Research Journal of Applied Sciences, Engineering and Technology 9(1): 18-28, 2015
DOI:10.19026/rjaset.9.1371
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: April 12, 2014 Accepted: May 24, 2014 Published: January 05, 2015

Research Article

In-depth Permeability Modifier for Improvement of Sweep Efficiency in a Heterogeneous Oil Reservoir: A Review

Abdelazim Abbas Ahmed and A.P. Ismail Mohamed
Department of Petroleum Engineering, UTP, 31750 Tronoh, Perak, Malaysia

Abstract: This study reviews and assessed some of in-depth permeability modification techniques used in the industry with regards to improving conformance problems in heterogeneous oil reservoirs. Reservoir conformance problems frequently limit the success of many of water and chemical EOR flooding projects. Basically, there are many types of conformance problems and many different conformance improvement techniques. The challenge is to properly identify and then to select a suitable conformance improvement technology. Conventionally, *In-situ* gels have been widely used and placed near the well-bore of injectors or producers to improve conformance. However, in heterogeneous reservoirs permeability variation extends throughout the whole reservoir structure and in some cases presence of cross-flow between adjacent layers limits the effectiveness of *in-situ* gels. Alternatively, conformance improvement has been obtained by continuous polymer injection. This method still by-passes significant amounts of oil as evidenced from a number of recent reports. Preformed cross-linked gel particles have become an interesting technology to overcome some of the distinct drawbacks of in *In-situ* gels and polymer flooding. Although, this method show promising oil improvement, lack of in-depth knowledge is available as well as their mechanisms to plug rock pores are not fully understood. It's the aim of the study to review the reservoir conformance problems as well as conformance improvement techniques. The focus has been given to studies of current in-depth permeability modifiers and highlight chemistry, applications and inadequacy of these technologies. Finally we briefly outline the major challenges, which must be addressed to successfully implement preformed cross-liked particles in improving sweep efficiency applications are highlighted.

Keywords: Conformance problems, polymer gels, preformed cross-linked gels

INTRODUCTION

Chemical enhanced oil recovery, surfactant-polymer or alkali-surfactant-polymer, is of increasing interest due to high oil price and the need to increase the oil production (Douarche, 2011). For the majority of oil reservoirs, large amount of oil left after extensive water flood (today average worldwide recovery factor is 32%) (Moreau *et al*., 2010). Chemical EOR technology is a promising tertiary recovery technique to improve both sweep and displacement efficiencies. Advancements in technologies and better understanding of failed projects made chemical EOR promising in future. Chemical flooding relies on the addition of one or more chemical compounds to an injected fluid either to reduce the interfacial tension between the reservoir oil and the injected fluid or to improve the sweep efficiency of the injected fluid (Ronald, 2001). There are three general methods in chemical flooding technology. The first is polymer flooding, in which a large macromolecule is used to increase the displacing fluid viscosity and thus control mobility. The mobility control process is based on creating a favorable mobility ratio to improve reservoir sweep efficiency. Figure 1 shows improvement of macroscopic displacement efficiency when using polymer flooding compared to water flooding. The second and third methods, micellar-polymer and alkaline flooding, make use of chemicals that reduce the interfacial tension between oil and a displacing fluid (Sheng, 2011).

Surfactant flooding is a fundamental chemical process, in which the key mechanism is to reduce interfacial tension between oil and a displacing fluid. The mechanism, because of the reduced IFT, is associated with the increased capillary number, which is a dimensionless ratio of viscous-to-local capillary forces. Experimental data show that as the capillary number increases, the residual oil saturation decreases (Lake, 1989). Figure 2 is a schematic representation of the capillary number correlation. The correlation suggests that a capillary number greater than 10-5 is necessary for the mobilization of unconnected oil droplets. Therefore, as IFT is reduced through the addition of surfactants, the ultimate oil recovery is increased (Ronald, 2001).

Corresponding Author: Abdelazim Abbas Ahmed, Department of Petroleum Engineering, UTP, 31750 Tronoh, Perak, Malaysia

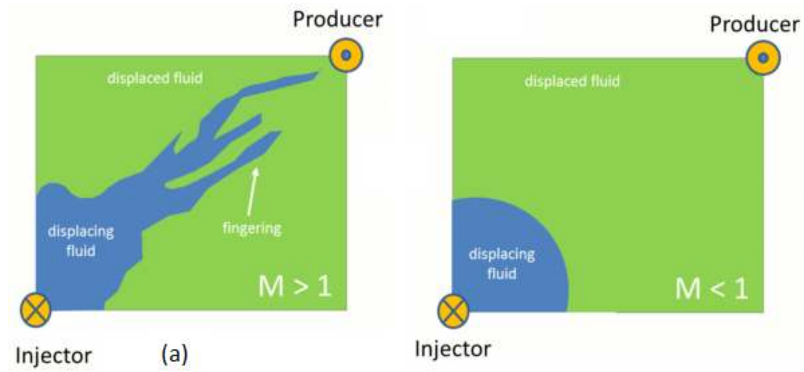


Fig. 1: Schematic of macroscopic displacement efficiency improvement by polymer flooding (b) over water flooding (a). Guenther glatz (Stanford University, 2013)

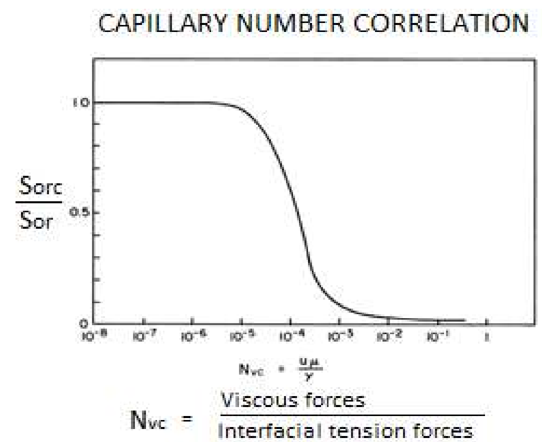


Fig. 2: Capillary number correlation (after Ronald, 2001)

In recent chemical EOR, the most important processes are to reduce the amount of injected chemicals and to fully explore the synergy of different processes. This effort has resulted in the Alkaline-Surfactant-Polymer (ASP) process. Laboratory investigations supported by pilot tests and full field applications have proven the greatest potential for enhancing oil recovery. However, some problems, such as poor reservoir conformance, formation damage, scaling and emulsion, have also emerged in practical applications (Sheng, 2011). The poor reservoir conformance problems are key challenges when trying to achieve optimum enhanced oil recovery with chemical EOR. The most important question to be answered when designing for example ASP flooding is, “where do the expensive fluid go?”. In order to answer this question, reservoir heterogeneities need to be considered since they affect vertical and areal conformance of fluids being injected (water or chemicals). Eventually, an injected fluid loses its effect after the oil from all the easily reached pores has been recovered, water or chemicals begins emerging from the production well instead of oil.

