Journal of Petroleum Science and Engineering 94–95 (2012) 79–88

Contents lists available at SciVerse ScienceDirect

Journal of Petroleum Science and Engineering

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

CFD modeling of the effect of polymer elasticity on residual oil saturation at the pore-scale

Ali Afsharpoor [a], Matthew T. Balhoff [a,*], Roger Bonnecaze [b,1], Chun Huh [a]

[a] Petroleum and Geosystems Engineering, The University of Texas at Austin, 1 University Station C0300 Austin, TX 78712-0228, USA
[b] Department of Chemical Engineering, The University of Texas at Austin, 1 University Station C0400 Austin, TX 78712-0231, USA

ARTICLE INFO

Article history:
Received 28 December 2011
Accepted 14 June 2012
Available online 26 June 2012

Keywords:
Viscoelastic flow
Residual oil saturation
Normal forces
Pore-scale model
CFD modeling

ABSTRACT

Polymers are used in enhanced oil recovery (EOR) to increase sweep efficiency, but recent experimental and field data suggest that viscoelastic polymers such as hydrolyzed polyacrylamide (HPAM) reduce residual oil saturation as well. The observed reduction contradicts decades of belief that polymers could not be used to reduce residual oil because the additional pressure required to overcome capillary pressure is orders of magnitude greater than provided by the more viscous polymer. However, additional forces (such as normal stress forces) may be significant for viscoelastic fluids that are ignored in analysis of purely viscous fluids.

We perform computational fluid dynamics (CFDs) simulations of viscoelastic flow around static oil droplets in geometries representative of pore throats. We show that normal forces are significant for viscoelastic fluids and increase with *De* and the total force imposed on the droplet may be larger than an equivalent Newtonian fluid with the same viscosity. Results indicate that normal forces could dominate and the total, effective force would be enough to mobilize trapped oil.

1. Introduction and background

The flow of viscoelastic fluids in porous media is important in many applications including composite manufacturing in fibrous materials (Skartis et al., 1992; Preziosi et al., 1996), filtration of polymer solutions (Kozicki and Kuang, 1994), removal of liquid pollutants in soils (Londergan et al., 2001; Sochi, 2009), blood flow in capillaries (Thurston, 1974; Canic et al., 2006; Rojas, 2007), and enhanced oil recovery (EOR). In EOR polymer flooding is one process used to improve the sweep efficiency in oil reservoirs. The additional viscosity of the polymer solution allows for a more piston-like displacement of oil and results in additional recovery.

1.1. *Effect of viscoelastic polymers on residual oil saturation*

Despite the use of polymers to improve sweep efficiency, conventional wisdom has suggested that they could not be used to reduce residual oil saturation (Lake, 1989; Sorbie, 1991; Willhite and Green, 1998). At the pore-scale, capillary forces play an important role and can prevent the non-wetting phase from flowing. Capillary force by a snap-off mechanism makes the oil phase unconnected and difficult to mobilize. It is believed that trapped oil is restricted from being drawn out of the tight pores because the pressure force across the oil droplet in water or polymer flooding is not high enough to overcome the capillary pressure forces. If the pressure gradient were sufficiently high, the oil droplet would stretch out toward the adjacent pore, squeeze through the constriction, and then flow to the next pore.

It is believed that the additional viscosity of polymers would not provide nearly enough pressure drop to overcome capillary forces and mobilize a significant amount of residual oil. This is true for a purely viscous Newtonian fluid and can be demonstrated using simple calculations. For example, consider a typical water-wet reservoir (contact angle, $\theta = 0^\circ$), relative permeability (k_w) of 100 mD, and a 1 cp viscosity (μ) fluid flowing at a Darcy velocity (v_w) of 1 ft/day. The applied pressure gradient would be less than 0.1 psi/ft. For a typical pore geometry with length 50 μm, throat radius of 10 μm, pore body radius of 50 μm, and surface tension (σ) of 30 dynes/cm, the required pressure gradient to mobilize the residual oil is approximately 4000 psi/ft; about 4–5 orders of magnitude higher than the applied pressure gradient. Using a more viscous fluid (EOR polymers are usually 10–100 cp) would provide additional pressure gradient, but it would still be at least two orders of magnitude less than required to reduce residual oil saturation (Stegemeier, 1974).

