Preformed Particle Gel for Conformance Control

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Preformed particle gel (PPG, a kind of Super Absorbent Polymer) has been successfully applied to control conformance in around 2,000 wells in China oilfield. The paper summarizes: (1) why we proposed the method, (2) What are the properties of thermal-stable PPG products, (3) where it has been used and how to select a good well candidate for a PPG treatment, (4) how to improve PPG treatment results, (5) what lessons we have learned from the field applications, and (7) how to improve the current technology for better conformance control results.

Introduction

Gel treatments are a cost-effective method to improve sweep efficiency in reservoirs and reduce excess water production during oil and gas production. A newer trend is applying preformed gels for the purpose because the preformed gels can overcome some distinct drawbacks inherent in in-situ gelation systems, such as lack of gelation time control, uncertainness of gelling due to shear degradation, chromatographic fractionation or change of gelant compositions, and dilution by formation water. The preformed gels include preformed bulk gels (Seright 2004), partially preformed gels (Sydansk 2004, 2005), and particle gels which include preformed particle gel – PPG (Coste 2000, Bai 2007), microgels (Chauveteau 2000, 2001, Rousseau 2005, Zaitoun 2007) and pH sensitive crosslinked polymer (Al-Anazi 2002, Huh 2005), mm-sized swelling polymer grains (currently marketed by service companies), and Bright Water® (Pritchett 2003, Frampton 2004). Their major differences are their sizes and swelling times. Microgels (U.S. patent 6579909) and Bright Water (U.S. patent 6984705) are patented products but are commercially available. Published documents show that PPG, microgels and Bright Water® were economically applied to reduce water production in mature oilfields. PPGs were applied in about 2,000 wells to reduce fluid channels in waterfloods and polymer floods in China (Liu 2006). This paper will introduce the technology of using preformed particle gels to control conformance for mature oilfields.

Motivation

Mature reservoirs are requiring us to control conformance.

Most reservoirs in China have become mature due to long term of water flooding. These reservoirs have a high average water cut of more than 85%. Water production becomes a major problem as these oilfields mature. Higher levels of water production result in increased levels of corrosion and scale, increased load on fluid-handling facilities, increased environmental concerns, and eventually well shut-in (with associated workover costs). Consequently, producing zones are often abandoned in an attempt to avoid water contact, even when the intervals still retain large volumes of recoverable hydrocarbons. Controlling water production has been one objective of the oil industry.

Reservoir heterogeneity severely affects the flow of gas, oil, and water in the reservoir and thus effects the choice of production strategies, reservoir management, and ultimate oil recovery. Reservoir heterogeneity is the single most important reason for low oil recovery and early excess water production. Most oilfields in China, which were discovered in continental sedimentary basins, are characterized by complex geological conditions and high permeability contrast inside reservoirs. To maintain reservoir pressure, these reservoirs were developed by water flooding from the early stage of their development. Many of them have been hydraulically-fractured, intentionally or unintentionally, or have been channeled due to mineral dissolution and production during waterflooding (Liu, 2006). Reservoirs with induced fractures or high-permeability channels are quite common in the mature oilfields. Gel treatment is one of the most important methods to correct the reservoir heterogeneity.

Traditionally, gels have been placed near wellbore of production or injection wells as shown in Fig.1, which mainly has been used to correct inter-layer heterogeneity or heal fracture. However, the remaining oil on the top of a thick heterogeneous layer is the most important target to improve oil recovery as a reservoir matures. A newer trend in gel treatment is to apply “in-depth diversion” products (Seright, 2004, Frampton, 2004, Sydansk, 2005, Chang, 2004, Rousseau, 2005, Bai, 2007). These in-depth diversion gels have been reported to penetrate deeply into higher permeability zones or fractures and seal or partially seal them off thus creating high flow resistance in former, watered-out, high permeability zones. When successful, these gel systems divert a portion of the injection water into areas not previously swept by water shown in Fig. 2.

