Simple microfluidic stagnation point flow geometries

Greet Dockx,¹ Tom Verwijlen,¹ Wouter Sempels,² Mathias Nagel,³
 Paula Moldenaers,¹ Johan Hofkens,² and Jan Vermant^{3,a)}

¹*Department of Chemical Engineering, KU Leuven, Celestijnenlaan 200F, Heverlee, Belgium*

²*Department of Chemistry, KU Leuven, Celestijnenlaan 200F, Heverlee, Belgium*

³*Department of Materials, ETH Zürich, Vladimir-Prelog-Weg 5, HCI H 503, Zürich, Switzerland*

(Received 5 May 2016; accepted 16 June 2016; published online 24 June 2016)

A geometrically simple flow cell is proposed to generate different types of stagnation flows, using a separation flow and small variations of the geometric parameters. Flows with high local deformation rates can be changed from purely rotational, over simple shear flow, to extensional flow in a region surrounding a stagnation point. Computational fluid dynamic calculations are used to analyse how variations of the geometrical parameters affect the flow field. These numerical calculations are compared to the experimentally obtained streamlines of different designs, which have been determined by high speed confocal microscopy. As the flow type is dictated predominantly by the geometrical parameters, such simple separating flow devices may alleviate the requirements for flow control, while offering good stability for a wide variety of flow types. *Published by AIP Publishing.*
[\[http://dx.doi.org/10.1063/1.4954936\]](http://dx.doi.org/10.1063/1.4954936)

I. INTRODUCTION

The ability to apply well-defined flow types is essential for the study of flow induced structures in materials such as drop deformation and coalescence in multiphase systems,^{1–5} alignment and stretching of molecules,^{6–9} or flow-induced changes in colloidal dispersions.^{10–13} Flow application is also relevant in the study of biological processes such as tissue organization and cell sorting.^{14,15} For example, shear-stress sensitive lenticular vesicles have high potential for targeted drug delivery in treating cardiovascular diseases.¹⁶ Or the von Willebrand factor undergoes a conformational transition under high shear stress that plays a key role in the initiation of the formation of thrombi.¹⁷ Advanced microscopy techniques combined with cells having well-defined flow fields with a stagnation point may have an impact in many areas of rheology and biological soft matter.

Given the need to obtain well-defined flow fields with a stagnation point, where the flow velocity is zero but the velocity gradients are not, a four-roll mill device was designed by Taylor¹⁸ in 1934. By individually adjusting the speed and rotation direction of the four rollers, controlled application of different flow types is possible. Although control over the nature of the flow field is outstanding, direct optical observation is limited due to the large optical path-lengths (cm scale) and associated small magnifications. To circumvent this problem, the development of simple, yet adequate microfluidic devices has received growing interest. Microfluidic flow geometries can be fabricated with great reliability and at low cost with soft lithography. An additional advantage of this approach is that only small sample amounts are required.^{19–21}

Microfluidic devices with geometrically simple cross-slot geometries have been instrumented in studying single polymer dynamics in extensional flow, as recently reviewed by Schroeder and coworkers.⁹ By using rather advanced automated feedback control systems, molecules or particles can be trapped with high spatial accuracy for extended periods of time.^{22,23}

^{a)}Electronic mail: jan.vermant@mat.ethz.ch

However, aside from extensional flow, linear mixed flows with varying amounts of extensional and rotational components such as simple shear flow are equally relevant for both fundamental studies of the dynamics of soft matter systems and for their processing. The presence of vorticity in the flow field fundamentally alters the deformation of the constituents which make up a complex fluid, as they can be reoriented with respect to the principal directions of the deformation field. To be able to vary the amount of vorticity relative to extension in a microfluidic device, Hudson and coworkers presented a “micro-analog” of the four-roll mill design, using intersecting channels with asymmetric baffles.^{24,25} Whereas all types of planar flow can be generated, control over six in- and outlets is required to achieve a stagnation point flow. Pure rotation cannot be achieved due to a slight asymmetry of the geometry. To overcome this limitation, Lee *et al.* presented a new, symmetric geometry which now however has as much as eight in- and outlets, yet fully capable of covering the entire spectrum of flow types.²⁶ The effect of channel aspect ratio was investigated using numerical calculations to study the effect on the flow field and to determine the limits of a two-dimensional (2D) approximation. Their geometry was used to study the dynamics of DNA tumbling in shear to rotational mixed flows.²⁷ The effects of the dimensions of their geometry as well as the volume flow rate on the elongation and rotation of droplets were investigated by a 2D spectral boundary element method.²⁸