Reservoir heterogeneities as a result of inter-layer heterogeneity, geological layering and fractures are the most factors that significantly reduce the hydrocarbon recovery. Although, polymer or surfactant-polymer flooding can enhance the oil recovery, there are many authors reported that pilots or field applications projects have not achieved objectives due to reservoir heterogeneities. In the heterogeneous oil reservoirs polymer and/or surfactant fingering phenomena take places along high permeability anomalies (channeling and fractures).

The investigation carried out by Holley and Cayias (1992), to re-evaluate the design and operation of the surfactant-polymer pilot test in Ranger oil field, USA, showed that main problem encountered was massive reservoir heterogeneity. This caused over injection of surfactant and polymer into high permeability zones. And they concluded that pilot test did not achieve its design objectives because of reservoir heterogeneity and reduced sweep efficiency (Holley and Cayias, 1992). Another example is polymer injection conducted in the Wilmington field, California, USA; Kerbs analyzed the failure of this polymer flooding, in which 1.3 million Ib of polymer, at an average concentration of 213 ppm, was injected with no significant increase in oil recovery. One of the main causes of the failure was early polymer breakthrough due to the existence of high permeability zones, which was not considered as an important factor during the polymer flooding design stage (Krebs, 1976). According to Liu (2011) and Feng (2012), polymer flooding was successfully implemented in Daqing oilfield, China, which was the largest polymer flooding project in the world. As a result water cut at producers was reduced and oil recovery increased, by 10%. Despite there are 16 blocs polymer flooding blocks start after polymer water flooding, near 50% of reserve still remaining in reservoir and water breakthrough is very serious and water cut rise fast in oil producers (Liu *et al*., 2011).

As mentioned above, a conventional uncross-linked polymer can improve only adverse mobility ratio and it is most effective in relatively homogeneous reservoirs to mitigate viscous fingering problems as well as minimize early polymer breakthrough in offset ratio usually is complicated by permeability heterogeneity. In this case early and large amount of polymer production in producers is expected as well as un-swept oil will be left in low permeability zones. For successful implementation of any enhanced oil recovery process, reservoir heterogeneity risk need to be quantified and considered to reduce possible negative impacts on the performance of the EOR-flooding operations which increase chance of technical and economic success.

We first discuss the reservoir conformance problems and conformance improvement techniques that applicable for each case which can improve oil recovery through modifying the profile of the injected fluids. Review and outline the limitations of traditional *In-situ* gel systems and how these challenges have been mitigated by the new preformed cross linked polymer gel. Finally, we recommend and propose directions for future study.

Reservoir conformance problems: Overall displacement efficiency of any oil displacement process is the product of microscopic and macroscopic displacement efficiencies (Green and Willhite, 1998):

$$E = E_D\, E_V \tag{1}$$

where, E is overall displacement efficiency, E_D is microscopic displacement efficiency and E_V is macroscopic (volumetric) displacement efficiency. To increasing E, overall sweep efficiency, E_D and/or E_V should be increased.

The concept of volumetric displacement efficiency are effectiveness of displacing fluids in contacting the reservoir in volumetric sense. Therefore, E_V can be subdivided into areal and vertical sweep efficiency:

$$E_V = E_A\, E_L \tag{2}$$

producing wells. In most reservoirs, adverse mobility where, E_A and E_L are areal and vertical displacement efficiency, respectively. Since reservoir heterogeneity is spacial variation of rock properties, mainly permeability and porosity, it is significantly affecting volumetric sweep efficiency E_V. Accordingly, reservoir conformance is defined as the measure of the volumetric sweep efficiency during an oil-recovery flood or process being conducted in an oil reservoir (Borling *et al*., 1994). In context of reservoir producing with some kind of external fluid drive, conformance describes extend to which drive fluid uniformly sweeps the hydrocarbon toward the producing wells. A perfectly conforming drive provides a uniform drive across the entire reservoir; an imperfectly conforming drive fluid leaves un-swept pockets of hydrocarbon (Yang *et al*., 2005).

However, the effect of heterogeneity on immiscible displacement processes depends on horizontal and vertical non-uniformities that allow fluids to move preferentially through the high permeability porous medium. This can give justifications to why part of the oil in place to be bypassed in lower permeability areas (Robert and Laua, 2011). Injection profiles can be used to show where fluids enter the reservoir through the wellbore. To understand what conformance and conformance problems are about, Fig. 3 can visually shows the answer. As actual depicted in the figure, there is high permeability channel mid-way vertically within the matrix rock reservoir. This high permeability channel causes poor vertical conformance. Consequently early break-through of injecting fluid and un-swept oil located above and below high permeable channel. In Fig. 3b shows areal conformance, there is a vertical fracture that extends from the injection well to one of the four production wells.

