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Research on Profile Control and Water Shut-off Performance of Pre-crosslinked Gel Particles and Matching Relationship between Particle and Pore Size[1]

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Abstract: Experiments on injectivity and profile control performance of pre-crosslinked gel particles widely used in oilfields were done .The results show that, the injectivity of pre-crosslinked gel particle is poor Most of particles pile up in the front of sand pack, and the migration distance of pre-crosslinked gel particles is less than twenty centimeter, which lead to the formation of filter cake and the poor effects of depth profile control. The injection of pre-crosslinked gel particle is selectivity. In the early stage of profile control, the diversion rate of low permeability layer increases slightly. After long-term waterflooding, due to the easily breakthrough in higher permeability layers, the diversion rate of low permeability layer declines in comparison that before the operation. It is indicated that pre-crosslinked gel particles will harm low permeability layers. It is calculated and analyzed that the diameters of current pre-crosslinked gel particles are bigger than pore size. Theoretically, current pre-crosslinked gel particles are difficult to be applied in depth profile control.
Key words: pre-crosslinked gel particle; profile control and Water Shutoff; particles diameter; pore size

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Many oil fields in China has entered the high water cut production period or period of high water cut, oil production wells water production rate has reached 80% or even more than 90%. Oilfield Injection Water has formed a lot of inefficient or ineffective circulation, which not only reduces the oil production efficiency but also reduces China's strategic energy oil production, with affecting the national energy security. it is an important measure to ensure national energy security by the effective water shutoff and profile control operations. Water shutoff profile control technology as an important measures to improve the efficiency of water injection to achieve stable oil production and controll the water production , has always been concerned. In recent years we proposed a new type of water shutoff and profile modification that is pre-crosslinked gel particles.this paper Carried out experimental analysis for its injection and profile modification .

1. INJECTION EXPERIMENT MODEL

This experiment used 1m long unconsolidated sand as a model,which has five pressure measuring points,it could record and monitor the pressure distribution along the way. It determine the size of the pre-crosslinking of different particles of the characteristics of migration and blocking at different permeability conditions ; Such as Figure 1.

