Wellbore to fracture proppant-placement-fluid rheology

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A R T I C L E   I N F O

Article history:
Received 1 May 2015
Revised 23 November 2015
Accepted 1 January 2016
Available online 6 February 2016

Keywords:
Fracturing fluid
Induced viscoelasticity
Fracture flow
Entrance effects

A B S T R A C T

Novel reservoir engineering displacement fluids (cetyltrimethylammonium bromide and sodium salicylate in water) are examined as candidates for proppant placement during fracturing. The need for additional crosslinkers, breakers or contact with hydrocarbons to change the viscosity is eliminated. These materials have a viscoelastic response governed by flow. Two fluid compositions are investigated in relation to Newtonian fluids of similar base viscosity to determine how shear induced structures (SIS) influence flow properties in the near-wellbore region of a fracture. In Couette flow, the fluid displays shear thickening and thinning within a discrete shear regime. Extensional flow tests in a microfluidic device reveal a flow resistance up to 25 times higher than Newtonian fluids. This extra flow resistance is due to an induced intermicellar network and has potential application for improved proppant carrying after injection via a perforation. Particle image velocimetry is used to visualise the entrance flow in a fracture. Instabilities are reduced as flow through the perforation increases. The viscosity contrast ratio between zero-shear viscosity and maximum viscosity response determines the extra proppant carrying capacity.

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Introduction

Hydraulic fracturing is used to stimulate unconventional oil and gas reservoirs where extremely low permeability prevents easy access to the resources. Unconventional reservoirs such as tight sandstone and shale formations have matrix permeability \( k_{\text{mat}} \) ranging from 1 to 500 \( \mu \)D and 1 to 1000 nD respectively compared to 1 mD and higher for conventional reservoirs (King, 2012). Fracturing increases the exposed matrix surface area and creates a path for hydrocarbons to flow from the reservoir to the wellbore. In this work we concentrate on the role of the fluid and its properties during proppant placement in a fracturing treatment. The stage of filling a fracture with proppant is critical to the success of the whole process and subsequently determines the production rates achieved and how long these can be maintained. Production is directly related to the ability of the proppant pack to retain fracture conductivity \( k_f \) defined as the product of propped fracture width \( w \) and the permeability of the propped zone \( \kappa \) \( (k_f = w \cdot \kappa) \) (Bennett et al., 2005). Filling vertical fractures with proppant requires a specific fluid rheology. High viscosity is required to carry proppant into the fracture. It is also increasingly accepted that elasticity plays a significant role in proppant suspension (Hu et al., 2015). These are the main rheological features sought for proppant placement fluids. Other factors such as the physical nature of the proppant, including size and density as well as the rate at which the slurry is pumped are also central to successfully fill fractures (Terracina et al., 2010).

A crucial period is the transport from the injection wellbore to the near wellbore region inside the fractures. This often occurs via casing perforations. The initial injection of proppant through the perforations in the wellbore can often make or break a fracturing treatment (Daneshy, 1973). Early bridging or settling of proppant in the near-wellbore zone of the fracture will limit further packing deep into the fracture. This transport is determined by the rheological properties of the fluid to effectively transport the proppant away from the near-wellbore (Gruesbeck and Collins, 1982). The fracture aperture geometry (tortuosity and alignment), proppant concentration and pump rate also determine proppant transport from the perforation into the fracture (Romero et al., 1995). Most studies in an oil and gas context focus on wellbore to perforation (i.e. injection/stimulation) or reservoir to perforation (i.e. production) (Brooks and Haggerty, 2011; Gruesbeck and Collins, 1982; Li et al., 2012; Razi et al., 1995). In this work we investigate novel viscoelastic fluids and determine flow performance from a perforation into an open fracture with a view to optimise carrying capacity – the fluid’s ability to suspend proppant during shear flow as a result of its viscoelastic properties. There has been considerable work using viscoelastic surfactant fluids,
however these still require some modifying chemical interaction e.g. contact with hydrocarbons or breakers, in order to change their proppant carrying characteristics, in particular the viscosity (Samuel et al., 1999). In the near-wellbore in particular, shear rates are much higher than at the fracture tip (Constien et al., 2000). Traditional fracturing fluids are shear-thinning and therefore have a lower viscosity in this region. Indeed, insufficient viscosity to transport proppant in this region is known to cause screenouts (Aud et al., 1994). By contrast the fluids in this study exhibit flow-induced viscoelasticity (FIVE), meaning that they do not have reduced proppant carrying capacity in the near-wellbore. This is investigated by studying the fluid’s rheological properties when undergoing extensional flow (such as that from perforation to fracture) and relating this rheology to expected proppant transport ability.

In recent years viscoelastic surfactants (VES) have found increasing application in hydraulic fracturing owing to their high viscosity and elasticity and their polymer-free nature which eliminates residue associated with guar gums for example (Barati and Liang, 2014). A large body of literature is available covering a range of applicable studies for such fluids. VES fluids have been shown to improve proppant placement and conductivity (Fry and Stegent, 2014). By contrast the fluids in this study exhibit flow-induced viscoelasticity (FIVE), meaning that they do not have reduced proppant carrying capacity in the near-wellbore. This is investigated by studying the fluid’s rheological properties when undergoing extensional flow (such as that from perforation to fracture) and relating this rheology to expected proppant transport ability.