Improvement of the conformance is in fact important during ASP floods. Poor conformance could substantially slow fluid output and delay production from pattern (Robert and Laua, 2011). The first

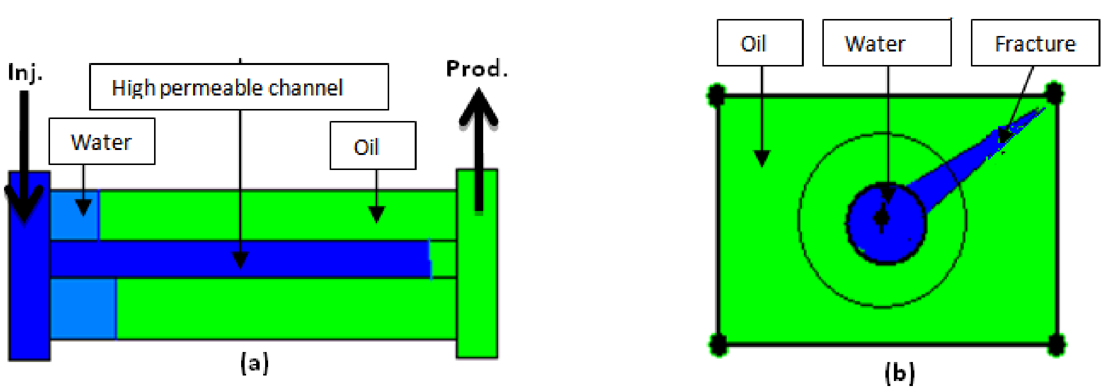


Fig. 3: (a) Matrix-rock channel (left) vertical conformance problems and (b) fracture (right) areal conformance problems (Robert and Laua, 2011)

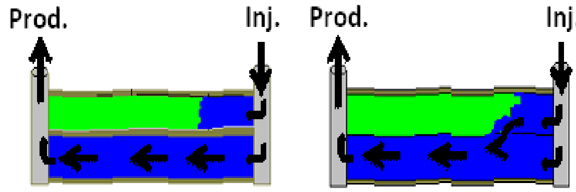
step of conformance is to understand and identify the flow of the fluids. This is done with careful and thorough reservoir characterization, with subsurface logs, cross well tomography, petro-physical laboratory analysis and 4-D seismic as part of that analysis.

Further information can be gained through by periodically conducting injection and production tests, by zone if applicable. These tests can be conducted with or without tracer chemicals. Geological surveys have also stated from the use of logs that there are many formations that follow a specific grain size distribution, which may translate into specific permeability variations in the vertical direction. Fining upward and fining downward (coarsening upward) are the main trends in this classification. Fining upward describes formations that consist of smaller grain sized particles and lower permeability at the top of the porous medium and coarser grains and higher permeability in the downward direction of the sequence of the formation. Fining downward cases are just the opposite. It consists of a permeability distribution that increases in the upward direction (Stiles, 1949). Wagoner *et al*. (1990), stated that, the main causes of vertical reservoir heterogeneities depend on the depositional environment of the formation and geologic time in which it occurs, having several geologic processes characterize the sedimentation of the reservoir.

As mentioned above, the recommended strategies during the design of any EOR operations are to build an appropriate reservoir conformance improvement to achieve the project intended goals and optimize the oil recovery.

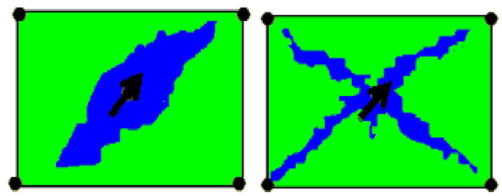
Typical oil conformance problems: The root cause of petroleum-reservoir conformance problem is spatial variation in the fluid-flow capacity because of reservoir permeability heterogeneity (Robert and Laua, 2011). In addition, conformance problems can be dominated by mobility induced viscous fingering (Sydansk and Seright, 2006). Typical oil conformance problems are described below. Reservoir conformance due to poor well integrity such as flow behind casing and casing leakage are not discussed in this study.

Layered reservoir without cross flow: In many reservoirs there are significant gradations in permeability from layer to layer (Azari and Soliman, 1996). Figure 4a shows the vertical conformance problem that involves high permeability matrix rock strata, zones or channels in matrix-rock reservoirs where there is no fluid cross-flow and pressure communication between the various reservoir strata. This conformance problem often results from geological strata from strata of differing permeability overlaying one another in petroleum reservoir.



(a) (b)

Fig. 4: (a) Rock matrix channeling without cross flow, (b) rock matrix channeling with cross flow



(a) (b)

Fig. 5: (a) Horizontal directional high permeability trend, (b) viscous fingering (poor mobility ratio)

Layered reservoir with cross-flow: Figure 4b illustrates same vertical conformance problem in the first case (a) except there is fluid cross-flow and hydrodynamic pressure communication between the two reservoir layers. The level of treating this type of conformance problem is a difficult. Cross-flow reduces the effectiveness of the post-treatment water-flood compared with the case with no interlayer communication (Abdo *et al*., 1984). Increasing viscosity of injected fluids can enhance the production to some extent. Because viscous fluid can follow same water preference pathways and bypassing oils in low permeability zones. The successful treatment depends on how deep into reservoir permeability modified.

Directional trends of high permeability: Areal conformance problem and associated poor sweep efficiency that is caused by areal directional high-permeability tends (Fig. 5a). This also is a difficult conformance problem to remedy.

Viscous fingering problems: Mobility induced viscous fingering, even in homogeneous reservoir, cause poor conformance during an oil-recovery flooding operation (Robert and Laua, 2011). This viscous fingering (Fig. 5b) results from the displaced oil having a higher viscosity than of displacing fluid (e.g., water). Mobility induced conformance issues are often compounded by heterogeneous reservoir permeability.

Water coning problems: Figure 6a, shows one of common type of water production problems. Water

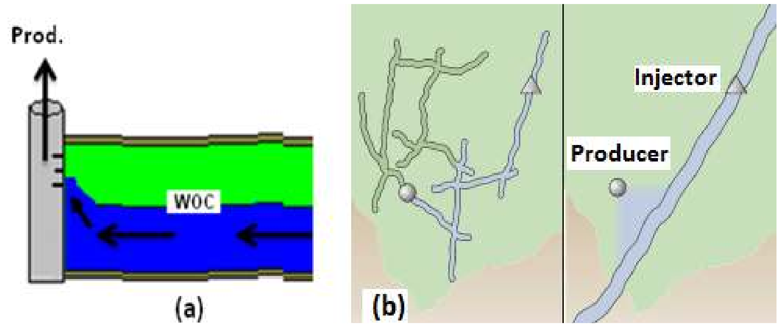


Fig. 6: (a) Matrix water coning, (b) fracture channeling problems

conning up to producing interval of a vertical well from an aquifer underline the oil Reservoir. Treatment of this vertical conformance problem also is very difficult. Most past treatments have shown temporary water reduction.