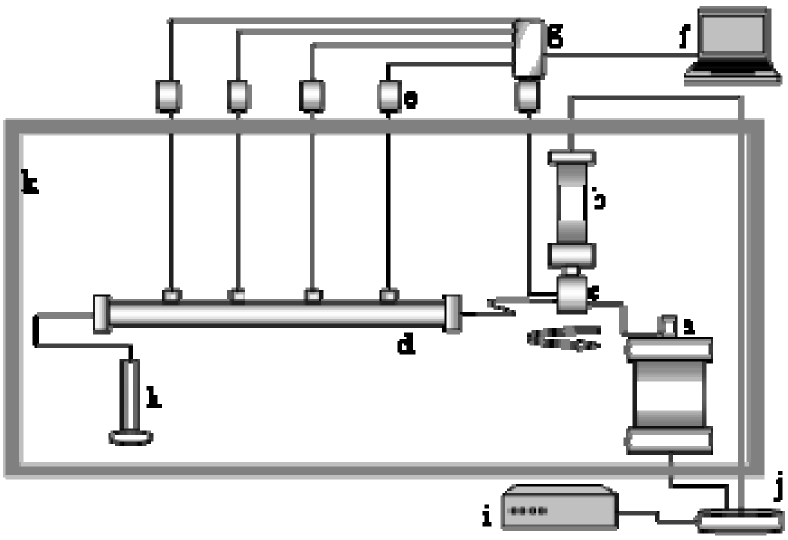


Fig 1. The Experminent Model for Injectivity Evaluation

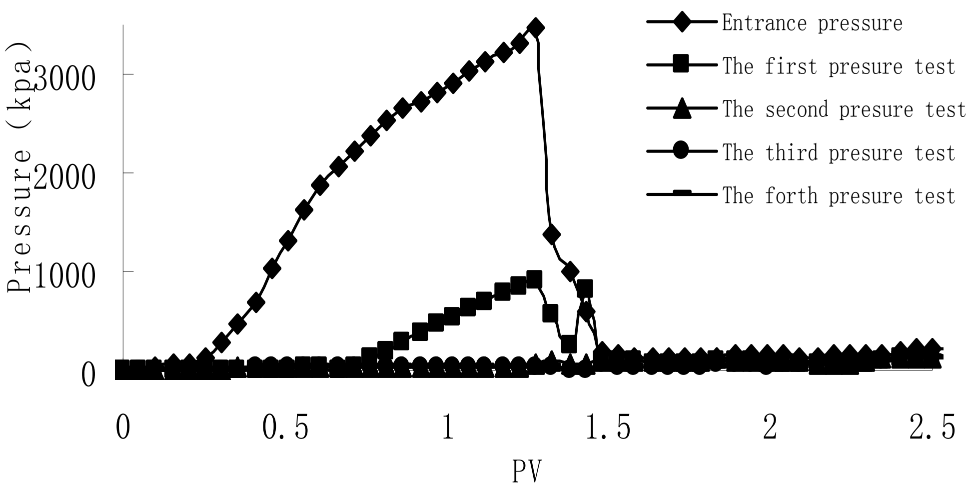
The middle container with simulated formation water b. The middle container with pre-crosslinked gel particles c.Three control valves d.Sand tube e.Pressure sensors f.Computer g.Pressure sensor module h.Measuring cylinder i. Advection pump j.Six-way valve K.Incubator

2. THE MIGRATION FEATURES OF THE PRE-CROSSLINKED GEL PARTICLES

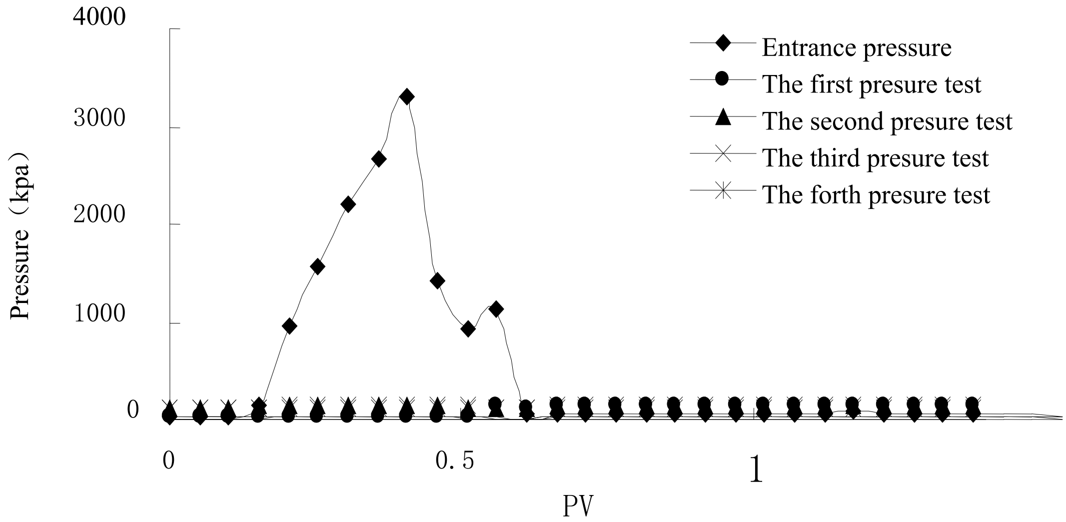
2.1 The Migration Features of the pre-crosslinked gel particles

In this experiment Model were average divided into 5 by four pressure tests point. When the segment test point pressure rises, you can explain pre-crosslinked gel particles arrive at the paragraph. and it has certain degree of plugging effect. Model uses 60 mesh quartz filling. permeability is grade Ⅱ,permeability is about 800mD .when we inject pre-crosslinked gel particles of 150 mesh. The following is the pressure curve .