The aforementioned designs require precise and rather elaborate pressure control over six or eight in- and outlet streams to obtain a stable flow. This complicates the set-up in practice and requires an active feedback loop. The active control limits the maximum obtainable flow rates whereby the deformation rates are in the order of 1 s^{-1} .²⁴ For many instances, higher deformation rates are required, for example, when chewing food in the mouth, deformation rates of at least 100 s^{-1} may be reached in the smallest passages between teeth.²⁹ It can also be interesting to use mixed flows since these are more realistic for many real world applications and industrial processes such as ink jet nozzles or spinnerets, which combine shear and extensional flows.^{5,29–31}

In the present work, we propose a separating flow geometry for study with high speed confocal microscopy which is easy to make and control, in which high deformation rates can be achieved and where the entire range of flow types can be obtained by a small modification of the space between the separating walls. This is simple to control but requires a distinct geometry for each flow type. We compare Computational Fluid Dynamics (CFD) simulation results with observations of the streamlines using confocal microscopy.

II. GEOMETRY CHARACTERISATION

A. Design

The cross-section of the proposed geometry is depicted in Fig. 1. There are two in- and two outlets each of width W , fed with flow rate Q . The distance between top and bottom surface is the height, h . The stagnation point region is formed by a counterflow in two channels with a small gap g between them. The corners are rounded off to a circle with radius R to locally smooth the flow profiles. The width W of the channels is set to $2R$, the thickness of the separating wall. In this way, the geometry is completely characterised by the dimensionless gap g/R and the aspect ratio AR (defined as h/W).

FIG. 1. Schematic of the flow cell. Left: top view of the cross-section through the middle. Q indicates the flow rate, W is the width of the channels, R is the radius of the rounded corner, and g is the gap length. Right: 3D rendering. h is the height and the dotted volume is used in the 3D simulations.

The design creates a combined mixing and separating flow, similar to those discussed by Cochrane *et al.*³² The main difference between simple separating flows and the present design is the use of a thick plate with rounded edges rather than a thin plate with sharp edges. Afonso *et al.*³³ concluded from simulations that in the latter case the effect of plate thickness is limited, in agreement with the experiments of Cochrane *et al.*^{32,34} However, in the present study, we use a confined flow with rounded edges and a plate which is not thin relative to the width of the opposing channels. The geometry also resembles the co-rotating two-roll mill, with the difference that the edges/walls do not move.³⁵ It is therefore relevant to investigate the flow type using simulations, as a function of the dimensionless gap g/R which can be set at will, and the aspect ratio AR , which will be determined by what is possible with current day lithographic manufacturing techniques.

B. Simulations

Three-dimensional (3D) numerical calculations are performed using the commercial finite element package COMSOL 5.0. The governing equations are the stationary Navier-Stokes equations combined with the continuity equation for incompressible flow. Fully developed laminar flow is used as a condition for the in- and outlets, and the no-slip boundary condition is imposed on all walls of the geometry. The mesh is refined until mesh convergence is achieved. It consists of around 10 000 prism, 1500 hexahedral, 1700 quadrilateral, and 1400 triangular elements with a mesh volume in the order of 10^{-12} m^3 . The calculations are performed for a Newtonian fluid, with as typical parameters a viscosity of 10 mPa s and a flow rate Q of $5 \mu\text{l}/\text{min}$, to compare with experiments. These conditions correspond to a maximum Reynolds number of 0.05, indicating that inertial effects are small, and the linear Stokes equations are solved. To reduce the computation time, the (anti)symmetry of the geometry and the symmetry of the governing Stokes equations are used so that only 1/8 of the geometry is simulated as illustrated by the dotted volume in Fig. 1. The number of degrees of freedom is around 175 000.

To quantify the nature of the flow field in the stagnation point, the flow-type parameter ξ is evaluated, defined as²⁶

$$\xi = \frac{|E| - |\Omega|}{|E| + |\Omega|}, \quad (1)$$

with $|E|$ and $|\Omega|$ being the magnitudes of the rate of deformation and vorticity tensors, respectively, which are defined by

$$E = \frac{1}{2} [\nabla v + (\nabla v)^T], \quad (2)$$

$$\Omega = \frac{1}{2} [\nabla v - (\nabla v)^T]. \quad (3)$$

The flow-type parameter ξ can vary from -1 (rotation) over 0 (shear) to 1 (extension).

