

Viscoelastic Surfactant Fluids Filtration in Porous

Media: a Pore-Scale Study

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/aic.16229

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Received: Nov 28, 2019; Revised: Feb 04, 2020; Accepted: Mar 20, 2020

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Abstract We investigated the flow of viscoelastic surfactant (VES) solutions, an important type of fracturing fluids for unconventional hydrocarbon recovery, through a diverging-converging microfluidic channel that mimics realistic unit in porous media. Newtonian fluid and viscoelastic hydrolyzed polyacrylamide (HPAM) solution were used as control groups. We vary Deborah numbers (De) up to 61.2, and found that the flow patterns of HPAM and VES solutions become very different once $De \geq 6.12$. This is attributed to different generation mechanisms of viscoelasticity, thus different responses to extensional rates at pore-throats, for HPAM and VES solutions. It results in significantly smaller pressure drop of VES solutions through the microchannel compared to HPAM solution. It interprets higher filtration loss of VES solution than HPAM in core experiments and in field observations. The set-up can be generalized as a prototype to effectively evaluate the filtration of fracturing fluids.

Keywords: filtration, viscoelastic surfactant solution, microfluidics, hydraulic fracturing

Introduction

The recovery of unconventional reservoirs, including shale gas, coalbed methane, etc., has drawn great attention in oil and gas industry.¹⁻⁵ Hydraulic fracturing technology has been proven to be an effective technique to improve the recovery efficiency of unconventional reservoirs.⁶⁻⁹ It helped to increase 57 percent of gas production, and 23

percent of oil production over the past ten years.¹⁰ The performances of certain viscoelastic fluids serving as fracturing fluids are the keys to successful fracturing operations. Polymer fracturing fluids, hydrolyzed polyacrylamide (HPAM) solution for example, and viscoelastic surfactant (VES) solutions are two representative hydraulic fracturing fluid systems to enhance oil and gas recovery.¹¹⁻¹⁴

Due to the low formation damage as well as the recovering ability of viscoelasticity after shearing,^{9, 11} VES solutions have attracted a vast research interests. VES solution systems widely used include cationic cetyltrimethylammonium p-toluene sulfonate (CTAT) and anionic sodium dodecyl sulfate (SDS),^{16, 17} cetyltrimethylammonium bromide (CTAB) and sodium salicylate (NaSal),¹⁸⁻²¹ CTAB and hydrotropic salt 3-hydroxy naphthalene-2-carboxylate (SHNC),¹⁵ as well as cetylpyridinium chloride (CPyCl) and NaSal.²² Among them, CTAB/NaSal solution is one of the most commonly applied VES solution systems. Compared to polymer, the thickening processes for VES is distinguishing. The viscoelastic of polymer solutions come of the entanglement of polymers, while VES solutions' viscoelasticity is generated by the assemblies of surfactants and additives forming wormlike micelles first then the micelles entangling with each other. The formation and collapse of wormlike micelles are in dynamic equilibrium causing the different flow characteristics between polymer solution and VES solution.¹⁵

To evaluate the economic efficiency and performance of VES solution as fracturing fluids, filtration loss is the primary concern.^{6, 23} Core experiments are well adopted to characterize filtration performance of viscoelastic fluids.^{24, 25} Dehghanpour and Kuru applied core experiments to study the rheological properties of viscoelasticity fluids on filtration loss.²⁶ Their results indicated that the increase of the elastic properties of the polymer solution decreased the filtration loss. However, classical filtration assessment in core experiments are achieved by analyzing macroscopic information such as pressure drop, with very little information on the pore-scale mechanisms. Without the understanding of pore-scale physics, the conclusions achieved from one set of filtration tests can hardly be well-generalized to different conditions, which limits the design, modelling and application of fracturing fluids.⁶

Recent development of microfluidic devices allows the study of flow behaviors of viscoelastic fluids in micro pore-unit directly.²⁷⁻³¹ Researchers are able to analyze quantitatively the velocity fields of viscoelastic fluids,³² migration of crude oil droplet,³³ and interface merging or breakup of bubble.³⁴ Experiments on VES solutions flowing through microfluidic analogue of porous media have presented complex flow phenomena. A series of VES solutions were used to study the flow behaviors in microchannels with different structures, which were designed to simulate the shear and extension characteristics of porous media.³⁵⁻³⁸ Cheung et al.³⁹ mainly considered the

shear component, indicating that the wormlike micellar solution was able to produce a stable permanent flow-induced structured phase (FISP) in straight microchannel. The flow behaviors of VES solution were similar to Newtonian fluids at high shear rates. While Rojas et al.¹⁷ founded that the extension component facilitated the entanglement of wormlike micellar, changing the viscosity of VES solution, which affected the flow characteristics as well. Nevertheless, the views of shear and extension effect on the flow characteristics of VES solutions are not entirely uniform. The characteristics of shear and extensional deformation need further study.

Previous studies focused on the flow characteristic of VES solutions in microdevices with single pore-unit. However, realistic porous media are formed by sequential pore-units, which are rarely considered before. In this work, filtration test on real rock samples are first conducted to compare the filtration losses between different fracturing fluids. Then, microfluidic experiments are conducted in a continuous micro diverging-converging structure (pore-unit), where the flow patterns of VES solution are studied and compared to those of HPAM solution and Newtonian fluid. Flow behaviors of VES solutions at pore-scale are correlated to the cores-scale filtration performance.

Materials and Experimental Methods

Experimental parameters and dimensionless groups

All the experimental parameters are listed in Table. 1. There were two dimensionless numbers used in our work to quantitate the flow field observed in micro pore–unit. Reynolds number (Re) is defined as

$$Re = \frac{\rho \bar{V}_p D_h}{\eta_p} = \frac{2\rho Q}{(w_p + h)\eta_p} . \quad (1)$$

Here, hydraulic diameter $D_h = 2w_p h / (w_p + h)$.

Deborah number (De) is the ratio of the relaxation time of a solution to the residence time in the flow is given as ⁴⁰

$$De = \frac{\lambda_1}{w_p l h / Q} = \frac{\lambda_1 Q}{w_p l h} . \quad (2)$$

Materials

Two types of viscoelastic fluids were used: polymer solution and VES solution. Besides, a Newtonian solution was selected as the control group. The polymer solution was 0.2 wt% HPAM with a molecular weight of 9.6×10^6 g/mol. The VES solution was formed of 20 mMol/L CTAB and 13 mMol/L NaSal, the structure of CTAB and worm-like micellar are illustrated in Figure 1. In contrast, the Newtonian fluid was 78% glycerol–water solution with a viscosity of 65 mPa·s. The rheological characteristics of the fluids were tested by a HAAKE MARS 60 rheometer.

Filtration loss experiment

Flowchart of the filtration loss experiment are illustrated in Figure 2. The cores were saturated with brine (2.0 wt% KCl + 5.5 wt% NaCl + 0.45 wt% MgCl₂ + 0.55 wt% CaCl₂) for 24 h firstly. After saturation, the cores were placed in the core holder. All parts were connected as Figure 2, the stainless steel tubing of the core experiment device was filled with brine. Then, the confining pressure of the core holder was set at 6 MPa, and the injection pressure was maintained at 3.5 MPa. The filtration starting time was set at the first droplets of fluid flowing into the graduated cylinder. Different point-in-time (1, 4, 9, 16, 25, 36 min) and the corresponding filtration volume were recorded to calculate the filtration loss.

The core properties are listed in Table 2. Among them, core No. 1 and No. 2 have similar permeabilities of approximately 16 μm^2 , whereas core No. 3 and No. 4 approximately 41 μm^2 . The core composition and structure obtained by scanning electron microscope (SEM) are listed in Table 3 and S. 1 (Supporting Information S. 1).