Despite this fundamental understanding of strong capillary forces and decades of belief that polymers should have no impact on residual saturation, both experimental and field observations have suggested that viscoelastic polymers (specifically hydrolyzed

---

[*] Corresponding author. Tel.: +512 471 3246; fax: +512 471 9605.
E-mail address: Balhoff@mail.utexas.edu (M.T. Balhoff).
[1] Tel.: +512 471 5238; fax: +512 471 7060.

0920-4105/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.petrol.2012.06.027

polyacrylamide (HPAM)) are effective at reducing residual oil and improving recovery by as much as 20% additionally. Wreath (1989) and then Wang (1995) showed decreased residual oil saturation in corefloods using HPAM in strongly water-wet Antolini sandstones when compared to waterfloods or even floods using inelastic polymers (e.g. Xanthan gum). Residual oil was reduced significantly (up to 22%) in the experiments by Wang (1995). Reduced residual oil using viscoelastic polymers in corefloods of water-wet media was also found by Zaitoun and Kohler (1987, 1988), Schneider and Owens (1982), and Bakhitov et al. (1980). Similar observations have been found in mixed-wet and oil-wet experiments (Wang et al., 2010) and field studies (Putz et al., (1988); Wang (2000)).

A few hypotheses have been proposed for the observed reduction of residual oil, including accelerated drainage of oil films on rock surfaces, scoured oil in dead-end pores, and trapped oil pulled out in stable oil threads (Wang et al., 2001; Huh and Pope, 2008). Adding polymer to water causes an increase in both macro and micro scale sweep efficiency. Wang (2000) showed higher molecular weight and higher concentrations of polymer result in higher elasticity. They hypothesized that the higher molecular weight causes a reduction in maximum velocity, so a velocity gradient at the wall increases, resulting in stripping off oil from the pore walls. In dead-end pores, the elasticity of polymer results in dragged oil and may further reduce the residual oil saturation. For water-wet media in particular, the elasticity of the fluid may help prevent snap-off (or re-connects snapped-off fluid). The non-wetting oil phase can then be pulled through the pore throat as a stable thread. The simulations conducted in this work test this hypothesis, in which wetting fluid flows around an oil droplet.

To investigate the displacement efficiency (E_D), the micro forces are neglected for fluids without elastic effects. This is a reasonable assumption because the micro forces are negligible compared to viscous forces which are proportional to pressure gradient (Wang et al., 2010). Micro forces are categorized into two forces, normal force and kinetic force which are both caused by change in flow lines in pore bodies. Experiments and simulation show that flow lines for viscoelastic fluids are significantly different from those of Newtonian fluids. Viscoelastic fluids behave like an elastic solid as well as viscous fluid; the elastic behavior leads to flow lines that appear as an expanding and contracting piston flow. Wang et al. (2000) showed that micro forces for viscoelastic fluid flow are comparable to macro forces, which should be considered in analysis of fluid dynamics. They also showed that only the first normal force differential and its corresponding Weissenberg number (or equivalently Deborah number, *De*) affect the shape of the flow lines; other elastic properties and the viscosity of the driving fluid do not affect flow lines, therefore they do not affect the E_D. They predicted that the capillary number and viscoelasticity both influence the displacement efficiency and residual oil saturation.

