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# Modeling preformed particle gel surfactant combined flooding for enhanced oil recovery after polymer flooding

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## HIGHLIGHTS

- A mechanistic model for PPG/surfactant/polymer combined flooding was proposed.
- The interaction between PPG and surfactant was mathematically described.
- The newly presented model was validated with core flooding cases.
- Two pilots from China fields were used to verify the coupled model.
- The sensitivity of different parameters to the recovery factor was discussed.

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## ABSTRACT

Preformed Particle Gel (PPG) surfactant combined flooding, designed to simultaneously improve the sweep efficiency and displacement efficiency, has emerged as a promising Enhanced Oil Recovery (EOR) method after polymer flooding. The fundamental mechanisms have been investigated by many lab experiments and the feasibility has been evaluated by some field applications. However, there is no model that can handle this combined EOR process. In this paper, a mechanistic model is proposed to predict the EOR performance after polymer flooding. This new coupled model incorporates the surfactant transport module into the model of PPG treatment after polymer flooding. Especially, the interaction mechanisms between PPG and surfactant are mathematically described according to the lab experiments. An implicit pressure explicit composition method is adopted to numerically solve the coupled model. The newly presented model is firstly validated with a commercial simulator and some core flooding experiments. Then, the verified model is employed to predict the performance for actual field pilot cases. Parameters analysis is conducted on a conceptual model for PPG conformance control after polymer flooding. The results show that the coupled model provides an efficient and accurate method for predicting PPG-surfactant flooding performance after polymer flooding, which aids to determine the technical feasibility of the field project.



## 1. Introduction

With the decline in new oil discoveries in recent years, the EOR technology is a good approach to meet the energy demand in years to come. The increasing energy demand and the high oil price greatly spur the EOR field applications all around the world. Current total world oil production from EOR is approaching 3 MMBD representing about 3.5% of the daily global oil production [1]. As a great promising method, chemical EOR is becoming an alternative mitigation activity in many mature oilfields. There are three main EOR mechanisms for chemical flooding: (1) increasing the capillary number to mobilize residual oil; (2) decreasing the mobility ratio for better sweep; (3) emulsification of oil to facilitate production. Chemical EOR methods have shown an increase in oil recovery in pilot tests and a few large field implementations [2]. China is the country with the largest oil production from Chemical EOR projects which mainly comes from polymer flooding. The high molecular polyacrylamide dissolved in water significantly increase water viscosity to decrease the mobility ratio and thus increase the sweep efficiency in the reservoir. Polymer flooding alone contributed more than 10 million tons of oil in 2006 in Daqing oil field

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**Nomenclature**

| | |
|---|---|
| $b_1$, $b_2$, $b_3$ | parameters for surfactant concentration change |
| $B$ | formation volume factor |
| $c$ | mass concentration, mg/L |
| $CMC$ | critical micelles concentration, mg/L |
| $\hat{c}$ | adsorption mass concentration of unit formation rock |
| $d$ | diffusion factor |
| $d_1$, $d_2$, $d_3$ | parameters for pressure gradient threshold |
| $D$ | depth, m |
| $e_1$, $e_2$ | IFT parameters for surfactant/PPG |
| $F$ | inaccessible pore volume factor, dimensionless |
| $PPG_{sol}$ | solubility of PPG, fraction |
| $gradp$ | pressure gradient, MPa/m |
| $IFT$ | interfacial tension, mN/m |
| $K$ | permeability, mD |
| $K_r$ | relative permeability, mD |
| $P$ | pressure, MPa |
| $q$ | volumetric flow, $m^3/s$ |
| $R_s$ | dissolved gas oil ratio |
| $R_p$ | generation or consumption mass concentration rate |
| $S$ | saturation, fraction |
| $SHR$ | shear breaking ratio |
| $SWR$ | swelling ratio in polymer solution |
| $t$ | time, days |
| $v$ | flow velocity, m/s |

*Greek symbols*

| | |
|---|---|
| $\delta$ | retention |
| $\phi$ | porosity, fraction |
| $\Phi$ | diameter, m |
| $\rho_R$ | rock density, $kg/m^3$ |
| $\gamma$ | gravity |
| $\mu$ | fluid viscosity, mPa·s |
| $\nabla$ | gradient |