Fig. 2 plots the flow-type parameter ξ in the stagnation point as a function of the dimensionless gap g/R (see Fig. 1), for a series of aspect ratios, AR . Additionally, 2D calculations are performed to evaluate the limit for aspect ratios going to infinity. As can be seen, the curves for different aspect ratios are qualitatively similar, although the shift between them is significant. For each aspect ratio, two values of g/R are obtained where $\xi = 0$, with the lower one more sensitive to variations in g/R , which may occur during the manufacturing process. High aspect ratios (h/W) are expected to improve the flow uniformity, as shown by Hudson *et al.* for the microfluidic four-roll mill.²⁴ An AR that could be readily manufactured (see further in Section III A) was found to be 2.8 for the sizes of the channels selected.

For small values of the dimensionless gap, the flow-type parameter ξ in Fig. 2 is a strong decreasing function of g/R , and after a sharp discontinuity, it increases smoothly from values expected for a rotational flow to those for an extensional dominated one. To better understand

FIG. 2. Effect of the dimensionless gap (g/R) on the flow-type parameter ζ in the stagnation point for different aspect ratios (AR).

the trends in Fig. 2 of the influence of g/R on the flow type, the calculated invariant flow-type parameter ζ and the calculated streamlines in the midplane are plotted in Fig. 3 for $AR = 2.8$. As can be observed, for a value of $g/R = 0.6$, two vortices occur and extensional components are present in the region surrounding the stagnation point in the center, leading to large values of ζ , at least very locally. For a value of $g/R = 1.1$, the vortices disappear and a more or less square circulation region surrounds the stagnation point, approaching rotational flow and hence vanishing extensional components. These conditions correspond to the minimum in Fig. 2.

Upon further increasing the gap, the orientation of the region where the deformations occur now changes shape, vortices are no longer observed, and the flow profile changes smoothly from rotational to extensional dominated. For a value of $g/R = 1.7$, a central region of around $30 \times 20 \mu\text{m}$ surrounding the stagnation point displays simple shear since the value of ζ is zero in this region. For $g/R = 2$, two vortices occur again, however, their arrangement is rotated by 90° compared to the vortices occurring in the case of $g/R = 0.6$. The streamlines from both channel flows touch in the stagnation point, and small extensional contributions are present as can be seen from the values of ζ . Finally, for $g/R = 3$, the extensional contributions in the stagnation point become larger, and there are also two small circular regions with large rotational contributions present close to the stagnation point. A value of 6.8 for g/R is necessary to obtain pure extensional flow (not shown in Figs. 2 and 3).

The homogeneity of the flow field near the stagnation point depends on g/R and the nature of the flow field. This is quantified in Table I where the region where ζ varies by maximally 5% is given as a percentage of the small gap g between the channels. In the z direction, the

FIG. 3. Effect of g/R for $AR = 2.8$ on (a) calculated flow-type parameter ζ and (b) calculated streamlines in the midplane. The black frame indicates the situation for which simple shear flow is obtained ($g/R = 1.7$), with the dotted lines indicating the central region.

TABLE I. Size of the region around the stagnation point where ξ varies maximally 5% given as a percentage of g (x and y) and of the height for the vertical direction (z), respectively.

g (μm)	x (%)	y (%)	z (%)
30	19	10	41
55	24	8	24
85	35	24	51
100	9	7	16
150	9	20	36

variation is typically very small and is given as a percentage of AR . In the x and y directions, the extent of the region is minimum 7% and maximum 36% of g .

Fig. 2 shows that there are two values of g/R where ξ equals zero, thus generating simple shear flow. However, the higher value for g/R is preferred for the geometry design, because its flow field is less sensitive to the exact value of g/R as the flow field changes more smoothly than for smaller values of g/R . The main reason for the strong sensitivity of ξ left of the minimum in Fig. 2 is the occurrence of the two small vortices which change the local flow field near the stagnation point. These vortices also entail more spatial variations of ξ .