We investigate the effects of extensional flow on fluid rheology in a specifically designed fracture flow cell. The questions studied are: (1) what does the flow profile of the fluid tell us about its rheological properties as it enters a fracture through a perforation? (2) Is this suitable for proppant transport in the near-wellbore region? And (3) can a shear-induced fluid system obviate the need for viscosifiers and breakers? Section “Background” outlines the background physical and chemical properties. An experimental description follows in Section “Experiment and materials” and the results are discussed and analysed in Section “Results and discussion”.

### Background

#### Hydraulic fracturing processes

During a fracturing treatment, fluid is injected at high pressures that crack the rock open to form fractures. To maintain fracture permeability once the pressure is reduced, sand particles known as proppants are packed inside the fracture to “prop” it open. For simplification a fracturing treatment can be divided into three stages: in the first stage called the “pad”, a proppant-free gel fluid is injected to induce fracturing. In the second stage called placement, a proppant slurry is injected into the newly formed fracture. The third stage is known as flowback/closure and fluids are pumped back to the surface for post-treatment and the fracture is allowed to close on the proppant pack.

Each stage requires different fluid properties: low viscosity in the wellbore is needed for easy injection and to minimize frictional pressure loss. High suspension ability – i.e. viscosity – is needed to transport proppant deep into the fracture. Low viscosity is needed again when fluid is removed from the packed fracture so as not to displace proppant particles. Traditionally polymers are combined with added chemicals that viscosify by crosslinking molecules, and later chemical breakers “break” viscosity to enable flowback.

#### Rheology of classical hydraulic fracturing fluids

Natural polymers such as guar gum are the benchmark for proppant placement. The high viscosity required for good carrying capacity is created with the use of ionic crosslinkers such as borates. Once the fracture is filled with proppant a time-delayed viscosity breaker (usually an ionic oxidizer, acid or enzyme) is used to thin the fluid and allow for easy flowback (Montgomery, 2013).
Apart from the requirement for a variety of added chemicals, polymeric fluids often damage the proppant pack by leaving behind a residue which reduces its permeability. Polymers can also create a filtercake on the fracture surface which decreases the flow of hydrocarbons from the porous matrix to the fracture (Gulbis et al., 1991). In recent years alternative fracturing fluids and techniques have been employed to overcome these challenges. These include slick water fracturing with low viscosity water-like fluids, hybrid fracturing, foamed fluids and viscoelastic surfactants (VES) (Gupta, 2009). Viscoelastic fluids used for fracturing are usually shear thinning, with high zero-shear viscosity and intrinsic viscoelasticity (Kefi et al., 2004). In this case they transport proppant well but require breakers during flowback. The fluids investigated here are a different class of VES that do not have gel-like low-shear behaviour and have previously not been applied to hydraulic fracturing.

In this study we use a viscoelastic surfactant (VES) that forms flow-induced viscoelastic (FIVE) solutions with unique properties outside the traditional ranges of behaviour associated with non-Newtonian fluids. Unlike most other treated water-based systems, they are non-polymeric, non-power law, and as we shall show, non-monotonic in their shear response (Hartmann and Cresseley, 1998, 1997a,b). They do however display Newtonian, thinning and thickening, and viscoelastic behaviour depending on the shear regime. This behaviour is tuneable owing to their micelles made up of surfactant molecules that self-assemble into a variety of different structures (Rothstein, 2008). The ability for VES fluids to undergo such changes is influenced by the concentration of surfactant and salts in solution as well as fluid strain history and temperature (Ezrabi et al., 2006).

The VES components consist of a surfactant and a co-solute dissolved in water. Such a pair is cetyltrimethylammonium bromide (CTAB), a quaternary-ammonium cationic surfactant and sodium salicylate (NaSal), an aromatic salt. Surfactant molecules like CTAB are composed of a non-polar carbon chain and a polar head group. This allows them to form aggregates that reduce their entropy in aqueous solutions. At very dilute concentrations isolated molecules will exist. Above the critical micelle concentration (CMC) small spherical balls form. These extend into rod-like cylinders when the concentration is increased and further into worm-like structures similar to flexible polymers (Yang, 2002).

When CTAB is combined with NaSal two intriguing properties develop; the fluid exhibits elasticity coupled with strong viscous behaviour and also a non-monotonic shear-viscosity response (Vasudevan et al., 2008). NaSal acts as a counter-ion, electrostatically shielding the CTAB’s polar head groups from each other. This shielding facilitates the formation of extended micellar networks (Kim and Yang, 2000). It is the presence of worm-like micelles that give rise to the non-Newtonian rheology of surfactant solutions. These shear effects differ depending on the relative concentrations of CTAB and NaSal so the fluid can be “tuned” to provide the desired rheology in the desired shear regime.

