Rheological Behavior of a Novel Switchable Surfactant in High Salinity Carbonate Reservoirs

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ABSTRACT

Core flood and glass bead experiments were carried out to characterize the rheology of a viscoelastic surfactant solution in porous media with respect to the shear rate. To compare the apparent viscosity with the measured bulk viscosity, a relationship between apparent shear rate inside the core and fluid injection rate was used. Compared to the bulk viscosity resembling shear thinning behavior, the apparent viscosity in porous media displays a shear thickening response and deviates significantly from the bulk viscosity at higher shear rates. Experiments consist of solutions comprised of 0.5 wt%. Duomeen TTM (DTTM), a cationic surfactant, and 20 wt%. NaCl. At this state, the surfactant's viscoelastic properties resemble that of flexible polymer. Discussion will generalize the potential reasons for this rheological shift amongst polymer and viscoelastic surfactant solutions.

Keywords: viscoelastic, surfactant, porous media, rheology

1 INTRODUCTION

The use of viscoelastic (VES) or polymer-like surfactant solutions are important in applications related to enhanced oil recovery and subsurface conformance control. VES resembles polymer where it acts as a mobility control agent to promote a better sweep efficiency by increasing the waterflood's viscosity [1]. However unlike polymer, VES is able to sustain viscoelasticity when encounter with high saline, high temperature reservoirs [2]. In particular, viscoelastic properties of the surfactant solution are triggered and fine-tuned by changes in different physical factors such as salinity, surfactant concentration, pH, and temperature of the solution [3]. These characteristic can be decoupled systematically using a rheometer for sensitivity analysis. In all, the objective of this study is to determine if the bulk rheology data can predict the rheological behavior in porous media.

This study was conducted to mathematically express the correlation between bulk viscosity and apparent viscosity in porous media (limestone core and glass beads) for a novel switchable surfactant. A packed bed of glass beads provides the most idealized case where the permeability and tortuosity can be set and flow can be visually seen, while flow through the limestone core is more difficult to analyze because of the lack of visibility and uncertainty of the exact nature of the media [4]. Steady state shear rate in porous media was derived from the injection rate, porosity, and permeability to compare bulk and apparent rheology sets at the same shear rates.

The rheological behavior of the bulk and the core flood for a 0.5% wt. DTTM and 20% wt. NaCl solution was found to be contradicting of one another. Bulk rheology data resembles shear thinning behavior while apparent viscosity in the porous media show a thickening response with increasing shear rate. This thickening phenomenon due to large pressure drops at high injection rates could be attributed to permeability reduction, extensional flow, tortuosity, plugging and surfactant retention in the carbonate rock [1]. The observed non-Newtonian rheology of this particular VES at high salinity is similar to that of some polymeric solutions at low salinities for subsurface applications. These findings suggest that porous media applies complexity to rheological behavior, which requires methodical evaluation to define the underlying effects that alter the viscoelastic properties.

2 METHODOLOGY

2.1 Glass Beads Setup

This setup, shown in Figure 1, comprises of two accumulators that supply brine (20 wt% NaCl) or surfactant solution (0.5 wt% DTTM, 20 wt% NaCl) to the glass column. The porous media was flushed with brine to characterize the pore volume, porosity and permeability of the column. Mass differences between the bulk versus saturated column defined pore volume and porosity was calculated using the ratio of pore volume to bulk volume. In addition, monitoring the differential pressure drop when the flow rate of the brine varies measures permeability of the porous media. A fraction collector deposits the effluent. Table 1 displays pore volume, porosity and permeability values for the glass beads setup.

Chauveteau and Zaitoun et al. formulated shear rate relationships for glass beads assuming the porous media has similar pore shapes [5]. The equations listed below were used for this study to characterize the apparent shear rate as a function of pore radius and flow rate.