Fig. 4 plots the second, higher value for g/R for which ξ is expected to be zero, i.e., a geometry for generating a simple shear flow, as a function of the aspect ratio. It can be seen that AR has a significant effect, with g/R needing to be varied between 1.2 and 1.8 for AR between 1 and 3.5. For $AR=3.5$, the g/R value is only 1.5% smaller than the 2D solution, confirming that the aspect ratio is sufficiently high for the 3D nature of the flow field to be neglected. In addition to the flow type, the rate of deformation is of importance. One of the advantages of the present set-up is that relatively high rates can be readily obtained. For a width of $100\ \mu\text{m}$, an aspect ratio AR of 2.8, and a dimensionless gap g/R of 1.7, a simple shear flow is obtained with a deformation rate in the stagnation point of $64\ \text{s}^{-1}$ for a flow rate Q of $5\ \mu\text{l}/\text{min}$. The deformation rate $\dot{\gamma}$ is defined as the magnitude of the second invariant of the rate of deformation tensor: $\dot{\gamma} = \sqrt{2\mathbf{E}:\mathbf{E}}$. By increasing the flow rate to $30\ \mu\text{l}/\text{min}$, a deformation rate of $385\ \text{s}^{-1}$ can be obtained. The proportional relationship between shear rate at the stagnation point and flow rate is given by $\dot{\gamma} = 12.8 \cdot Q$, with $\dot{\gamma}$ and Q in s^{-1} and $\mu\text{l}/\text{min}$, respectively, for this specific geometry. For typical syringe pumps, shear rates between 1 and several $100\ \text{s}^{-1}$ can be readily obtained. It is thus possible to impose large deformation rates in complex fluids without complications from inertial effects.

FIG. 4. The value of the dimensionless gap g/R for obtaining simple shear flow ($\xi = 0$) as a function of the aspect ratio AR .

III. MATERIALS AND METHODS

A. Microfluidic device fabrication

Different designs were fabricated using soft photo-lithography. Since the effect of the aspect ratio on the flow-type parameter is less for high values as shown in Fig. 4, an *AR* of minimum 2.5 was aimed for, which corresponds to a height of minimum 250 μm ($W = 100 \mu\text{m}$). However, due to intrinsic limitations, high aspect ratios for thick films are difficult to produce. The maximum *AR* was 3.5. Nevertheless, this fabrication method was chosen because of its simple, rapid, and low cost fabrication, making it an ideal method for fast prototyping.³⁶ The gap length g was varied between 39 and 135 μm ($g/R = 0.78\text{--}2.7$) to capture a range of flow types.

A layer of SU-8 photoresist (100 series, MicroChem, USA) was spincoated on a 3 in. silicon wafer at 1000–1200 rpm. After the spincoating, the wafer was placed on a levelled plate for 21 h (at room temperature) to allow the photoresist to further spread to improve the uniformity of the height. Evaporation of the solvent was slowed down by covering the wafer with a watch glass. Following this, the plate was heated to 80 °C and after 1 h the watch glass was removed to soft bake the photoresist for 1 h 45 min. To avoid thermal cracking of the photoresist, the wafer remained on the plate until it reached room temperature.

The photoresist was then UV-exposed (600 mJ/cm²) through a photomask (Selba, Switzerland), subsequently the SU-8 layer was again placed on a levelled plate for the post-exposure bake at 80 °C for 18 min. To avoid thermal cracking of the SU-8 layer, the wafer was again placed on the plate during its heating which took 13 min. After the plate was cooled down to room temperature, the SU-8 layer was developed in propylene glycol methyl ether acetate (Sigma Aldrich) to remove unexposed resist. Finally, a ramped hard bake at 150 °C was performed for 1 h. Poly(dimethylsiloxane) (PDMS) monomer and crosslinking agent (Sylgard 184, Dow Corning, USA) was mixed, degassed, and poured onto the wafer mould and kept in the oven for 2 h at 80 °C. The resulting PDMS slab was sealed to a microscope slide (Menzel-Gläser, 24 × 60 mm, #1) using oxygen plasma treatment. The microfluidic chip was kept in the oven at 80 °C for 12 h to improve the bonding.

Spincoating of a very viscous liquid can lead to a significant variation in height (Figure S1). To improve this, moulds were fabricated with a less viscous SU-8 photoresist. In this case, 2.6–2.7 g SU-8 photoresist (2005 series, MicroChem, USA) was poured onto the wafer and placed on the levelled plate. Again the photoresist was allowed to spread. Due to the lower viscosity of the SU-8 layer, the spreading time was decreased. The SU-8 layer was kept for 45 min at room temperature and 30 min at 80 °C (including pre-heat step of the plate). After this, the watch glass was removed and the SU-8 layer was soft baked for 5 h at 80 °C. Following the soft bake, the procedure was continued as described above. The exposure dose was lowered to 550 mJ/cm². In this way, the variation of the height within one geometry was reduced to a standard deviation of maximum 3% compared to the initial 12%.