Fracture channeling (Fig. 6b): A direct communication between an injector and a producer may be present because of natural fractures or geological structures or it may have occurred by fracture stimulation treatments (Azari and Soliman, 1996). Fracture also causes areal conformance problem though a reservoir that possess natural fractures. Usually this can only be accomplished using aggressive profile modification strategies. Fracture-channeling has been successfully treated though the application of polymer gels.

TYPES OF CONFORMANCE-IMPROVEMENT METHODS

The general means that are employed to improve conformance in conventional oil reservoir are briefly discussed below.

Increasing the viscosity of the displacing fluid: Increasing the viscosity of the injection water is an effective means to promote conformance improvement within matrix rock oil reservoirs (Robert and Laua, 2011). High-molecular-weight water-soluble polymers in dilute concentration increase the viscosity significantly. Viscosity-enhancing power of a polymer is related to the size and extension of the polymer molecule in a particular aqueous solution (Sorbie, 1991). Two types of polymers are commonly used for mobility control in water floods; partially hydrolyzed polyacrylamide and xanthan biopolymers (Sheng, 2011; Shah, 2009; Bai, 2007a). HPAM has been used extensively with a great success in China's Daqing field (Sheng, 2011). When one fluid displaces several mobile fluids ahead, it is assumed that the displacing fluid mobility should be equal to or less than the total mobility of the several mobile fluids ahead (Gogarty, 1969; Gogarty *et al*., 1970; Lake, 1989). This is presently the most widely used means to improve conformance of viscous fingering. Improving mobility ratio has been found very effective in homogeneous reservoir. Polymer flooding cannot be applied efficiently in reservoirs having a high heterogeneity due to early breakthrough in high-permeability channels, hence poor sweep efficiency (Yang *et al*., 2005). Although increasing viscosity of the injected water by using high polymer concentration will improve sweep efficiency, the loss of well injectivity and high cost still remain challenging.

Increasing the permeability of low perm zones: Another method to improve conformance within the reservoir rock phase is to increase the permeability and/or the flow capacity of reservoir low-permeability flow paths. For conformance-improvement purpose the application of this technique is mostly limited to the relatively near-wellbore region of injection wells.

Improving conformance through the wellbore: There are many techniques that can be effective for use in improving conformance in conventional reservoir, where the techniques are not applied within rock of an oil reservoir. This type of conformance called mechanical methods, which applied at, or within, the wellbore especially when there is a matrix geological strata of differing permeability overlying one another with no cross-flow between them.

Reducing the permeability of high perm zones: Reducing permeability or totally plugging High-Permeability flow channels and/or anomalies is the second most widely applied method to promote conformance improvement within the oil reservoir itself (Robert and Laua, 2011). The objective of *In-situ* permeability-modification process is to treat the reservoir in such a way that the effective permeability of the high-permeability zones is significantly reduced (Bai, 2007a). This means of improving conformance is applied within the rock of the reservoir and is not applied in or at the wellbore.

Permeability-reducing conformance-improvement technologies: There are two distinct conformance-improvement techniques that can be applied within the oil-reservoir rock itself. The first technique is to increase the viscosity of displacing fluid (polymer flood). The second technique is the placement of a permeability-reducing material in the high permeability channels (e.g., polymer gels). The permeability reduction techniques will be further discussed below.

There are two main materials categories that can be used to reduce high permeability channels, silicate system and polymer based gels. Silica based systems have been widely used in the past. Nevertheless, their application is diminished due to its relatively bigger particle size and brittle nature (Robert and Laua, 2011). Recently, research studies have again explored the potential of SiO_2 nanoparticle in enhanced oil recovery and conformance control. Recently advances in Nanoparticles (NPs) silica base engineering have shown a great possibility of using them as EOR agents. NPs proved to increase CO_2 and surfactant mobilities as well as ability to change rock wettability and thermo stability at high reservoir temperature (Shah, 2009; Le *et al*., 2011; Onyekonwu and Ogolo, 2010). Nguyen *et al*. (2012) studied synergistic blend of composite SiO_2-core/polymer-shell nanoparticles with surfactant for EOR in high-temperature and high brine hardness offshore reservoirs. Their experiment results showed that clear enhancement in both fluid-flow viscosity and lower oil-water IFT and thermostability at 92°C (Nguyen *et al*., 2012).

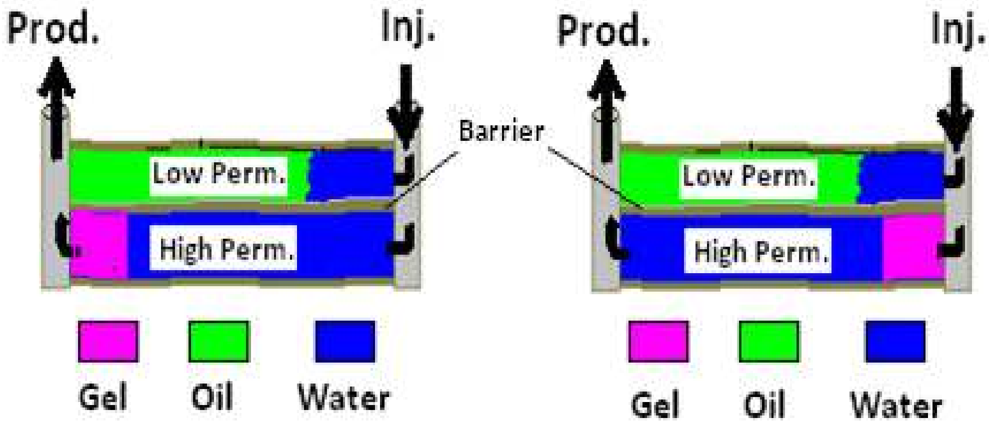
Polymer gel is a polymeric material that has both solid and liquid-like properties. Gels are mostly liquid in composition in terms of weight and volume and their structure is a solid like. Improving the conformance and/or sweep efficiency for any given injected fluid during a reservoir flooding operation involves improving one, or both, of two components of flood sweep efficiency: vertical and areal sweep efficiency. Gels have proved to be one of the most effective and popular materials for use in reducing permeability (Abdo *et al*., 1984; Seright *et al*., 2003; Bai *et al*., 2007). In principle, there are two methods of polymer gel injection-bulk gel and Sequential. In bulk gel injection, polymer and cross-linker are mixed at surface to form a homogeneous gel solution and then injected into formation. High polymer and cross-linker concentrations make it uneconomical to inject large volumes of gel to correct in-depth problems. Also, rapid cross-linking reaction rate make in-depth placement difficult. In contrast, sequential gel injection involves injecting slugs of polymer and crosslink separately, resulting in the formation of layers of polymer and cross-linker forming on pore walls within the rock also referred to as *In-situ* gel. This type of gel has been used in the past to try and achieve in-depth placement by keeping polymer and cross-linker separated until they are in the formation. Because it is difficult to control the transport and reaction of chemicals in heterogeneous reservoirs, the success of field applications of *in situ* gelation has been mixed (Mack and Smith, 1994).

