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## Impact of fluid elasticity on miscible viscous fingering

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## HIGHLIGHTS

- Flow experiments are performed by displacing Boger fluids with water.
- Observations are compared to Glycerol displacement with water.
- Elasticity is observed to retard the growth of fingers.
- Dominant wave number at onset of instability is increased by elasticity.

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## ABSTRACT

An experimental study is performed to investigate the impact of fluid elasticity on miscible viscous fingering. Rectilinear flow experiments are performed by displacing aqueous Boger fluids (constant-viscosity elastic fluids) with water. The observations are compared to those in Newtonian fluids (glycerol solutions) of the same viscosity. Elasticity is observed to reduce the width of fingers, leading to formation of thinner and longer fingers in fully developed flow. The shielding effect is reduced due to fluid elasticity resulting in growth of multiple fingers as compared to a single thick dominant finger observed for Newtonian fluids. The dominant wave number for the onset of instabilities is observed to be higher in more elastic fluids i.e. the interface breaks down into greater number of fingers in the more elastic fluid. Data is presented to show that fluid elasticity retards the growth of fingers. Elastic effects are observed to reduce the thin film of the displaced fluid on the walls of the Hele–Shaw cells.

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## 1. Introduction

Displacement of a more viscous fluid by a less viscous fluid leads to flow instabilities resulting in the formation of fingers of the less viscous fluid. The onset and evolution of instabilities is referred to as viscous fingering (Saffman and Taylor, 1958; Chouke et al., 1959; Peters, 1979; Homsy, 1987). Viscous fingering has been the subject of extensive study over the past years due to its applications in many processes, which include flow through porous media (Homsy, 1987), secondary and tertiary oil recovery (Lake, 1989; Peters et al., 1987, 1989), proppant placement in hydraulic fractures (Liu et al., 2007; Malhotra et al., 2013, 2014) and flowback from hydraulic fractures (Pope et al., 1996).

A vast body of theoretical, numerical and experimental work devoted to understanding various aspects of the instabilities is available in the literature (Zimmerman and Homsy, 1991; Sader et al., 1994; Loggia et al., 1995; Tanveer, 2000; Riaz and Meiburg, 2003; Smirnov et al., 2005). Saffman and Taylor (1958) presented theoretical solutions for the formation of viscous fingers between two Newtonian fluids in Hele–Shaw cells. The problem is a Laplacian free-boundary problem and in spite of being highly non-linear, the problem has been solved numerically (Coulter, 1991). In some limiting cases, analytical results have also been obtained (Howison, 1986). On the other hand the instabilities in non-Newtonian fluids are not very well understood. Patterns different and more complex than those in Newtonian fluids, have been observed in non-Newtonian fluids (Allen and Boger, 1988; Zhao and Maher, 1993; Kawaguchi et al., 1997a, 1997b; Lindner et al., 2002; Li et al., 2006). The fluids include liquid crystals (Buka et al., 1986; Buka and Palffy-Muhoray, 1987) polymer solutions (Kawaguchi et al., 1997a; Li et al., 2006; Makino et al., 1995), suspensions (Kawaguchi et al., 1997b; Chevalier et al., 2007), foams (Park and Durian, 1994), gels (Lindner et al., 2000), clays (Lemaire et al., 1991), emulsions (Enjamoori et al., 2010), Bingham-plastic fluids (Chen et al., 2005) etc.

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In this work, we focus on the role of fluid elasticity on fingering patterns. Allen and Boger (1988) performed experiments displacing Boger fluids with Newtonian fluids and observed that the finger patterns in Boger fluids were similar to those in Newtonian fluids of same shear viscosity. Sader et al. (1994) pointed out that the influence of elasticity on fingering pattern depends upon the Deborah number  $De$  (defined as the ratio of fluid relaxation time,  $\lambda$  to fluid flow time,  $t_f$ ). The flow conditions under which the experiments were performed by Allen and Boger (1988) pertained to small Deborah numbers, which explains the absence of fracture-like patterns. Kawaguchi et al. (1997a) performed experiments with hydroxypropyl methyl cellulose (HPMC) and observed morphological transitions from dense branching to tip-splitting and tip-splitting to skewering in high molecular weight HPMC solutions. Similar pattern transitions were not observed in low molecular weight solutions. The difference was attributed to higher elasticity of high molecular weight solutions. Zhao and Maher (1992, 1993) demonstrated fingering-fracturing transition as the injection rate exceeds a threshold value, and the transition was observed to be consistent with the Deborah number scaling. Depending on the polyethylene oxide (PEO) concentrations and injection rates, they showed that the patterns can be made to resemble the diffusion limited aggregation (DLA) model. Vlad and Maher (2000) observed that immiscible viscous fingers growing in Boger fluids are unstable to tip splitting at lower velocities compared to viscous fingers growing in Newtonian fluids. No fracture-like instabilities were observed. Lindner et al. (2002) performed experiments in linear Hele–Shaw cells and displaced polyethylene oxide (PEO) solution with air. They observed wider fingers than for Newtonian fluids, which were attributed to higher normal stress in the PEO solutions. It was also observed that the propagation velocity of fingers did not change from that in Newtonian fluids. Linear stability analysis on viscoelastic fluids has shown a shift in the most unstable wavelength and maximum growth rate due to fluid elasticity (Wilson, 1990; Mora and Manna, 2010). Mora and Manna (2010, 2012) performed a linear stability analysis of an air front pushing an upper convected Maxwell fluid inside a Hele–Shaw cell and showed that a unique dimensionless time parameter controls the elastic effects. The stability analysis showed a divergence in the growth rate due to elastic effects, leading to fracture-like patterns at high values of the dimensionless parameter.