B. Confocal microscopy

To test the performance of the microfluidic flow cell, a colloidal suspension with yellow-green fluorescent carboxylated 200 nm sized beads (Life Technology, USA) was used with a concentration of 0.002% w/v in a 65% w/w, 80% w/w or 92% w/w glycerol-water solution. A dynamic viscosity of 10 mPa s, 57 mPa s, and 280 mPa s at 20 °C was measured for the different suspending media. Thorough mixing and homogenisation obtained a well-dispersed, dilute colloidal suspension which is ideal to map out the flow profiles. The size of the particles is close to the optical resolution limit of the microscopy system while minimising effects of particle inertia and gravitational effects. As the beads are negatively charged, possible interactions between the glass cover slip and the sample are minimized.

Fluorescent imaging of the samples is performed using an adapted commercial based multi-beam confocal microscope (VisiTech International, UK).³⁷ An IX-71 microscopy body (Olympus) is equipped with oil-immersion objectives (20 × 0.85 NA, 60 × 1.35 NA and 100 × 1.4 NA,

Olympus) using a fiber coupled 488 nm diode with complementary dichroic mirrors and filters, imaged on an EM CCD camera (C9100-13, Hamamatsu). The image detection pinhole size was set on $40\text{ }\mu\text{m}$ while full-frame (512×512 pixels) confocal images were acquired with exposure times ranging from 500 ms to 1 s. A microfluidic control system (MFCS, Fluigent, France) enabled pressure control and simultaneous flow rate monitoring of the four channels, connected by Teflon® and PEEK tubing (Achrom, Belgium) to the microfluidic geometry.

IV. RESULTS AND DISCUSSION

Fig. 5 and supplementary videos S1–S4 show the streamlines as obtained by confocal microscopy imaging for four designs, in which W and R were kept constant at $100\text{ }\mu\text{m}$ and $50\text{ }\mu\text{m}$, respectively. The images were taken with the focal plane at a height between 130 and $150\text{ }\mu\text{m}$ above the bottom of the flow cell. This was at the limit of the working distance of the objective used. Thus only for designs with an AR larger than 3, it was not possible to record at the mid-plane of the geometry. By using the classification by Lagnado and Leal,³⁸ the flow type parameter ξ can be calculated from the experimentally observed streamlines: for extensional dominated flows ($0 < \xi \leq 1$), the streamlines form a family of hyperboles with asymptotes separated by an angle ϕ and $\sqrt{\xi}$ equals $\tan(\phi/2)$. On the other hand, for rotational dominated flows ($-1 \leq \xi < 0$), the streamlines form a family of ellipses with major axis length a and minor axis length b and $\sqrt{-\xi}$ equals b/a . These values can then be compared with the flow-type parameter determined in Equation (1) in the simulations. The simulated streamlines are also shown in the bottom row of Fig. 5.

The design shown in panel 5(b) has a small dimensionless gap g/R of 0.78. AR was determined to be 3.2 by measuring the height of the SU8-structure using a profilometer. The experiment was performed at $Re = 0.02$. Qualitatively, the experimentally observed streamlines are similar to the calculated ones, except that the numerically calculated vortices close to the stagnation point were not observed for the exposure times and low flow rates used. The experimentally determined flow type parameter in the stagnation point is -0.45 , which differs quite significantly of the calculated one (in the midplane) of 0.16. As during the experiments, the vortices on both sides of the stagnation point were not observed, there is less of an extensional component in the flow field. Referring to Fig. 2, it can be seen that for values around this g/R , small variations in geometry (AR or g/R) lead to large variations in ξ , which is specifically due to the presence or absence of these two vortices. As the geometrical values may vary a bit with height (see [supplementary material](#)), these vortices are suppressed and this rationalises the observed differences.

FIG. 5. Linear quality enhanced confocal images of streamlines for different dimensions of the microfluidic flow cell with their corresponding simulated streamlines (same g/R and AR as microfluidic device used in experiment). (a) Location of imaging. Flow close to stagnation point is classified as: (b) Extensional dominated flow. (c) Rotational dominated flow. (d) Simple shear flow. (e) Extensional versus rotational dominated flow. Images (a)–(c) and (e) were taken with a $100\times$ objective while image (d) was taken with a $60\times$ objective. The scale bars denote $10\text{ }\mu\text{m}$.