The state-of-art technology in polymer gel process is to form particles gel at surface same like the bulk gel approach and inject the particles into reservoir. The descriptions and limitations of traditional *In-situ* gel and new preformed cross linked polymer will be discussed in the following.

Technology 1:
***In-situ* gel system:** *In-situ* polymer gels are classical gels where cross-linked polymer network is essentially infinite in nature. *In-situ* gelling system is usually composed of polymer, cross-linker and some other additives (Sheng, 2011). Polymer is usually HPAM and cross-linkers can be the compounds of Cr^{3+}, Cr^{6+}, or Al^{3+}. Additives are used to adjust gelation time, control gel strength and thermo-stability. The gelant, mixture of polymer and cross-linker, is injected into a target formation and cross-linking reaction take place in the formation mainly via temperature effect to form gel and thus completely or partially seal the formation where gel is placed. Therefore the gelation process occurs in reservoir conditions.

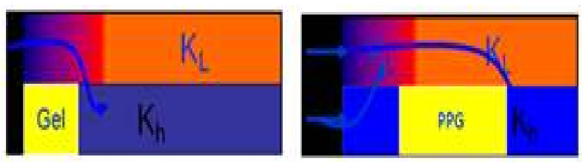
Benefits and limitations of this technology: *In-situ* cross-linked polymer gels have been used in the past attain deep placement into reservoir by keeping polymer and cross-linker separated until they are in the formation. In Fig. 7 *In-situ* gel has been successfully applied to producer or injector when there barrier between zones. Why it's success because it has lower cost, easy to make up, adjustable strength and good injectivity. However, there are distinct drawbacks inherent in *in-situ* gelation systems, such as uncontrolled gelation and variations in gelation due to shear degradation and gelant compositional changes induced by contact with reservoir minerals and fluids (Bai, 2007a). In addition, *in-situ* gelation systems behave as a polymer solution before gelation. According to polymer flooding mechanisms, polymer solution will more enter the zones unswept by water during water flooding. Once gelant forms gel in unswept zones, it will seriously damage the potential oil production zones.

Technology 2:
Preformed cross-linked polymer gels: A new trend of soft solid-particle-like for conformance-improvement technologies was developed and reported as an effective method for deep profile control and/or relative permeability modification for water production control (Bai, 2007a; Zaitoun *et al*., 2007; Rousseau *et al*., 2005; Frampton *et al*., 2004; Pritchett *et al*., 2003; Chauveteau *et al*., 2003, 2004). There are different types of preformed cross-linked gels mainly different in



(a) (b)

Fig. 7: Suitable and successful application of *in-situ* gelation either in producer or injector



(a) (b)

Fig. 8: Advantages of preformed particle gel (b) compared to *in-situ* gelation (a) Bai (2007b, 2008)

their particle sizes and plugging mechanisms. These types of gel can overcome the problems associated with *In-situ* gel system (technology 1). Because of formed at surface, so they do not have prior reaction control problems. However, for preformed particle gel to effective modify permeability deep propagation, good selectivity plugging and high retention need to be achieved.

Benefits and limitations of this technology: Preformed cross-linked polymer gel has become an interesting study and research issues. Because of it is relatively low cost, environmentally friendly and controllable size. In addition, 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 gelantcompositions and dilution by formation water. Nevertheless, some of developed cross-linked polymer gels are difficult to place deep in the reservoir because they cause a very high-pressure drop near the injection well and also tend to show mechanical trapping and filtration (Sheng, 2011). Figure 8 shows the deep profile modification to the high permeability zone and diverts the injected fluid to the less swept zone.

TYPICAL PREFORMED CROSS-LINKED GEL

Preformed Particle Gels (PPG): PPG are permeability reducing agents that are gaining attention and popularity for use in conformance-improvement. Preformed Particle Gel (PPG) is formed at surface facilities before injection; the formed bulk gel is crushed to particles and then is injected into reservoirs (Bai *et al*., 2007). PPG have the following unique advantages over traditional *In-situ* gel, including:

- PPG are strength- and size-controlled, environmentally-friendly and they are stable in the presence of almost all reservoirs minerals and formation water salinity.
- PPG 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
- PPG has only one component during injection.
- PPG can be prepared with produced water without influencing gel stability. Tow largely forms of PPG for treating high-permeability anomalies (e.g., fracture) has been developed and widely applied (Robert and Laua, 2011). The first PPG is first established and initially applied in china (Abbasy *et al*., 2008). This PPG involves aqueous gel particle that are formed by polymerizing the acrylamide monomer with N, N'-methyl-enebisacrylamidecross-linker. The result bulk gel is then disaggregated into preformed gel particles. The Second PPG was primary developed in the United State (Smith, 1995). This PPG involves swell-able aqueous-gel particles that are

manufactured gel particles involving cross-linked specially sodium-acrylate-base polymers. However, the PPG injectivity and mechanisms to control conformance and its applied conditions are still questionable to many reservoir engineers because its size is usually much larger than the pore sizes of conventional cores from reservoirs. Table 1 illustrates the comparison of main feature of in-site gel and PPG and current available gels (Borling *et al*., 1994).