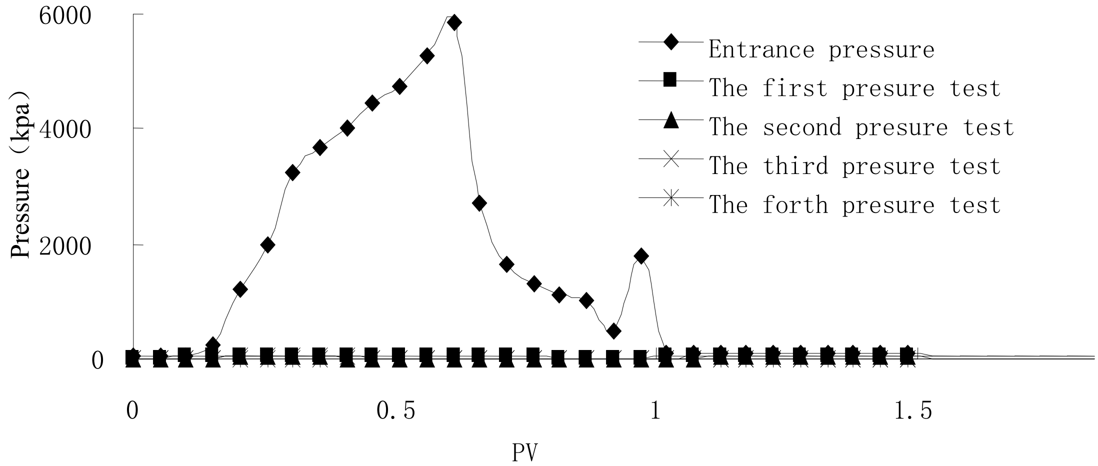
0.3PV150 mesh the pre-crosslinked gel particles inject 60 mesh sand model pressure variation curve



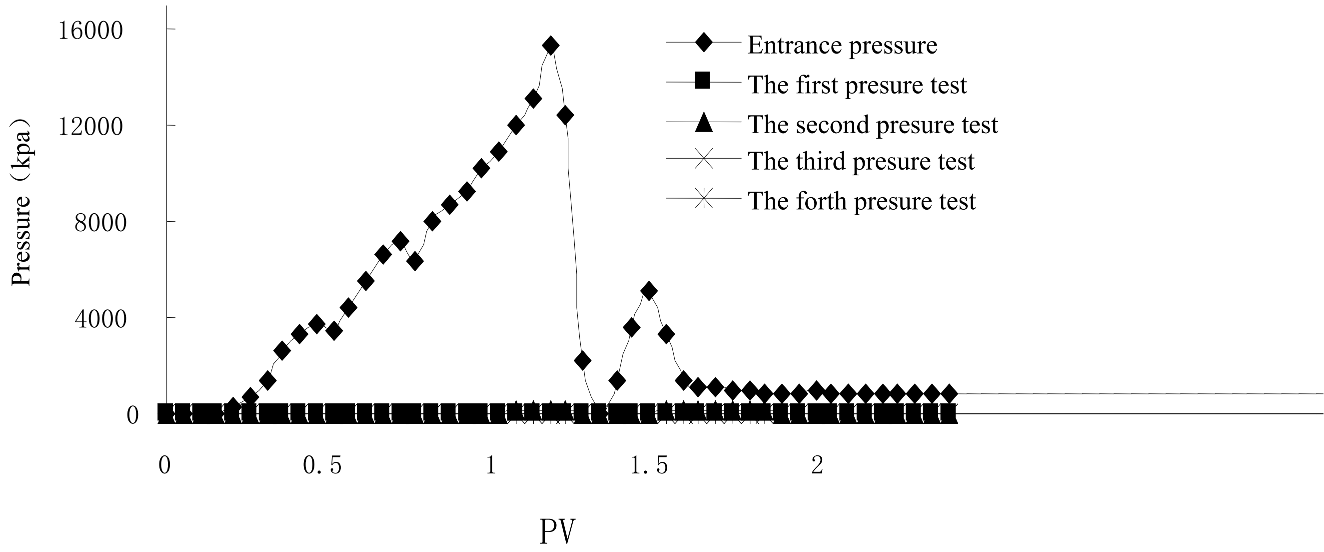
a. Injecting 1PV the pre-crosslinked gel particles of 150 mesh on the 60 mesh sand model



