A New Type of Gelled Foam Plugging Agent with Resistance to Temperature, Salt and Dilution

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Abstract. The conventional foam plugging agent is susceptible to factors such as dilution of formation water, high temperature and high salinity, which usually shortens its effective period and undermine its application. Based on conventional foam plugging agents, an anti-dilution gelled foam plugging agent suitable for oil reservoirs with high temperature and high salinity is proposed in this paper. The research results show that the density of the gelled foam plugging agent (0.6~0.9 g/cm³) is controllable and easy to prepare, and it can be stabilized at 130℃ and 2.2×10⁵mg/L mineralization for at least 72 h. The indoor physical simulation experiments show that the plugging rate of gelled foam plugging agent is more than 98%, and the plugging effect is obvious, showing a good channeling plugging capability.

1. Introduction
As the major oil fields in China enter the late stage of water injection development, the edge water and bottom water in the reservoir continue to break through, which leads to the increasing water production and decreasing oil production capacity of the oil well. At present, the vast majority of oil wells in China have entered the period of high-water content or extra high-water content [1], which is characterized by poor development effect and low economic benefits [2]. Therefore, it is very important to effectively block the high permeability water layer and improve the water flooding effect in the oil field.

The water plugging and profile control technology of oil fields is one of the most important measures to achieve stable production of oil reservoirs [3]. At present, the most widely-used chemical agents for oil field plugging are mainly polymer gel plugging agents, the plugging principle of which is based on physical plugging. It realizes water plugging with the gel producing physical plugging in the medium gap, due to the crosslinking effect produced by the contact of a large number of reactive groups on the polymer chain and crosslinking agent, through certain development changing into a net structure which can make the lattice structure contain water, thus forming a viscous and elastic freeze gel to achieve the effect of water plugging. It has the advantages of low cost, simple process and good plugging effect [4]. In addition, foam plugging agents have also entered the people's vision in recent years due to its excellent characteristics of low stratum damage, selective plugging and increasing reservoir flow resistance [5-8], allowing agents not only to block the high permeability layer, but also to improve the oil washing efficiency to a certain extent. The surfactant is a common foaming agent,
which can be adsorbed on the oil-water interface and reduce the interfacial tension between oil and water, thus facilitating the oil washing process.

Pu et al. [9] carried out an indoor experimental study on foam plugging using a foaming agent and the self-generating gas system developed by Xi’an Shiyou University. The experimental research results show that this self-generating foam plugging system has good results in both plugging and oil displacing, laying a theoretical foundation for its application in the oil field. Liu [10] adopted the technique of foam gel profile control for the current situation of water plugging and profile control in Liaohe Oil Field, and designed the nitrogen foam gel with good plugging ability through foaming agent screening, performance test of foaming agent, parameter optimization of nitrogen foam gel injection and other indoor experiments. The system constructed six wells in the Liaohe Oil Field, increasing oil by more than 2000 tons in a single cycle. Foam plugging agent is a modern water plugging technology developed in recent years, showing good effect and application effect, which is still a hot research direction.

However, there are a series of problems in the application of foam plugging agents. Due to the high temperature and high salinity of the reservoir, the stability of the foam plugging agent becomes worse and the half-life of the foam system is shortened. Because of the dilution effect of the formation water on the foam plugging agent, the viscosity loss is large, and the fluidity control ability is weakened, so it is difficult to maintain long-term water plugging control ability. Therefore, in this paper, an anti-dilution gelled foam plugging agent suitable for oil reservoirs with high temperature and high salinity is proposed. The purpose is to improve the stability of the conventional foam system by using the gel system with fast gel formation and strong gel formation strength at high temperature.

2. System preparation

2.1. Reagent
Gelled foam plugging agents include gel system and foam system. Gel system includes three kinds of reagents, acrylamide monomer (AM), N-N methylene bisacrylamide (MBA) and tert-butyl hydroperoxide (SA). The foam system includes two kinds of reagents, salt sensitive fast crosslinking polymers and the foaming agent Tetradecyl Hydroxysulfobetaine (THSB), among which the salt sensitive fast crosslinking polymer can rapidly form hydrogels to solidify and form a “quasi curing foam system” when it meets divalent ions (Ca\(^{2+}\), Mg\(^{2+}\), etc.) in solution. The foam system has good mechanical strength, structural strength and shear resistance, which can effectively resist formation water dilution of the system. The cationic solution was prepared with calcium chloride, and the simulated water (with mineralization degree of 2.2×10^5 mg/L) was used in the experiment.

