Chemical Engineering Science 148 (2016) 219–228

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

# Self-regulating solutions for proppant transport

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## HIGHLIGHTS

- VES fluids are tested for a flow-regulated viscosifier- and breaker-free system.
- The fluid is Newtonian at low flowrates and viscoelastic at high flowrates.
- Proppant is suspended in the viscoelastic regime above a critical flowrate.
- Viscoelastic behavior disappears upon the secession of high shear rates.
- The fluid is low viscosity and Newtonian during flow through a proppant pack.

ARTICLE INFO

*Article history:*
Received 19 January 2016
Received in revised form
30 March 2016
Accepted 2 April 2016
Available online 4 April 2016

*keywords:*
Fracturing fluid
Viscoelastic surfactant
Shear-induced structures
Fracture flow
Particle tracking velocimetry
Proppant conductivity

ABSTRACT

Fluids displaying flow induced viscoelasticity are tested for proppant placement and flow back. The viscosity is self-regulating and obviates the need for viscosifiers and breakers. The flow induced viscoelasticity degrades at higher flow rates enabling good injectivity. Particle tracking velocimetry is performed to study the influence of flow rate on the particle settling under different flow regimes. These tests show that above a critical flow rate particles are maintained in suspension and settle with a constant velocity giving the fluid an apparent viscosity up to 200 mPa s compared to a zero-shear viscosity of 2 mPa s. During flowback in porous proppant packs the fluid has a low flow resistance with a viscosity comparable to its zero-sheared state. Pack permeability is retained after flowback of the fluid thereby resulting in optimum fracture clean-up.



## 1. Introduction

Placement of proppant particles in hydraulically fractured reservoirs requires that the fluid used to transport proppant displays two apparently incompatible properties:

- High carrying capacity for the placement phase of proppants.
- Low carrying (or at least low proppant displacement) capacity during the succeeding flowback phase so that the proppant pack remains intact.

The change in properties is usually achieved by the use of acids or enzymes to break down the molecular cross-linking which has increased the carrying capacity in order to assist placement (Kefi et al., 2004; Montgomery, 2013). The different properties for the two stages – placement and flowback – are thus achieved using somewhat severe chemical modifications both in cross-linking following injection and subsequent viscosity breaking after placement. This has been a factor in the controversy around fracturing technology in general (King, 2012).

In this work we look at an alternative way of generating these desired rheological characteristics. The property of “carrying capacity” is usually identified with the fluid viscosity (Montgomery, 2013) although it is increasingly accepted that fluid elasticity also contributes significantly to the ability to carry proppant (Hu et al., 2015). As such, viscoelastic fluids are currently the state-of-the-art with regards to fracturing fluids for proppant placement (Barati and Liang, 2014) although in the current form these still require viscosity breaking chemicals as outlined above (Omeiza and Samsuri, 2014). In this paper we investigate a fluid that exhibits flow-induced viscoelasticity. The fluid has low viscosity at low pressure drops with no elastic behaviour. However at higher flow rates, shear-induced structures are formed which give rise to highly viscoelastic properties with correspondingly higher fluid resistance at these higher flow rates (van der Plas and Golombok,

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http://dx.doi.org/10.1016/j.ces.2016.04.008
0009-2509/

**Symbols**

*Latin*

| | |
|---|---|
| $g$ | gravity |
| $G'$ | elastic modulus |
| $G''$ | viscous modulus |
| $h$ | height |
| $k$ | conductivity |
| $P$ | pressure |
| $Q$ | flow rate |
| $R$ | particle radius |
| $t$ | time |
| $Ta$ | Taylor number |
| $u$ | fluid velocity |
| $v$ | particle velocity |
| $w$ | width |
| $x$ | $x$-distance |

*Greek*

| | |
|---|---|
| $\dot{\gamma}$ | shear rate |
| $\Lambda$ | relative particle settling velocity |
| $\mu$ | viscosity |
| $\rho$ | density |
| $\kappa$ | permeability |
| $\gamma$ | strain |
| $\tau$ | stress |
| $\omega$ | frequency |