Microfluidic device design

The microfluidic channel was fabricated on a plate (120 × 100 × 8 mm) of polymethylmethacrylate (PMMA) by precisely milling and sealed with another PMMA plate (120 × 100 × 2 mm). One microchannel consisted of an injection point, an outlet point and a pore-unit (Figure 3(a)), used for the observation of velocity fields. Another one consisted of three pore-units and two pressure measurement points (Figure 3(b)),

used for the pressure drop measurement. The pore-unit possessed a contraction–expansion structure at upstream and an expansion–contraction structure at downstream (Figure 3(c)), and had a uniform depth of 100 μm . The x-axis is the flow direction, y-axis is perpendicular to the flow direction, and z-axis is perpendicular to the x–y plane. A syringe (25 mL, Hamilton) driven by a syringe pump (PHD/ULTRA, Harvard) was connected to the inlet point to obtain accurate and stable flow rates.

Flow visualization

A micro-particle image velocimetry ($\mu\text{-PIV}$, MITAS, LaVision) was used to measure quantitative flow fields in the pore-unit. Flow visualization was followed the same method with our former work.³²

Result and Discussion

Filtration loss difference between HPAM solution and VES solution

The rheology measurement result is shown in Figure 4. Owing to the rheological characteristics of shear thinning, the shear viscosities (η_p) of the HPAM solution and VES solution are similar as shearing rate $\dot{\gamma} > 10 \text{ s}^{-1}$, which is the regime of interest during hydraulic fracturing operation. According to the Maxwell Model,⁴¹ relaxation time λ_1 is the reciprocal of the intersection of storage modulus (G') and loss modulus (G''), which is 1.61 s for the VES solution and 0.59 s for the HPAM solution (Figure 4(b)).

The experimental filtration coefficient, C , was calculated according to Eq. (3),

where m is the slope of the filtration curve and A is the acreage of the core (petroleum and natural gas industry standards SY/T 5107-2016).

$$C = 0.005 \times m/A \quad (3)$$

As shown in Figure 5, the slopes of the filtration loss curves are 1.98, 1.21, 0.776, and 0.467 ml/min^{1/2}, respectively. The value of filtration coefficient, C , is 7.76×10^{-4} m/min^{1/2} for the VES solution, and is 4.67×10^{-4} m/min^{1/2} for the HPAM solution for the cores with permeability of 16 μm^2 . The value of C is 1.98×10^{-3} m/min^{1/2} for the VES solution, and is 1.21×10^{-3} m/min^{1/2} for the HPAM solution for the cores with permeability of 41 μm^2 . As illustrated in Figure 4(a), although the viscosities of these two fracturing fluids are similar at the shear rates of interest (zero, and the interval from 10 s⁻¹ to 170 s⁻¹), the difference in the filtration coefficients is still obvious. The filtration performance comparison of different fracturing fluids cannot be simply evaluated by the viscosity without considering the flow patterns in the pore-unit.

Microfluid experiment

Flow pattern of Newtonian flow in pore-unit

The velocity fields of the Newtonian fluid in the pore-unit are illustrated in Figure 6. The velocity fields of the Newtonian fluid with five different flow rates have same flow patterns. Namely, the flow pattern for Newtonian fluid is almost independent on flow rate. With the increase of Re from 5.17×10^{-3} to 0.517, the velocity component in

y direction come close to each other, as illustrated in Figure 6(b). These observations are mathematically expected for Navier–Stokes equation with constant viscosity and absence of inertia term, and are in coordinate with a former study.⁴² At the joint of throat and pore, the flow consists of both the x- and y-axis direction velocity components. Then the velocity at the centerline gradually reduces until it reaches a relatively stable value, the streamlines tend to follow the expected stable behaviors such that the velocity is mainly in x direction and barely changes. Subsequently, the streamlines accumulate to the centerline, causing an increase in the velocity near the joint of pore and throat.

Flow patterns of the HPAM solution in pore–unit

Figure 7 shows the flow pattern of HPAM solution. The velocity fields at low flow rates ($Re = 3.58 \times 10^{-4}$, $De = 0.221$) are qualitatively similar to those of the Newtonian fluid. The streamlines are divergent at the joint of throat and pore. Then the streamlines tend to accumulate to the centerline at the downstream. However, the flow patterns are different from those of Newtonian fluid shown in Figure 6. The convergence of the streamlines of HPAM solution starts earlier, farther away from the joint of pore and throat occurring at approximately $x = -150 \mu\text{m}$.

With the increase of flow rate from 1 to 10 mL/h (as shown in Figure 7), the flow characteristics of the HPAM solution transform into patterns distinct from those presented in Figure 6. As the flow rate is more than 1 mL/h, the flow patterns of the

HPAM maintained the convergence the entrance to the exit. Additionally, the arrows of the velocities in the flow fields show that the velocity components are only along the x-axis, without any components toward the y direction. The velocity away from centerline was quite low compared to that at the centerline. This feature was also discussed by Campo-Deano et al.,⁴³ who stated that at high flow rates, long-chain molecules are not able to sufficiently stretch when the polymer solution passes through the convergence and divergence structures, resulting in no obvious expansion of the streamlines. That fits in one's intuition that a classic viscoelastic fluid naturally tends to avoid any sharp change of flow pattern.

Flow patterns of VES solution in pore-unit

The flow patterns of the VES solution are quantitatively similar to those of the HPAM solution and Newtonian fluid at low flow rates ($Re = 3.04 \times 10^{-4}$, $De = 0.612$), as shown in Figure 8. However, as the flow rates increase ($Re \geq 3.04 \times 10^{-3}$, $De = 6.12$), the streamlines of the VES solution maintain the pattern of diverging-converging, which is very different from those of HPAM at similar De , and appears to be closer to Newtonian fluid. It is anti-intuitive as the rheological properties of VES measured from the rheometer are very similar to those of HPAM solution than to those of Newtonian fluid.

Furthermore, the differences in flow patterns between VES and Newtonian fluid

still exist. The streamlines are not symmetry in x-direction. The streamlines diverge immediately around the joint of throat and pore, but start to exhibit the contractive behavior in front of the half-way between two throats. Therefore, a fast divergence and a slow convergence of streamlines are presented. The asymmetry is enhanced when De increases to 12.2. Further increase in flow rate (De) changes the flow pattern insignificantly. It should be noted that the highest Re we applied in the study is far less than 1 so inertia is not significant.

Velocity distribution in pore-unit

Three-dimensional (3D) velocity fields

To better characterize the flow patterns of the three concerned solutions in the pore-unit, the three-dimensional (3D) velocity fields were established at $Q = 10$ mL/h, which demonstrate directly the velocity distribution in fracturing fluids.³ The heights of the 3D-velocity fields represented the velocity at each point, which were marked with different colors, as shown in Figure 9.

The velocity contours in the above-mentioned 3D velocity fields primarily explain the velocity distributions captured by the μ -PIV. As shown in Figure 9(a), the flow pattern of the Newtonian fluid is approximately symmetrical in both x- and y- direction. Two peak velocity points appear at the inlet and outlet of the pore-unit. At high flow rates (illustrated in Figure 7), the pattern of the HPAM solution had shown an obvious

contractive behavior as the velocity component is mainly along the x-axis. Thus, the 3D velocity field of the HPAM solution presented a banded shape where the streamlines concentrate upon the centerline ($y = 0$, shown in Figure 9(b)). In Figure 9(c), the velocity distribution of the VES solution is similar to that of the Newtonian fluid near the joint of pore and throat (from $x = 400 \mu\text{m}$ to $x = 200 \mu\text{m}$). Subsequently, two velocity maximums emerged at both sides of the centerline, accompanied by the accumulation of the streamlines of the VES solution.

Velocity profiles in y direction

To show the differences between the solutions at the same x-position (from $x = 360 \mu\text{m}$ to $x = -320 \mu\text{m}$), seven representative positions were selected to extract flow field data in the pore-unit as shown in Figure 10.

For the HPAM solution (red lines in Figure 11), the velocity profiles are broadly unchanged at the different x-positions, showing a single-peak shape. Moreover, the velocity is mainly distributed from $y = -100 \mu\text{m}$ to $y = 100 \mu\text{m}$, with the highest velocity value of approximately 0.17 m/s at the centerline.

