



Retention characteristics of enhanced preformed particle gels (PPGs) in porous media: Conformance control implications

Hamid Reza Saghafi¹

EOR/IOR Research Institute, National Iranian Oil Company, Tehran, Iran



ARTICLE INFO

Keywords:

Preformed particle gel (PPG)
Conformance control
Retention
Particle size

ABSTRACT

Preformed Particle Gels (PPGs) treatment can be mentioned as one of the most reliable methods to enhance conformance control in mature water flooded oil reservoirs. Prediction and evaluation of PPGs' behavior through porous media is essential. In this contribution, advanced PPGs designed for reservoir with high temperature and high salinity conditions will be presented. Special slim tubes, filled with crushed reservoir core samples, were used to assess the impacts of various factors on the Preformed Particle Gels (PPGs) retention at reservoir conditions. The factors whose impacts were assessed included the diameter of the PPGs, the temperature, the rate of flow as well as the porosity of the medium. The results showed for passage pattern, adsorption was the dominant mechanism in retention of PPGs and retention increased when smaller size of PPGs product was used. Results also showed that PPGs retention decreased as the flow rate, permeability and temperature of the porous media increased. According to the findings of the breakage-passage pattern, if the ratio of swelled PPGs size to pore throat size increases to a particular, entrapment will be the main mechanism in retention process and retention increased dramatically by using a larger size of PPGs product and lower permeability of porous media. Accordingly, the findings of the study are enlightening especially in the area of choosing the most suitable strategy for effective regulation of conformance in the oil reservoirs.

1. Introduction

Notably, researchers have put a special focus on the studies to investigate how the efficiency of the water flooding sweep can be enhanced. Water injection can lead to undesirable effects because of the diversity of the geological characteristics of the oil reservoirs. For instance, it can cause unstable and irregular flooding of the oil all over the reservoir. In addition, high water cut generates additional costs due to corrosion and scale deposition. Besides, it adds an extra expense of water-oil separation. High water cut reduces the productivity of the reservoir, while increasing the expenses (Almohsin et al., 2014; Bai and Zhang, 2011; Imqam et al., 2014; Seright, 1997). As such, scholars are interested in finding ways of improving the efficiency of the water flooding sweep (Almohsin et al., 2014; Bai and Zhang, 2011; Imqam et al., 2014; Seright, 1997).

Accordingly, the cross-linked polymer gel has been the conventional technology used to regulate conformance (Chauveteau et al., 2003; Durán-Valencia et al., 2014; Elsharafi and Bai, 2013; Goudarzi et al., 2015; Imqam and Bai, 2015; Sang et al., 2014). Nonetheless, this technology has the disadvantage of unmanageable gelation times. Besides, the technology yields disparity in gelation time. This problem

partly results from the shear degradation. Further, the problem is aggravated by the changes in the composition of the gelant. These changes occur when the gelatin interacts with the minerals and fluid in the oil well (Goudarzi et al., 2015; Imqam and Bai, 2015; Saghafi et al., 2016b). Moreover, before gelation, the in-situ gelation system acts as a polymer solution. During a polymer injection process, flood of polymer enters more in the media swept by water during previous water flooding practice. However, on the occasion that gelant forms gel in unswept medium, it will extremely impair the hydrocarbon recovery of the reservoir (Bai et al., 2009).

However, the Preformed Particle Gels (PPGs) technique has overcome the limitations of the cross-linked polymer gel technique. The PPGs are hydrophilic polymeric particles with elastic properties. They are powder products containing of cross-linked polymers that swells when they are dispersed in the injection saline water to be used in the normal water injection process. This technology has some advantages over conventional in-situ gels:

One of the advantages of the PPGs is that they are eco-friendly. Secondly, their size and strength can be varied. Thirdly, their mechanical properties can be controlled. Also, their swelling ratios can be adjusted. In addition, they remain stable in most formations of water

E-mail address: saghafi.saghafi@gmail.com.

¹ Tel.: +98 9153058016.

salinities. Having one component in addition to easy preparation with water are other advantages of this system. Also, they enter into channels and fractures while lessening penetration of gel into tight rocks (i.e., zones having low permeability) (Bai et al., 2007, 2008; Tang, 2007). Field applications of PPGs have had very positive results (Bai et al., 2008); In China, the PPGs technology has been employed in over 4000 wells to minimize fluid channeling in flooding operations (Bai et al., 2013).