b. Injecting 0.3PV the pre-crosslinked gel particles of 100 mesh on the 60 mesh sand model



c. Injecting 0.6PV the pre-crosslinked gel particles of 100 mesh on the 60 mesh sand model



d. Injecting 1PV the pre-crosslinked gel particles of 100 mesh on the 60 mesh sand model

Fig.2 The pressure change curves

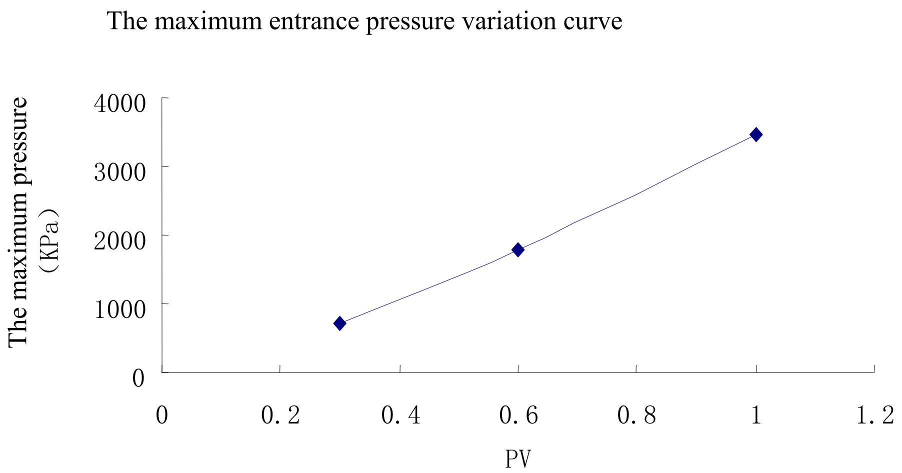


Fig.3 The maximum entrance pressure variation curve

As Fig.2 shows, ①the pre-crosslinked gel particles did not achieve the desired effect of long-distance migration. When we inject relatively small PV, the pressure point without the entrance pressure measure point all were not significantly show. When injected only 1PV the first pressure measuring point produce pressure .It Shows that the majority of the injected particles deposited on the front of the unconsolidated sand, failed to achieve the long-distance migration, let alone achieve the desired depth profile modification . ②as figure 3 shows. The maximum injection pressure increased with the increase of the number of the PV. ③If it has not stable injection pressure ,it can not injected well .

2.2 Injection characteristics of preformed gel particles

Usually pre-crosslinked gel particles through porous media has the following several ways：1, smooth injection, that is, the water-swelling diameter of pre-crosslinked gel particle is smaller than the core throat diameter. Or according to the “1/3 bridging theory”, it is possible to pass smoothly when the pre-crosslinked gel particle diameter is smaller than one-third of the core throat diameter. However, particles of this size injected into the core to carry on the water plugging and profile control operation, its function is obviously invalid.2, deformation and injection, when the pre-crosslinked gel particle is larger than the core diameter, particles form the stack at the injection end and a large number of pre-crosslinked gel carrying liquid inject into the core. 3, extrusion broken and injection, when the pre-crosslinked gel particle is much larger than the core throat diameter, the carrier fluid will massively enter into the core leaving the particles deposited on the injection face. When the concentration of the pre-crosslinked gel particles solution increased to a certain extent, the particles will gradually enter to the core due to the role of force. In this process, the particles will be cut into tiny particles and the particles can be injected on this condition.4, squeezing deformation of injection. When the difference between particles and core-hole throat is extremely large, the particles are more concentrated after the massive de-solvent. Because of the pressure of solution continuing to step-up, large amount of particles accumulate at the surface. At the same time, those particles will be squeezed into the core and the particles will be transformed from bulk to banding. Also the diameter change will be dozens of times.