$$r = \left(\frac{8k}{\phi}\right)^2 \quad (1)$$

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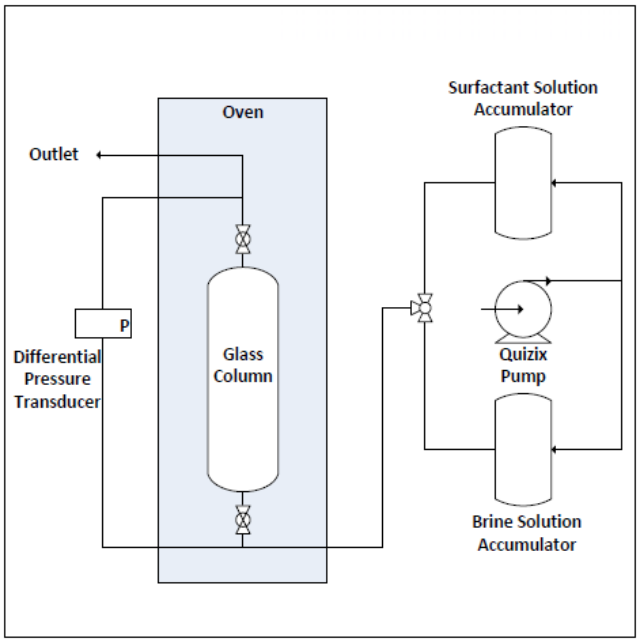

Figure 1: Glass bead setup for viscosity analysis. Glass Column dimensions: W = 2.54 cm, D = 30 cm

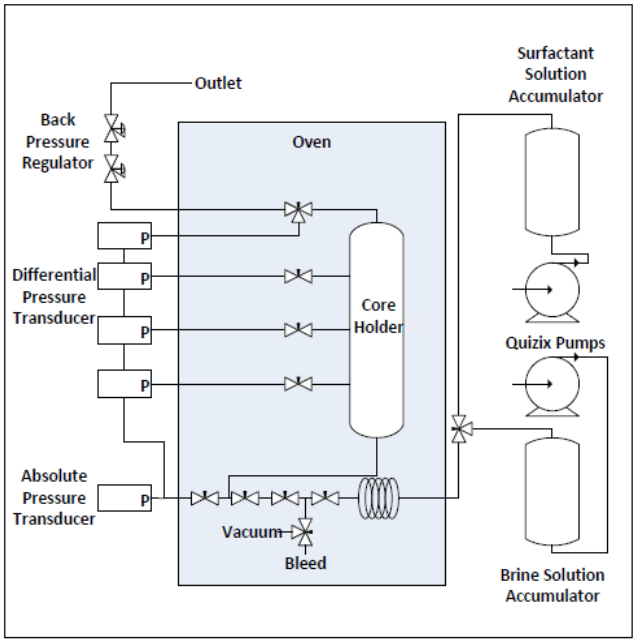

Figure 2: Limestone core setup for viscosity analysis. Core Holder dimensions: W = 2.5 cm, D = 29.2 cm

Parameter	Value	Units
Pore Volume	58	cm^3
Porosity	38	%
Permeability	1.1 x 10^{-7}	cm^2

Table 1: Intrinsic properties for glass bead setup. Values assumed to remain unchanged during the experiment.

Parameter	Value	Units
Pore Volume	52	cm^3
Porosity	36	%
Core Permeability	8.3 x 10^{-10}	cm^2

Table 2: Intrinsic properties for core flood setup. Values assumed to remain unchanged during the experiment.

$$\dot{\gamma}_{app} = \frac{4\alpha v}{r} \quad (2)$$

where k is permeability (cm^2), Φ is porosity (%), r is the average hydrodynamic pore radius in homogeneous unconsolidated porous media (cm), v is superficial velocity (cm/s) and α is equal to 1.7 for large spheres having the same diameter.

2.2 Limestone Core Setup

Illustrated in Figure 2, the core setup uses two pumps to transfer the brine and surfactant solution to the core. Pressure taps within the core holder provide pressure readings from the influent, intermediate and effluent regions of the limestone core. Pore volume is calculated by the difference of total volume injected to total volume produced. Porosity and permeability measurements were equated the same as in section 2.1. These results are displayed in Table 2.

The main objective of this core flood is to study the shear rate dependence of the apparent viscosity in porous media in a non-ideal and less predictable environment.

The relationship between the injection rate and apparent shear rate is given below.

$$\dot{\gamma}_{app} = \alpha \frac{4Q}{A\sqrt{8K\phi}} \quad (3)$$

$$\alpha = \frac{3n+1}{4n} \quad (4)$$

where Q is flow rate (cm^3/s), A is cross sectional area of the core (cm^2), K is permeability (cm^2), Φ is porosity (%), and α is a coefficient in which n is flow behavior index of the bulk solution.