For the design shown in panel 5(c), the dimensionless gap g/R was increased to 1.26 and the measured AR was 2.6. The experiment was performed at a Re of 0.0055, and the flow type parameter at the stagnation point obtained from the experiments and simulations equals -0.24 and -0.38 , respectively. The flow profile is dominated by rotational components, and the experimentally calculated streamlines agree quite well. The design shown in panel 5(d) has an even higher g/R of 1.5 and AR was measured to be 2.8. Re equaled 0.005 and the flow type parameter calculated from the streamlines and the simulations is -0.09 and -0.12 , respectively. The resulting flow profile approximates simple shear flow quite well, and the agreement between experiments and simulations is satisfactory. Finally, the design shown in panel 5(e) has a g/R of 1.46 and AR of 2.7. In this experiment, Re equaled 0.001, and the experimentally determined flow type parameter is 0.16, while the flow type parameter determined from simulations equals -0.15 . Indeed, the observed streamlines are very different from the calculated ones, namely, extensional versus rotational dominated flow. Again a small increase of g with height could lead to the observed differences.

Comparing the experimentally observed flow type parameters and streamlines with those calculated from 3D CFD calculations reveals some differences, which mainly reflect the sensitivity of ξ to small variations in geometry. The numerical differentiation which is required to calculate the flow parameter is also prone to error propagation and leads to an estimated error of 0.05 on ξ . This value was obtained by applying the same procedure as in the experimental protocol to the calculated streamlines and comparing the thus obtained value of ξ with the one obtained from the exact solution of the flow field. Second, the value of ξ can be extremely sensitive to small variations in g/R for values left of the minimum in Fig. 2. For example, for $g/R = 0.80$, a 10% variation in geometric dimensions results in a 100% variation of the predicted ξ value. It is therefore recommended to use a value of g/R larger than 1 for producing the flow field in a reliable way. Third, the value of ξ varies over the height as shown in Fig. 6. 3D components in the velocity can be presented as seen in the supplementary videos corresponding to the designs from Fig. 5, where z-scanning was performed. Non-uniformity in height is a typical problem with chips fabricated with the more viscous photoresist (see Section III A). Negatively sloped sidewalls are also a common shortcoming in fabricating tall structures by photolithography as explained in the [supplementary material](#). These latter two reasons clarify the large difference between the experimentally obtained value of ξ and the simulation result for microfluidic chip e.

In the designs discussed so far, W and R were kept constant at $100\ \mu\text{m}$ and $50\ \mu\text{m}$, respectively. It is of course possible to vary these geometric parameters as shown in Fig. 7 and supplementary video S5. In this design, W and R are equal to $115\ \mu\text{m}$ and $40\ \mu\text{m}$, respectively (so

FIG. 6. Variation of ξ with height (measured from the midplane) for a flow cell with $g/R = 1.46$ and $AR = 2.7$ (panel (e) in Fig. 5). Point 0 on the axis is thus the stagnation point while $135\ \mu\text{m}$ is the top of the flow cell ($W = 100\ \mu\text{m}$).

FIG. 7. Experimentally obtained and calculated streamlines, the latter being a $1.8\times$ magnification of the white frame, for a design with $g/R = 2.7$ and $AR = 1.6$. For this design $W = 115\ \mu\text{m}$ and $R = 40\ \mu\text{m}$ so $W \neq 2R$. The image was taken with a $20\times$ objective. The arrows indicate the direction of flow. The scale bar denotes $50\ \mu\text{m}$.

$W \neq 2R$). The streamlines are qualitatively similar as those shown in fifth panel of Fig. 3(a). The arrows indicate the direction of flow, and the amount of liquid entering the stagnation point region, that is reversed, is larger for $g/R = 3$ in Fig. 3(a). The amount of reversed liquid increases with gap length and after a certain gap length, unidirectional flow is now longer observed, in agreement with Walters and Webster.³⁴ The results of the CFD calculations are quantitatively different from Fig. 2 since the condition of $W = 2R$ is no longer valid: $\xi = 0.27$. The calculated flow type parameter from the experimentally obtained streamlines equals 0.34 which is in agreement with the simulations.