2.3 Pre-crosslinked gel particles plugging performance

Here are the several kinds of evaluation index of water plugging profile modification agent:

(1) Residual resistance coefficient of water phase (RRW): the ratio of water phase permeability before and after the water shut-off. The formula is :

$F_{rrw} = K_w a / K_{wb}$

In the formula: K_{wa} —water phase permeability before the treatment；

K_{wb} —water phase permeability after the treatment.

（2）water plugging rate(E)：It refers to the extent of the blocking agent to reduce core permeability. Expression:

$E = [1 - K_{wb}/K_{wa}] \times 100\ \%$

(3) Breakthrough pressure P_o: the critical pressure of injected water breakthrough the plugging slug.

The Summary of plugging index using different mash pre-crosslinked gel particles plugging different sand packs:

As we can seen in Table 1：(1) Under the condition of same medium and mesh of pre-crosslinked gel particles, , Residual resistance coefficient, water plugging rate, Breakthrough pressure and other parameters go up with the increase of PV. (2) The particles mostly piles up at the surface of injection and in the transportation pipeline, has not been able to enter in the sand packs when 100 mash particles inject into 60 mash sand pack by 0.3PV and 0.6 PV. Therefore the residual resistance coefficient and water plugging rate are smaller than the ones of 150 mesh particles. (3) When 100 mash particles inject into 60 mash sand pack and the injection volume is 1 PV, residual resistance coefficient and water plugging rate increased sharply. This phenomenon is mainly due to particles and pore throat does not match, so the particles can not be successfully injected. Then the broken particles pushed into the sand pack and sealed blocked the water channels, this caused the sharply increase situation.（4） the residual resistance coefficient and water plugging ratio values are higher when 40 mesh of sand pack is injected by 120 mesh of particles. This indicates that the particle diameter is larger than the pore throat diameter and the injection method is already the extrusion broken and injection at this time. Pre-crosslinked gel particles are entirely in the form of colloidal instead of particles.

Table 1: Blocking Evaluation Parameters

		PV	F_{RRW}	E（%）	Po（KPa）	The maximum pressure during injection（KPa）
60 mesh sand packs	150 mash pre-crosslinked gel particles	0.3	2.24	55.39	183	726
		0.6	2.45	59.18	192	1783
		1	2.98	66.47	216	3454
	100 mash pre-crosslinked gel particles	0.3	1.69	40.85	73	3306
		0.6	2.00	49.87	1769	5867
		1	22.80	95.61	5055	15299
40 mesh sand packs	120 mash pre-crosslinked gel particles	0.3	298.17	99.66	5677	16395.6
		0.6	357.80	99.72	8738	29258.9

3. PRE-CROSSLINKED GEL PARTICLES PROFILE CONTROL CHARACTERISTICS

3.1 Experimental model of profile control

The injection medium is a two-tier heterogeneous core, the upper core's permeability is 800md, the lower core's permeability is 3200md, permeability radio is 4 and there is an impenetrable layer in the middle. This model uses the same-in-different-out pattern which means the injection end is at the same end but the out side is divided into upper and lower faces. We use two cylinders to measure the shunt flow volume of each layer. Using this way we can get different shunt flow volume and permeability to aqueous data in the case of different diameter of injected pre-crosslinked gel particles, so we can evaluate the selective plugging ability of pre-crosslinking body and identify the tenability of pre-crosslinked gel particles on the non-homogeneous layer.

