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Research highlight

A new mechanism of viscoelastic fluid for enhanced oil recovery: Viscoelastic oscillation

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Abstract:
This report summarizes our recent experimental findings [Xie et al., Phys. Rev. Lett., 2022] and pore-scale simulation results [Xie et al., Phys. Rev. Fluids., 2020] on viscoelastic oscillation, which is a new observation of viscoelastic instability in the multiphase flow state. The viscoelastic oscillation causes trapping of droplets in contraction-expansion micro-channels regardless of the injection rate. Based on the force balance analysis of the viscous, capillary and elastic forces, the oscillation amplitude is found to linearly increase with viscoelasticity, and the trapped droplet size is determined by the elasto-capillary number. The oscillation also helps to extract droplets from their originally trapped positions such as dead-ends once a critical Deborah number is reached. These results successfully explain the phenomenon that the alternative injection of viscoelastic and inelastic fluids continually produces additional oil, indicating that the viscoelastic oscillation is a new important mechanism of viscoelastic fluid for enhanced oil recovery.

Viscoelastic fluid is a non-Newtonian fluid that has both viscous and elastic properties. It has been widely applied to many important industrial applications such as enhanced oil recovery (EOR). Wang et al. (2000) showed evidence that viscoelastic polymer can reduce residual oil after the Newtonian glycerol flood. Previously, the EOR mechanisms of viscoelastic fluids mainly included: the improvement of mobility ratio due to the increase in its apparent viscosity (Xie and Balhoff, 2021); the "pulling" effect due to the tangential elastic force at the interfaces; and the forming of continuous oil flow channels. However, most of these understandings remain at the epi-morphological level, which are unable to explain the uncertainty of polymer applications in many oilfield sites. Therefore, it is important to further investigate the mechanisms of viscoelastic fluid for EOR.

In our work, droplet displacements by viscoelastic fluids in a contraction-expansion channel (300 μm in width) were studied. In the micromodel experiments (Xie et al., 2022), displacements using both viscoelastic and inelastic fluids were compared. The injection rate and relaxation time were changed to control the viscoelasticity of fluids, leading to various Deborah numbers (De). For all inelastic displacements, the droplet length decreased with an increasing flow rate, and the droplet eventually passed through the throat. While for all viscoelastic cases, the droplet size no longer decreased once a critical state was reached, instead, it kept oscillating in the main channel and was trapped upstream of the throat (Fig. 1(a)). The trapped droplet length was found proportional to $\mathrm{Ec}^{1/3}$ (where $\mathrm{Ec} = \mathrm{De}/\mathrm{Ca}$ is the elasto-capillary number), by analyzing the force balance of the viscous, capillary and elastic forces at the onset of oscillation. The oscillation amplitude was also found to linearly increase with De once the viscoelasticity exceeded a critical De (Fig. 1(b)). This relationship agrees well with our theoretical derivations that used the analogy of

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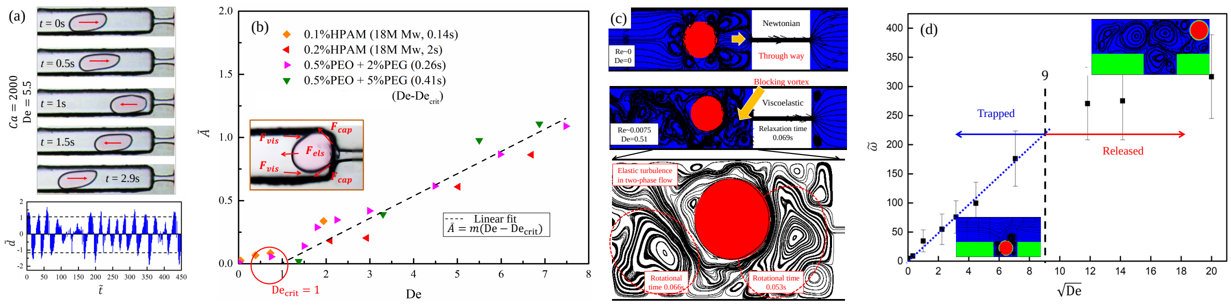

Fig. 1. (a) The oscillation and trapping of a Newtonian droplet in a contraction-expansion channel when displaced by a viscoelastic fluid. (b) The linear relationship between the viscoelasticity and oscillation amplitude $\widetilde{A}$. (c) The essence of viscoelastic oscillation: memory effect induced viscoelastic instability. (d) The relationship between the vorticity magnitude $\widetilde{\omega}$ and $\sqrt{\mathrm{De}}$. Figures are reproduced with permission from: (Xie et al., 2022) © 2022 APS; and (Xie et al., 2020) © 2020 APS.

the simple harmonic motion based on the memory feature of elastic force.

The mechanisms for the above viscoelastic oscillation were further explained by our lattice Boltzmann simulations (Fig. 1(c)) using the multiphase viscoelastic model (Xie et al., 2018). The two-dimensional numerical configuration mimics the geometry in the experiment, but the pore-to-throat width ratio was adjusted to ensure the same area ratio. Our simulations (Xie et al., 2020) also showed the oscillation of the droplet in viscoelastic fluids, while it never occurred in the Newtonian fluids. Comparing the streamlines, there existed a clear through-way that allowed pass-through of the droplet in Newtonian cases, while a large vortex blocking the droplet was observed in all viscoelastic cases, which should be the direct reason that trapped the droplet. It was also observed that the streamlines in the Newtonian cases were symmetric and smooth, while in the viscoelastic cases they were chaotic, similar to the observations by Clarke et al. (2016). The self-rotational times of the two big vortices beside the droplet in the viscoelastic fluid were close to the fluid's relaxation time, indicating that the chaotic streamline was a phenomenon of "elastic turbulence". Therefore, the viscoelastic oscillation is a new observation of viscoelastic instability in the multiphase flow state.

It could be interpreted that the viscoelastic oscillation induced droplet trapping hinders EOR, however, our further simulations also confirmed that this oscillation would help to extract droplets from their originally trapped positions once a critical De was reached (Fig. 1(d)). These opposing effects might explain the interesting results recently found by Erincik et al. (2018) that the alternating injection of viscoelastic polymers and inelastic fluids continually produced additional oil as: viscoelastic fluids can mobilize trapped oil, but these extracted droplets may oscillate and hesitate in big pores; while a subsequent inelastic fluid can steadily push these hesitating droplets out but may also lead to new trapped positions; in such a cycle, alternative injection continues to increase oil recovery.

In summary, droplet oscillation in viscoelastic fluids was found by both micromodel experiments and pore-scale simulations, which is a new important mechanism of viscoelastic fluids for EOR. The viscoelastic oscillation is demonstrated to be a novel observation of viscoelastic instability in the presence of another fluid, which provides new possibilities for the manipulation of droplets.

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Conflict of interest

The authors declare no competing interest.

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