Certainly, the PPGs have a greater potential and are more efficient in accessing a successful retention in case of flooding. This efficacy and potential can be attributed to the interaction between the particles and the surface of the formation. In a flooding scenario, the deepness of penetration of the microgel is determined by the retention level (Chauveteau et al., 2004; Cozic et al., 2008). Notably, the size and shape of the adsorbed particle can change. As such, the diameter of the adsorbed particle is inversely proportional to the shear rate. Alternatively, the diameter is directly proportional to the concentration. (Almohsin et al., 2014). Wang (2012) carried out PPGs flow experiments to study the PPGs propagation through a sand-packed model. The results indicated that PPGs with sizes larger than pore throats diameter passed through the porous media due to deformation caused by high pressure drops. The results further showed that PPGs migrated to the deep formation rather than deposition near the wellbore which is more favorable for in-depth dynamic profile control applications (Wang, 2012). There are few studies that investigate thermal effect on PPG migration. Al-Ibad and Civan (2013) developed empirical correlation to investigate the thermal effect on near wellbore treatment by particle gels. However, these few studies did not directly address the effect of temperature on PPGs retention. The chemical retention plays a major role in the success of any enhanced oil recovery process. As such, factors that affect the retention of the PPGs should be considered. The factors as named elsewhere in this paper include temperature, permeability, the thickness of the particles, as well as the injection flow rate. The study of these factors would be vital in understanding the flow behavior of Preformed Particle Gels in the reservoir. In a recent study, Saghafi et al. (2016c) prepared a new class of PPG. The PPG was meant to assess the conformance control in harsh reservoir conditions (i.e., high temperature and salinity). According to their findings, the new PPGs remained stable at a temperature of 145 °C and a salinity of 225,000 mg/L. Moreover, in the same study, the scholars presented a rheological study that was aimed at developing a mathematical framework for predicting the storage modulus. Similarly, in related studies, the scholars examined various characteristics of PPGs namely, resistance factor, the residual resistance factor, as well as the viscous properties in the porous media (2016b). The results presented in this study are continuation of our previous researches on PPG (Farasat et al., 2017a, 2017b; Saghafi et al., 2016a, 2016b, 2016c). Here, the PPG retention characteristic during flow in porous media is systematically investigated.

2. Experiments

2.1. Additives

PPGs: Preformed Particle Gels: Enhanced PPGs were developed using various monomers as listed below:

- Acrylamide: 98.5% (purity)
- N,N-dimethyl acrylamide: 98.5% (purity)
- N,N-dimethyl acrylamide: 99.0% (purity)
- N,N-dimethyl acrylamide: 98.0% (purity)
- N,N'-methylenebis (acrylamide): 99.0% (purity)
- N,N',N,N'-tetramethylethylenediamine: 99.0% (purity)

The N,N'-methylenebis (acrylamide) was the linking agent, while N,N',N,N'-tetramethylethylenediamine, and sodium persulfate were the

catalysts and initiator for the synthesis of the polymer gel. All the material was obtained from Beijing Chemicals in China (Beijing). However, the nano clay montmorillonite Na⁺ was purchased from Aldrich (St Louis, MO, America). It was used for modifying the mechanical properties of the PPGs. Further, the nitrogen was obtained from DelvarAfzar Gas Industrial Group. It had a purity of 99.995%.

The Preformed Particle Gels in this experiment were prepared using a free-radical polymerization using a molar mass ratio of 2:1:1:2 of acrylamide, N,N-dimethyl acrylamide, N-vinylpyrrolidone, 2-acrylamido-2-methylpropane sulfonic sodium salt monomers. The monomers were polymerized with 0.55 wt % N,N'-methylenebis (acrylamide) as well as 2.5 wt% nano clay montmorillonite Na⁺ at a temperature of 27 °C (room temperature) in distilled water. The first phase of the manufacturing process entailed putting the Nano clay montmorillonite Na⁺ in distilled water that had been set aside for the process. Subsequently, the mixer was placed in an ultrasonic bath for duration of 4 hrs. All this time, the bath was in uninterrupted irradiation. Subsequently, the required quantity of acrylamide and N-vinylpyrrolidone monomers were weighed. They were then sprinkled lightly in the clay solution; whilst the stirring the solutions. N,N-dimethyl acrylamide, and 2-acrylamido-2-methylpropane sulfonic sodium salt monomers were then weighed and simultaneously added into the solution together with a particular temperature stabilizer. The solution was then stirred for 1 hr. This process was necessary; in order for all the monomers to be fully dispersed. Subsequently, a specific weight of the N,N'-methylenebis (acrylamide) was added. In this process, vigorous stirring endured and nitrogen riddance was used. After 40 min of vigorous stirring, weighed quantities of Sodium persulfate as well as the N,N,N',N'-tetramethylethylenediamine catalysts were put into the mixture. After that, the nitrogen riddance was discontinued. Within no time, the exothermic reaction had begun. Accordingly, the hydrogel formation manifested within half an hour. Subsequently, the gel was cut into pieces, then dried them in an oven at around 55 °C for 24 hrs. The drying was conducted under vacuum condition. The resultant product was the PPGs (see Fig. 1).