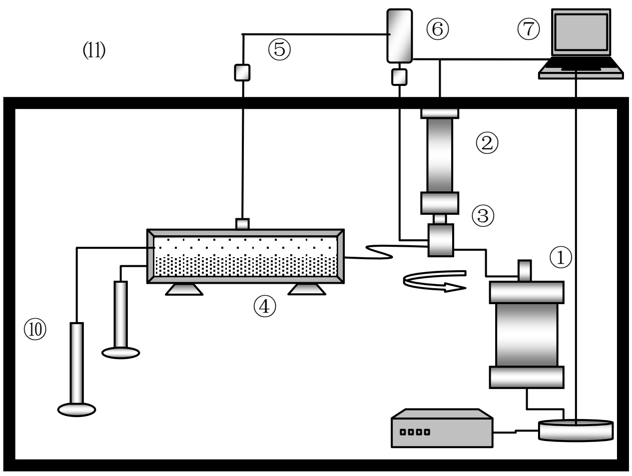


Fig.4 Experimental chart for profile control

①The middle container with simulated formation water, ②The middle container with pre-crosslinked gel particles, ③Three control valves, ④Core holder, ⑤.Pressure sensors, ⑥Pressure sensor module, ⑦Computer, ⑧Advection pump, ⑨Six-way valve, ⑩Measuring cylinder, ⑪ .Incubator.

3.2 Results and discussion of profile control characteristics experiment

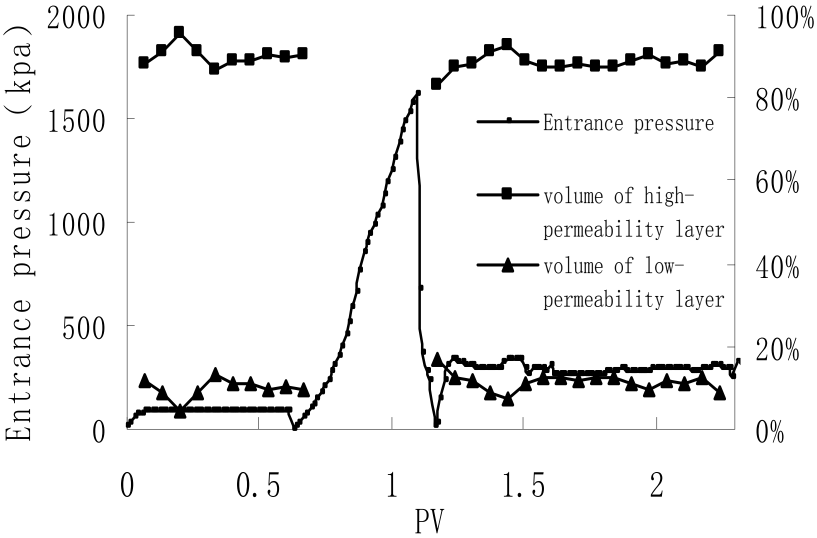


Fig. 5 Profile control performance of A1-type pre-crosslinked gel particles into the four-fold differential model