Micro gel systems: Micro gels are colloidally stable hydrogelsparticle that are formed at low polymer concentration below the polymer's critical overlap concentration in the gel make up brine. Micro gel conformance-improvement technologies are often intend to be placed in and function, deeply (far wellbore) in matrix rock reservoir (Robert and Laua, 2011). Such microgel technology includes narrow-particle width-size microgels, Colloidal Dispersion Gel (CDGs) and preformed nano-sizedcross-linked-polymer gel particle.

Thermally activated micro-particles (brightwater): The particles are designed to pop/swell-in-size by factor of roughly 10 after being placed deep in the reservoir and after experiencing some gel-particle-popping trigger, usually increased reservoir temperature (Frampton *et al*., 2004; Pritchett *et al*., 2003). This Bright Water is systems of time-delayed, highly expandable thermal sensitivity particles. The material is a highly cross-linked, sulfonate-containing polyacrylamide micro-particle in which the conformance is constrained by both labile and stable internal cross links (Robert and Laua, 2011). When subjected to elevated temperatures, the rate of decross-linking of the labile cross-linker accelerates. This reduces the crosslink density of particle and allows particle to expand by absorbing the surrounding water. The preparation of these types of microgels is using inverse-emulsion-polymerization process to assure a preselected particle size range. Depending on synthetic method, the original particle diameter of polymeric microparticle can be made ranging approximately from 0.1 to 3 μm. The product called Brightwater was

Table 1: Gels used for conformance control

Parameters	*In-situ* gel system	Preformed cross-linked gel
Injection	Gelant is injected into formation and gel is formed under reservoir conditions	Gel is formed in surface facilities before injection
Gelation	Take place in the reservoir	Take place in surface facilities
Cross-linking reactions	Reactions affected by pump shear, formation water dilution, adsorption and chromatography separation	Gel reactions is controlled at surface
Possibility to damage formation	Cause damage to the un-swept low permeability zone	Possible no damage to low permeability zone

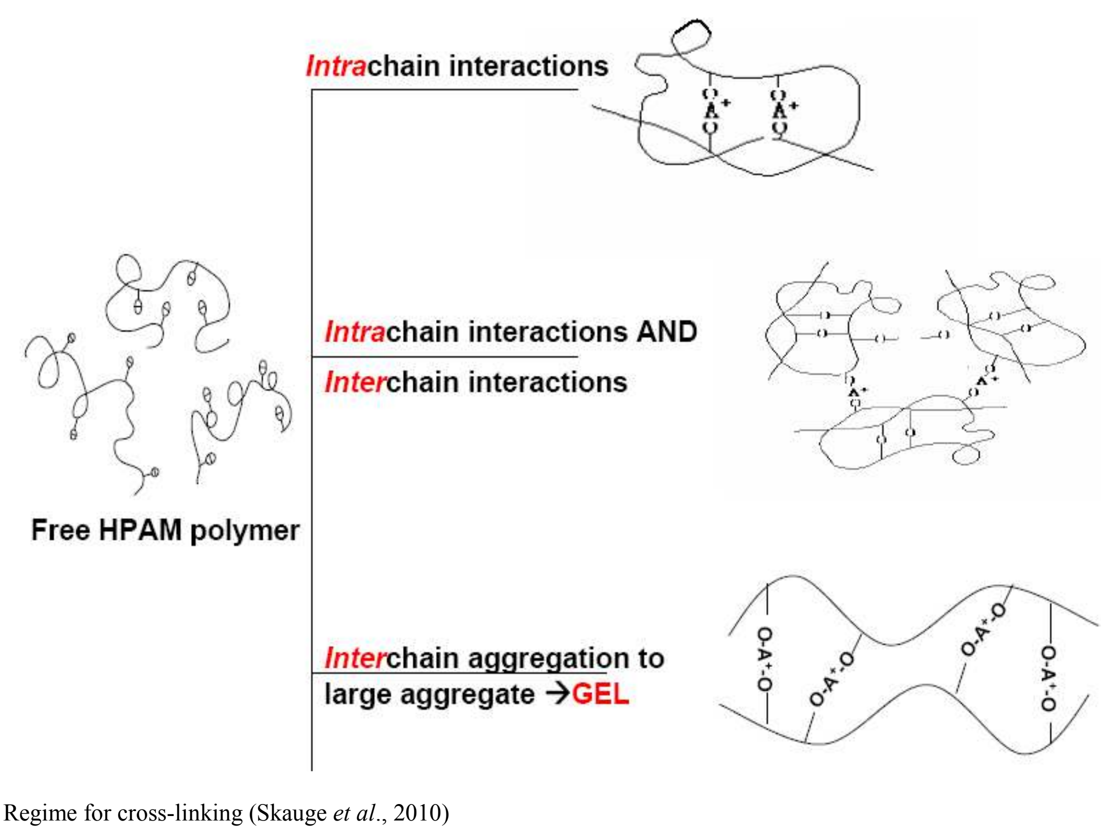


Fig. 9: Regime for cross-linking (Skauge *et al*., 2010)

developed by an industry consortium formed by BP, Chevron, Mobil and Nalco. There are several commercial products, applicable in rage of temperature (35-140°C) and salinity up 120000 ppm TDS.

Colloidal Dispersed Gel (CDG): CDGs are a conformance-improvement technology that has been widely applied (Mack and Smith, 1994; Smith, 1995; Wang, 2008) for the purpose of improving conformance deep in heterogeneous "matrix-rock" in sandstone reservoir. CDG defined as dilute aqueous solutions of cross-linked polymer molecules. In the literature, they are known as movable gel, weak gel, weak viscoelastic fluid, Linked Polymer Solution (LPS), intra-molecular cross-linked polymers (Maleki, 2005) or deep diverting agent. CDG is made of low concentration of polymer and cross-linkers. CDG aqueous microgels are formed by cross-linking 100 to 1200 ppm high molecular weight hydrolyzed-polyacrylamide polymer with aluminum citrate or chromic-triacetate cross-linkers. The ratio of polymer to cross-linker is 10 to 100. The basic idea is that the CDGs will flow as a viscous solution above a certain differential pressure, called the transition pressure (Smith, 1989).