Crushed particles: The end pieces of the core from an offshore carbonate oil well in Iran were cleaned in Soxhlet extraction. The cleaning agent had been set up with a mixture of methanol and toluene for fourteen days. The setup had been maintained at a temperature of 90 °C. After the cleaning, the core plugs were pounded using a hammer in a pan. Subsequently, the materials were sieved and the ideal size was collected.

Slim tubes: slim, stainless steel tubes (Swagelok) measuring half-meter in length were used. The tubes were packed with the sieved crushed core. Subsequently, a fitting was put at each end of the tubes. This was meant to avoid the production of the sand particles. The use of varying sizes of the ground crushed particles, yielded more tubes of



Fig. 1. Dried PPGs.

Table 1
Specifications of slim tubes used in retention tests.

Slim tube Outside Diameter (mm)	Length (cm)	Internal Volume (cm ³)	Inside Radius (mm)	Thickness (mm)
25.4	50	176.41	10.6	2.10

varying permeability.

Table 1 shows the details of the slim tubes.

2.2. Experimental set up

The set up was made up of the following apparatus

- > Displacement pump (Vinci Technologies).
- > Transfer vessels for brine and gel solutions.
- > PC and a system for data acquisition
- > Pressure transducer

2.2.1. Retention tests

The preparation of experimental materials and apparatus for retention tests were as follows:

- 1 The PPGs are placed in distilled water with the desired concentration at room temperature until they are completely swollen.
- 2 The swollen PPGs are packed in the transfer vessel (recombine type) which is equipped with a piston and also another transfer vessel is filled with distilled water.
- 3 Two screw caps, equipped with an inlet and outlet nozzle, are used to pack the transfer vessels.
- 4 Recombine vessel is equipped with thermal jacket and its temperature is set at the desired value for 60 min before starting the test.
- 5 Slim tube is placed in the oven at the desired temperature for 60 min before the test starts.
- 6 A pressure transducer was connected to the inlet of the slim tube. It was used to record the pressure progressively.

Notably, there are higher chances of sand movement in slim tube experiments. In case of a sand movement, the high differential pressure is recorded within the slim tubes. Accordingly, a backflow is used to counter this issue. Therefore, after setting up the experiment as shown

in Fig. 2, the flow in the slim tubes was tested in order to assess the efficiency of the PPGs retention in permeable material.

The test was conducted in the following process:

- 1 The slim tube was weighed together with the devices connected to it; before filling it with the crushed core (A).
- 2 The slim tube packed with the crushed core was weighed together with its connection (B).
- 3 The weight difference between them is the weight of the crushed carbonate cores. (B-A)
- 4 Air was removed from the slim tube before flooding it with distilled water.
- 5 The volume of the pore space and the permeability were determined. The sand-packed tubes were flooded at varying rates of flow (between 5 and 40 ml/min), in order to determine the permeabilities of the media.
- 6 3000-ppm preformed particle gels solution was made using the specific weight of the dried PPGs. Sufficient pore volumes of the prepared solution were used to flood the slim tube. The process was continued for a minimum of half an hour; when the pressure fell to a stable value, and both the inlet and outlet achieved equal concentrations. The process was conducted at a favorable temperature.
- 7 The inlet and outlet diameters of PPGs should be monitored.
- 8 Several pore volumes of distilled water are injected at the same flow rate of step 6, until no PPGs can be found in effluent. The effluent from beginning of step 6 should be collected, dried and weighed.
- 9 Finally, the slim tube is held in the oven at 70 °C. Then, slim tube should be removed from the oven and its weight should be recorded weekly until its weight became constant for three consecutive weeks, which means its content is dried completely. (C)
- 10 Difference between C and B considered as the weight of the PPGs retention. (C-B)

All the experiments were conducted multiple times until the 4 successive weights were equal, within an experimental error of $\pm 1\%$.

Afterwards, the retention value for each slim tube was obtained using Eq. (1) shown below:

$$Re = \frac{PPGs\ Retention}{Rockweight} = \frac{1000 \times (C - B)}{B - A} \quad (1)$$

The numerator of equation (1) (C-B) is the difference between weight of dried slim tubes after PPG injection (C) and weight of filled



Fig. 2. The experimental set up for retention experiments.

slim tubes (with crushed carbonate cores) before PPG injection (B). The unit of equation (1) is mgr. of PPGs/gr. of rock. Results should be agreed with weights difference between the injected dried PPGs and collected dried effluent for each test.

