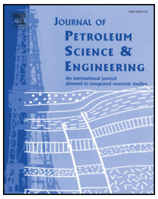
Journal of Petroleum Science and Engineering 168 (2018) 72–80

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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



Investigation of restarting pressure gradient for preformed particle gel passing through pore-throat

Wei Zhao[a,b], Huiqing Liu[a,b], Jing Wang[a,b,*], Hongling Zhang[a,b], Chuanjin Yao[c], Linlin Wang[a,b], Pengpeng Qi[d]

[a] *State Key Laboratory of Petroleum Resources and Engineering in China University of Petroleum, Beijing, 102249, China*
[b] *MOE Key Laboratory of Petroleum Engineering in China University of Petroleum, Beijing, 102249, China*
[c] *China University of Petroleum, East China, 266580, China*
[d] *The University of Texas at Austin, TX 78712, USA*

ARTICLE INFO

Keywords:
Preformed particle gel
Deformation behavior
Mathematical modeling
Restarting pressure gradient

ABSTRACT

Excess water production is prevalent in mature reservoirs, which reduces production profits. Water treatment by polymers/gels is one of the most efficient ways to solve this problem. Preformed particle gel with the size from nanometer to micrometer has been applied as an effective and commercial crosslinked polymer for conformance management. However, few quantitative mathematical models were studied, especially the unique deformation-restarting property which reflects the deformation and in-depth propagation performance of PPG. In this paper, a single pore-throat cell based on the rearranged sand spheres was chosen. Then, the restarting pressure gradient model for PPG passing through pore-throat unit was made based on elastic mechanics theory and micro-element analysis. The forces on the deformable PPG, such as driving force, frictional and extruding resistance, were considered in stress analysis. Meanwhile, a variable diameter capillary model similar to the structure of the pore-throat was constructed to validate the PPG propagation process. Sensitivity analyses indicated that elastic modulus had the most significant impact on restarting pressure. Moreover, the restarting pressure gradient was a function of PPG size, pore-throat size, elastic modulus, friction coefficient and Poisson's ratio. The experimental data have a good agreement with the mathematical results. The restarting pressure gradient increases with increasing of the diameter ratio of PPG to pore throats. This study can provide a way to evaluate the process of “plugging-deformation-restarting” for PPG passing through the pore-throat and a good start for future advanced models.

1. Introduction

Most oil fields in China characterized by complex geologic conditions and high permeability contrast have already entered high or even extra high water cut stage (Bai et al., 2013; Wang et al., 2012, 2013). Excess water production becomes a major problem for most mature waterflooding reservoirs (Seright, 1997; Qi et al., 2017). Injected water that flows into thief layers through high permeability channels results in problems like high residual oil saturation in low permeability layers, and early well shut-in. Reducing high water cuts is essential to extend reservoir economic production period.

Preformed particle gel (PPG) has been proved to be an effective and economical method for conformance control and it improves sweep efficiency in heterogeneous fields (Liang et al., 1993; Chauveteau et al., 2000; Feng et al., 2003; Bai et al., 2007a,b; Zhu et al., 2017). Compared to traditional in-situ bulk gels that directly injected into reservoirs where the gelation occurs at reservoir temperature, PPG has obvious advantages due to its formation on the ground before injection (Chauveteau and Omari, 2001; Elsharafi and Bai, 2013). PPGs can overcome some distinct drawbacks of the traditional in-situ gel, such as lacking of gelation-time control, gelling uncertainty under the effects of the shear force, gel composition changes due to chromatographic fractionation and formation water dilution (Bai et al., 2007a,b; Sang et al., 2014; Imqam and Bai, 2015). PPGs with different strengths and sizes can be made and controlled at surface. Different from rigid particles which can be easily captured near wellbores, PPG with micro- or nano-scale particular sizes can flow into thief zones and it is suitable for high water-cut reservoirs (Wang et al., 2013a,b, 2017).

Many kinds of literature have studied PPG properties, such as its transport behaviors through porous media and mechanisms for enhancing oil recovery (Bai et al., 2007a,b; Wu and Bai, 2008; Imqam and Bai, 2014, 2015; Goudarz et al., 2015). Bai et al (2007a,b) investigated

---

[*] Corresponding author. State Key Laboratory of Petroleum Resources and Engineering in China University of Petroleum, Beijing, 102249, China.
E-mail address: wangjing8510@163.com (J. Wang).

https://doi.org/10.1016/j.petrol.2018.05.005
Received 1 March 2018; Received in revised form 26 April 2018; Accepted 1 May 2018

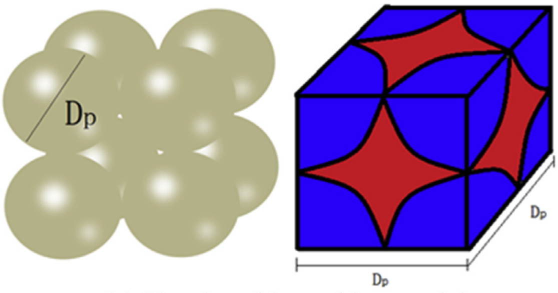
PPG propagation mechanisms through porous media mainly include six behavior patterns-direct pass, deformation, plugging, breakage, shearing, and trap. Those are similar to fine particles filtration behaviors, such as entrainment and deposition (Gruesbeck and Collins, 1982). However, PPG propagation mechanisms are different. The special features of PPG are that particle size of the swollen PPGs is larger than pore-throat size. Therefore, PPGs can be captured and thus block high permeability channels firstly. In addition, when driving pressure gradient becomes large enough, PPG can deform and pass through pore-throat into the deep formation. This behavior reflects profile control of deep formation (Wang et al., 2017). Other preformed gels like dispersed preformed gels (DPGs) and microspheres with nano-micro size also have the deformation performance. Zhao et al. (2014) demonstrated that DPGs particles could pass directly or by deformation through porous media and enter deep formation. Lin et al. (2015) studied the conformation and plugging properties of microspheres. Microspheres are soft and deformable and they can deform when the sufficient pressure is supplied.