Preformed nano-sized cross-linked polymer gel: In the field of conformance improvement technologies, nanotechnology offers to transform EOR mechanism and process (Fletcher, 2010). Nano-sized cross-linked gels are promising for enhancing oil recovery in heterogeneous oil reservoirs. Thermally activated nano-particle gel (Brightwater) has been field-tested for improving oil recovery. Nano-sized cross-linked gels or also known linked polymer system (LPS, Eq. (3) and (4)) is a new interesting trend for in-depth permeability modification, which formed by cross-linking of Acrylamide-Polymer (HPAM) /Aluminum-Citrate (AlCit):

$$\mathrm{AlCit} \leftrightarrow \mathrm{Al}^{3+} + \mathrm{Cit}^{-2} \quad (3)$$

$$Al^{+3} + HPAM \leftrightarrow LPS \quad (4)$$

Figure 9 shows the cross-linking interaction between HPAM and AlCit. LPS formulations are likely to have a mix of intra- and inter-chains cross-linking. Whether the solution is dominated by intra- or intermolecular interactions depends on a number of factors including polymer type and concentration, ratio of polymer to crosslink, salinity and reaction temperature. Nano-particle cross-linked polymer can potentially offer significant advantages in terms of smaller particle size (50-400 nm), good stability at both high temperature (85°C) and high salinity (35000 μg/g), but more systematic studies are required to understand pore plugging mechanisms, selectively propagation in matrix rock and optimized conditions are needed to obtain controllable size and reproducible systems.

CONCLUSION

- Permeability variation as a result of inter layer heterogeneity, geological layering and fractures significantly reduce oil recovery and increase water production. Poor reservoir conformance problems are key challenges when trying to achieve optimum enhanced oil recovery.
- Polymer flooding has proven to enhance oil recovery through reducing water mobility and thus reduce viscous fingering phenomena. In most reservoirs viscous fingering is magnified by reservoir heterogeneity. Thus polymer flooding is not ideal for conformance treatment.
- Polymer gels made of partly Hydrolyzed Polyacrylamide (HPAM) cross-linked ionically with chromium acetate or aluminum citrate is widely used in oil field applications due to the versatility of HPAM.
- Various types of preformed particle gel are studied to provide in-depth-permeability modifier included PPG, thermally activated microparticle and CDGs. They are mainly different in their particle sizes and plugging mechanisms.
- Recent studies reveal a new possibility of using nanoparticle cross-linked polymer that formed by intra-molecular cross-linking of low concentration of HPAM with aluminum citrate, as in-depth permeability modifier. Because of its higher retention in porous media, low polymer concentration, more resistance to shear rate and high thermal stability compared to uncross-linked polymer make it attractive in future. But pore plugging mechanisms, propagation in matrix rock and whether it is really superior to uncross-linked polymer are questionable.

REFERENCES

Abbasy, I., J. Vasquez, L. Eoff and D. Dalrymple, 2008. Laboratory evaluation of water swellable materials for fracture shutoff. Proceeding of the SPE North Africa Technical Conference and Exhibition. SPE 111494, Marrakech, Morcco, March 12-14.

Abdo, M.K., H.S. Chung and C.H. Phelps, 1984. Field experience with floodwater diversion by complexed biopolymers. Proceeding of the SPE/DOE Symposium on Enhanced Oil Recovery. SPE 12642, Tulsa, Oklahoma, USA, April 15-18.

Azari, M. and M. Soliman, 1996. Review of reservoir engineering aspects of conformance control technology. Proceeding of the Permian Basin Oil and Gas Recovery Conference. SPE 35171, Midland, Texas, USA, March 27-29.

Bai, B., 2007a. Performed particles gel for conformance control. University of Missouri.

Bai, B., 2007b. Conformance control by preformed particle gel: Factors affecting its properties and applications. Paper SPE 89468, Aug 2007, pp: 415-421.

Bai, B., 2008. Case study on preformed particle gel for in-depth fluid diversion. Proceeding of the SPE/DOE 16th Symposium on Improved Oil Recovery (IOR, 2008). Tulsa, OK, USA, April 20-23.

Bai, B., L. Liangxiong, L. Yuzhang, L. He, W. Zhongguo and Y. Chunmei, 2007. Preformed particle gel for conformance control: Factors affecting its properties and applications. SPE Reserv. Eval. Eng., 10(4): 415-422.

Borling, D., K. Chan, T. Hughes and R. Sydansk, 1994. Pushing out the oil with conformance control. Oilfield Rev., 6(2): 44-58.

Chauveteau, G., R. Tabary, M. Renard and A. Omari, 2003. Method for preparing microgels of controlled size. US Patent 6579909 B1, 17 June 2003.

Chauveteau, G., R. Tabary, N. Blin, M. Renard, D. Rousseau and R. Faber, 2004. Disproportionate permeability reduction by soft preformed microgels. Proceeding of the 14th SPE/DOE Improved Oil Recovery Symposium. Tulsa, USA, April 17-21.

Douarche, F., 2011. Modeling Chemical EOR Processes: From Lab to Reservoir Scale. IFP Energies Nouvelles, Reservoir Engineering Division 1 et 4, France, February 15, Retrieved from: http://ceor-alliance.com/wp-content/ uploads/ EAGE2011- ASP-MODELING2.pdf.

Feng, H., 2012. Study of the multiple-profile control system to enhance oil recovery after polymer flooding. J. Petrol Explor. Prod. Technol., 2: 133-139.

Fletcher, A., 2010. How EOR can be transferred by nanotechnology. Proceeding of the SPE Improving Oil Recovery Symposium. Paper SPE 129531, Tulsa, USA, April 24-28.

Frampton, H., J.C. Morgan, S.K. Cheung, L. Munson, and K.T. Chang 2004. Development of a novel waterflood conformance control system. Proceeding of the SPE/DOE 14th Symposium on Improved Oil Recovery (IOR, 2004). Tulsa, OK, USA, April 17-21.

Gogarty, W., 1969. Processes for the simultaneous displacement of petroleum and water in formations. US Patent No. 3,443,636, May 13.

Gogarty, W. and H.P. Meabon and H.W. Milton, 1970. Mobility control design for miscible-type waterfloods using micellar solutions. J. Petrol. Technol., 22(2): 141-147.