In the present study, the corners are rounded off to a half circle. The influence of this curvature on the simple shear profile could further be optimized to maximize the region of constant deformation rate by a numerical shape optimization routine, as employed by Alves,³⁹ Haward and coworkers⁴⁰ for the case of the cross-slot geometry.

It can be concluded that to obtain a microfluidic chip for which the flow field is most predictable, it is best to choose the dimensionless parameters in the regimes where the slope of the curves in Fig. 2 with respect to g/R is small; i.e., geometries for shear and extension can be obtained with good predictive power over the flow field. The simple control of the set-up entails a very good stability of the flow field for viscous fluids. Viscous fluids reduce the pressure sensitivity of the set-up, impairing the fluctuations. The rotational dominated flow field was stable up to 1 h without feedback control mechanism, as observed from overlaid images. Even for the more difficult to control extensional flows, it was possible to have stable flow profiles for 20 min. For shear flows, stable profiles for 40 min were observed. However, a feedback control loop is still necessary to avoid advection of the particle away from a stagnation point. This control will also increase the inherent stability of the flow field even more and due to the limit amount of inlets will be easier to implement.

V. CONCLUSIONS

A microfluidic flow cell was designed and fabricated using soft photolithography. The geometry can be used to generate a wide range of flow types in the stagnation point region whereby high deformation rates can be reached. By simulating the three-dimensional flow field numerically, the effect of the geometrical parameters was investigated. The flow type depends on the dimensionless gap length and on the aspect ratio of the channels when the aspect ratio $AR \leq 3.5$. Different device geometries were tested using confocal microscopy imaging to experimentally validate the simulated streamlines. Geometries for shear and extension can be obtained with most predictability, and it is advisable to make geometries with sufficiently large gaps, so no vortices occur. This simple geometry makes it possible to obtain deformation rates as high as $100\ \text{s}^{-1}$, while maintaining a stable flow field. However, issues of sloping sidewalls and non-uniform thickness caused fluctuations in the stagnation point position and led to some

discrepancies between simulations and experiments. The geometries should be well suited to use in conjunction with super resolution microscopies.

SUPPLEMENTARY MATERIAL

See [supplementary material](#) for videos and for more information about the height variations of the microfluidic devices.

ACKNOWLEDGMENTS

G.D. and W.S. are grateful for the financial support from the FWO-Vlaanderen and IWT-Vlaanderen, respectively. The Hercules foundation (HER/08/21) and the Swiss National Science Foundation (Project No. 200021-157147) Pieter Gijsenbergh and Frederik Ceyssens are thanked for the help with the photolithography. Stijn Coertjens is thanked for the help with the SEM measurements. Raf De Dier is thanked for his help with image analysis.

