UNDERSTANDING POLYMER RETENTION IN POROUS FORMATIONS USING MICROFLUIDICS
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ABSTRACT
Understanding polymer transport through porous media is key to successful field implementations of polymer-based enhanced oil recovery (EOR) schemes. The proposed approach of integrating microfluidics and single-molecule fluorescence microscopy represents a novel approach to replicate polymer flow in porous formations and to obtain molecular scale visualization of polymer retention mechanisms. For the first time, we achieved direct visualizations of two polymer transport mechanisms: mechanical entrapment and hydrodynamic retention, that manifest at dynamic conditions.

KEYWORDS: microfluidics, single-molecule microscopy, polymer retention, enhanced oil recovery.

INTRODUCTION
Polymer-EOR has been studied and practiced by the oil&gas industry for decades [1]. However, the various mechanisms of polymer retention within the porous reservoir formation are not fully understood. The presumed underlying mechanisms of polymer retention are: adsorption, mechanical entrapment, and hydrodynamic retention [2]. Polymer adsorption represents the interaction of polymer molecules with the rock surface and constitutes the static component of polymer retention. On the other hand, mechanical entrapment and hydrodynamic retention occur during flow and represent the dynamic components of polymer retention. Retention by mechanical entrapment corresponds to the phenomenon when polymer molecules become lodged in narrow pore-throats, while hydrodynamic retention corresponds to molecules slow-down in stagnant flow regions and dead-end pores. Until now, polymer retention in porous media has only been inferred from differential pressure and effluent concentration.

The opacity of rocks acts as a restriction for direct visualization of fluid flow. Therefore, microfluidics is gaining interest due to the ability to mimic porous media and provide pore-scale insights at the resolution of rock pores, at the micro-scale (1-100μm) [3]. However, molecular scale resolution (0.1-1μm) is required to study polymer retention mechanisms corresponding to the characteristic scale at which these mechanisms manifest. We propose a new approach to assess polymer retention mechanisms in porous formations using integrated microfluidics and single-molecule fluorescence microscopy.

EXPERIMENTAL
The design of the microfluidic chips honors the pore-size distribution of oil-bearing conventional reservoir rocks, with pore-throats ranging from 2 to 10 μm, while removing the inherent complexity of three-dimensional porous networks, which can mask the desired mechanisms. We used a tailored soft-lithography technique to build a microfluidics device out of polydimethylsiloxane (PDMS), conceptually referred as “Reservoir-on-a-Chip”.

We conduct single-phase polymer flooding experiments on the designed micromodels to study polymer transport behavior in porous formation. Single-molecule fluorescence imaging experiments were conducted on a custom-built epifluorescence microscopy setup. The experiments allowed us to visualize polymer retention mechanisms at the molecular level owing to the use of fluorescently-labeled polymers with 56 000 Dalton molecular weight and single-molecule tracking techniques.

RESULTS AND DISCUSSION
We show direct molecular scale visualization of the dynamic components of polymer retention, which to our knowledge, has not been achieved previously. These visualizations reflect the flow behavior of polymer molecules and agglomerates within the hosting aqueous phase of the solution. The gray scale images acquired with 35ms sampling time and 500 nm pixel size were converted to color scale based on fluorescence intensity levels to reflect the concentration of polymer molecules. Magenta represents no polymeric material, while red and yellow represent polymer molecules and polymer agglomerates, respectively.
The mechanical entrapment captured in Figure 1 occurred when a polymer agglomerate got trapped in the middle 5μm channel. The incompatibility in polymer molecules and pore-throat sizes led to a complete pore-clogging, which is one of the major concerns for operational aspects of polymer flooding processes.

![Figure 1: Snapshot showing a polymer agglomerate (indicated by the arrow) mechanically entrapped (left) and the cumulative streamlines in yellow, over a stack of 1000 captions, illustrating the resulting complete clogging of the channel (right).](image)

In hydrodynamic retention, polymer molecules were observed to be drifted towards a channel with restricted transport for the polymeric material. The aqueous phase continued to flow through that channel, which dragged and retained the agglomerates at the entrance of the channel. Afterward, due to changes in flow conditions, the retained polymers were discharged into the flux and drifted towards other channels (Figure 2). This observation shows that the hydrodynamic retention mechanism is reversible and does cause neither permanent flow alteration nor divergence.

![Figure 2: Time-lapse fluorescence showing a polymer agglomerate, in yellow, retained for several seconds (in the inclosed area), in caption 1, the agglomerate flowing through the upper channel, in caption 103, and no entrapment in that area, in caption 200.](image)

**CONCLUSION**

Motivated by the importance of polymer transport mechanisms for the field implementation of polymer-based EOR process, this study presents:

- A novel approach to study polymer transport by integrating microfluidics and single-molecule microscopy, which achieves resolutions suitable to capture the pore-scale of rocks and the molecule-scale of polymers.
- First direct evidence of two flow-induced mechanisms of polymer retention: mechanical entrapment and hydrodynamic retention.
- New insights on fundamental flow mechanisms of polymers including pore-clogging and reversibility.
- This work contributes to a deeper understanding of polymer retention mechanisms leading to improved polymer screening in industrial applications and the development of new models that account for the reversibility of the phenomenon.

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**REFERENCES**


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