As for the Newtonian fluid and VES solution, velocity profiles (black lines and yellow lines in Figure 11) presented distinguishing characteristics. Initially, the streamlines of the Newtonian fluid and VES solution are divergent after flowing through the inlet. The velocity line of the VES solution shown in Figure 11(a), is more

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divergent compared to that of the Newtonian fluid at $x = 360 \mu\text{m}$. Compared to Newtonian fluid, the VES solution has a lower speed in the center area (from $y = -100 \mu\text{m}$ to $y = 100 \mu\text{m}$) and higher speed at both sides of the centerline (from $y = -400 \mu\text{m}$ to $y = -100 \mu\text{m}$ and from $y = 100 \mu\text{m}$ to $y = 400 \mu\text{m}$). Velocity component of the VES solution is mainly along the y -direction at the vicinity of $x = 360 \mu\text{m}$, while the velocity component along the x -direction barely exists (shown in Figure 8 at $Q = 10 \text{ mL/h}$). Based on the Navier–Stokes equations, this phenomenon occurs if the fluid is close to an inviscid-like fluid.

As the fluids flew downstream (from $x = 180 \mu\text{m}$ to $x = 100 \mu\text{m}$, Figs. 11(b) and (c)), the velocity lines of the Newtonian fluid and VES solution are similar with each other, and the velocity curves are relatively flat. Subsequently, the streamline of the VES solution accumulated from both sides of the pore channel to the center. At $x = 0 \mu\text{m}$ (Figure 11(d)), two velocity maximums were observed at $y = -196 \mu\text{m}$ and $y = 193 \mu\text{m}$, which were nearly symmetric. With the VES solution flowing forward, the maximums were observed approaching each other and appearing at $y = -121$ and $120 \mu\text{m}$ with $x = -95 \mu\text{m}$ (Figure 11(e)) and $y = -49$ and $48 \mu\text{m}$ with $x = -220 \mu\text{m}$ (Figure 11(f)). Finally, the maximums gradually merge at $x = -320 \mu\text{m}$ (Figure 11(g)), coincident with the contour plots of the velocity shown in Figure 9(c).

In summary, flow characteristics of the VES solution are unlike the Newtonian

fluid, there is an ‘inviscid-like flow area’ in the joint of throat and pore. We conjecture that the wormlike micelles of the VES break into free short rod-like micelles or even smaller structure under shear and extension effect at the vicinity of joint of throat and pore.⁴⁴ Away from the inlet, the influence of the viscosity and elastic on the flow patterns came back, owing to the recombination of wormlike micellar on relaxation⁴⁴ and causing the accumulation of streamlines from sides to the centerline at downstream.

Mechanism of generation of ‘inviscid-like flow area’ of VES solution in pore–unit

In order to verify the mentioned assumption of the sharp decreasing in the viscosity of VES solution through the inlet, theoretical model is applied to calculate the extension viscosity in this section.

The uniaxial extension viscosity, η_{Ext} , was calculated following the convoluted models.⁴⁵ The simple uniaxial extension viscosity is derived as expressed in Eq. (4).

$$\eta_{Ext} = 3\eta_s + \frac{3\eta_{p0} f}{(f - 2\lambda_1 \dot{\epsilon})(f + \lambda_1 \dot{\epsilon})} \quad (4)$$

Above, $\dot{\epsilon} = dv/dL$ is the extension rate. The dimensionless functional, f , is defined as $f = (\eta_{p0}/\eta_p)$. In the convoluted models, the f -function becomes Eq. (5), where $\varepsilon_{PTT} = 0.25$,⁴⁶ and the result is illustrated in Figure 12.

$$(f - 2\lambda_1 \dot{\epsilon})(f + \lambda_1 \dot{\epsilon}) \ln \left[\frac{f}{1 + \frac{3\lambda_s \frac{k}{n_\infty} G_0 \lambda_1 \eta_{p0} \dot{\epsilon}^2 f}{(f - 2\lambda_1 \dot{\epsilon})(f + \lambda_1 \dot{\epsilon})}} \right] - 6\varepsilon_{PTT} \lambda_1^2 \dot{\epsilon}^2 = 0 \quad (5)$$

The experimental extension-rate, $\dot{\epsilon}$, in the pore-unit was calculated by Eq. (6), where v is the velocity measured by μ -PIV at the centerline.

$$\dot{\epsilon} = \frac{dv}{dL} = \frac{Q / w_c h - v}{l - x} \quad (6)$$

The dimensionless extension-rate $\lambda \dot{\epsilon}$ and uniaxial extension viscosity, η_{Ext} , at $x = 360 \mu\text{m}$ were 4332 and 22 mPa·s, respectively. As the VES solution flowed through the throat-channel without any deformation along the y -direction, the dimensionless extension rate and uniaxial extension viscosity were 0 and 9762 mPa·s, respectively. After flowing through the convergence and divergence structures, the extension viscosity of the VES solution reduced to 1/443. In conclusion, a high-viscosity (9762 mPa·s) area located at the throat-channel and a low-viscosity (22 mPa·s) area at the joint of throat and pore were found. Because of this significant viscosity difference in these areas, the VES solution in the low-viscosity area could be regarded as an ‘inviscid-like flow area’ and the streamlines might be parallel to the y -axis near the convergence and divergence structures.

Relationship of flow patterns and pressure drop in pore-unit

The correlation between the pressure drop and flow rates in the pore-unit with the flow of the Newtonian fluid, HPAM solution, and VES solution was measured individually.

As illustrated in Figure 13, the transformations of the different flow patterns

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closely correspond with the variation tendency of the pressure drop as flow rate increases from 1 to 10 mL/h. Figure 6 indicates that the flow characteristics of the Newtonian fluid in the pore-unit are barely influenced by the increasing flow rate. The pressure drop varies linearly with the flow rate in the ΔP - Q curve of the Newtonian fluid, which follows the expected Darcy flow behavior. Moreover, the slope of the Newtonian fluid curve is 0.62 kPa·h/mL. However, the ΔP - Q curves of both the HPAM solution and VES solution deviate from the linear relationship with a constant slope at $Q = 1$ mL/h. The flow patterns shown in Figs. 7 and 8 are associated with distinct transformations of the characteristics, which differ from the Newtonian-like flow patterns. As the flow rate exceeds $Q = 1$ mL/h, the slope of the HPAM solution curve accelerates more than that of the VES solution curve to reach 4.12 kPa·h/mL; in comparison, the slope of the VES solution curve is 2.55 kPa·h/mL. At the same flow rate, a larger pressure drop occurs for the HPAM solution compared to that for the VES solution. Note that the HPAM solution and the VES solution present very similar apparent shear viscosity as shown in Figure 4(a).

Among all the flow patterns, the increasing flow rates caused a marked accumulation of the streamlines near the outlet and inlet of the microchannel, with which an increasing pressure drop was found. The additional pressure drop compared to that of the Newtonian flow supported the formation of a contracted flow far away

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from the outlet of the microchannel. In the pore-unit, the flow patterns of the HPAM solution showed a strong contraction such that the streamlines accumulated in the entire microchannel, including both the outlet and inlet. Unlike this characteristic, the contractive flows of the VES solution were only observed at the downstream of the structure, whereas the streamlines at the upstream maintained a Newtonian-like behavior. In addition, the differences in the contractive characteristics of the HPAM solution and VES solution explained the variations in the ΔP - Q curves. This indicated that the flow rates of the VES solution were higher than those of the HPAM solution at the same injection pressure, which was in accordance with the filtration loss experiments. Compared to the flow patterns of the VES solution, those of the HPAM mainly accumulated in the center area of the microchannel at high flow rates, with barely any velocity component toward the wall surface, causing a small filtration loss in the matrix of the cores.

Conclusions

In conclusion, core experiments demonstrate that the filtration losses of two viscoelastic fracturing fluids (VES and HPAM solutions) exhibit significant differences, even when they share similar apparent shear viscosities at the shear rates in operation. Therefore, predicting the filtration loss only by using viscosity measurements can be unreliable.