**Application potential**

Fig. 1 shows the typical non-monotonic viscosity of a CTAB/NaSal solution in a (Couette) rheometer test. We apply each shear regime to a different stage in the fracturing process described previously:

- In the wellbore, at high deformation in the turbulent regime and high shear, a low viscosity fluid is required to reduce pressure losses during injection.
- As the fluid enters the fracture, laminar flow takes over and intermediate shear rates allow for the formation of a sustained micellar network to suspend proppant.
- Finally during flowback and low shears, the fluid is recovered through the porous proppant pack and low viscosity is required so as not to disturb it and prevent residue remaining.

Considering the unusual characteristics of these solutions that, within a certain concentration and ratio range, exhibit a thickened and elastic gel-like phase induced by shear, the potential for subsurface application is clear: a polymer-free fracturing fluid free of viscosifiers and breakers.

It is important to note that the shear-rates during each stage of fracturing as well as within the fracture itself are highly variable and the boundaries not always clear. The description above does however give an indication of expected values. We also note that the fluid described here has the ability to be “tuned” based on additive concentrations and ratio (Vasudevan et al., 2008) allowing the viscous profile to be matched to predicted flow regimes throughout the treatment.

Numerous authors have investigated FIVE systems and CTAB/NaSal specifically mostly in the context of material properties in a Couette cell (Lin et al., 1994; Vasudevan et al., 2008). For a fixed surfactant concentration C_s, micelles extend from spherical to wormlike micelles with increasing co-solute concentration CHS. Lin et al. (1994) also showed that at low C_s there is no micelle entanglement, and the solution behaved as a Newtonian fluid in Couette cell tests. Above a critical C_s value, the solution had a “Newtonian plateau” at low shear rates and then shear thickened within a higher discrete shear-rate range and at much higher shear rates the solution thinned and plateaued at the low-shear viscosity. As the co-solute concentration increased further the solution had a higher zero-shear viscosity and the critical shear rate required for shear thickening decreased. At even higher C_s concentrations only shear-thinning behaviour occurred (Hartmann and Cresseley, 1998, 1997a,b). Vasudevan et al. (2008) suggests the shear thickened phase is gel-like and composed of sheared induced structures that form a micellar network dispersed within a lower viscosity solution.

These features are shown conceptually in Fig. 1 above where we define a number of key features: The viscosity in the Newtonian...
The shear rate at which thickening occurs is termed the critical shear rate, $\gamma_c$. The shear rate at which the maximum viscosity $\eta_{\text{max}}$ occurs is termed $\gamma_{\text{max}}$. The shear regime in which shear induced structures (SIS) are present is termed the SIS regime.

Of course, the description so far has only referenced Couette flow. It is well known that non-Newtonian fluid behaviour in fractures cannot be easily predicted – and this is particularly true for the fluids under discussion here because they are non-power law and also not monotonic in response to shear. VES fluids are also known to form shear-bands resulting in multiphase flow within an aperture (Huang and Desroches, 2004). This is related to the flow induced viscoelasticity (FIVE) effects identified above. To overcome the difficulty in analysing experimental results that may arise from shear-banding phenomenon we compare our FIVE fluids with Newtonian fluids of the same Newtonian plateaux viscosity. This allows us to predict the rheological regime of the VES fluids without speculating on the specific shear rates across the aperture.

Previous work has examined low concentrations of viscoelastic surfactants for steady state flow in channels (including capillaries and fractures) (van der Plas and Golombok, 2015a, 2015b). They showed that similar concentrations of the fluids studied here selectively retard flow in larger flow channels as a result of the shear-induced structures. They also showed that extensional effects contribute additional flow resistance. It is this additional flow resistance that we aim to exploit as a means to improve fluid rheology for propellant carrying in the near-wellbore. Here we are concerned with the effect on the fluid of a change in aperture dimension which we now consider.

Transition effects

We consider expansion fluid flow from a perforation into a fracture where the flow cross-sectional area increases when going from the perforation into the larger fracture. In this case the fluid has a non-zero velocity gradient in the direction of flow $du/dx \neq 0$, known as the extension rate and extra flow resistance is caused by the presence of extensional viscosity (Macosko, 1994). In addition, for VES fluids, an elastic contribution results in much higher pressure drops over an expansion or contraction (Ober et al., 2013). As such, it is important to determine whether SIS fluids exhibit viscoelastic properties when undergoing extensional flow indicating if the preferential flow-induced viscoelasticity is present in the near-wellbore and in this way can potentially aid proppant suspension.

Extending rheological parameters from a rheometer or particle settling tests to fracture flow is challenging because the mechanical stresses on the fluid are different. In complex geometries such as expansions extensional effects also play a role. In this paper we are concerned with novel fluid rheologies and their behaviour at the most vulnerable stage of fracturing application i.e. proppant placement during the transition from the wellbore to fracture through the casing perforations. Expansion flows have been extensively studied in both Newtonian and non-Newtonian fluids (Mishra and Jayaraman, 2002). Although the flow profiles for a sudden expansion are determined by the fluid rheology, theory to predict other parameters analytically such as the entrance lengths required to achieve fully developed flow are limited (Forrester and Evans, 1997). Rather, numerical methods alone are available to determine, for example, recirculating zones (eddies) that occur in the corners downstream of the inlet.