1.2. Mathematical modeling of viscoelastic flow in porous media

Modeling viscoelastic flow in the presence of trapped oil at the pore scale could better explain the fundamental reasons for reduction in residual oil. Furthermore, this could lead to new EOR strategies and the design and synthesis of polymers with optimal rheological properties. Several authors have studied single-phase viscoelastic fluids experimentally and numerically in both porous media and constrictions representative of pores. Marshall and Metzner (1967) presented a model for viscoelastic flow in porous media as a function of the dimensionless *De* ($=\lambda/t_r$); where λ is relaxation time and t_r is the residence time. They performed experimental tests in packed beds of spheres and supported the analysis. They observed the deviation from the drag coefficient-Reynolds number relationships for a purely viscous fluid at the critical value of *De* which depends on different variables such as homogeneity. Deiber and Schowalter (1981) used the method of geometric iteration to solve the momentum equation for a Maxwell fluid through sinusoidal ducts. They observed a higher flow resistance than expected from purely viscous fluids at high flow rate, and this effect is the result of fluid elasticity, even without a secondary flow. Later, Gupta and Sridhar (1985) analytically evaluated stress of polymer solutions through a tube having a periodically varying diameter. They found that if the deformation rate is assumed constant, the stress depends not only upon *De*, but also on the aspect ratio.

Other authors numerically studied the extensional effects of viscoelastic fluids in planar and axi-symmetric contraction/expansions (Rajagopalan et al., 1990; Fan et al., 1999; Alves et al., 2003; Binding et al., 2006; Aguayo et al., 2008) and reported shear-thickening behavior. Several attempts have been made to overcome convergence issues for this highly nonlinear problem to reach a higher *De* number. For instance, Huang and Feng (1995) used POLYFLOW software to simulate the viscoelastic fluid flow around a sphere placed in a cylindrical tube. They used an EVSS (elastic–viscous stress split) formulation for stress and unstructured triangle meshing to reach $De\sim2.5$. In the EVSS interpolation, the constitutive equation is not solved in terms of the viscoelastic extra-stress tensor. Instead, the viscoelastic extra-stress tensor is split into purely viscous and elastic components. This split form is substituted into the constitutive equation, which is re-written in terms of the elastic component and solved. Combining both viscous and elastic components recovers the actual viscoelastic stress tensor. Further details on the EVSS method can be found in Van Schaftingen and Crochet (1984) and Rajagopalan et al. (1990).

Binding et al. (2006) studied the Olydroyd-B model for a 4:1 contraction (channel geometry which abruptly constricts by a factor of four), and 4:1:4 cases (geometry also expands after constriction). Pressure drop was calculated using POLYFLOW software for both planar and axisymmetric contraction–expansion cases. They also used the EVSS (elastic–viscous split stress) formulation for stress calculation. They observed that the pressure drop initially reduces with *De* as the elasticity increases but as *De* number is further increased, it eventually rises significantly above the equivalent Newtonian pressure drop. Several authors have reported this same trend; Webster et al. (2004) conducted the simulations for Olydroyd-B and Phan-Thien Tanner (PTT) models and showed linear declining of pressure drop with increasing *De*. Szabo et al. (1997) studied an Oldroyd-B fluid and finitely extensible nonlinear elastic (FENE) model and observed a similar result.

Here we model the flow of viscoelastic fluids around oil droplets in converging/diverging pore throats with the goal of obtaining a fundamental understanding of the micro forces imposed on the droplet. Additional normal forces, not present for purely viscous fluids, may explain the observed decrease in residual oil saturation in core flood experiments and field studies. Section 2 of this paper describes the mathematical and numerical approach used to solve the nonlinear problem of viscoelastic flow around oil droplets in a converging and diverging throat. Section 3 presents qualitative pictures of the flow fields and stresses as well as quantitative results of the forces present on a droplet for a Newtonian versus a viscoelastic fluid at various *De*. These results are discussed along with possible explanations for reduced residual oil saturation. Finally, Section 4 presents some conclusions drawn from this work as well as proposed future studies.

2. Mathematical and numerical approach

In order to better understand the observed decrease in residual oil in experiments and field data, CFD modeling is performed here for viscoelastic flow around stationary oil droplets. The hypothesis of this work is that large normal forces in viscoelastic fluid flow leads to