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Experiments on microfluidic diverging-converging pore-unit geometry reveals that the flow patterns of VES solution is very different from classic polymeric viscoelastic liquids. Under high shear rate, the streamlines of VES solution diverges sharply at the inlet of a pore which behaves like an inviscid fluid, and slowly contracts towards the outlet. At $De = 61.2$, the extensional viscosity of the VES solution at the inlet of pore-unit reduced drastically from 9762 to 22 mPa·s, leading to the appearance of an “inviscid-like flow area”. We attribute this special flow pattern to a dynamic balance between the free short rod-like micelles, free worm-like chains, and entangled worm-like chains when flow channel sharply diverges and converges. It results in a much lower pressure drop, and therefore more filtration loss.

In addition, this work also provides a simple and cheap workflow to evaluate the filtration performance of different fracturing fluids, which can be applied as a good supplement to highly-costly traditional core experiment.

Acknowledgments

The work was supported by the National Natural Science Foundation of China (U1663206, 51704313), Chang Jiang Scholars Program (T2014152).

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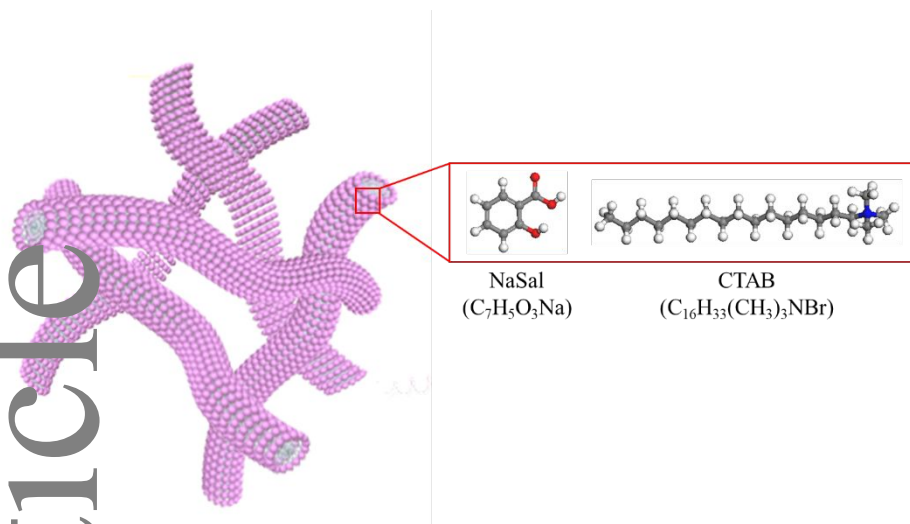


Fig. 1 Structure of CTAB/NaSal worm-like micellar.

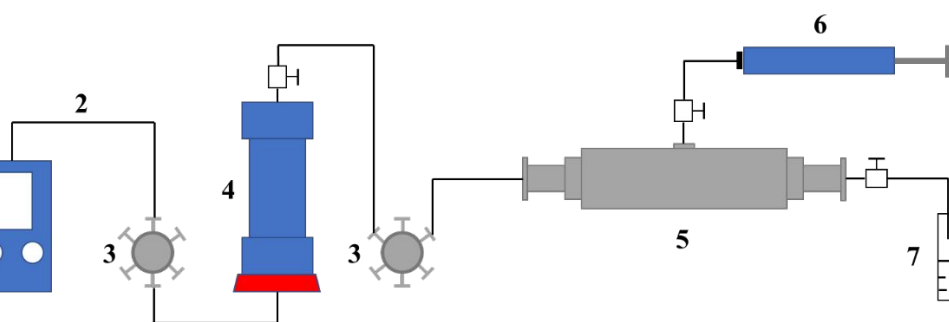
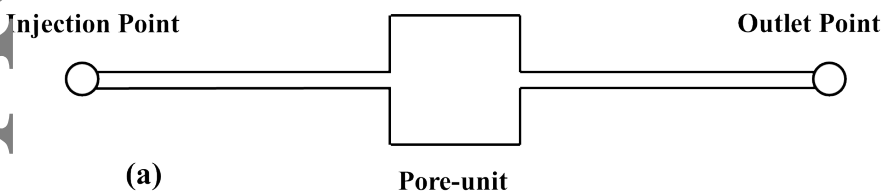


Fig. 2 Flowchart of the filtration loss experiment: (1) constant-pressure pump; (2) stainless steel tubing; (3) six-way valve; (4) fracturing fluid container; (5) core holder; (6) confining pressure pump; (7) graduated cylinder.



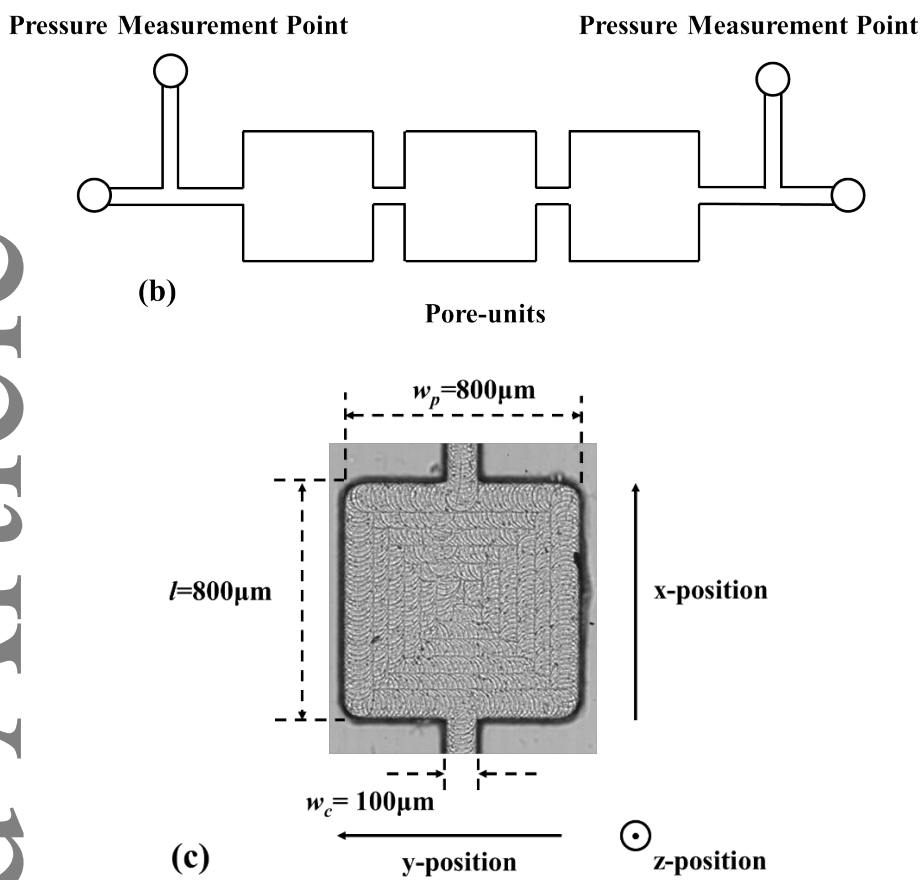


Fig. 3 Layout design of the microchannels (a) and (b). (c) Geometric parameters of the pore-unit.

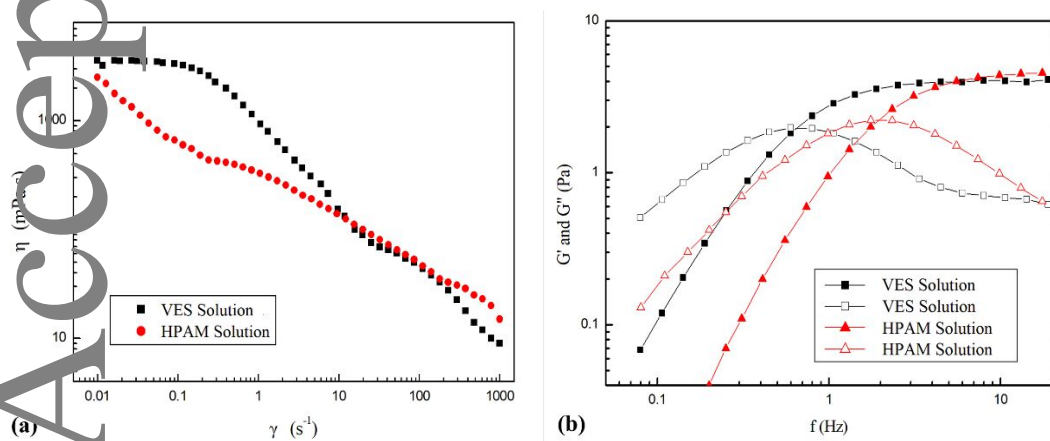


Fig. 4 (a) Shear viscosity η_p of the HPAM solution and VES solution as shear rates ranging from 0.01 s^{-1} to 1000 s^{-1} and (b) Oscillatory measurement of storage modulus (G') and loss modulus

(G'').