- ¹B. J. Bentley and L. G. Leal, *J. Fluid Mech.* **167**, 241 (1986).
- ²J. J. M. Janssen, A. Boon, and W. G. M. Agterof, *Am. Inst. Chem. Eng.* **43**, 1436 (1997).
- ³Y. T. Hu, D. J. Pine, and L. G. Leal, *Phys. Fluids* **12**, 484 (2000).
- ⁴H. Yang, C. C. Park, Y. T. Hu, and L. G. Leal, *Phys. Fluids* **13**, 1087 (2001).
- ⁵E. Boonen, P. Van Puyvelde, and P. Moldenaers, *J. Rheol.* **54**, 1285 (2010).
- ⁶G. G. Fuller and L. G. Leal, *Rheol. Acta* **19**, 580 (1980).
- ⁷E. C. Lee and S. J. Muller, *Macromolecules* **32**, 3295 (1999).
- ⁸I. V. Nesterova, M. L. Hupert, M. A. Witek, and S. A. Soper, *Lab Chip* **12**, 1044 (2012).
- ⁹D. J. Mai, C. Brockman, and C. M. Schroeder, *Soft Matter* **8**, 10560 (2012).
- ¹⁰C. J. Dibble, M. Kogan, and M. J. Solomon, *Phys. Rev. E* **74**, 041403 (2006).
- ¹¹K. Masschaele, J. Fransaer, and J. Vermant, *J. Rheol.* **53**, 1437 (2009).
- ¹²X. Cheng, J. H. McCoy, J. N. Israelachvili, and I. Cohen, *Science* **333**, 1276 (2011).
- ¹³D. Anne-Archard, M. d'Olce, M. Tourbin, and C. Frances, *Chem. Eng. Sci.* **95**, 184 (2013).
- ¹⁴J. El-Ali, P. K. Sorger, and K. F. Jensen, *Nature* **442**, 403 (2006).
- ¹⁵W. J. Polacheck, J. L. Charest, and R. D. Kamm, *Proc. Natl. Acad. Sci. U.S.A.* **108**, 11115 (2011).
- ¹⁶M. N. Holme, I. A. Fedotenko, D. Abegg, J. Althaus, L. Babel, F. Favarger, R. Reiter, R. Tanasescu, P.-L. Zaffalon, A. Ziegler, B. Müller, T. Saxer, and A. Zumbuehl, *Nat. Nanotechnol.* **7**, 536 (2012).
- ¹⁷R. M. Vergauwe, H. Uji-i, K. De Ceunynck, J. Vermant, K. Vanhoorelbeke, and J. Hofkens, *J. Phys. Chem. B* **118**, 5660 (2014).
- ¹⁸G. I. Taylor, *Proc. R. Soc. London, Ser. A* **146**, 501 (1934).
- ¹⁹H. A. Stone, A. D. Stroock, and A. Ajdari, *Annu. Rev. Fluid Mech.* **36**, 381 (2004).
- ²⁰T. M. Squires and S. R. Quake, *Rev. Mod. Phys.* **77**, 977 (2005).
- ²¹G. M. Whitesides, *Nature* **442**, 368 (2006).
- ²²M. Tanyeri, M. Ranka, N. Sittipolkul, and C. M. Schroeder, *Lab Chip* **11**, 1786 (2011).
- ²³A. Shenoy, M. Tanyeri, and C. M. Schroeder, *Microfluid. Nanofluid.* **18**, 1055 (2015).
- ²⁴S. D. Hudson, F. R. Phelan, M. D. Handler, J. T. Cabral, K. B. Migler, and E. J. Amis, *Appl. Phys. Lett.* **85**, 335 (2004).
- ²⁵F. R. Phelan, S. D. Hudson, and M. D. Handler, *Rheol. Acta* **45**, 59 (2005).
- ²⁶J. S. Lee, R. Dylla-Spears, N. P. Teclemariam, and S. J. Muller, *Appl. Phys. Lett.* **90**, 074103 (2007).
- ²⁷J. S. Lee, E. S. G. Shaqfeh, and S. J. Muller, *Phys. Rev. E* **75**, 040802 (2007).
- ²⁸J. Wang, J. Han, and D. Yu, *Eng. Anal. Boundary Elem.* **36**, 1453 (2012).
- ²⁹T. J. Ober, S. J. Haward, C. J. Pipe, J. Soulages, and G. H. McKinley, *Rheol. Acta* **52**, 529 (2013).
- ³⁰J. S. Hur, E. S. G. Shaqfeh, H. P. Babcock, and S. Chu, *Phys. Rev. E* **66**, 011915 (2002).
- ³¹N. J. Woo and E. S. G. Shaqfeh, *J. Chem. Phys.* **119**, 2908 (2003).
- ³²T. Cochrane, K. Walters, and M. F. Webster, *Philos. Trans. R. Soc., A* **301**, 163 (1981).
- ³³A. M. Afonso, M. A. Alves, P. J. Poole, P. J. Oliveira, and F. T. Pinho, *J. Eng. Math.* **71**, 3 (2011).
- ³⁴W. Walters and M. F. Webster, *Philos. Trans. R. Soc., A* **308**, 199 (1982).
- ³⁵C. Hills, *Q. J. Mech. Appl. Math.* **55**, 273 (2002).
- ³⁶J. McDonald and G. Whitesides, *Acc. Chem. Res.* **35**, 491 (2002).
- ³⁷W. Sempels, R. De Dier, H. Mizuno, J. Hofkens, and J. Vermant, *Nat. Commun.* **4**, 1757 (2013).
- ³⁸R. R. Lagnado and L. G. Leal, *Exp. Fluids* **9**, 25 (1990).
- ³⁹M. A. Alves, in *Proceedings of the XVth International Congress on Rheology, The Society of Rheology 80th Annual Meeting, Monterey*, edited by A. Co, L. G. Leal, R. H. Colby, and A. J. Giacomin (American Institute of Physics, Melville, 2008), p. 240.
- ⁴⁰S. J. Haward, A. Jaishankar, M. S. N. Oliveira, M. A. Alves, and G. H. McKinley, *Biomicrofluidics* **7**, 044108 (2013).