In this work we investigate the effect of elasticity on miscible viscous fingering by performing displacement experiments in rectilinear Hele–Shaw cells. Aqueous Boger fluids are displaced with water and the observations are compared to the experiments performed in Newtonian fluids (glycerol solutions), of the same viscosity, displaced with water. The comparison helps in a direct identification of the effect of fluid elasticity on flow instability. Experimental results are presented for the first time to show that fluid elasticity retards the growth of fingers in miscible viscous fingering in rectilinear flow conditions. The dominant wave number at the onset of instability is observed to increase with fluid elasticity. Results are presented to show that elasticity reduces the thickness of the thin film of the displaced fluid left on the walls of the Hele–Shaw cell.

**Table 1**  
Concentrations and viscosities of the PEG–PEO solutions used in the experiments.

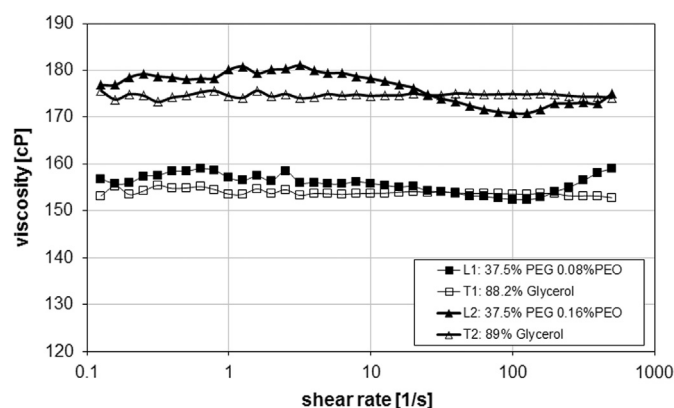
Liquid	Amount of PEG-8000 (wt%)	Amount of PEO-4000,000 (wt%)	Viscosity (cP)
L1	37.5	0.08	156 ± 3.3
L2	37.5	0.14	176 ± 5.1

## 2. Description and characterization of fluids

The Boger fluids chosen for this study are based on the findings of Dontula et al. (1988). The fluids are prepared by adding small amounts of a high-molecular weight polymer (polyethylene oxide (PEO) with a molecular weight of 4000,000 g/mol obtained from Aldrich) to a more concentrated aqueous solution of the same polymer but of a lower molecular weight (polyethylene glycol (PEG) with a molecular weight of 8,000 g/mol obtained from Fischer Scientific). Stock solutions of PEG were prepared by adding the oligomer to distilled water (1 l) and mixed for at least 24 h over a magnetic stirrer. The solutions were allowed to stand for 24 h. Different amounts of PEO were added to smaller volume of PEG solutions (400 ml) and mixture was left to mix for at least 24 h over a magnetic stirrer. All final mixtures were colorless, odorless and transparent to the eye. Table 1 shows the concentrations of PEG and PEO used for preparing the two fluid mixtures used in this study.

Steady shear-viscosity measurements and dynamic oscillatory-shear measurements are made using the ARES rheometer by TA Instruments using a double wall concentric cylinder fixture (inside cup diameter: 27.95 mm, inside bob diameter: 29.50 mm, outside bob diameter: 32.00 mm, outside cup diameter: 34.00 mm, bob length: 32.00 mm). Fig. 1 shows the viscosity ( $\eta$ ) as functions of shear rate ( $\dot{\gamma}$ ) for liquids L1 and L2. The fluid viscosity is constant (variations of viscosity are confined to 1–3% of the viscosity value at low shear rate). Once the PEG–PEO solution viscosity is measured, a glycerol solution is prepared and the water weight percentage is adjusted so as to achieve the same viscosity. Fig. 1 also shows the viscosity as a function of shear rate for glycerol solutions. Table 2 shows the viscosities of the two glycerol solutions used as test fluids. The variation of the viscosity over the range of shear rate and between different runs is quantified in the table.

The oscillatory-shear measurements were made over a range of frequencies from 0.1 rad/s to 100 rad/s. Fig. 2 shows the elastic modulus,  $G'$  and the viscous modulus,  $G''$  as functions of angular frequency,  $\omega$  for liquids L1 and T1. The values of the moduli are presented on a logarithmic scale. It is observed that the two fluids have similar  $G''$  values but different  $G'$  values, suggesting that the two fluids have similar viscous properties but different elastic properties, with the polymer solution being more elastic. Fig. 3 shows the elastic and viscous moduli for liquids L2 and T2. The measurements were reproducible between different batches of polymers prepared during the evaluation phase for selection of Boger fluids. The elastic and viscous moduli are simultaneously fitted to a series of Maxwell elements with relaxation times  $\lambda_k$  and relaxation strengths  $G_k$ , represented using the following equations



**Fig. 1.** Steady shear viscosity as a function of shear rate for Liquids L1 and T1.

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