The nature of the entrance length gives an indication of the rheological state of the incoming fluid as well as the distance expected for stable flow. Knowledge of this allows fluids and pump rates to be tuned to match the requirements in the near-wellbore. Macango and Hung (1967) showed the size of the recirculation zone increased linearly with inlet Reynolds number for Newtonian fluids where Reynolds number is given as $Re = (\rho u_i d_i) / \mu_i$; $u_i$ and $d_i$ are the inlet average velocity in the perforation tube and diameter respectively. This was supported by Oliveira and Pinho (1997) for laminar, inlet Reynolds numbers ($0 < Re < 250$) showing that entrance length $L_e \propto Re$.

Additional complications arise for non-Newtonian fluids in sudden expansions. In computational studies Mishra and Jayaraman (2002) found for a planar expansion of 1:16, shear thinning fluids reduced the size of the recirculating zones compared to Newtonian fluids with the same inlet Reynolds number. These findings were confirmed for laminar flow by Ternik (2009). Conversely, shear thickening fluids have an opposite effect by elongating the recirculation zone (Dhinakarana et al., 2013). When the fluid in a sudden expansion has elastic properties however, the recirculation zones are smaller – thus elasticity has a damping effect (Oliviera, 2003).

Experiment and materials

We outline the experiments used to characterise the SIS fluids when undergoing extensional flow. This is done with a view to tune fluids so that they have high viscoelasticity in the near-wellbore. Traditionally, Couette measurements are used to determine the rheology of fracturing fluids. Only for Newtonian fluids however, do a Couette cell and slit rheometer give the same value of fluid resistance to flow (i.e. viscosity) (van der Plas and Golombok, 2015b). Thus Couette measurements cannot be easily extended to pressure driven flow in fractures and, moreover, give no indication of extensional behaviour. Nevertheless such measurements are used in this study as a means to compare different SIS fluids and Newtonian fluids with the same zero-shear viscosity.

Extensional flow is the central theme of this study as a means to understand and optimise the rheological properties of the SIS fluid as it enters a fracture from a wellbore. This is tested in two ways: (1) a microfluidic device measures pressure drop across a contraction–expansion in pressure driven flow. In this way additional resistance due to extensional flow is determined. (2) A perforation-like inlet into a fracture flow cell is used to image the flow profile of SIS fluids. This is compared to that of Newtonian fluids and the rheological regime of the entering SIS fluid can be inferred.

Couette cell

An Anton Paar MCR-302 rotational Rheometer with a 1 mm double gap cylindrical geometry and Peltier temperature control was used. The torque range of the rheometer is 10–200 mNm and the angular velocity is $10^{-9}$ – 314 rad/s. In order to determine the optimum measuring time, the fluid was sheared at a constant shear rate for 120 s. From this it was found that 60 s was sufficient to reach a stable viscosity for all concentrations. Shear rates were then increased logarithmically between 1 s$^{-1}$ and 3000 s$^{-1}$ to determine the shear–viscosity profile in the range relevant to hydraulic fracturing.

Extensional cell

To test the fluid resistance through a perforation expansion we used a microfluidic rheometer known as the “extensional viscometer–rheometer-on-a-chip” (EVROC) manufactured by RheoSense Inc. This consists of a rectangular flow channel with a central hyperbolic contraction – a schematic diagram is shown in Fig. 2. The hyperbolic geometry ensures a constant extensional rate across the centre line. Four integrated micro-electromechanical
pressure sensors are moulded into the channel, two before and two after the contraction/expansion allowing for $\Delta P$ measurements in the extension-free rectangular channels as well as over the hyperbolic section. The channel width $w_u$ is 3 mm, the height $h$ is 0.19 mm and the throat width $w_l$ is 0.4 mm. Pressure drop was measured across each section ($\Delta P_{1-2}$, $\Delta P_{2-3}$, $\Delta P_{3-4}$) for flowrates ranging from 150 $\mu$l/min to 4 ml/min (4–106 mm/s in the straight channel). Before each measurement we flushed the cell at high flowrates with 10 ml of fluid to dispel any other fluids and air bubbles. During the test, each flowrate was measured for 60 s to ensure pressures are in equilibrium. Only data for the last 30 s of the measurement were used for analysis.

Traditionally, rheology information from a Couette cell is used to determine flow behaviour in a fracture. A Couette cell applies a constant shear-rate across the fluid and does not impose an extensional strain. In capillary or fracture flow there is a distribution of shear rates across the flow (van der Plas and Golombok, 2015b). The form any viscoelastic effects take is also not obvious for a proppant carrying application. As such, it is difficult to extend the previous findings directly to other shear flows.