Using Preformed Gels to Control Conformance Has Become a New Trend for Gel Treatments

Traditionally in-situ gels have been widely used to control conformance. The mixture of polymer and crosslinker called gelant is injected into target formation and react to form gel to fully or partially seal the formation at reservoir temperature. So the gelation occurs in reservoir conditions. However, a newer trend is applying preformed gels for the purpose. Preformed gel is formed at surface facilities before injection, and then gel is injected into reservoirs. So no gelation occurs in reservoirs. Preformed gels have become a newer trend because they can overcome some distinct drawbacks inherent in in-situ gelation system such as lack of gelation time control, uncertainness of gelling due to shear degradation, chromatographic fractionation or change of gelant compositions, and dilution by formation water.

Preformed gel can effectively reduce gel damage on unswept low permeability oil zones. It is quite common that most gels cannot penetrate into milli-Darcy formation. Preformed gels can form gel cake on the low permeability formation or core surfaces which can effectively prevent gel penetration into the formation. However, in-situ gels behavior polymer solution when they are injected as gelants. According to polymer flooding mechanisms, more gelants will sweep into un-swept low permeability oil zones than water. Once the gelants crosslink in these oil zones, not only they will waste polymer but they will also block these zones, which will cause seriously damage on these potential productive oil zones.

Motivation for mm-sized Preformed Particle Gel

Waterflooding has significantly changed reservoir pore structures and physical parameters. Induced fractures or high permeability streaks/channel quite common exist in mature reservoirs, as evidenced by the following field experiences:

- Interwell tracer test: many reservoirs have no initial fracture, but tracer tests show in many cases it only took less than 15 days even a few days or hours for the tracers to move to adjacent producers from an injector with a distance of around 200 meters. Tracer test explanation through software showed the permeabilities of these channels or streaks are usually around a few hundred Darcy to tens of thousand Darcy and the volume of those channels is only 1 to 10% of the reservoir volume but they adsorb about 80-90% of injected water.
- Gel treatments: Hundreds of large in-situ gel treatments (usually more than 5,000 m^3) have been operated in China's oilfields in the past years. The gelation time is usually only a few hours to less than one day but all gelants have been successfully injected into those wells without any injection problems even the injections continue to 15 days even a couple of months. More often, most large

volume of gel treatments have not increased water injection pressure as expected after treatment.

- Particle injection: Many kinds of particles, such as montmorillonite clay, are quite often applied to control conformance. For examples, many wells can be injected around a few thousands of cubic meters of 5-10% clay and have not found any injection problems. The particle injection practices suggest us the formations have more serious voids or fractures than we expected.

Moreover, our lab tests have showed gelants form dispersed gels but not bulk gels in the porous media at flowing condition, shown in Fig.3.

Based on above field practices and our lab results, we proposed to develop preformed gel particles to control conformance in 1996. Field injectivity pilots demonstrated mm-sized gel particles have no any injectivity problem in most mature reservoirs.

Development and Properties of Preformed Particle Gel

Preformed particle gel is an improved super adsorbent polymers (SAPs). SAPs are a unique group of materials that can absorb over a hundred times their weight in liquids and do not easily release the absorbed fluids under pressure. Superabsorbent polymers are primarily used as an absorbent for water and aqueous solutions for diapers, adult incontinence products, feminine hygiene products and agriculture industry. However, the traditional SAPs in the markets do not meet the requirements for conformance control due to their fast swelling time, low strength and instability at high temperature. A series of new SAPs called preformed particle gels (PPGs) have developed for the conformance control purposes (Bai et al, 2007). In summary, PPGs have following properties:

- PPG size are adjustable: µm-cm
- Swelling ratio in formation water: 30~200 times original
- Salt resistance: all kinds of formation salts and concentrations are acceptable
- Thermal stability: more than 1 years below 110 ºC.
- Strength: adjustable, high strength product available
- Swelling rate: slightly controlled (swelling rate controllable PPGs is still in research)