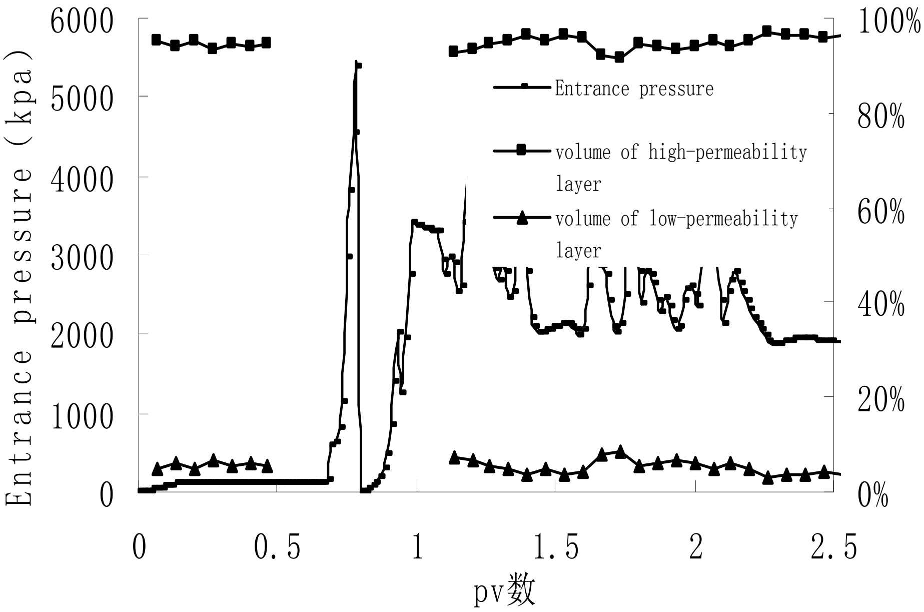


Fig. 6 Profile control performance of A2-type pre-crosslinked gel particles into the four-fold differential model

Table 2: Blocking Evaluation Parameters of profile control experiments

Types	RRW	E%	P0（KPa）	The maximum pressure during injection（KPa）	the original Shunt rate （%）	The shunt rate after treatment （%）
A1	3.86	74.12	343	1623	10.71	12.50
A2	19.00	94.74	4954	5371	6.25	8.26

We can get the following conclusion from Table 2: (1) the plugging effect of pre-crosslinked gel is good. The water plugging rate were 74.2% and 94.74%, the residual resistance coefficient were 3.86 and 19 respectively. (2) AS it shown in the Fig. 5 and 6, the shunt rates before and after treatment have not improved, and the shunt flow volume of low-permeability layer is still continuing at a very low level which means the profile control is less effective.

(3) After injected much PV of simulation formation water into the two models above we can find that almost all of the injected water passed through the high permeability layers instead of the lower one.

The reason for this phenomenon is duo to the diameter of pre-crosslinked gel did not fit well with the core throat, causing the particles were squeezed into the rock and the characteristic of pre-crosslinked gel particles that can selectively access to the high permeability layer could not be represented. When carried on the following water flood, the water flood breakthrough in high permeability layer is much earlier than in the low permeability layer after the pre-crosslinked gel particles were squeezed both into High-permeability layer and low permeability layer, because the low permeability layer is still being blocked by the pre-crosslinked gel particles. Therefore, during a high PV water flooding, the flow of high-permeability layer is getting larger and larger and the Low-permeability layer has not still been activated.

4. PRE-CROSSLINKED GEL PARTICLES AND CORE THROAT DIAMETER COMPATIBILITY COMPUTATION

As we can see in the profile control performance test, the plugging is very effective but not profile control. The main reason for this result is that the pre-crosslinked gel is compatible with the diameter of core throat that means the diameter of particle is much larger than the pore throat radius. Under this condition, the pre-crosslinked gel particles are both injected in the low and high permeability layer at the same time that causes the overall decline of permeability. During the succeeding water flooding, the earlier breakthrough in high permeability layer causes the inefficient profile control and the decline of shunt rate in low permeability layer during a high PV water flooding.

4.1 Calculation method of permeability and pore throat radius

Accord to the Poiseuille equation, the capillary bundle flow q（cm3/s）:

$$q = \left(\frac{n\pi r^4}{8\mu} \right) \frac{\Delta p}{L} \qquad (4.1)$$

Flow can also be calculated by Darcy equation as follows:

$$q=\left(\frac{KA}{\mu}\right)\frac{\Delta p}{L} \qquad (4.2)$$

And: $A=n\pi r^2$ (4.3)

By equation (4.1) (4.2) and (4.3):

$$r=\sqrt{\frac{8k}{\phi}} \qquad (4.4)$$

According the research of zhu huaijiang et al., in the common range of permeability (800～1600mD), the natural core's pore throat median radius is 5. 48～8. 17μm, the pore median radius is 37. 17～40. 18μm ; the quartz sand cemented core's pore throat median radius is 3.71～5.48μm, the pore median radius is 52. 48～57. 21μm. The measurement results showed that: the measured pore throat radius is different from the calculated results but the difference is only a few microns. The results showed that the average of throat radius is in the range of 4～16μm.

