverted microscope (Nikon Eclipse Ti). The micro-
scope is equipped with a volume illumination μ-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 δt 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 δt and hence local velocity
vector, denoted as 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
δm ≈ 170 μm or ≈0.3L. ⋅

Figure 2 summarizes the results of μ-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 uni-
axial elongation as viewed in the $z = 0$ plane, showing inflow along y
and the outflow accelerating along x from a central stagnation point

![Diagram](image-url)
into the outlet channels. Figure 2(b) shows a similar contour plot measured in the $x = 0$ plane, showing how the inflow along the $y$ and $z$ directions converges into a "sinklike" central stagnation point located on the $x$-axis. The ability to view the flow from various planes is a feature of this device that may provide some interesting new opportunities for deformation dynamics studies and is not possible with conventional opposed jets since the nozzles themselves obscure the view along the axial direction. The experimental velocity fields in Figs. 2(a) and 2(b) are in good qualitative agreement with the results of finite-element numerical simulations (performed using COMSOL Multiphysics), as shown in Figs. 2(c) and 2(d). The numerical method solves the equations of motion and mass conservation for laminar flow of a Newtonian incompressible fluid, assuming no-slip boundary conditions on all walls and applying fixed pressure at inlets and outlets. The mesh is composed of 321 370 tetrahedral elements. The Reynolds number $Re = \rho U_{out} L / \eta = 4.4$ and channels are long enough to ensure fully developed flow upstream of the central cross region.

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 $Q_{in}, 0.3 \leq Re \leq 6$, 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 $\mu$-PIV setup, $\delta m \approx 0.3L$. 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 $\mu$-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 "source-like" 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
$Q_m$ values show good collapse in Fig. 3(c). The average experimental elongation rates between the outlet channel mouths are $\dot{\varepsilon}_{yy} \approx \dot{\varepsilon}_{zz} \approx 2.8 U_{\text{out}}/L$. The numerically predicted extensional rates along the outlet axes are $\dot{\varepsilon}_{yy} = \dot{\varepsilon}_{zz} \approx 3.8 U_{\text{out}}/L$. 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 $c^* \approx 2000\,$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 $2048 \times 2048$ pixel camera. The system provides spatially resolved ($\approx 0.55\,$μm/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 $\dot{\varepsilon}_{xx}$ 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 external confinement of the polymer.

In equibiaxial extension, we could also measure a birefringent signal in the $z = 0$ plane, as shown in Figs. 5(a) and 5(c) for progressively increasing values of $Q_m$. 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 $\approx 10\,$μm from Fig. 5) compared with that along either $y$ or $z$ ($\ell_y = \ell_z \approx L = 590\,$μm), 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$_{\text{out}} \approx 4$), 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 external...
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