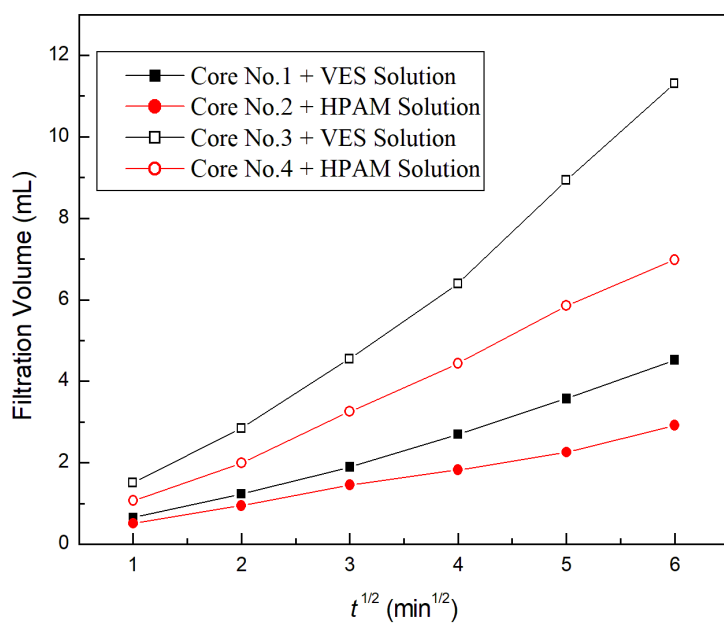
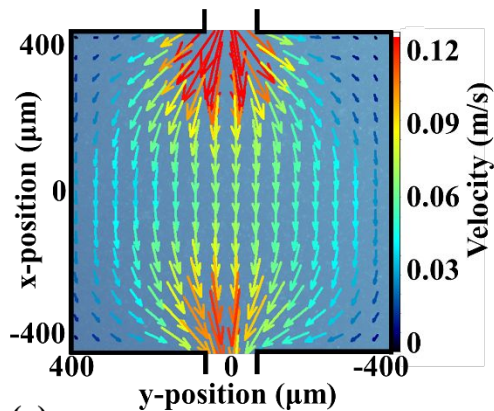
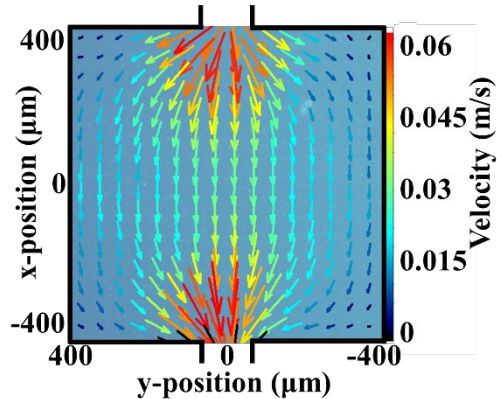
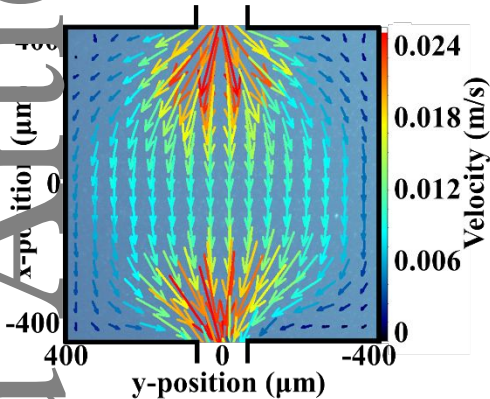
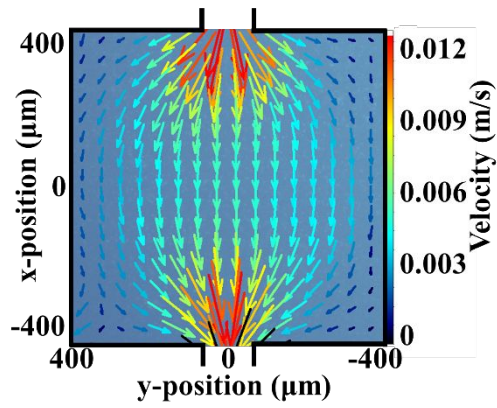
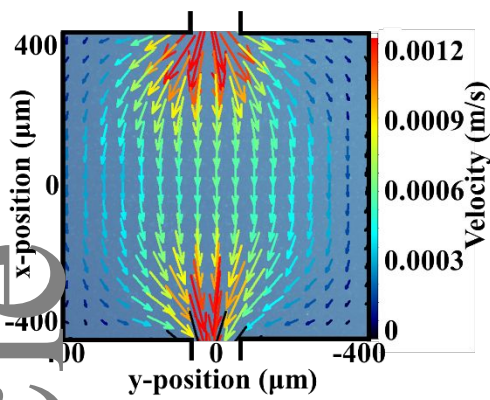


Fig. 5 Filtration loss curves of the VES solution and HPAM solution.



(a) $Q = 10 \text{ mL/h}$, $Re = 0.517$

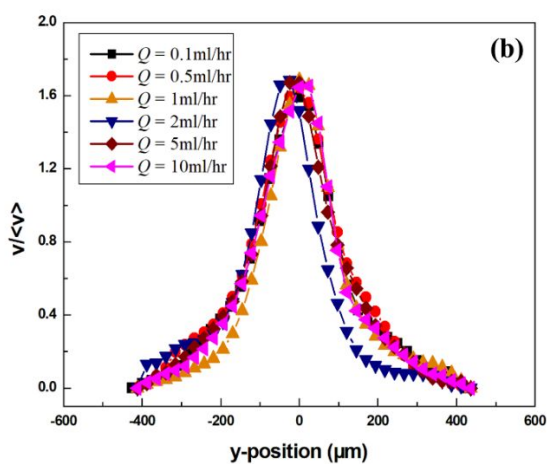
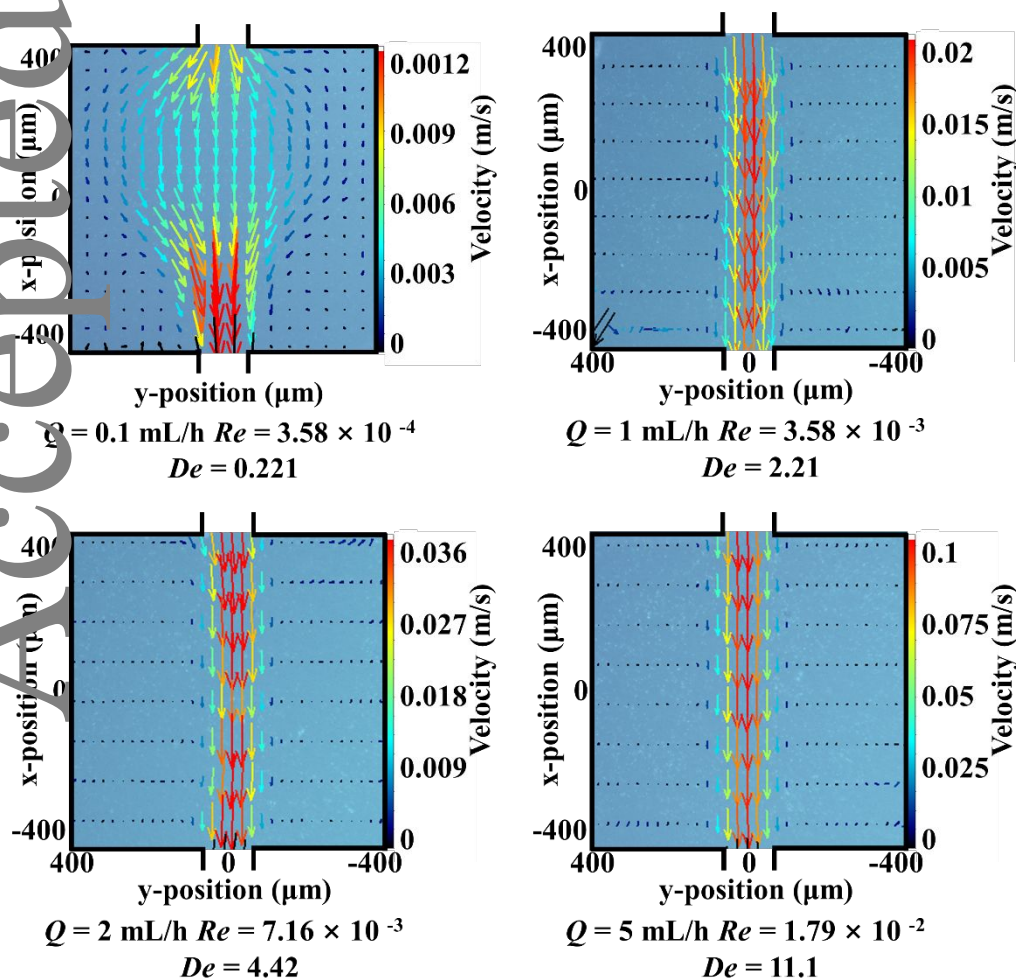