3 RESULTS AND DISCUSSION

This section comprises of bulk and apparent viscosity results followed by discussion of mechanisms of the shear thickening response for surfactant floods that may impart the trends defined in our results.

3.1 Bulk Rheology

Bulk measurements were conducted using a rheometer and will be compared to glass beads and core flood viscosity results. Figure 3 displays the viscosity behavior of the surfactant solution at steady-state shear rate. It can be seen the viscosity profile resembles shear thinning, which is a representative behavior of viscoelastic surfactant solutions. A power law trendline exhibited on the chart will be used for future analysis.

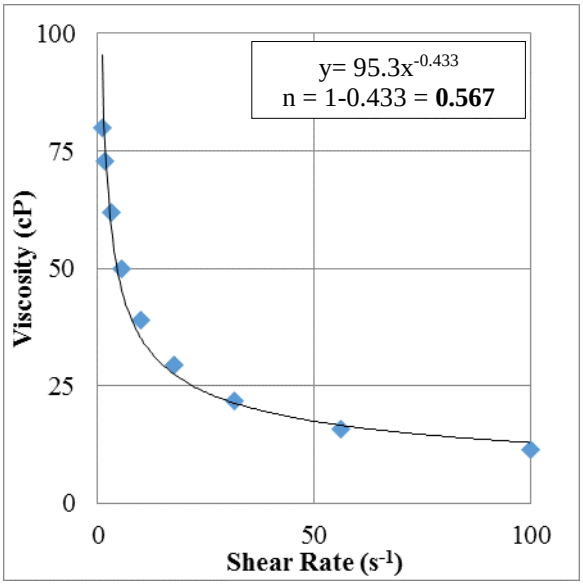

Figure 3: Bulk viscosity measurements at 0.5 wt%. Duomeen TTM and 20 wt%. NaCl.

3.2 Glass Beads

Shear rates going from 9 to 1 s^{-1} with corresponding flow rates ranging 0.61 to 0.07 cm^3/min were applied to analyze the pressure drop amongst the inlet and outlet of the glass bead column. The short range in shear rates is due to the pressure limitations of the glass column (maximum pressure assumed 50 psi). Even though the final pressure drop at 9 s^{-1} was around 25 psid, at higher shear rates the differential pressure will overshoot and slowly decline to equilibrium. This overshot can be 20 psid higher than the equilibrated pressure differential.

Shown in Figure 4, the apparent viscosity displays shear thickening aspects unlike the bulk viscosity clearly exhibiting thinning behavior. At low shear, the viscosity trends converge due to low pressure differentials. It can be said that pressure is the principal factor dominating the empirical shear rate equation causing the shear thickening phenomenon.

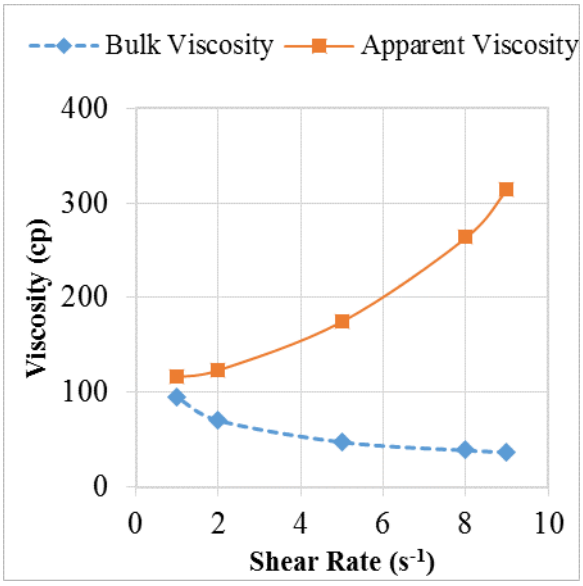

Figure 4: Glass Beads: comparison of apparent and bulk viscosity in porous media. Shear thickening is observed for apparent viscosity.

3.3 Limestone Core

The same methodology was applied as the glass beads experiment, but the shear rates range from 33 to 4.75 s^{-1} with flow rates of 0.10 to 0.01 cm^3/min, respectively. As seen in Figure 5, similar trend with a different magnitude was observed with apparent viscosity shear thickening throughout the core.