Some empirical models were proposed to explain the propagation laws in the past few years (Wu and Bai, 2008; Imqam and Bai, 2014; 2015; Goudarz et al., 2015; Wang et al., 2017). Imqam and Bai (2014) conducted experiments to study the mechanisms of PPG extrusion and placement in conduit systems. Two empirical correlations models considering gel strength and particle-opening ratio were developed. Wu and Bai (2008) proposed a conceptual mathematic model using continuum method based on the experimental data. Mass conservation principle, a modified Darcy's law, and constitutive relationships are considered in this model, which evaluates PPG performance in porous media. Goudarz et al. (2015) also developed a numerical model that includes swelling ratio, resistance factor, and residual resistance factor. It was implanted into the UTGEL reservoir simulator to match and simulate the experimental data obtained from the homogeneous fracture and sandpack model. The process of “plugging-deformation-restarting” is a unique and significant behavior, which reflects that PPG plugs pore-throat and deforms to restart the migration into the deep formation. It mainly depends on the driving pressure, particle size, throat size and PPG property, rather than colloidal and surface forces (Wang et al., 2017). The remigration characteristic of PPG will affect the deep fluid diversion and profile control. However, there are few quantitative or mathematical models for such unique behavior. In terms of the pore-throat unit, it is necessary to understand the transport performance and single PPG particle mechanisms in unit cells quantitatively. It is the foundation of building a more reliable model for PPG treatment.

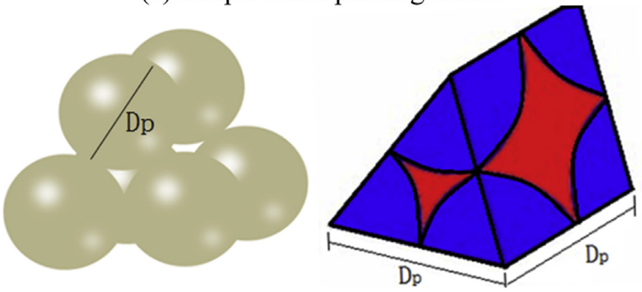
In this paper, we first extracted a pore-throat unit cell from a porous media and simplified the element to a computable model which provided a propagation pathway for the deformable PPG. The deformation process and stress state were then analyzed based on the pore-throat model. The restarting pressure gradient model was proposed according to the elastic-plastic mechanic theory. To validate the mathematical model, capillary experiments with variable diameter were conducted and the restarting pressures were measured. PPG property sensitivity analyses with our model were finally presented.

2. Simplified model for porous media

Most porous media structures are irregular and complicated, which does not allow rigorously geometrical descriptions. Here, sand particles are assumed to have uniform spheres. As shown in Fig. 1a, the traditional simple cubic (SC) packing model consists of 8 uniform spheres, which has 6 square openings in one-unit cell. The structure is the same in horizontal and vertical directions (Mayer and Stowe, 1965; Dullien and Batra, 1970; Dong et al., 2005). The porosity was 47.64% in this case. However, permeability has orientation in actual porous media, where horizontal permeability outclasses vertical permeability due to structural morphologies and rock properties (Wang et al., 2011a; 2011b). To develop more accurate models, we rearrange sand spheres and simplify the unit cells of the porous media, as shown in Fig. 1b. The 6-uniform-spheres unit cell has 3 square openings and 2 triangular openings, which shows a different flow capacity. The length of the unit cell is the particle size marked as D_p. The internal space surrounded by six particle spheres is regarded as the pore body. Obviously, the cross-section size of the pore is variable and computable. With the given value of the sand particle diameter, the size and shape of the throat are determined because of the constant uniform-spheres arrangement. The pore throat radius at a specified location is defined as the equivalent radius. The area of the circle is the same with that of the triangular cross-section at the same location. Fig. 2a shows the convergent-divergent pore structure in series according to the hypothetical model. Fig. 2b shows the investigated pore element and Fig. 2c indicates the pore radius at any specified location with different sand particle sizes. The pore-throat radius will increase with the increase of sand-particle size. The experiential relationship between pore radius and point location can be expressed as



(a) Simple cubic packing model



(b) Modified packing model

Fig. 1. Arrangement of sand particles.

$$R(x_D) = R_P \times \{a \exp[-(x_D - 0.5)^2/b] + c\} \tag{1}$$

where x_D is the dimensionless distance, which is the ratio of x to D_p; x is the distance from the entrance, as shown in Fig. 2b, in μm; a, b, c are regression coefficients, $a = -0.75$, $b = 0.23$, $c = 0.9$.

The unit cell volume can be calculated by *Eq.* (2):

$$V_P = D_P \int_0^1 \pi R(x_D)^2 dx_D \tag{2}$$

The porosity in the new case is 0.38 which is reasonable for a quartz sand pack.

3. Restarting pressure gradient model

Fig. 3 shows the physical deformation-restarting process of the single PPG migration in the unit cell. The suspended PPGs enter into the pore throat driven by displacing pressure (see Fig. 3a). If the PPG size is larger than the pore throat size, the surface capture caused by the size exclusion will occur and the PPG will deform elastically under the supportive force on the pore throat surface (see Fig. 3b). The shape of the particles will no longer be uniform spheres and its shape changes with their positions in the pore throat. With PPG flow continue, particle deformation will reach the maximum value gradually (see Fig. 3c). When PPG particles pass through the throat center, they will swell to