Profile control performance and field application of preformed particle gel in low-permeability fractured reservoir

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Abstract

Water well profile control is the main way to control water channeling in low-permeability fractured reservoirs, and preformed particle gels (PPGs) are commonly used. A preformed particle gel was prepared and the synthesis conditions were optimized. The temperature and salt resistant performance, plugging performance were investigated and the field application was tested. The results showed PPGs exhibited good temperature and salt resistant performance. PPGs with larger particle size showed greater plugging strength but shorter valid period. Field tests suggested that multiple rounds of profile control should be employed using PPGs with different particle sizes to achieve deep profile control.

Keywords Preformed particle gel · Low-permeability fractured reservoir · Profile control · Field application · Plugging strength

Introduction

Water production in oil-producing wells becomes more and more serious as the wells mature, especially in the exploitation of low-permeability fractured reservoir, such as water flooding, gas flooding and chemical flooding (Gu et al. 2014; Xu 2017; Zhang et al. 2018).

Water well profile control is the main way to control water channeling in low-permeability fractured reservoirs. For low-permeability fractured reservoirs, a good profile control agent should have the following characteristics: injectable, good plugging performance, movable and pollution-free (Zhou et al. 2017). At present, the common profile control agents for fractured reservoirs include polymer gel (He et al 2009; Lu et al 2010), preformed particle gel (PPGs) (Imqam et al 2017; Sun et al 2019), polymer microspheres (Hua et al 2014; Li et al 2019), etc. As to particles like PPGs or microspheres, it is required that the initial size of the profile control agent must be smaller than the pore throat diameter of the formation; the profile control agent must

expand and have certain elasticity, and can produce deformation and breakthrough under certain pressure, so as to have the advantages of good plugging performance to achieve deep profile control.

Before further injection implementation in oilfield, characterizing in situ rheology in porous media is critical (Santoso et al 2017, 2018, 2020) and a series of influencing factors on flow characteristics of injection fluid should be considered, such as Non-Newtonian behavior in porous media, possible injection issues in the wellbore, shear-dependent viscosity and retention-agglomeration process at pore-scale (Torrealba et al. 2019; Zhang et al 2010). If the injected concentration or injection rate is too big, particles can buildup inside the pore throat, which can reduce the permeability of the reservoir (Santoso et al 2017).

In this paper, a preformed particle gel was prepared by solution polymerization and the synthesis conditions were optimized. The temperature and salt resistant performance, plugging performance were investigated through laboratory experiments and the field application was tested, as shown in Fig. 1.

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Fig. 1 The flowchart of our workflow

Experimental

Materials

Acrylamide (AM) was recrystallized twice from acetone and then dried under vacuum. Potassium persulfate (KPS) was used as the initiators, which was recrystallized from deionized water. N,N'-methylene bisacrylamide (MBAA) was used as the cross-linking agent. Na_2CO_3 , NaHCO_3 , NaCl , CaCl_2 , MgCl_2 and Na_2SO_4 were used to simulate the formation water. All aqueous solutions were prepared using deionized water. All reagents were all analytical reagents obtained from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China).

The total salinity of the simulated formation water is 71,785 mg/L; K^+ , Na^+ 17,305 mg/L; Ca^{2+} 8348 mg/L; Mg^{2+} 458 mg/L; Cl^- 43,391 mg/L; SO_4^{2-} 1920 mg/L; CO_3^{2-} 56 mg/L; HCO_3^- 307 mg/L.

Synthesis of preformed particle gels

PPGs were formed by acrylamide monomer adding cross-linking agent with the initiator of potassium persulfate to form a three-dimensional network structure (Imqam et al. 2015; Saghaei et al 2016; Heidari et al 2019). In this paper, MBAA was employed as the initiator. Sodium carbonate was added to hydrolyze it into negative electric hydrogel with carboxyl group. In order to improve the expansion

ratio and temperature resistance of pre-cross-linking system, additives such as 2-Acrylamide-2-methylpropanesulfonic acid (AMPS) can be added.

Performance evaluation of preformed particle gel

Expansion property

The particle size of preformed particle gel was determined by laser particle size analyzer, and the expansion rate was defined as follows:

$$S_w = \frac{D_{50}}{d} \quad (1)$$

where D_{50} indicates the corresponding particle size (μm) of the PPGs in simulated formation water at certain conditions on the cumulative distribution curve when the probability is 50%, while d indicates the average particle size (μm) of dry particles.

Plugging performance

Core flooding device (as seen in Fig. 2) is used to evaluate the plugging performance of PPGs. The plugging performance is generally evaluated by plugging rate, breakthrough pressure gradient, etc.

Plugging rate

Fig. 2 Plugging performance experimental instrument of core test

$$E = \left[1 - \frac{K_{wb}}{K_{wa}} \right] \times 100\% \quad (2)$$

where K_{wa} and K_{wb} is the permeability before and after injection of PPGs.

Breakthrough pressure gradient

$$P_{\max} = \frac{P_0}{L} \quad (3)$$

where P_0 is the pressure difference at breakthrough and L is the length of experimental core.

Results and discussion

Optimization of synthesis conditions of preformed particle gel

The synthesis conditions of the PPGs were optimized by evaluating the expansion rate of PPGs in 10,000 mg/L NaCl solution at 70 °C and the results were shown in Fig. 3. The optimized synthesis conditions were as follows: the cross-linker concentration, monomer concentration, initiator concentration and the reaction temperature were 0.06%, 20%, 0.5% and 60 °C, respectively.