To infer rheology in a pressure-driven flow we adapt previous work (van der Plas and Golombok, 2015b) modelling the pressure drop as resulting from a flow resistance $R$ composed of rheological factors and a geometric resistance $R_{geo}$ and a function of flow rate $Q$:

$$\Delta P = R_{geo} Q$$  \hspace{1cm} (1)

For Poiseuille flow between parallel plates (present in the rectangular section of the EVROC between pressure transducers $P_1$ and $P_2$) the shear viscosity is related to that obtained in a Couette cell but given as a bulk viscosity $\mu_b$ since a distribution of shear rates are present. For a Newtonian fluid the shear-specific and bulk viscosity are the same. In this case the resistances are therefore given as:

$$R_{\eta} = \mu_b \quad \text{and} \quad R_{geo}|_{1-2} = \frac{12dx}{h^2 w_u}$$  \hspace{1cm} (2)

For the flow inside the contraction, the geometric resistance is not easily defined. The flow resistance is also composed of an additional extensional resistance. Since the uniaxial extension is however constant across the centre-line and the contraction/expansion is symmetric, the contribution of Newtonian extensional viscosity is cancelled out over the hyperbolic section – this was verified experimentally. We can therefore simply use the bulk viscosity $\mu_b$ obtained from Eqs. (1) and (2) and $\Delta P_{1-2}$ to determine the geometric resistance in the extensional zone:

$$R_{geo}|_{2-3} = \frac{\mu_b Q}{\Delta P_{2-3}}$$  \hspace{1cm} (3)

Once this is known, the total flow resistance (composed of both shear and extensional viscosity) can be determined from Eq. (1) for the VES fluids and compared to that for the Newtonian fluids. Note that this approach is purely phenomenological. There is no estimation of extra stress terms. Although pure Darcy flow strictly speaking, only applies to Newtonian fluids, the non-Newtonian application here is nevertheless a pressure difference driven flow and in such circumstances the application of effective viscosities or equivalently, resistance factors, is an accepted way of quantifying these effects (Rojas et al., 2008). This is particularly useful when it comes to application for flow in a model fracture which we now describe.

**Flow cell**

We use an optically clear cell simulating a smooth fracture with a sudden expansion inlet, comparable to a perforation, to investigate the flow behaviour of the SIS fluid. The entrance length required to reach steady flow is compared to Newtonian fluids with the same zero-shear viscosity and hence the rheological state of the incoming fluid can be determined, i.e. we use entrance lengths as a means to infer expected fluid rheology in the near-wellbore. This is then compared to rheology from extensional flow tests described above. In this way flow induced viscoelasticity due to shear of the SIS fluids tested in this paper can be optimised to promote rheological properties that aid proppant carrying capacity.

The flow cell is shown in Fig. 3 below. Wellbore perforations are typically 3–13 mm in diameter (Daneshy, 1973). For this reason we designed cylindrical inlets into the flow cell of 6 mm – comparable to mean perforation sizes. The cell is equipped with three inlets to allow for different experimentation. However for entrance length studies only the central inlet was used. The channel width is 3.4 mm and comparable to average hydraulic fracture widths in the subsurface. Shear rates vary from 40 s$^{-1}$ to 380 s$^{-1}$ (Navarrete et al., 1994) in most hydraulic fracturing treatments, with higher shear rates present at the start of a treatment. (As the fracture widens the pressure drop decreases with shear rate and fluid is lost to the surrounding matrix.) To achieve this shear-rate range a 60 cm $\times$ 20 cm clear glass channel was formed by sandwiching spacers between two Schott Borofloat® glass plates. A stainless steel frame was used to hold the two glass panels and spacers together.

The fluid was circulated through the fracture with a Masterflex L/S Variable Speed Digital Drive pump for 5 flowrates (300, 600,
1200, 1800 & 2400 ml/min). Pulse dampers downstream of the pump outlet eliminated pressure oscillations and ensured a smooth flow. A stirred buffer tank between the pump inlet and fracture outlet was used to maintain particles in suspension.

**Particle image velocimetry (PIV)**

The flow was visualised using particle image velocimetry (PIV) to create a complete profile from the inlet rapid expansion to the outlet. The fluid is seeded with silver coated glass sphere particles that have a density of 1.01 g/cm³, comparable to the fluid (ρf = 1.0 g/cm³) so as not to disturb the flow field. In this way, the trajectories of the particles follow the fluid streamlines. Correlations between the positions of particles from one image to the next allow fluid velocity vectors to be calculated at each point in the flow.

A schematic diagram of the experimental setup is shown in Fig. 4 (view from above).

Four lights were used to illuminate the PIV particles from behind the fracture. Photographs were obtained with a LaVision GmbH high-speed 2 kHz CMOS camera and a 50 mm, f/1.4 Nikon lens. The camera could image 20 cm × 20 cm sections and was placed 65 cm from the fracture. In this way it was possible to measure 3 different zones inside the 60 cm long fracture (inlet, middle and outlet regions) and later combine PIV data. Image post-processing and vector calculation was performed with DaVis software from LaVision.