*Subscripts*

| | |
|---|---|
| $g$ | gas |
| $ppg$ | preformed particle gel |
| $o$ | oil |
| $p$ | polymer |
| $surf$ | surfactant |
| $w$ | water |

[3]. The second largest field wide polymer flooding application in China is in the Shengli oil field in the Bohai Bay area. In addition, polymer flooding is gaining interest for heavy crude oil reservoirs and offshore fields. The combination of conformance control technologies (gel treatments) to improve injection profile and sweep efficiency after polymer flooding shows promise in some China projects [4].

Although polymer flooding has achieved industrial application in China, the EOR potential is sometimes very limited in actual field performance. Still half the oil reserve remains in the reservoir after polymer flooding because of severe reservoir heterogeneity, immature well pattern and high temperature high salinity [5]. The problems with polymer flooding result from limited sweep efficiency improvement and little oil displacement efficiency. Hence, the techniques proposed for EOR after polymer flooding should consider the two fundamental starting points. Improving the sweep efficiency (also known as conformance control) is the prerequisite for enhancing oil recovery after polymer flooding. Polymer micro gels, including colloid dispersed gel, preformed particle gel (also called gel microsphere), bright water and pH sensitive cross-linked polymers, are the most widely used agents for chemical conformance control [6].

Preformed Particle Gel (PPG) is a kind of effective polymer gel to improve sweep efficiency. Its gelling process takes place on surface and it can overcome some drawbacks inherent in the in-situ gel systems [7]. Its main mitigation mechanisms in porous media and influencing parameters were explored by conducting many lab experiments [8]. Sand-packed flow experiments are employed to investigate the PPG plugging deposition mechanisms and the permeability variation owing to PPG retention [9]. Some field and lab experience with PPG conformance control was analyzed for a water flooding field [10]. Furthermore, it can also reutilize the polymer remaining in the reservoir, and it can be used for conformance control after polymer flooding. A series of lab experiments were conducted to study the main interaction mechanisms for PPG profile control after polymer flooding [11].

Surfactant is the most efficient agent to enhance displacement efficiency. Adding surfactant in injected solution will decrease the oil-water interfacial tension (IFT). The capillary number will increase when the IFT decreases, which will lead to a large reduction in residual oil saturation [12]. The wettability of rocks are improved to allow water to be better absorbed into the pores with oil, which results in faster water moving and more oil displaced. Surfactants are widely used combined with other chemical EOR methods, such as SP flooding or ASP flooding. Surfactant can also be implemented with conformance control method such as PPG treatment to enhanced oil recovery after polymer flooding [13]. The PPG slug is firstly injected to block the high permeability zone or thief zone after polymer flooding, which improves the sweep efficiency. Then the surfactant slug is injected to displace the remaining oil, which improves the displacement efficiency. The PPG-surfactant can not only be employed in sandstone reservoirs [14], it can also be adopted in carbonate reservoirs [15]. The interaction between PPG and surfactant was also investigated by an experiments study to evaluate the EOR potential [15]. Some physical properties of PPG, such as PPG dynamics, will be changed as it encounters with surfactant. Some physical properties of surfactant will also be changed correspondingly [16].

To optimize a field development plan, numerical simulation is needed for the PPG-surfactant hybrid EOR project plan. To the authors' knowledge, some researchers have proposed some basic models. A simple conceptual model was established for PPG migration in water flooding reservoir [17]. A PPG model was established based on laboratory experiments to study excess water management [18]. This model takes the water relative permeability decrease by considering gel strength, permeability and flow rate. A one-dimensional experiment data driven filtration model was presented to describe the interaction between PPG and remaining polymer [19]. This model was later extended to a three-dimensional model for PPG conformance control optimization after polymer flooding [11]. Recently, a preliminary PPG-surfactant model has been developed for hybrid EOR after polymer flooding, and the interaction between PPG and surfactant was firstly mathematically described [20]. The PPG-surfactant mathematical model in this paper is mainly inherited from this model. This paper is a following study, which enhances the development of the theory and further validates the model and presents field applications simulation study.