Green, D.W. and G.P. Willhite, 1998. Enhanced Oil Recovery. Textbook Series, Richardson, Texas, 6: 73-75.

Holley, S.M. and J.L. Cayias, 1992. Design, operation and evaluation of a surfactant/polymer field pilot test. SPE Reservoir Eng., 7(1): 9-14.

Krebs, H.J., 1976. Wilmington field, California, polymer flood: A case history. J. Petrol. Technol., 28(12): 1473-1480.

Lake, L., 1989. Enhanced Oil Recovery. Prentice Hall, Englewood Cliffs, New Jersey.

Le, N.Y.T., D.K. Pham, K.H. Le and P.T. Nguyen, 2011. Design and screening of synergistic blends of SiO2 nanoparticles and surfactants for enhanced oil recovery in high-temperature reservoirs. Adv. Nat. Sci. Nanosci. Nanotechnol., 2(3).

Liu, H., Y. Wang, G. Li and H. Shang, 2011. An enhanced oil recovery technology continually after polymer-flooding. Proceeding of the SPE Enhanced Oil Recovery Conference. Kuala Lampur, Malaysia, July 19-21, 2011.

Mack, J. and J. Smith, 1994. In-depth colloidal dispersion gels improve oil recovery efficiency. Proceeding of the SPE/DOE Improved Oil Recovery Symposium. Tulsa, Oklahoma, USA, April 17-20.

Maleki, A., 2005. Effect of shear on intramolecular and intermolecular association during cross-linking of hydroxyethylcellulose in dilute aqueous solutions. J. Phys. Chem. B, 109: 12329-12336.

Moreau, P., M. Morvan, P. Rivoal, B. Bazin, F. Douarche, J.F. Argillier and R. Tabary, 2010. An integrated workflow for chemical EOR pilot design. Proceeding of the SPE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA, April 24-28.

Nguyen, P.T., B.P.H. Do, D.K. Pham, Q.T. Nguyen, D.Q. Pham Dao *et al*., 2012. Evaluation on the EOR potential capacity of the synthesized composite silica-core/ polymer-shell nanoparticles blended with surfactant systems for the HPHT offshore reservoir conditions. Proceeding of the SPE Reservoir International Oil Nanotechnology Conference. Noordwijk, Netherlands, June 12-14.

Onyekonwu, M.O. and N.A. Ogolo, 2010. Investigating the use of nanoparticles in enhancing oil recovery. Proceeding of the Nigerian Annual International Conference and Exhibition. Tinapa-Calabar, Nigeria, 31 July-7 August.

Pritchett, J., H. Frampton, J. Brinkman, S. Cheung, J. Morgan, K.T. Chang, D. Williams and J. Goodgame, 2003. Field application of a new in-depth waterflood conformance improvement tool. Proceeding of the SPE International Improved Oil Recovery Conference in Asia Pacific. Kuala Lumpur, Malaysia, Oct. 20-21.

Robert, D.S. and R.Z. Laua, 2011. Reservoir conformance improvement. Society of Petroleum Engineers, Richardson, TX.

Ronald, E., 2001. Enhanced Oil Recovery. University, Academic Press 2001.

Rousseau, D., G. Chauveteau, M. Renard, R. Tabary, A. Zaitoun, P. Mallo, O. Braun and A. Omari, 2005. Rheology and transport in porous media of new water shutoff/conformance control microgels. Proceeding of the SPE International Symposium On Oilfield Chemistry. Houston, TX, USA, Feb. 2-4.

Seright, R.S., R.H. Lane and R.D. Sydansk, 2003. A strategy for attacking excess water production. Proceeding of the SPE Permian Basin Oil and Gas Recovery Conference. Midland, Texas, May 15-17.

Shah, R.D., 2009. Application of nanoparticle saturated injectant gases for EOR of heavy oils. Proceeding of the SPE Annual Technical Conference and Exhibition. New Orleans, Louisiana, USA, October 4-7.

Sheng, J.J., 2011. Modern Chemical Enhanced Oil Recovery: Theory and Practice. Gulf Professional Publications, Amsterdam, Boston.

Skauge, T., K. Spildo and A. Skauge, 2010. Nano-sized particles for EOR. Proceeding of the SPE Improved Oil Recovery Symposium. Tulsa, Oklahoma, USA, April 24-28.

Smith, J.E., 1989. The transition pressure: A quick method for quantifying polyacrylamide gel strength. Proceeding of the SPE International Symposium on Oilfield Chemistry. Houston, Texas, USA, February 8-10.

Smith, J.E., 1995. Performance of 18 polymers in aluminum citrate colloidal dispersion gels. Proceeding of the SPE International Symposium on Oilfield Chemistry. San Antonio, Texas, USA, February 14-17.

Sorbie, K., 1991. Polymer-Improved Oil Recovery. Blackie, Glasgow and London.

Stiles, W.E., 1949. Use of permeability distribution in water flood calculations. J. Petrol. Technol., 1(1): 9-13.

Sydansk, R.D. and R.S. Seright, 2006. When and where relative permeability modification water-shutoff treatments can be successfully applied. Proceeding of the SPE/DOE Symposium on Improved Oil Recovery. Tulsa, Oklahoma, USA, April 22-26.

Wagoner, J.C.V., R.M. Mitchum, K.M. Campion and V.D. Rahmanian, 1990. Siliclastic sequence stratigraphy in well logs, cores and outcrops: Concepts for high-resolution correlation of time and facies. AAPG Methods Explor. Ser., 7: 3-55.

Wang, D., 2008. Key aspect of project design for polymer flooding at the daqin oil field. Proceeding of the SPE 89464-PA Reservoir Evaluation and Engineering.

Yang, Y., H. Liu, J. Wang and F. Wang, 2005. A new method for profile control with compound ion gel before polymer flooding. Paper SPE 93359. Technical Report, Daqing Oilfield Co. Ltd.

Zaitoun, A., R. Tabary, D. Rousseau, T.R. Pichery, S. Nouyoux *et al*., 2007. Using microgels to shut off water in a gas storage well. Proceeding of the International Symposium on Oilfield Chemistry. Houston, 28 February-2 March.