Application of PPGs for Conformance Control

Using large volume of PPG to control conformance was initiated in 1996 by RIPED, PetroChina. The first successful large volume of PPG treatment was in Zhongyuan oilfield, SINOPEC in 1999. The selected reservoir has serious conditions: high temperature (107 ºC) and high salinity (150,000 mg/l). So far, about 2,000 wells have been treated using PPG or PPG combined with other gels in most oilfields in China, covering both sandstone reservoirs and naturally fractured carbonate reservoirs with temperature from 20 to 110 °C and formation water salinity from 2,000 to 280,000 mg/l. The common weight of PPG is from 8 to 40 tons and concentrations range from 1,000 to 5, 000 mg/l. For example, PPG has been applied in Daqing oilfield since 2001. Ninety-one wells were treated from 2001 to 2004, 44 wells from water flooding area and 47 wells from polymer flooding area. Injected PPG concentrations are from 2,000 to 4,500 mg/l, and injection volume of PPG suspension is from 5,000 to 200,000 m^3. PPG alternating with water (PAW) or continuous injection method is used depending on pressure response during PPG injection. After treatments, average water injection pressure increased about 0.6 MPa. There are 366 producers connecting with these treatment wells. Average incremental oil of these producers is about 2.6 t /d/well and water cut decreased about 2.6%. More than 200,000 tons of oil was increased from these treatments. For the application in the polymer flood area, the produced polymer concentration also decreased. PPG treatment has been widely accepted and is seeing more use by operators of Chinese oilfields because it has some advantages over traditional in-situ gel for some applications listed in Table 1.

Table 3. PPG advantages over traditional in-situ gel.

		PPG	Bulk Polymer Gel
Chemical reaction		Manufactured particle, no in-situ reactions	Affected by interactions with reservoir rocks and fluids
Viscosity		Suspension, low viscosity	Bulk chemical solution, high viscosity
Temperature Resistance		120 ºC	Depend on polymer, usually below 90 ºC
Salinity Resistance		Any salt and concentration	Depend on polymer, more sensitive to divalent cationic
Possible damage on formation		SMART particle, Selectively enter super-K zones/interval.	Like polymer flooding during injection. Gel may form in low permeability zones
Preparation of fluids	Water	Any convenient water	Usually fresh water required
	Mixing	Quickly, well disperse	At least 30-60 minutes
Injection Scheme		Slug, Alternated injection of PPG/W	Consecutive, Alternated slugs of W/Chemicals not allowed
Pressure monitoring as an indicator during injection		Quick, good diagnotic to adjust particle size, strength and conc.	Not a diagnostic for gel behavior.
Costs		One composition	Polymer+Crosslinker+ Additives
Environmental		Friendly (Salty water)	Fresh water usually required

Lessons from these applications

Field experiences learnt from field applications are summarized as follows.

Criteria of Well Selection

- Reservoir temperature below 120°C;
- Reservoir with high permeability channels or fractures;
- High injectivity and low PI (pressure index);
- High water cut and high liquid rate of connected producers;
- Well group with low oil recovery preferential;
- Salinity not limited.

Before determining to inject PPG, some tests and measurements are strongly recommended, mainly including water tracer test, well tests and water absorption profile.

PPG Injection Design

- Simple injection facility can be used to inject PPG shown as Fig. 4.
- Produced water can be used to prepare PPG suspension.
- At the beginning of PPG treatment, a small amount of high concentration, large-size PPG is preferred to be injected at a high flow rate so that PPG particles can form surface plugging to prevent followed PPG penetrating into low permeable oil zones.
- An alternated method of PPG suspension and water is usually designed to conduct PPG treatments.
- PPGs are usually designed to be injected at low concentration and low-flow-rate so that particles have enough time to move in-depth of the reservoir. High concentration, high-flow-rate PPG injection may cause a large pressure pulse near wellbore, which may cause the formation to be fractured.
- Real-time injection pressure should be monitored so that we can adjust some of our initial designed scheme, including PPG size and strength, according to the monitored pressure result. The adjustment is necessary because the reservoir is a black box, and we cannot completely understand it when we make the initial design. This is another advantage of PPG over traditional in-situ gelling systems.

Treatment Results Analysis

Sucessful PPG treatment is often accompanied by an injection-pressure increase, an oil-rate increase and water-cut decrease, but injection pressure may not be an evaluation criterion because PPG may move into in-depth of reservoir so followed water injection pressure does not greatly increase.