It should be noted that as the proposed model is based on difference of dried weight of slim tubes after PPG injection, (C) and the weight of filled slim tubes, (B) (see equation (1)), presence of any salt in water leads to a significant error in the measurement of retention. Thus, equation (1) is only applicable for distilled water.

3. Results and discussion

When the PPGs solution flows through a porous rock, there is usually a measurable amount of PPGs retention. The retention was attributed to the surface adsorption, entrapment or both.

The following tests were carried out for measuring the retention amounts of the newly introduced PPGs into slim tubes packed with crushed carbonate reservoir rock under different conditions. This work addresses the effects of PPGs size, injection flow rate, temperature and media permeability on PPGs dynamic retention. It is worth to mention that adsorption of species in distilled water is more than in impure water, e.g. sea water (Appelo and Postma, 2005). Hence, the usage of distilled water causes the experiments to show the maximum value of PPGs adsorption in each case.

3.1. Effect of PPGs size

The prepared PPGs were crushed and sieved to obtain four varying particle sizes. The diameter of these particles was between the range of 40.5 μm and 89.5 μm. The diameter of the swelled PPGs was between 157 μm and 346 μm. The four tubes were then filled with sand material measuring between 600 μm and 850 μm in diameter. Subsequently, a corrected capillary model (Gruesbeck and Collins, 1982) was used to approximate the corresponding hydrodynamic pore thickness of the slim tube, D_{th} :

$$D_{th} = 2 \times 1.15 \sqrt{\frac{8k}{\phi}} \tag{2}$$

The ratio of PPGs diameter to pore throat diameter, which is opening-particle ratio, were calculated by using Eq. (2) and varied from 1.3 to 2.88 (See Table 2).

The temperature during the retention tests was maintained at 95 °C. Similarly, the rate of injection was maintained at a constant value of 0.5 ml/min. For the first three dry PPGs, the sizes of the corresponding swollen PPGs were observed at the inlet and outlet of the slim tubes. Accordingly, the swelled particle gels whose particle opening ratio was ≤ 2.21 passed through the permeable material. Their passage was linked to deformation and surface adsorption; as opposed to entrapment (See Fig. 3).

In addition, the results depicted in Fig. 4 overrule the presence of a monotonic tendency of retention. At first, increasing the average size of PPGs up to 68.5 μm led to the gradual decrease in retention. This tendency can be explained by the large size of the preformed particle gels, exhibiting a small surface area per unit weight. This makes the PPGs experience a decreased inclination towards the surface of pore.

Table 2
Slim tubes specification of retention tests-effect of PPGs size.

No.	PPGs size (mesh)	Permeability (Darcy)	Porosity (%)	Equivalent hydrodynamic pore diameter (μm)	Average PPGs diameter before swelling (μm)	Average PPGs diameter after swelling (μm)	Ratio of PPGs diameter to pore diameter
1	325	136	39.5	120	40.5	157	1.3
2	250	136	39		53.5	206	1.72
3	200	137	39.1		68.5	266	2.21
4	150	137	39.5		89.5	346	2.88

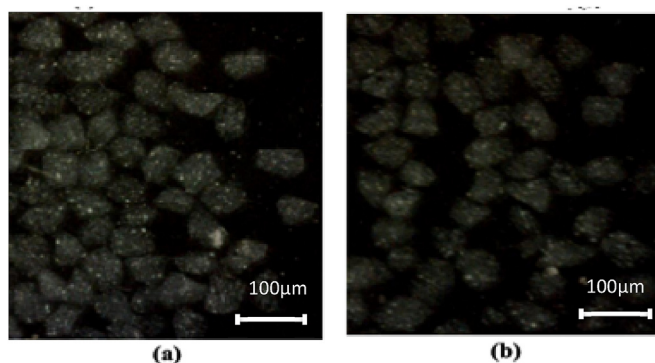


Fig. 3. PPGs size, 200 mesh (68.5 μm) (a) before and (b) after injection in porous media.

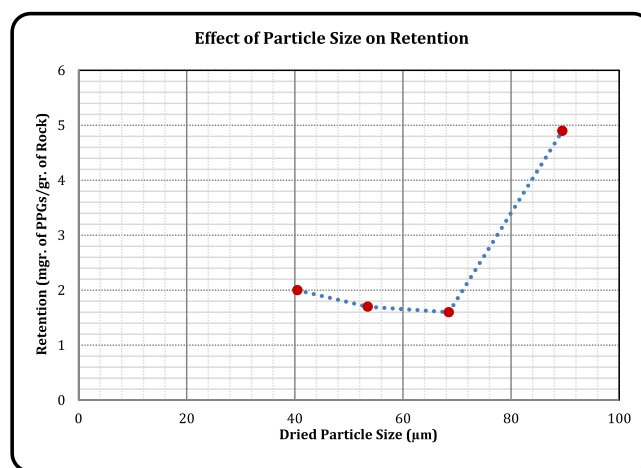


Fig. 4. Effect of PPGs size on retention in porous media.