4.2 Determination of pre-crosslinked gel particle diameter

Base on the "1/3 bridging theory" or "2/3 bridging theory", generally it is appropriate for the particle-based blocking agent's diameter to be 1 / 3 ~ 2 / 3 of the formation average pore diameter. According to the above formula we can get the particle's diameter against different permeability as table 3.

From Table 3 we can see that if the formation's permeability ratio is 4 and respectively, the permeability is 400 mD and 3200 mD, the particle size after expansion will be at micron level.

At present we can produce the pre-crosslinked gel particle at the micron level, but the particle will expand 30~200 times [7]after the contact with water, so it is difficult for particle to be at a micron magnitude after the expansion. It will be very difficult to inject the particles which are ten or a hundred times larger than the throat diameter. Usually they will be crushed and squeezed into the formation. Because of this, those pre-crosslinked gel particles will not have the selectivity during the profile control operation and this will cause the overall block. As the relationship between size of the pre-crosslinked gel particle and the throat diameter, the "1/3 bridging theory" will not available for the particle during the migration and blocking. As it shown in fig 5, the particles will accumulate at the end of the injection surface instead of entering the core entirely due to the mismatch between the particle diameter and the pore throat diameter. If the accumulation does not form at the goal stratum, the injected particles will be harmful to the other formation. So when carry on the pre-crosslinked gel profile control operation, we should use the layered injection but not the general injection. Otherwise, not only will not achieve the desired results, but also may play a role in the opposite.

Table 3: Correspondence table of permeability and pre-crosslinked gel diameter

K	R（μm）	Average particle diameter（μm）1/3~2/3	
0.4D	8.08	2.69	5.39
0.8D	11.43	3.81	7.62
1.6D	16.16	5.39	10.77
3.2D	22.86	7.62	15.24
6.4D	32.32	10.77	21.55
12.8D	45.71	15.24	30.48

Fig. 7 Pre-crosslinked gel stack at the injection end

Based on the experimental results and conclusions, we can the information that the prospect of particulate water shutoff profile control is very broad, but it is quite strict for the particle. The ideal pellet should have the following several natures: 1. the expanded particles should still occupy a micron dimension so that the particles can be successfully injected into the deep reservoirs and complete the flowing diversion. 2. The particles should have good flexibility, so that they can pass through the pore by Deformation.

The particle should be very good at anti-shear that is a certain intensity, to fight for the shearing during the migration process.4 low costs and can obtain the promotion and the application in the majority oil fields.

5. CONCLUSION AND SUGGESTION

1) This pre-crosslinked gel particle for long-distance migration has not been able to realize so it have not the function of depth profile control..

2) From the analysis of water phase residual resistance, water plugging rate and breakthrough pressure we can get conclusion that the pre-crosslinked gel particles plugging is effective.

3) When carry on the profile control performance experiment, the pre-crosslinked gel particle plays weak in overall profile control and diversion rate during the initial period of subsequent water flooding, it is harmful for the low permeability formation after the large PV injection.

4) The results of calculations show that the size of pre-crosslinked gel particles dose not match with the pore throat diameter which means that the particles can almost not be injected into the core smoothly and does not have the selectivity when use the general injection, so they are harmful for the non-target zones.

5) In order to achieve the selectivity of injection and depth profile control, the pre-crosslinked gel particles need to carry on a very big improvement.