Knowing Updated Reservoirs

PPG has been injected in many mature oilfields, and most reservoirs have no fracture at the beginning of their development. But no injectivity problem has been encountered until now for more than 95% cases, which indicates channels widely exist in mature waterflooded oil fields because PPG cannot be injected into those normal porous media without a fracture or channel. It is suggested that we should reconsider the mature reservoirs which may be completely different from their original conditions. Water flooding has resulted in these reservoirs change significantly. Knowing the undated reservoirs is very important for improved oil recovery technology applications.

Limitation for PPG Application

PPG can be used to control conformance for the reservoirs with small fractures or high permeability channels. But it should be noted that PPG cannot be injected into normal porous media without fractures or channels. In addition, the PPG cannot singly be applied in the reservoirs with very severe open channels or super-high-permeability open fractures because PPG will be flushed out from producers.

Future Development

New PPG Development

Common PPG can only be injected into those porous media with permeability above 10 Darcy. One objective to extend PPG application is to develop softer and swelling-rate controllable gel particles so that PPGs can be applied to relatively low permeability reservoirs.

Particle Transport Mechanisms through Fractures

Preliminary studies on PPG through porous media have been carried out using granular porous media without open fractures (Bai, 2007). However, unless special efforts are made during gel placement (e.g., zone isolation), theoretical studies demonstrated that gel treatments are most likely to be successfully when treating fractures or fracture-like features that cause channeling in reservoirs (Seright 1988, 1993). So it is necessary to identify how the particle gels best work for fracture or fracture-like reservoirs and how to improve the gel treatment efficiency and optimize the gel treatment design.

Improved Particle Gel Treatments

Some novel processes may improve gel particle treatment efficiency. One method involves addition of second crosslinker. Delayed crosslinking after gel-particle placement can make the dispersed gel form a bulk gel—thus increasing the resistance to wash out.

A second method incorporates gel particles with surfactant, so that the filtrate that is squeezed into the matrix during gel injection alters the wettablity of rock near the fracture faces. A third method involves exploration of gravity segregation to control gel placement. Usually particle gels have a higher density than the carrier fluid thus the density difference may be exploited to optimize gel placement in vertical fractures where we wish to plug the bottom part (i.e., the water-source zone) while leaving the upper part open (i.e., the oil source zone).

Summary

The success of gel treatments depends on reservoir problem identification, appropriate candidate selection, gel selection, parameter design, and gel placement. Particle gels have great potential due to their unique advantages over traditional in-situ gels.

- Particle gels are synthesized in surface facilities, thus overcoming distinct drawbacks inherent in in-situ gelation systems, such as uncontrolled gelation times and variations in gelation due to shear degradation, chromatographic of gelation compositions, and dilution by formation water.
- Preformed particle gels are strength- and size-controlled, environment-friendly, and their stability is not sensitive to reservoirs minerals and formation water salinity.
- Preformed particle gels can preferentially enter into fractures or fracture-feature channels while minimizing gel penetration into low permeable hydrocarbon zones/matrix. Gel particles with the appropriate size and properties should transport through fractures or fracture-feature channels, but they should not penetrate into conventional rock or sand. The minimized gel penetration in low permeable areas will also result in significant reductions in the required gel volumes because fracture or fractured-like channels usually comprise less than 10% of the reservoir volume.
- These gels usually have one component during injection. Thus, it does not require many of the injection facilities and instruments that often are needed to dissolve and mix polymer and crosslinker for conventional in-situ gels. The simple injection operation processes and surface facilities can significantly reduce operation and labor costs.

- These gels can be prepared with produced water without influencing gel stability. In contrast, traditional in-situ gels are often very sensitive to salinity, multivalent cations, and H_2S in the produced water. This not only can save fresh water but it also can protect our environment.
- Real-time monitoring data can be used to adjust previous design for better gel treatment results.