*Subscripts*

| | |
|---|---|
| 0 | zero shear |
| $cr$ | critical |
| $f$ | fluid |
| $fr$ | fracture |
| max | maximum |
| $p$ | particle |
| $pr$ | propped zone |
| $s$ | settling |
| $t$ | terminal |
| $w$ | wall |

*Acronyms*

| | |
|---|---|
| CTAB | Cetyltrimethylammonium bromide |
| NaSal | Sodium salicylate |
| SIS | shear-induced structures |

2015a, 2015b; van Santvoort and Golombok, 2015a, 2015b). At very high flow rates associated with wellbore flow, the viscoelastic properties degrade (see below).

The questions studied are: (1) Can flow-induced viscoelastic effects regulate proppant suspension at different flow rates? (2) Are these effects absent during low-shear flowback operations in a proppant pack? (3) Does this fluid system obviate the need for viscosifiers and breakers? Section 2 outlines the background physical and chemical properties. Optical tracking of proppant particles in a simulated glass fracture and flowback in a porous conductivity cell are described in Section 3. The results are discussed and analysed in Section 4 with a comparison to shear and oscillatory rheometry tests.

## 2. Background

Hydraulic fracturing is the process used to improve production from “unconventional” tight and shale gas reservoirs where natural permeability ranges from 1 to 1000 μD and 1 to 1000 nD respectively, compared to $>1$ mD for “conventional” carbonate and sandstone reservoirs (King, 2012). The process creates fractures that increase the well's contact area to the reservoir and provides highly permeable flow paths on the order of Darcies. The process consists of three stages:

1. The “pad” – Proppant-free fluids are injected into the matrix via the wellbore at high pressure and volumes. When the minimum horizontal normal stresses in the rock are overcome, cracks extend into fractures which can be up to 300 m long and range from 1–10 mm in width (Yu and Sepehrnoori, 2013).
2. Proppant placement – To keep fractures open, sand called proppant is packed into the fracture, transported by gelled fluids.
3. Closure and flowback – Once the fracture is filled, the pressure is let down and the fracture partially closes on the proppant. Closure stress often ranges from 2000–12000 psi (140–830 bar) depending on the formation (Palisch et al., 2007). Fluid is recovered to the surface leaving a propped fracture into which gas can diffuse from the matrix and then flow to the wellbore.

In this background section we briefly review the benchmark current standard, present the new materials, review particle settling and viscoelastic fluids and conclude with a review of their application in porous media.

### 2.1. Traditional fracturing fluids

During the proppant placement stage, a proppant-laden slurry is pumped into the fracture. Proppant particles are often composed of silica or ceramic and have densities comparable to sand ($\sim$2.5 g/cm$^3$). The size range is 0.2–2 mm in diameter (Coker and Mack, 2013). To maintain heavy particles in suspension while pumping, a fluid with a high carrying capacity is required. In the flowback stage when fluid is recovered to the surface, low flow resistance is required so as not to carry back proppant (Brown et al., 2000).

Traditional fracturing fluids are produced from guar gum. As such they are polymeric, have high viscosity at low shear rate and are shear thinning (Kapoor et al., 2013; Kesavan and Prud'homme, 1992). To achieve the gel-like viscoelasticity associated with high carrying capacity, borate ions are used to cross-link guar polymers (Kefi et al., 2004). In addition, the stability of cross-linked guar is highly pH dependent and such fluids require buffers to prevent gel-degradation and the formation of insoluble material (Kesavan and Prud'homme, 1992). To break viscoelasticity during flowback, time-delayed acids or enzymes are employed (Montgomery, 2013). While this aids flowback, it often results in the formation of residue that remains within the proppant pack, reducing conductivity. Failure to completely break the fluid, particularly near the fracture tip, results in proppant being back-produced and loss of propped fracture length (Barati and Liang, 2014).

Guar gum remains the most widely used fracturing fluid, although alternatives are being developed and deployed. Slick-water