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Flow induced viscoelasticity in fractures

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ABSTRACT

The behaviour of viscoelastic surfactant solutions under pressure driven flow in fractures is studied with particle image velocimetry. We demonstrate that flow is selectively retarded in larger conduits and we zoom in to smaller scales in order to distinguish local flow resistance effects. At low velocities in the conduit, the viscosity is low and relatively constant giving a quasi Hagen-Poiseuille profile. At higher velocities, enhanced aperture size dependent viscosities are obtained. The different flow characteristics enable size selective retardation. This can be attributed to shear rates in larger fractures which extend into the viscoelastic enhancement regime associated with shear induced structures.

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1. Introduction

Fractures in oil reservoirs are a major source of fluid loss. Injected water displaces oil from the porous matrix. However fractures in the reservoir have a lower resistance and divert the injected water. As a result, oil is not displaced from the porous matrix [1,13]. Small amounts of flow induced viscoelasticity (FIVE) additives can greatly boost water viscosity for a specific range of shear rates [4–6,11]. Such additives improve the profile conformance and increase recovery [7–9,15]. However it is unclear how the additive solutions behave in different situations such as in different sized fractures. Although the average flow in conduits has been studied [14,15] the changes from Poiseuille profile when these FIVE additives are used, is unknown.

This study investigates these flow induced viscoelasticity (FIVE) additives in water under fracture/conduit flow conditions. Besides pressure – flow experiments, particle image velocimetry (PIV) experiments are performed in glass rectangular channels to investigate fluid velocity profiles. The focus is on channel apertures at pressure gradients similar to those used during injection into hydrocarbon or geothermal reservoirs. Section 2 summarizes the problem of applying standard rheological methods to predicting performance of the novel non-power law, non-Newtonian, non-polymer and non-monotonic materials with which we are concerned. In Section 3 we describe the experimental set-ups and the results follow in Section 4.

2. Background

Newtonian fluid flow (such as water) through a fracture can be described by the Darcy equation [2]

$$u = \frac{\kappa}{\mu}\frac{\Delta p}{L} \tag{1}$$

with the average velocity (u), the permeability (κ), the viscosity (μ) and the pressure drop gradient ($\Delta p/L$). The microscopic analogue is the flow through a rectangular duct. If the height (H) of the duct is much larger than the width ($H \gg W$) then this duct flow yields a Poiseuille profile

$$v(y) = \frac{1}{2\mu}\frac{\Delta p}{L}\left(y^2 - \frac{W^2}{4}\right) \tag{2}$$

where y is the dimension across the conduit. The corresponding derived shear rate is given by

$$\dot{\gamma} = \frac{1}{\mu}\frac{\Delta p}{L}w \tag{3}$$

An average velocity from the parabolic velocity profile of Eq. (2) gives the Darcy equation (Eq. (1)) with $\kappa = W^2/12$ [19].

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Symbols

h	fracture height
L	fracture length
p	pressure
Q	fluid flow
R	resistance factor
u	average velocity
v	velocity
y	fracture width
W	parameter of the fracture width (i.e. smallest wall to wall distance)
$y*$	non-dimensionalised width

Greek

$\dot{\gamma}$	shear rate
κ	permeability
μ	shear viscosity from rheometer

Subscripts

app	apparent
c	critical
max	maximum
l	large
s	small
w	wall

Abbreviations

FIVE	flow induced viscoelasticity
PIV	particle image velocimetry
RF	retardation factor
SIS	shear induced structure
SRF	size selective retardation
VES	viscoelastic surfactant
VR	velocity retardation

For Newtonian fluids, Couette rheometer data gives enough information to predict how the fluids behave in the subsurface. This is not the case for non-Newtonian fluids which are used to improve oil recovery [5,13]. The classical categories are shear thinners and thickeners. These show respectively monotonically decreasing and increasing responses to shear strain rate and are often assumed to follow a power law response. Such monotonic response materials have been shown [15,16] to be insufficient for application in oil reservoirs. What is required is a material which shows shear thickening over a limited range of shear response and shear thinning at high shear rates. This will correspondingly give selective retardation of flow in larger fractures while allowing the fluid to flow unimpeded in the well bore.

There has been some previous use of viscoelastic fluids in the petroleum world – these are normally shear thinning polymer solutions such as cross linked guar gum, polyacrylamides or polyethylene oxides, which have limited utility for our purposes given the restrictions outlined above. However in this study we concentrate on a relatively new category of solutions which display induced viscosity when subjected to pressure driven flow. We refer to them as flow induced viscoelasticity (FIVE) solutions to differentiate them from previously applied viscoelastic surfactant (VES) materials with the usual description of the latter as displaying "shear induced structures" (SIS). This last designation is more applicable when they are subject to a single well defined shear as in a Couette cell where the viscosity of these fluids depends on a single applied shear rate. Corresponding to the shear induced structures, in pressure drive flow we have flow induced structures: FIVE materials slow down the flow more in large fractures than in smaller ones [14]. How different are the profiles from the Newtonian ones? This is the subject of this paper.

Yamamoto et al. [20] measured the velocity profile of viscoelastic gel materials with particle tracking velocimetry in capillaries and showed a plug like velocity profile. Hashimoto et al. [12] did pressure drop flow experiments and velocity profile measurements in capillaries with small angle light scattering for similar gelling strength materials considerably higher in concentration and viscosity than applicable for oil recovery. Such oil recovery effects require materials which are almost water like under some shear conditions, whereas these other studies all worked in high viscosity response regimes for all flow conditions.

Britton and Callaghan [3] did nuclear magnetic resonance (NMR) velocimetry experiments for high viscosity viscoelastic gels in pipes. They found a transition from Newtonian to "spurt" flow once the shear rate at the wall exceeded the critical shear rate value (around 1 s^{-1}). Above the critical shear rate, a layer of high shear rate was always at the wall although it was unclear if equilibrium had been attained. All of these above studies used high (>25 mM) VES concentrations well outside the regime applicable for oil recovery. These solutions do not show non-monotonic behaviour in a Couette cell measurement.

In our research we focus on FIVE material concentrations with a substantial non-monotonic shear rate viscosity response in a Couette cell. This means a peak viscosity at least twice that of the low and high shear rate values on either side of the viscosity peak (see below). These enable the desired selective retardation effects in high permeable "thief zone" regions such as fracture corridors in porous matrix. In previous work [14] velocity retardation has been shown to depend on pressure drop. The fluid resistance was indirectly measured and found to be higher in a 0.6 mm capillary compared to a 0.25 mm capillary. Other work [15] also shows retardation in smooth conduits.

3. Experimental

3.1. Couette cell

An Anton Paar MCR 302 double gap rotational cylinder rheometer is used to characterize the shear-viscosity response of the FIVE fluids. The fluid is held between a rotating bob and a stationary cup. The temperature of the measurement is held constant by a Peltier system and an external flow of warm water from a heating bath. The shear induced structures have finite formation and relaxation times on application and removal of shear respectively. In this study we use the equilibrium steady state values, i.e. we pre-shear for each shear strain measurement point until a constant viscosity is reached [15]. Prior to each measurement, the fluids are pre-sheared at the same shear rate as the subsequent measurement itself. The time for this equilibration typically varies between 1 and 5 min depending on the shear rate.

3.2. Slit rheometer

To obtain bulk properties of the FIVE fluid in different geometries, flow through and pressure drop over a conduit are recorded. A schematic overview of the experimental setup is given in Fig. 1. The injection fluid in the intake container (1) is pumped by a

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