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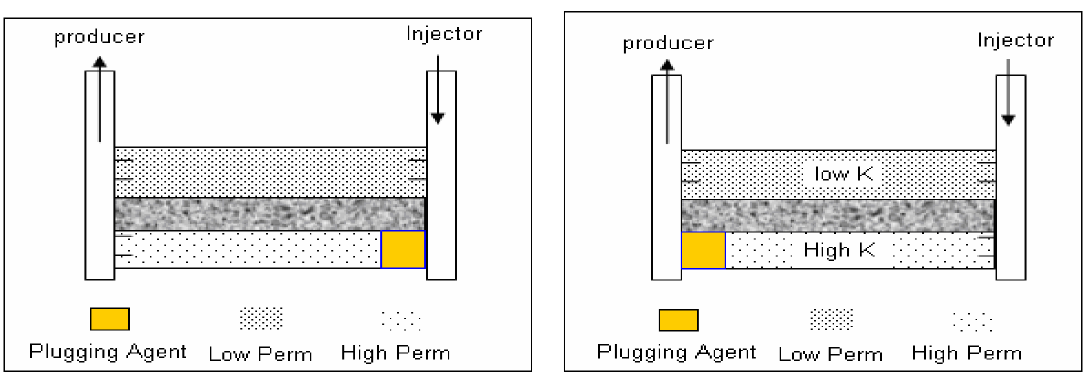

Fig. 1. Gel treatment for heterogeneous formation without crossflow (near wellbore treatment can effectively improve sweep efficiency)

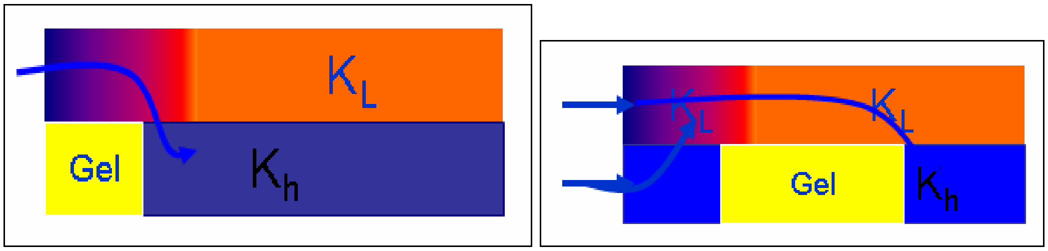

Fig. 2. Gel treatment for heterogeneous formation with crossflow

(Near well treatment has no effect on sweeping oil but in-depth treatment can improve sweep efficiency)

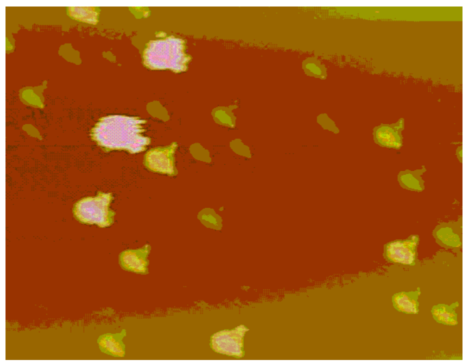

Fig.3. Dispersed gel particles from porous media.

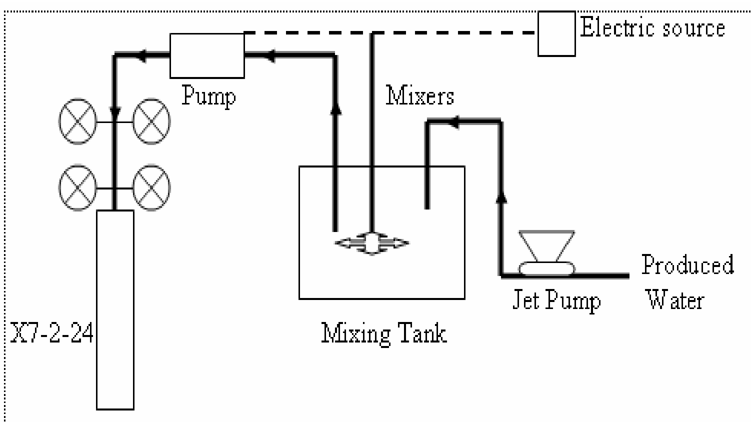

Fig.4. PPG Injection flow chart.