Fig. 6 (a) Flow patterns for the flow of the Newtonian fluid in the pore-unit, with flow rates range from 0.1 to 10 mL/h and $5.17 \times 10^{-3} \leq Re \leq 0.517$. (b) Velocity component in y direction at $x = -350 \mu\text{m}$.



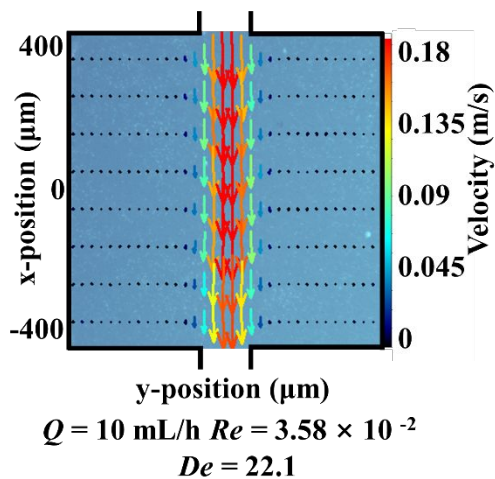
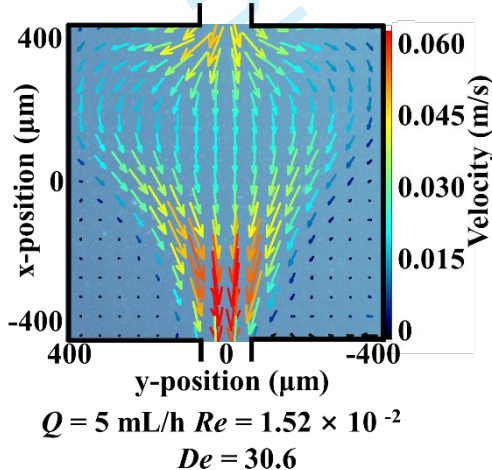
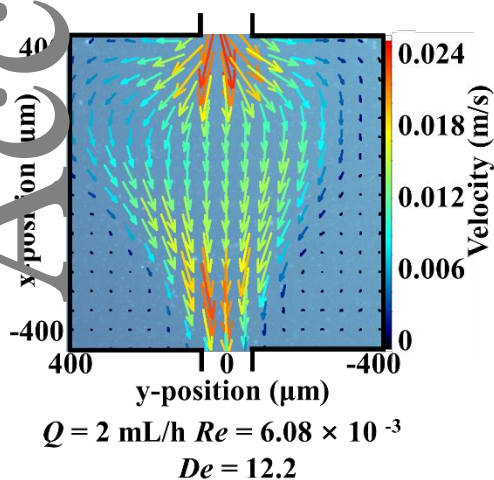
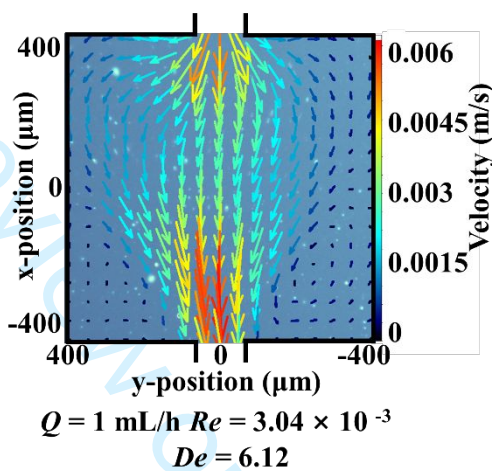
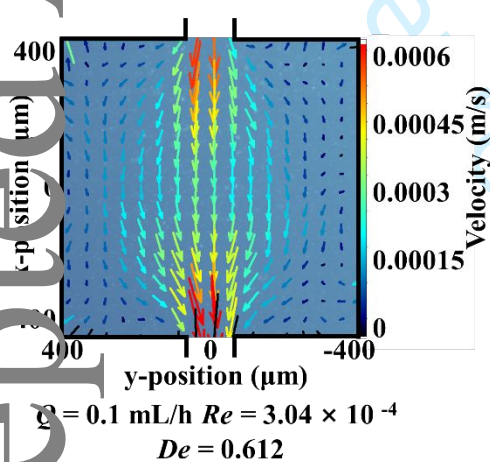


Fig. 7 Flow patterns for the flow of the HPAM solution in the pore-unit, with flow rates ranging from 0.1 mL/h to 10 mL/h, $3.58 \times 10^{-4} \leq Re \leq 3.58 \times 10^{-2}$, and $0.221 \leq De \leq 22.1$.