2.2. Experimental method

2.2.1 Preparation method of plugging agent
The salt sensitive fast crosslinking polymer, foaming agent THSB, polymer gel system and tap water were stirred and mixed in a certain proportion (stirring and mixing time of 6-8 h) until the system was clear and uniform, forming the polymer base solution. The calcium chloride, polymer gel system and tap water are stirred and mixed (stirring and mixing time of 1-28 h) until the system is clear and uniform, forming divalent cationic base solution. The abovementioned polymer solution is poured into the high-speed agitator, and the speed of the agitator is set to 4000~5000 rpm. The stirring time is 5 min until the polymer solution forms a uniform and dense foam system. The above-mentioned foam system was injected from the bottom of the above mentioned divalent cationic base solution in the ratio of foam volume to divalent cationic liquid volume of 2:1~6:1, so that the foam and solution were well mixed. A “quasi curing foam system” was created by taking advantage of the rapid formation of hydrogels of the salt sensitive fast crosslinking polymer meeting the divalent cationic Ca\(^{2+}\). The density of the foam system was controlled (0.6~0.9 g/cm\(^3\)) by changing the gas-liquid ratio of the foam volume to the solution.
2.2.2 Indoor physical simulation experiment

In this section, indoor physical simulation experiments were conducted using the core to verify the plugging effect and plugging ability of the gelled foam plugging agent in the actual formation environment. The diagram of the indoor experimental device was shown in Figure 1. The solution (simulated water or gelled foam system) was injected into the core by a micro pump, and the gelled foam system forms gel in the core to stabilize the foam, so as to achieve the effect of plugging the high seepage channel in the core. The plugging rate was calculated by recording the core permeability in the experiment, and the plugging rate was used as an important indicator of the plugging effect.

![Figure 1. The diagram of the indoor experimental device: 1-pump, 2-gelled foam system, 3- simulated water, 4-pressure gauges, 5-core holder.](image)

3. Results and discussion

3.1. Effect of gelled foam plugging agent

The gelled foam plugging agent is prepared by mixing foam system and divalent cationic solution with the gas-liquid ratios of 3:1 and 4:1. The components are: 0.8% salt sensitive fast crosslinking polymer, 0.3% THSB, 9% AM, 0.6% MBA and 0.05% SA, respectively. The plugging agent is put into ampoule bottle and placed in an oven at 130℃ to observe the situation of gelled foam plugging agent continuously. The results of the gelled foam system at 130℃ and 2.2×10⁵ mg/L mineralization in 24h, 48h and 72h are shown in Figure 2.

![Figure 2. the gelled foam system at 130℃ and 2.2×10⁵ mg/L mineralization in 24h, 48h and 72h.](image)
As can be seen in Figure 2, after 72h in 130℃, the gelled foam plugging agent still does not show any signs of gel breakage and the foam system is intact, except for the color change due to the gelation of the AM monomer polymer gel system, and the state difference of foam is small compared with the one that just put into the oven. At the beginning of 130℃, the curing reaction of salt sensitive fast crosslinking polymer meeting the divalent cationic can improve the stability of the foam system with structural viscosity. As the gel system is gradually gelled, the gelation rate of the gel system is much larger than the rate of foam disappearance of the foam system, thus stabilizing the foam system.

3.2. Application effect of gelled foam plugging agent

Three outcrop cores with a length of 10 cm and an inner diameter of 2.5 cm are used to carry out the physical model experiment. Firstly, three cores are saturated with simulated water of 2.2×10^5 mg/L, and then placed in the core holder successively, which are marked as cores 1#, 2# and 3# respectively. Then, the cores are conducted water flooding with simulated water of 2.2×10^5 mg/L until the displacement pressure is stable and the permeability k0 before plugging is measured. The gelled foam plugging agent is prepared. The components of experimental system are 0.8% salt sensitive fast crosslinking polymer, 0.3% THSB, 9% AM, 0.6% MBA, 0.05% SA and 0.15% CaCl2. Then, gelled foam plugging agent of 0.3 PV is injected in reverse and 2.2×10^5 mg/L simulated water of 0.1 PV is injected in the slug-type. Finally, the core holder is placed in a thermotank at 130 ℃ for 2 days. After taking it out, the simulated water of 2.2×10^5 mg/L is used for water flooding until the displacement pressure is stable and the permeability k1 after plugging is measured. The plugging rate of three cores is calculated according to the formula E= (k0-k1) /k0. The test results of plugging performance are shown in Table 1:

| Cores | k0/μm² | k1/μm² | E/% |
|-------|--------|--------|-----|
| 1#    | 10.66  | 0.21   | 98.03 |
| 2#    | 30.72  | 0.33   | 98.91 |
| 3#    | 60.15  | 0.39   | 99.35 |

The experimental results show that the plugging rate of the gelled foam plugging agent can reach more than 98%, which can meet the plugging demand of high temperature and high salinity reservoirs, which can effectively block the high permeability layer of the formation, so as to achieve the goal of enhancing oil recovery.

4. Conclusion

The gelled foam plugging agent solves the problem of poor stability of conventional foam plugging agent. It can be stable for 3 days at 130℃ and 2.2×10^5 mg/L mineralization, effectively plugging high permeability layer with a plugging rate up to 98%. The appearance of gelled foam plugging agent provides a new idea for profile control and water plugging technology for oil reservoirs with high temperature and high salinity.

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