For each zone across the fracture, 200 images were taken at 50 Hz, providing high resolution images for 4 s of flow. The software determines a vector field for each image pair. At the lowest flow rates, particles moved at the inlet point with a velocity of 180 mm/s giving a per-frame distance of 3.6 mm. This is rapidly reduced to 7 mm/s in the larger fracture and 0.14 mm per-frame distance. The camera was however limited to a lowest rate of 50 Hz. This relatively high frame rate can lead to increased uncertainty particularly at the lowest flowrates.

To ensure that the vectors are aligned and not changing we use a vector calculation to determine at which point fully developed flow is reached. The vector field average is a 32 × 32 uniform grid across the channel zone. Thus, if x is the direction of flow, we consider fully developed flow to be the point at which variations in the y-direction of velocity magnitude and angle are negligible. Therefore to define an entrance length, we impose the following criteria on the average for the vectors for all y-positions at a given x-position. The x-position at which these are met is defined as the entrance length required for fully developed flow to be established.

- The change in the average vector magnitude \( \frac{\Delta v}{v} < 0.0001 \text{s}^{-1} \).
- The change in the average angle \( \frac{\Delta \theta}{\theta} < 0.1 \text{°mm}^{-1} \).

**Materials**

A hydraulic fracturing guideline is that a fluid should have a viscosity of 100 mPa s at a shear rate of 100 s⁻¹ (Armstrong et al., 1995). Since we are interested however in elastic properties as a means to suspend proppant we focus rather on fluids that exhibit high SIS regime growth. From a Couette rheometer screening of VES formulations for application in fracture and porous matrix flow, (Golombok et al., 2008; Vasudevan et al., 2008; van der Plas and Golombok, 2015a) we identified two fluids for application – 30 mM CTAB, 10 mM NaSal (denoted 30/10) and 50 mM CTAB, 14 mM NaSal (denoted 50/14).

For all flow tests, we analysed VES SIS fluids as well as Newtonian fluids with the same viscosity as the Newtonian plateau of the SIS fluids. We also only tested VES fluids that displayed this plateau at low shear rates and that formed SIS, indicated by an increase in apparent viscosity in rheometer tests.

CTAB and NaSal were purchased from Sigma Aldrich. Solutions were prepared by adding CTAB to 51 of water and mixed. During mixing the solution was heated to 30 °C which aids dissolution of CTAB. The solution changes from a cloudy white to clear when all the CTAB has been dissolved. At this point NaSal is added and mixed until the solution again appears uniform and clear. Once mixed, the solution is removed from the heat and left to cool and equilibrate for two days. For viscous Newtonian fluids, glycerol obtained from VWR was mixed with water to obtain the desired viscosity. For PIV the fluid was seeded with 100 μm silver coated glass particles provided by LaVision. These had a density of 1.01 g/cm³.

A table of all solutions (in water) is given below (Table 1) with zero shear viscosity at 22 °C. The 30/10 solution and the Newtonian fluid with the same \( \mu_0 \) are designated pair A and the 50/14 solution and other Newtonian fluid, pair B. The rationale for comparing and contrasting these solutions pairs along with their Newtonian analogues, emerges from the screening using a Couette rheometer which we now discuss.

**Results and discussion**

**Couette cell shear rheology**

Fig. 5 shows the results of the Couette cell experiment. At low shear rates both 30/10 and 50/14 have a constant shear viscosity of 2 mPa s and 4 mPa s respectively. This behaviour is Newtonian and we term this region the “Newtonian plateau”. The higher viscosity for the 50/14 solution is due to the greater concentration of

**Table 1**

Concentrations and rheological properties of fluids used in the experiments. Newtonian and VES fluids are matched based on zero-shear viscosity and designated pairs A and B respectively.

<table>
<thead>
<tr>
<th>Pair</th>
<th>CTAB (mM)</th>
<th>NaSal (mM)</th>
<th>Glycerol (vol-%)</th>
<th>Zero shear viscosity (mPa s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>30</td>
<td>10</td>
<td>-</td>
<td>2.2</td>
</tr>
<tr>
<td>B</td>
<td>50</td>
<td>14</td>
<td>-</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>25</td>
<td>-</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>36</td>
<td>2.2</td>
</tr>
</tbody>
</table>
surfactant and counter-ion in solution. As the critical shear-rate $\gamma_{cr}$ is approached shear induced structures start to form and an increase in observed viscosity is seen. This occurs at $\gamma_{cr} = 50 \, s^{-1}$ for 30/10 and 110 $s^{-1}$ for 50/14. The thickened solution peaks at viscosities of $\mu_{max} = 10 \, mPa \, s$ at $\gamma_{max} = 380 \, s^{-1}$ and $\mu_{max} = 10 \, mPa \, s$ at $\gamma_{max} = 320 \, s^{-1}$ for 30/10 and 50/14 respectively. At higher shear rates up to 3000 $s^{-1}$ both solutions thin rapidly as micelle networks breakdown. Couette testing at even higher shear rates was not possible due to the solutions foaming. The relative viscosity increase from zero shear viscosity to maximum viscosity is defined as the viscosity contrast ratio:

$$R_{VC} = \frac{\mu_{max}}{\mu_0}$$

For 30/10, $R_{VC} = 4.3$ and for 50/14, $R_{VC} = 2.7$. 30/10 has a higher viscosity contrast ratio; this means that it forms a more extensive shear induced structure network relative to its relaxed state than does 50/14.