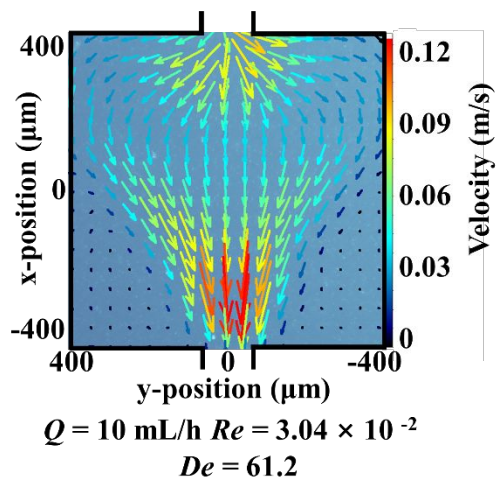
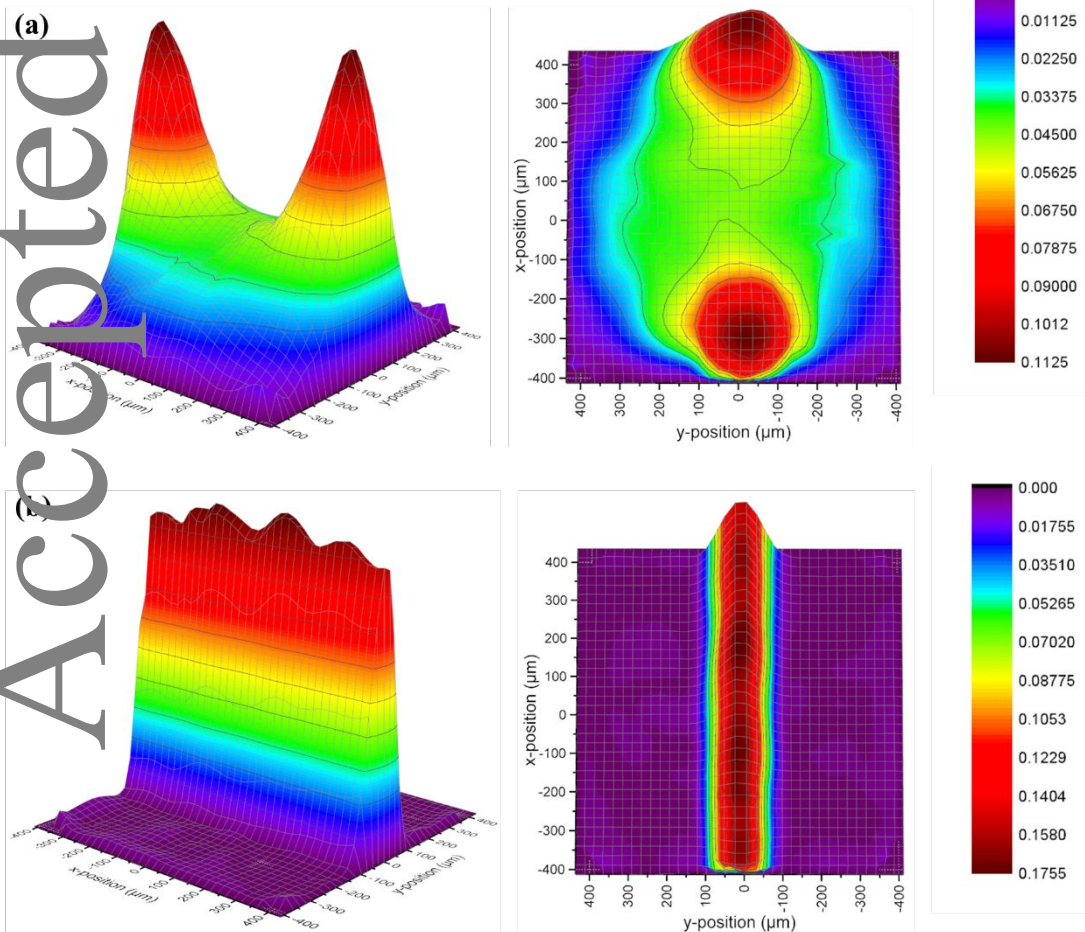


Fig. 8 Flow patterns for the flow of the VES solution in the pore-unit, with flow rates ranging from 0.1 mL/h to 10 mL/h, $3.04 \times 10^{-4} \leq Re \leq 3.04 \times 10^{-2}$, and $0.612 \leq De \leq 61.2$.



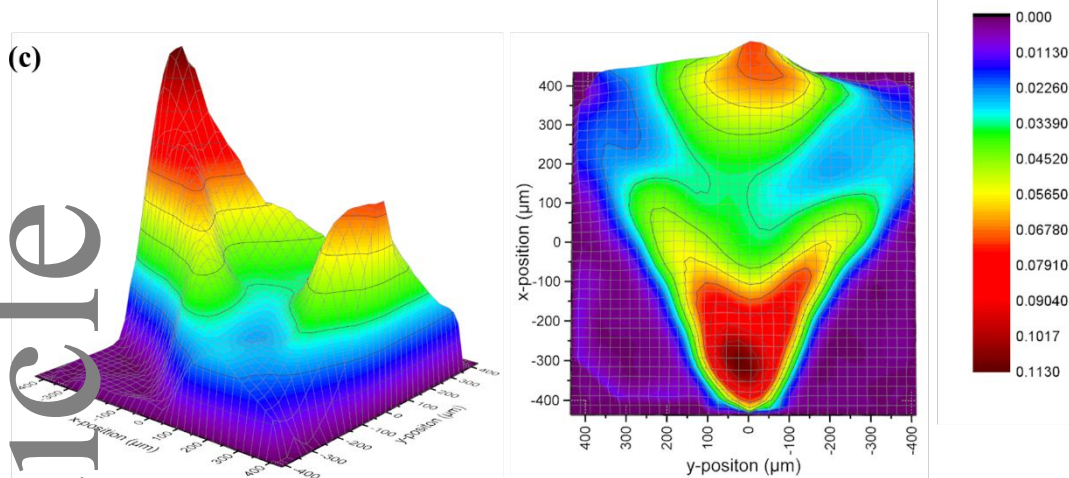


Fig. 9 Three-dimensional velocity fields of the (a) Newtonian fluid, (b) HPAM solution, and (c) VES solution in the pore-unit at $Q = 10$ mL/h.

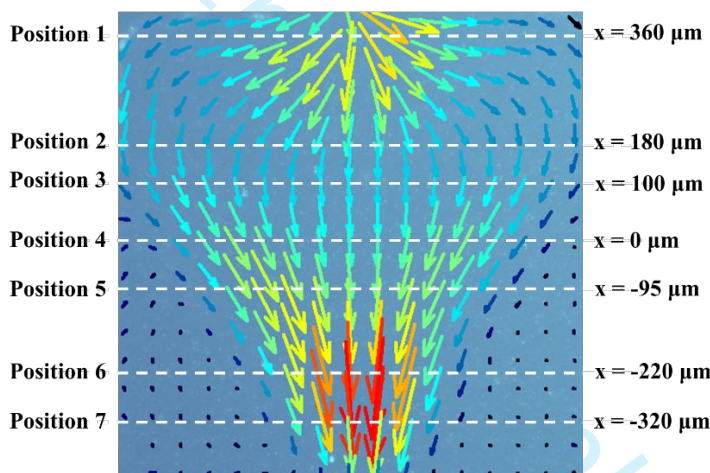
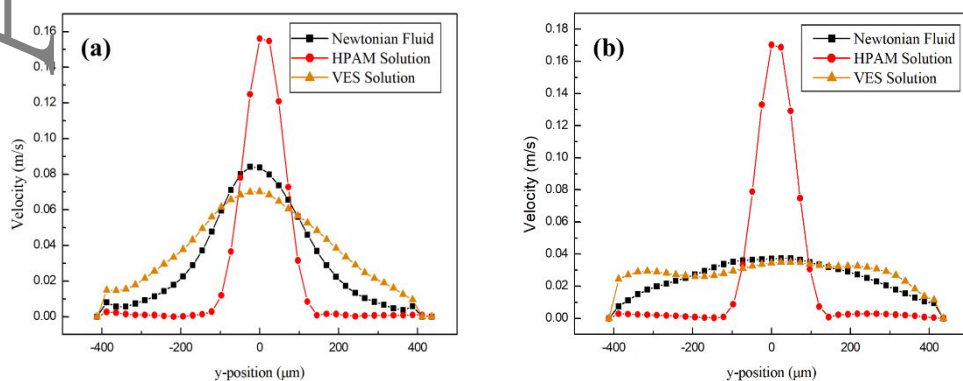


Fig. 10 Schematic of the position where velocity data were extracted.