Conversely, when the average diameter of the PPGs was increased from 68.5 μm to 89.5 μm, the retention increased significantly. In this case, it is clear that the rapid increment of the retention volume was being influenced by another principal factor rather than surface adsorption. As it is illustrated in Fig. 5, the dried particle gels of an average diameter of 89.5 μm were broken down and passed via the permeable material. This is an indication that when the swelled size to pore throat size ratio increases to 2.88, the particle gel is not able to pass through the permeable material due to deformation. Therefore, in such a scenario, the entrapment mechanism dominates the surface adsorption mechanism.

3.2. Effect of flow rate

The dried particle gel was sieved using a 250-mesh diameter. Subsequently, they were fully swelled in distilled water. Then, seven slim tubes were packed with sand material of a diameter ranging from 600 μm to 850 μm. The retention tests were then performed while the temperature was maintained at 95 °C. Subsequently, the corresponding

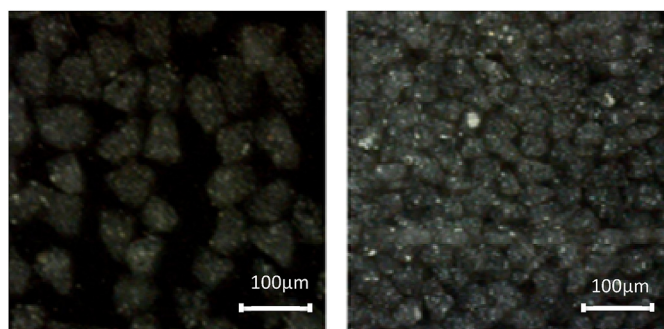


Fig. 5. PPGs size, 150 mesh (89.5 µm) (a) before and (b) after injection in porous media.

pore throat sizes were computed using equation (2). The ratio of PPGs size to pore throat size averaged at about 1.72 (See Table 3). The fact that this ratio was less than 2.0 is an indication that the particle gel deformed, and passed through the permeable media. It follows that the dominant factor in retention was the surface adsorption. This effect is supported by observing the sizes of the PPGs both at the inlet and outlet.

Fig. 6 shows that retention decreased as the flow rate increased. This phenomenon can be explained from two aspects. For higher flow rates, the duration of PPG contact in the media is much shorter and the amount of retention is lower. Furthermore, as it is known, there are many kinds of forces like electric force, gravity force, buoyancy force and drag force, which affect the particles movement in the porous media. When the flooding velocity is considerable, the drag force is the main force causes the particles to move (Zamani and Maini, 2009). This force depends mainly on the flow rate of carrying fluid. Therefore, increasing flow rate is equivalent to apply more drag force from fluid; resulting in higher deformation migration of particles deposited on the pore surface and lowers retention. By increasing flow rate to more than 0.5 ml/min the retention did not decrease further and minimum retention will be observed.

3.3. Effect of temperature

Four slim tubes were packed with sand particles whose size was between 600 µm and 850 µm were constructed (see Table 4). For each test a weight of the desired size of dried PPGs (250-mesh) swollen in distilled water was injected into slim tubes at a specific flow rate (0.5 ml/min) followed by an injection of distilled water.

After observing the sizes of the swelled particle gels at both the inlet and the outlet, it became clear that the PPGs were passing through the permeable media through the deformation mechanism. This was an indication that surface adsorption was the major factor for retention. This phenomenon was supported by the ratio of PPGs size to pore throat size. This ratio was computed using equation (2) as shown in Table 4.

The difficulty of passage for hard particles is higher than the soft ones to pass through the pore networks and throats; and due to this fact harder particles have higher retention in the porous media (Wu and Bai,

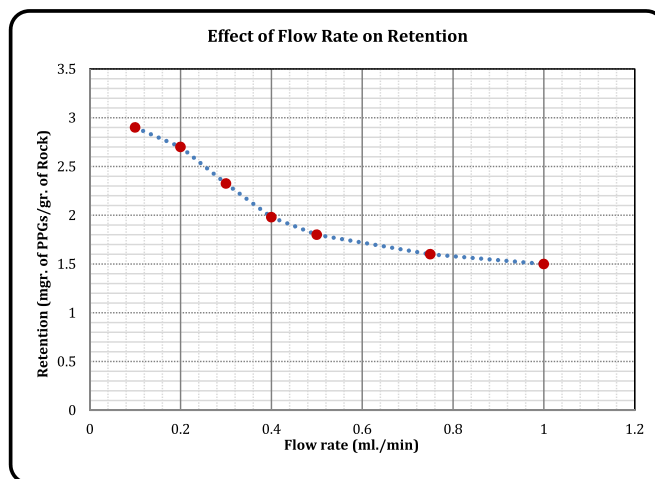


Fig. 6. Effect of flow rate on PPGs retention in porous media.