Performance of preformed particle gel

The temperature and salt resistant performance, plugging performance of PPGs were evaluated. The temperature and

salt resistant performance of the PPGs was shown in Fig. 4. The PPGs exhibited good temperature and salt resistant performance, the expansion rate of PPGs remained above 10 in 100,000 mg/L NaCl solution (70 °C) or at the temperature of 130 °C (10,000 mg/L NaCl solution).

The plugging performance of PPGs was investigated with simulated artificial fractures by using quartz sand filling tube with larger particle size of 40 mesh, as shown in Table 1. In this test, the mass concentration of PPGs was 0.5%, the injection rate was 1.0 mL/min and the temperature was 70 °C, and the particle size of PPGs was 100–120 mesh and 200–230 mesh.

It can be seen from Table 1 that the PPGs have good plugging performance for fractures, and the plugging rate can reach more than 90%. The larger the particle size, the greater the plugging strength and breakthrough pressure gradient. According to Tang's and Imqam's study, PPGs particles with larger particle size were more likely to retain in porous media (Tang et al 2004; Imqam et al 2017). Thus PPGs with larger particle size can exhibit greater plugging strength but difficult to achieve deep profile control which means shorter valid period in the profile control process.

Field application of PPGs in low-permeability fractured reservoirs

Field application of PPGs was conducted and the well location and reservoir properties were shown in Fig. 5. The reservoir properties were as follows: reservoir buried depth: 2246 m; reservoir temperature: ~ 70 °C; Porosity: 10.8%; Average permeability: $0.4 \times 10^{-3} \mu\text{m}^2$; Fracture direction:

Fig. 3 Optimization of synthesis conditions of preformed particle gel

NE–SW; Fracture density: $\sim 0.38/\text{m}$; Salinity: 71,785 mg/L, and the ionic composition was seen in Part 2.1; Total oil recovery: 7–8%. Before field Application of PPGs injection, the three oil production wells were shut in because they were waterflooded. The PPGs injection was firstly carried out in the water injection well WW-1, and WW-1 and the oil production well OW-1 were of the key monitoring regions at the beginning of the field test. The monitoring process during the field test mainly includes two aspects: the pressure drawdown curves of injection well and the production conditions of the oil well such as the liquid production, oil production, water cut, chloride ion content, dynamic liquid level height, etc.

The water injection well WW-1 injected 10.1 t PPGs with particles of 0.3–1.5 mm (30%) and 3–5 mm (70%) in 3 days and the oil pressure increased from 15.1 to 19.2 MPa. The

Fig. 4 The temperature and salt resistant performance of the PPGs

Pressure drawdown curves of injection well ww-1 before and after profile control using PPGs were shown in Fig. 6. The pressure drop was faster after well shut before profile control which showed obvious water absorption characteristics in fractures; while after profile control, the pressure decreased slowly with time which proved that PPGs achieved good plugging effect for water injection well WW-1.

The water injection of WW-1 was resumed after profile control with an average daily injection volume of 10 m³. The production conditions of the horizontal oil well OW-1 after injection of PPGs were shown in Fig. 7. After profile control, the water content and liquid production decreased, while the oil production increased which showed that the PPGs effectively blocked the fractures. But water logging after 15 days showed that PPGs probably accumulated in the near well area of the water injection well and the injected water can break through the near well area and flowed into the communication fracture between oil and water wells, resulting in water logging of oil production well again. It is suggested that multiple rounds of profile control should be employed using PPGs with different particle sizes to achieve deep profile control.

Conclusions

- (1) The synthesis conditions of the PPGs were optimized by evaluating the expansion rate and the optimized synthesis conditions were as follows: the cross-linker concentration, monomer concentration, initiator concentration and the reaction temperature were 0.06%, 20%, 0.5% and 60 $^{\circ}\text{C}$, respectively.

Table 1 Plugging performance of preformed particle gels for fractures

No	Porosity (%)	particle size (mesh)	PV	Permeability (um ²)		Plugging rate (%)	Breakthrough pressure gradient (MPa/m)
				Before	After		
1	34.2	100–120	1	8.7	0.28	96.8	3.2
2	35.6	200–230	1	9.8	0.74	92.4	1.7

Fig. 5 Well location and reservoir properties of the PPGs field test block **Fig. 7** The production conditions of oil well OW-1 after injection of PPGs **Fig. 6** Pressure drawdown curves of injection wells in profile control using PPGs

- (2) The PPGs exhibited good temperature and salt resistant performance. PPGs with larger particle size can exhibit greater plugging strength but difficult to achieve deep

profile control which means shorter valid period in the profile control process.

- (3) Field application of PPGs showed that PPGs achieved good plugging effect for water injection well. But PPGs probably accumulated in the near well area of the water injection well and the injected water can break through the near well area which resulting in water logging of oil production well again. So it is suggested that multiple rounds of profile control should be employed using PPGs with different particle sizes to achieve deep profile control.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval I certify that this manuscript is original and has not been published and will not be submitted elsewhere for publication. And the study is not split up into several parts to increase the quantity of submissions and submitted to various journals or to one journal over time. No data have been fabricated or manipulated (including images) to support the conclusions. No data, text, or theories by others are presented as if they were our own.

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