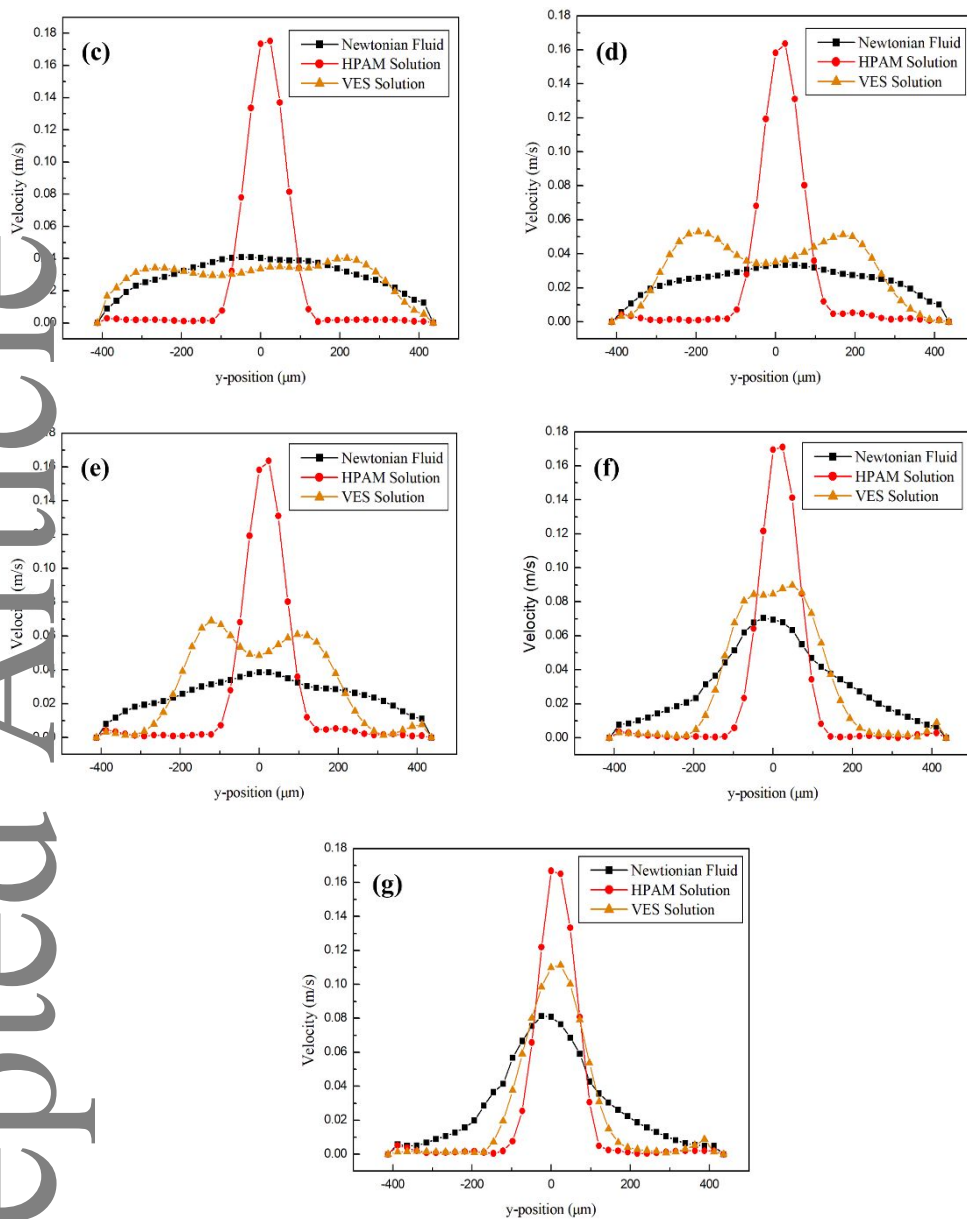


Fig. 11 velocity profiles in y direction of the Newtonian fluid, HPAM solution, and VES solution flowing through the pore-unit at (a) $x = 360 \mu\text{m}$, (b) $x = 180 \mu\text{m}$, (c) $x = 100 \mu\text{m}$, (d) $x = 0 \mu\text{m}$, (e) $x = -95 \mu\text{m}$, (f) $x = -220 \mu\text{m}$, and (g) $x = -320 \mu\text{m}$ at flow rate $Q = 10 \text{ mL/h}$.

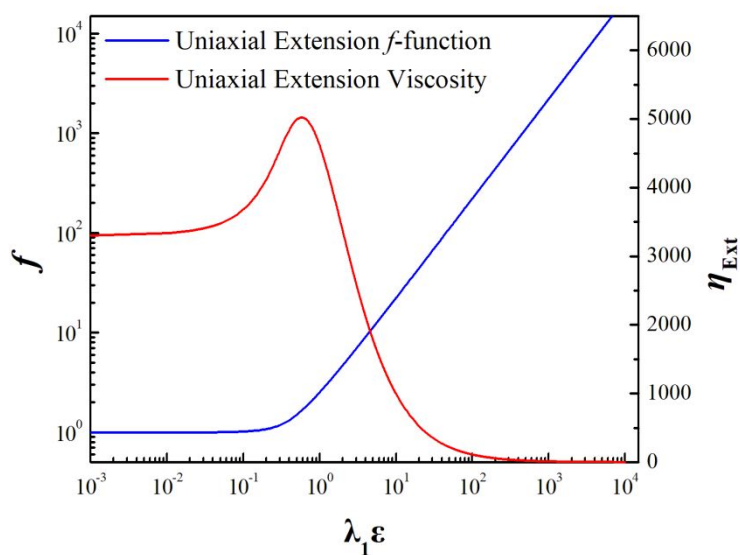


Fig. 12 f -function and η_{Ext} with the increase in the dimensionless extension rate from 1×10^{-3} to 1000.

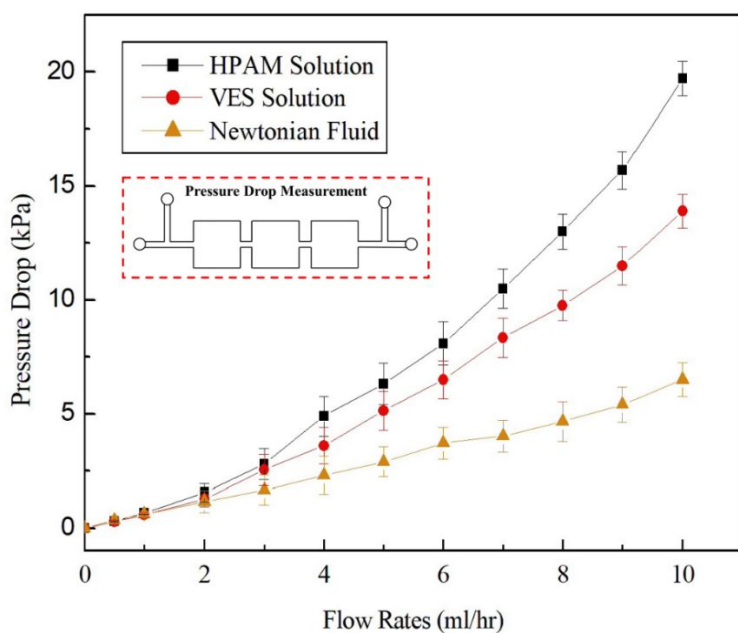


Fig. 13 Pressure drop measurements of the Newtonian fluid, HPAM solution, and VES solution.

Table. 1. Experimental parameters

Q (mL/H)	Flow rate	w_p (μm)	Width of the pore-unit
w_c (μm)	Width of the microchannel	L (μm)	Length of the pore-unit
h (μm)	Depth of the microchannel	ρ (g/cm^3)	Solution density
Re	Reynolds number	De	Deborah number
D_h (μm)	Hydraulic diameter	$\bar{V}_p$ (m/s)	Average flow velocity in a pore channel
C ($\text{m}/\text{min}^{1/2}$)	Filtration coefficient	η (mPa·s)	Apparent viscosity
η (mPa·s)	Shear-viscosity	η_s (mPa·s)	Solvent viscosity
η_{ext} (mPa·s)	Uniaxial extensional viscosity	η_{p0} (mPa·s)	Viscosity at zero shear rate
f	dimensionless functional	G_0 (Pa)	Elastic modulus at vanishing shear rates
k (Pa^{-1})	Inverse of the structure-destruction stress	$\bullet$	
K (μm^2)	Permeability of the core	ε (s^{-1})	extension-rate
ΔP (kPa)	Pressure drop	λ_1 (s)	Relaxation time

Table. 2. Core properties

Core No.	Fluid	Length (mm)	Diameter (mm)	Porosity (%)	Permeability (μm^2)
1	VES Solution	49.82	25.24	21.26	15.61
2	HPAM Solution	49.53	25.37	21.13	16.28
3	VES Solution	49.75	25.03	21.73	40.52
4	HPAM Solution	49.44	25.12	21.86	41.33

Table. 3. Composition of the cores

Core No.	Quartz (%)	Potash Feldspar	Plagioclase (%)	Calcite (%)	Dolomite (%)	Pyrite (%)	Clay mineral
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		(%)				(%)	
1-2	36.9	1.8	7.9	7.4	11.9	2.8	31.3
3-4	39.6	2.1	6.0	10.6	8.8	2.5	30.4