2008). When the swelling ratio was increased, the PPGs softened and the retention decreased. It is in accordance with observation of Saghafi et al. (2016c). By increase of swelling ratio, particles became softer, and less retention was observed. The results are illustrated in Fig. 7. Also it is worth to mention that with increasing temperature, the movement of adsorbed particles will increase. When the temperature was increased, the retention amount decreased. This was due to the separation of the adsorbed PPGs from the grounded core's surface.

3.4. Effect of permeability

Four different permeabilities were achieved by packing four slim tubes with the sand particles of varying diameter. Based on permeability-porosity relationships, it can be inferred that permeability is proportional to square radius of pores. Whereas the porosity is only function of packing arrangement of grain when the grain size distribution is approximately in the same range. As shown in the fourth column of Table 5, pore diameter of these four slime tubes varies from 77 to 207. Thus, permeability values are different for these slime tubes. While porosity values are nearly the same that indicate similar packing arrangement (Hexagonal or Orthorhombic) of crushed carbonate rocks for all slim tubes. Subsequently, the dried particle gel was sieved using a 20-mesh diameter to obtain PPGs with a diameter ranging from 44 µm to 63 µm. Then, the PPGs were fully swollen in distilled water at a constant temperature of 95 °C. This increased the average radius of the PPGs by a factor of approximately 3.7. As illustrated in Table 5, the hydrodynamic pore sizes (calculated from Eq. (2)) of the slim tubes and the PPGs size to pore throat size ratio ranged between 0.99 and 2.68.

During the test, the temperature was maintained at 95 °C. On the other hand, the rate of injection was maintained at 0.5 ml/min. At first, a gradual increment of the retention amount was recorded as the porosity of the slim tubes was reduced from 395 to 137 Darcy (as illustrated in Fig. 8). The fact that the swollen PPGs size to pore throat size

Table 3
Slim tubes specification of retention tests-effect of flow rate.

No.	Flow rate (ml/min)	Permeability (Darcy)	Porosity (%)	Equivalent hydrodynamic pore diameter (µm)	Average PPGs diameter before swelling (µm)	Average PPGs diameter after swelling (µm)	Ratio of PPGs diameter to hydrodynamic pore diameter
1	0.1	136	39	120	53.5	206	1.72
2	0.2	137	39.5				
3	0.3	136.5	39				
4	0.4	138	39				
5	0.5	137	39.5				
6	0.75	137.5	39.5				
7	1.0	138	39				

Table 4
Slim tubes specification of retention tests-effect of temperature.

No.	Temperature (°C)	Permeability (Darcy)	Porosity (%)	Equivalent hydrodynamic pore diameter (µm)	Average PPGs diameter before swelling (µm)	Average PPGs diameter after swelling (µm)	Ratio of PPGs diameter to hydrodynamic pore diameter
1	45	136	39	120	53.5	201	1.67
2	60	137	39.5			205	1.71
3	80	136.5	39			206	1.72
4	95	136	38.5			206	1.72

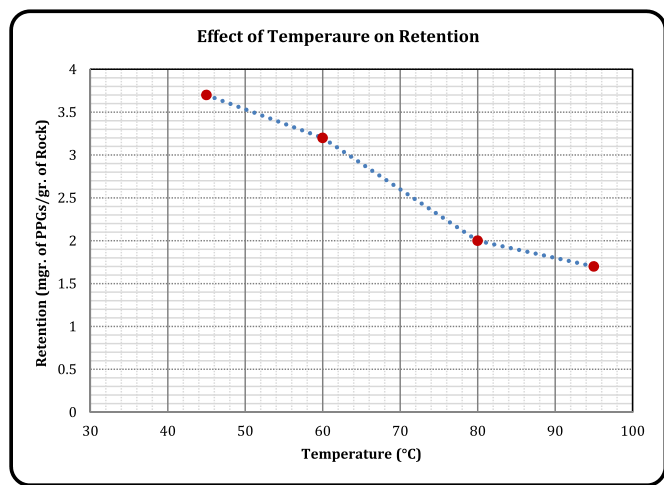


Fig. 7. Effect of temperature on PPGs retention in porous media.