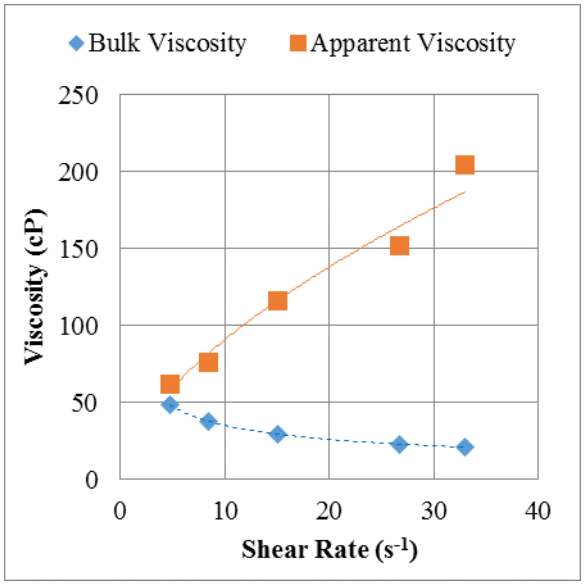

Figure 5: Limestone Core: comparison of apparent and bulk viscosity in porous media. Shear thickening is observed for apparent viscosity.

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3.4 Discussion

According to Savins (1969), there are several claimed mechanisms to explain the shear thickening behavior observed in porous media and shear thinning response in a viscometric flow device for micellar or polymer viscoelastic solutions. These include: temporary network formations of the viscoelastic solute, bridging, chain unwinding and intensification of intermolecular interactions, tortuosity of the path, extensional flow, elastic flow, pore blocking, adsorption, and plugging. In addition, at dilute to moderate concentrated solutions, flow destabilization and departure from laminar flow causes abnormal pressure differentials producing the shear thickening response [6].

Moreover, shear viscosity dominates at low shear rates while elongation viscosity is the principal factor at higher shear rates. The elastic portion of the viscoelastic surfactant is controlled by the relaxation time of the surfactant solution. If the relaxation time is comparable or larger than the transit time, the elastic effects become more significant. However, for this solution, the relaxation time is less than a minute (Figure 6) while the transit time can span hours, so the solution has the time to readjust to the changing flow conditions in porous media [6][7].

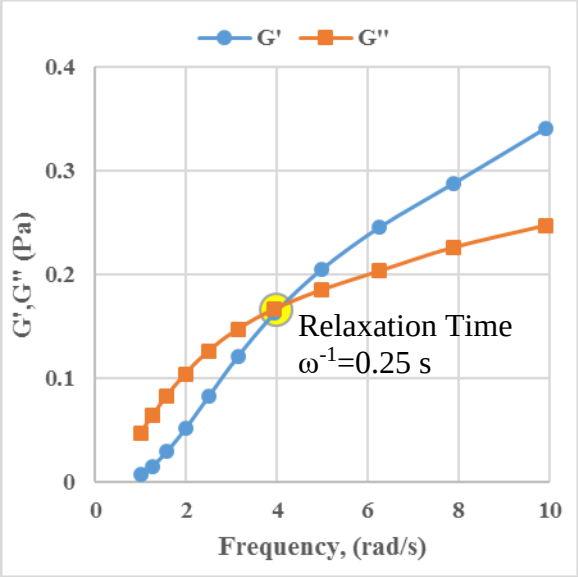

Figure 6: Frequency data for 0.5 wt%. DTTM amd 20 wt%. NaCl. The inverse frequency at the crossover of G' and G" defines the relaxation time of the solution.

Furthermore for both cases, plugging can cause shear thickening in porous media as a function of tortuosity of the pathways and molecular weight of the micellar structures [8]. Also, in the limestone core, surfactant adsorption can add to the shear thickening response due to the micelles being retained within the pore structure therefore lowering permeability of the core, but this mechanism should not pertain to the glass beads case.

4 CONCLUSION

A novel switchable surfactant was studied that displayed shear-dependent thickening behavior through porous media and exhibited shear thinning flow using a rheometer. While many mechanisms have been documented throughout the years, the exact reasons explaining these results are speculated from previous claims. Further investigation is warranted in determining the principal effects of the shear thickening response in porous media to better characterize how viscoelastic micellar solutions will engage in subsurface processes prone to changes in shear rates and heterogeneity.

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