The viscosity of the Newtonian glycerol solutions is shown in the same Fig. 5. These were formulated to match the pre- viscoelastic shear rate viscosity values of the VES solutions.

**Extensional effects**

Our aim is to assess a possible extra fluid carrying capacity factor which arises during developing flow in an expansion comparable to that from a perforation to a fracture. Although the EVROC is a microfluidic device, measuring pressure drops due to extensional flow in a 0.19 mm x 0.4 mm contraction (compared to 6 mm diameter perforation), the aim is to compare Newtonian and non-Newtonian flow under extensional flow. The small length scales in the microfluidic device are suitable to accurately measure the difference between shear and extensional flow resistance. This is because low flow in the straight channel ensures low Reynolds numbers but at the same time high deformation in the hyperbolic section. In a larger channel, the pressure drop would have to be higher to generate flow and as a result the range of shear rates would not be realistic.

For each fluid, the pressure at the four transducers of the EVROC was measured for 18 flowrates between 100 $\mu l/min$ and 4 ml/min. The $\Delta P$ data across the cell was analysed using the method described in Section “Extensional cell” above. As expected, in the rectangular section, the glycerol solutions have the same viscosities as those obtained in the Couette cell. These are used to determine the geometric resistance in the extensional section. Using Eq. (3) we get $R_{geo_{1-3}} = 8 \times 10^{12} \, m^{-3}$. From this geometric resistance factor, we calculate flow resistances for the VES fluids during extensional flow with Eq. (1). To assess the relative effect of SIS fluids compared to its Newtonian equivalent we calculated the ratio of flow resistances for each glycerol-SIS fluid pair. This is defined as the dimensionless extensional fluid flow resistance ratio $R_{ef}:

$$R_{ef} = \frac{R_{fl_{VES}}}{R_{fl_{NEW}}}$$

where the subscripts NEW and VES refer to the Newtonian glycerol and viscoelastic surfactant solutions respectively. In this way we can determine the extra extensional effects due to VES fluids.

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**Fig. 5.** Steady shear–viscosity measurements for Newtonian (open markers) and VES (closed markers) fluids. At low shear rate all fluids have Newtonian behaviour. At higher shear rates VES fluids for SIS exhibit shear-thickening.

**Fig. 6.** Extensional fluid flow resistance ratio for fluid pairs A and B versus flowrate through EVROC cell.
Fig. 6 shows the flowrate in the EVROC cell versus elastic fluid flow resistance \( R_{\text{el}} \). For both fluid pairs (A and B) the elastic resistance ratio is greater than 1. This reveals the added resistance due to extensional strain. The elastic resistance ratios are also highest at low flow rates and reduce to unity at the highest flow rates. This is because the elastic network for SIS fluids is only present in a discrete shear regime and broken down at higher flow rates. The ratio decreasing to unity shows that the micellar network breaks down to its Newtonian plateau viscosity.

A notable trend is that the elastic resistance ratio for 30/10 is always higher than for 50/14. We propose that this is due to the higher viscosity contrast ratio discussed above. The 30/10 solution has a higher \( R_{\text{el}} \) because of its higher viscosity increase and SIS formation shown in the Couette cell tests compared to its relaxed state (viscosity contrast ratio, \( R_{\text{VC}} = 3.5 \) for 30/10 vs. \( R_{\text{VC}} = 2.7 \) for 50/14). The difference between these two fluids shows the importance of viscosity contrast ratios for exploiting the SIS behaviour of VES fluids. In perforation-fracture flow we expect the induced elasticity due to SIS formation to be present and aid proppant suspension but to optimise this we must consider viscosity contrast ratios given by Eq. (4).

**Rapid expansion rheology**

EVROC results support the presence of an induced viscoelastic network for the VES fluids undergoing extensional flow. This rheological effect is now applied to flow behaviour of a transitional entrance effect based on perforation to fracture flow in a well bore. We compare the visual flow profiles from the VES fluids with their Newtonian plateau viscosity (\( \mu_0 \)) equivalents and see how this relates to findings from the Couette and extensional tests. We investigated the velocity profiles in the fracture for all fluids in Table 1. The entrance length is determined from the analysis method described in Section “Particle image velocimetry” and is shown versus fluid average velocity in Fig. 7.

For the Newtonian fluids (open shapes in the figure), the glycerol-25% has a higher entrance length compared to glycerol-36%. This is expected because for the same flowrate, the glycerol-25% has a lower viscosity which results in a higher Reynolds number – entrance length is proportional to Reynolds number (Oliveira and Pinho, 1997). The entrance length for a sudden expansion is often defined as the size of the recirculation zones which is linearly proportional to Reynolds number. In this study however it is determined by the vector calculation in Section “Particle image velocimetry” i.e. when variations in the flow field perpendicular to the flow are negligible. PIV showed this criterion yielded an entrance length significantly larger than the recirculation zones.