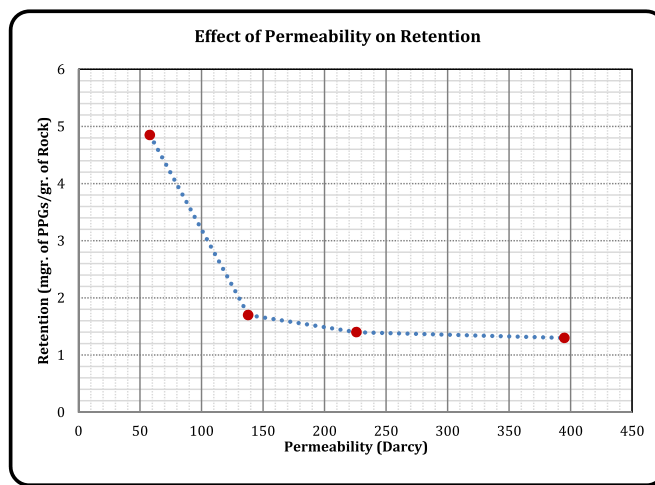


Fig. 8. Effect of permeability on PPGs retention in porous media.

ratio is less than 2.0, is an indication that the swollen particle gels moved through the permeable media due to deformation. For such a case, the surface adsorption was the determinant factor in retention. The increment in surface adsorption when the porosity was decreased is attributed to the reducing size of the sand particle, and hence increased surface area to adsorb more particle gels.

As illustrated in Fig. 8, reducing the porosity from 137 to 58 Darcy renders the PPGs size to pore throat size ratio at 2.56. It is not possible for the PPGs to pass through the permeable media at this ratio. However, introducing a threshold pressure will help in breaking down the PPGs, so that they pass through the porous media. The Breakage-passage pattern for the 2.56 ratio was supported by monitoring the size of the PPGs in the effluent. For media with high permeability (i.e., 58 Darcy), the ratio increased significantly. This indicates that entrapment was the dominant mechanism for retention. As such, a rapid increment in retention was observed.

Table 5
Slim tubes specification of retention tests-effect of permeability.

No.	Permeability (Darcy)	Porosity (%)	Equivalent hydrodynamic pore diameter (µm)	Average PPGs diameter before swelling (µm)	Average PPGs diameter after swelling (µm)	Ratio of PPGs diameter to pore diameter	PPG injection pressure drop (psig)
1	395	39	207	53.5	206	0.99	1.85
							1.83
							1.86
							1.86
2	226	39.5	156			1.32	3.10
							3.11
							3.13
							3.13
3	137	40	120			1.71	5.00
							5.04
							4.95
							4.95
4	58	41	77			2.68	11.00
							11.11
							10.95
							10.95

4. Conclusions

1. PPGs retention decreased as the flow rate, permeability and temperature of the porous media increased.
2. There was a relationship between the passing mechanism of PPGs through porous media and the particle-opening ratio. In passage pattern, adsorption mechanism was dominant in retention process and retention increased when using a smaller size of PPGs product and decreased as the flow rate, permeability and temperature of the porous media increased.
3. In breakage-passage pattern, when the ratio of size of swelled PPGs to pore throat size to increased certain value, entrapment was the main mechanism in retention process and retention increased dramatically by using a larger size of PPGs and lower permeability of porous media.
4. These novel PPGs can be successfully injected into reservoirs. Because, the injection velocity near the wellbore and reservoir temperature are usually high enough to lower the PPGs viscosity

and the amounts of PPGs retention. Therefore, penetrating deeply into reservoir will be possible.