For the VES fluids (also shown on Fig. 7), at the lowest velocities, the differences in entrance lengths for the VES fluid and the Newtonian match are not significant. As flowrate is increased the VES and Newtonian entrance lengths diverge and the difference increases with increasing velocity. The shorter entrance length for VES is due to SIS formation at higher velocity – viscoelasticity is induced and increases flow resistance as the shear rate is increased. This has positive implications for fracture flow where in most cases, shear thinning fluids are used which exhibit reduced carrying capacity with increased shear (Bazilevskii et al., 2010).

We then compared the entrance length with inlet Reynolds numbers for the four fluids (Reynolds number in the perforation tube where the inlet diameter 6 mm is the dimensional component). In Fig. 8a we use the Newtonian plateau shear viscosity of the VES fluids to calculate \( R_{\text{el}} \).

At low Reynolds number the entrance length is comparable for all. At Reynolds numbers above \( R = 50 \) the data for the Newtonian fluids are coincident but diverge from the SIS fluids. The reduced entrance length for VES fluids compared to Newtonian fluids is less than would otherwise be expected for the Newtonian plateau viscosity. This indicates the damping effect of SIS that gives rise to flow-induced viscoelasticity. The entrance length versus Reynolds number shown above does not have a linear relationship for the Newtonian fluids. This is because it is defined as fully-developed, non-varying flow rather than recirculation zone size. Next, we compute the Reynolds number for SIS based on the peak shear–viscosity \( \mu_{\text{max}} \) from the rheometer measurements \( R_{\text{el}} \). This is shown in Fig. 8b. In this case the curves are all coincident suggesting that the effective viscosity due to SIS formation is responsible for the damping and that for this geometry the VES fluids are most likely in the SIS state.

To analyse the extent of entrance length reduction due to SIS formation compared to Newtonian fluids we use a dimensionless reduction ratio \( A \). This is given as the ratio of entrance lengths. The minor differences in zero-shear viscosity between the glycerol and VES fluid are eliminated by normalizing the entrance lengths to Reynolds number calculated with zero-shear viscosity.
Fig. 9. Entrance length reductions ratio $\Lambda$ versus average velocity in fracture flow cell for each fluid pair A and B.

$$\Lambda = \frac{L_{\text{NEW}}}{L_{\text{VES}}} \times \frac{Re_{\text{VES}}}{Re_{\text{NEW}}}$$  (6)

Fig. 9 shows the reduction ratio $\Lambda$ versus inlet velocity for each fluid pair (A and B).

$\Lambda$ is 1 or greater for all velocities. This shows that the VES fluids always have an entrance length less than that of comparable Newtonian fluids. In addition, the reduction in length for 30/10 is always greater than for 50/14. As discussed previously this is due to the difference in the viscosity contrast ratio, where the relative SIS formation of 30/10 is greater than 50/14. Furthermore, the reduction ratio increases for both fluids with increasing inlet velocity until it reaches a maximum. This is probably due to the shear rate that is not high enough to form extensive SIS at lower inlet velocities (at the lowest velocity, Newtonian fluids have wall shear rates of 60 s$^{-1}$ and 15 s$^{-1}$ in the perforation and fracture cell respectively compared to >50 s$^{-1}$ required to form SIS in a rheometer). At higher velocities shear induced structures form and their presence leads to viscoelasticity and entrance length reduction.

For a hydraulic fracture, in the near well-bore region, VES fluids that develop flow-induced viscoelasticity (FIVE) have a shear–viscosity profile that is suitable for hydraulic fracturing applications. Compared to Newtonian solutions there is an increase in apparent viscosity in the discrete shear regime associated with proppant flow during placement in a fracturing treatment.

2. Extensional strain tests in a hyperbolic contraction/expansion cell show that VES fluids have a significant extensional component that increases flow resistance compared to Newtonian fluids. This increase in flow resistance due to elasticity is suitable for increased proppant carrying capacity of a fluid entering a fracture through a perforation. This will help to avoid premature blocking of the fracture in the near-wellbore region.

3. The flow profiles of VES fluids show the nature of this induced elasticity due to the extensional stress. The elasticity of the fluid results in a damping of the developing flow to reach fully developed flow in a shorter distance. This indicates the presence of elasticity not only in the extensional section but also in the open fracture.

4. When comparing two VES fluids, we have shown that the viscosity contrast ratio is important in determining the degree to which these effects occur. A higher viscosity contrast ratio results in greater elastic effects compared to a Newtonian fluid. This is independent of the actual composition of the fluid whereby a 30/10 solution has a higher viscosity contrast ratio than 50/14 and thus produces a more pronounced non-Newtonian effect.

Acknowledgements

A special thanks to Boaz van der Plas for helpful discussions and insights and for his development of the method used for contraction–expansion flow analysis. This work was funded by Shell Global Solutions International B.V.

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