References

- Al-Ibadi, A., Civan, F., 2013. Experimental investigation and correlation of thermal effects on near-wellbore formation treatment by gel particles. In: SPE International Symposium on Oilfield Chemistry. Society of Petroleum Engineers.
- Almohsin, A.M., Bai, B., Imqam, A.H., Wei, M., Kang, W., Delshad, M., Sepehrnoori, K., 2014. Transport of nanogel through porous media and its resistance to water flow. In: SPE Improved Oil Recovery Symposium. Society of Petroleum Engineers.
- Appelo, C.A.J., Postma, D., 2005. *Geochemistry, Groundwater and Pollution*. CRC press.
- Bai, B., Huang, F., Liu, Y., Seright, R.S., Wang, Y., 2008. Case study on preformed particle gel for in-depth fluid diversion. In: SPE Symposium on Improved Oil Recovery. Society of Petroleum Engineers.
- Bai, B., Li, L., Liu, Y., Liu, H., Wang, Z., You, C., 2007. Conformance control by preformed particle gel: factors affecting its properties and applications. *SPE Reserv. Eval. Eng.* 10, 415–421.
- Bai, B., Shuler, P., Qu, Q., Wu, Y., 2009. Preformed Particle Gel For Conformance Control. Presentations. (Missouri Energy Summit 2009).
- Bai, B., Zhang, H., 2011. Preformed-particle-gel transport through open fractures and its effect on water flow. *SPE J.* 16, 388–400.
- Bai, B., Zhou, J., Liu, Y., Tongwa, P., 2013. Thermo-dissoluble polymer for in-depth mobility control. In: IPTC 2013: International Petroleum Technology Conference.
- Chauveteau, G., Tabary, R., Blin, N., Renard, M., Rousseau, D., Faber, R., 2004. Disproportionate permeability reduction by soft preformed microgels. *Soc. Petroleum Eng.*
- Chauveteau, G., Tabary, R., Le Bon, C., Renard, M., Feng, Y., Omari, A., 2003. In-depth permeability control by adsorption of soft size-controlled microgels. In: SPE European Formation Damage Conference. Society of Petroleum Engineers.
- Cozic, C., Rousseau, D., Tabary, R., 2008. Broadening the application range of water shutoff/conformance-control microgels: an investigation of their chemical robustness. *Soc. Petroleum Eng.*
- Durán-Valencia, C., Bai, B., Reyes, H., Fajardo-López, R., Barragán-Aroche, F., López-Ramírez, S., 2014. Development of enhanced nanocomposite preformed particle gels for conformance control in high-temperature and high-salinity oil reservoirs. *Polym. J.* 46, 277–284.
- Elsaraf, M.O., Bai, B., 2013. Effect of strong preformed particle gel on unswept oil zones/areas during conformance control treatments. In: EAGE Annual Conference & Exhibition Incorporating SPE Europec. Society of Petroleum Engineers.
- Farasat, A., Sefti, M.V., Sadeghnejad, S., Saghafi, H.R., 2017a. Effects of reservoir temperature and water salinity on the swelling ratio performance of enhanced preformed particle gels. *Korean J. Chem. Eng.* 34, 1509–1516.
- Farasat, A., Vafaie Sefti, M., Sadeghnejad, S., Saghafi, H.R., 2017b. Mechanical entrapment analysis of enhanced preformed particle gels (PPGs) in mature reservoirs. *J. Petroleum Sci. Eng.* 157, 441–450.
- Goudarzi, A., Zhang, H., Varavei, A., Taksaudom, P., Hu, Y., Delshad, M., Bai, B., Sepehrnoori, K., 2015. A laboratory and simulation study of preformed particle gels for water conformance control. *Fuel* 140, 502–513.
- Gruesbeck, C., Collins, R.E., 1982. *Entrainment and Deposition of Fine Particles in Porous Media*.
- Imqam, A., Bai, B., 2015. Optimizing the strength and size of preformed particle gels for better conformance control treatment. *Fuel* 148, 178–185.
- Imqam, A., Bai, B., Al Ramadan, M., Wei, M., Delshad, M., Sepehrnoori, K., 2014. Preformed-particle-gel extrusion through open conduits during conformance-control treatments. *SPE J.*
- Saghafi, H., Naderifar, A., Gerami, S., Farasat, A., 2016a. Performance evaluation of viscosity characteristics of enhanced preformed particle gels (PPGs). *Iran. J. Chem. Chem. Eng. (IJCCE)* 35, 83–92.
- Saghafi, H.R., Emadi, M.A., Farasat, A., Arabloo, M., Naderifar, A., 2016b. Performance evaluation of optimized preformed particle gel (PPG) in porous media. *Chem. Eng. Res. Des.* 112, 175–189.
- Saghafi, H.R., Naderifar, A., Gerami, S., Emadi, M.A., 2016c. Improvement in thermo-chemical stability of nanocomposite preformed particle gels for conformance control in harsh oil reservoir conditions. *Can. J. Chem. Eng.* 94, 1880–1890.
- Sang, Q., Li, Y., Yu, L., Li, Z., Dong, M., 2014. Enhanced oil recovery by branched-preformed particle gel injection in parallel-sandpack models. *Fuel* 136, 295–306.
- Seright, R., 1997. Use of preformed gels for conformance control in fractured systems. *SPE J.* 12, 59–65.
- Tang, H., 2007. Preformed Particle Gel for Conformance Control in an Oil Reservoir. Google Patents.
- Wang, J., Liu, H-q, Wang, Z-l, Hou, P-c, 2012. Experimental investigation on the filtering flow law of pre-gelled particle in porous media. *Transp. Porous Med.* 94, 69–86.
- Wu, Y.-S., Bai, B., 2008. Modeling particle gel propagation in porous media. *Soc. Petroleum Eng.*
- Zamani, A., Maini, B., 2009. Flow of dispersed particles through porous media — deep bed filtration. *J. Petroleum Sci. Eng.* 69, 71–88.